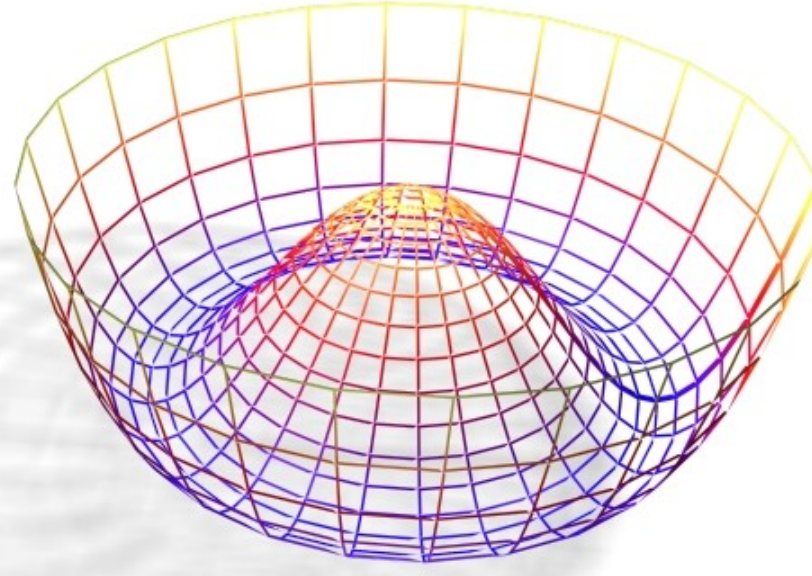
Seeking the Origin of Mass

Collider Searches for Higgs Bosons



Wade Fisher

Michigan State University

For the ATLAS, CDF, CMS & DØ collaborations

Today's Presentation

Higgs searches at colliders in a nutshell

- Brief history
- Context of modern Higgs searches
- Light overview of Tevatron and LHC experiments

Standard Model Higgs Searches

Beyond the

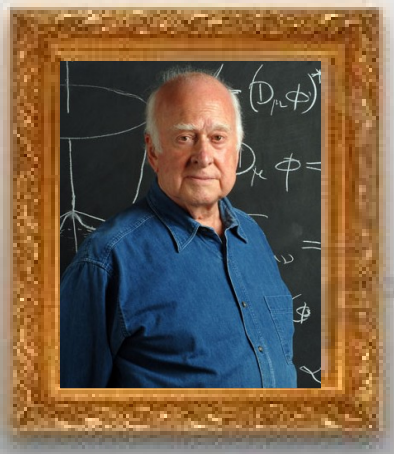
Standard Model Higgs Searches

A modest guess at things to come

"a rose by any other name"

2010 Sakurai Prize

... for "elucidation of the properties of spontaneous symmetry breaking in four-dimensional relativistic gauge theory and of the mechanism for the consistent generation of vector boson masses."



Electroweak Symmetry Breaking

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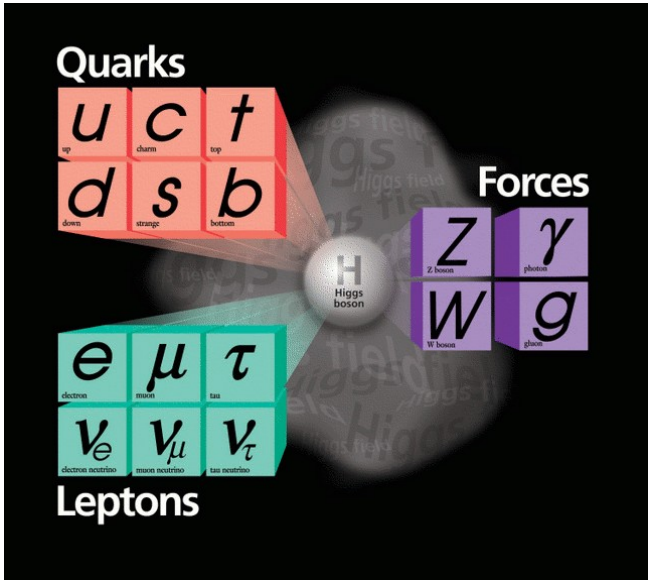
Higgs mechanism basics

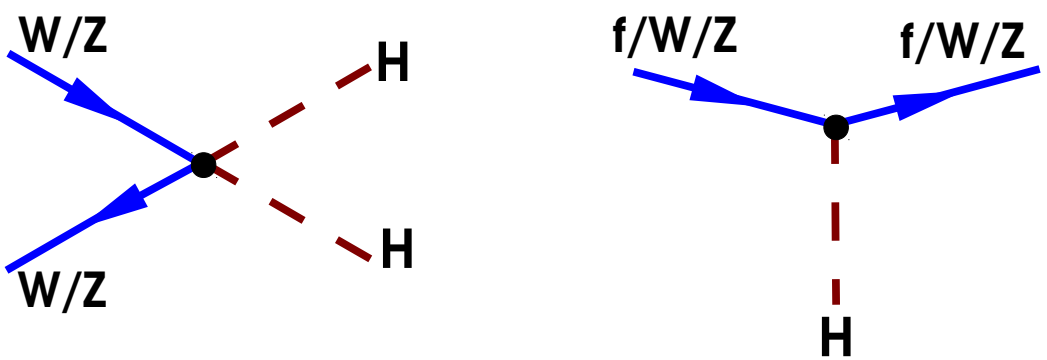
The idea: our universe is filled with a quantum field, which we call the Higgs field

Including this field in the EW Lagrangian gives rise to W/Z masses and preserves SU(2) gauge invariance

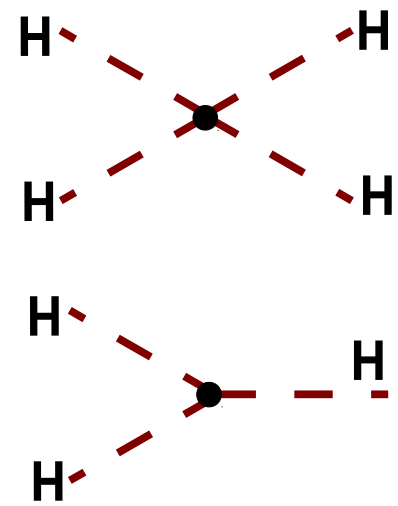
The quanta of the Higgs field is the Higgs boson



Higgs Field Interactions



Higgs Self Interactions



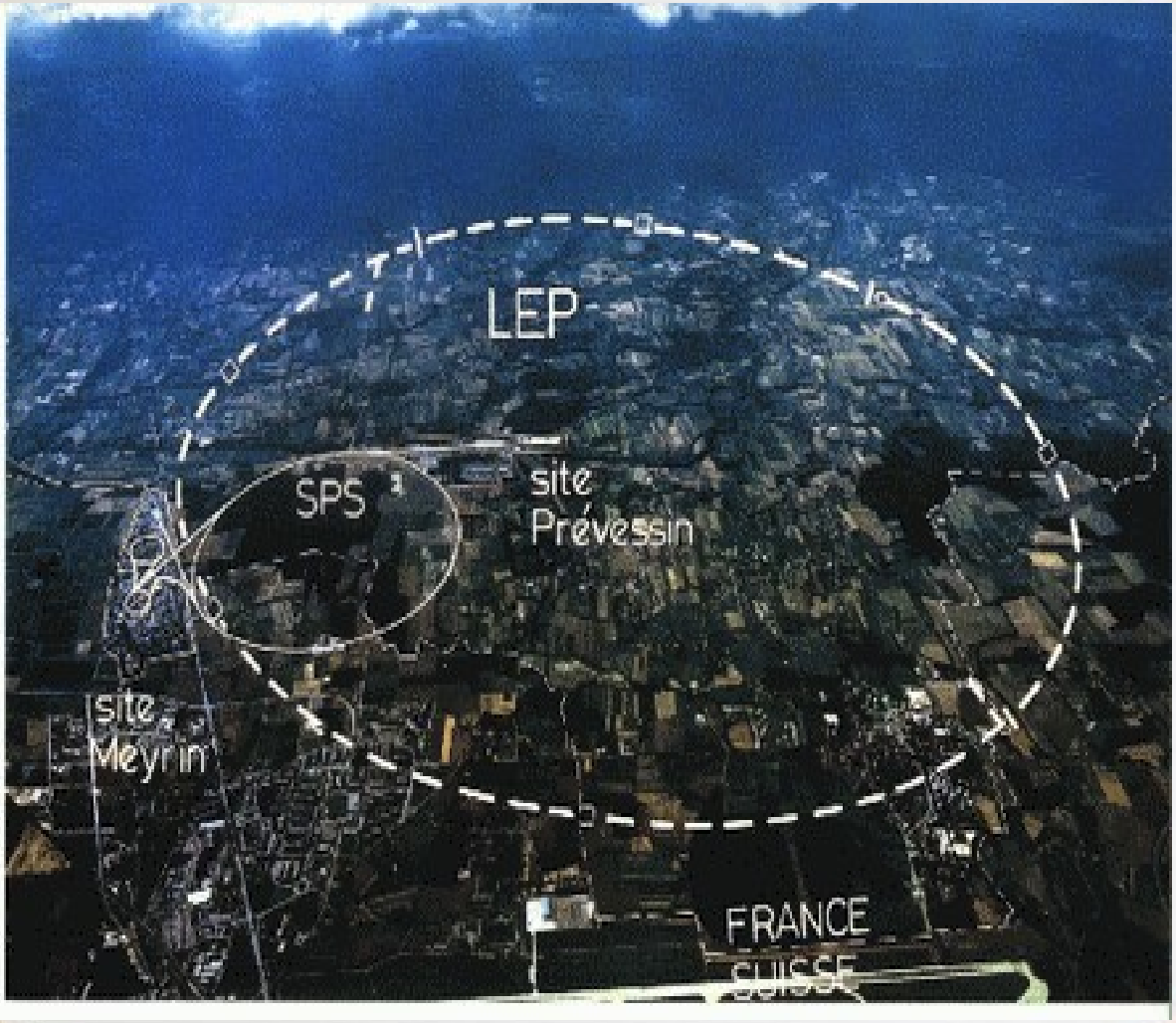
The mass of the Higgs boson is **not** predicted

If the Higgs does exist, its mass must be determined experimentally

What we ~~know~~ about the Higgs boson

DON'T KNOW

LEP 1989-2000



Direct Experimental Evidence

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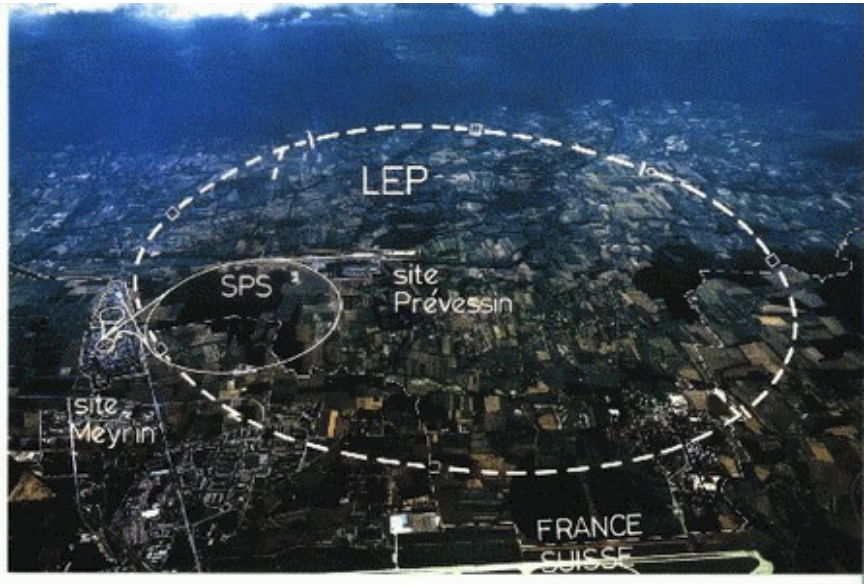
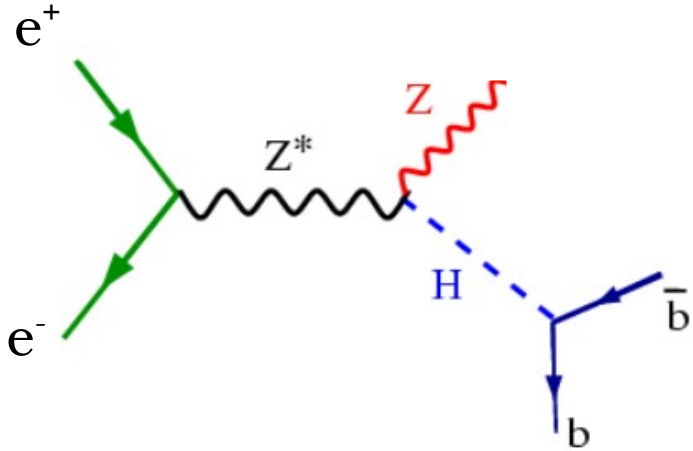
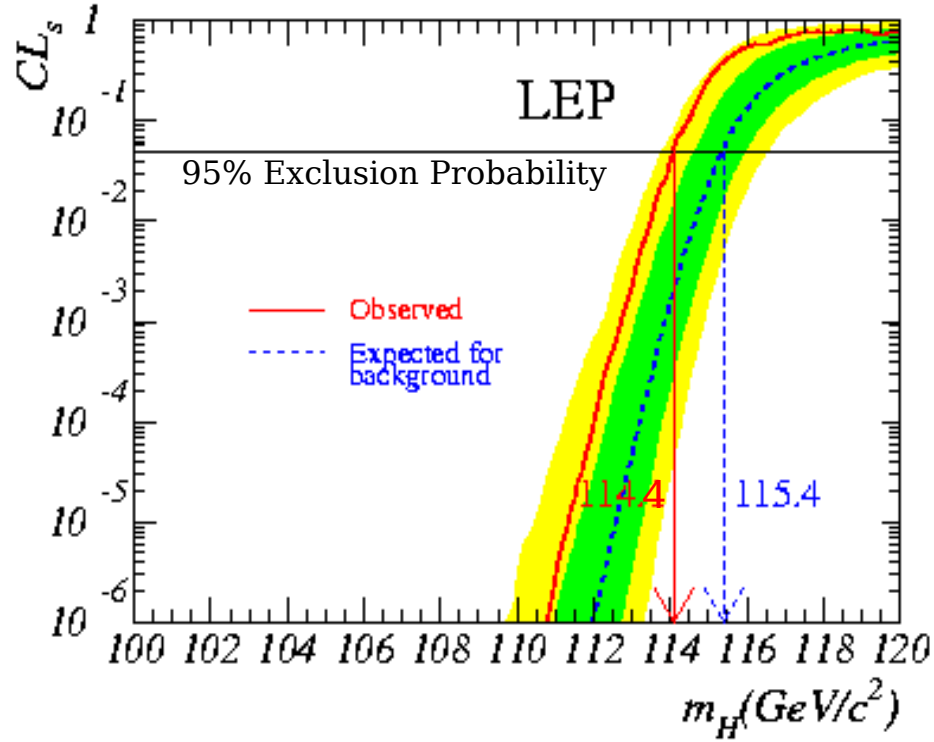
Direct searches have limited the potential places the Higgs can hide

LEP II direct search: M_H >114.4 GeV at the 95% Confidence Level (C.L.)



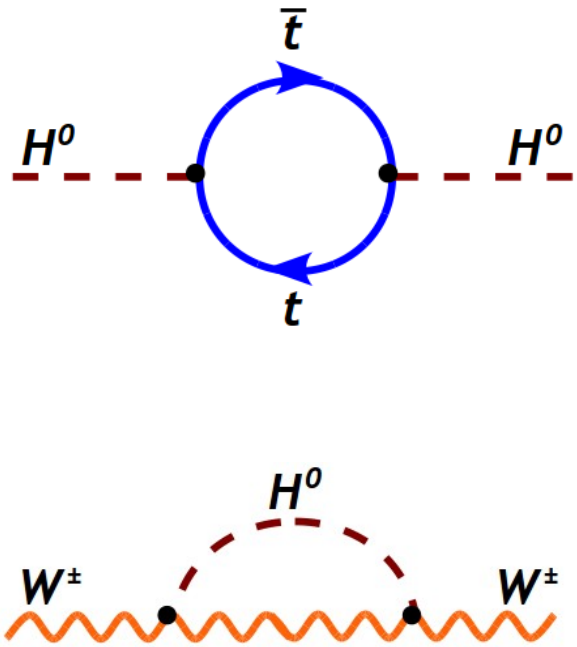


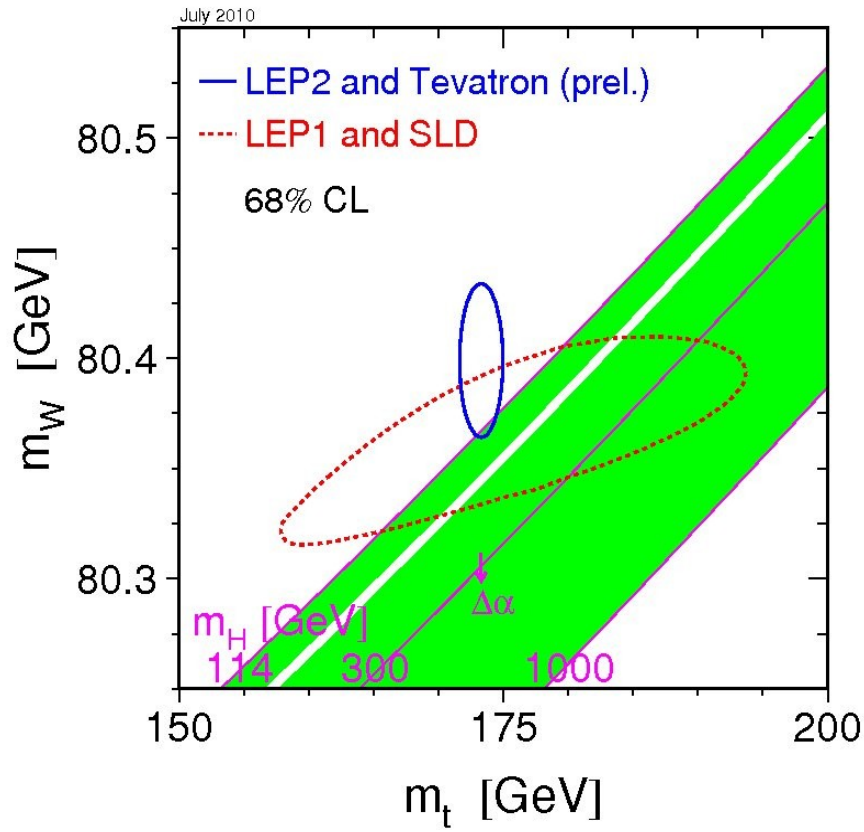


Indirect Experimental Evidence

The interactions between SM particles and the Higgs provide indirect evidence through radiative corrections to particle masses

- The heaviest particles couple most strongly to the Higgs
- **Refinements of top-quark and W-boson masses can indicate Higgs mass**





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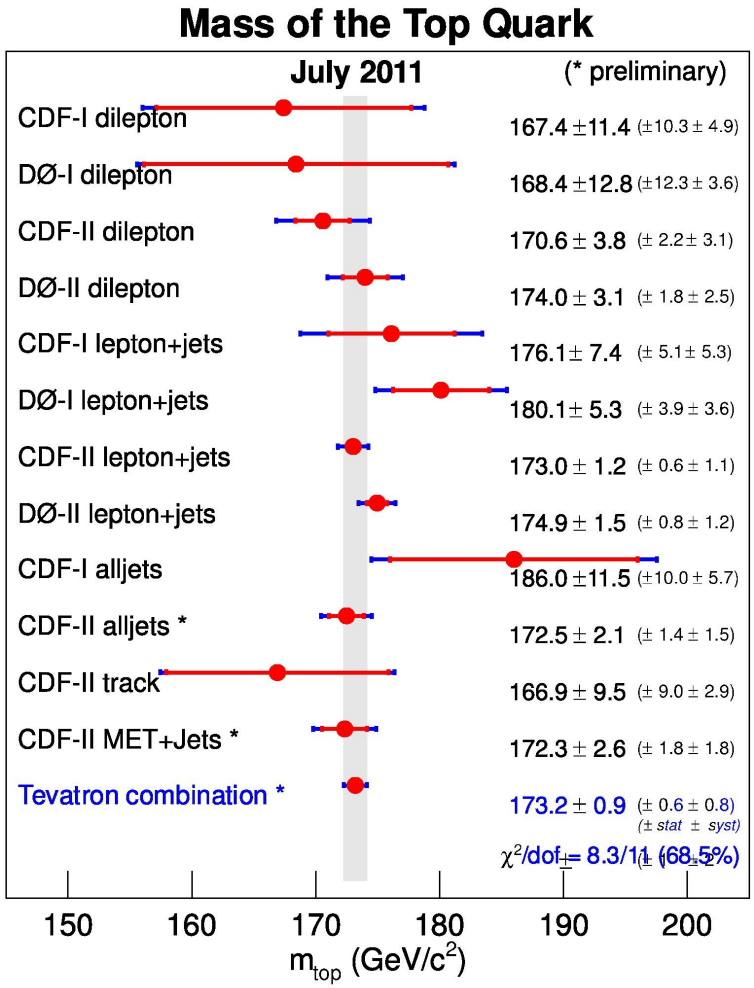

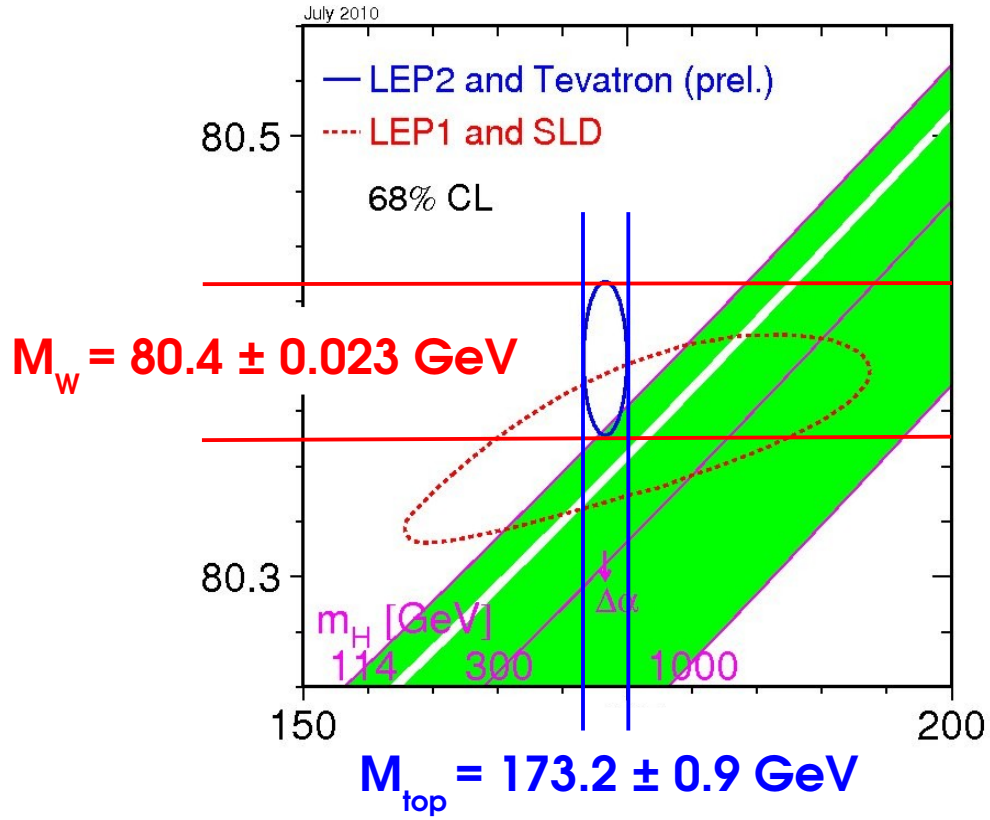

Indirect Experimental Evidence

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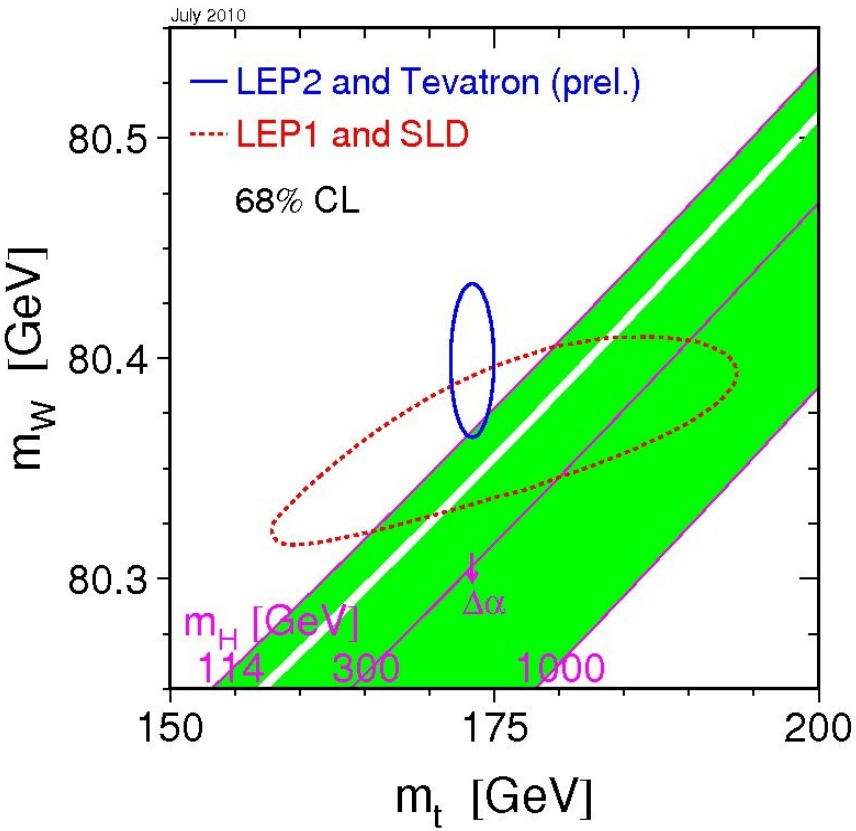
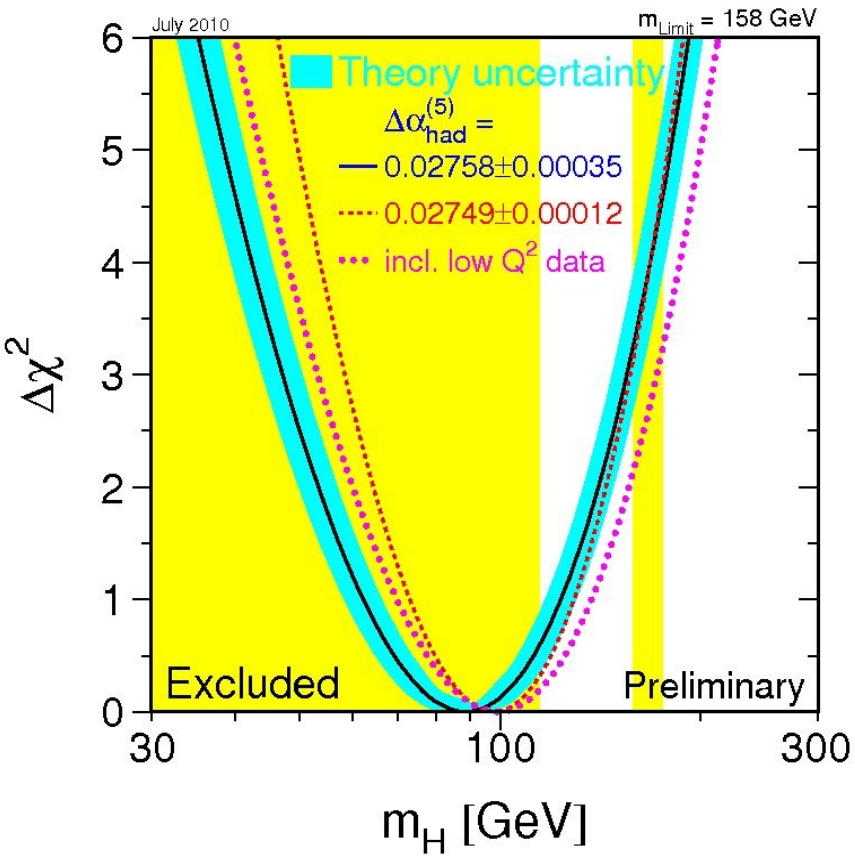
A fit of precision electroweak data yields: M_H < 158 GeV at 95% CL

(M_H < 185 GeV including LEP II limit)





The Continued Higgs Search

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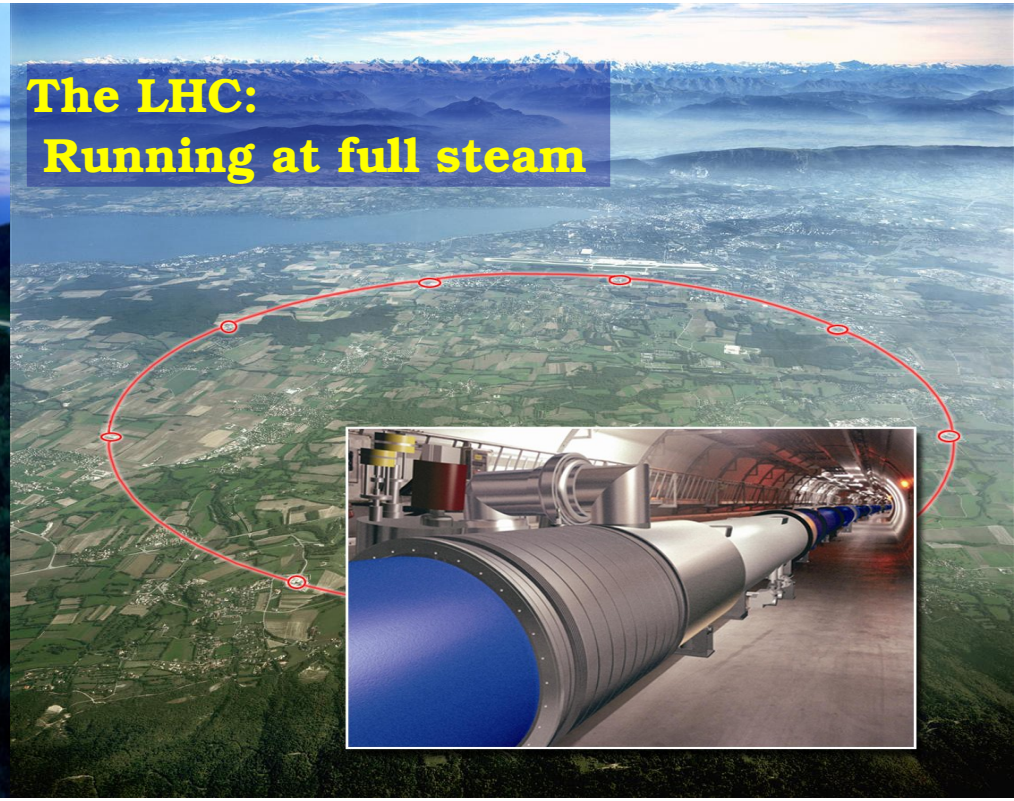
Generations of physicists are eagerly awaiting the next chapter

- Fermilab's Tevatron collider ($\sqrt{s} = 1.96\ TeV$) is focusing large efforts on the Higgs search
- The Large Hadron Collider ($\sqrt{s} = 7\ TeV$ for now) should be able to produce Higgs bosons for most theoretically preferred masses



Tevatron Experiments

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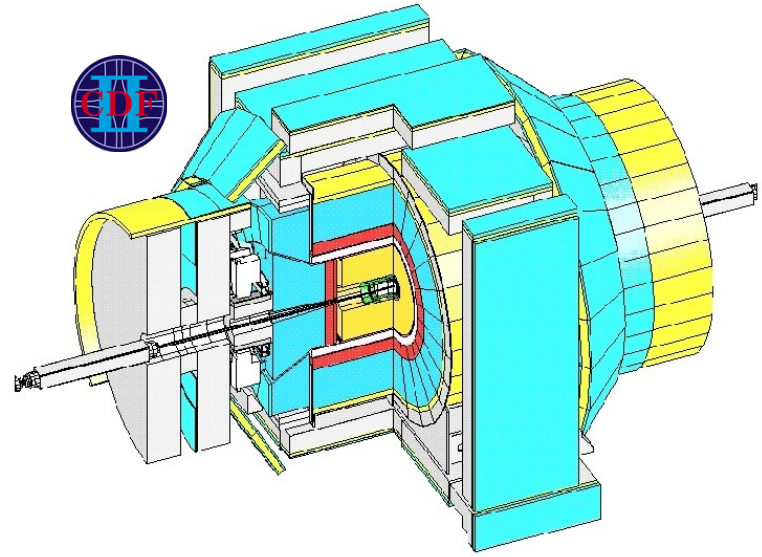
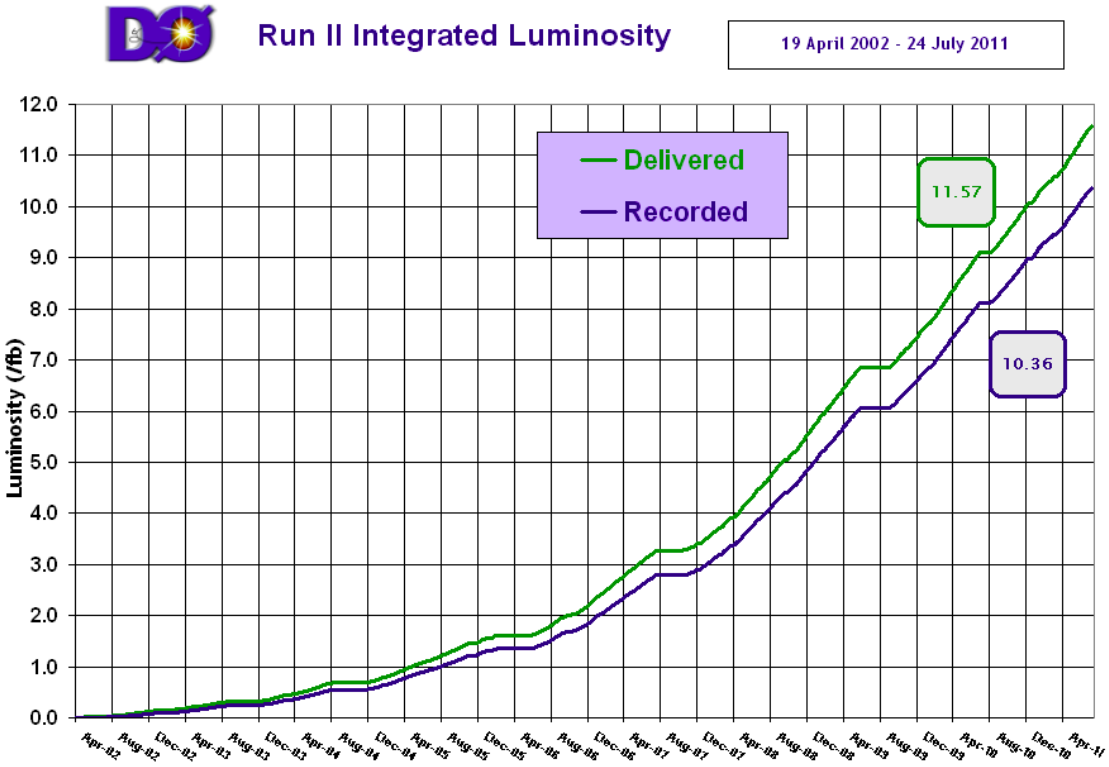
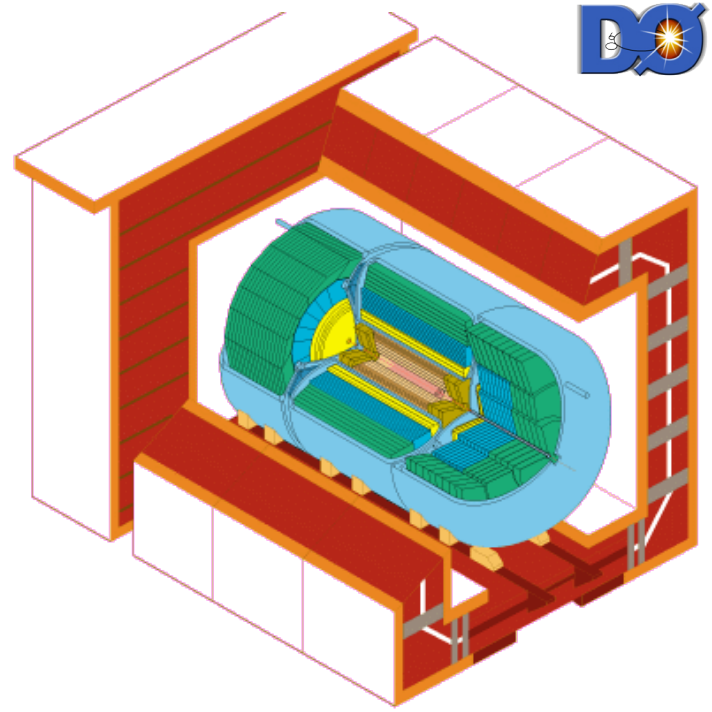
Tevatron complex has performed very well

- Proton-antiproton collisions at 1.96 TeV
- 10 year long Run II ending September 2011
- **Currently >10 fb^{-1} recorded per experiment**
  - Tevatron Run I top quark discovery: ~50 pb^{-1}







LHC Experiments

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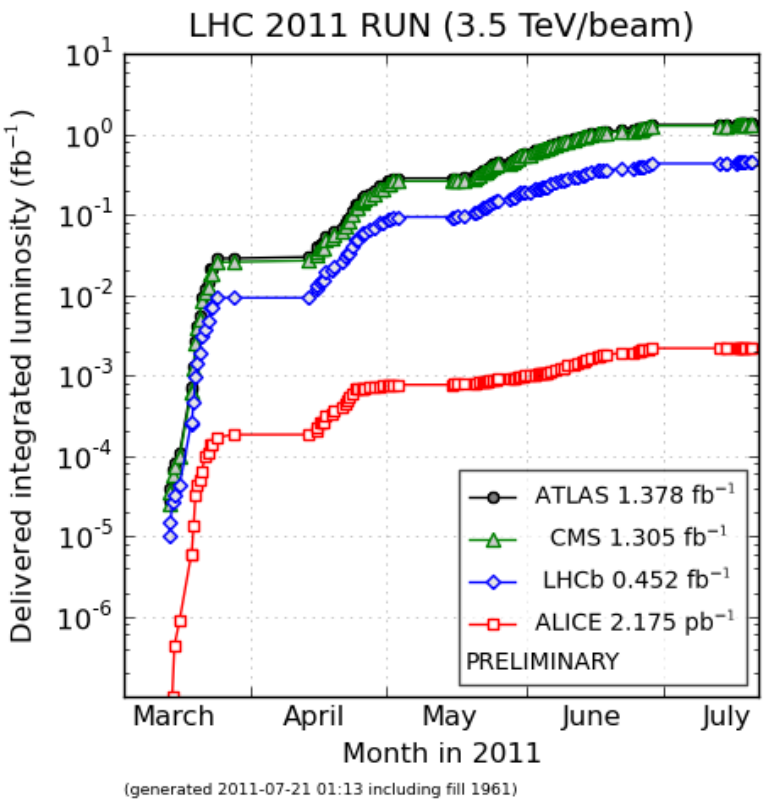
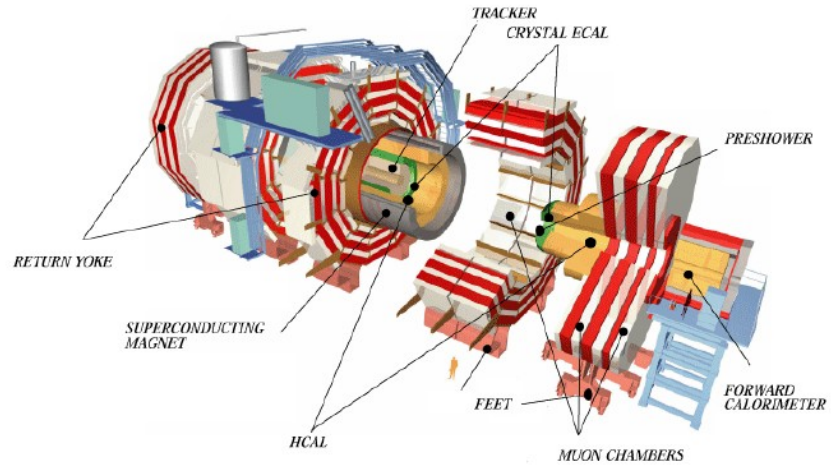
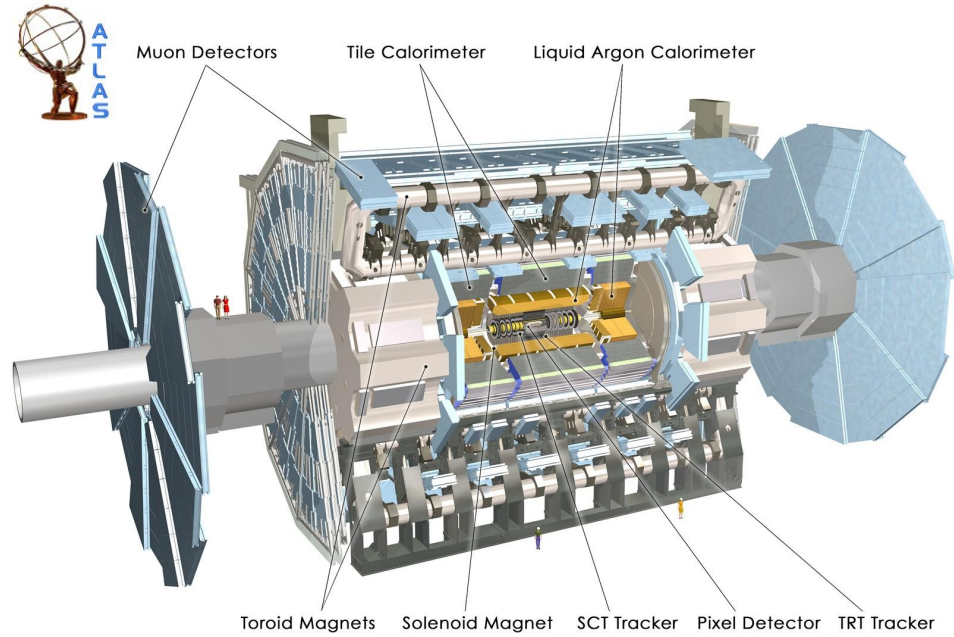
First collisions in 2009 & now running smoothly

- Proton-proton collisions at 7 TeV
- New results appearing routinely
- **~1.3 fb^{-1} delivered per experiement**



The CMS Experiment





Standard Model

Higgs Searches

Higgs Production

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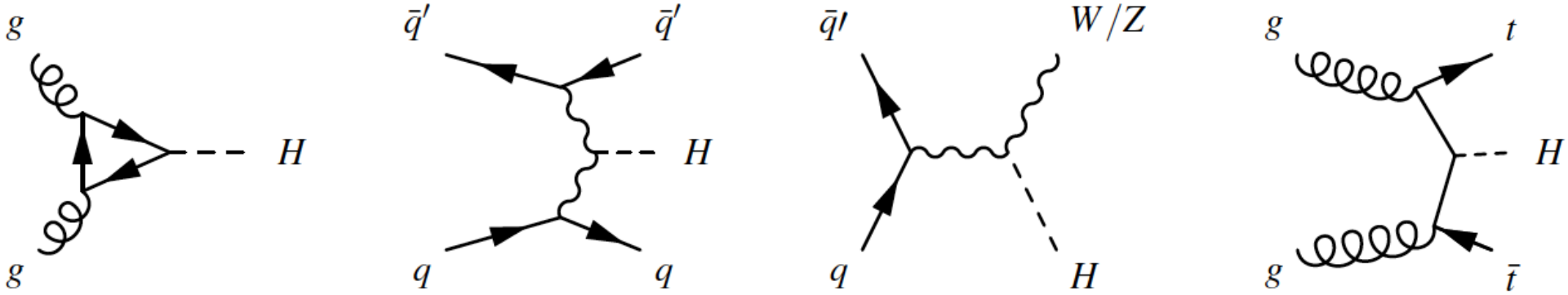
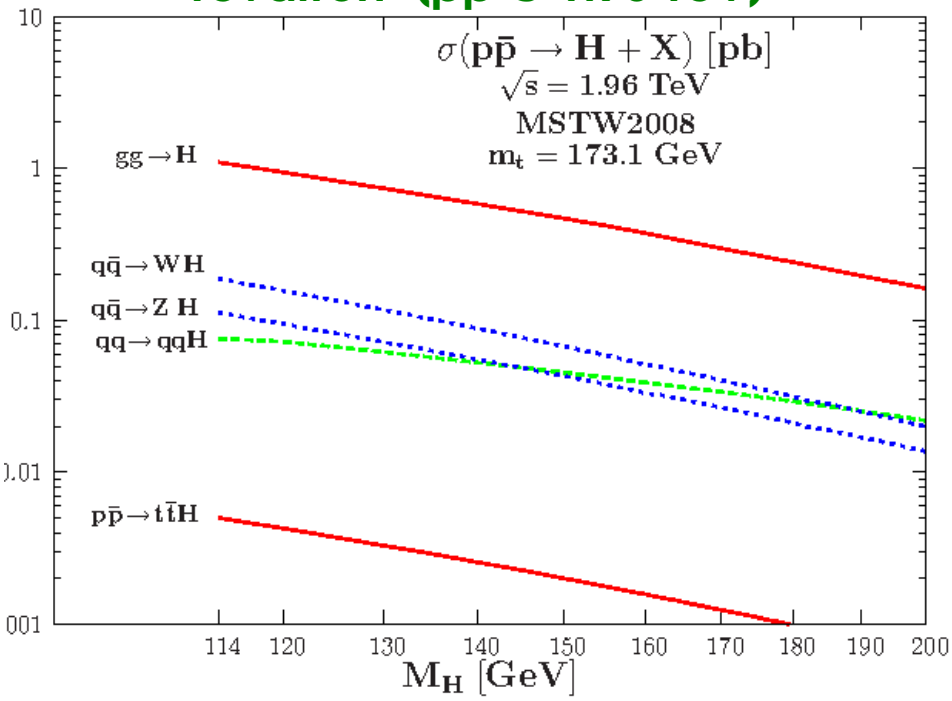
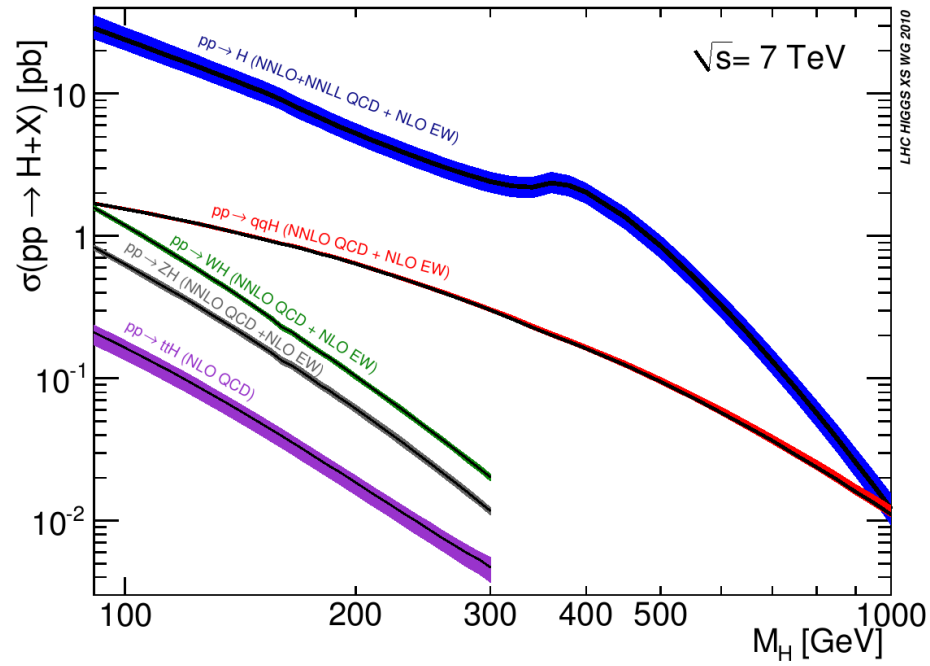


Tevatron ($p\bar{p}$ @ 1.96 TeV)



LHC (pp @ 7 TeV)



Higgs Production

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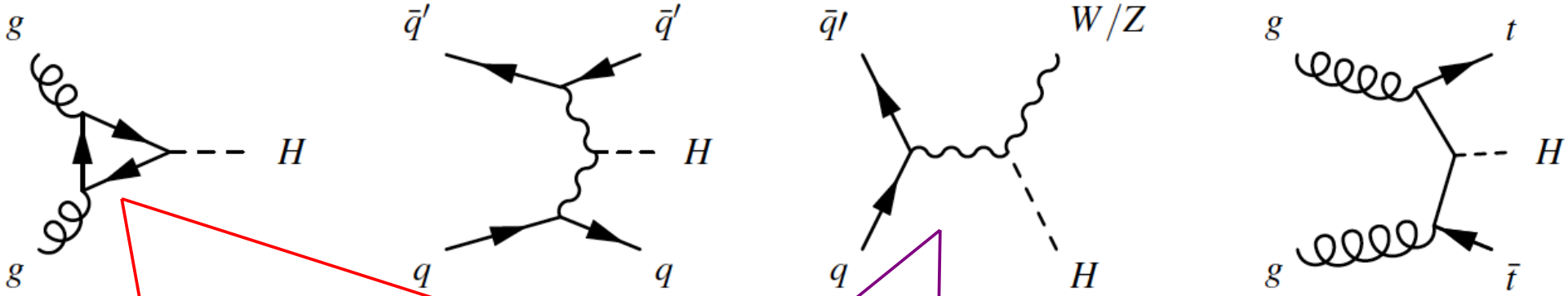

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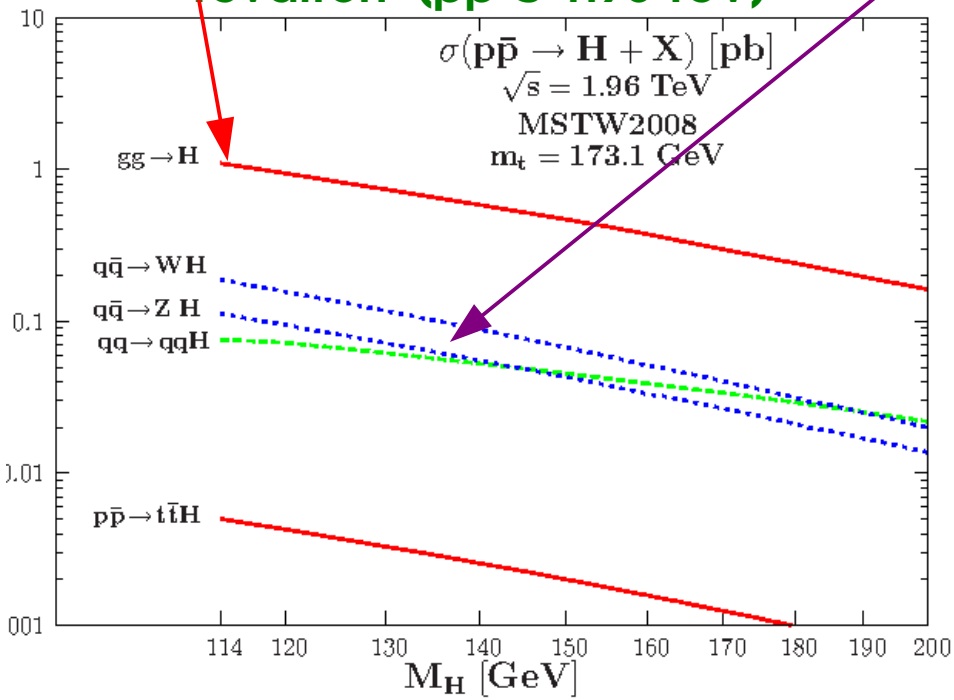

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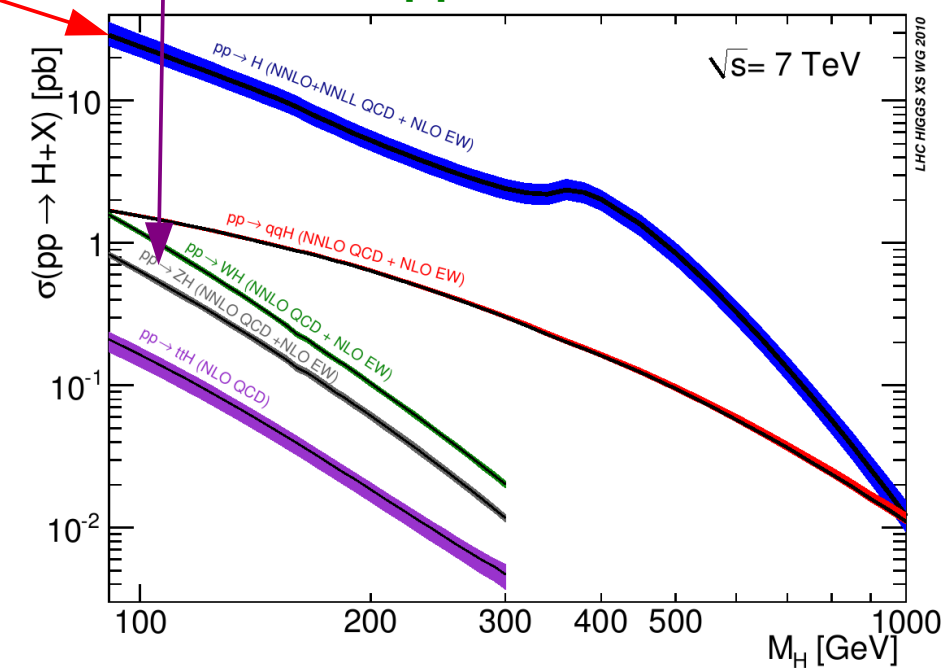

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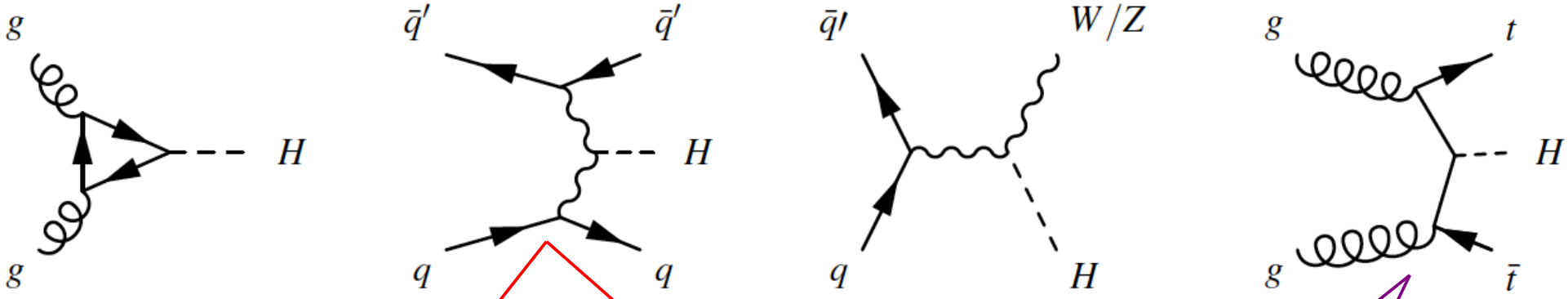

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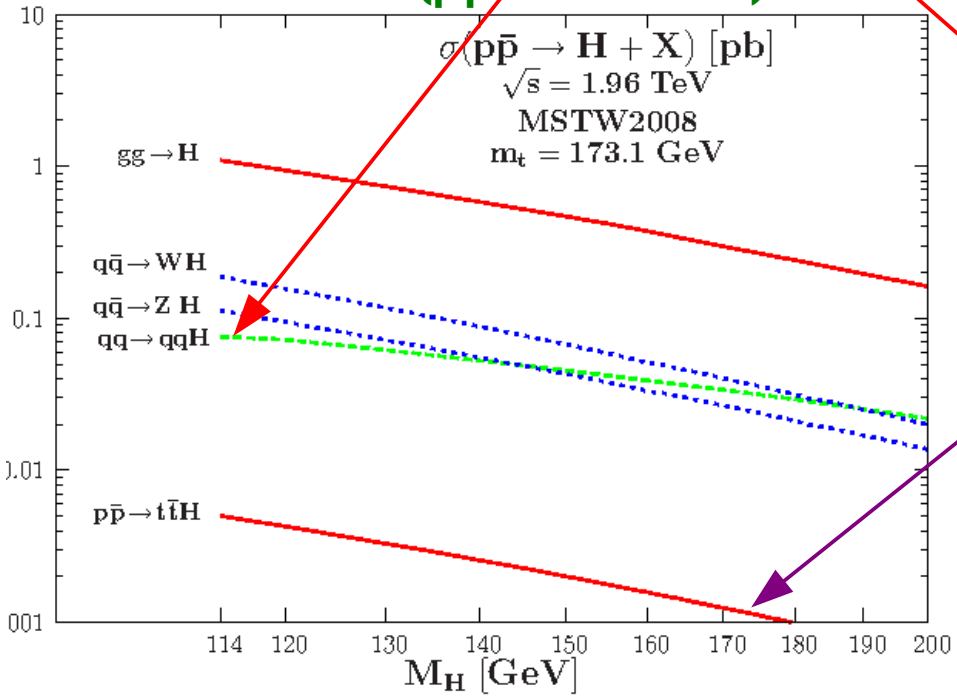

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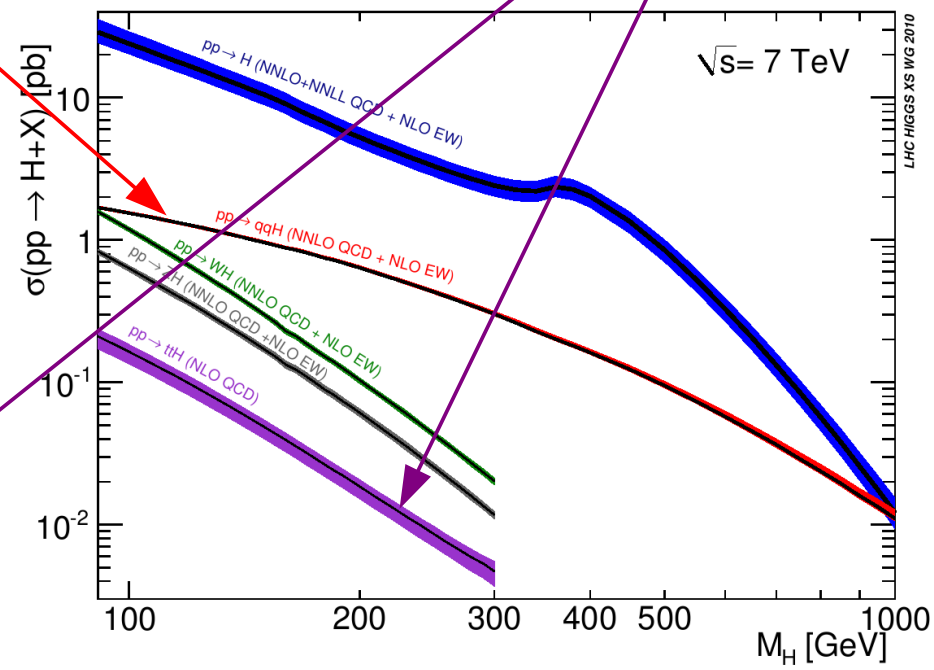


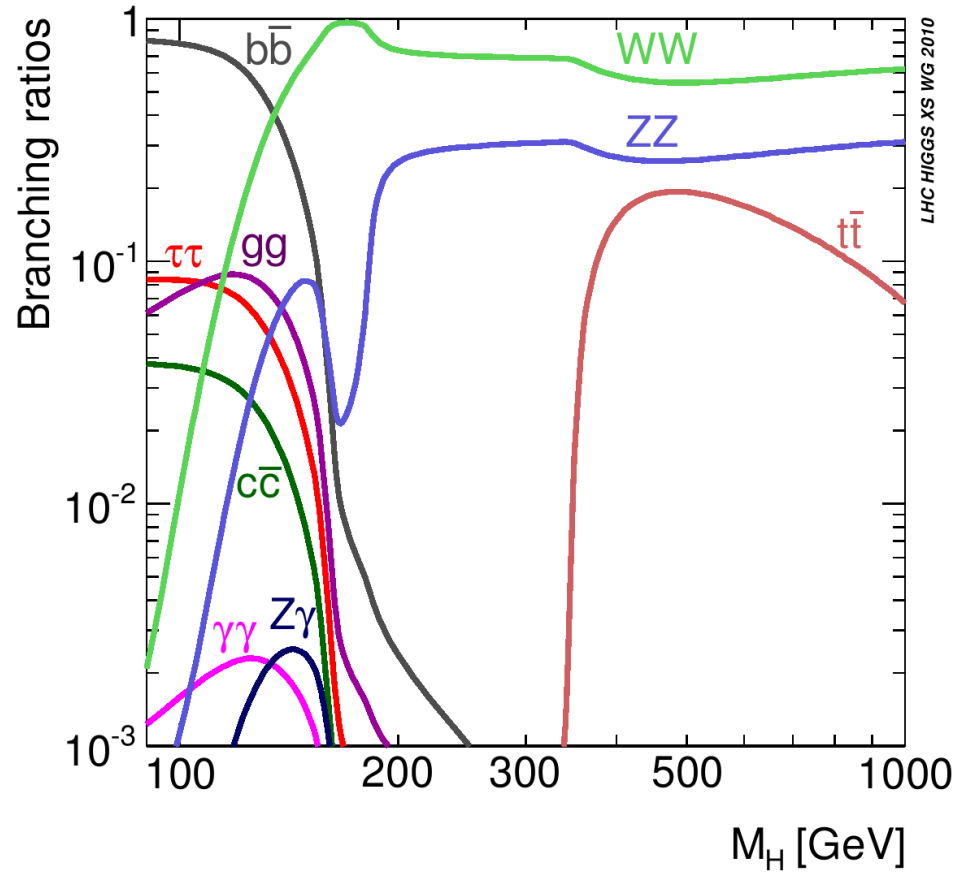
Higgs Decay Modes

The Higgs decay determines what we see in the detector

- Strong coupling to mass selects out most massive particles for each possible mass
- Hadron colliders are quark/gluon factories: leptons/photons provide important handles for background reduction

- At low mass (M_H<*135 GeV*), the dominant Higgs decay is H→bb
  - Hard to distinguish H→bb from huge jet background, easier when paired with associated particles (*W, Z, top*)

- At higher masses H→WW and H→ZZ decays dominate
  - Efficient and accurate reconstruction of lepton momenta gives reasonable Higgs mass resolution



Higgs Search Strategies

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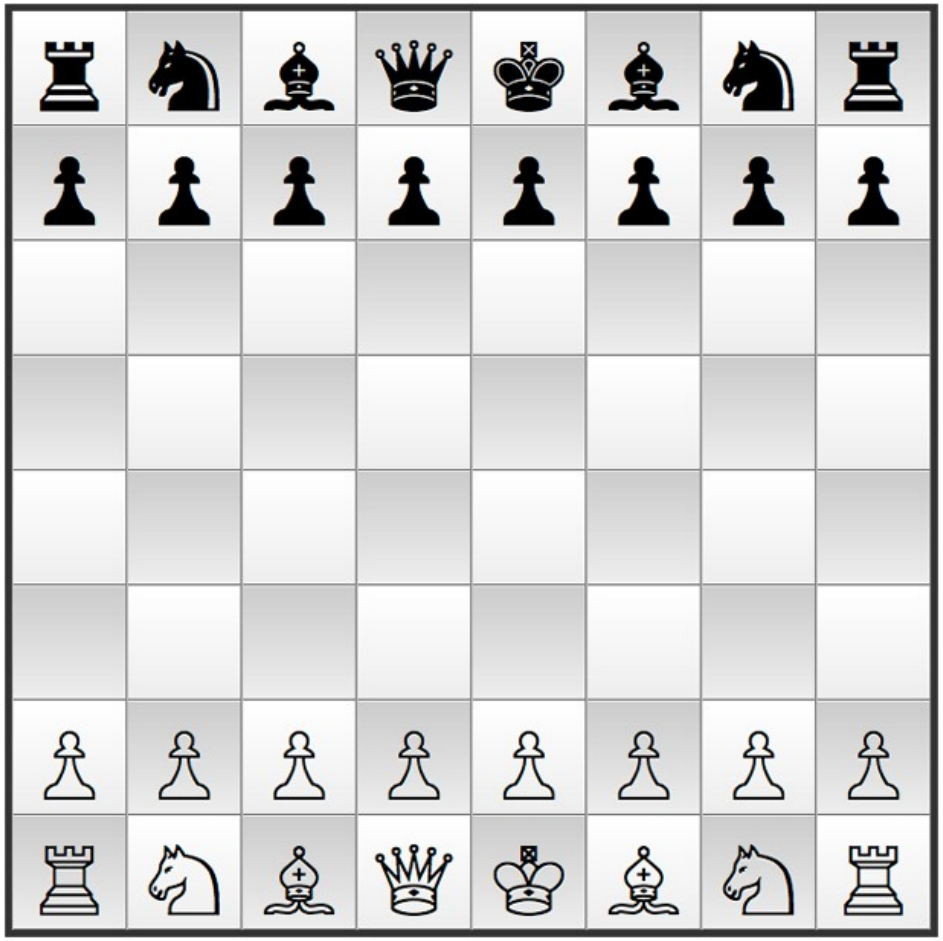
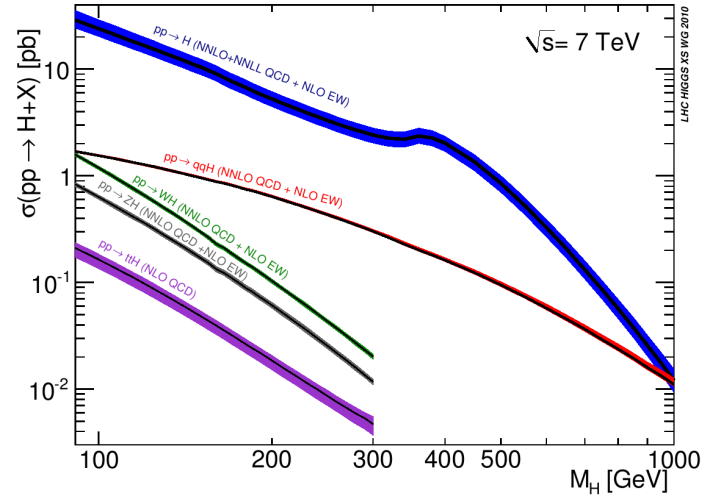
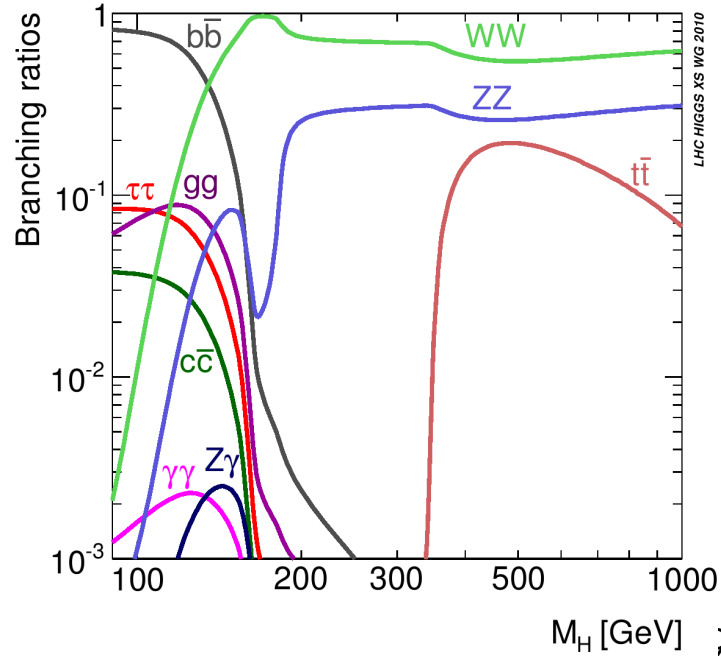
The theory and detector environment together define our search strategies

- Each search defined by pairing production and decay modes







Higgs Search Strategies

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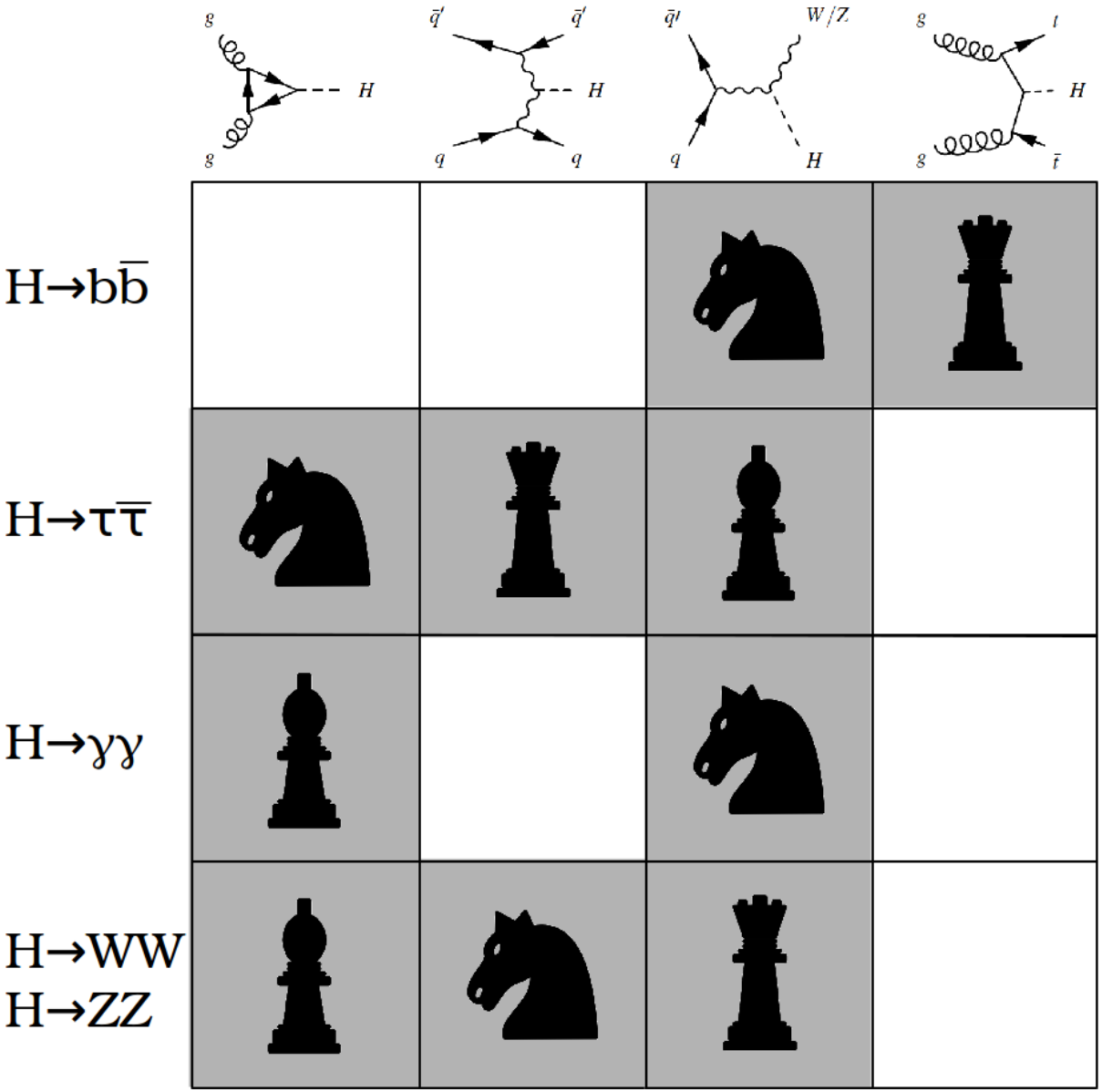

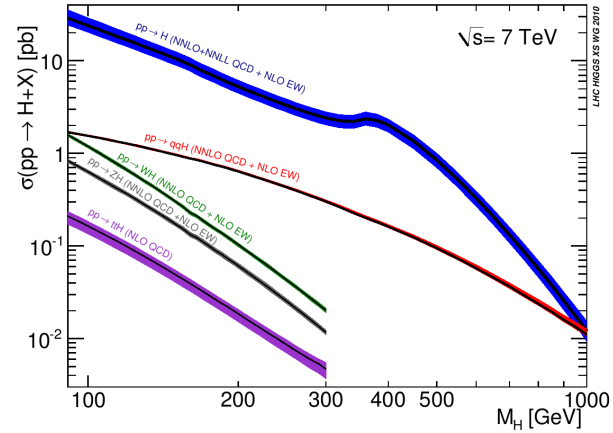

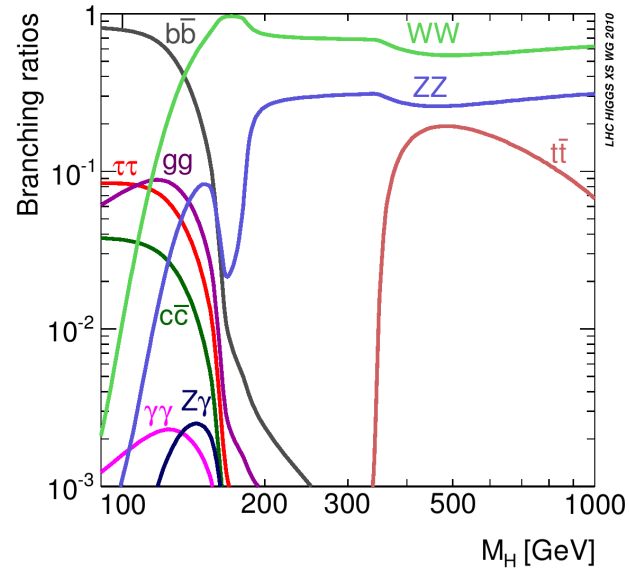

Searching for H→bb

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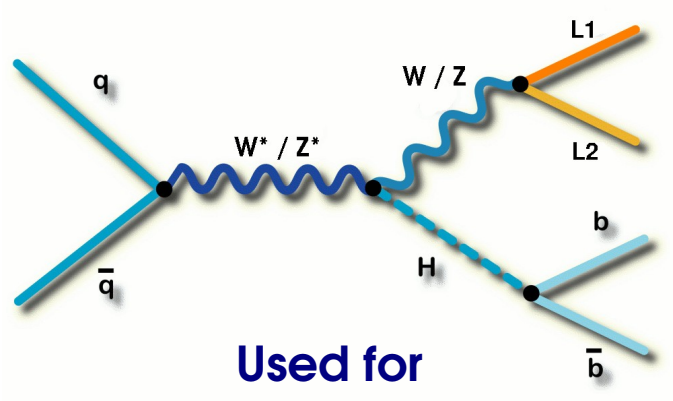
Start with events consistent with W/Z decays

- W→lν & Z→ll: Select events with **electrons** or **muons**
- Z→νν: Select neutrino signature (*large missing transverse energy*) and 2 jets signature

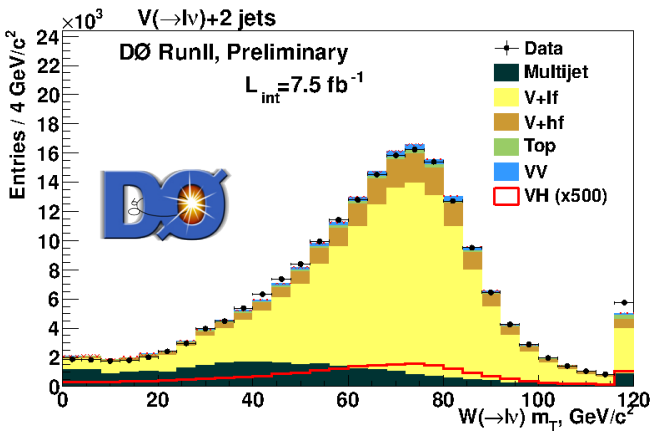
Each final state poses a unique challenge

- W→lν: Invisible neutrino limits degree of constraint
- Z→ll: Despite full kinematic constraint, limited by small branching fraction
- Z→νν: Multijet background difficult to model/control

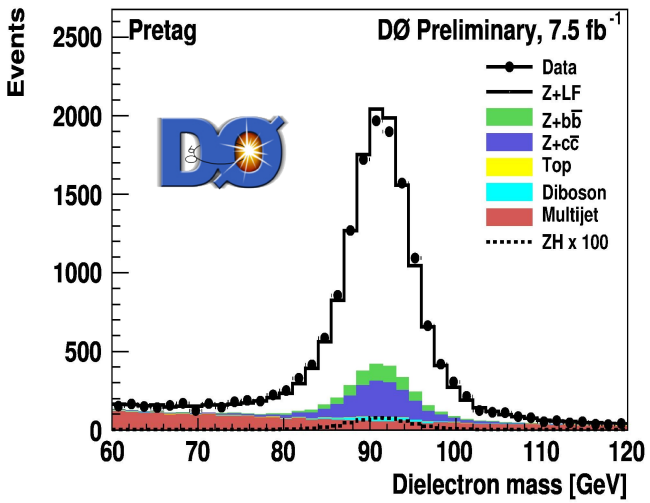


Used for M_H < 150 GeV

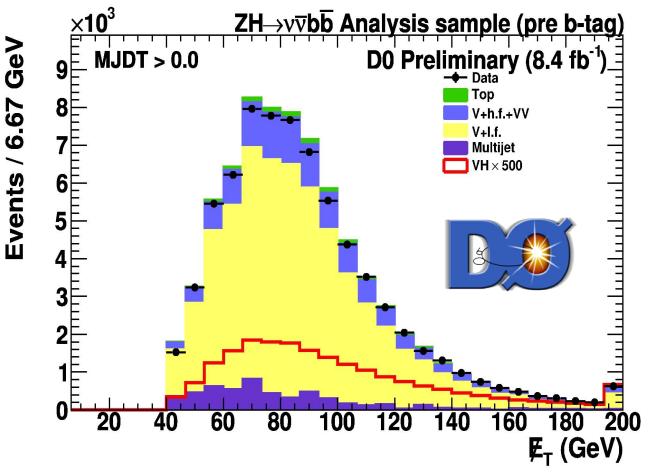
W→lν Transverse Mass



Z→ll Mass



Z→νν Missing Momentum Signature



H→bb: Jets and b-Tagging

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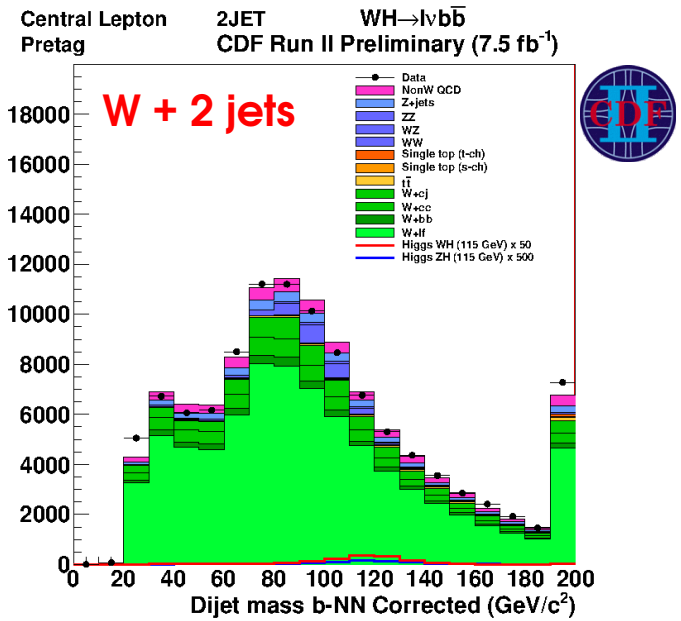
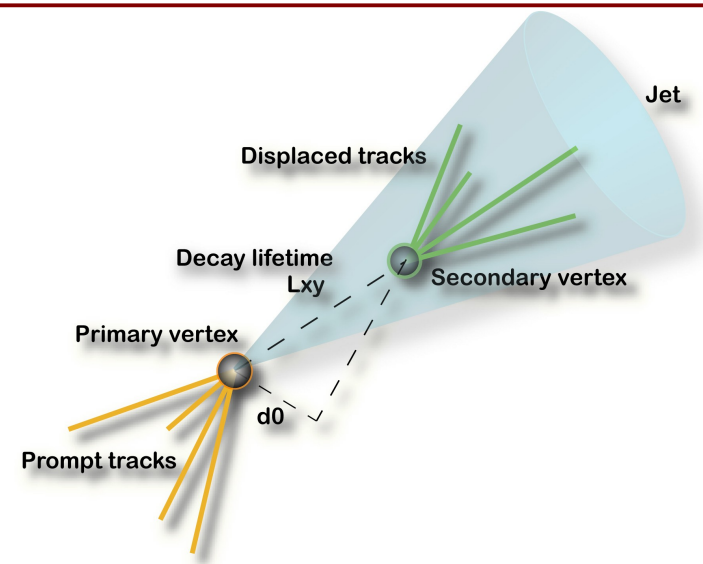
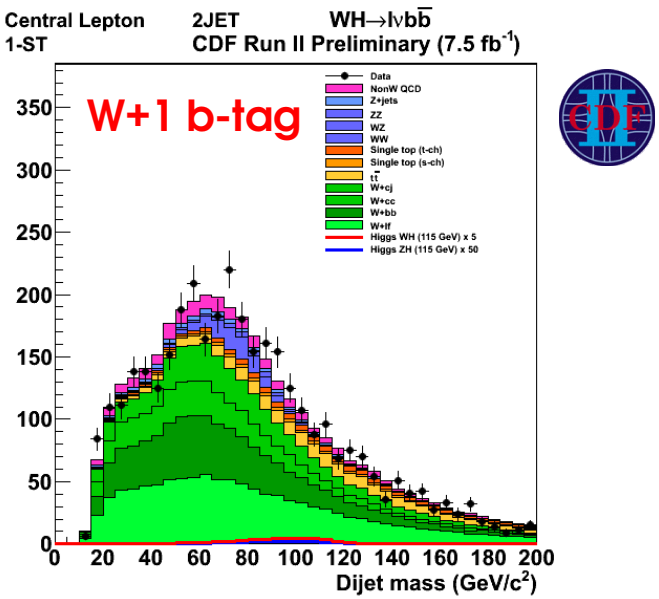
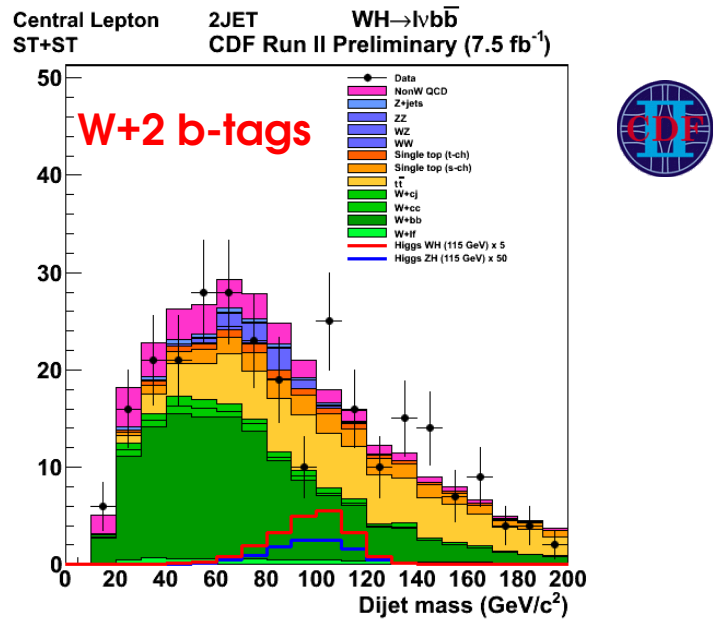




Background reduction enhanced by identifying heavy-flavor quark decays (b-Tagging)





$H \rightarrow \gamma\gamma$: A story in mass resolution

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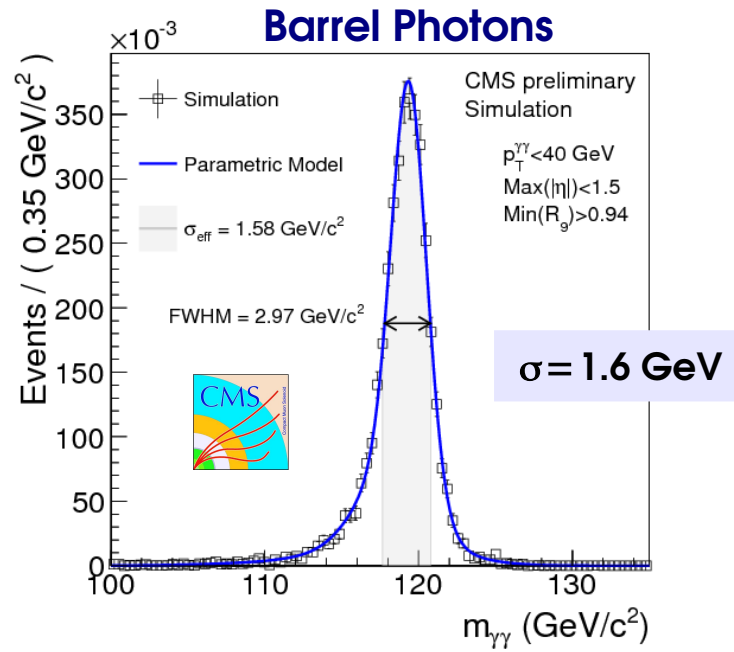
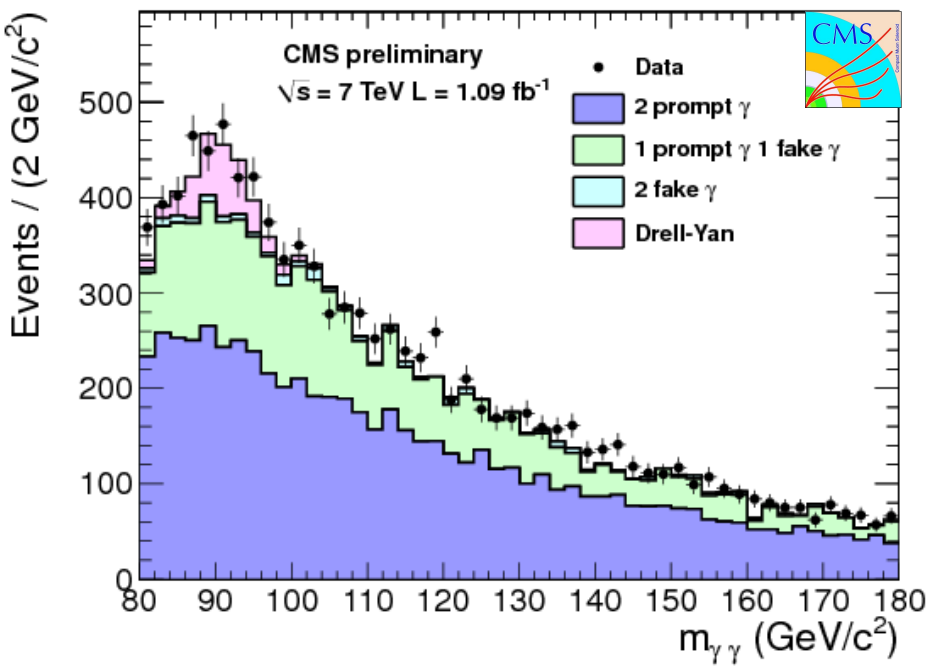
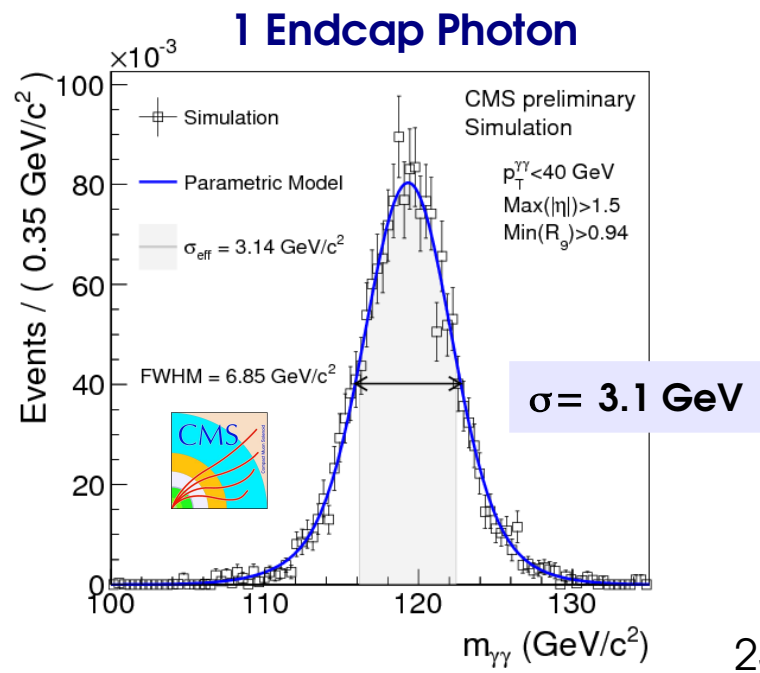
- Di-photon search depends strongly on mass resolution
  - Typical mass resolutions of 1-4%
  - Photons are categorized into regions of varying energy (→*mass*) resolution
- Irreducible di-photon background ultimately defines signal purity
  - Electron and jet fakes round out the remaining background







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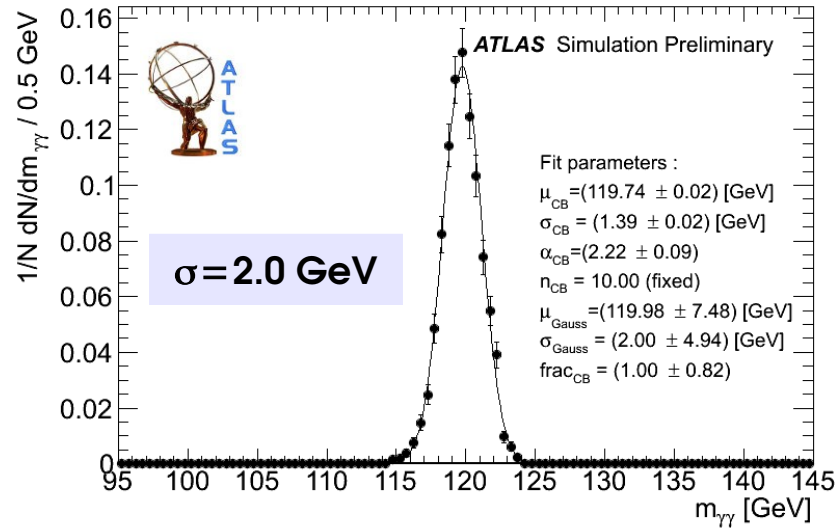
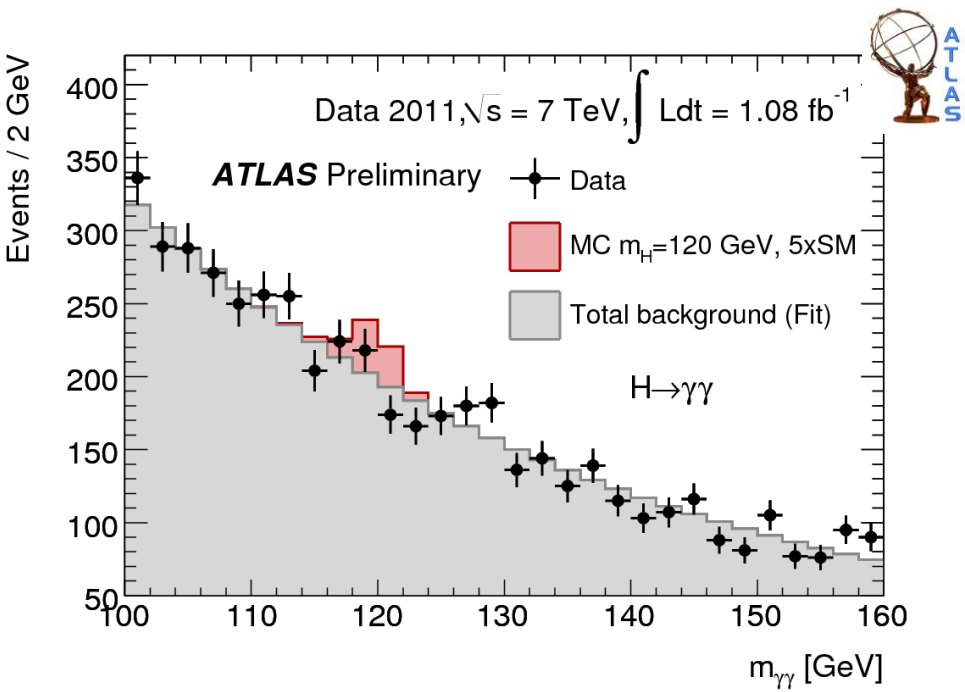
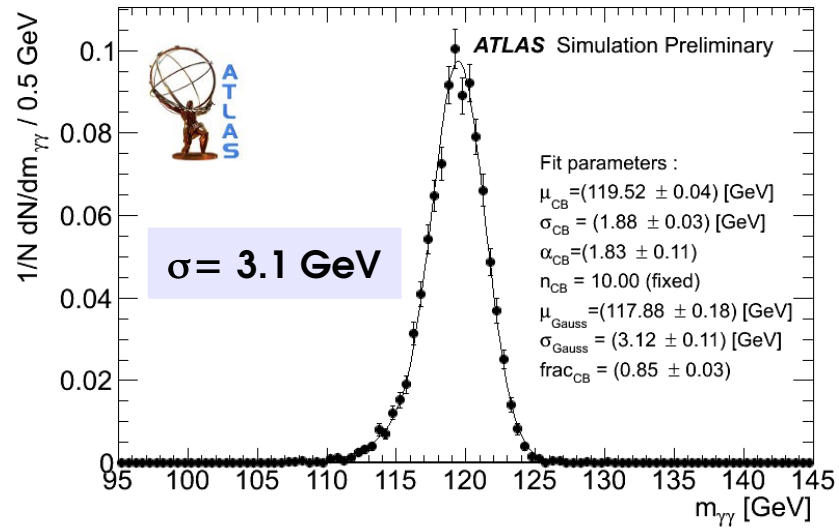
Unconverted Central Photons





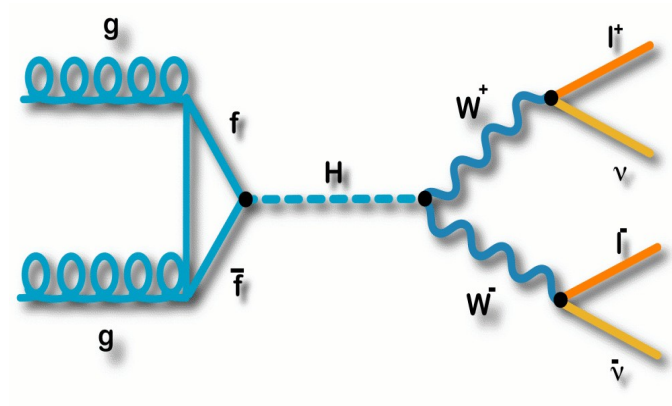
Converted Non-Central Photons



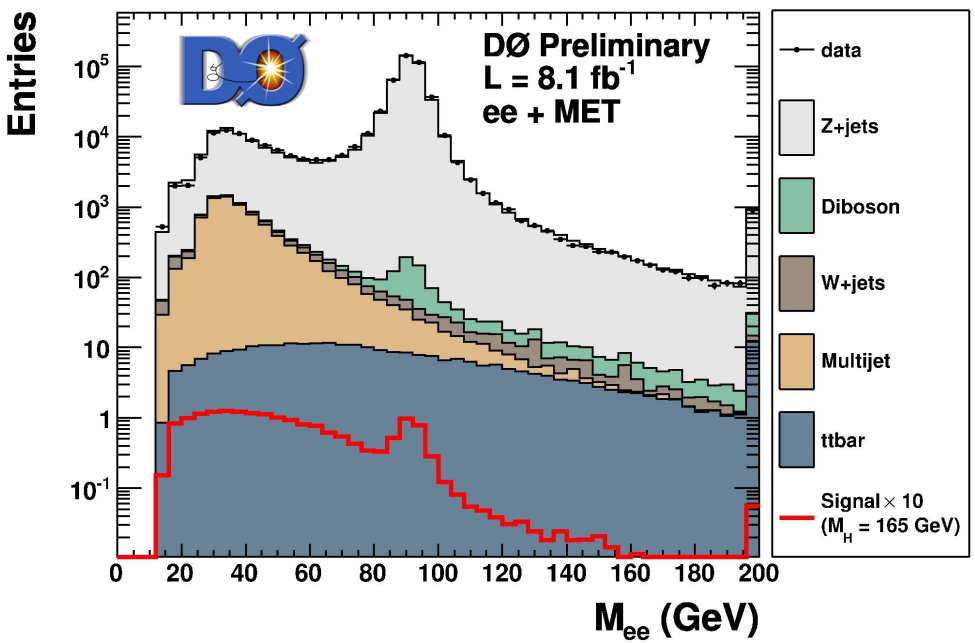
Searching for $H \rightarrow W^+W^-$

Selecting leptonic W-boson decays to reduce the very large multijet backgrounds

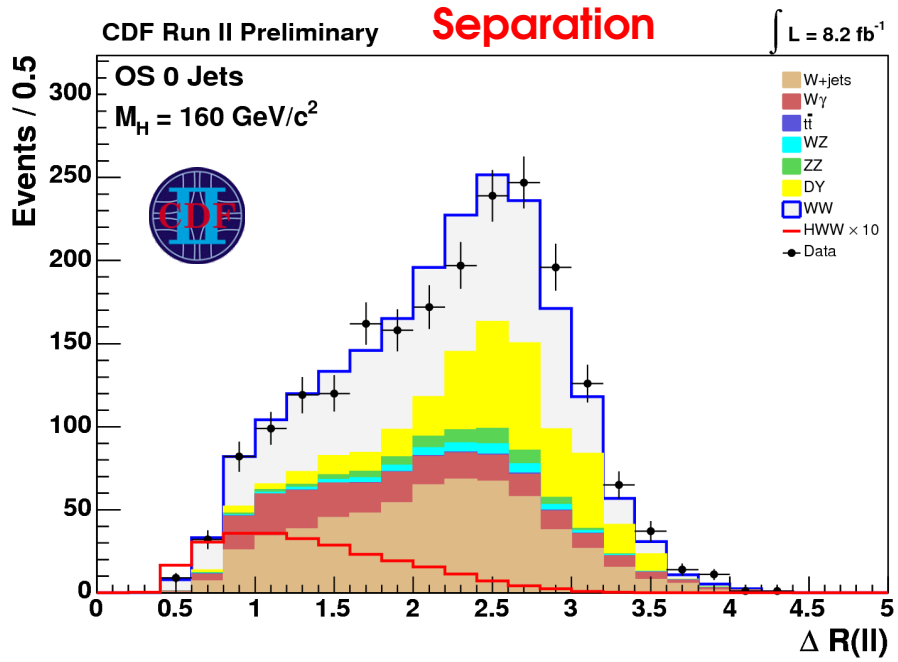
- Use Z mass for normalization, veto region near peak
- 2 neutrinos: missing E_T signature helps reject all but direct WW production
- Capitalize on spin correlations to discriminate WW background (*H = scalar, W/Z = vector*)



Di-lepton Invariant Mass



Di-lepton Angular Separation



Searching for $H \rightarrow W^+W^-$

Wade Fisher
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Selecting leptonic W-boson decays to reduce the very large multijet backgrounds

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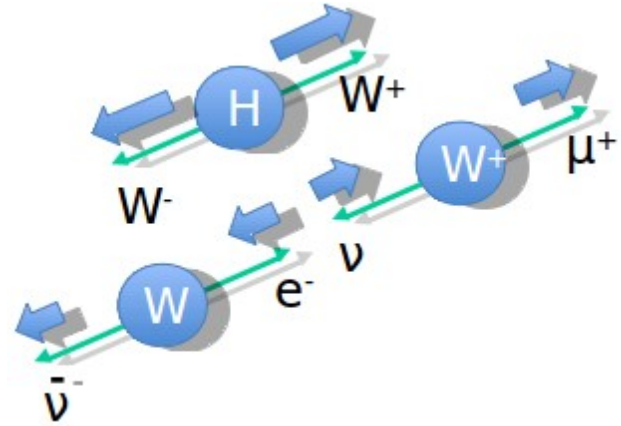
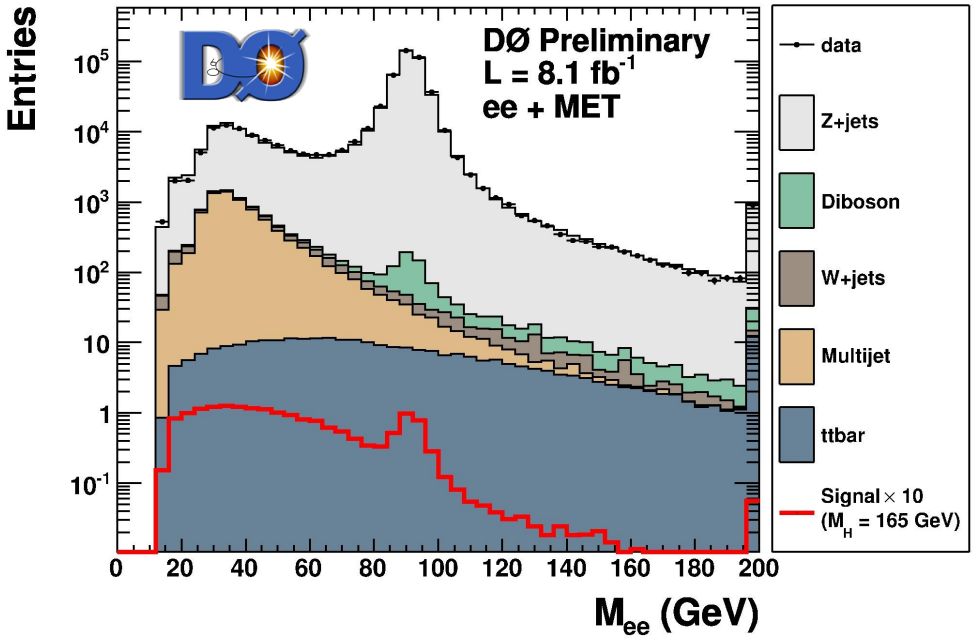
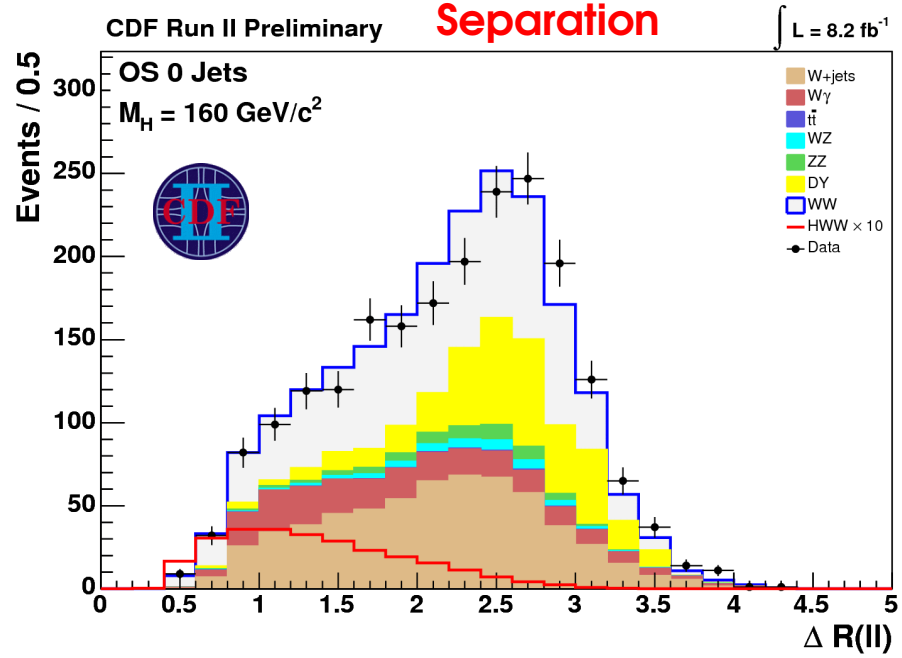


Particle spin (helicity) & momentum constrained to satisfy spin-0 Higgs decay

Di-lepton Invariant Mass



Di-lepton Angular Separation



Searching for $H \rightarrow W^+W^-$

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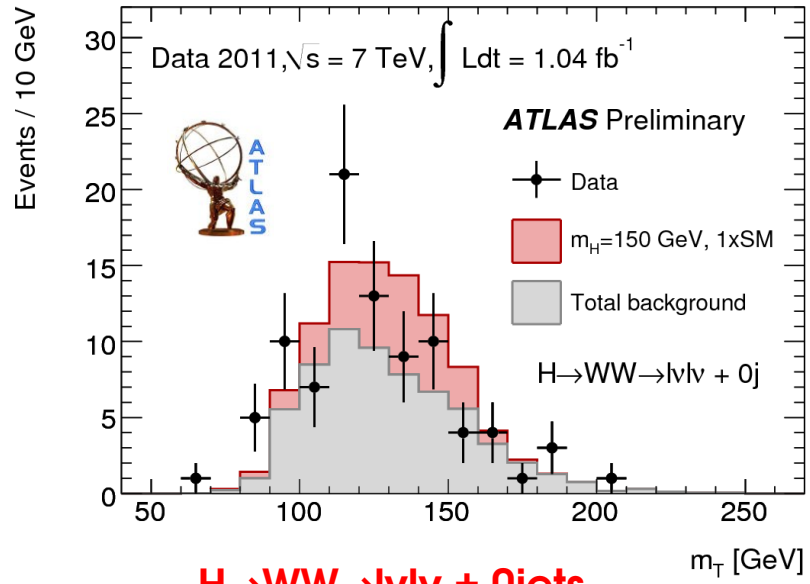
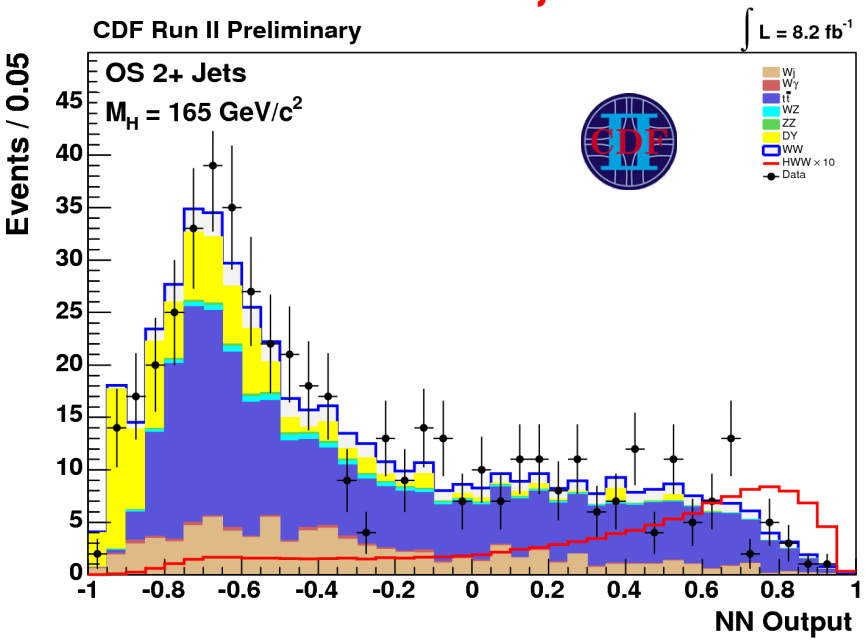
Two-neutrino final state precludes mass reconstruction

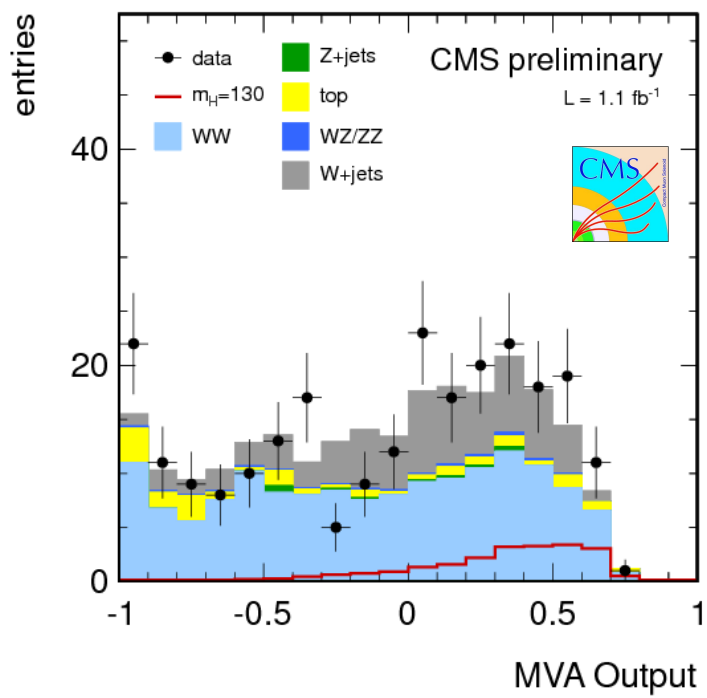
- With appropriate cuts, can use transverse WW mass to isolate backgrounds
- Or rely upon Multi-Variable Analysis filters to provide final event classification
- Typically achieve S/B ratios of ~1/3 or greater



H→WW→lνlν + 2jets



H→WW→lνlν + 0jets



Searching for H→ZZ

Wade Fisher
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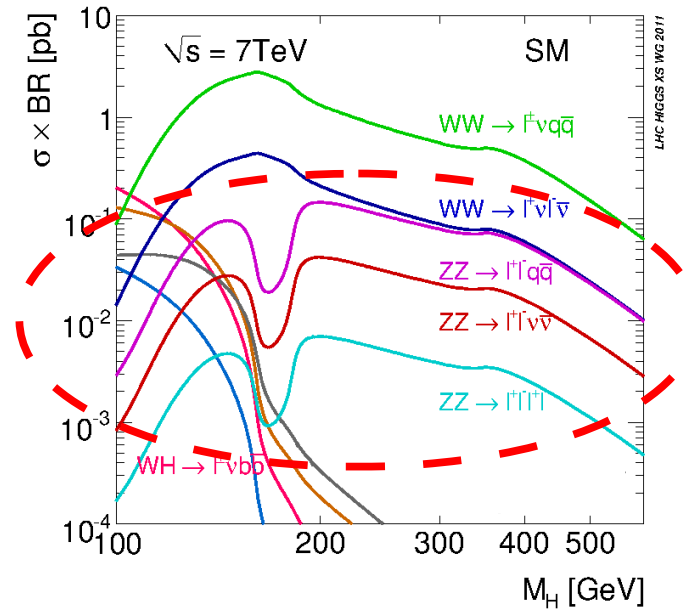
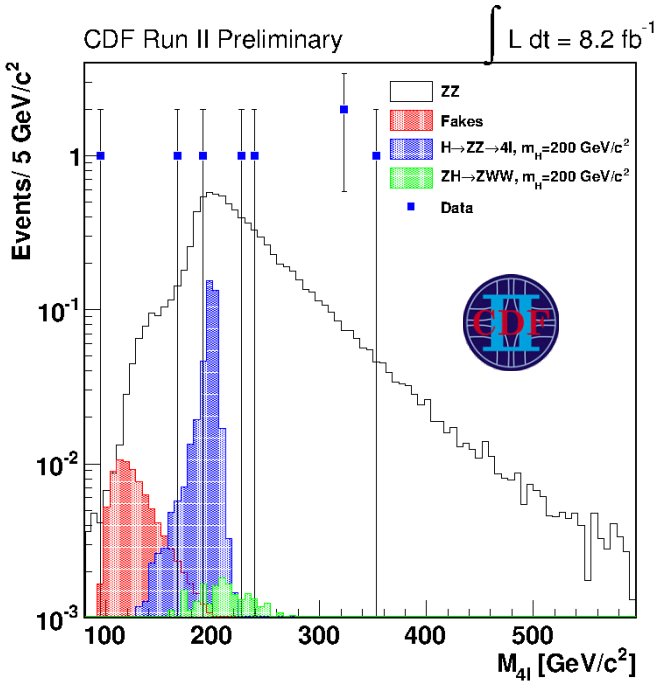
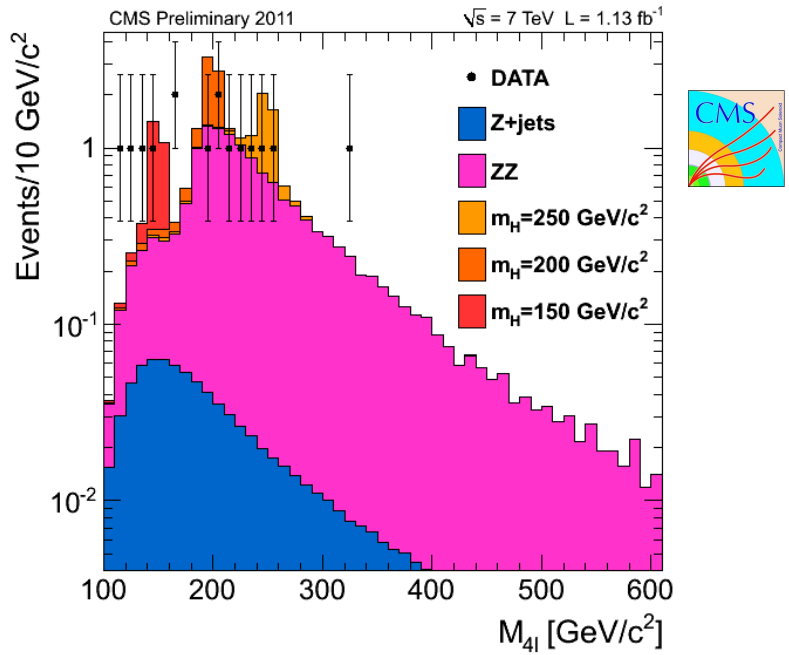
H→ZZ→4l is a "golden mode" for M_H>140 GeV

- Low rate due to H→ZZ and Z→ll branching fractions
  - Balanced by narrow 4-lepton mass resolution
- CMS & ATLAS have excellent mass resolution & trigger efficiency
- Though rate limited at the Tevatron, still a useful contribution





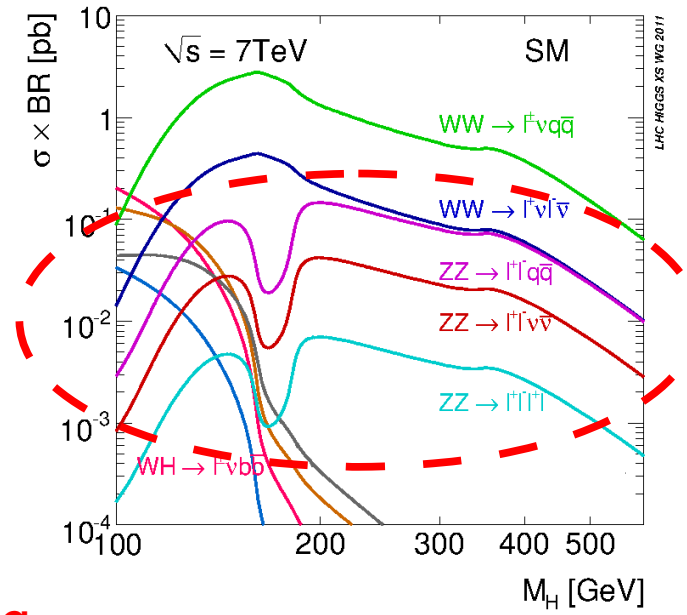


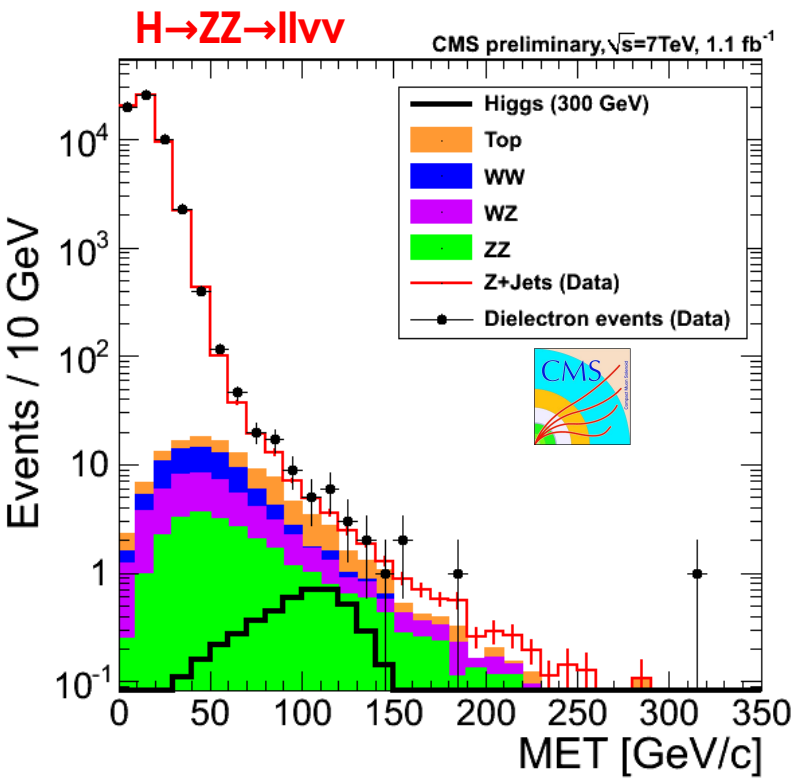
Searching for H→ZZ

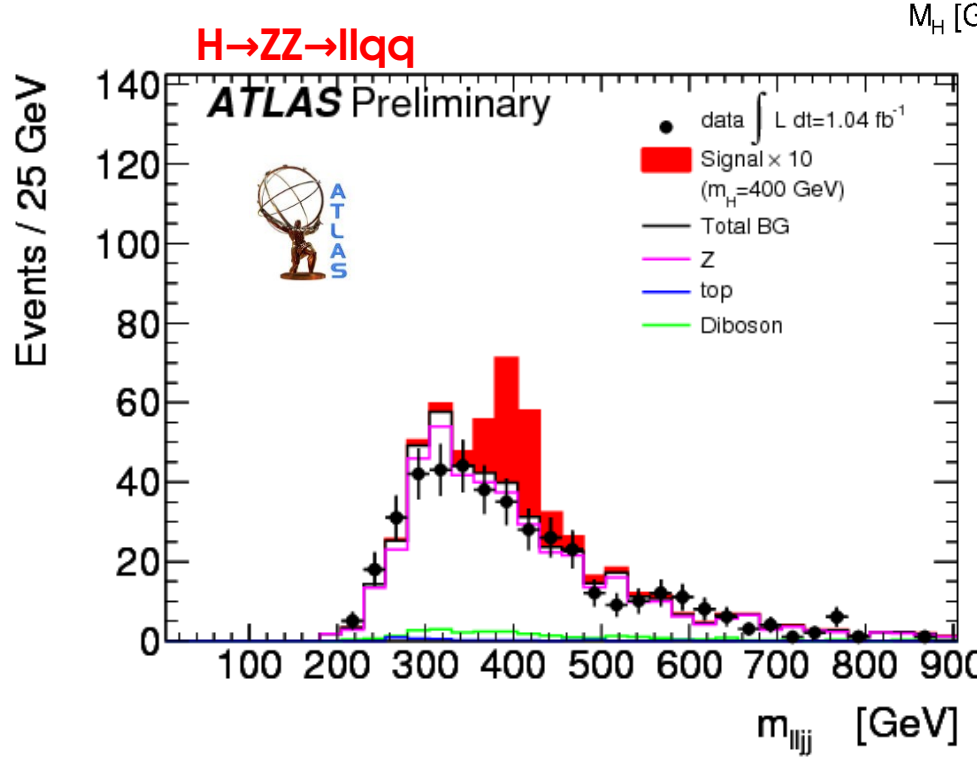
Wade Fisher
PANIC11

Adding H→ZZ→2l+2j/2ν boosts rate significantly

- H→ZZ→llqq:
  - No neutrinos! All 4 decay particles reconstructed.
- H→ZZ→llνν:
  - No Higgs peak, but signal lies in the tails of missing energy distributions.
- Benefits come at the cost of larger Z+jets background





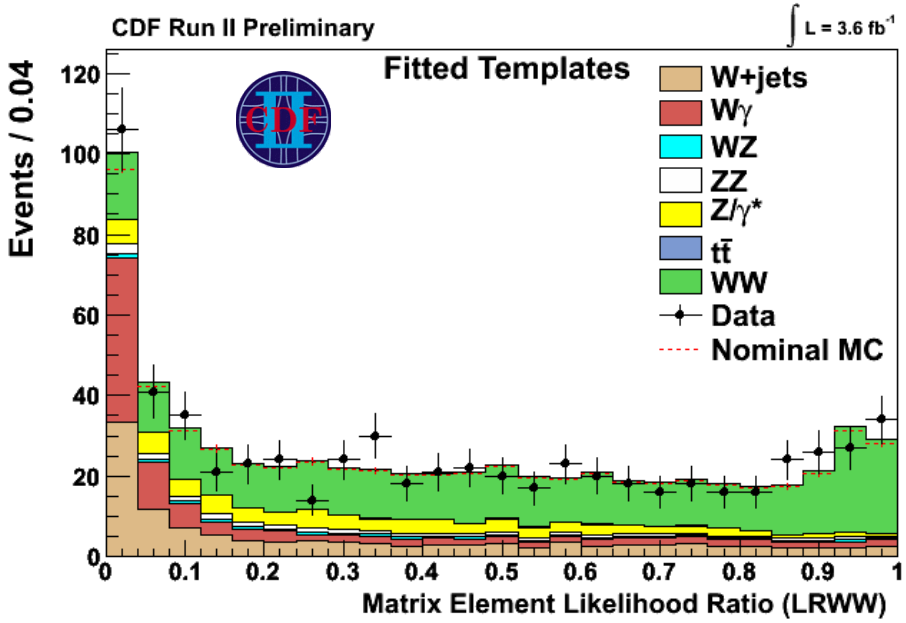


Search Validation

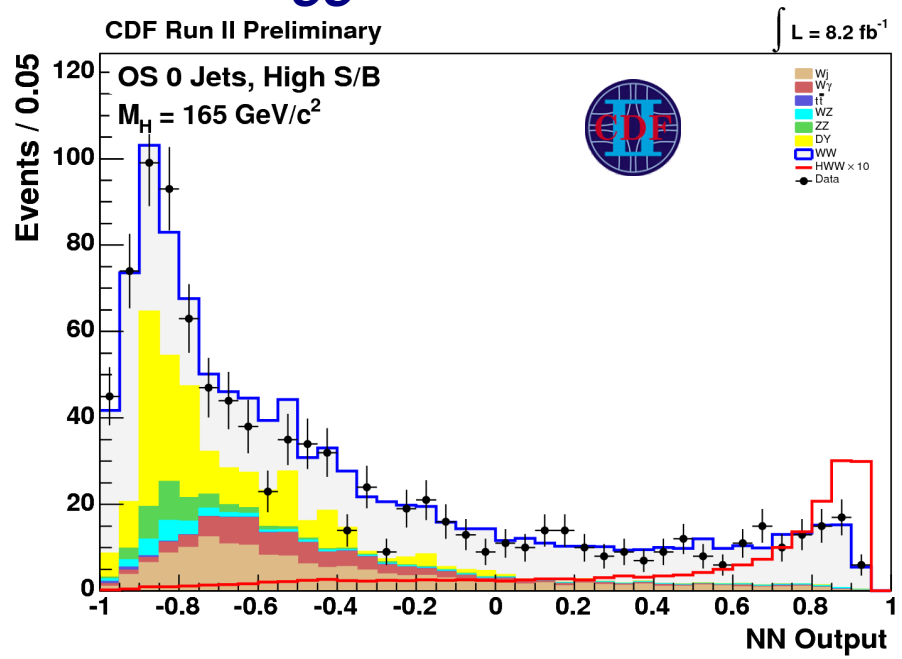
Confirming agreement with "standard candles" provides essential validation for search results

- Example: SM WW cross section
- Similar selections should yield similar results
- MVA should behave similarly for WW = signal and WW = background

SM WW Measurement



gg→H→WW Search



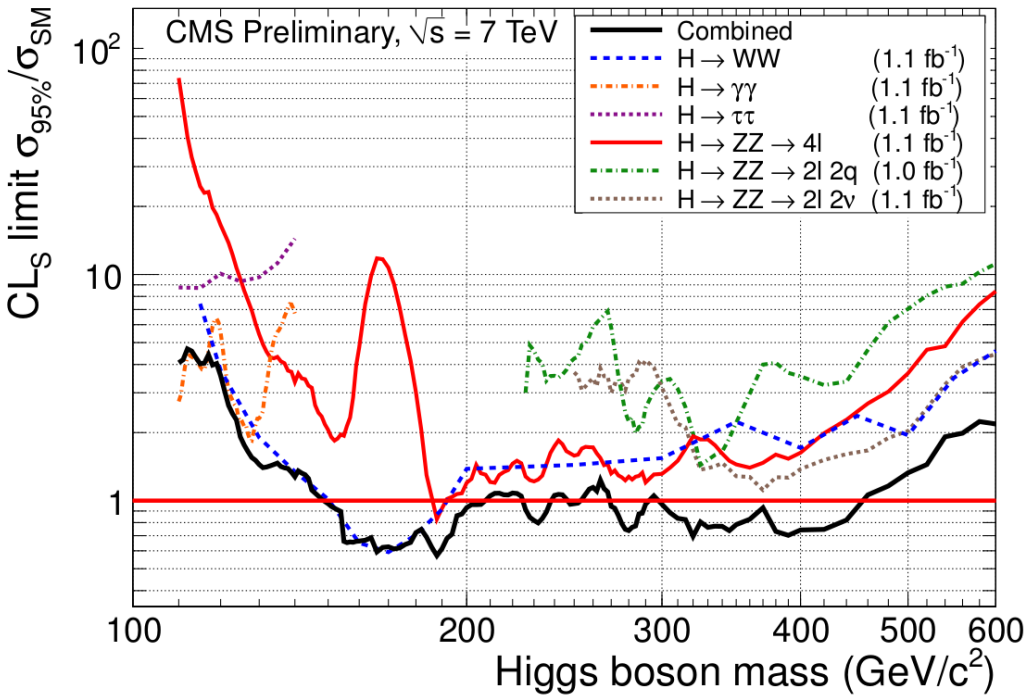
$$\sigma(p\bar{p}\rightarrow WW)^{EXPT} = 12.1 \pm 0.9(stat) \pm {}^{-1.6}_{1.4}(syst)\ [pb]$$

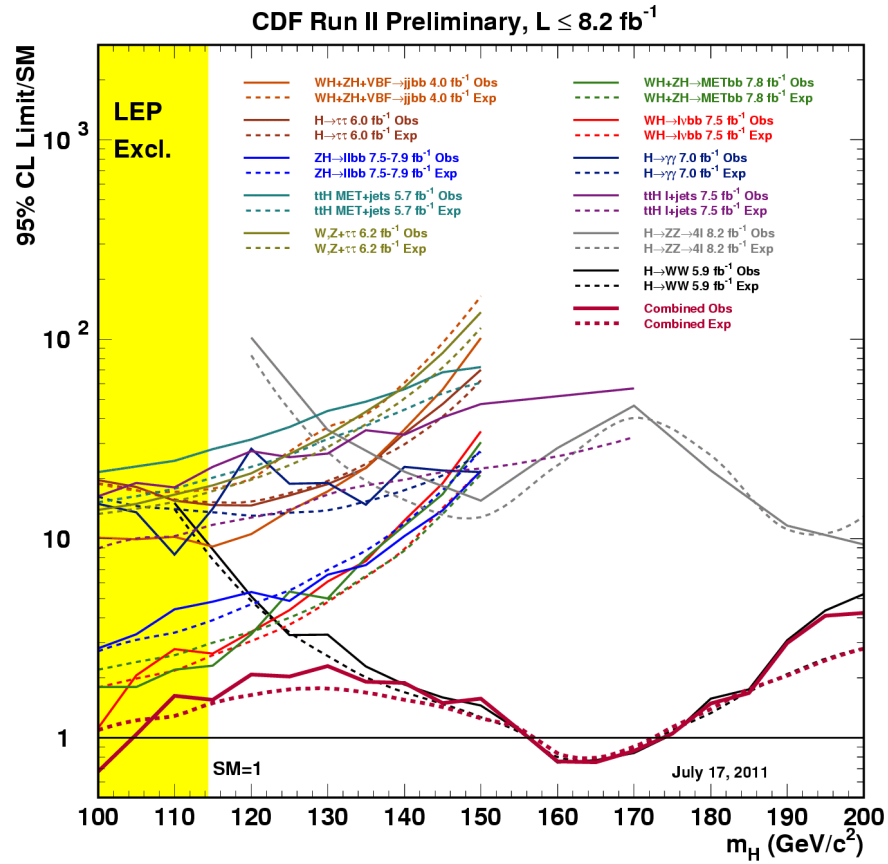
$$\sigma(p\bar{p}\rightarrow WW)^{THEORY} = 12.4 \pm 0.8\ [pb]$$

Limits on SM Higgs Production

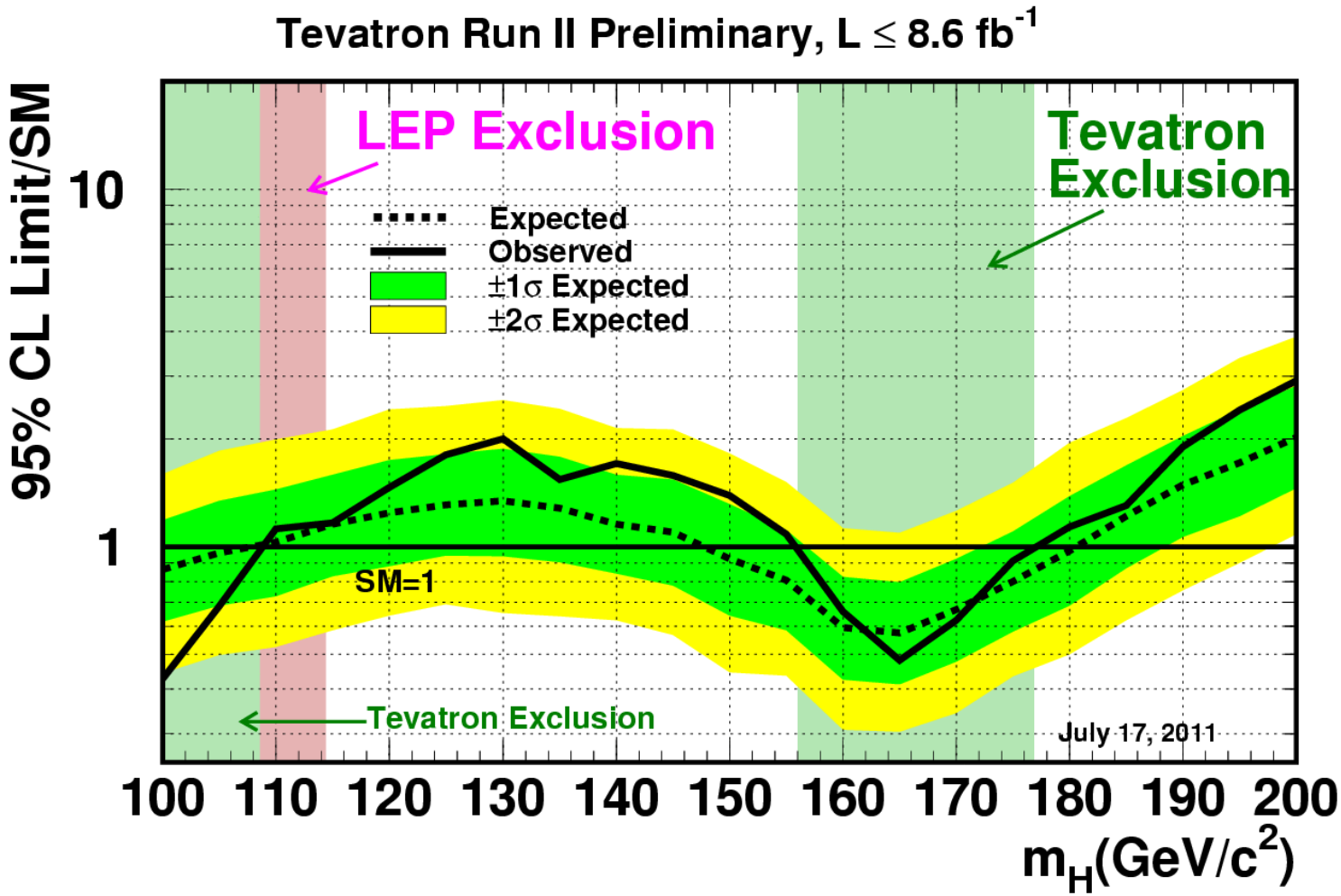
Upper limits on cross section are derived at the 95% C.L.

- Reported in units of the SM prediction: **Ratio = 1 is exclusion condition**
- Limits derived for a combination of all contributing search channels
- Limits include consideration of:
  - Limited MC statistics
  - Poisson sampling uncertainty
  - Systematic sources of uncertainty





Limits on SM Higgs Production

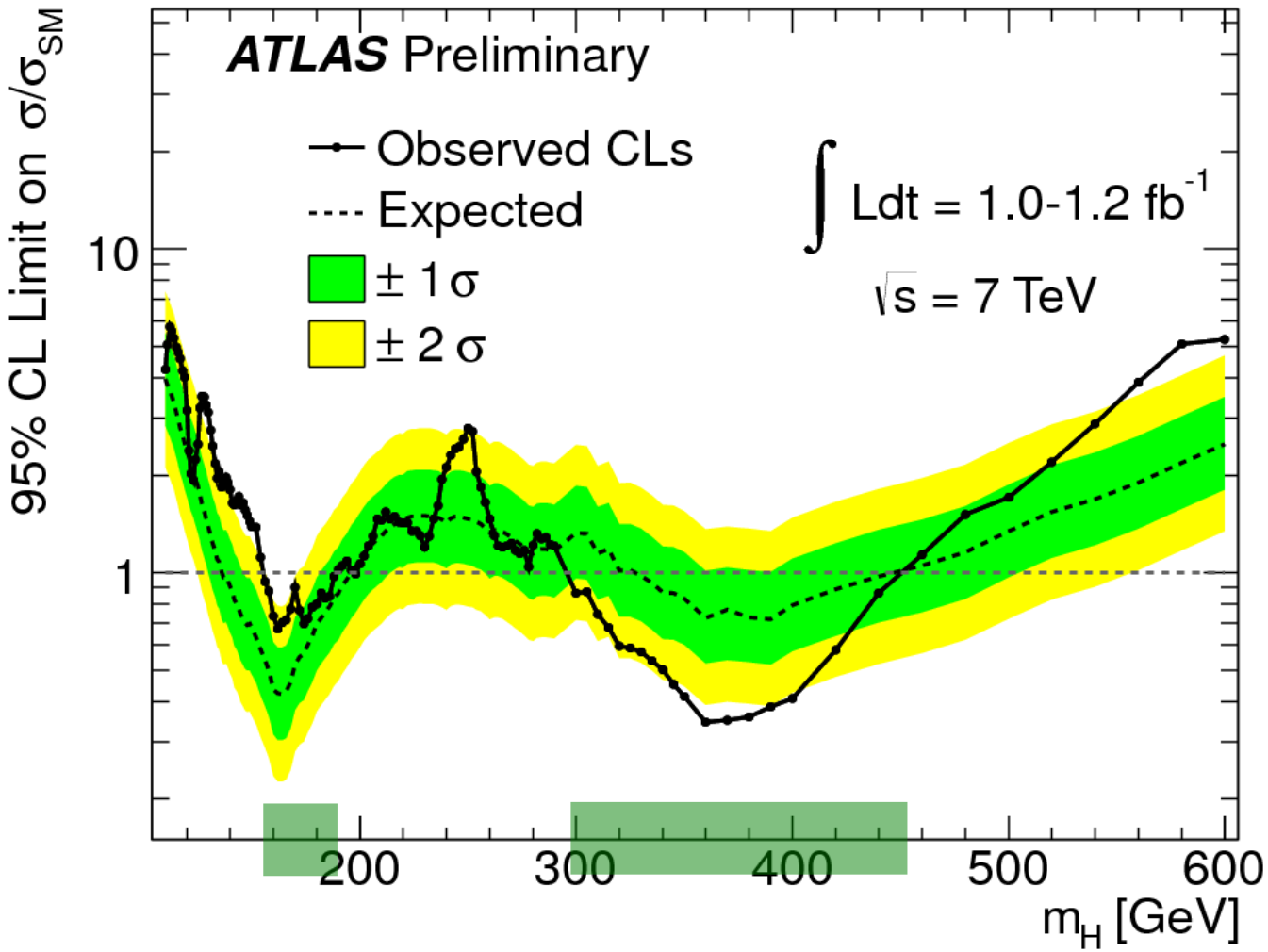


SM Higgs excluded at 95% C.L.

$M_H < 108$ GeV

$156 < M_H < 177$ GeV

Limits on SM Higgs Production

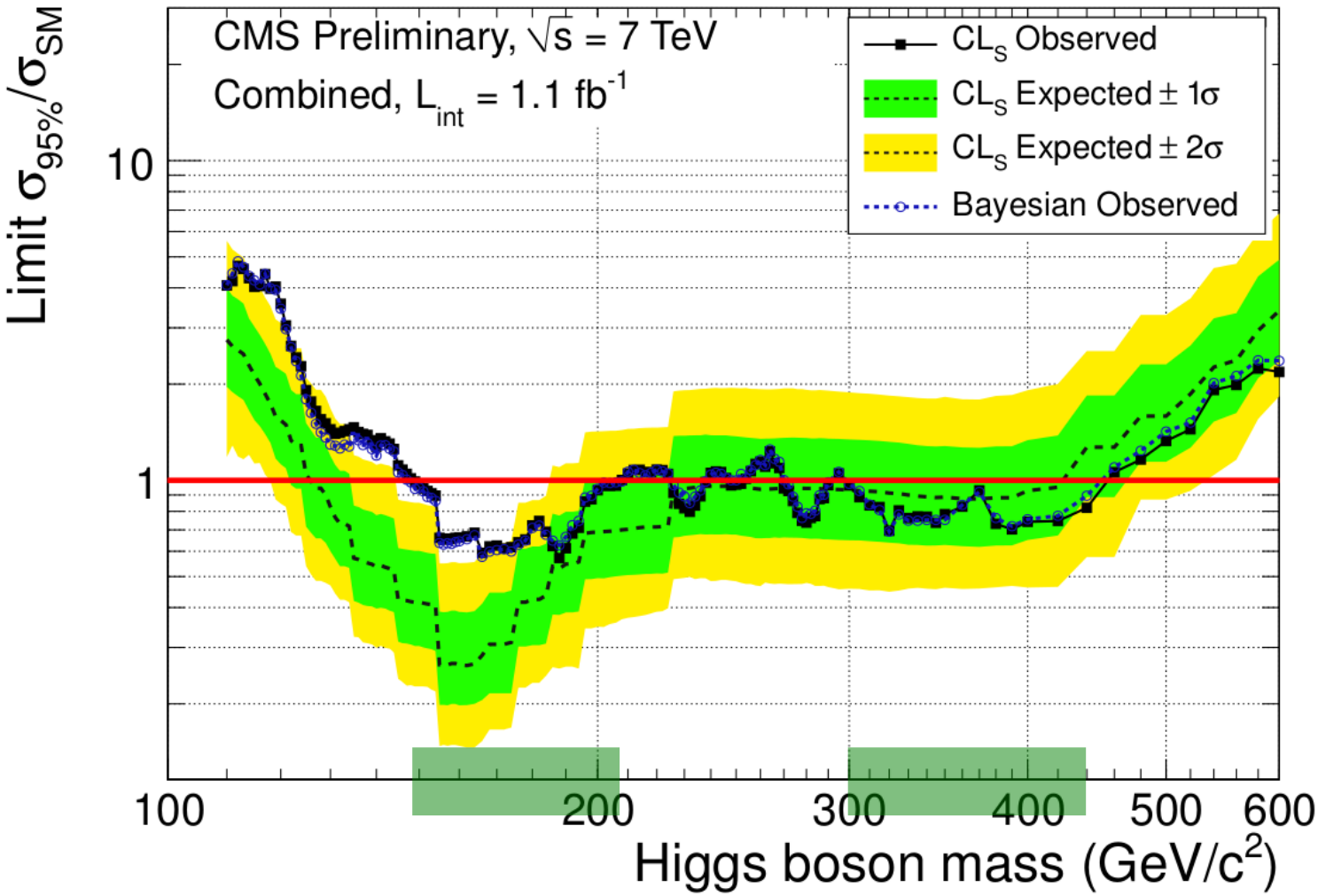


SM Higgs excluded at 95% C.L.

$155 < M_H < 190$ GeV

$295 < M_H < 450$ GeV

Limits on SM Higgs Production



SM Higgs excluded at 95% C.L.

$149 < M_H < 206$ GeV

$300 < M_H < 440$ GeV

Limits on SM Higgs Production

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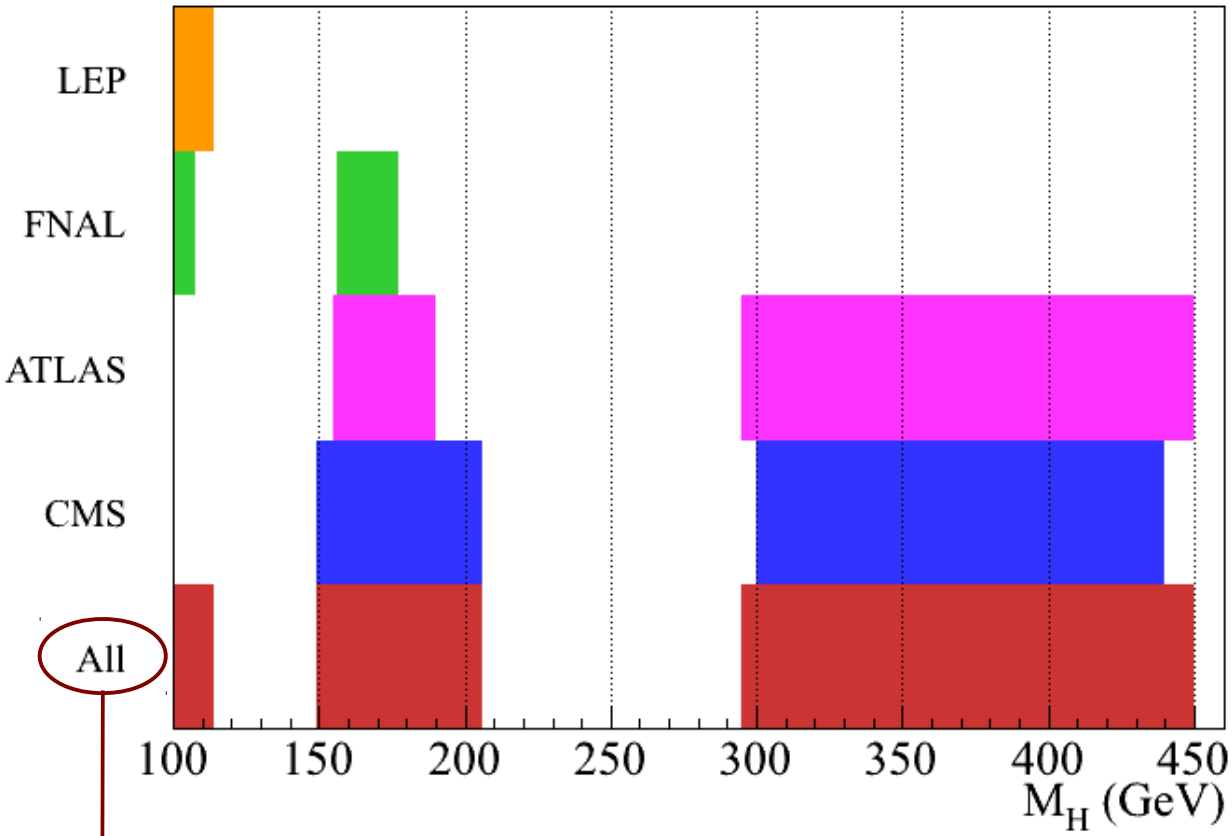
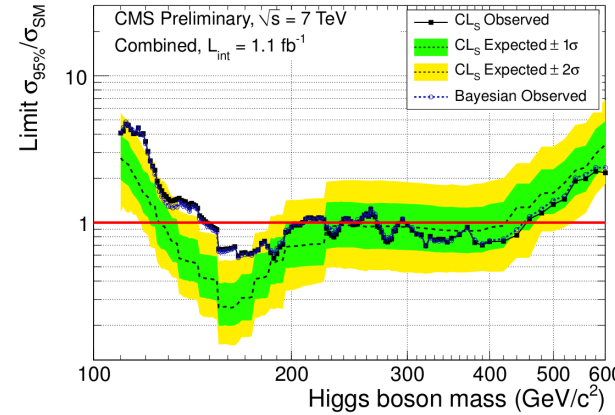
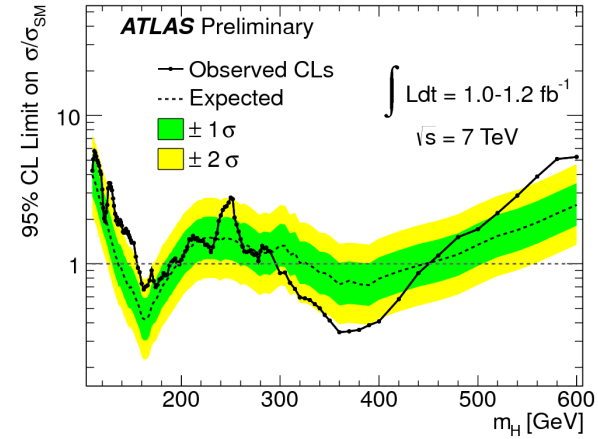
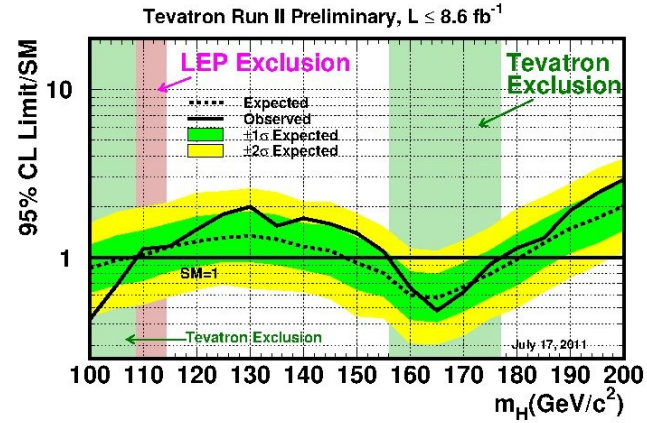
Summary of Collider SM Higgs Exclusions



Simple OR of exclusions







Limits on SM Higgs Production

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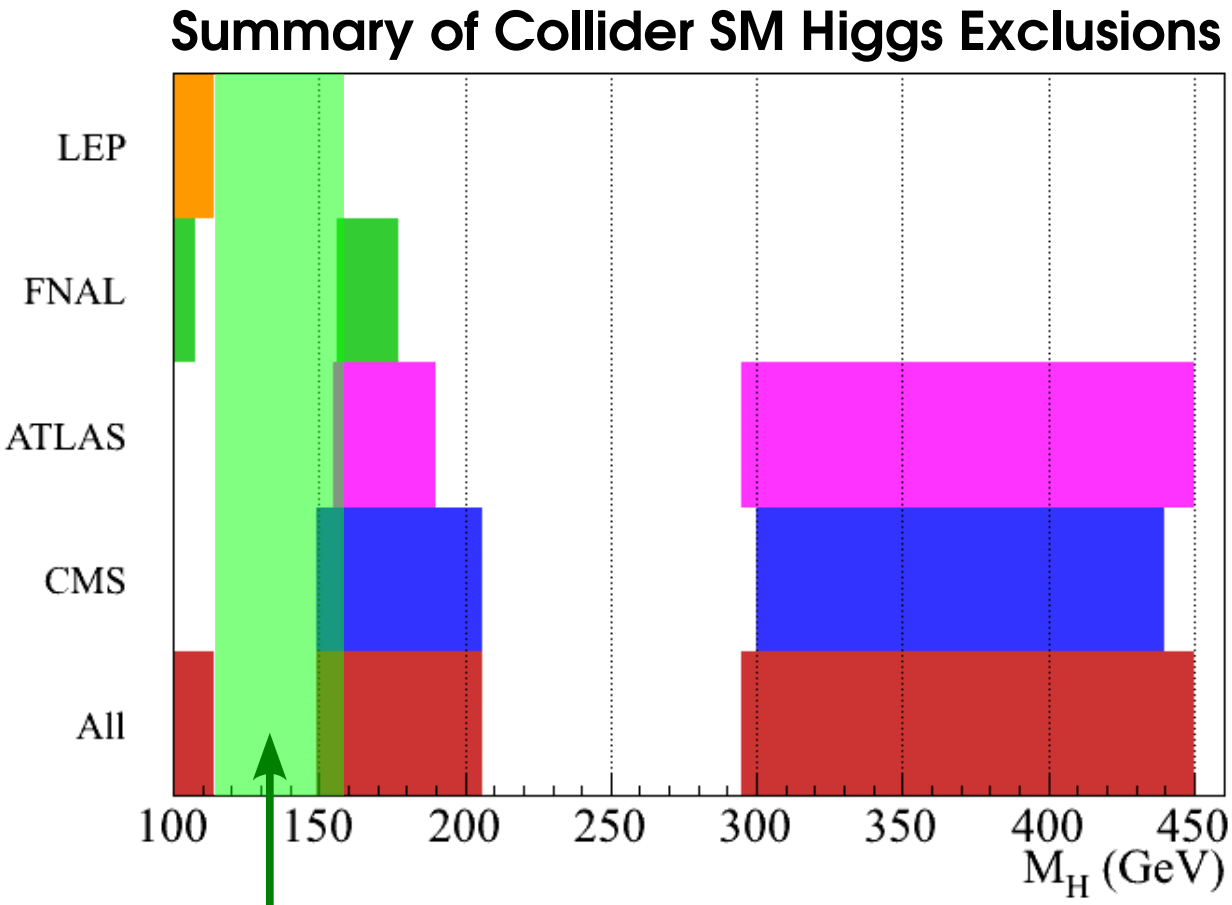
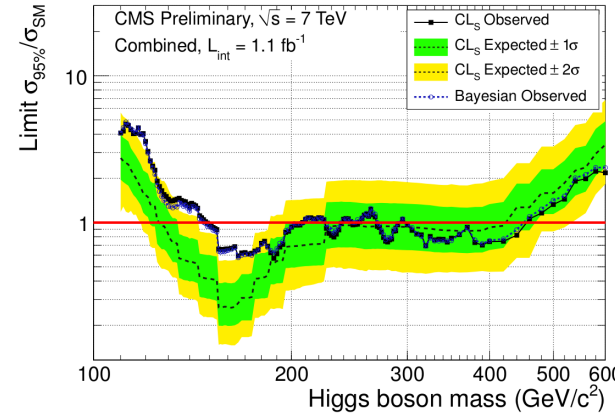
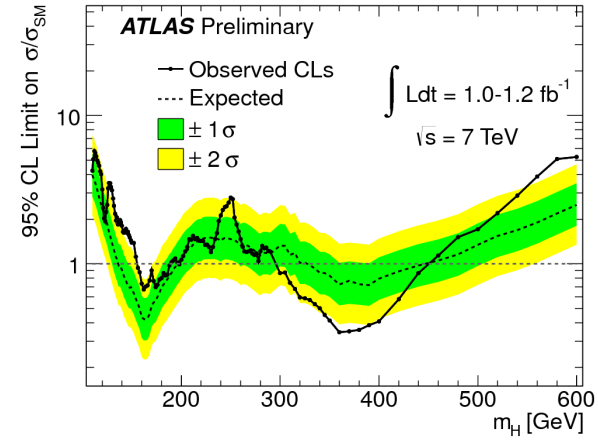
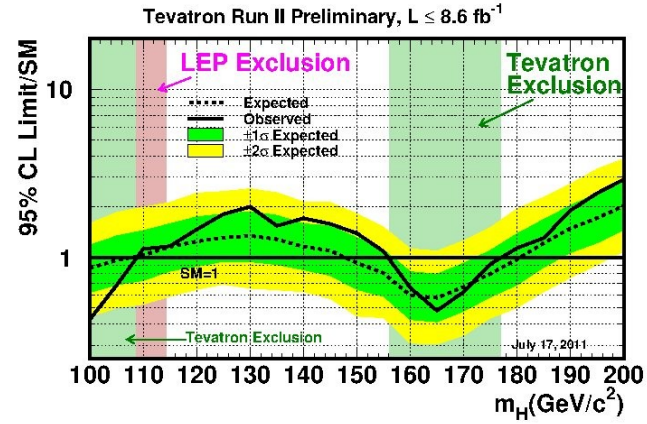


95% C.L. region preferred by fit to precision EW data







Beyond the Standard Model

Higgs Searches

Limits on 4th Generation Models

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An additional generation of quarks/leptons could drastically alter the Higgs landscape

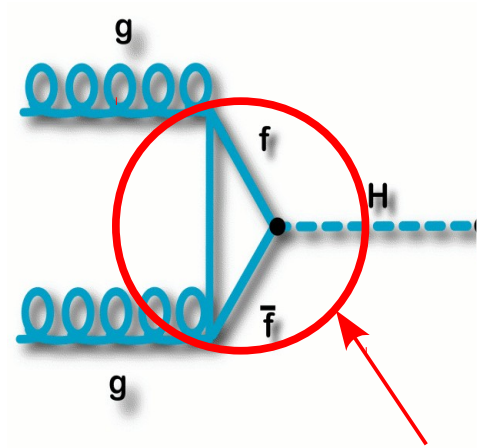
2 extra heavy quarks adds 2 more gg→H diagrams

Boost of ~9x in gg→H rate. No change in VH, VBF, ttH rates.

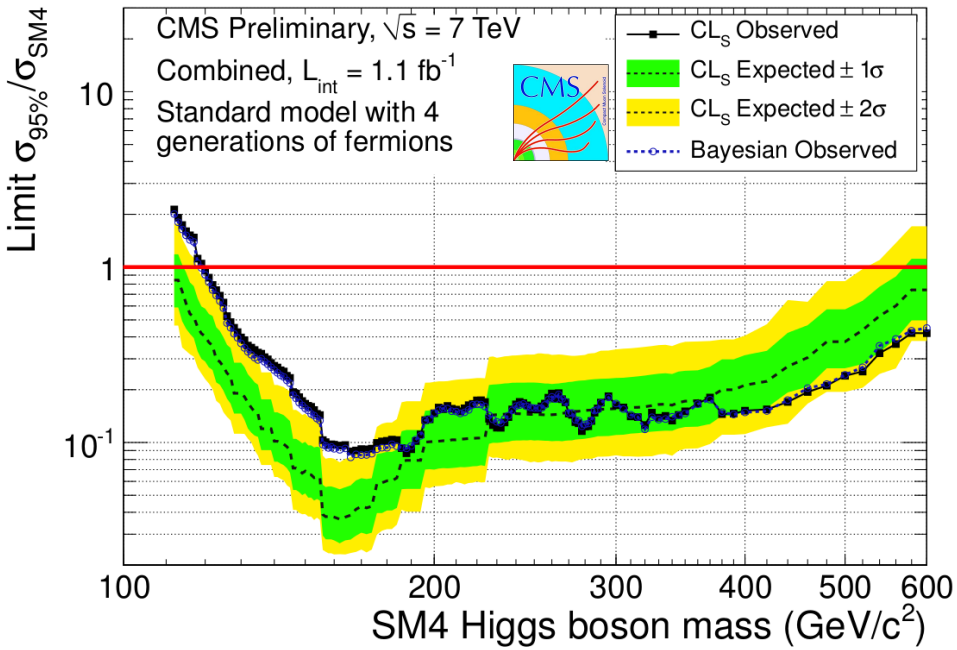
Limits on neutrino mass set a lower bound, but a large phase space remains with heavy quarks.

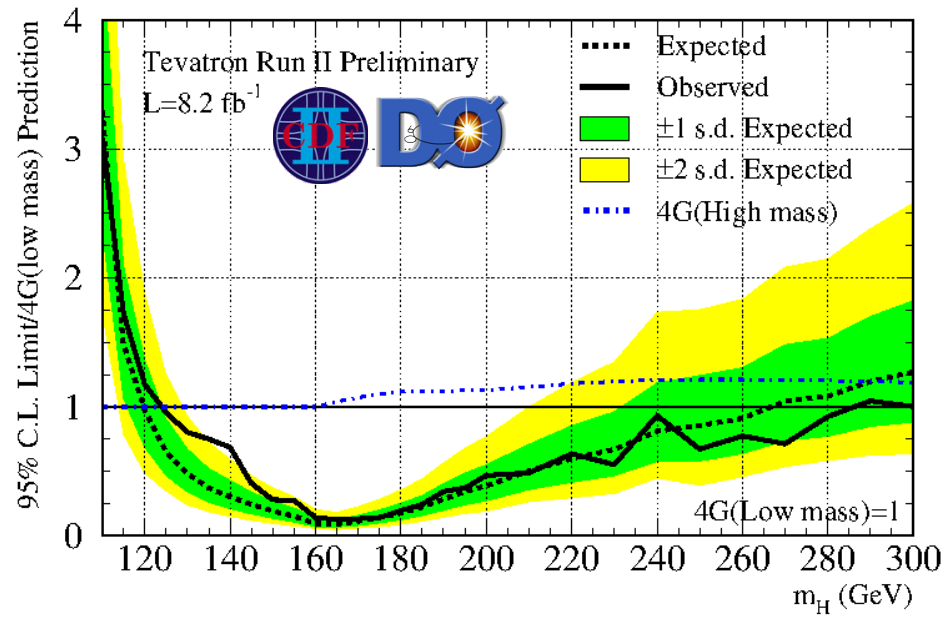
Typical mass of down-type 4th Gen quark for models tested:

Tevatron: 300-400 GeV LHC: 600 GeV



+2 new quarks = 9x in rate!



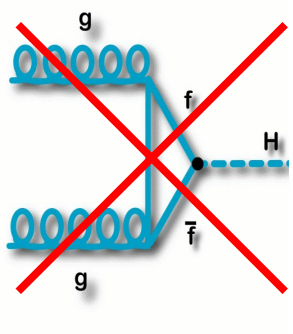


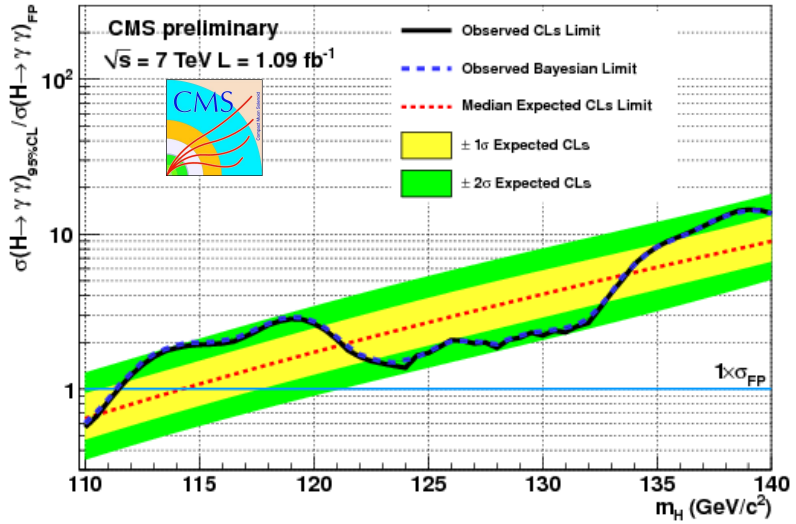
Fermiophobic Higgs

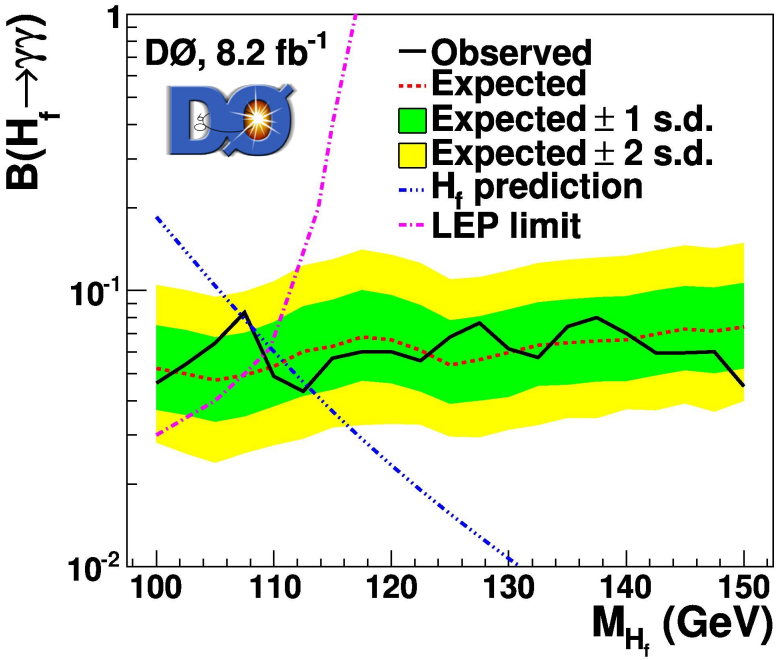
Wade Fisher
PANIC11

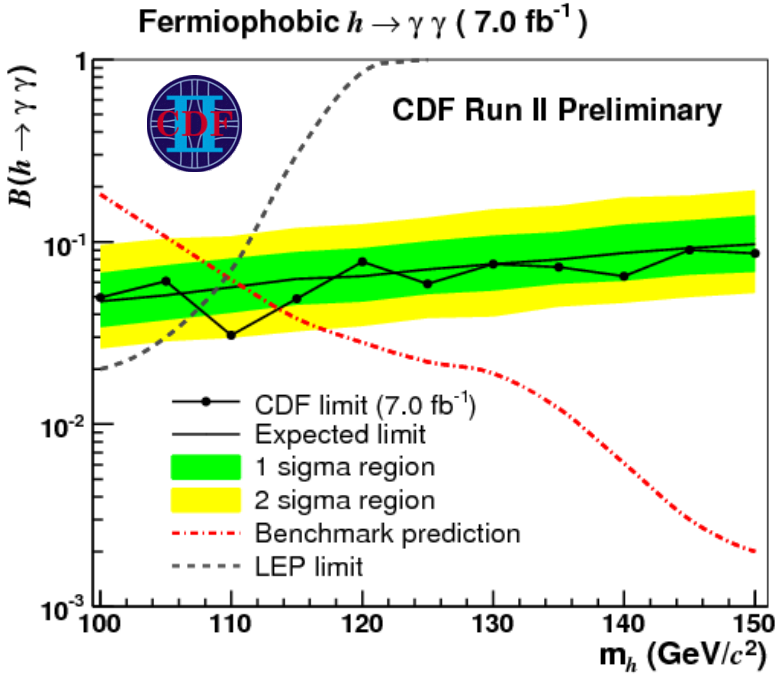
Some multi-doublet Higgs models predict Higgses with zero fermion couplings

Similar search strategies as SM search, but the gg→H diagram doesn't contribute









MSSM Higgs

Minimal SUSY Model (MSSM): Two doublets of scalar fields (only one in SM)

Total of 8 degrees of freedom results in 5 Higgs bosons:

3 Neutral: h, H, A **2 Charged: $H^{\pm}$**

In the Minimal SUSY Model:

Need at least 2 parameters to calculate all Higgs masses and couplings at tree level: **M_A** and **tan(β)** = ratio of vacuum expect'n values for the two Higgs doublets

Coupling of neutral Higgs bosons to bottom quarks is **enhanced by tan(β),** production **enhanced by $\tan^2(\beta)$**

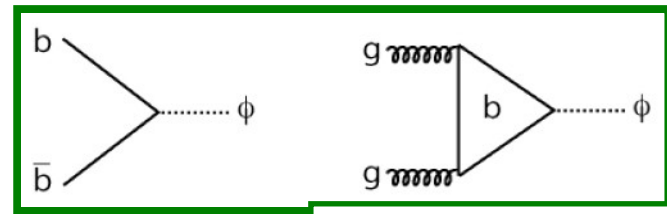
Neutral MSSM Higgs decays

- $\phi \rightarrow$ **bb ~ 90%**

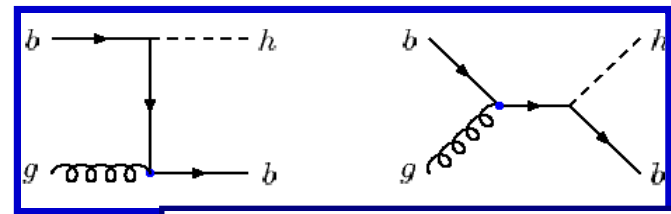
Large background

- $\phi \rightarrow \tau\tau$ **~ 10%**

More distinct signature



$\phi \rightarrow \tau\tau$



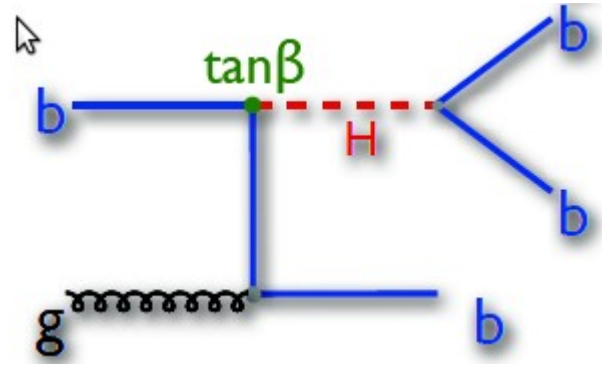
$b[b]\phi \rightarrow 3[4]b$ / $b[b]\tau\tau$

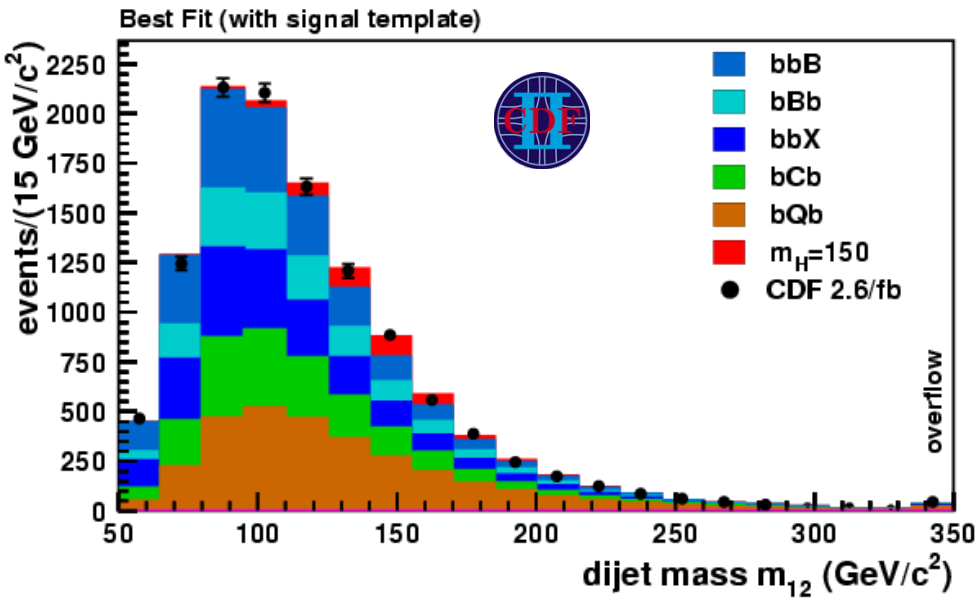
bH→bbb Search

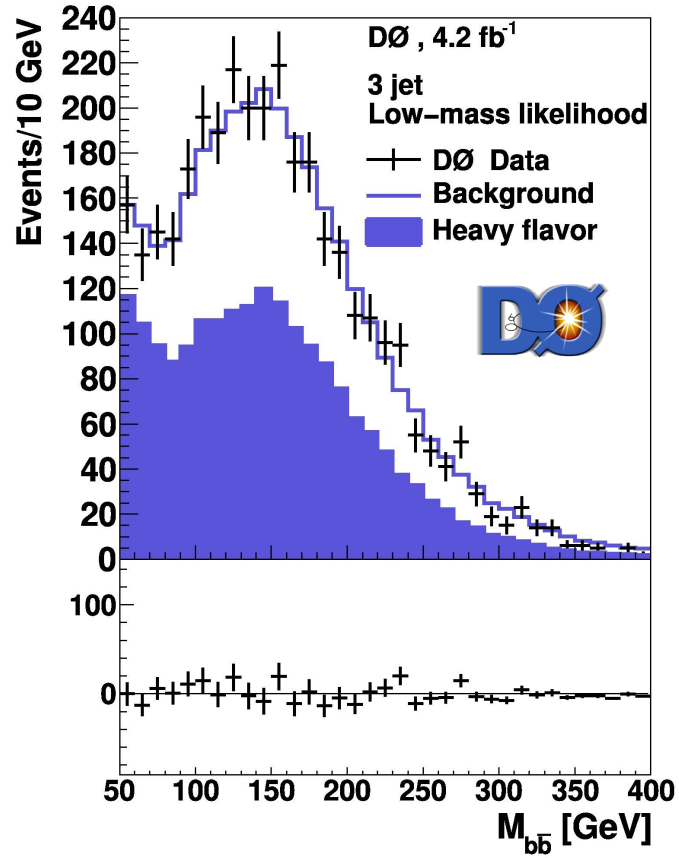
Wade Fisher
PANIC11

Challenging 3 b-quark final state only possible with very efficient b-tagging

- Theory predictions for background rates have large uncertainties
- Fit of templates to data provides normalization
  - Much care to be taken to ensure signal isn't "fitted away"





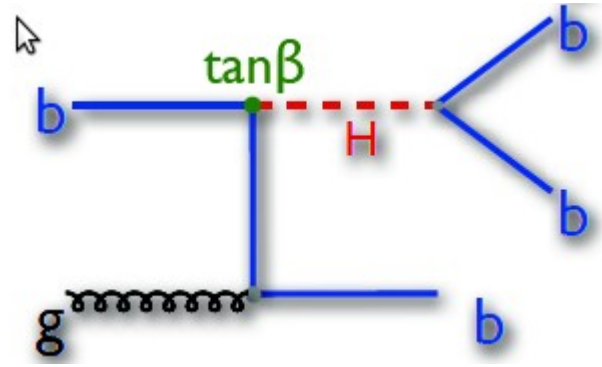


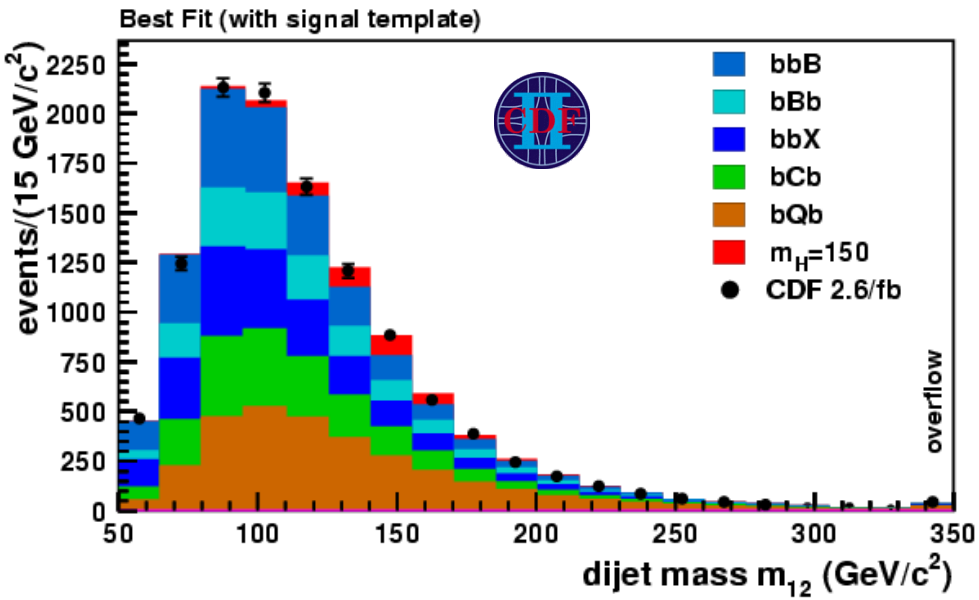
bH→bbb Search

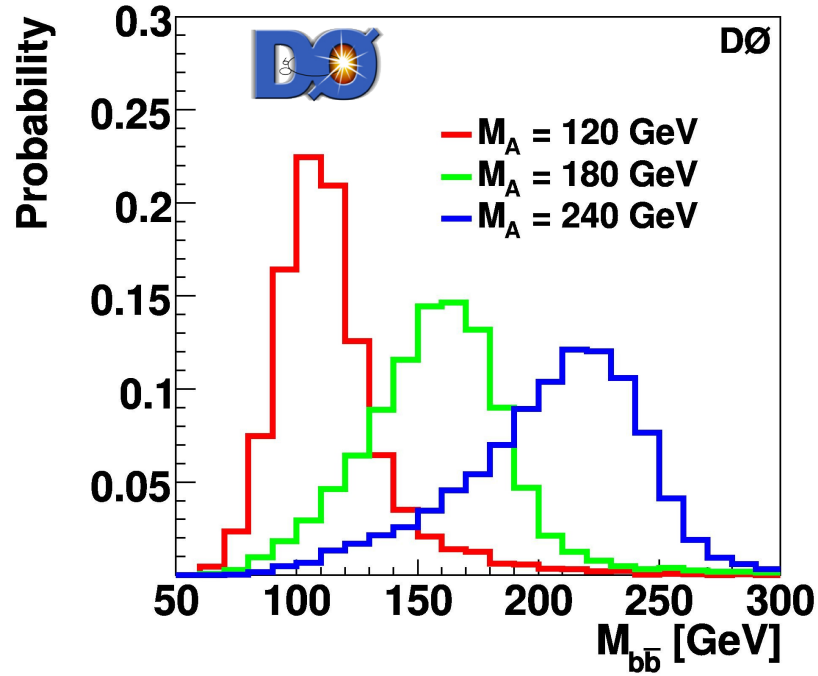
Wade Fisher
PANIC11

Challenging 3 b-quark final state only possible with very efficient b-tagging

- Theory predictions for background rates have large uncertainties
- Fit of templates to data provides normalization
  - Much care to be taken to ensure signal isn't "fitted away"
- Signal mass resolution ultimately limits high mass search potential



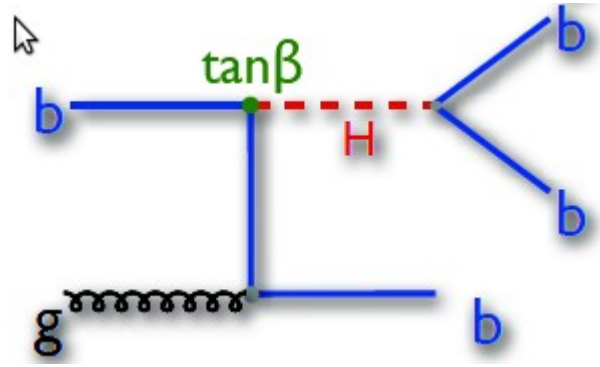


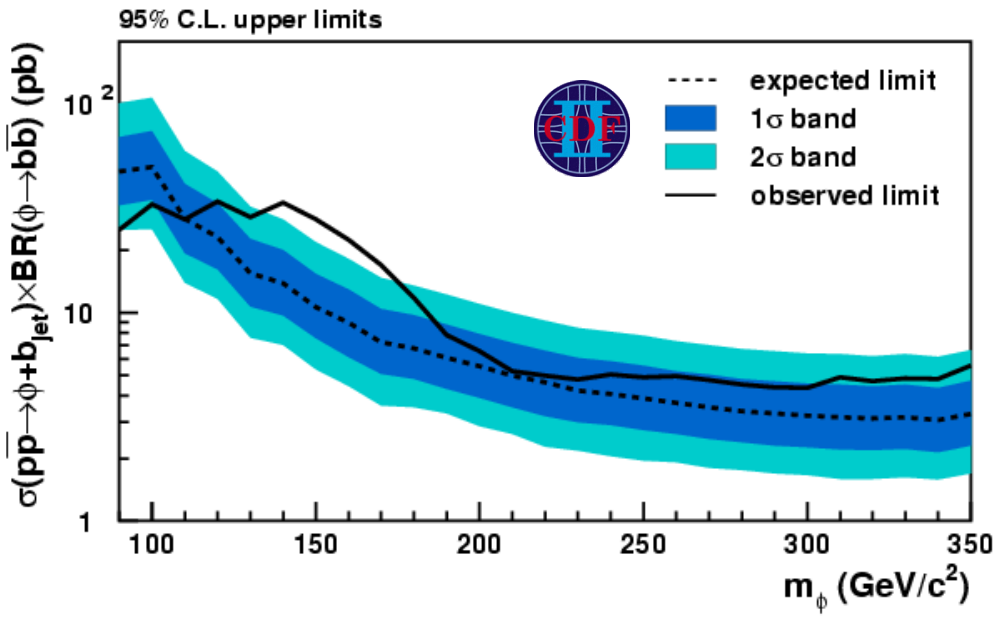


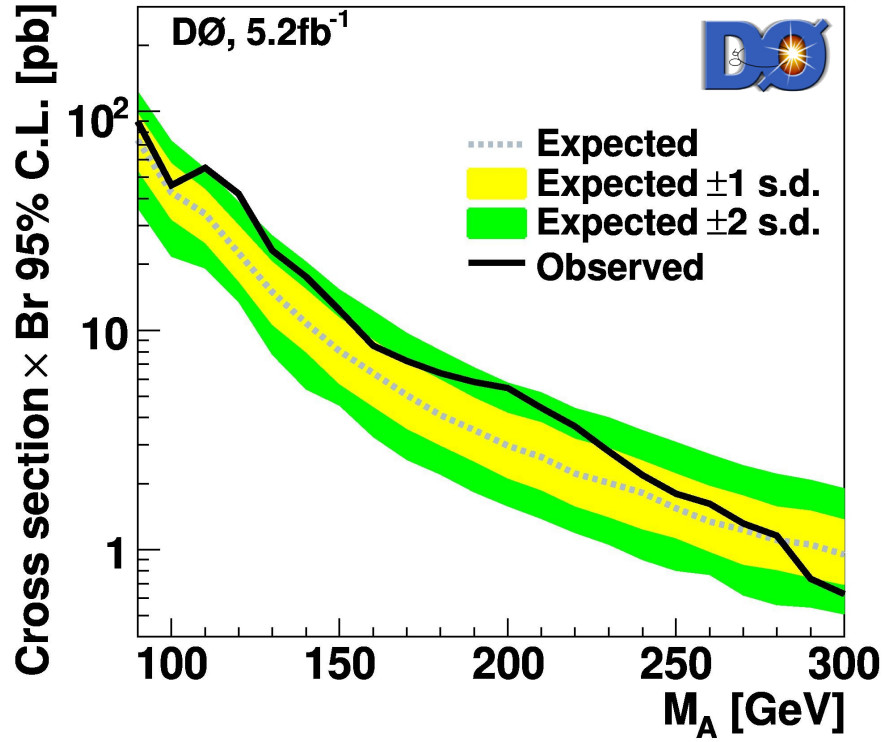
bH→bbb Search

Limits are derived in the same manner as with SM searches

- Data are compatible with the background predictions
  - But both CDF & DØ see ~2σ excesses around M_H=120-150 GeV.
- Combination of search results is being investigated



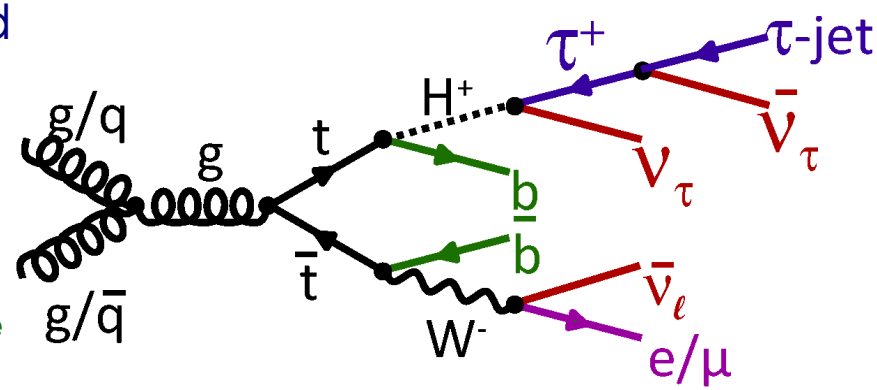


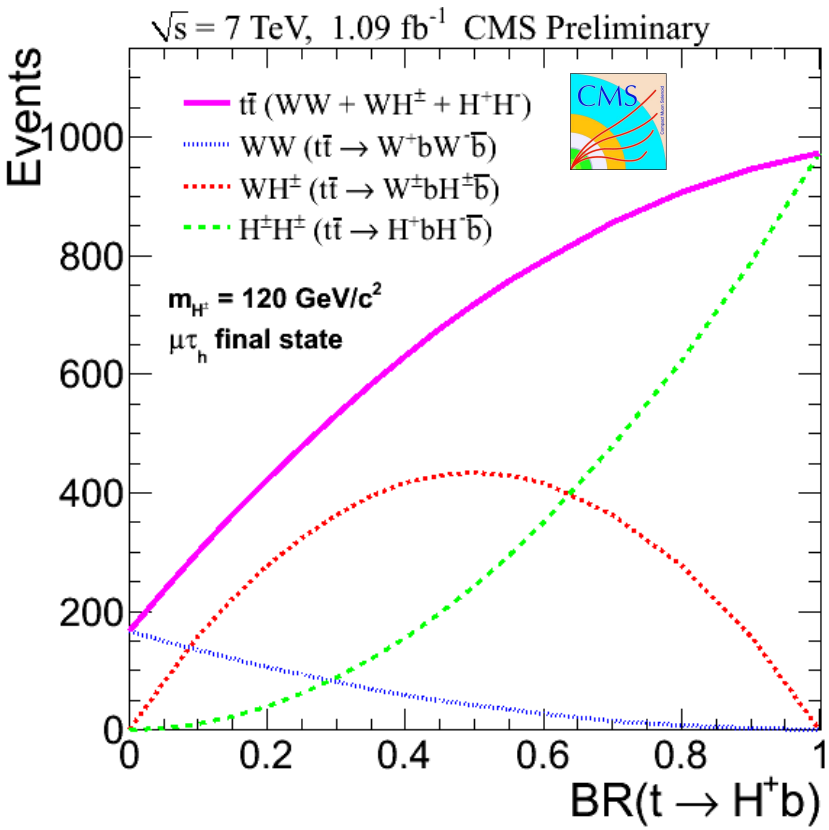


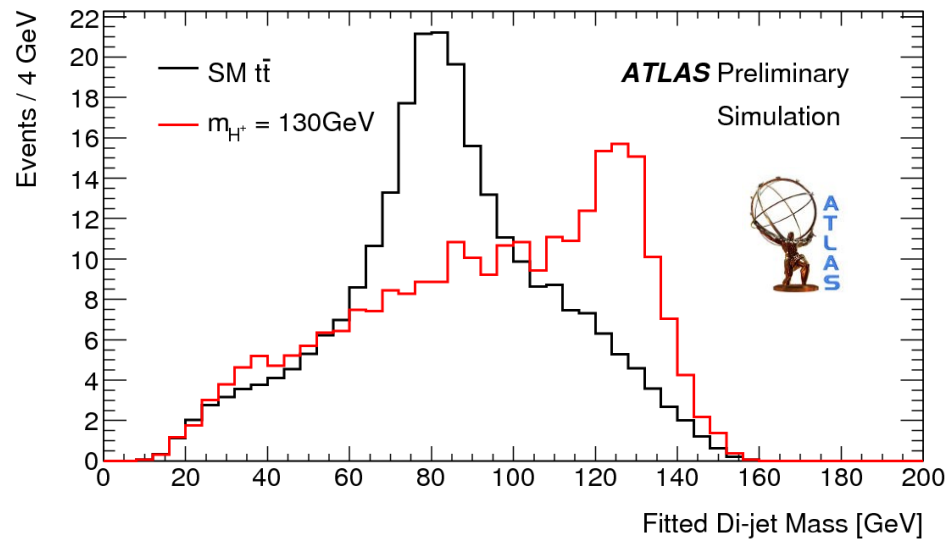
Charged Higgs Searches

The presence of charged Higgs bosons could manifest in non-SM top production rate

- Not necessarily obvious in a regular top quark measurement
- Presence of final state taus and/or resonant dijet mass ($H^+ \rightarrow cs$) would be the evidence







Charged Higgs Searches

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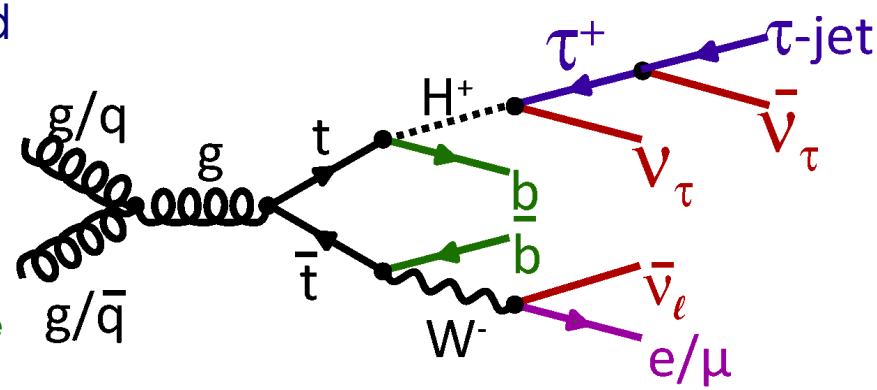
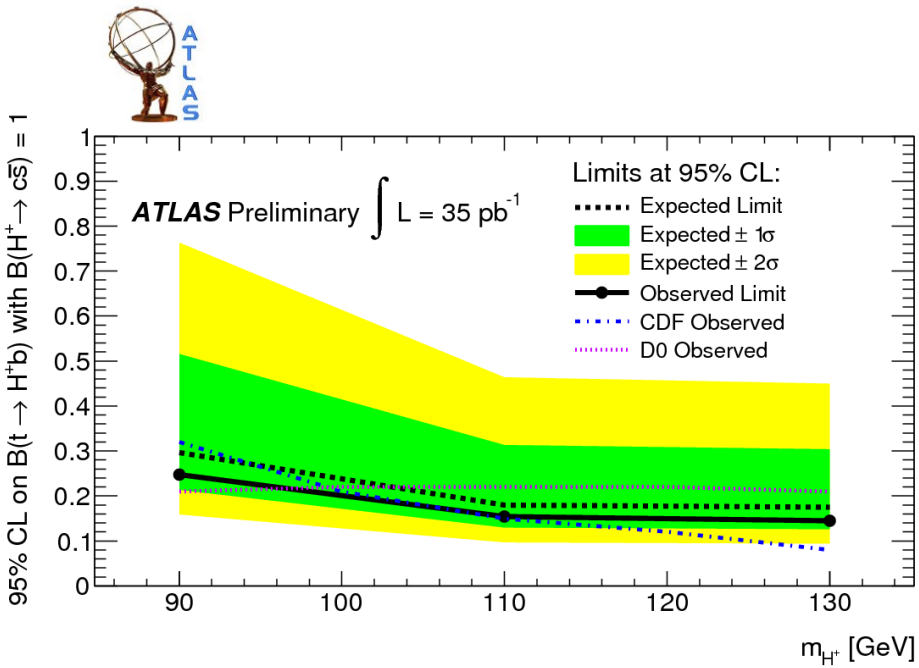
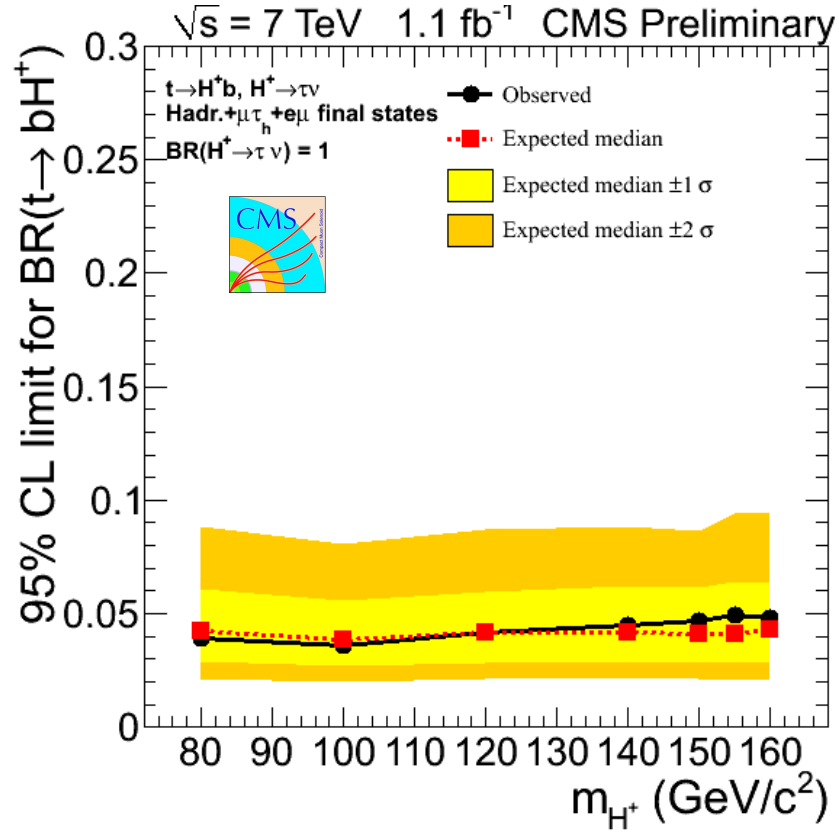
The presence of charged Higgs bosons could manifest in non-SM top production rate

- Not necessarily obvious in a regular top quark measurement
- Presence of final state taus and/or resonant dijet mass ($H^+ \rightarrow cs$) would be the evidence
- Limits from LHC & Tevatron thus far consistent with SM predictions







(b)H→(b)ττ Search

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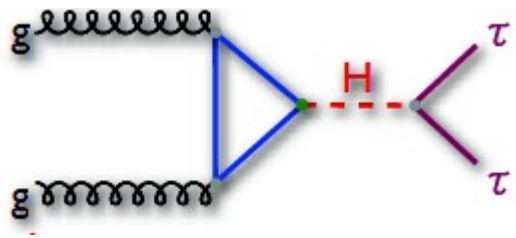
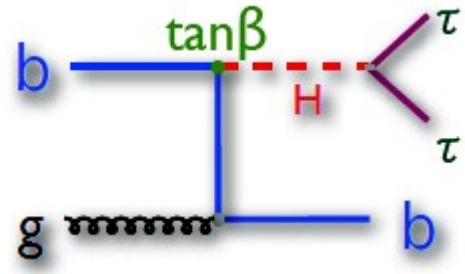
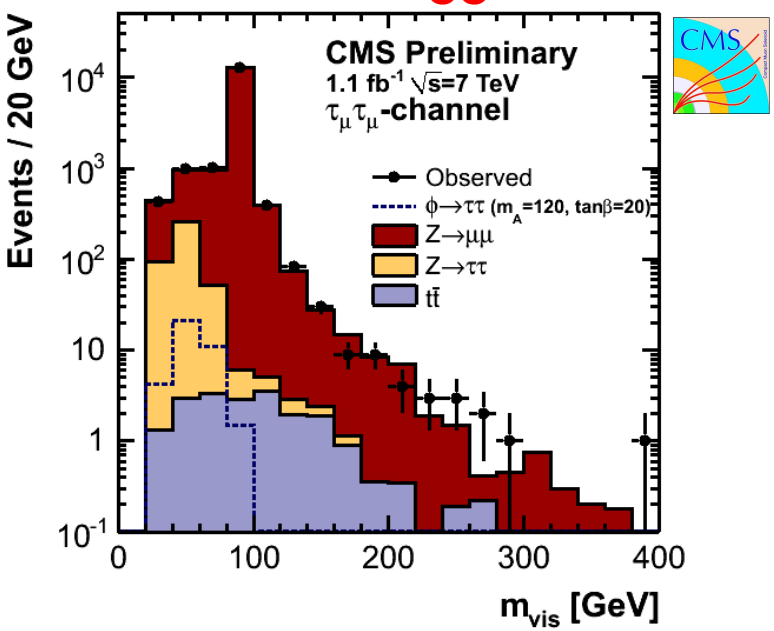
Di-tau searches contribute to both the MSSM and SM search efforts

- Both gluon-fusion and associated production diagrams contribute
  - →Analyses are separated into b-tagged and non-tagged final states
- Di-tau "visible mass" is one of the most powerful search criteria

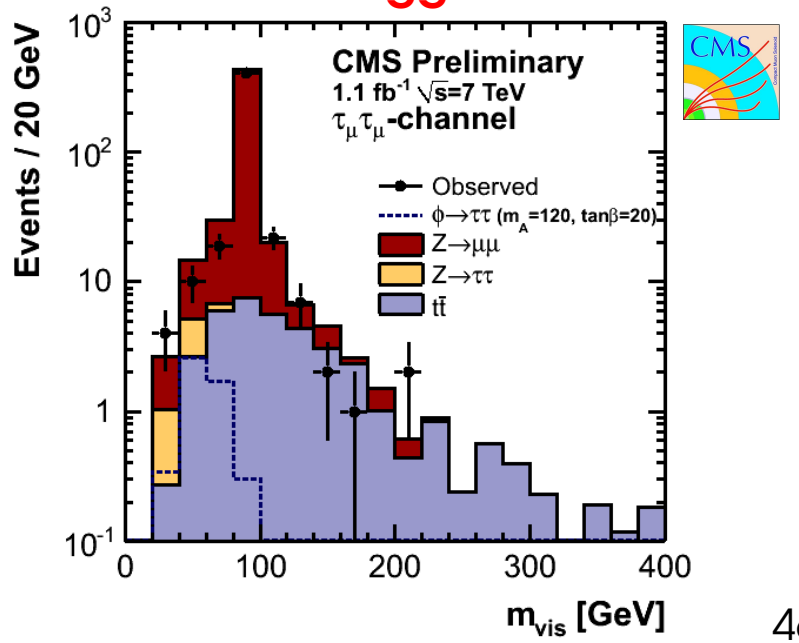




Non b-tagged



b-tagged



(b)H→(b)ττ Search

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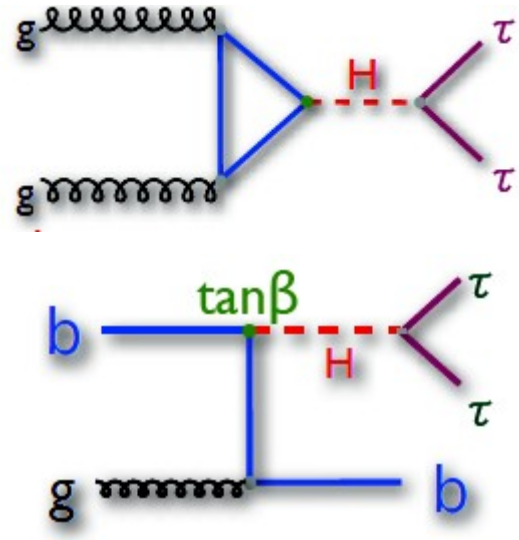
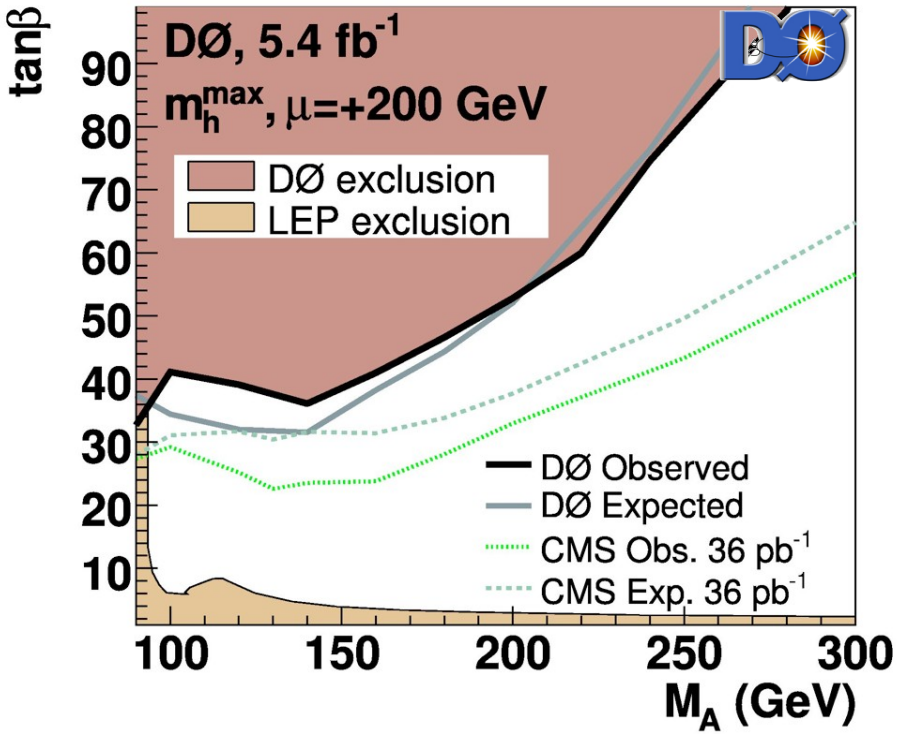
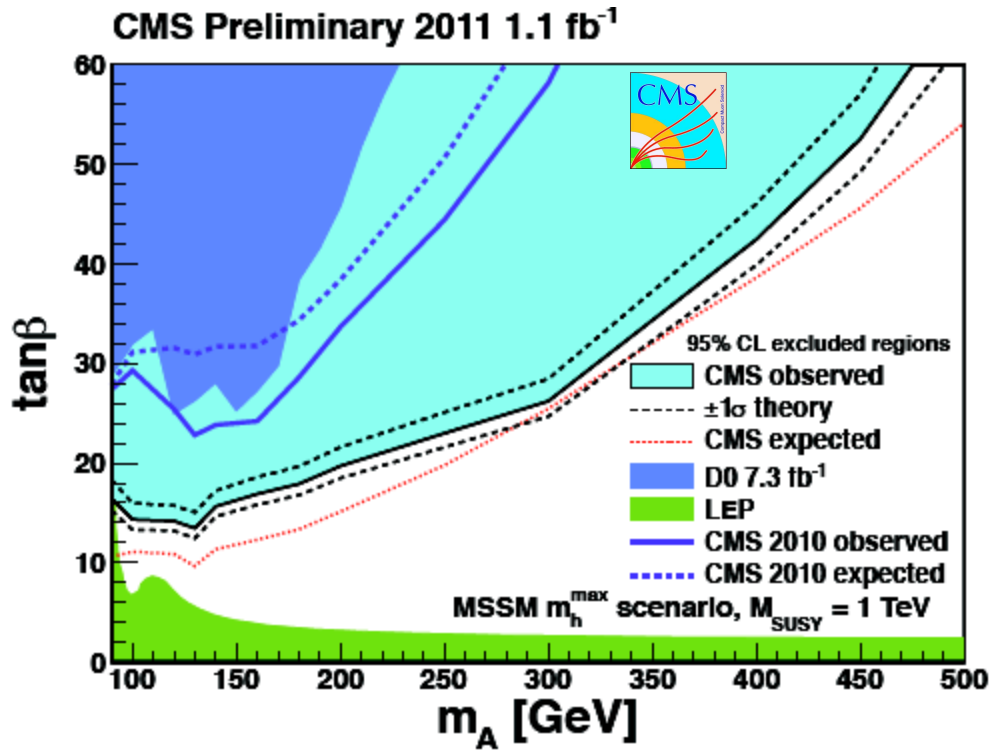
Powerful exclusions in tanB/M_A plane

CMS observes a broad excess for all M_A.

→Tevatron searches in similar final state exhibit excess at low M_A, but are less powerful.





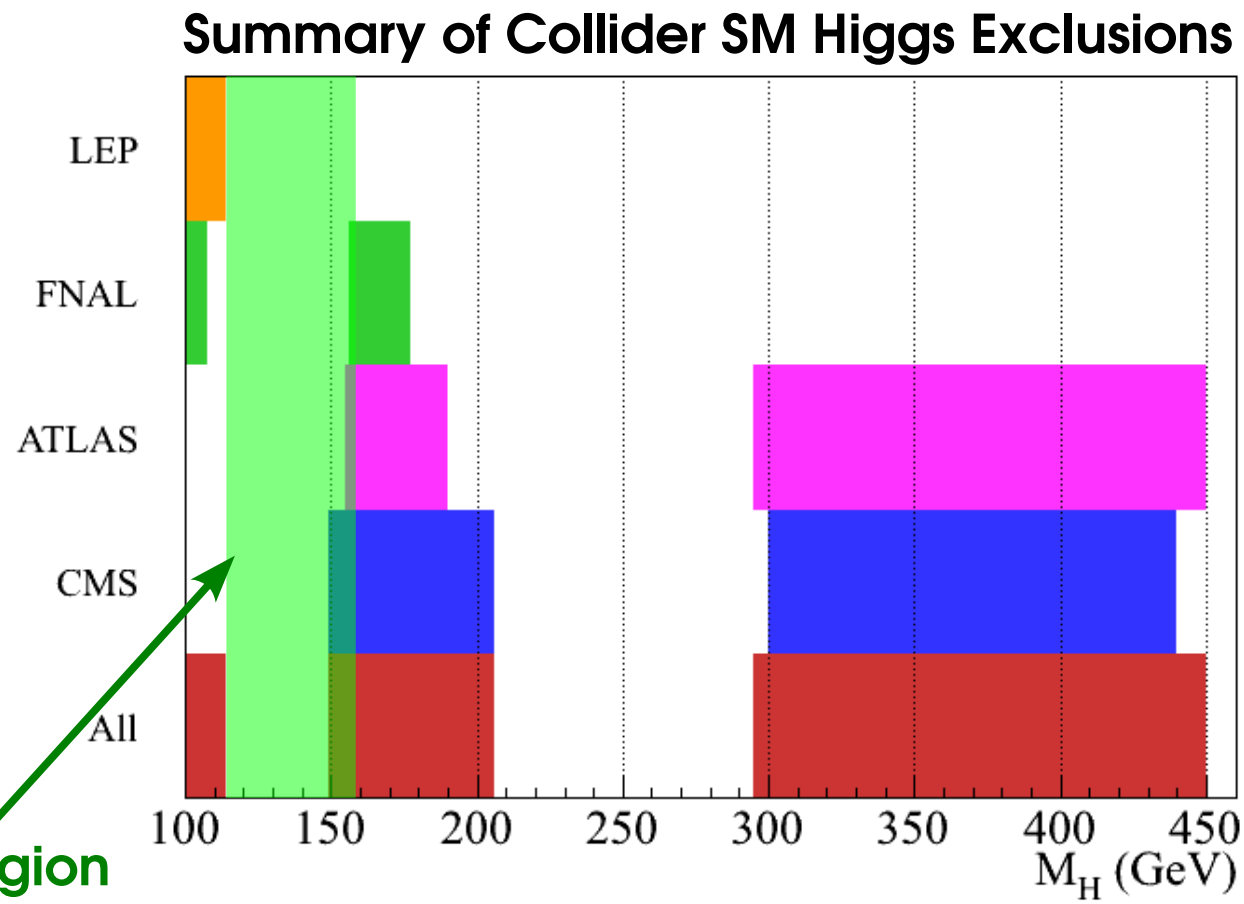


Glimpses into a possible future of Higgs searches

What do today's results tell us?

We now have the most extensive SM Higgs exclusions ever produced

- A null result is nearly as powerful an indicator as discovery
- But we have not excluded the region most favored by EW precision data



95% C.L. region preferred by fit to precision EW data

What do today's results tell us?

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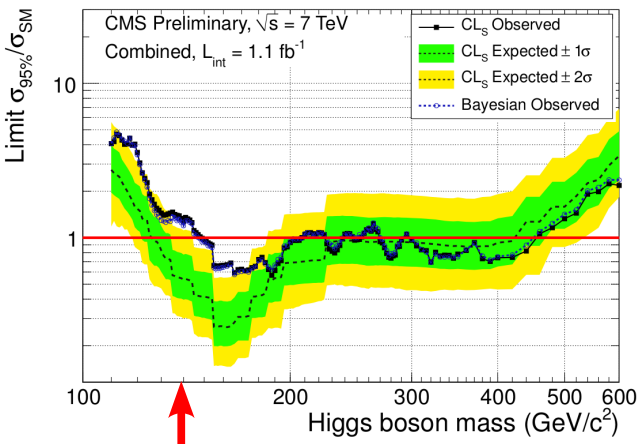
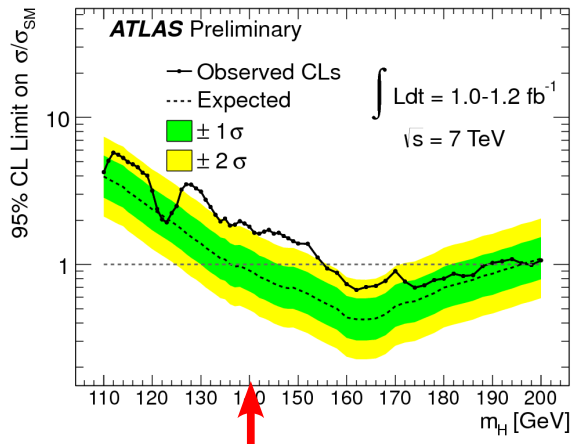
We now have the most extensive SM Higgs exclusions ever produced

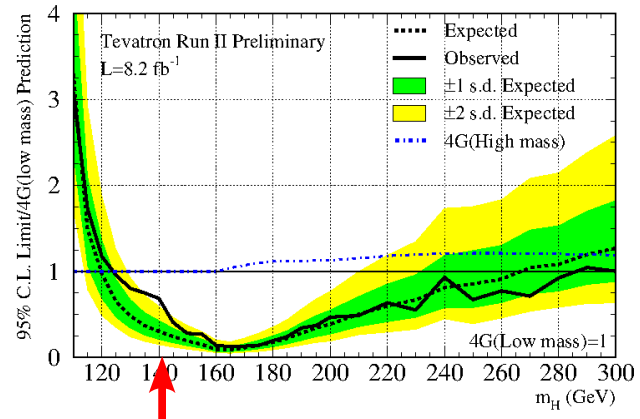
- A null result is nearly as powerful an indicator as discovery
- But we have not excluded the region most favored by EW precision data

Is there already emerging evidence of an excess?

- Inside the EW preferred region: searches dominated by gg→H production seem to have common features near M_H=140 GeV
- Excess doesn't seem compatible with 4th Generation predictions. There may still be a twist to the story







Higgs Search Projections

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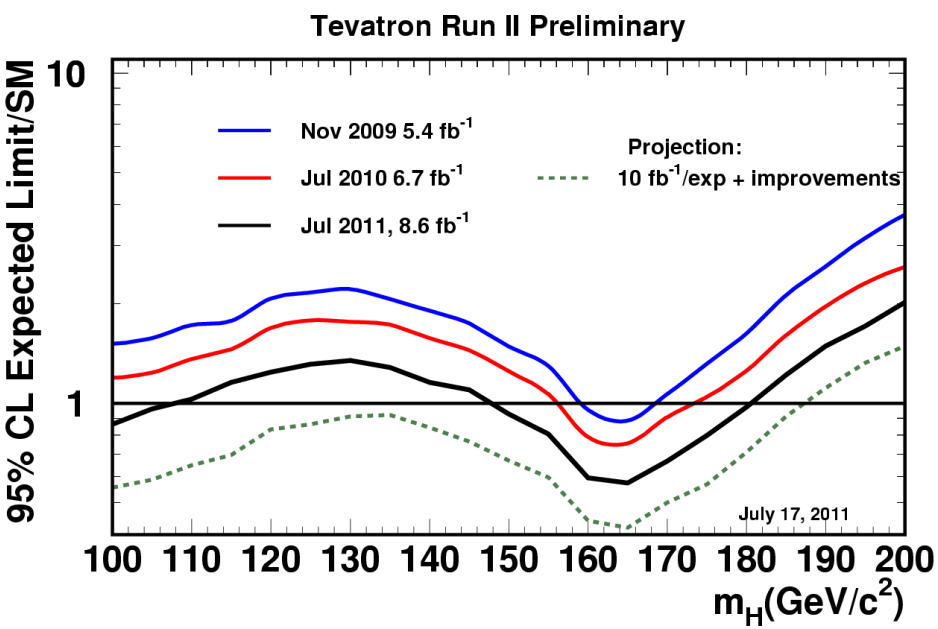
Tevatron experiments will collect data through Sept 30 2011

- Current results based on ~8.0 fb^{-1} on average, will have ≥10 fb^{-1} in the end.
- Including ongoing analysis improvements, could exclude M_H<190 GeV

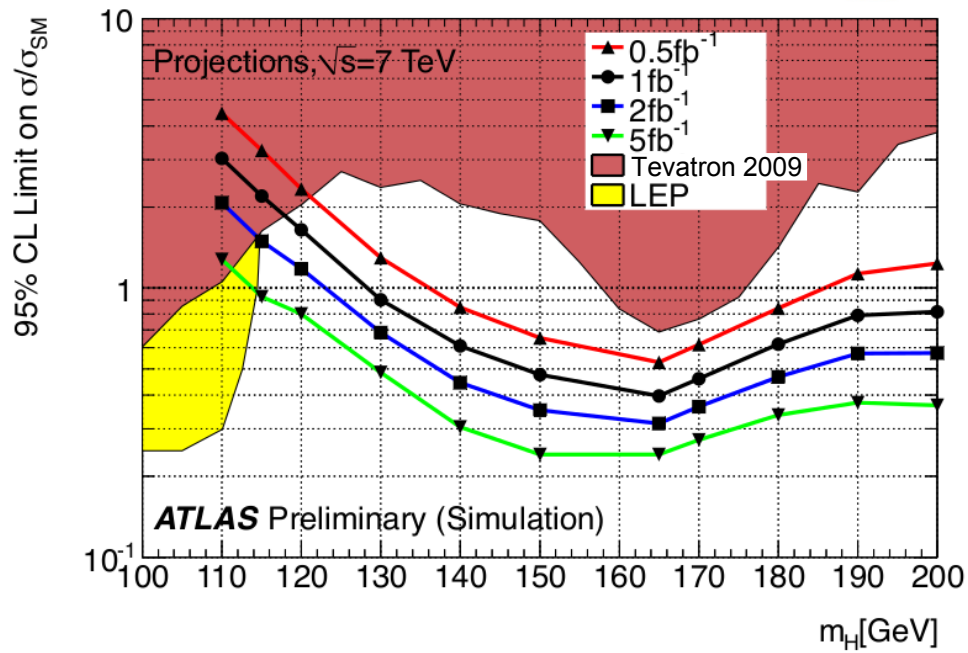
The LHC should have ~4 fb^{-1} on the timescale of Winter 2012 (*4x in statistics*)

- Broad discovery potential for M_H>130 GeV
- More difficult for M_H<130, reliant largely upon $H\to\tau\tau$ and $H\to\gamma\gamma$

Tevatron Exclusion Prediction



ATLAS Exclusion Prediction



Conclusions

We stand at the precipice of understanding for the mass generation mechanism

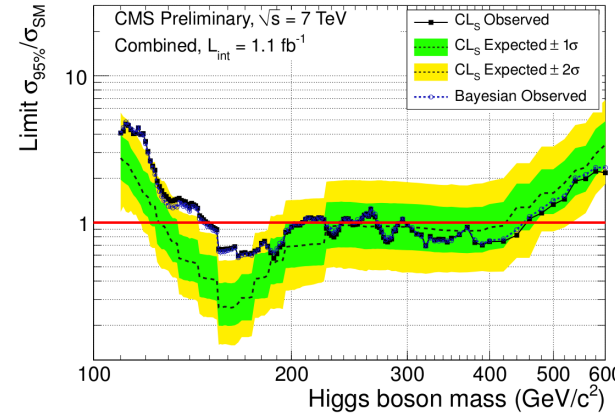
- Is the most successful theory in the history of particle physics complete?
- Or will the data point in a completely different direction?

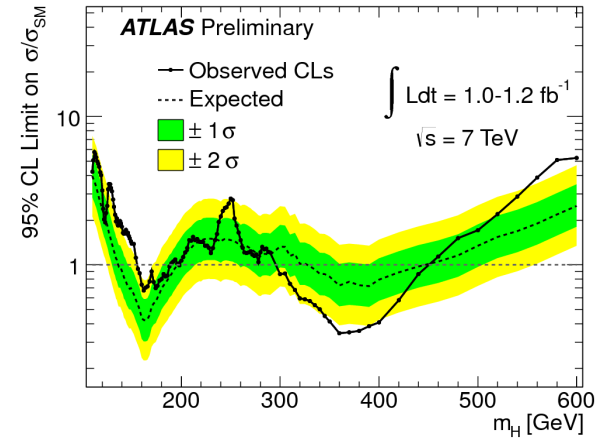
HEP collider programs have been very successful in assembling a Higgs search program

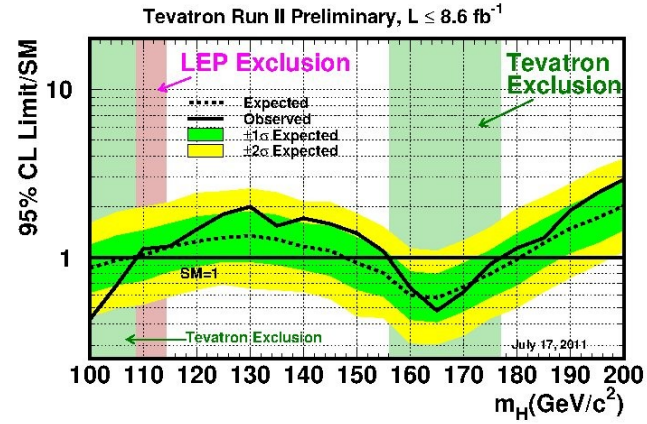
- The Tevatron was never expected (or designed) to be able to perform a Higgs search
- The LHC machine and experiments have worked as well as one could hope, with a bright future

With a broad search program ongoing, some real answers are likely very close

Please stay tuned!







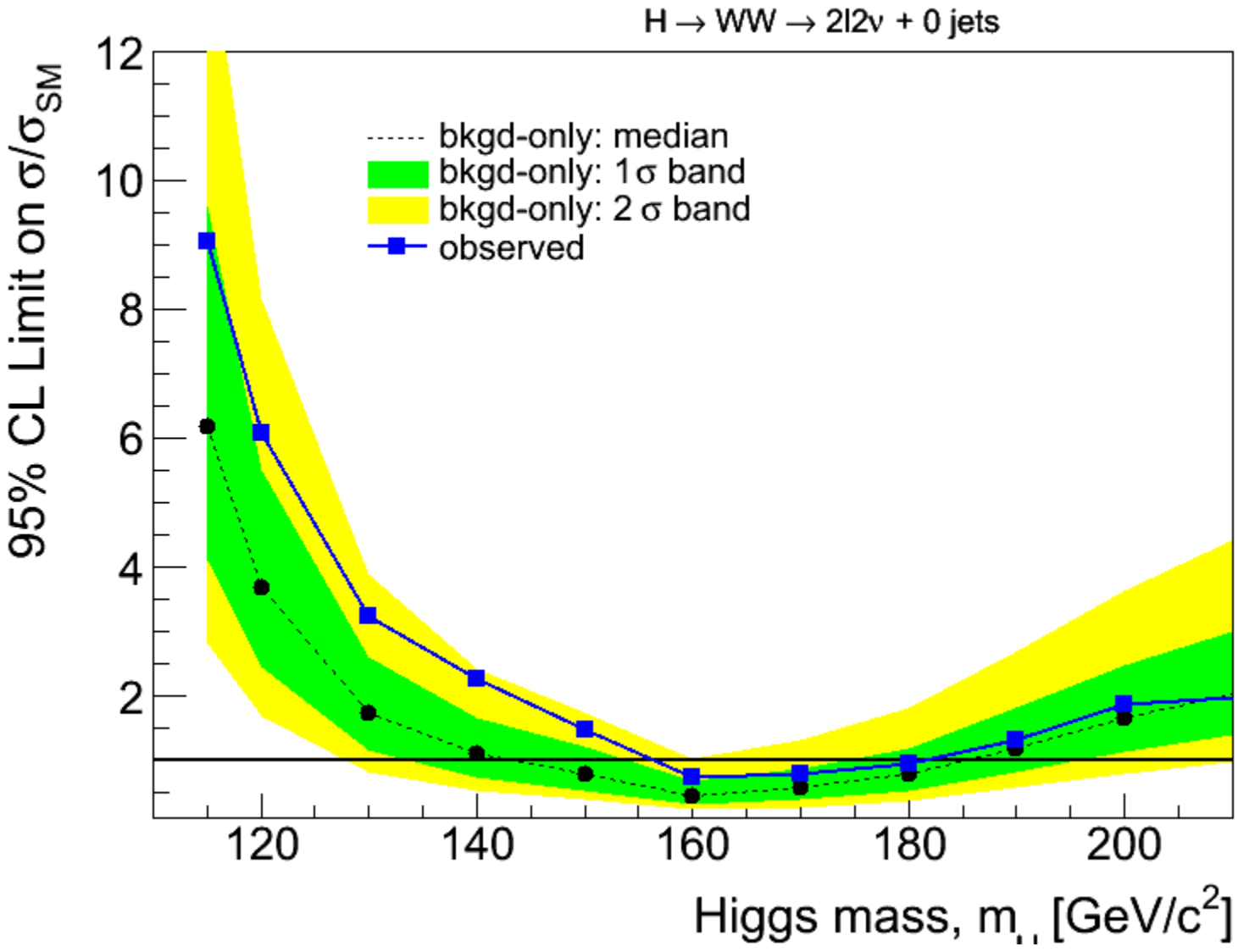
Backup Slides

CMS Signal Injection Study

Wade Fisher
PANIC11

Test of "fake" data made by injecting M_H=140 GeV signal into bkgd MC

Gives an indication of effective mass resolution

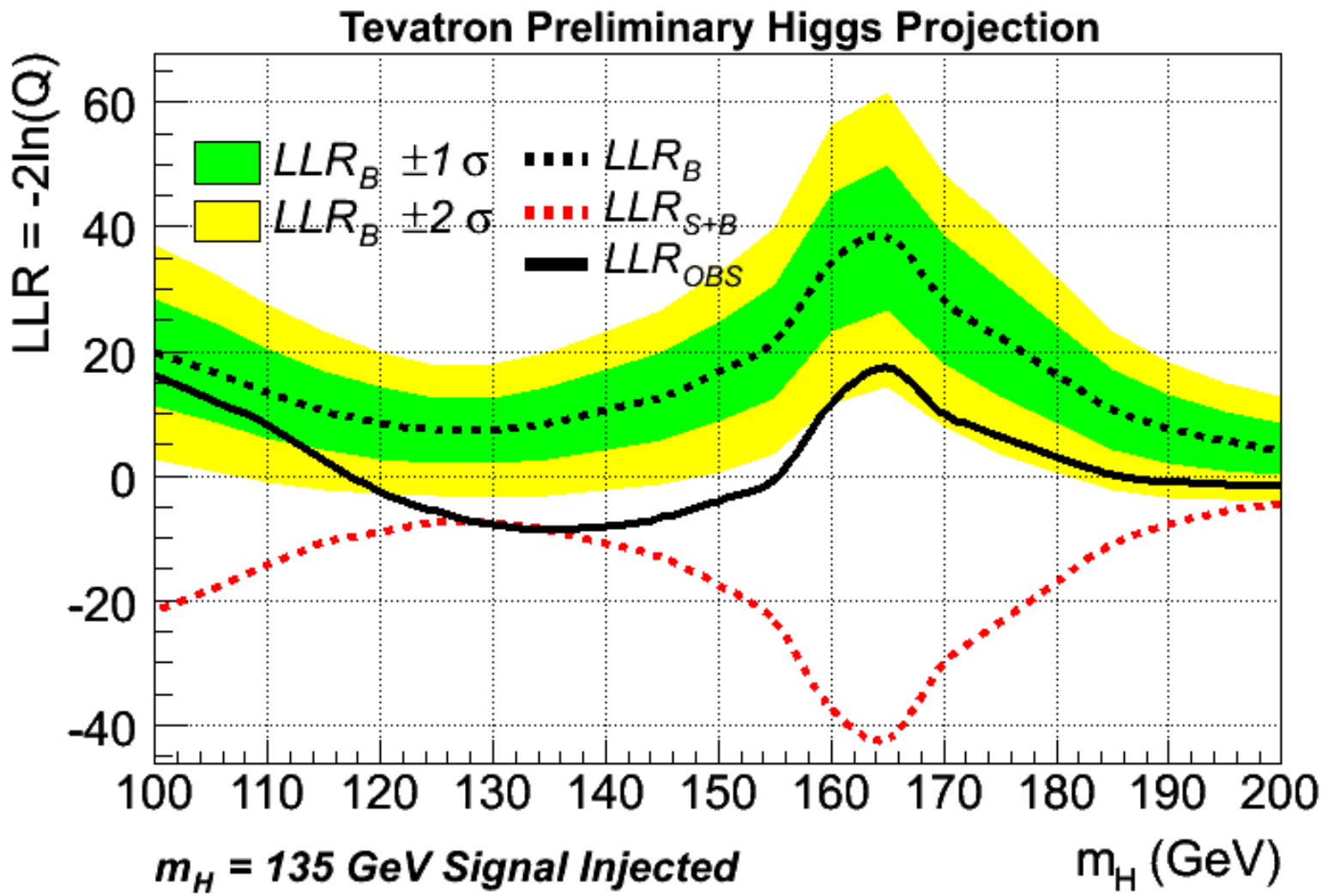


Tevatron Signal Injection Study

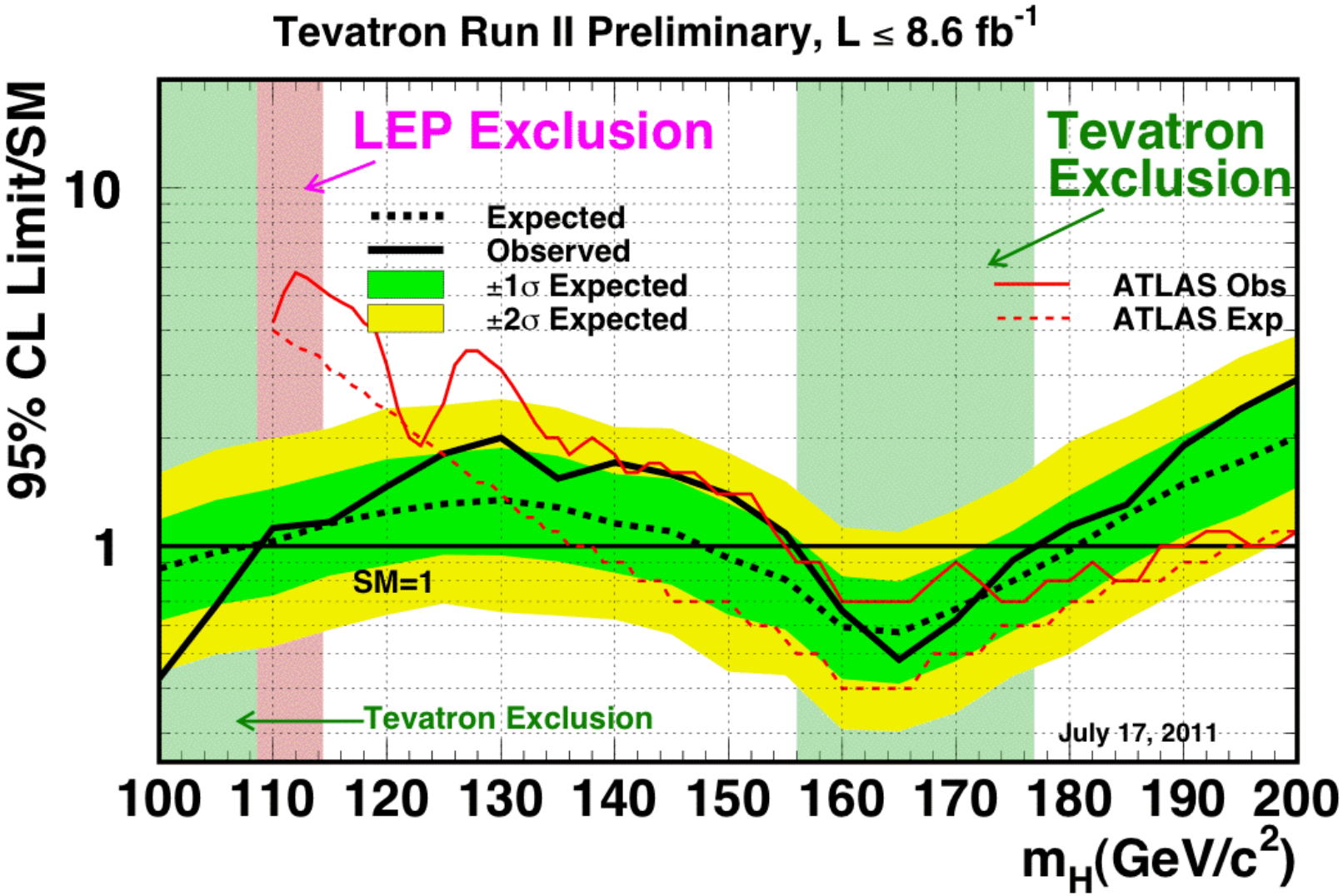
Wade Fisher
PANIC11

Test of "fake" data made by injecting M_H=135 GeV signal into bkgd MC

Gives an indication of effective mass resolution



Tevatron Comparison with ATLAS



Tevatron Impact to Global Fit

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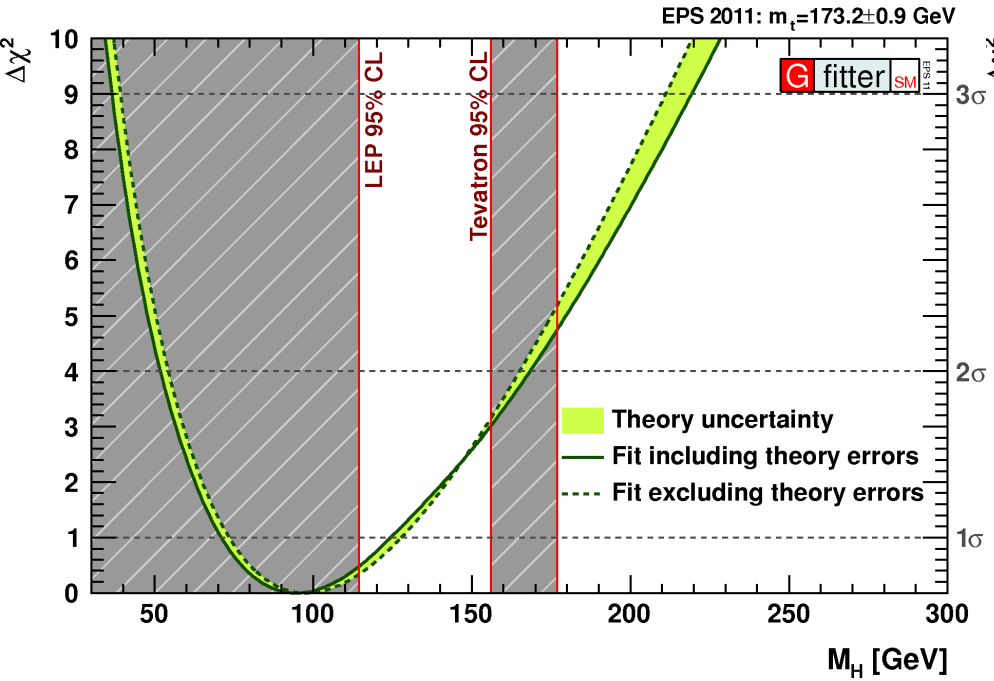
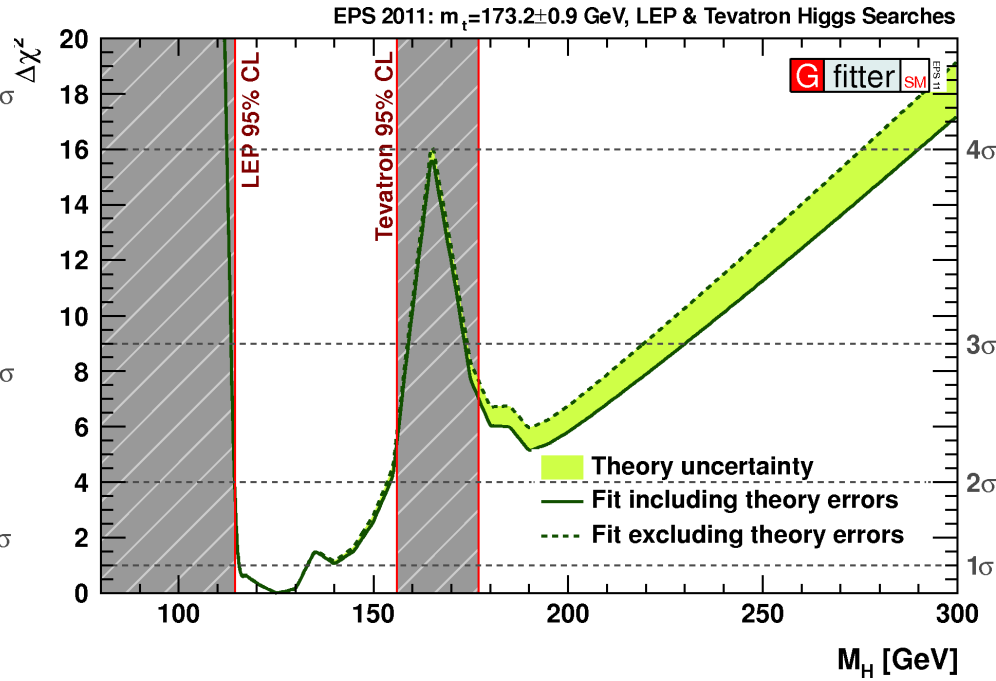
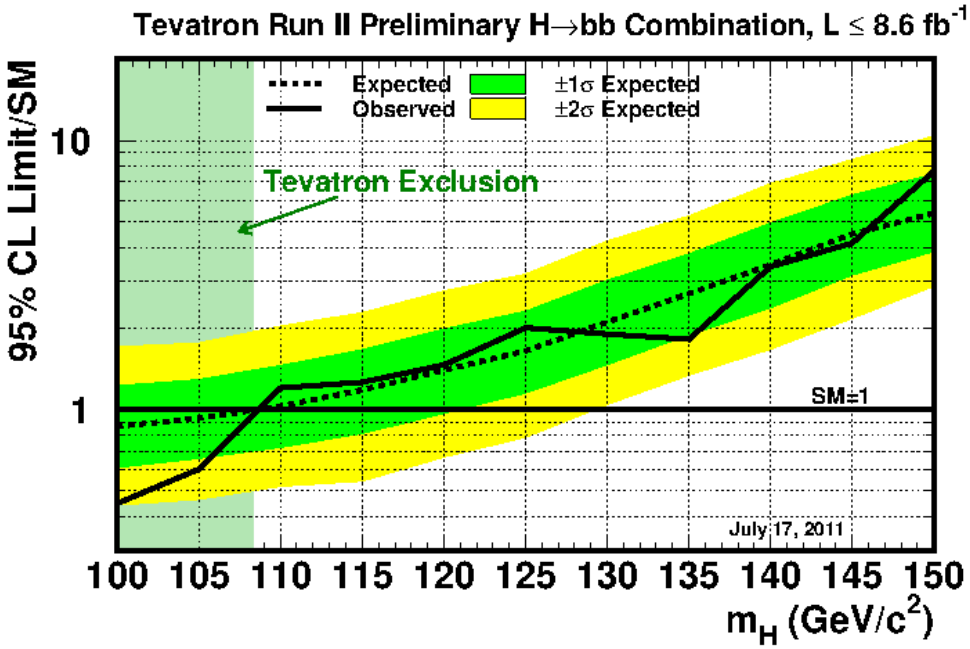
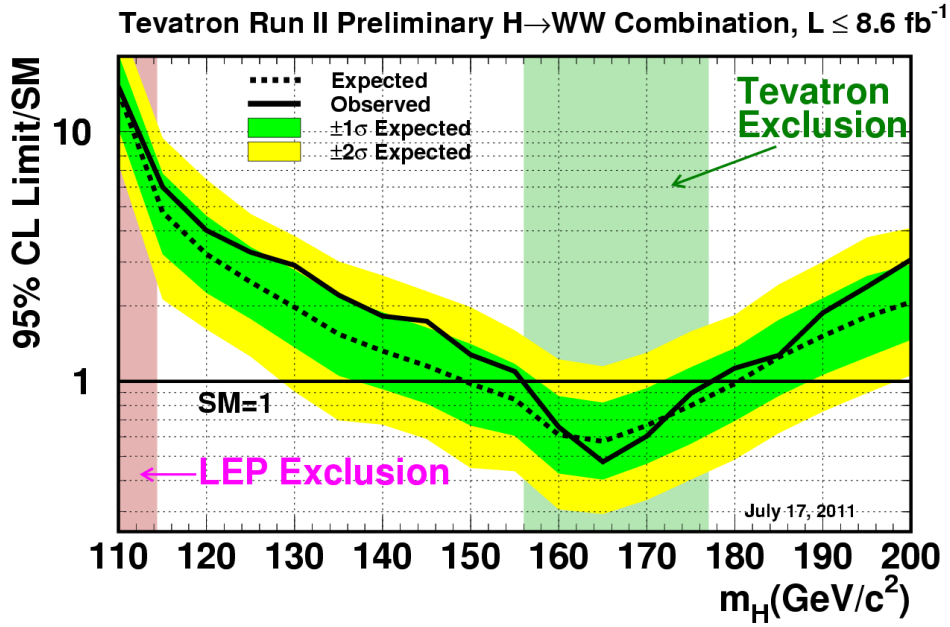


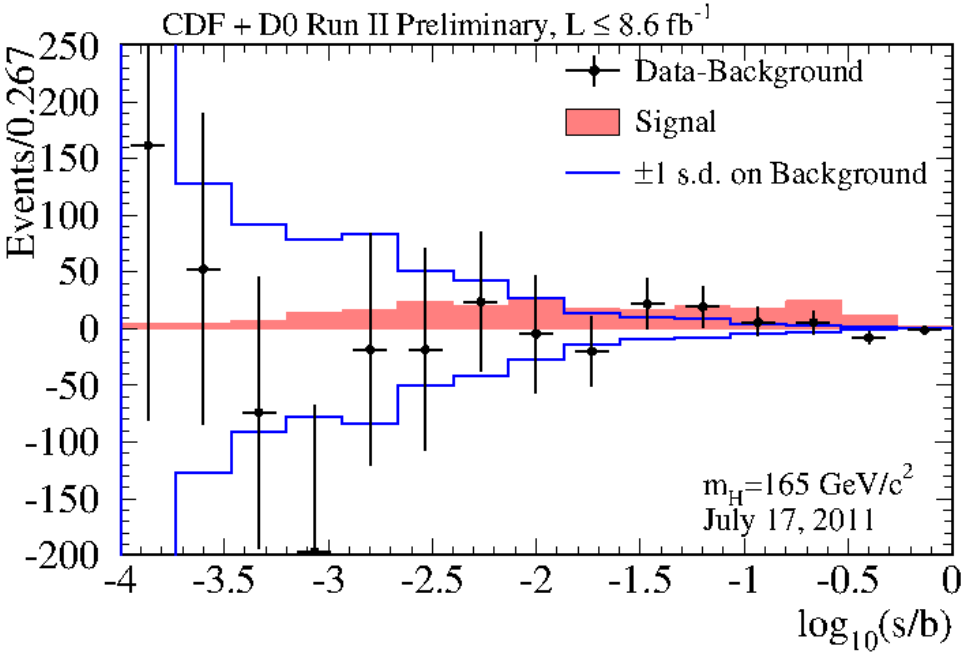


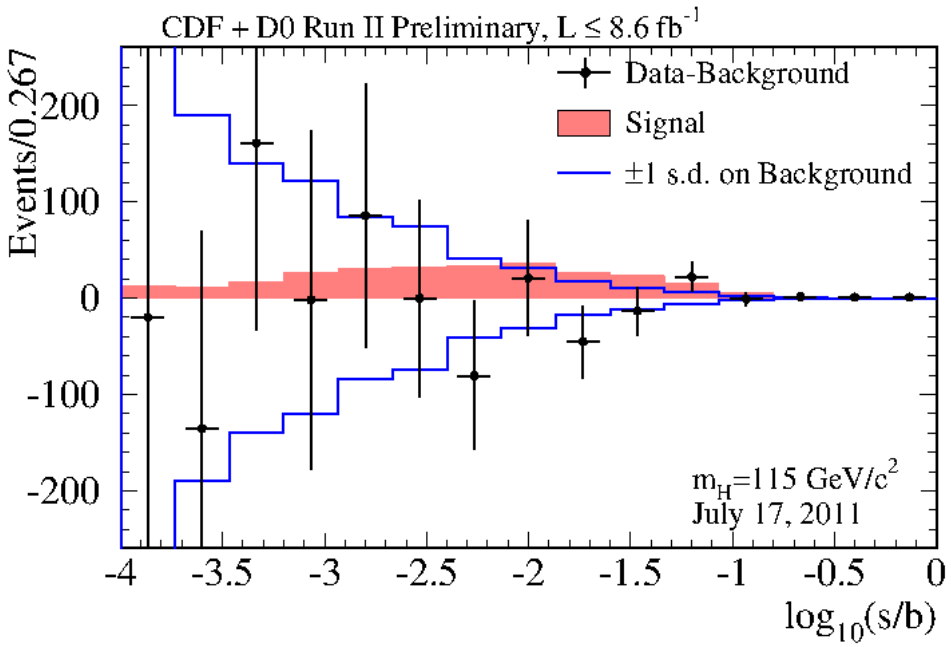
Tevatron H→bb vs H→WW





Tevatron Signal to Noise





MSSM Higgs

Minimal SUSY Model (MSSM): Two doublets of scalar fields (only one in SM)

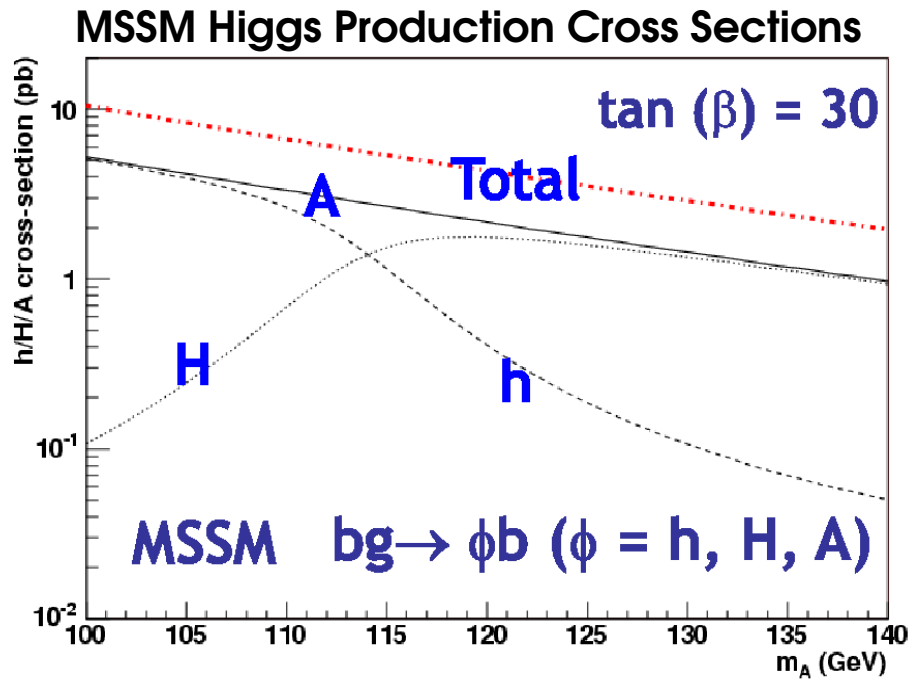
Total of 8 degrees of freedom results in 5 Higgs bosons:

3 Neutral: h, H, A 2 Charged: $H^{\pm}$

In the Minimal SUSY Model:

Need at least 2 parameters to calculate all Higgs masses and couplings at tree level: **M_A** and **tan(β)** (ratio of vacuum expect'n values for the two Higgs doublets)

All three neutral Higgs bosons can have same final states: extra 2x in effective rate



Searching for $H \rightarrow W^+W^-$

Wade Fisher
PANIC11

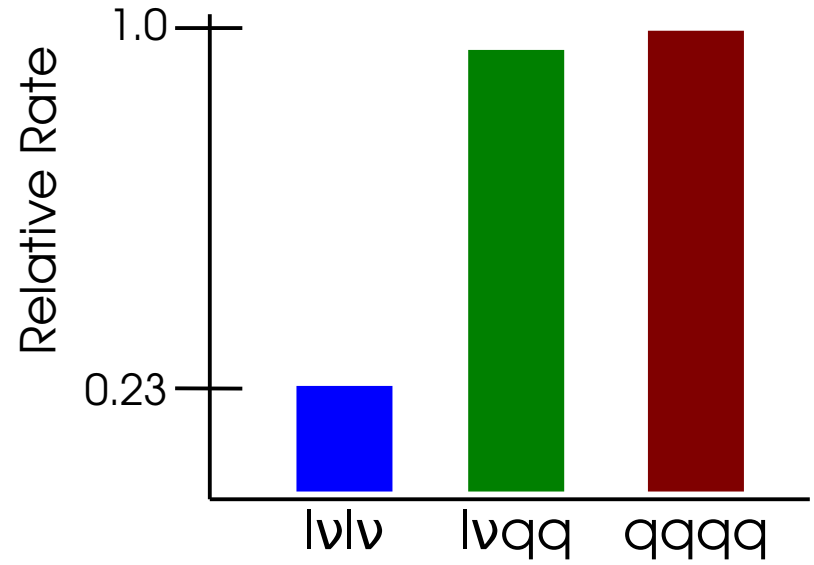
Semi-leptonic H→WW→lνqq decays can contribute a lot

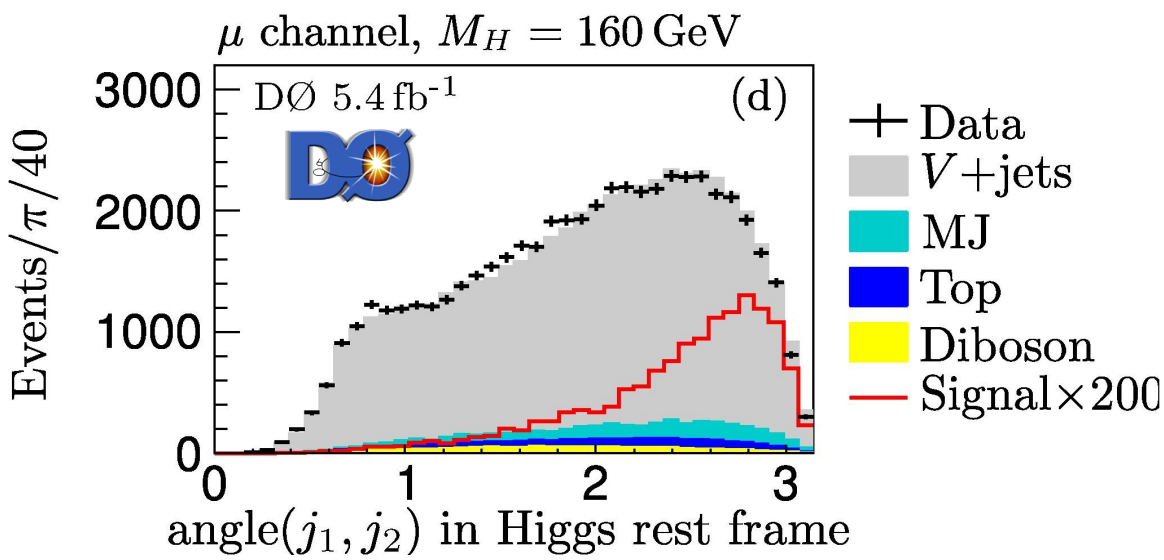
Signal is boosted by 4x over fully leptonic decays

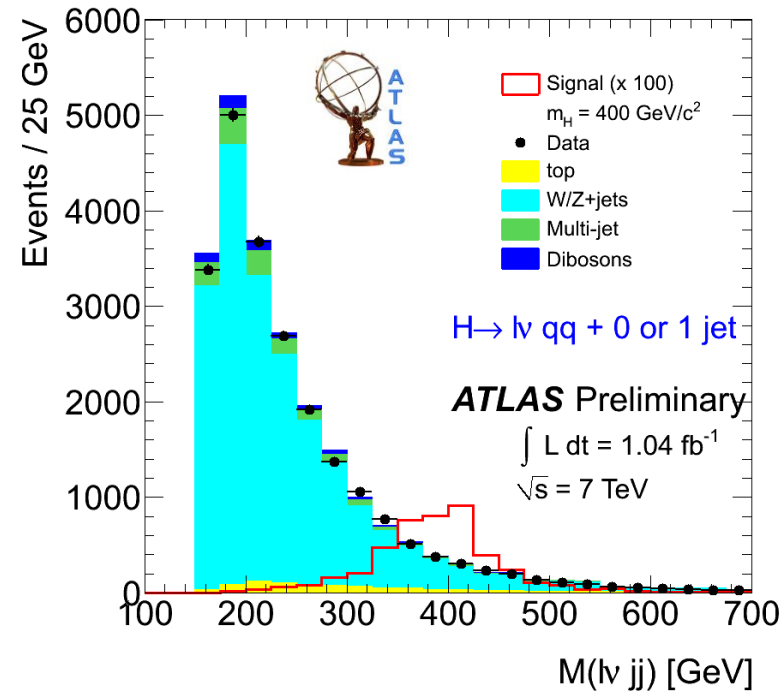
- W/Z+jets rate also grows significantly

Additional handle in kinematic rejection opens many doors for data analysis

- Guess at longitudinal neutrino momentum allows for estimate of M(lνqq)
- Angular correlations of signal provide further handle for background rejection





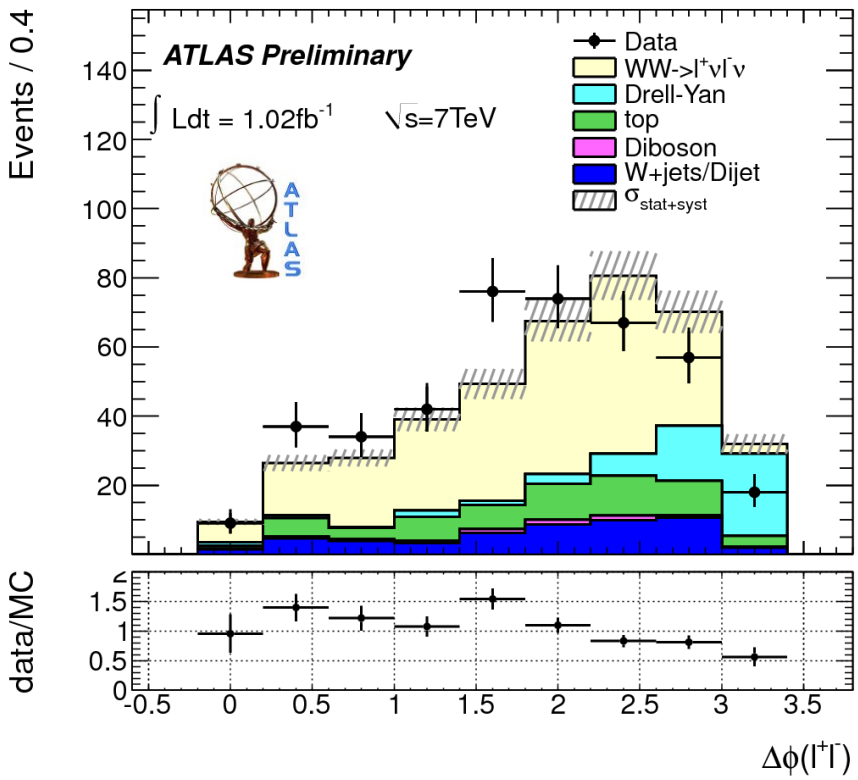


Search Validation

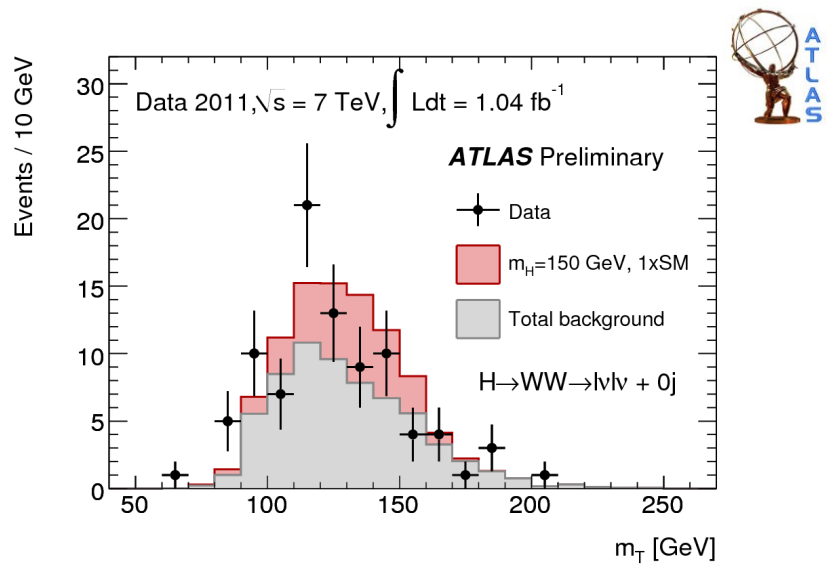
Confirming agreement with "standard candles" provides essential validation for search results

- Eg, SM WW cross section
- Similar selections should yield similar results

SM WW Measurement



gg→H→WW Search



$$\sigma(p\,\overline{p}\rightarrow WW)^{EXPT} = 48.2 \pm 4.0(stat) \pm 6.4(syst)\ [pb]$$

$$\sigma(p\,\overline{p}\rightarrow WW)^{THEORY} = 46 \pm 3\ [pb]$$

H→bb: Isolating Backgrounds

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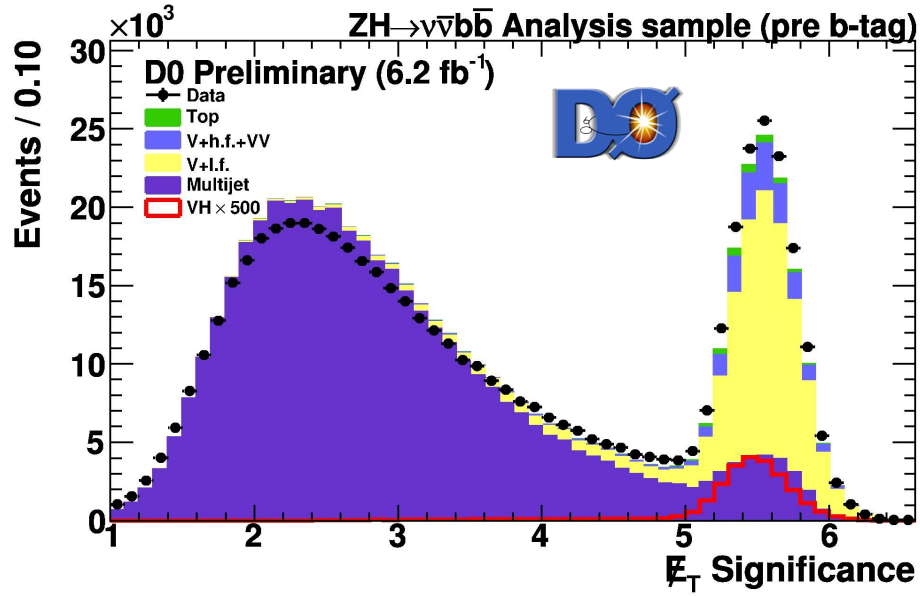
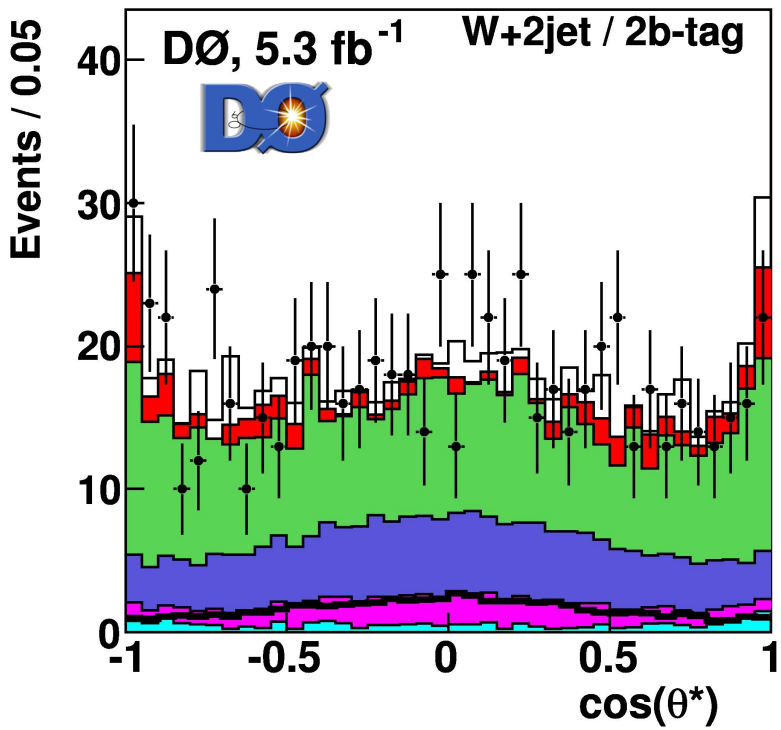
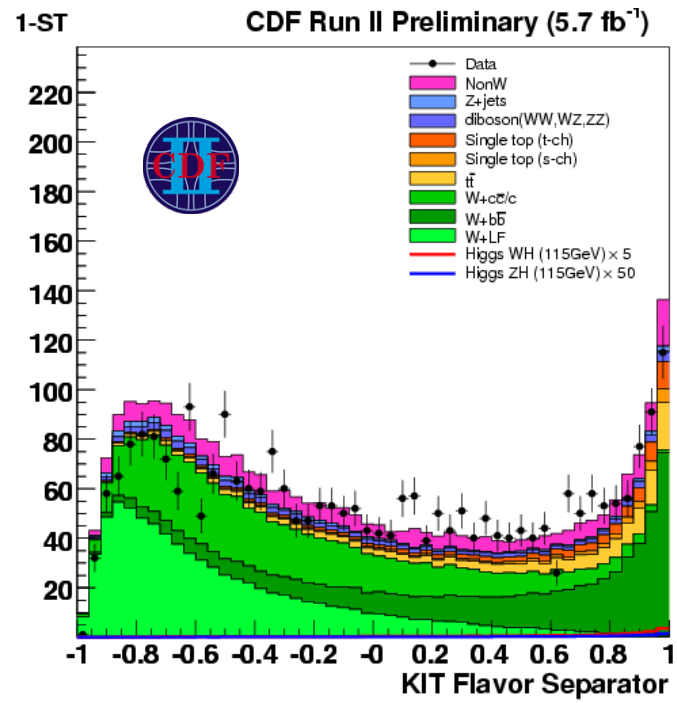
Dijet invariant mass is not the only discriminating variable

- Scalar Higgs spin information
- MET significance
- Bottom vs Charm flavor discrimination







H→bb: Multivariate Analysis

Multivariate techniques are used to improve signal to background ratios

- Boosted Decision Trees
- Neural Networks
- Matrix Element Discriminants

Typically achieve S/B of ~1/5-1/25

S/B ~1/100 for dijet mass alone