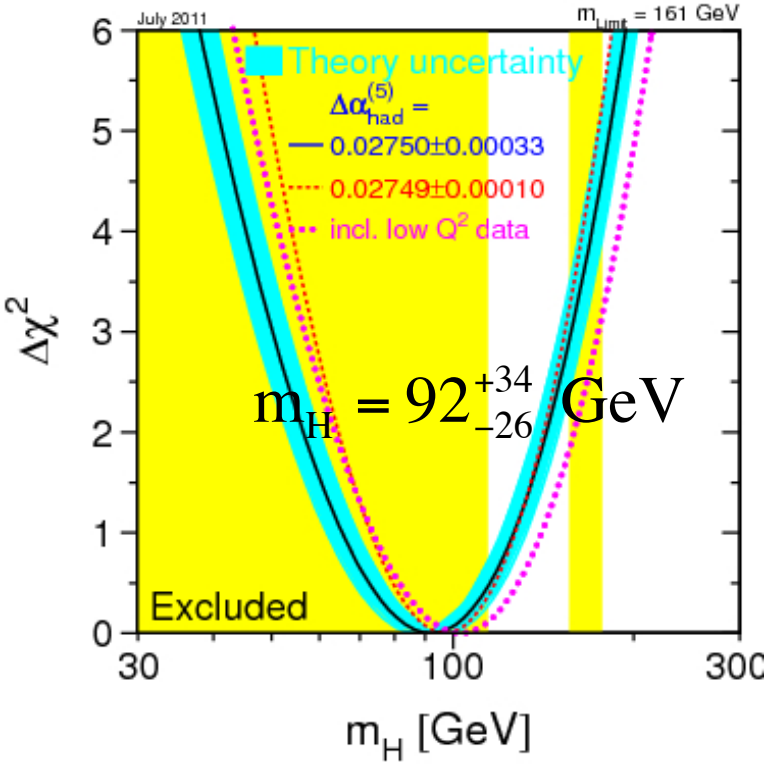
Experimental Summary

Aurelio Juste
(ICREA/IFAE, Barcelona)

Stalking the Higgs Boson

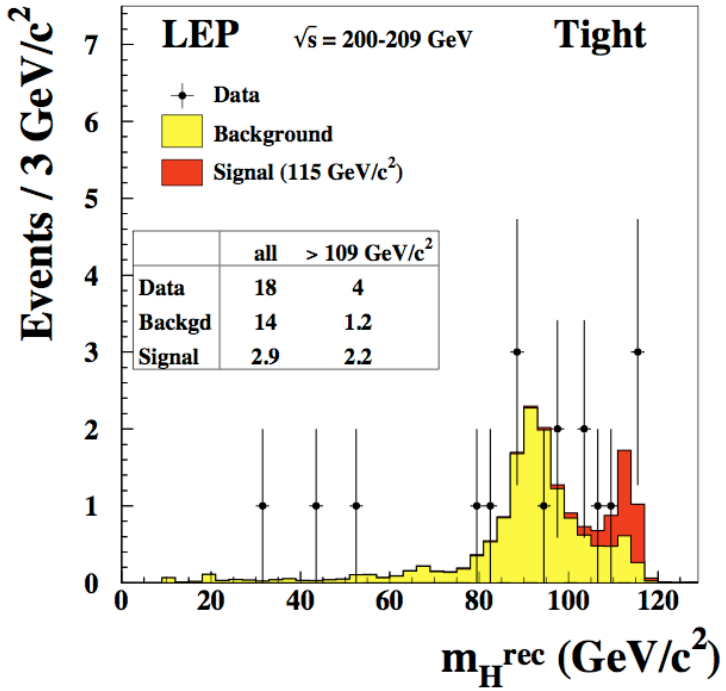
Indirect constraints

- Precision EW observables at the one-loop level.



Direct searches at LEP

- Tantalizing hints (~1.7σ) of a SM-like Higgs boson with m_H~115 GeV:



Kinematic limit: $\sqrt{s}-m_Z$~115.4 GeV

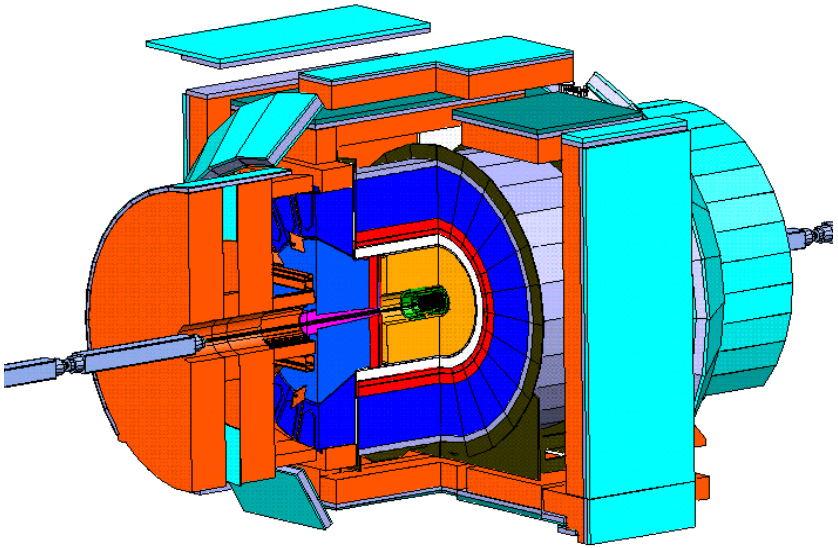
m_H< 161 GeV (95% CL)

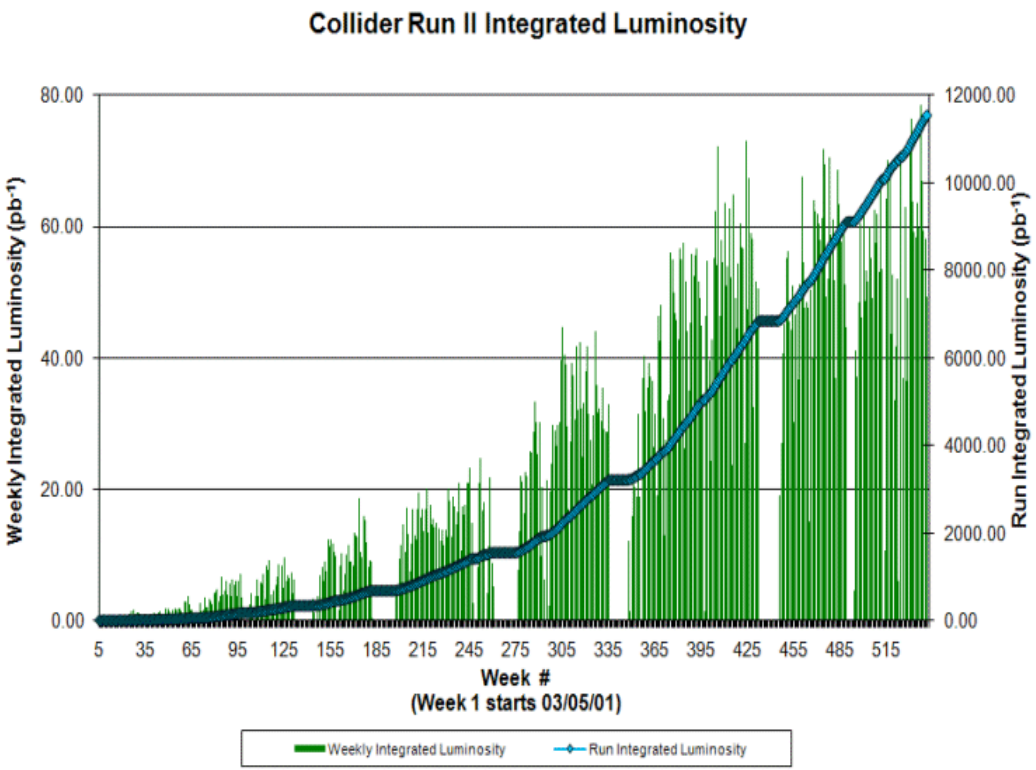
m_H> 114.4 GeV (95% CL)

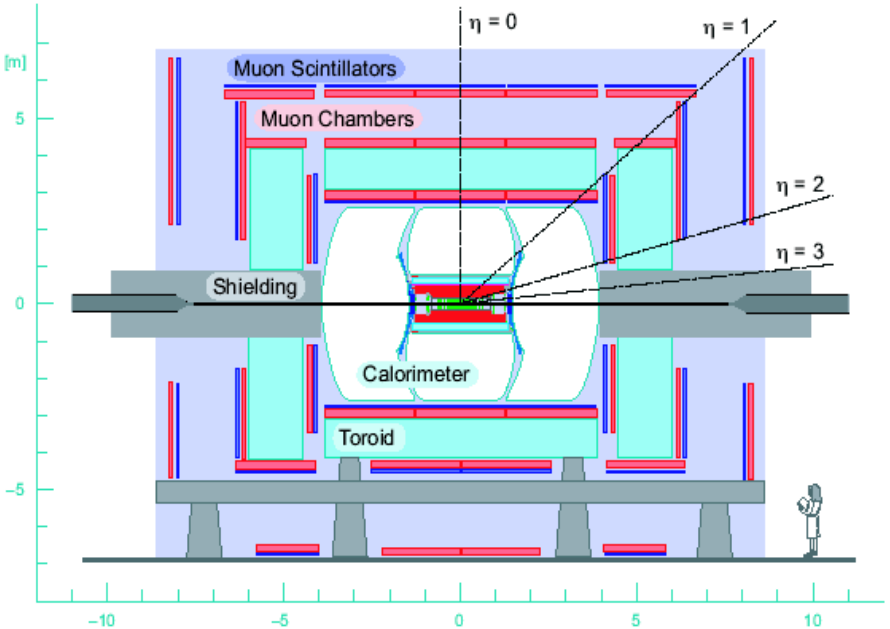
114.4 < m_H< 185 GeV (95% CL)

Tevatron Experiments

- Proton-antiproton collisions at 1.96 TeV.
- Excellent performance by Tevatron accelerator and CDF and D0 detectors.
  - 10-year long Run II ending Sept. 2011
  - >10 fb^{-1} recorded per experiment to date

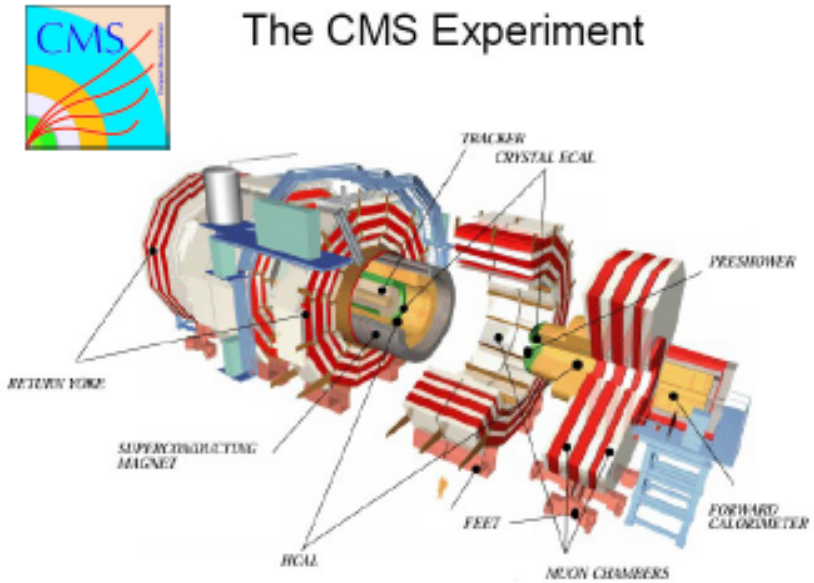


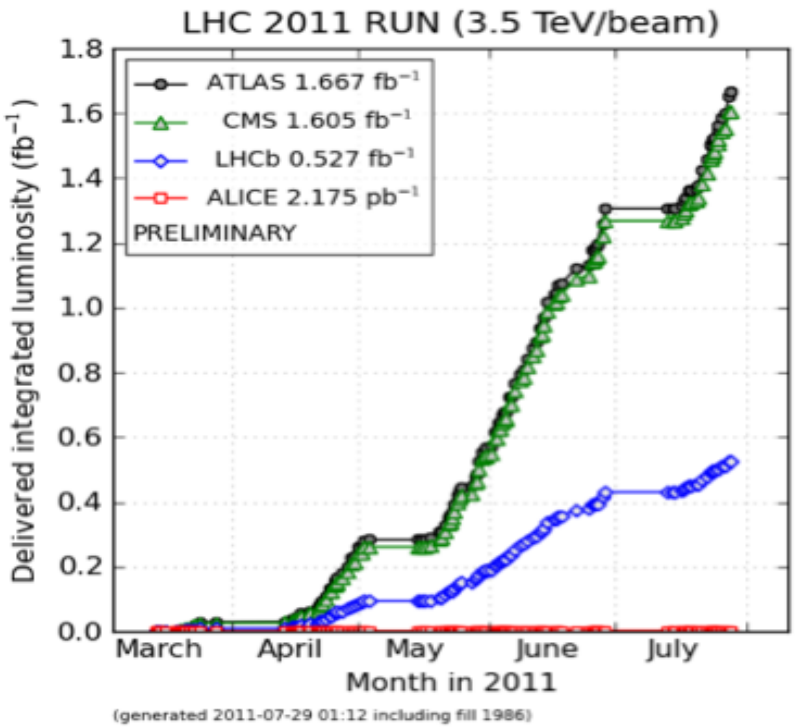


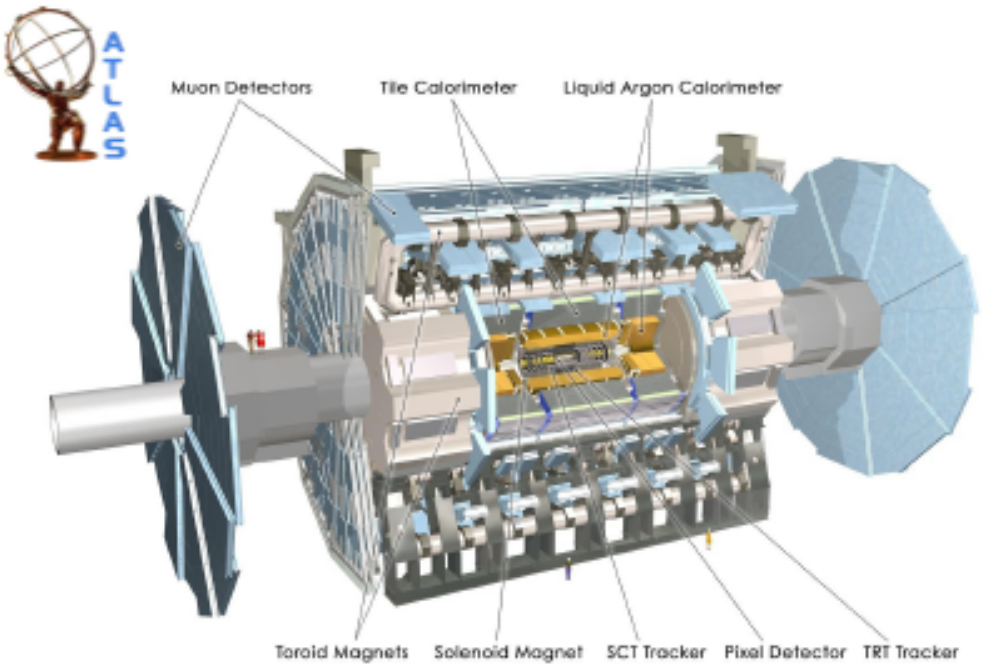


LHC Experiments

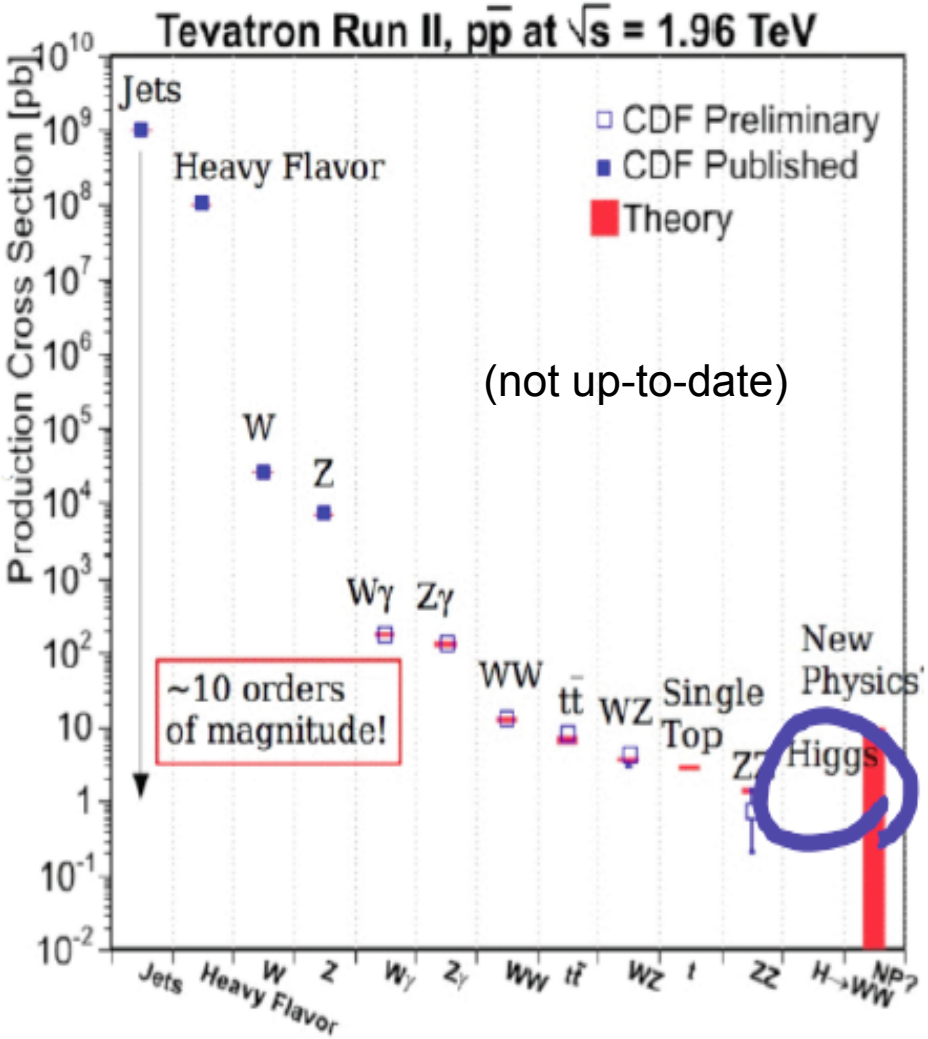
- First proton-proton collisions at 7 TeV in 2010.
- Amazing performance by the accelerator and detectors since then:
  - ~1.6 fb^{-1} delivered by the accelerator in 2011 so far.
  - High quality physics results with 1.1 fb^{-1} presented at Summer 2011 conferences!





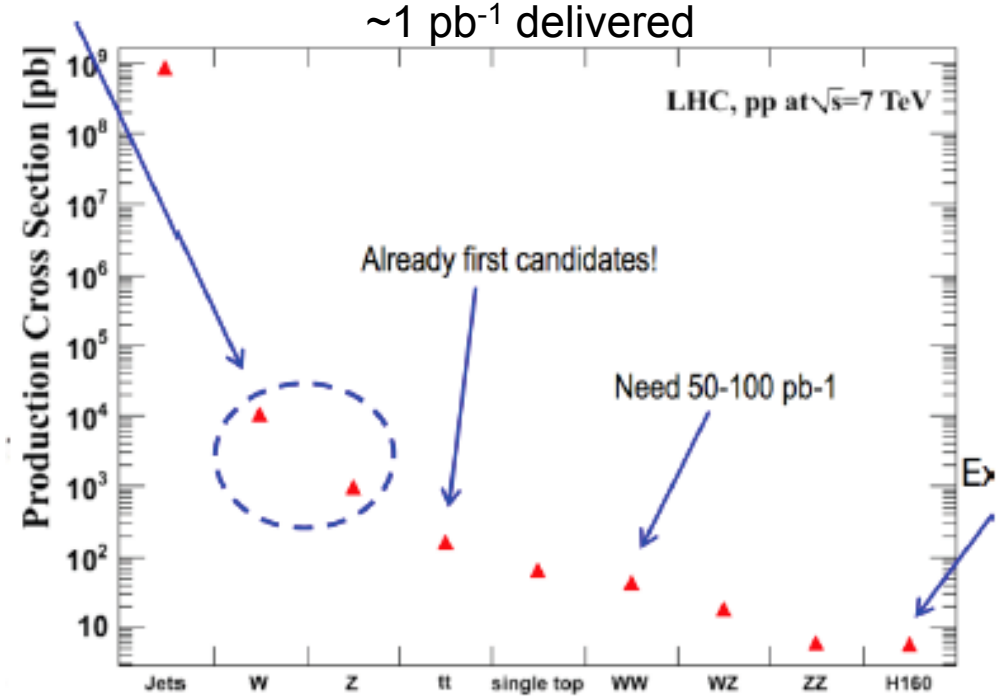


The Scale of the Problem

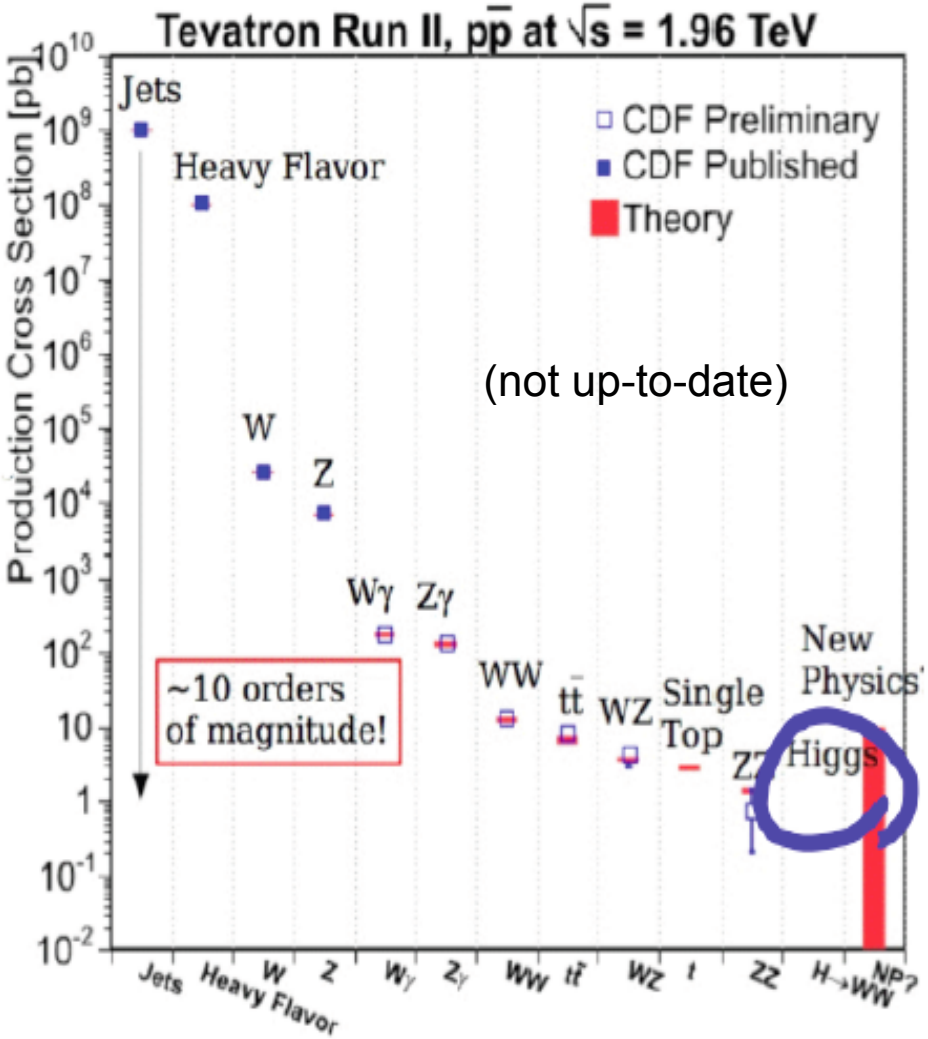


Plot from Higgs Hunting 2010 experimental summary talk

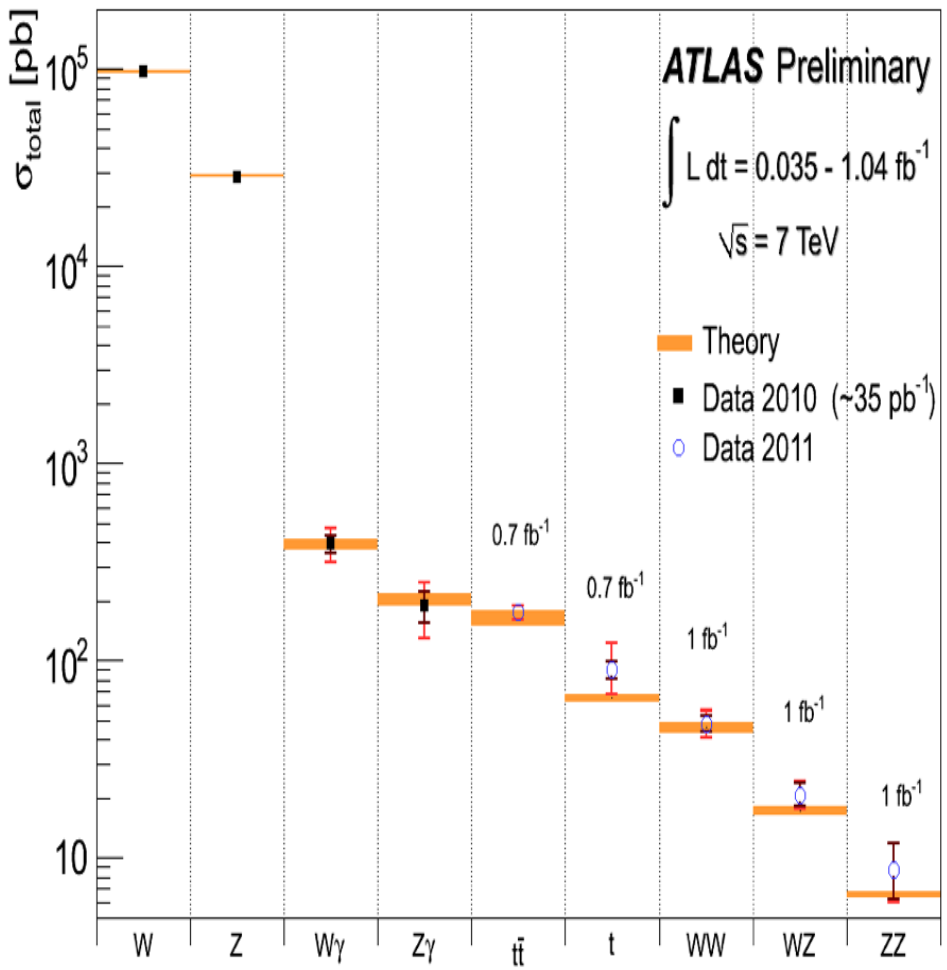
~1 pb^{-1} delivered



The Scale of the Problem

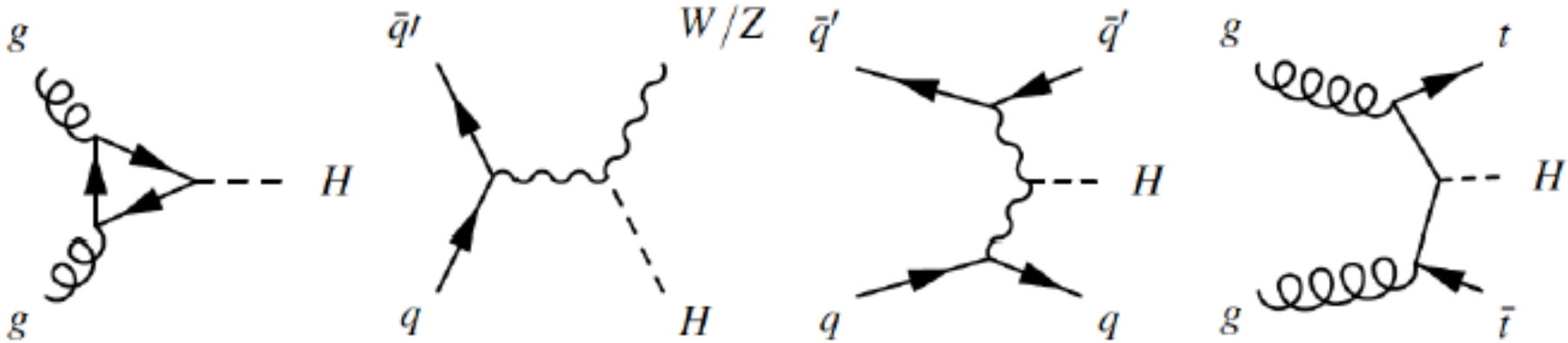


One year later…

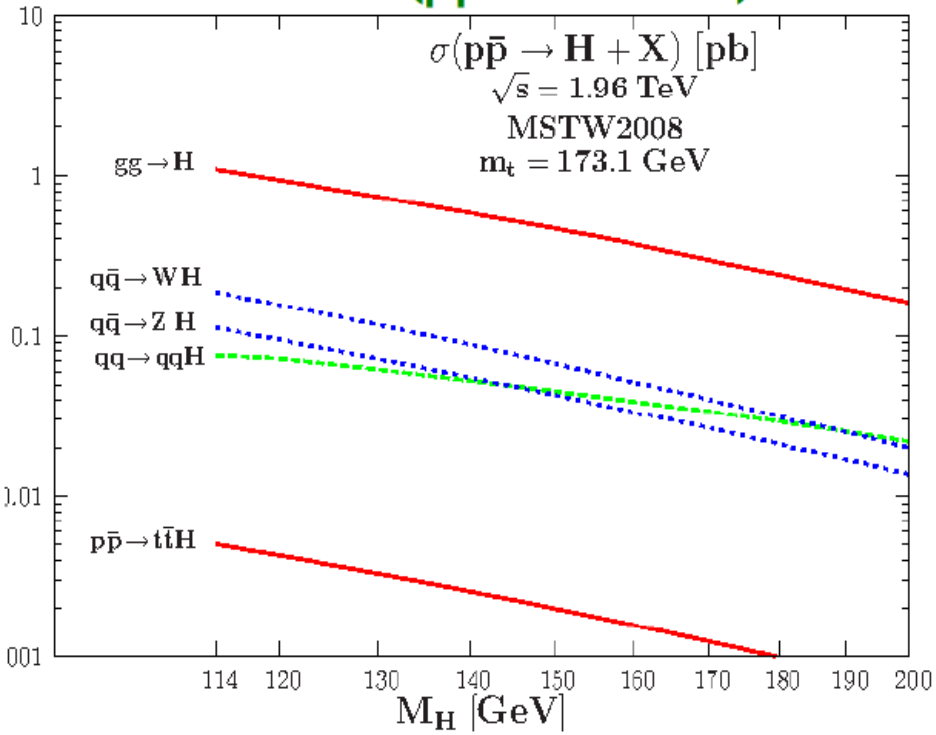


Experiments have established a solid foundation to search for the Higgs boson by establishing precise measurements of SM processes.

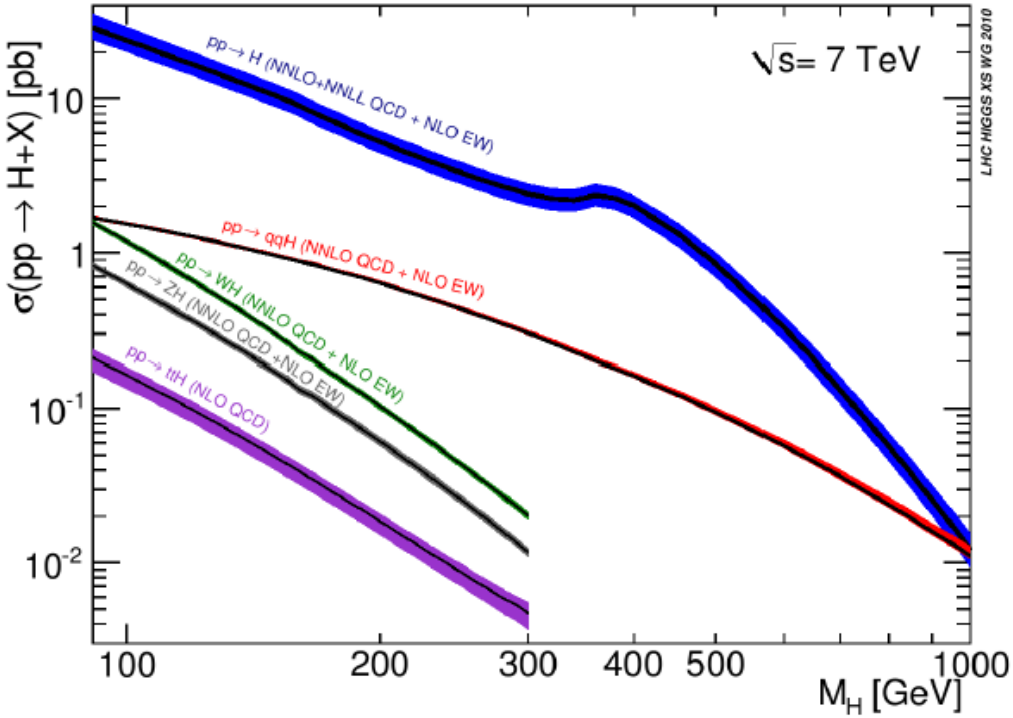
SM Higgs Production at Hadron Colliders



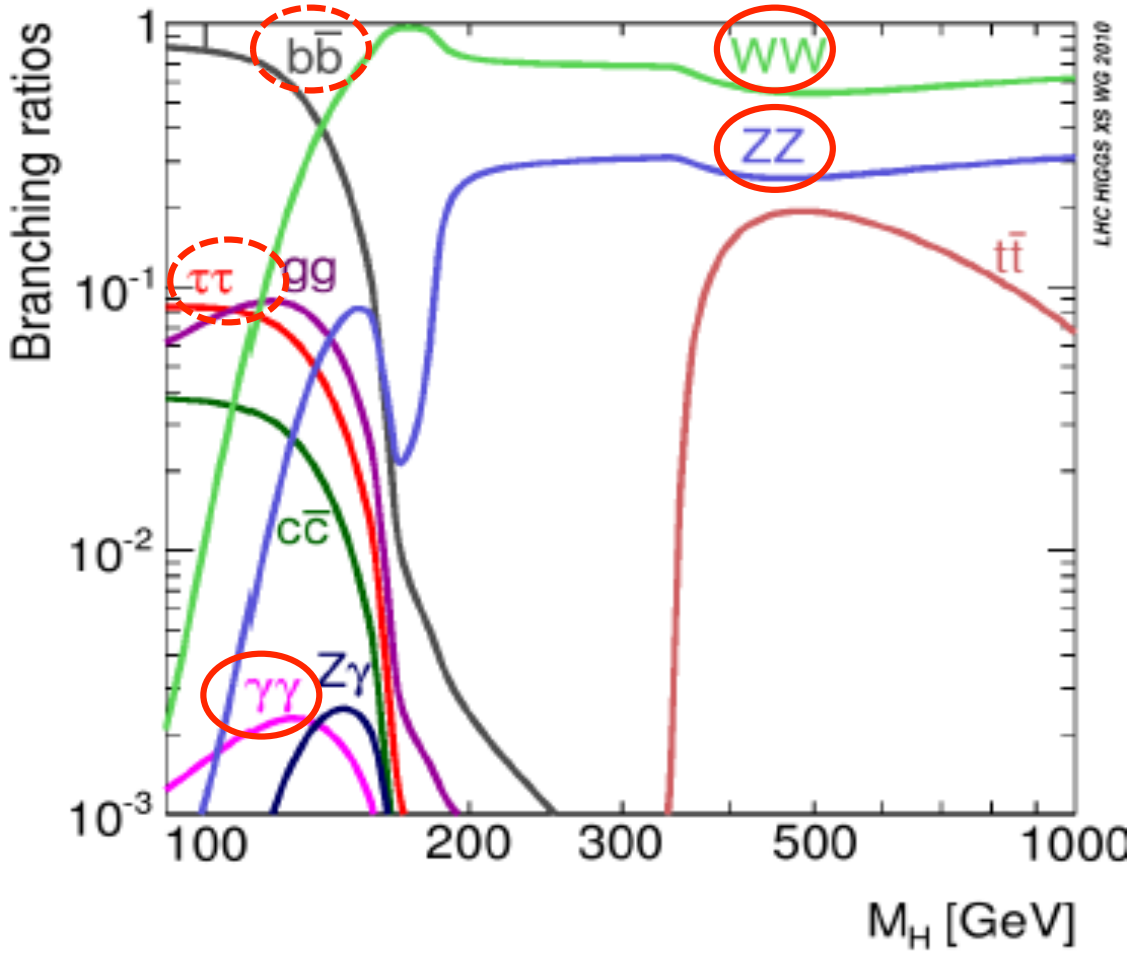
Tevatron ($p\bar{p}$ @ 1.96 TeV)



LHC (pp @ 7 TeV)



SM Higgs Decay Modes



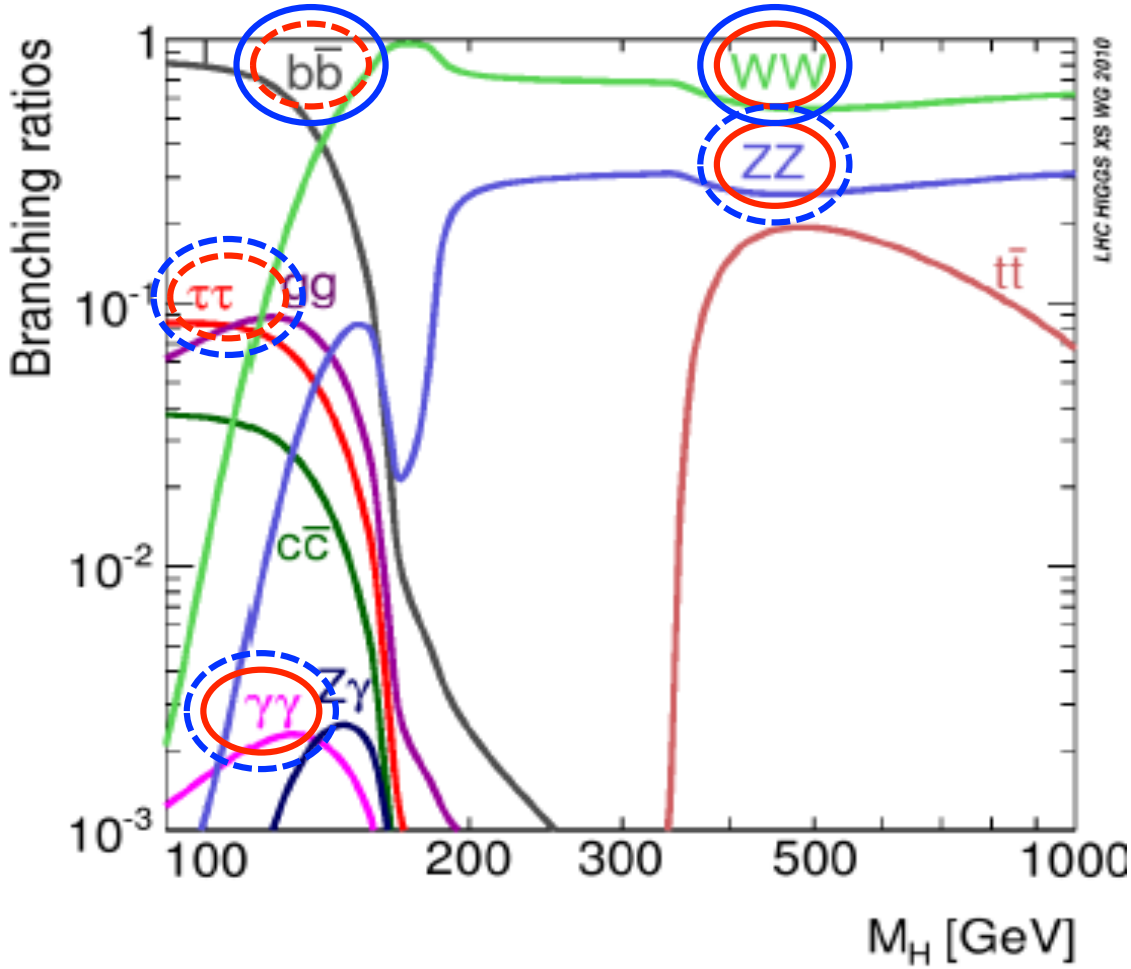
Main mode

Supporting mode

LHC

➔ Many decay modes being explored to increase the sensitivity of the search to the SM Higgs boson but also to a non-SM Higgs boson!

SM Higgs Decay Modes



Main mode

Supporting mode

LHC

Tevatron

➔ Many decay modes being explored to increase the sensitivity of the search to the SM Higgs boson but also to a non-SM Higgs boson!

Nature May Just Be More Complicated…

"SM-like" Higgs in MSSM

$M_h \sim 115$ -125 GeV

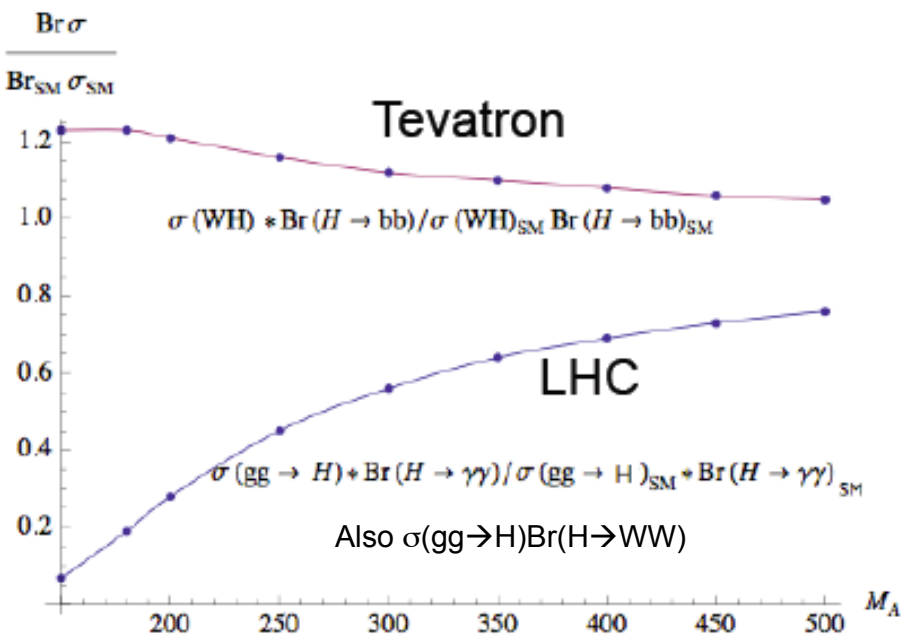
Carena, Heinemeyer, Wagner, Weiglein

- The m_h^{max} scenario: [Maximizes m_h]

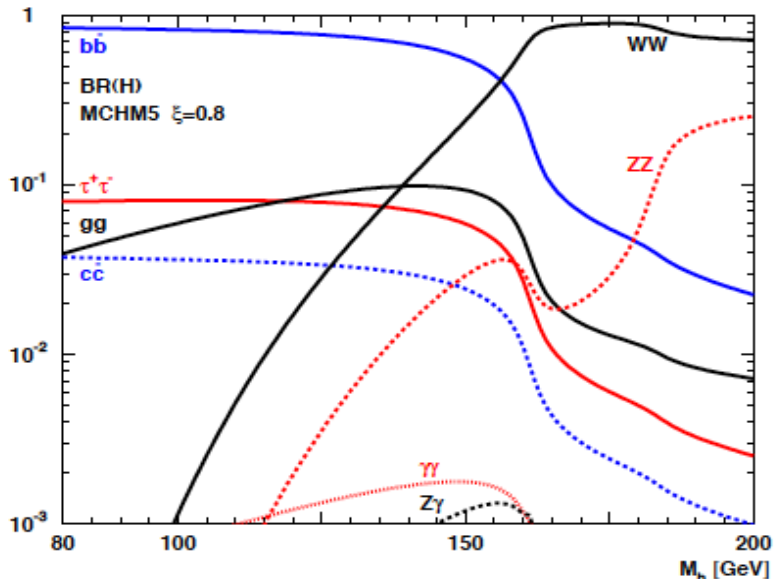
$M_S = 1$ TeV ; $X_t = 2.4\, M_S$; $m_{\tilde{g}} = 0.8\, M_S$; $M_2 = -\mu = 200$GeV; $A_t = A_b$

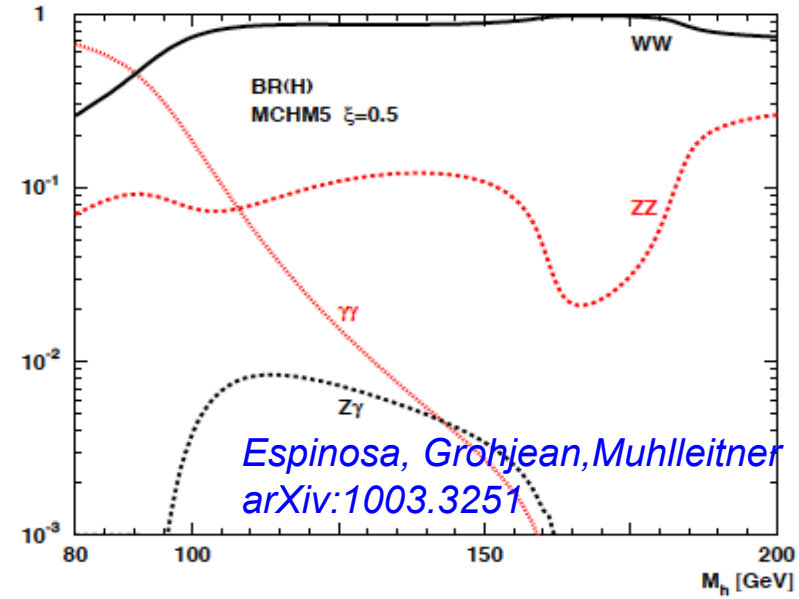
$g_{hbb}, g_{h\tau\tau} \sim \sin\alpha_{eff}/\cos\beta$ *enhanced* for low m_A and intermediate to large tan beta (analogous for H if $m_A > m_h^{max}$)

hence, strong suppression of BR($h \to \gamma\gamma$) and BR(h → WW) with respect to SM



Composite Higgs Models

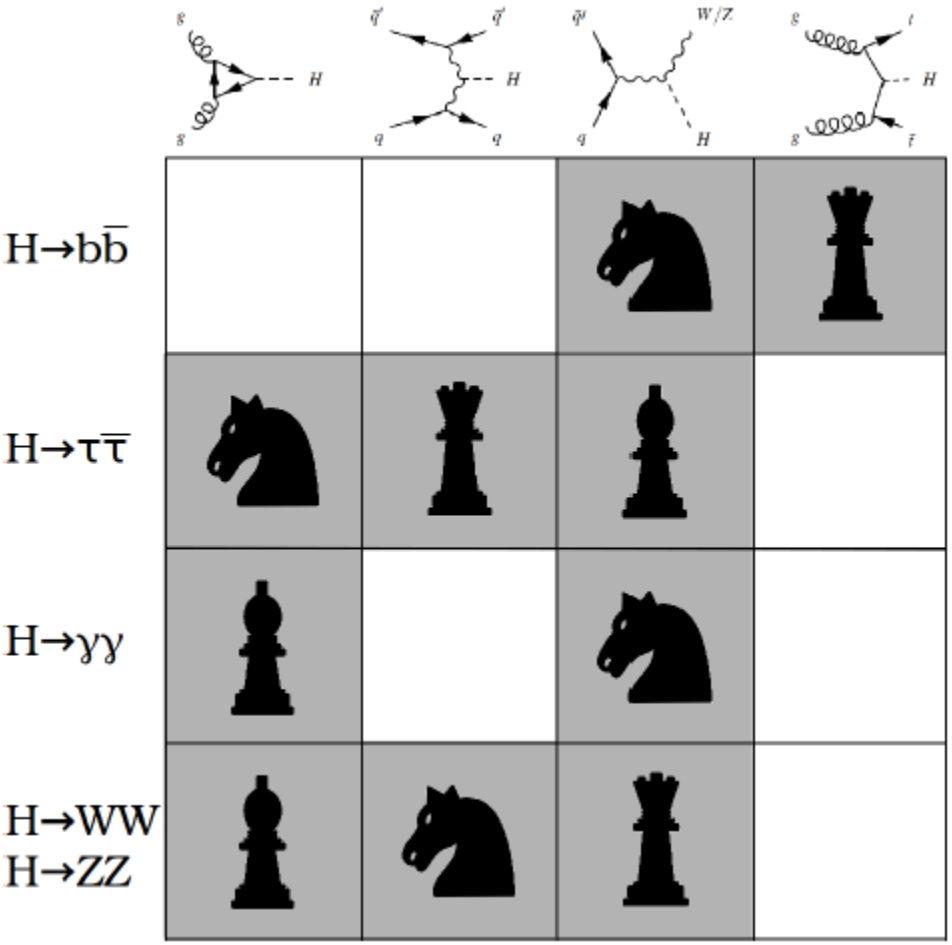


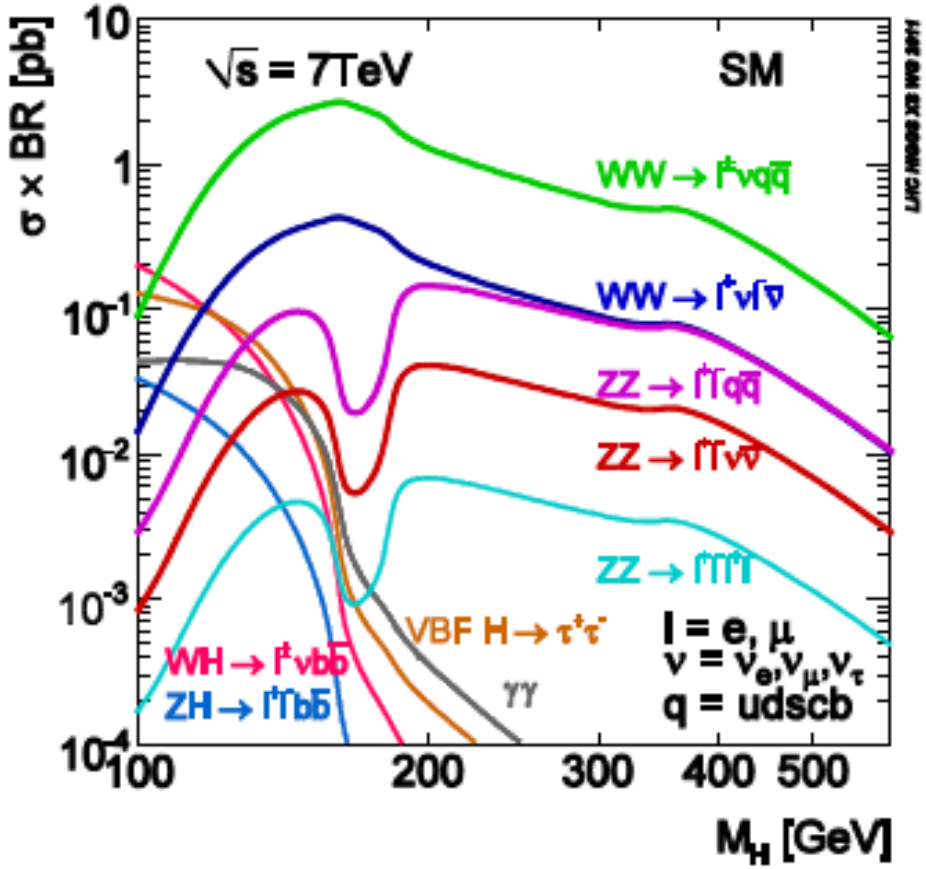


Espinosa, Grojean, Muhlleitner arXiv:1003.3251

Search Strategies

- Defined by a combination of theoretical and experimental considerations (large σxB but experimentally feasible: trigger, backgrounds….)





Tools of the Trade

LEP: small background, small systematic uncertainties

Tevatron/LHC: large background, large systematic uncertainties

➔ to counteract the degrading effects of systematic uncertainties, use a "profile likelihood", obtained by fitting MC expectations to data for each outcome

A. Read

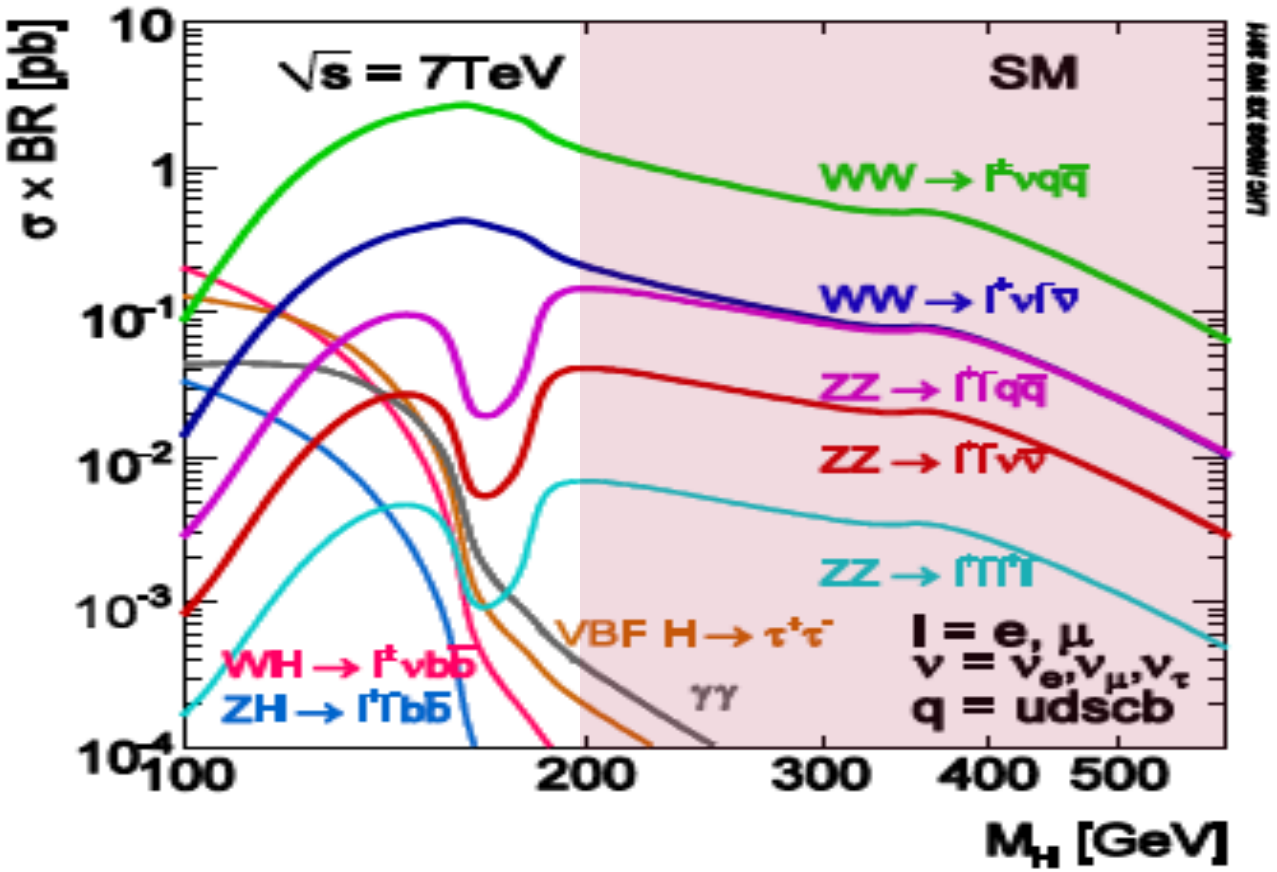
	Test statistic	Test statistic	Nuisance parameters	Pseudo-experiments
LEP	$-2\ln\frac{L(\mu,\tilde{\theta})}{L(0,\tilde{\theta})}$	Simple LR	Fixed by MC	Nuisance parameters randomized about MC
Tevatron	$-2\ln\frac{L(\mu,\hat{\hat{\theta}})}{L(0,\hat{\theta})}$	Ratio of profiled likelihoods	Profiled (fit to data)	Nuisance parameters randomized about profiled
LHC	$-2\ln\frac{L(\mu,\hat{\hat{\theta}})}{L(\hat{\mu},\hat{\theta})}$	Profile likelihood ratio	Profiled (fit to data)	New nuisance parameters fitted for each pseudo-exp.

LHC sampling of test statistic is frequentist, LEP and Tevatron Bayes-frequentist hybrid

CL_s can be used together with any of these – must be specified! No longer sufficient to write e.g. "the CL_s method was used".

SM Higgs

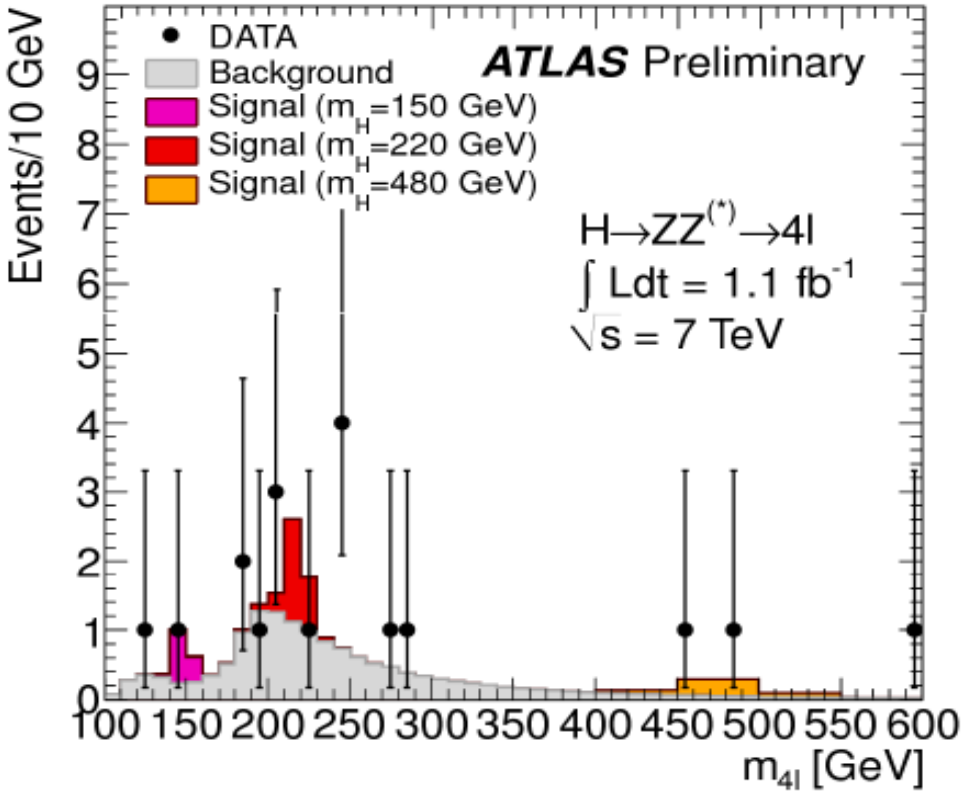
High Mass (200-600 GeV)

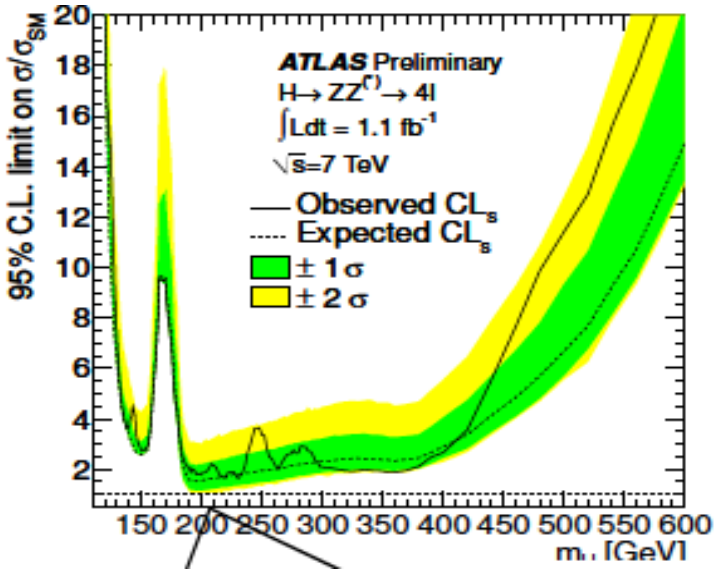


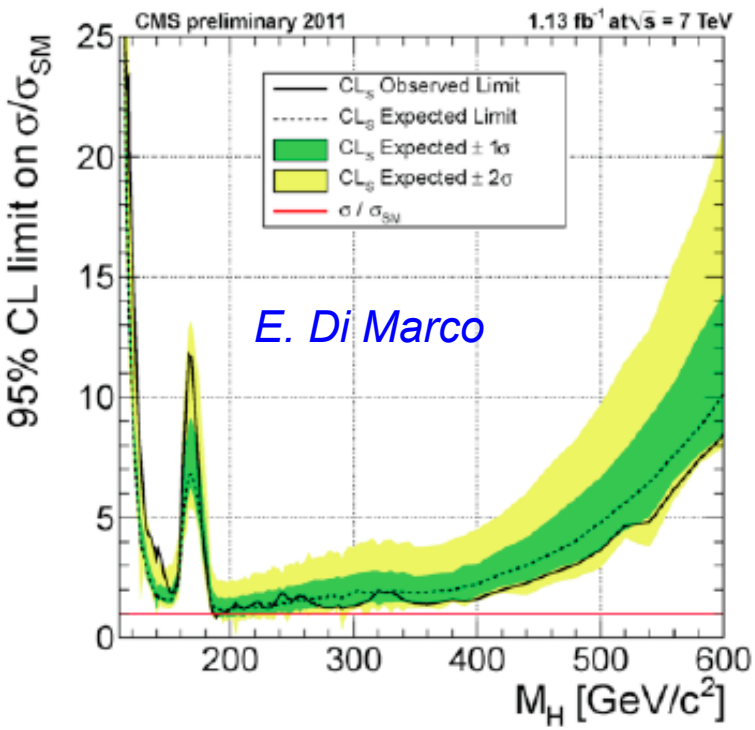
H→ZZ→4l

- Cleanest channel at high mass but small statistics.
- Main background ZZ production.
- Higgs mass reconstruction with good resolution!

P. Thompson





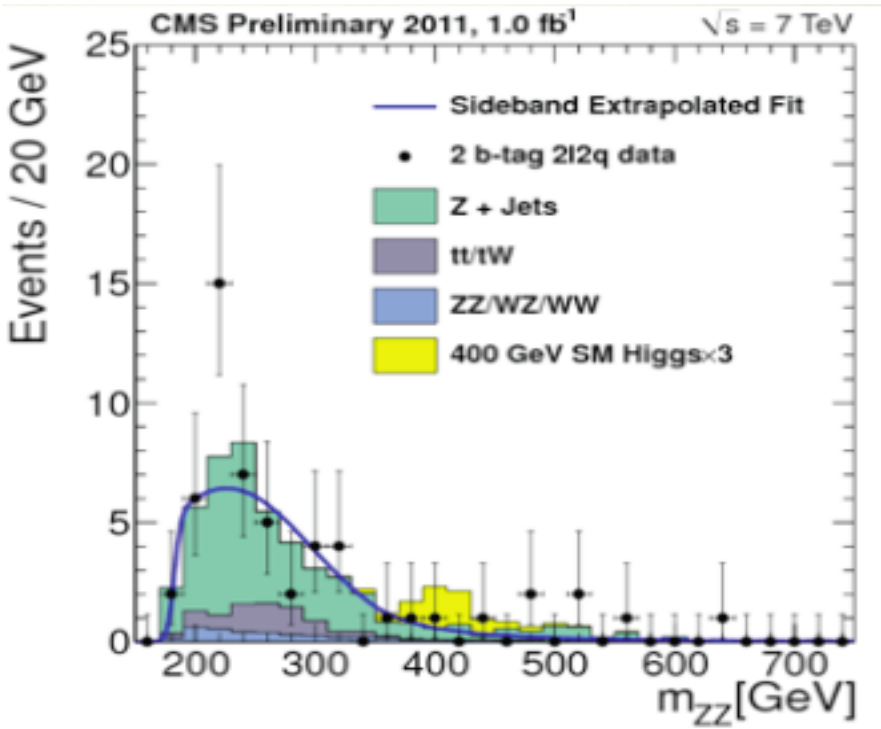


E. Di Marco

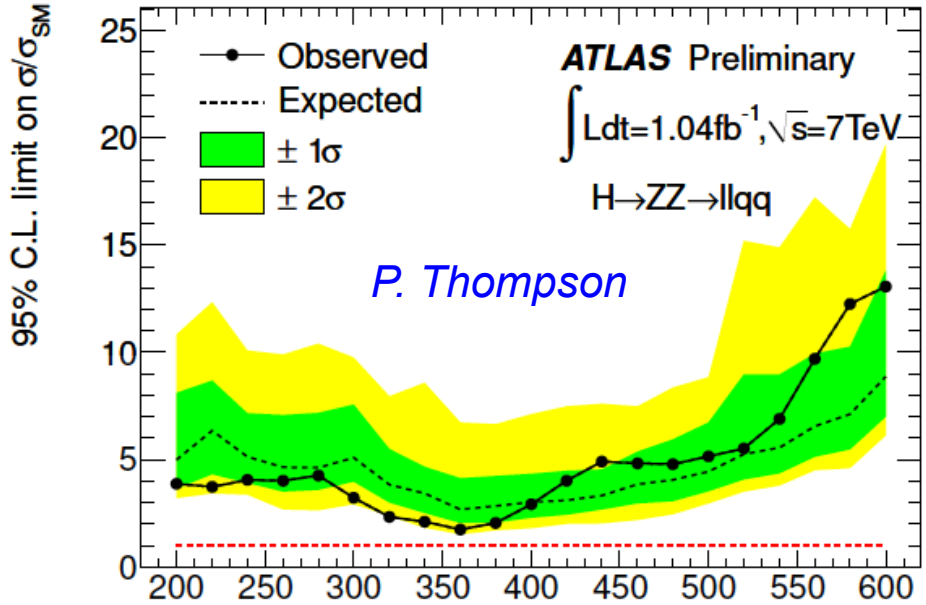
- No excess observed.
- Expected limit: ~2xSM in M_H~200-350 GeV

H→ZZ→lljj

- Benefits from high B(Z→jj).
- Still good mass reconstruction capabilities.
- Dominant background from Z+jets.
- Improved S:B by split sample in <2 b-tag and =2 b-tag.

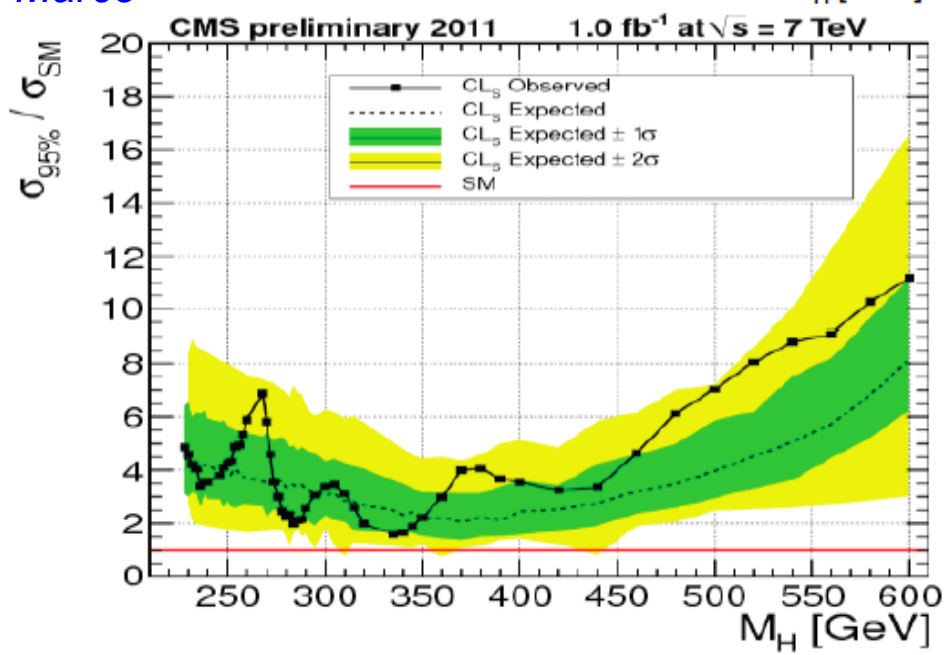


- No excess observed.
- Expected limit: ~2xSM at M_H~350 GeV



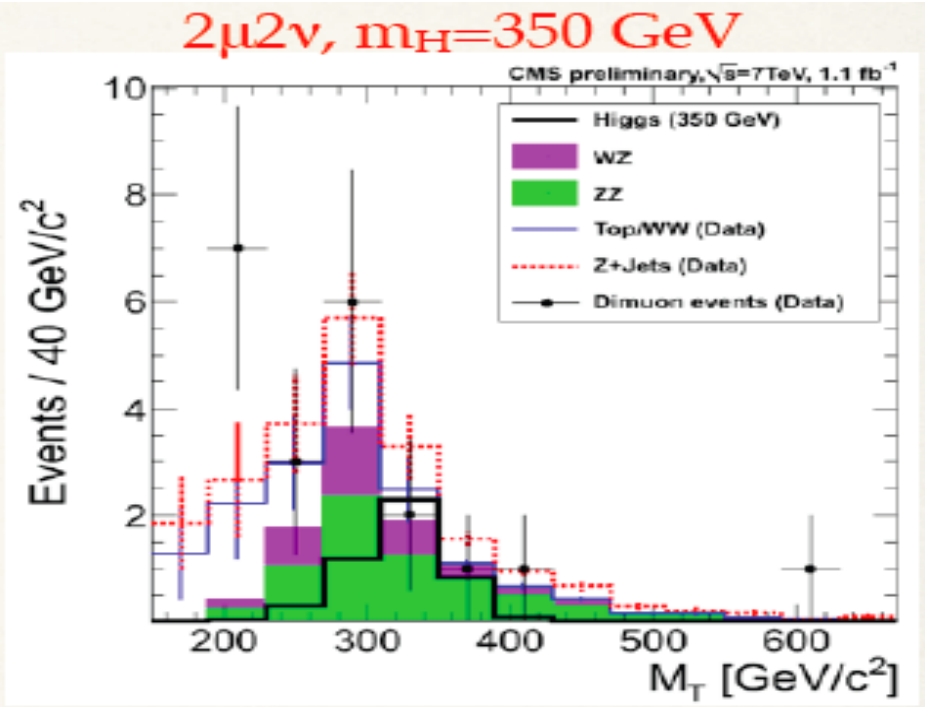
P. Thompson

E. Di Marco

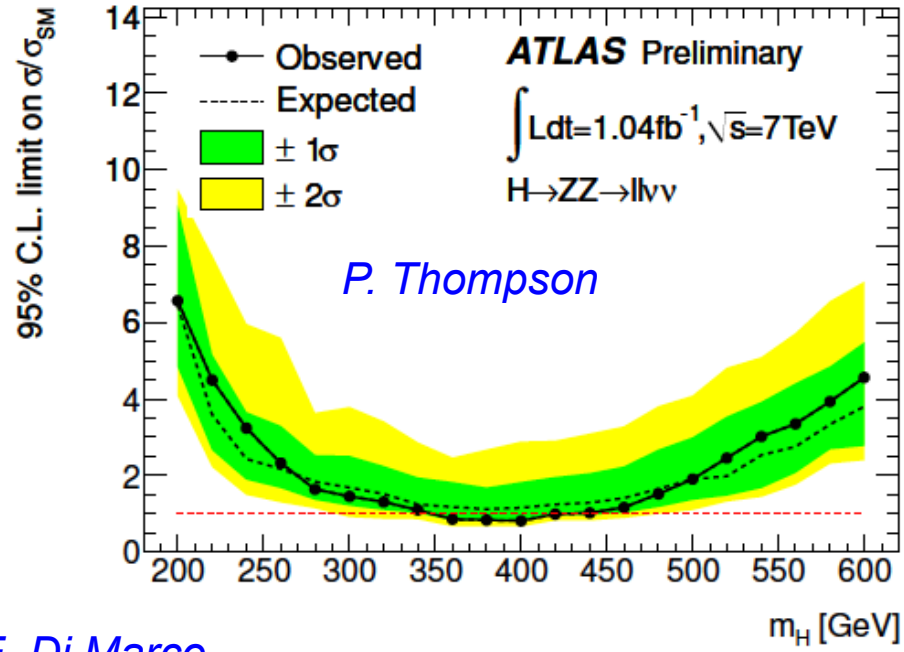


H→ZZ→llνν

- Benefits from sizable B(Z→νν).
- Signature: ee/μμ+MET
- Main backgrounds dibosons and top suppressed by 3rd lepton and b-tag vetoes
- Final discriminant: M_T(llνν)



- No excess observed.
- Expected limit: <2xSM in M_H~300-500 GeV
  ATLAS: excludes M_H~360-420 GeV



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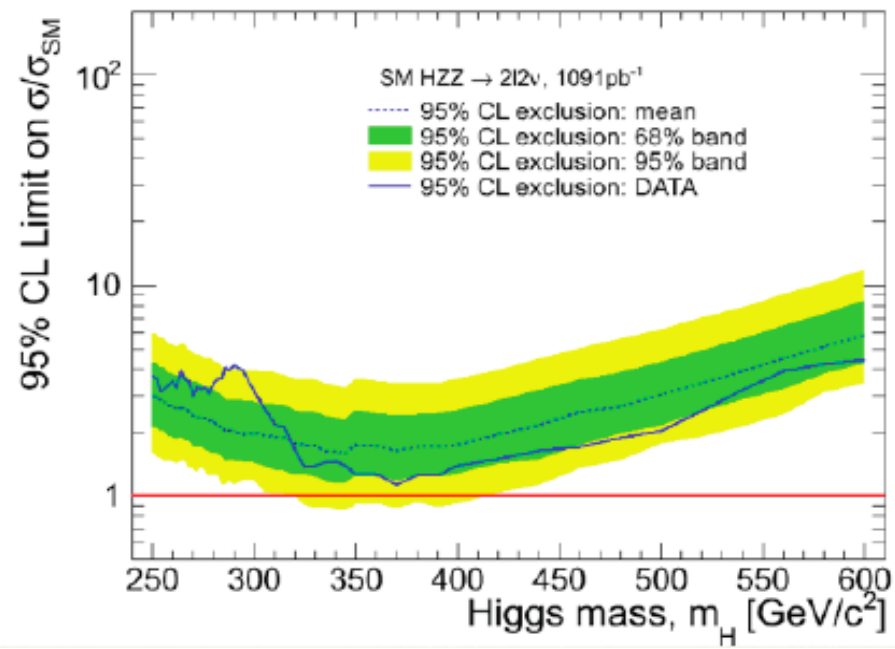
E. Di Marco

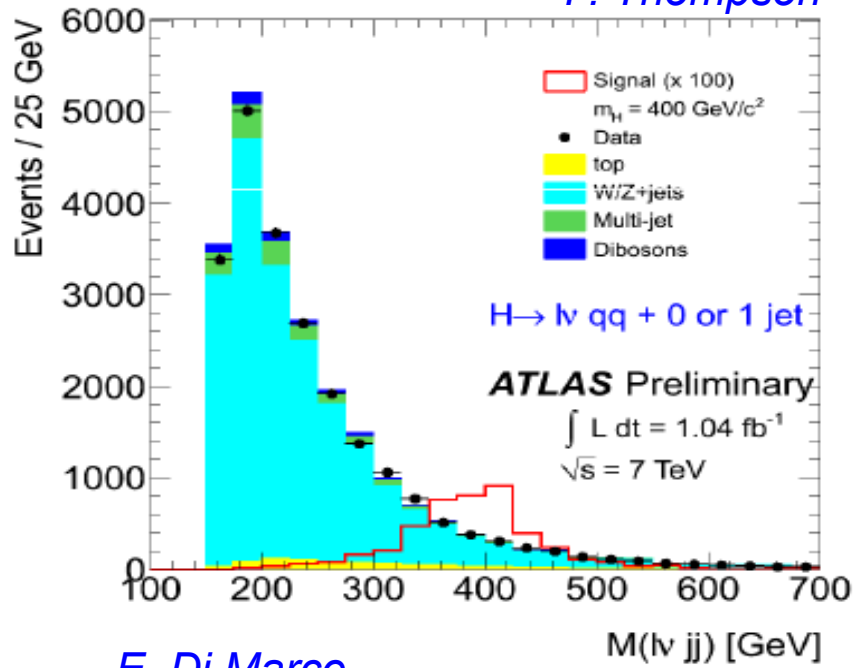


H→WW→lνjj

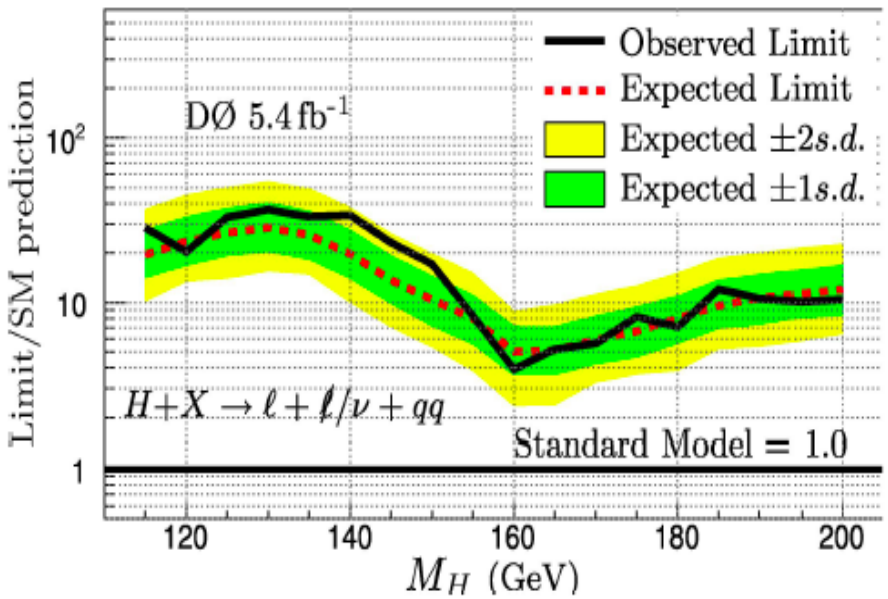
- Largest σxB at high mass.
- Possibility to reconstruct Higgs mass imposing W mass constraint but worse resolution than for H→ZZ→lljj.
- Worse S:B from large W+jets background.

- Tevatron and LHC searches have comparable sensitivity in different mass regions.

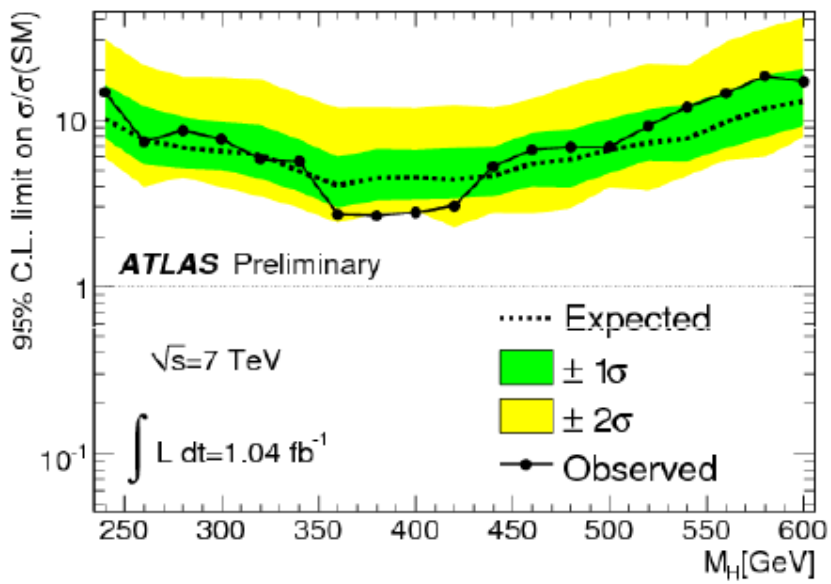
P. Thompson



E. James

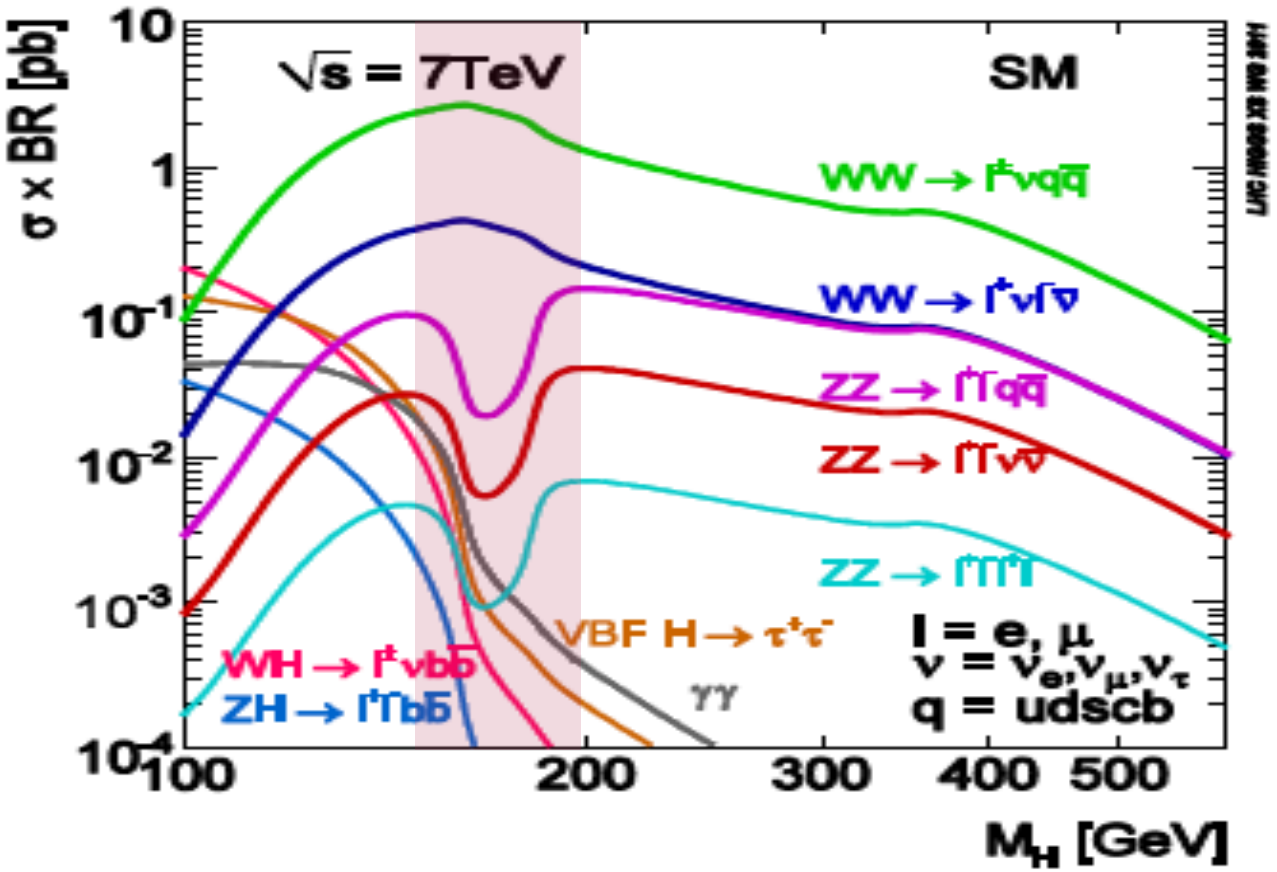


E. Di Marco



SM Higgs

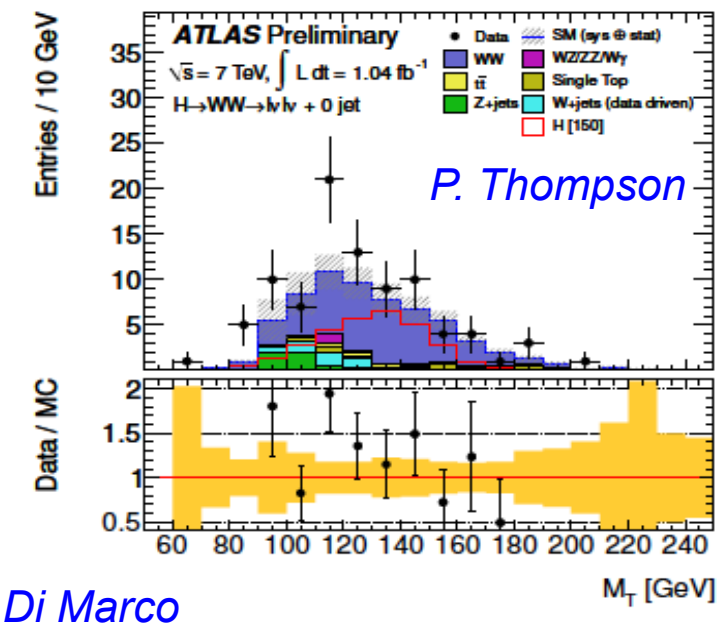
Medium Mass (140-200 GeV)



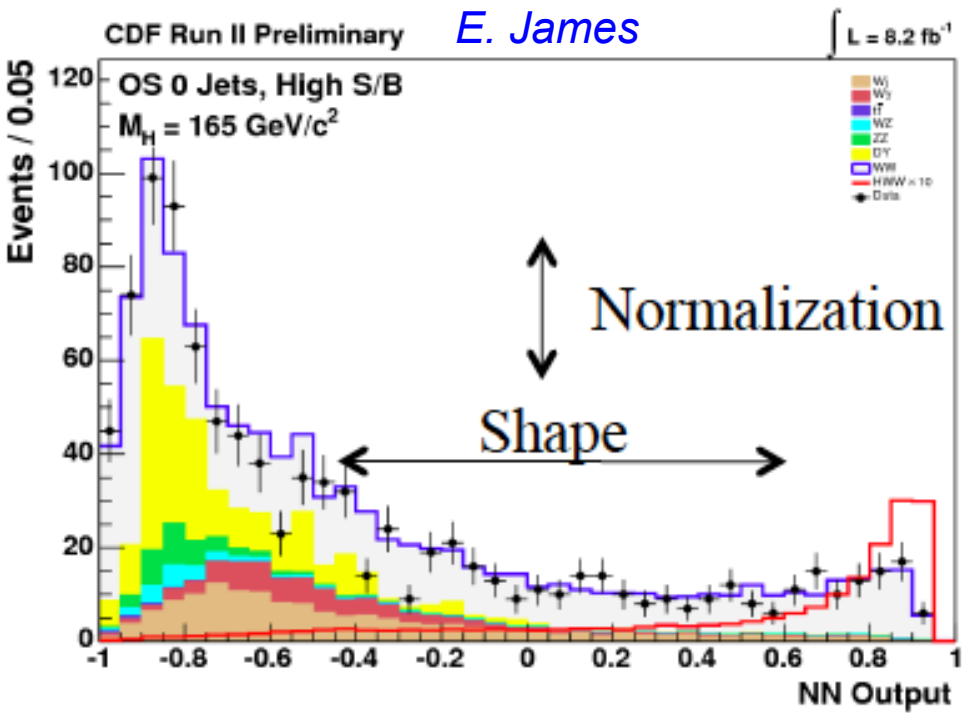
H→WW→lνlν

- Highest sensitivity channel in M_H~130-200 GeV range.
- Clean dilepton+MET signature.
- Main backgrounds after MET cut: WW, V+jets.
- Exploit spin correlations between W bosons
  - ➔ Use $\Delta\phi(l,l)$ or $M_T(WW)$ (LHC)
  - ➔ Or rely on multivariate techniques (Tevatron, LHC)
- Include additional signals beyond gg→H (Tevatron).

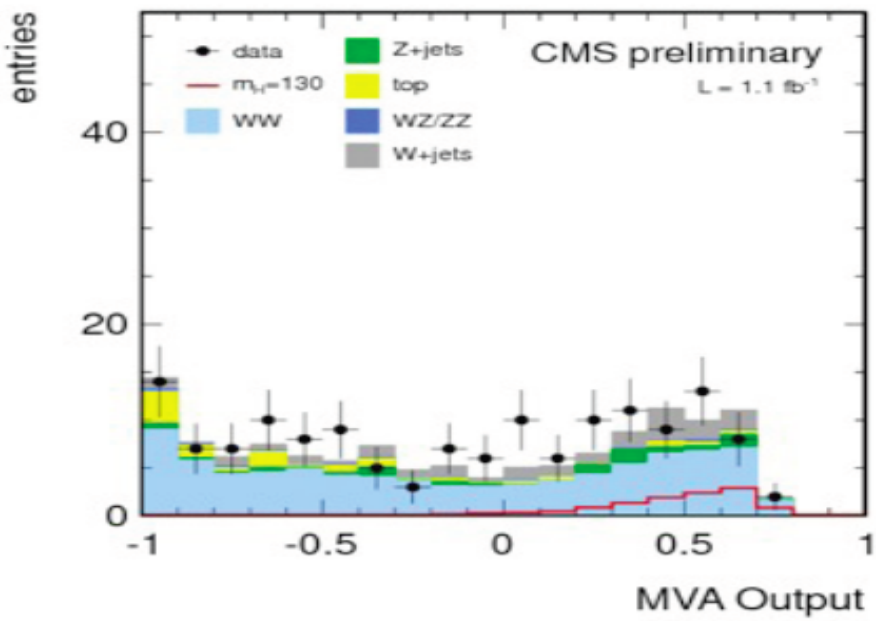
M_T after all cuts:



E. James



E. Di Marco



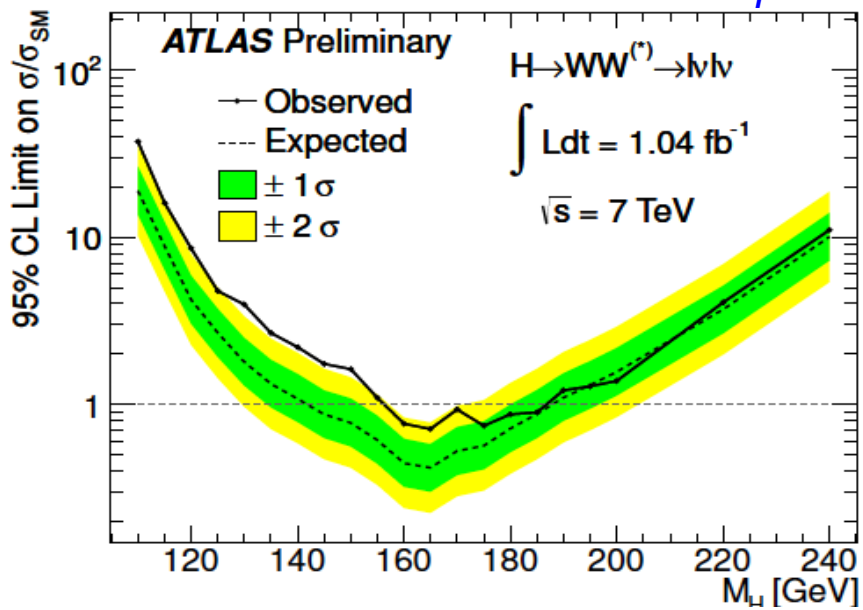
H→WW→lνlν

- Consistent exclusions by four experiments:
  - Tevatron: 156-177 GeV (obs)
  - ATLAS: 158-186 GeV (obs)
  - CMS: 150-193 GeV (obs)

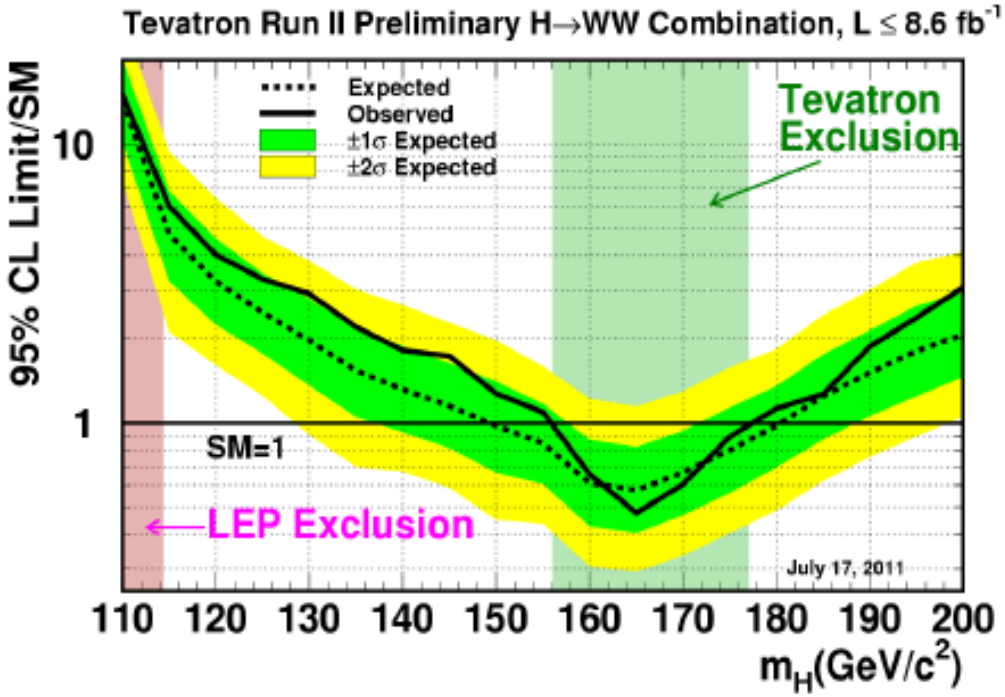
but also tantalizing broad excesses in ~120-160 GeV mass region….

(Mass resolution ~20%).

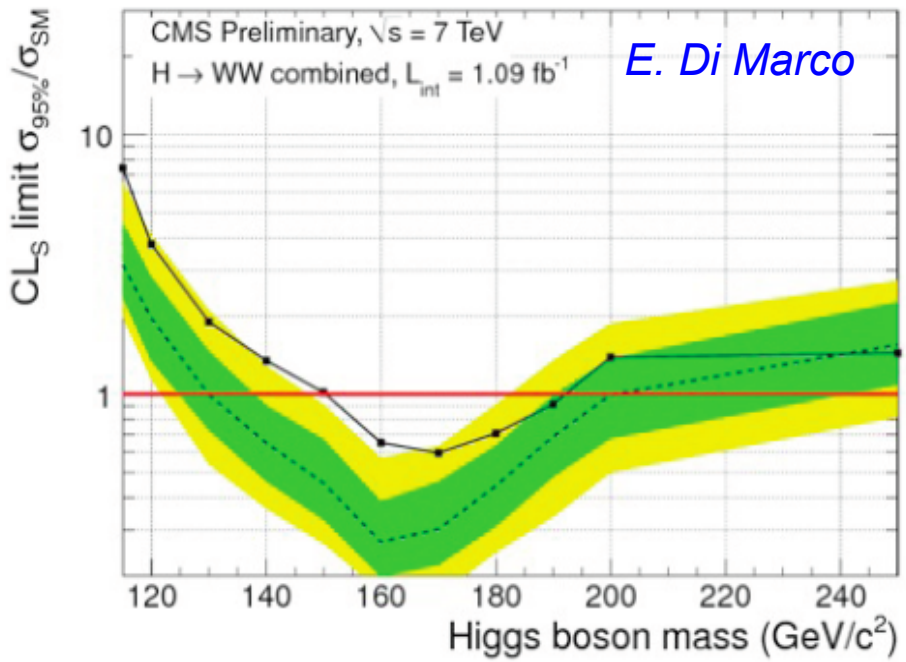
P. Thompson



G. Davies



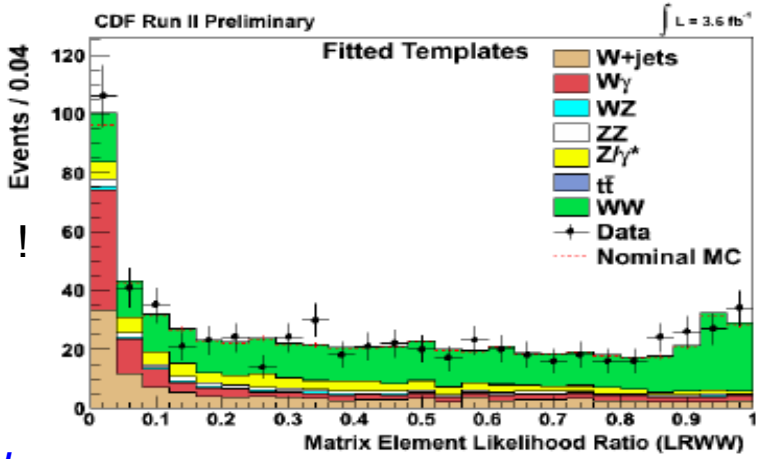
E. Di Marco



Validation of Search Techniques

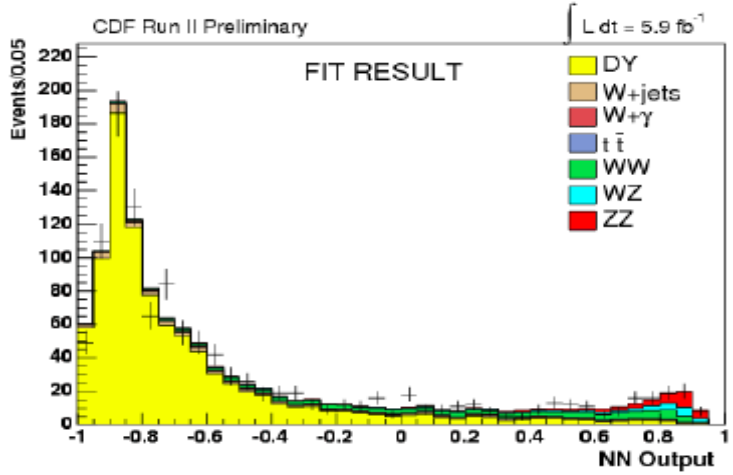
- Critical to validate experimental strategy and tools using SM backgrounds that share characteristics with the signal.

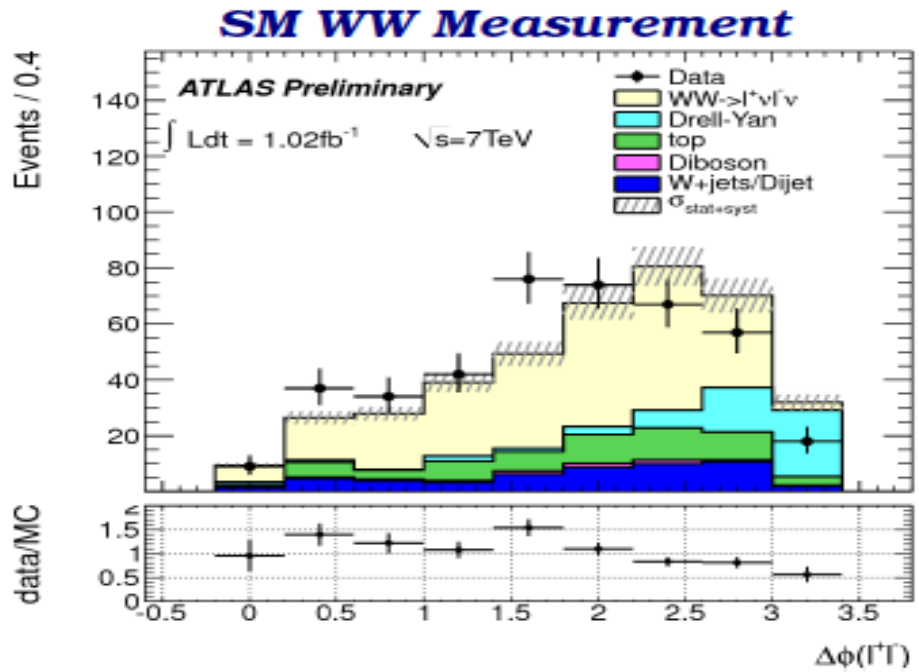
$WW \rightarrow l\nu l\nu : \sigma(WW) = 12.1\ ^{+1.8}_{-1.7}$ pb



E. James

$ZZ \rightarrow ll\nu\nu : \sigma(ZZ) = 1.45\ ^{+0.60}_{-0.51}$ pb



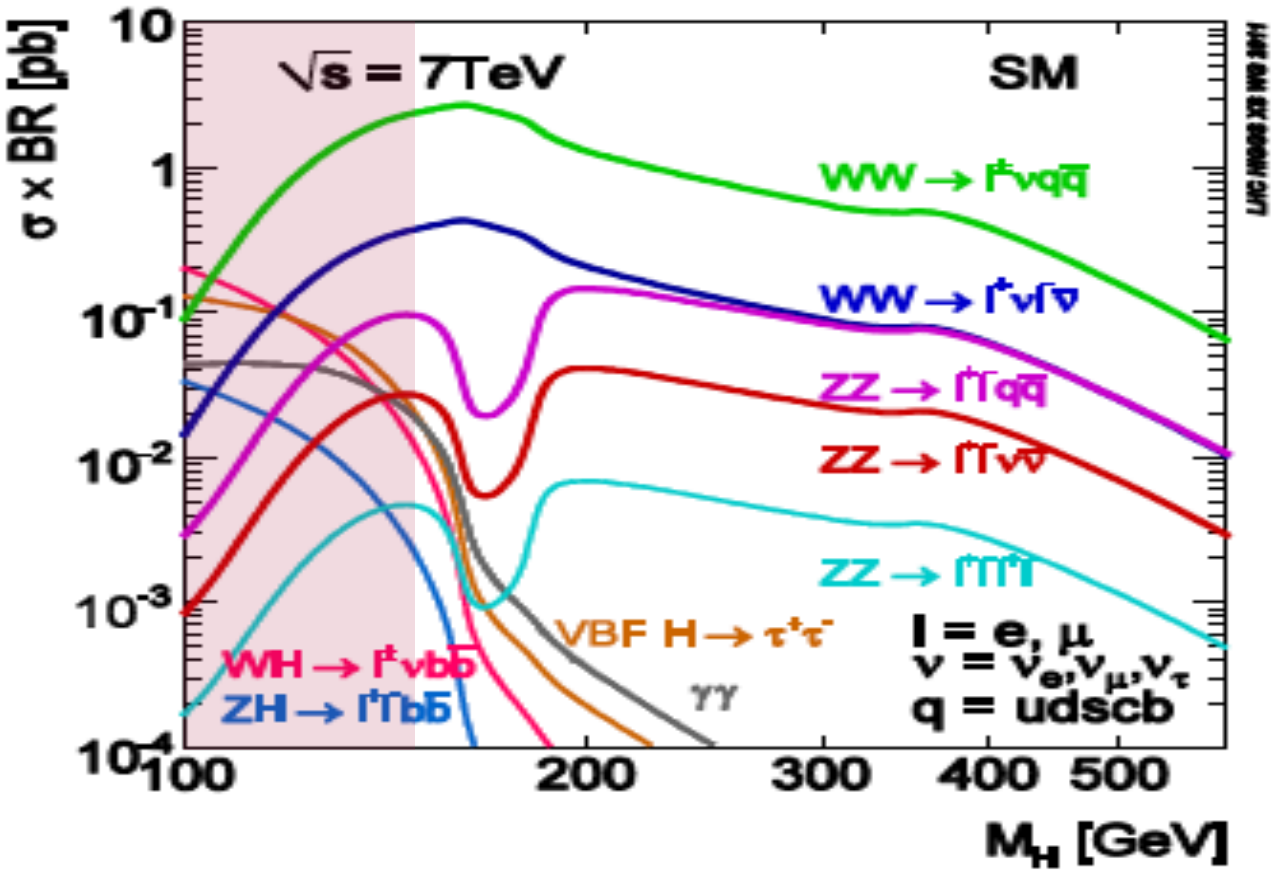


$$\sigma(p\bar{p} \rightarrow WW)^{EXPT} = 48.2 \pm 4.0(stat) \pm 6.4(syst)\ [pb]$$

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

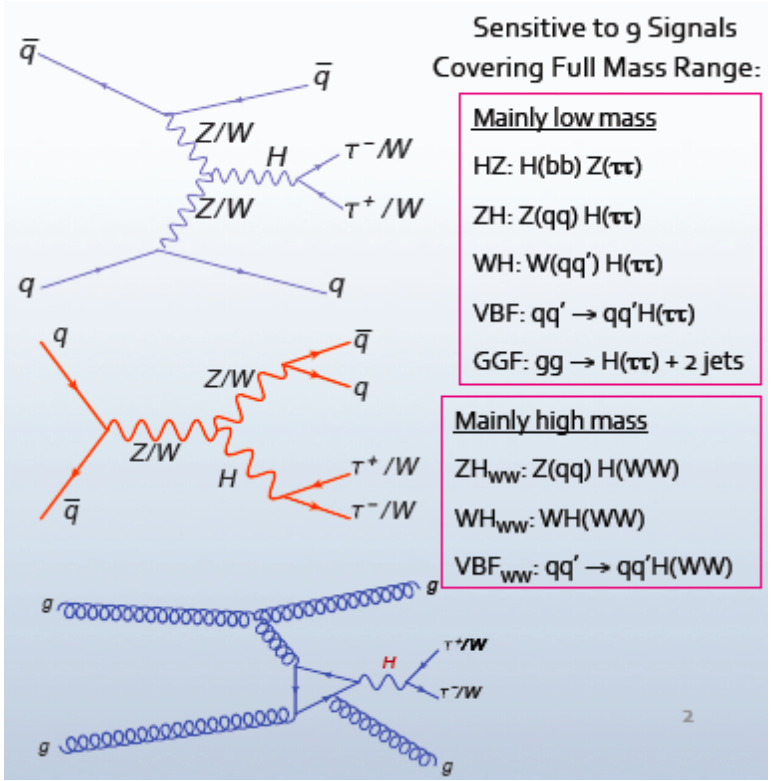
SM Higgs

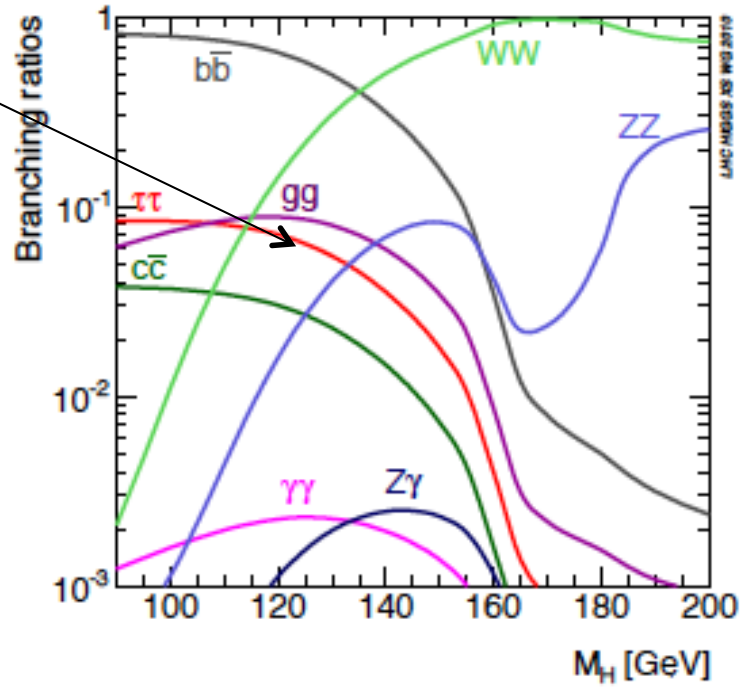
Low Mass (100-140 GeV)

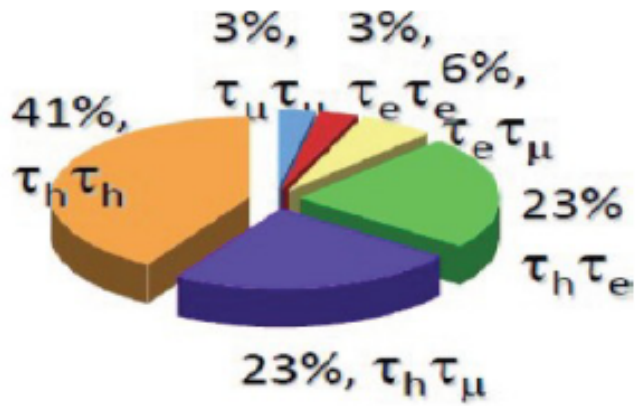


Searching for H→ττ

- H→ττ: second largest BR(~8%) at low mass!
- Select events with $\tau_l\tau$+X (l=e,μ) final states.
- Challenges:
  - Efficient categorization of many possible signal processes! E.g. $\tau_l\tau_h$jj



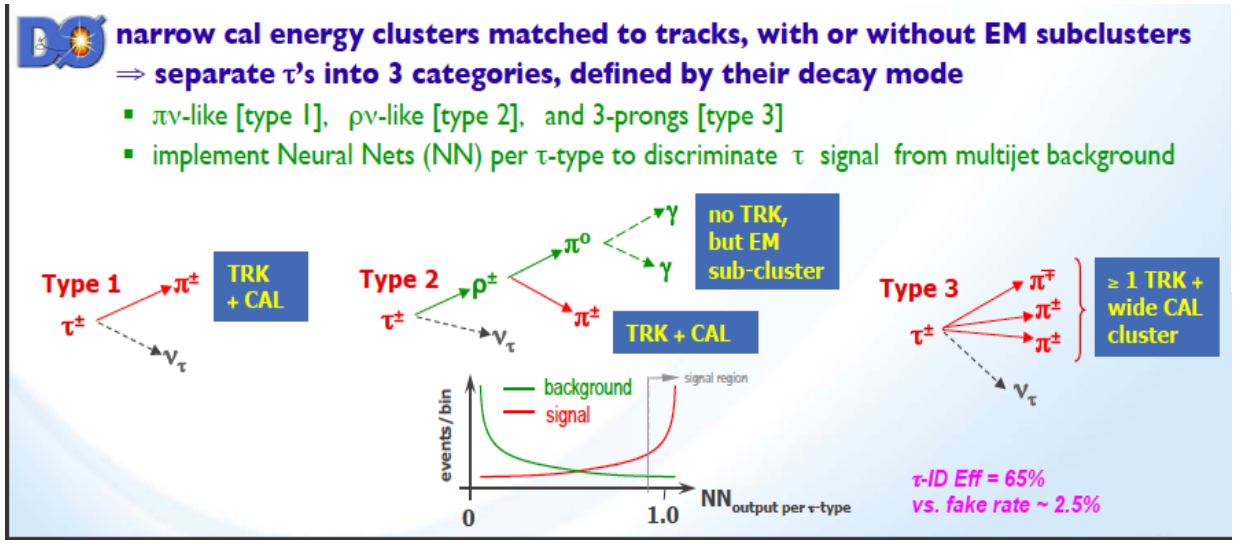




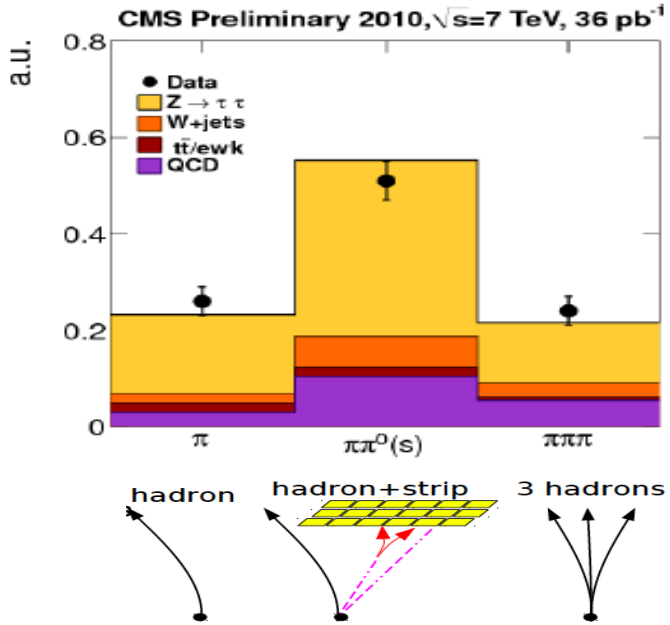
- Considering H→WW decays turns this also into a "high mass" search.

Searching for H→ττ

- Tau ID algorithms very well developed at the Tevatron: E.g. D0 NN-based τID: eff~65%, fake rate~2.5%



A. Patwa



Uncertainty's source	HPS combined loose Δβ
Muon Momentum Scale	<< 1%
τ-Jet Energy Scale	< 1%
Track Reconstruction	3.9%
Track Momentum Scale	< 1%
Lead. Track P_T Cut	1%
Loose Isolation	2.5%
Jet → τ_{had} Fakes	1.2%
Lead. Track Corr. Factor	1.7%
Loose Iso. Corr. Factor	2.1%
Fit (Statistical Uncertainty)	2.6%
Sum	6.0%

New! In winter was 23%

- Amazing progress by LHC experiments on τID in 2011: E.g. CMS Particle-Flow based τID:
  - eff~50%, fake rate~1%
  - Uncertainty on τID: 23% → 6%!!

E. Friis

Searching for H→ττ

Searches in different final states:

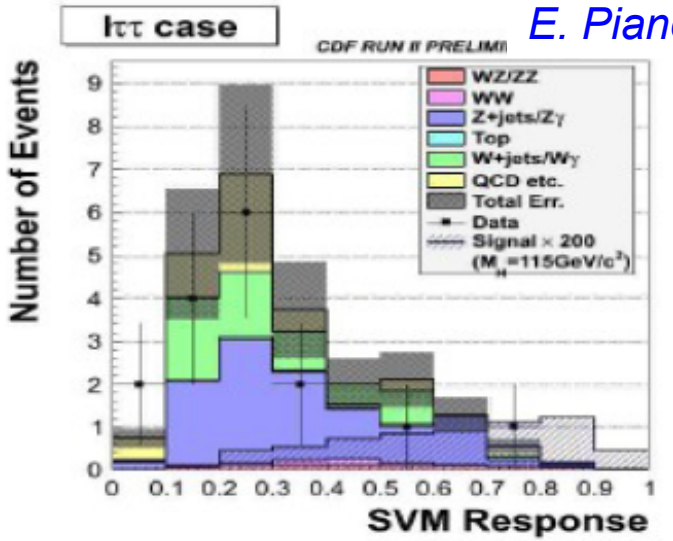
- ZH→llττ/WH→lνττ: consider 5 signatures:

  lll, $ll\tau_h$, $e\,\mu\tau_h$, $l\tau_h\tau_h$

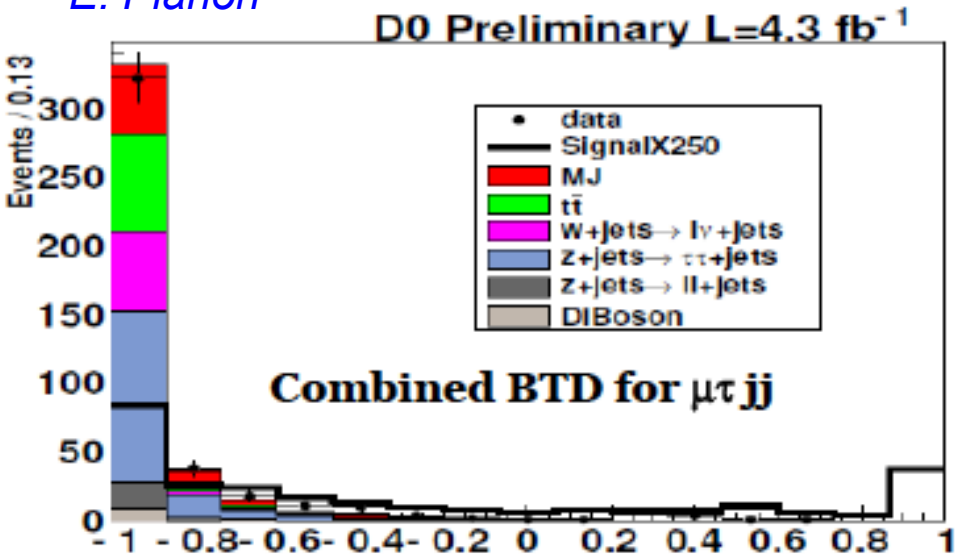
  4 leptons (any type)

- $\tau_l\tau_{had}$+1j, $\tau_l\tau_{had}$+2j, $\tau_l\tau_l$+2j
  - Mainly VH, VBF but also some gg→H
  - Many relevant production and decay mechanisms at the Tevatron vs mass!
  - Dedicated VBF analysis by CMS

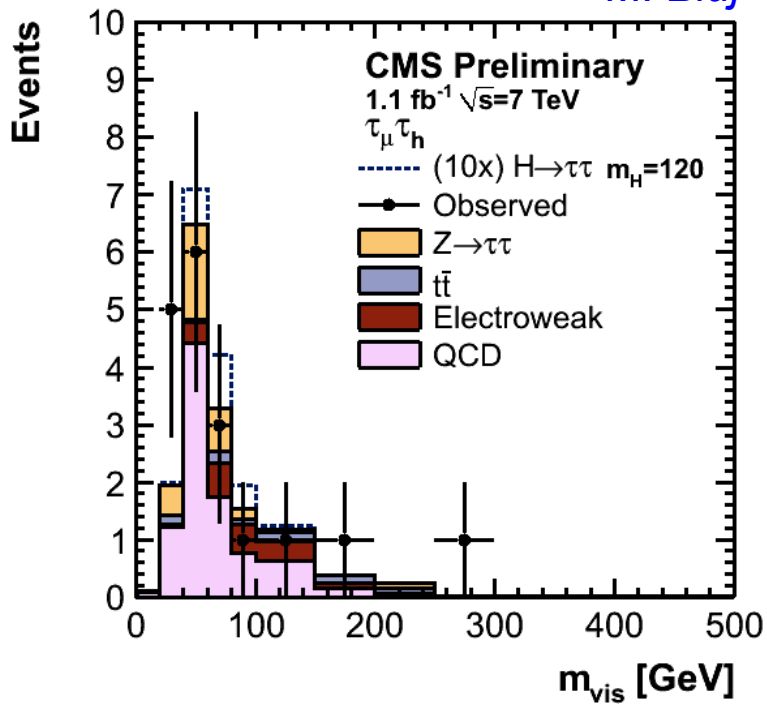
E. Pianori



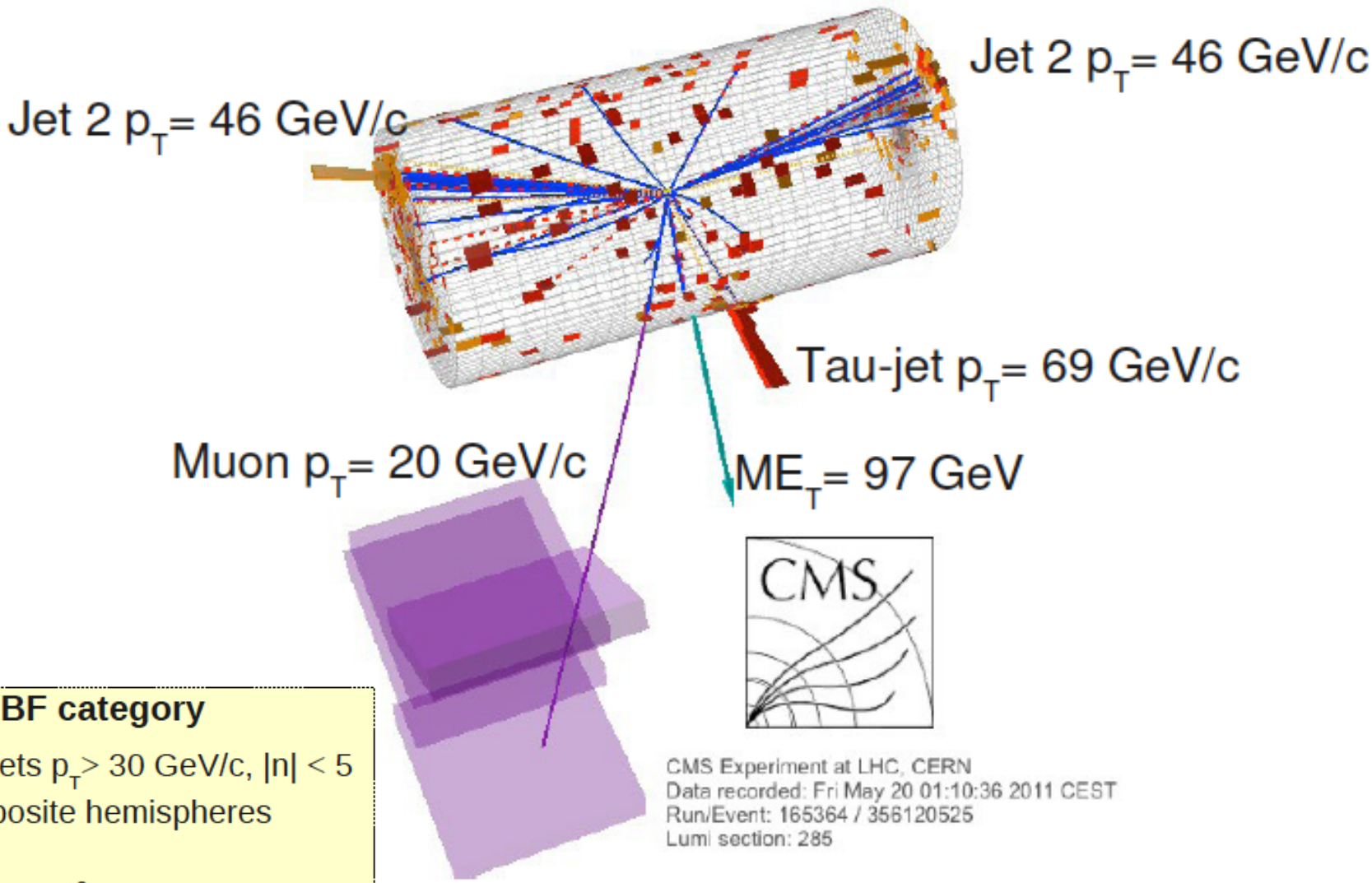
E. Pianori



M. Bluj



VBF H → ττ event candidate



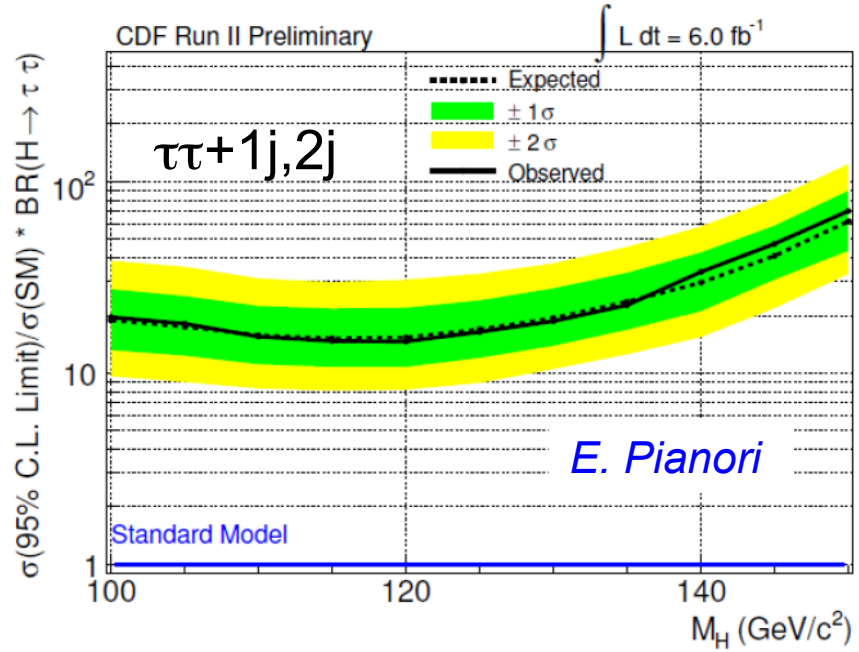
M. Bluj

VBF category

- Exactly 2 jets p_T> 30 GeV/c, |η| < 5
- Jets in opposite hemispheres
- $\Delta\eta_{jj} > 3.5$
- $M_{jj} > 350$ GeV/c^2

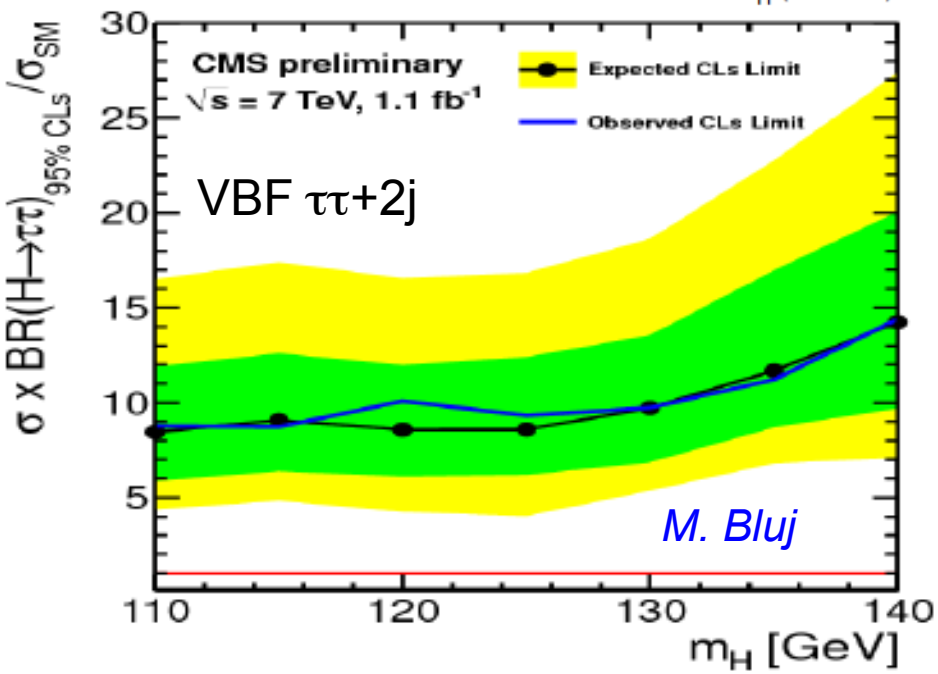
Searching for H→ττ

- Comparable sensitivity for different searches.
- Large potential for improvement in the near future:
  - More data to analyze.
  - Further refinements to analysis possible.



95% CL Limits at m_H = 115 GeV

Channel	Exp/obs Limit (σ/SM)
ττ+1j,2j (6.0 fb^{-1})	15.2/14.7
llττ/lνττ (6.2 fb^{-1})	17.3/18.5
ττ+2j (5.4 fb^{-1})	12.8/32.8
VBF ττ+2j (1.1 fb^{-1})	9.0/9.0

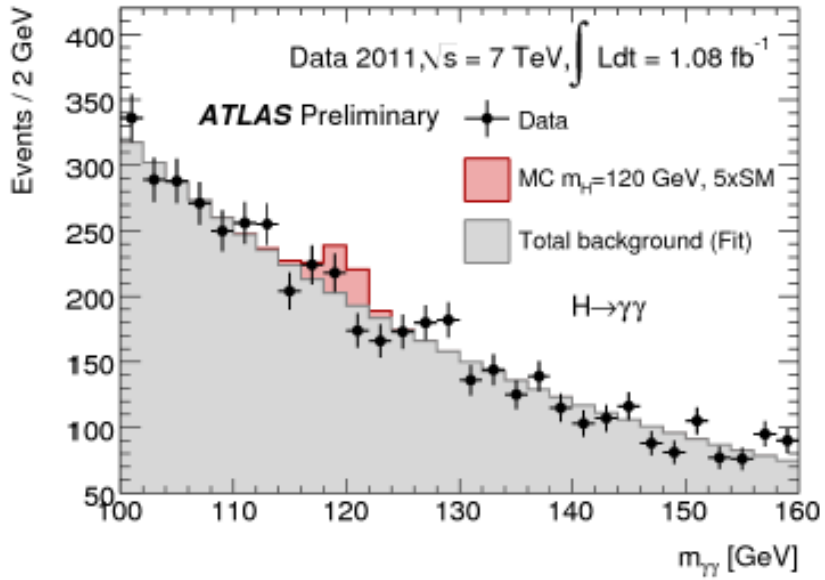


Searching for H→γγ

J.-F. Marchand

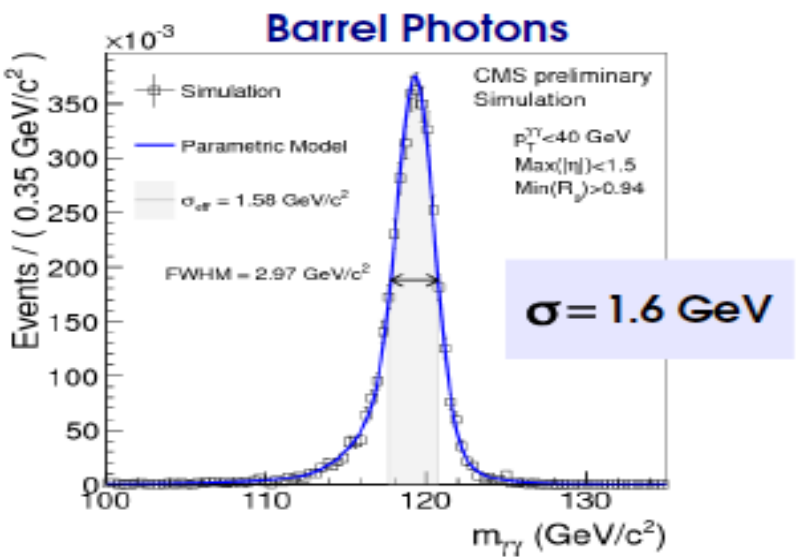
- Tiny BR in SM (~0.2%) but clear signature of narrow diphoton resonance on top of steeply-falling background.

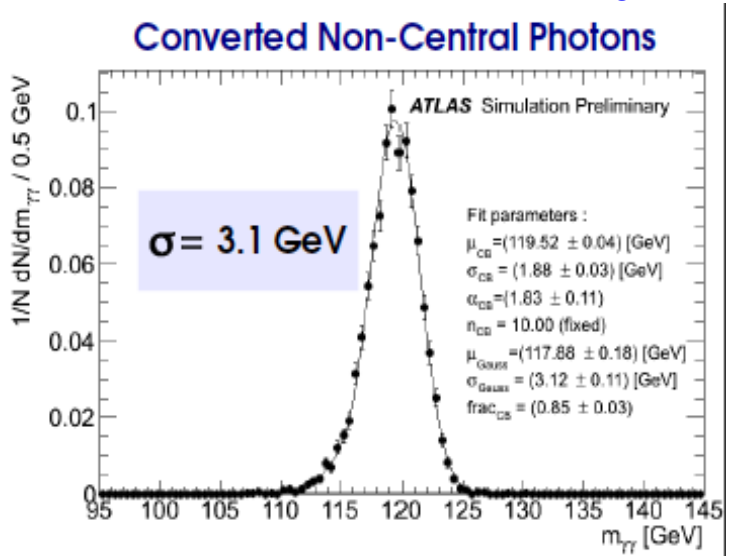
- One of the most promising channels at the LHC for discovery in the 115-150 GeV region. Also being exploited at the Tevatron!



- Diphoton mass resolution:
  - Dedicated corrections for material upstream the calorimeter, vertex position, etc
  - Categorize events depending on expected mass resolution

J.-F. Marchand

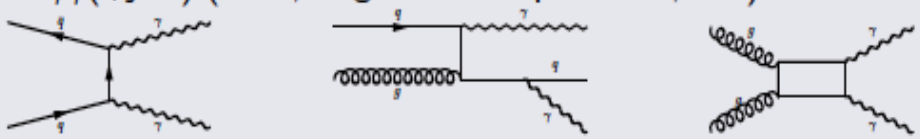




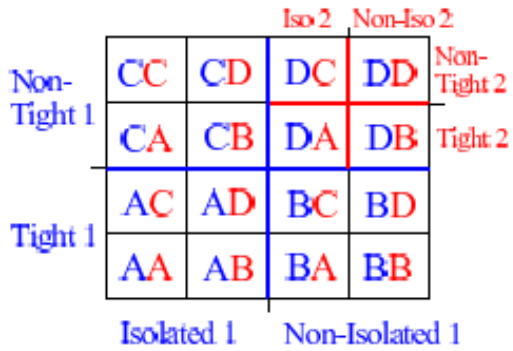
Searching for H→γγ

Background

- Irreducible : γγ(+jets) (Born, fragmentation processes, box)

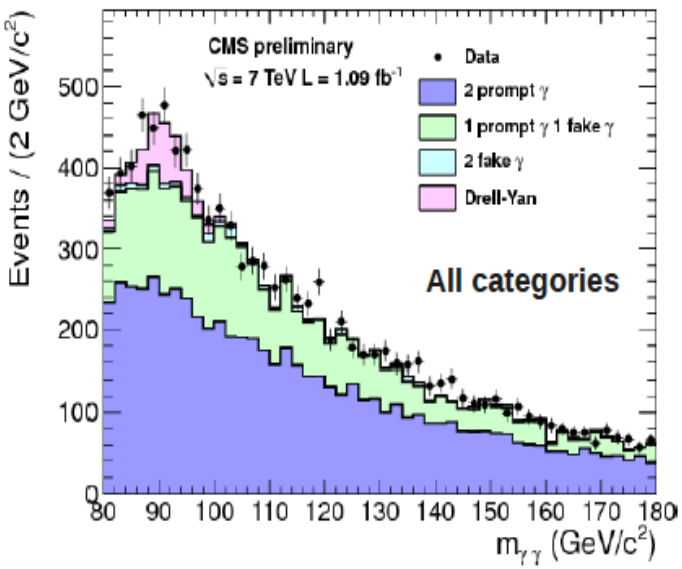


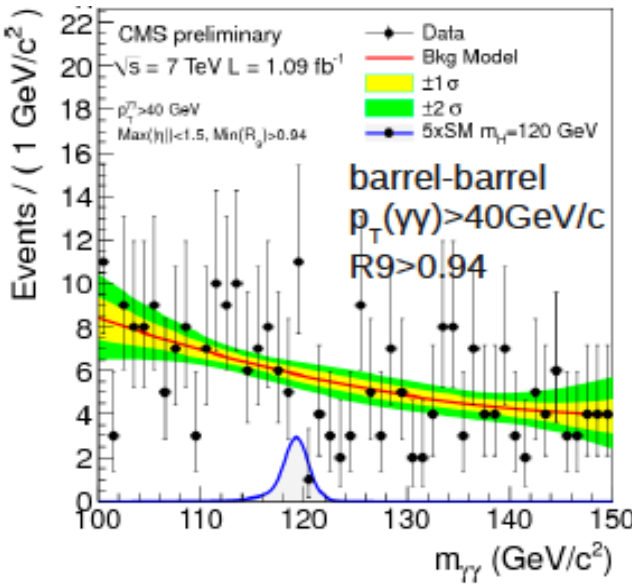
- Reducible : γ/jet(s), jet(s)/jet(s)
- Drell-Yan events : both e misidentified as γ



- Detailed understanding of background composition achieved via data-driven techniques.
- Background fitted to exponential model and side-band analysis performed in different categories

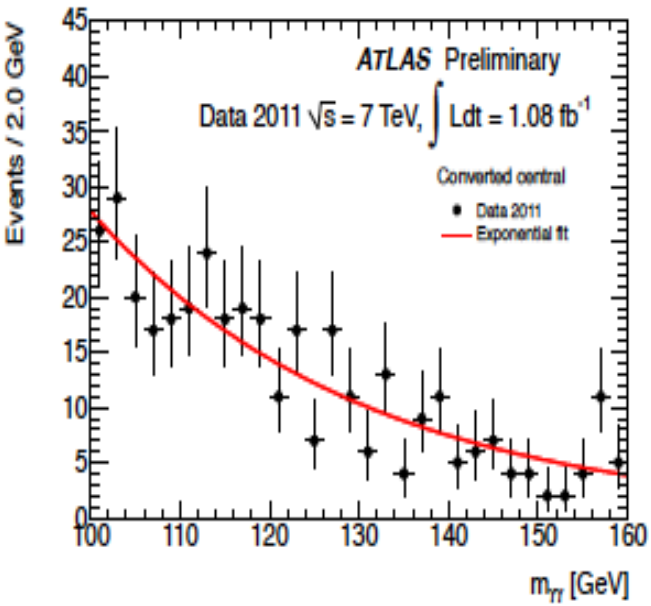
M.Bluj





J.-F. Marchand

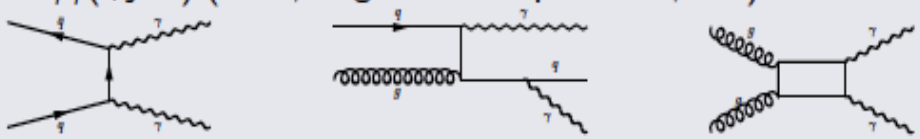
Converted-central



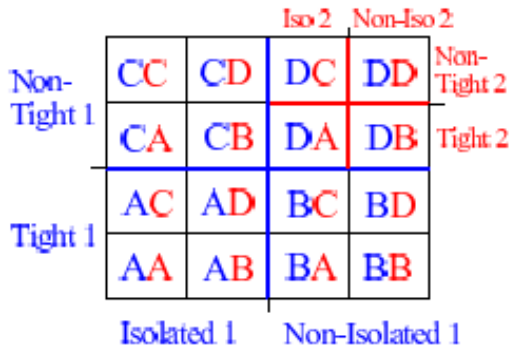
Searching for H→γγ

Background

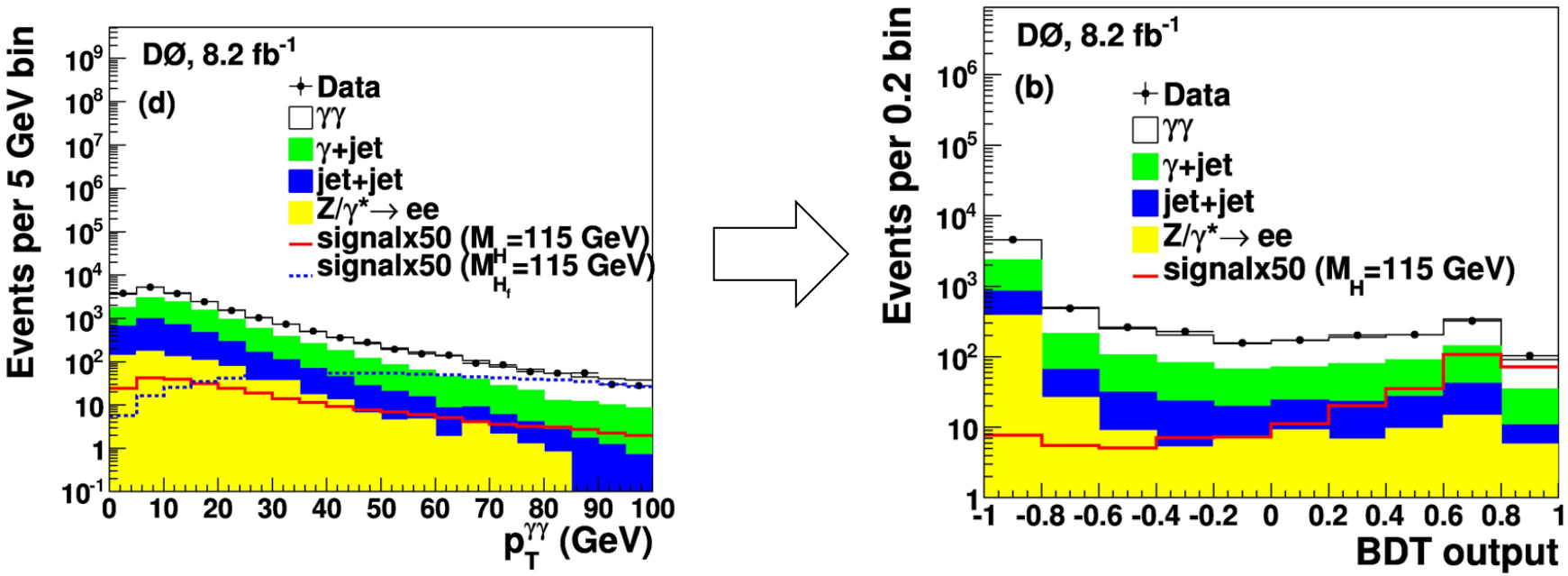
- Irreducible : γγ(+jets) (Born, fragmentation processes, box)



- Reducible : γ/jet(s), jet(s)/jet(s)
- Drell-Yan events : both e misidentified as γ

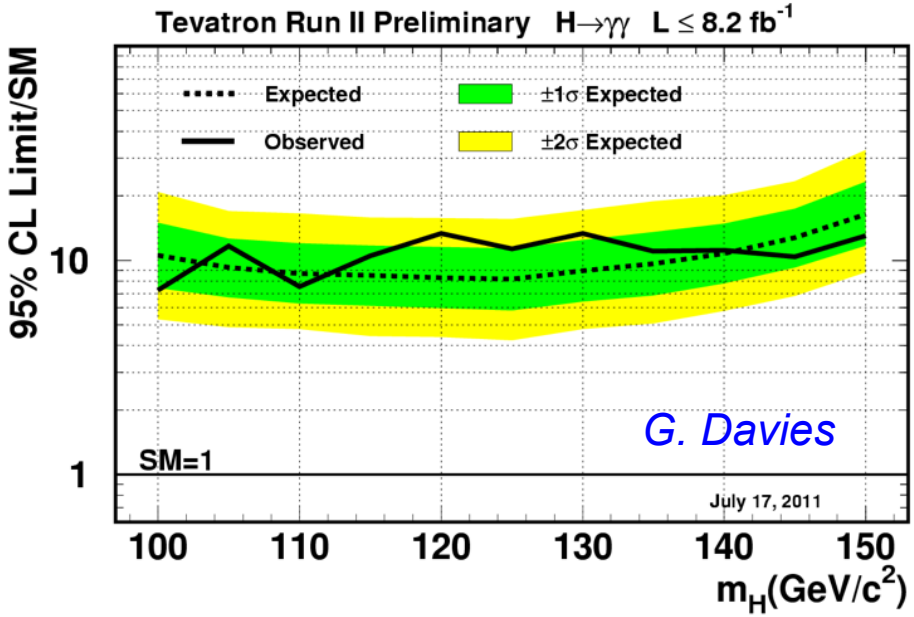


- Detailed understanding of background composition achieved via data-driven techniques.
- Good data/MC agreement in diphoton kinematics allows multivariate treatment to improve sensitivity.



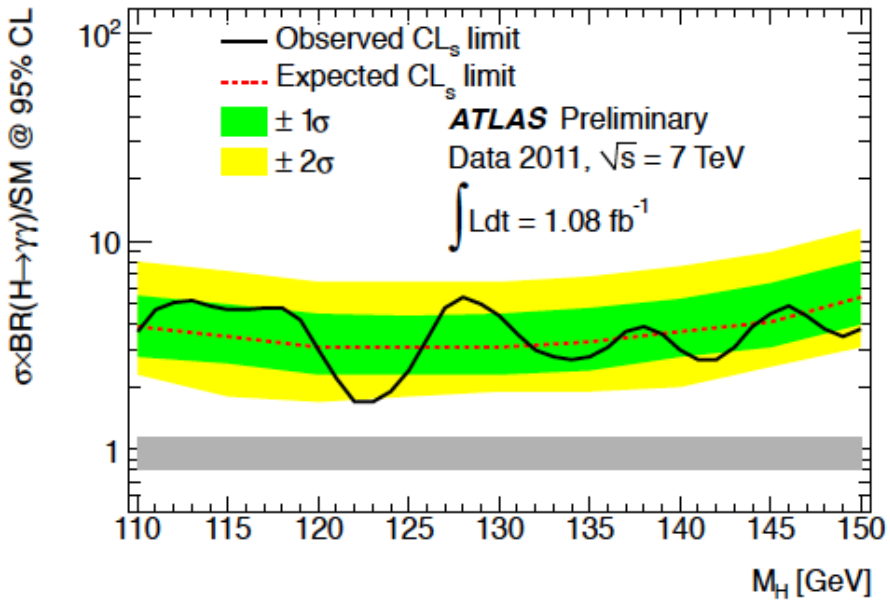
Searching for H→γγ

- Tevatron (7-8.2 fb^{-1}): expected limit ~8.5xSM



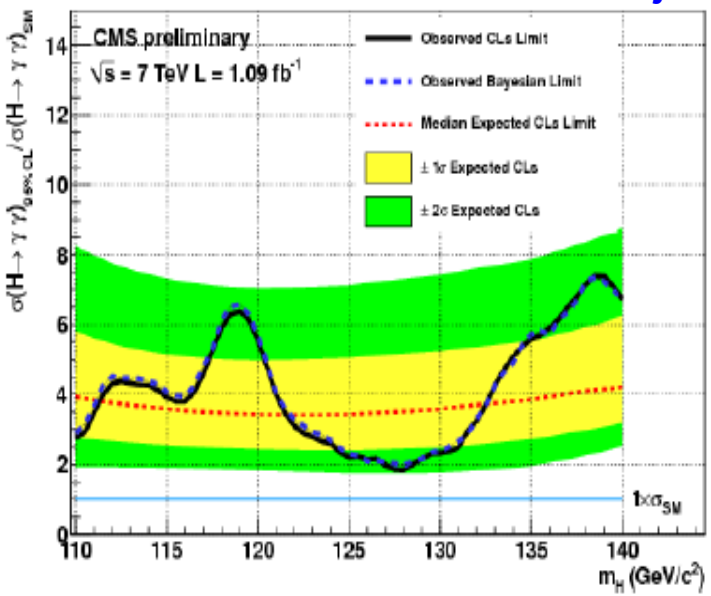
G. Davies

J.-F. Marchand



- LHC: Large dataset and refinements to analysis has lead to big jump in sensitivity:
  - Expected limits ~4xSM
  - No significant excess seen
  - Observed limit consistent with statistical fluctuations around the background-only hypothesis

M.Bluj

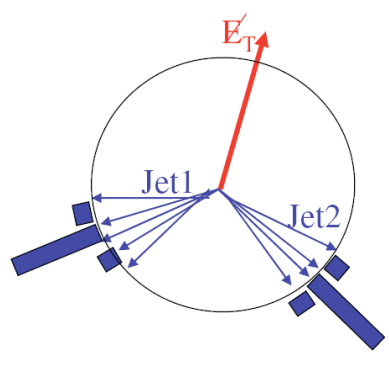


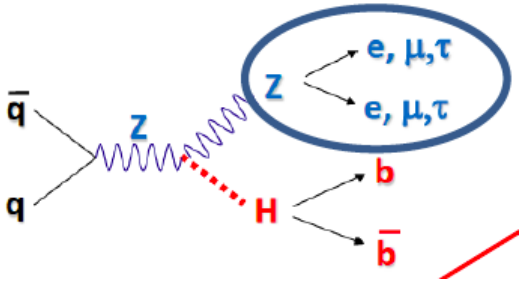
Searching for H→bb

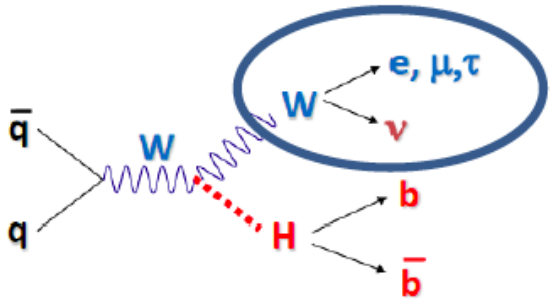
Identify events consistent with leptonic W/Z decays.

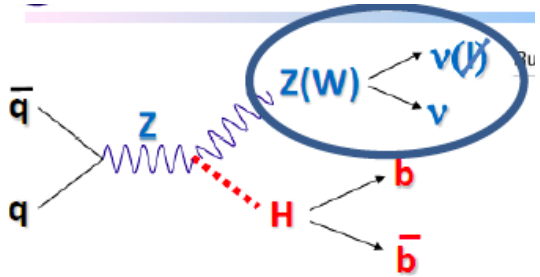
Y. Enari

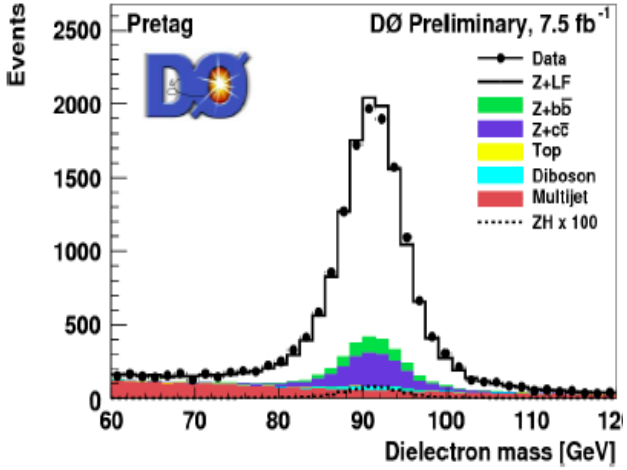
- W→lν: e or μ and high MET
- Z→ll: ee or μμ consistent with Z resonance
- Z→νν: no charged leptons; two acoplanar jets and MET
  - ➔ challenging to trigger on (MET+jets)
  - ➔ large instrumental background from QCD multijet car controlled with careful event selection

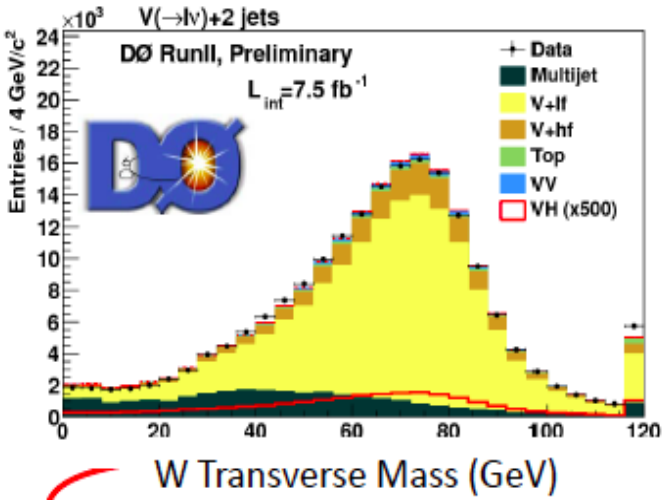


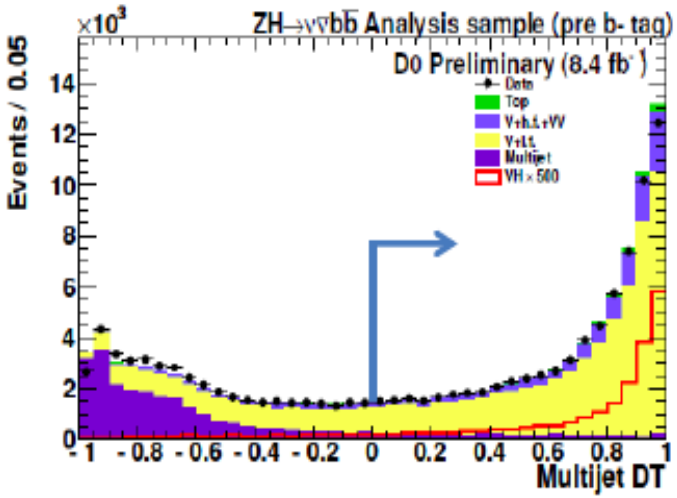








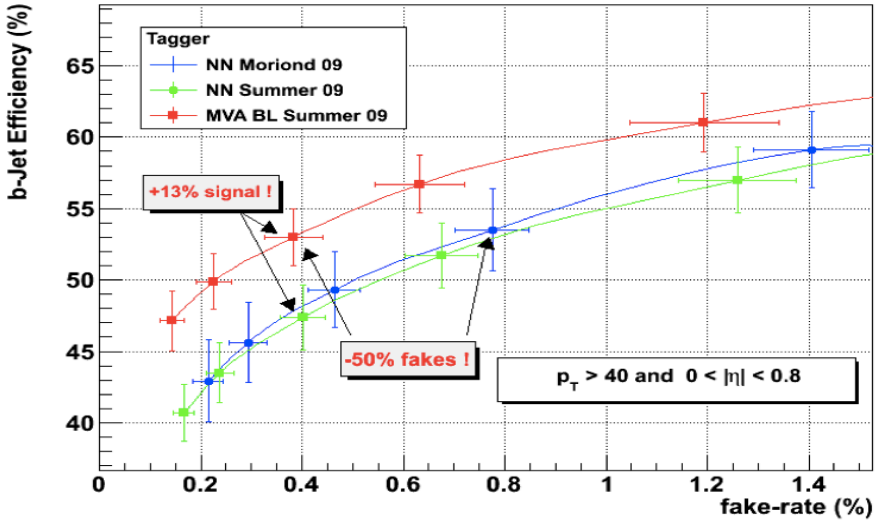


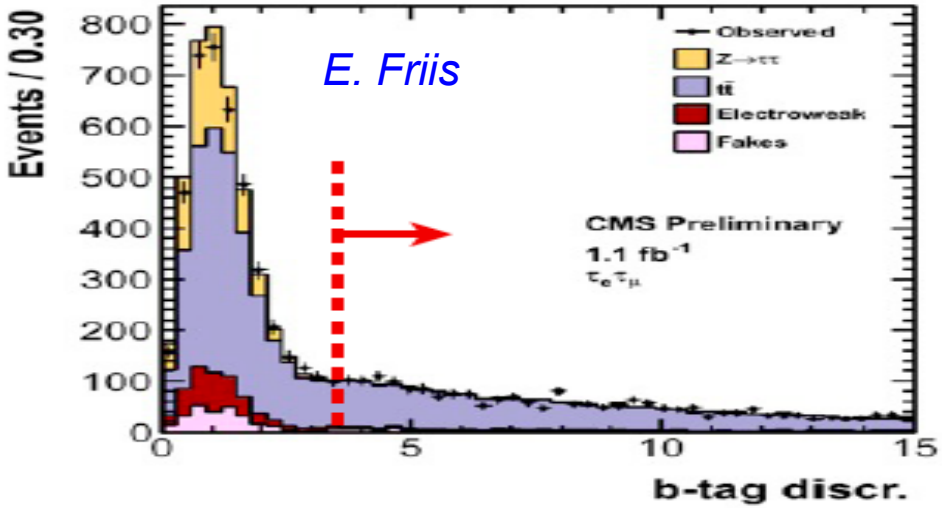


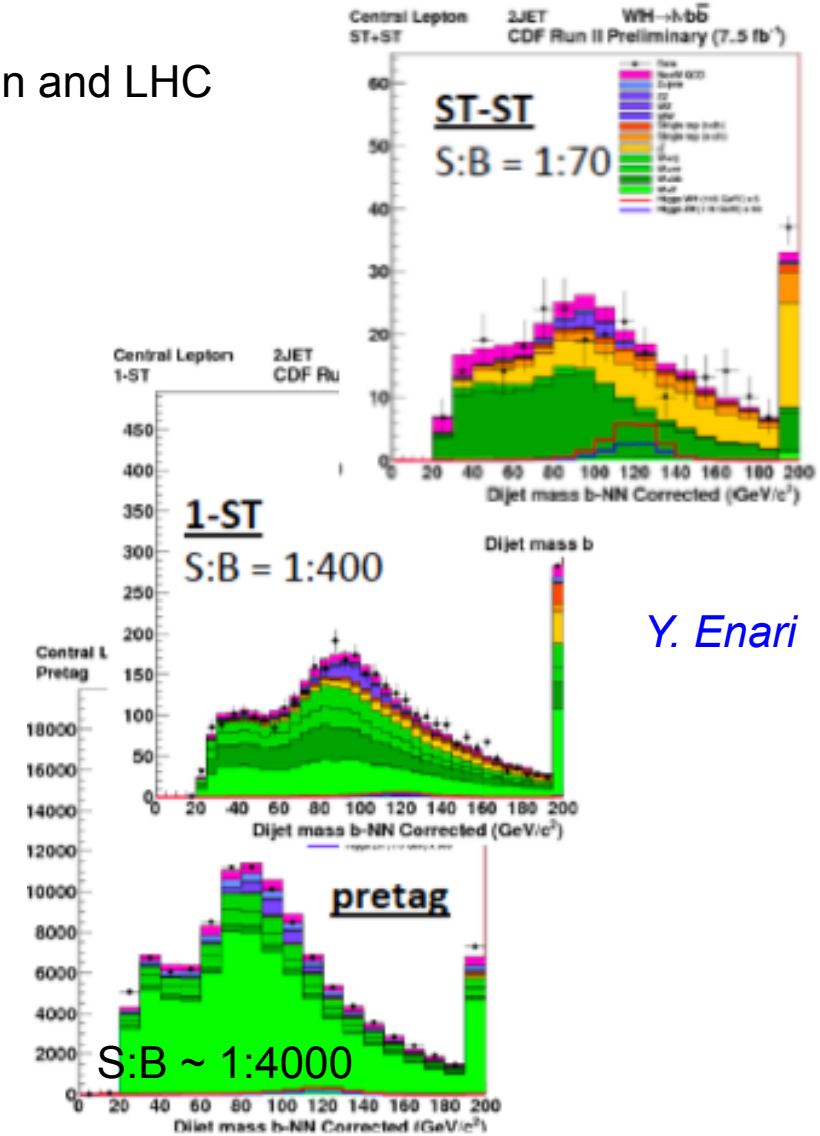
Searching for H→bb

- B-tagging critical to improve S:B.
  ➔ very sophisticated tools in use at both Tevatron and LHC experiments!

Y. Enari





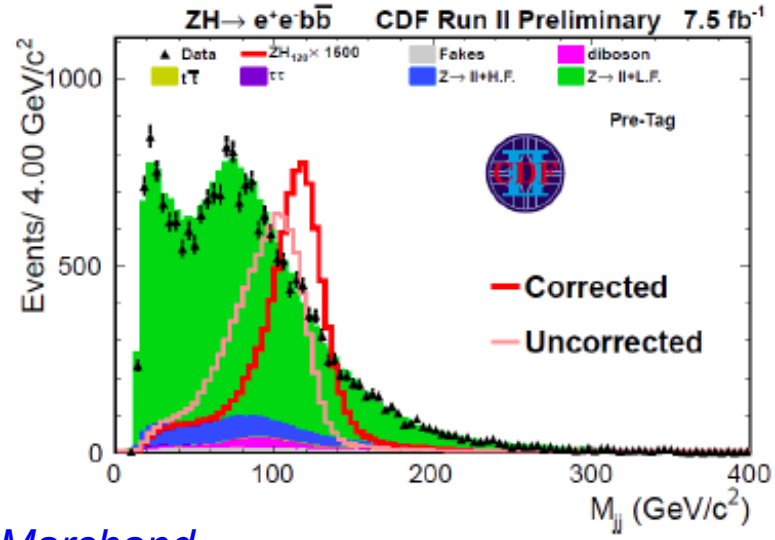


Y. Enari

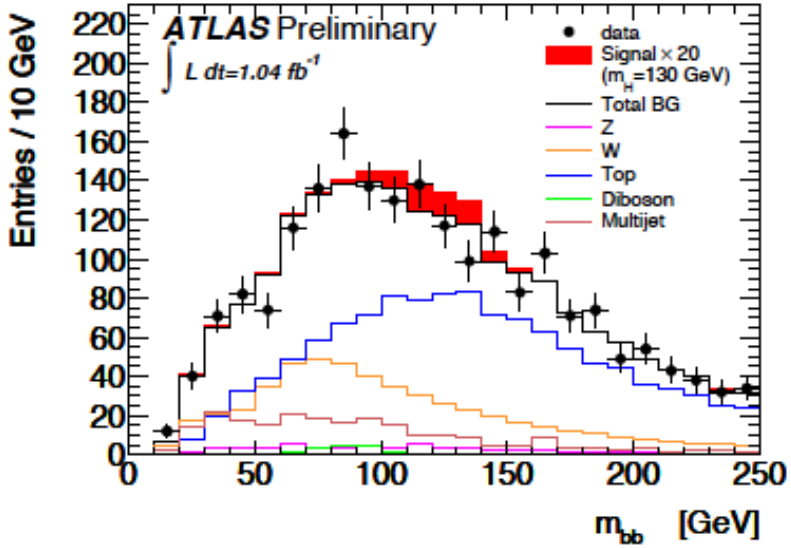
Searching for H→bb

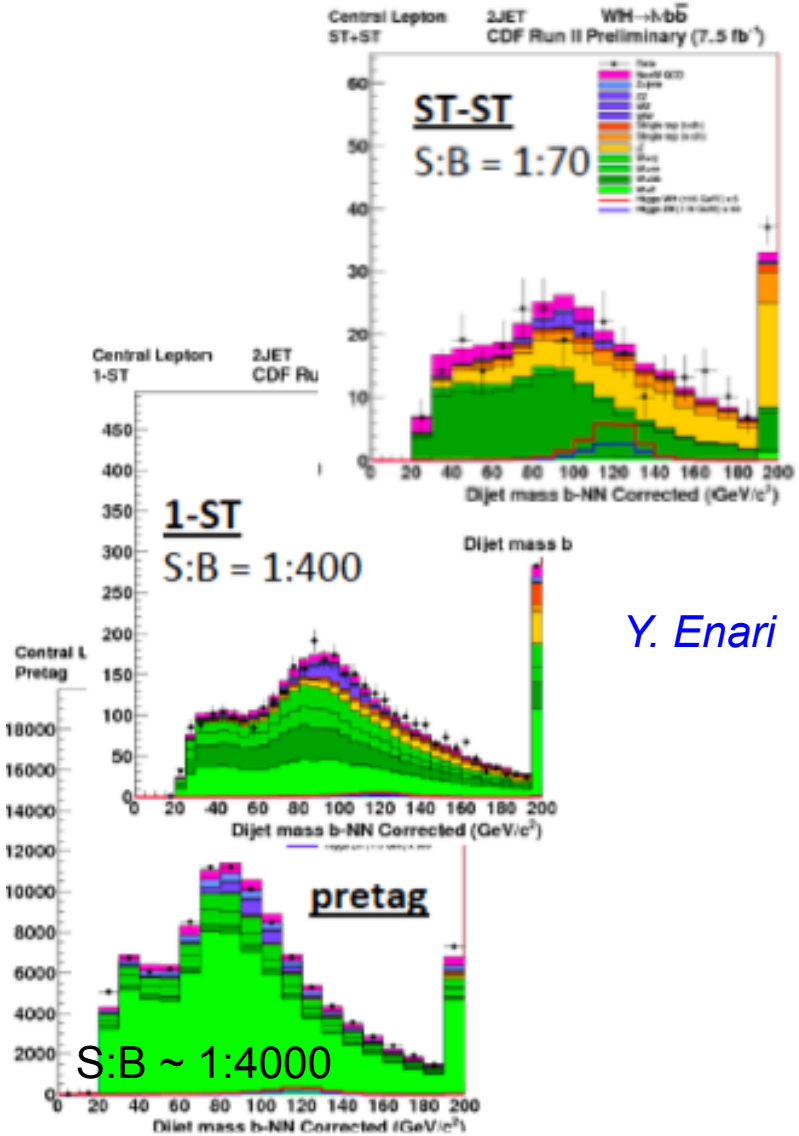
- Main discriminant is dijet mass:

Y. Enari



J.F. Marchand



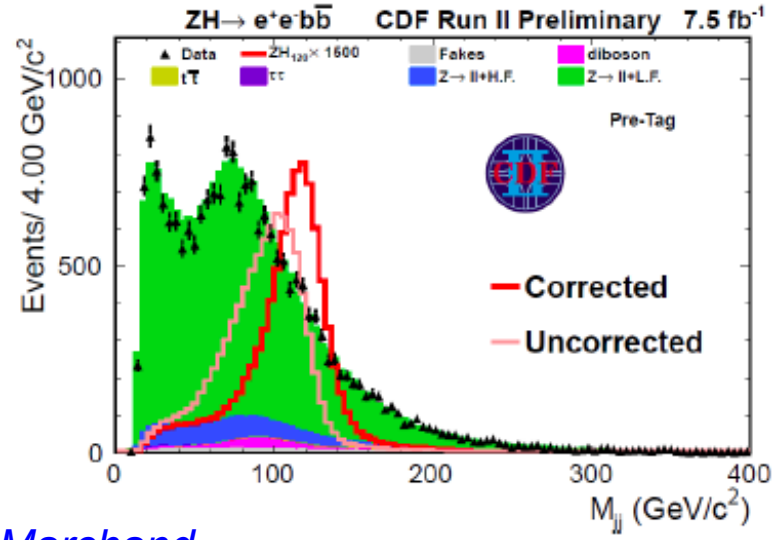


Y. Enari

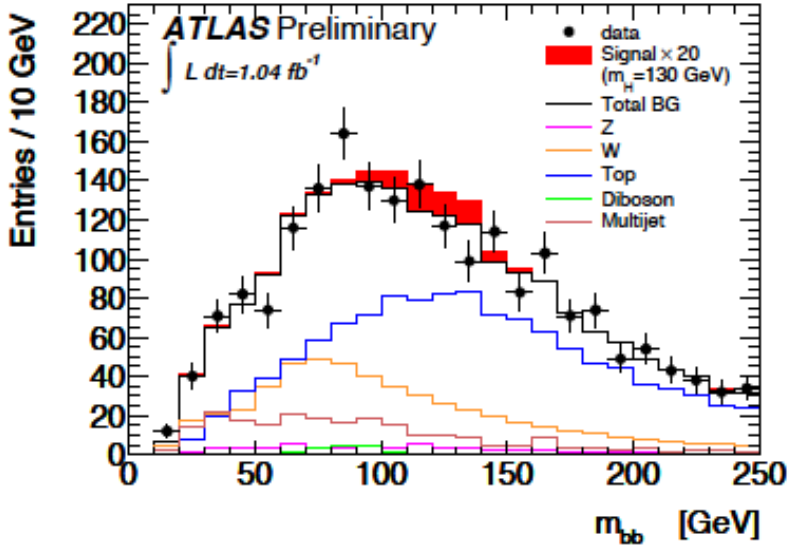
Searching for H→bb

- Main discriminant is dijet mass:

Y. Enari

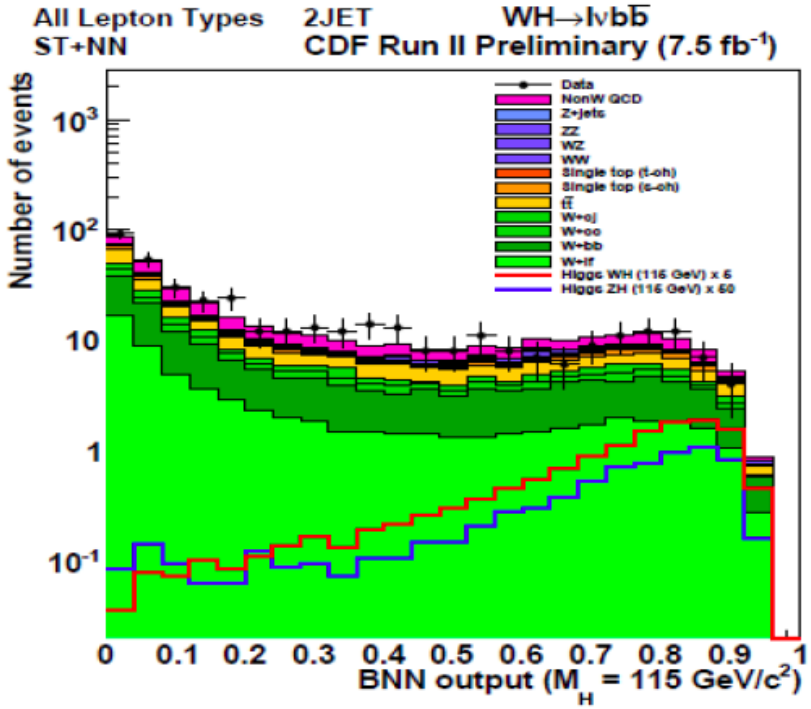


J.F. Marchand



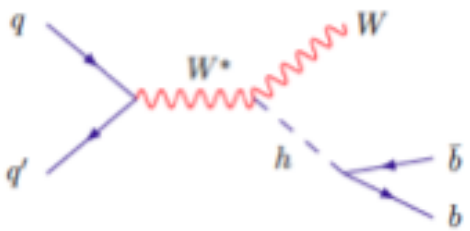
- Sophisticated multivariate techniques gain ~20-30% additional sensitivity

Y. Enari

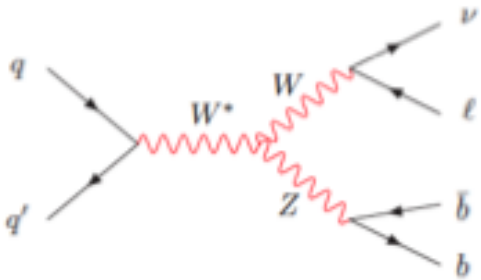


Validation of Search Techniques

- Critical to validate experimental strategy and tools using SM backgrounds that share characteristics with the signal.



VS



For m_H=115 GeV
$WH \rightarrow l\nu bb$: σ = 26 fb

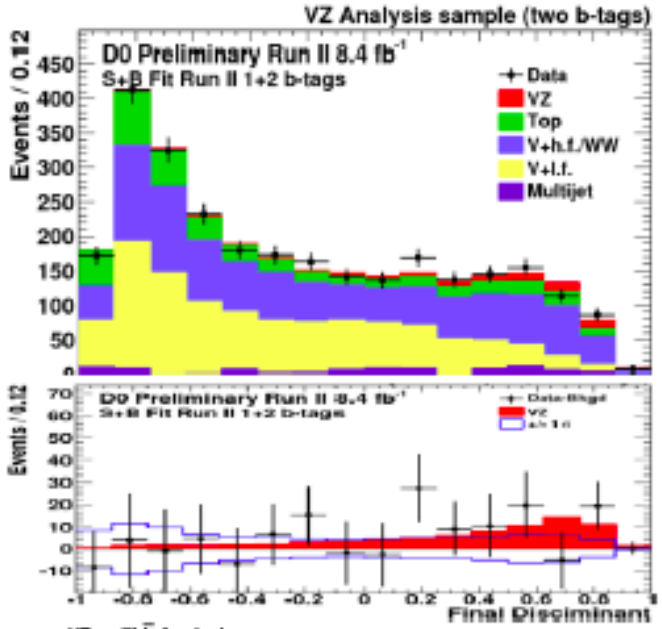
$WZ \rightarrow l\nu bb$: σ = 105 fb

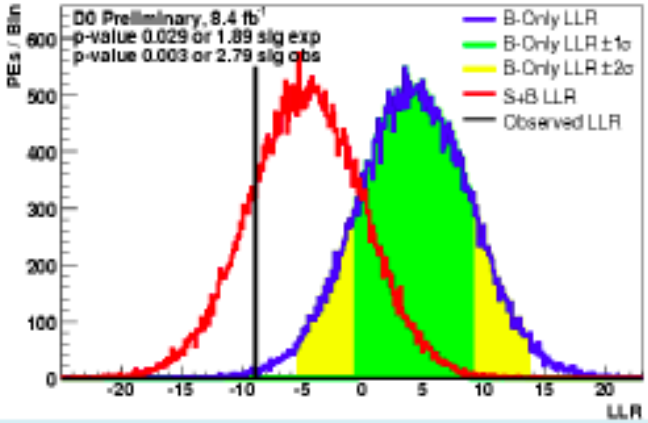
➔ x5 larger σxB but sits at lower mass and has peaking WW background.

- Low mass Higgs analyses will be used to measure WZ/ZZ (Z→bb) cross section.

  ➔ Tevatron combination upcoming!

Y. Enari



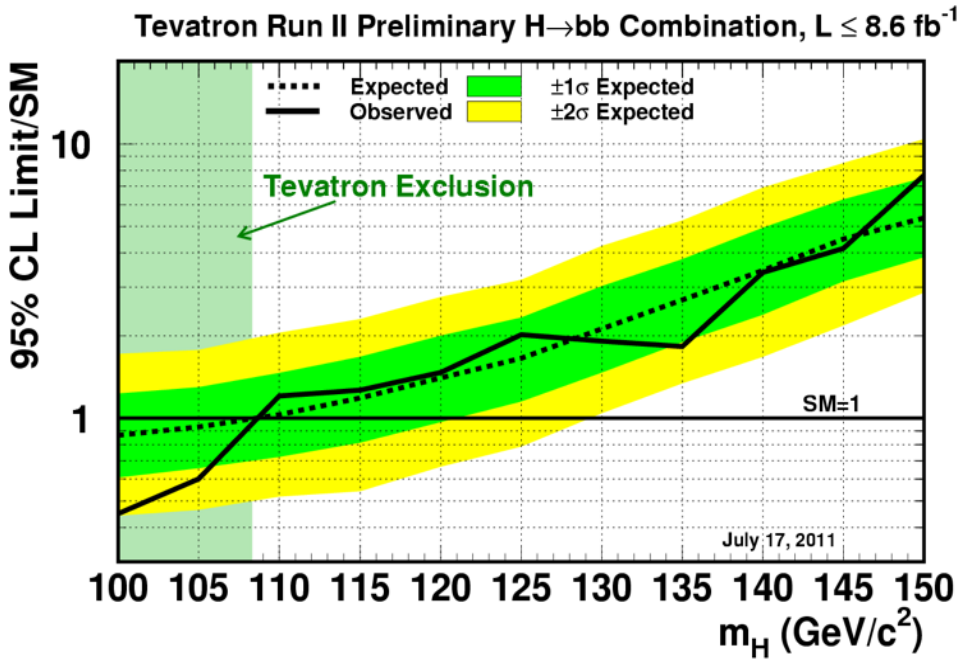


Cross-section measurement:
$\sigma(WZ+ZZ)_{mes}/\sigma_{SM}$= **1.5 ± 0.5**
2.8 s.d. from BG only hypo.

Searching for H→bb

95% CL Limits at m_H = 115 GeV

Channel	Exp/obs Limit (σ/SM)
WH→lνbb (7.5 fb^{-1})	2.7/2.6
ZH→ννbb (7.8 fb^{-1})	2.9/2.3
ZH→l^+l^-bb (7.9 fb^{-1})	3.9/4.8
WH→lνbb (8.5 fb^{-1})	3.5/4.6
ZH→ννbb (8.4 fb^{-1})	4.0/3.2
ZH→l^+l^-bb (8.6 fb^{-1})	4.8/4.9
WH→lνbb (1.0 fb^{-1})	~25/20
ZH→l^+l^-bb (1.0 fb^{-1})	~25/20
VH/VBF→jjbb (4.0 fb^{-1})	17.8/9.1
ttH→l+jets (7.5 fb^{-1})	11.722.9
ttH→jets (5.7 fb^{-1})	20.2/28.1

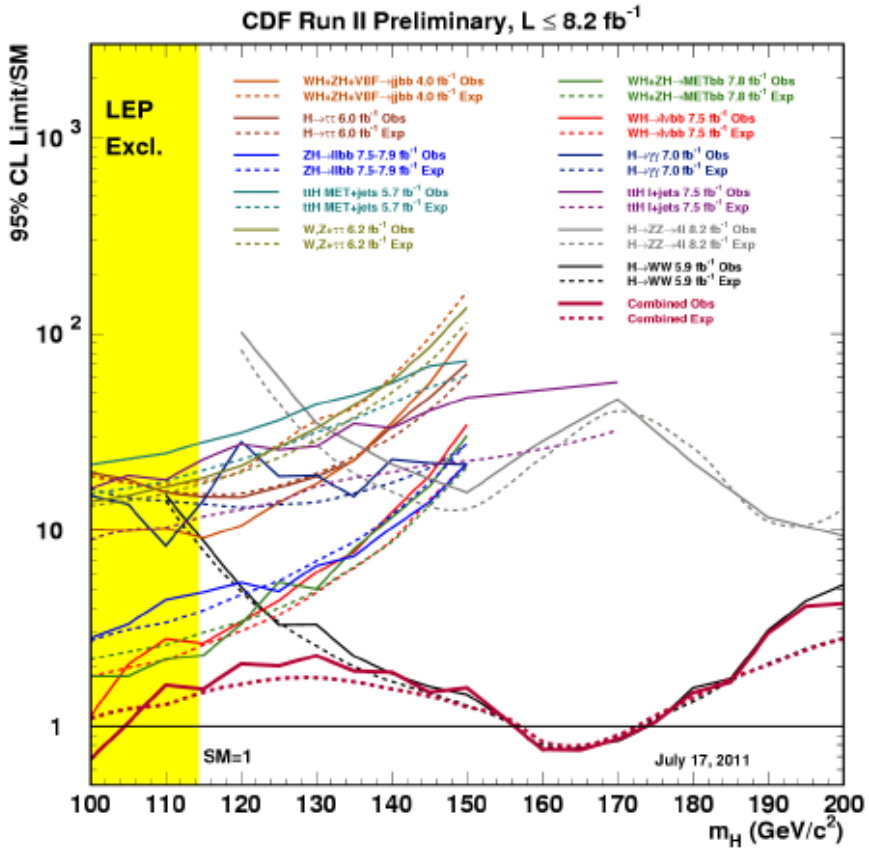


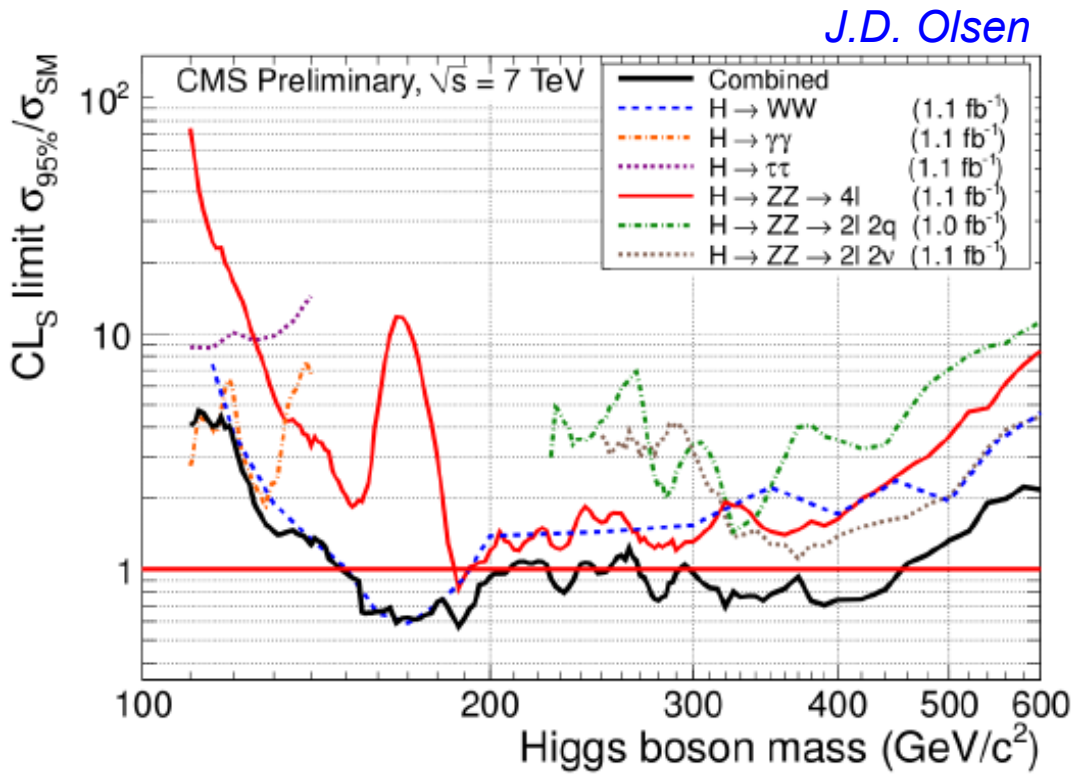
- At 115-120 GeV
  - Almost at 1*SM sensitivity
  - No excess seen
  - Inconsistent with CMS & ATLAS
- At 130-140 GeV
  - 2*SM – 3*SM sensitivity
  - No excess seen – would expect observed limit to be 1*SM high

G. Davies
B. Kilminster

Combination of SM Higgs Searches

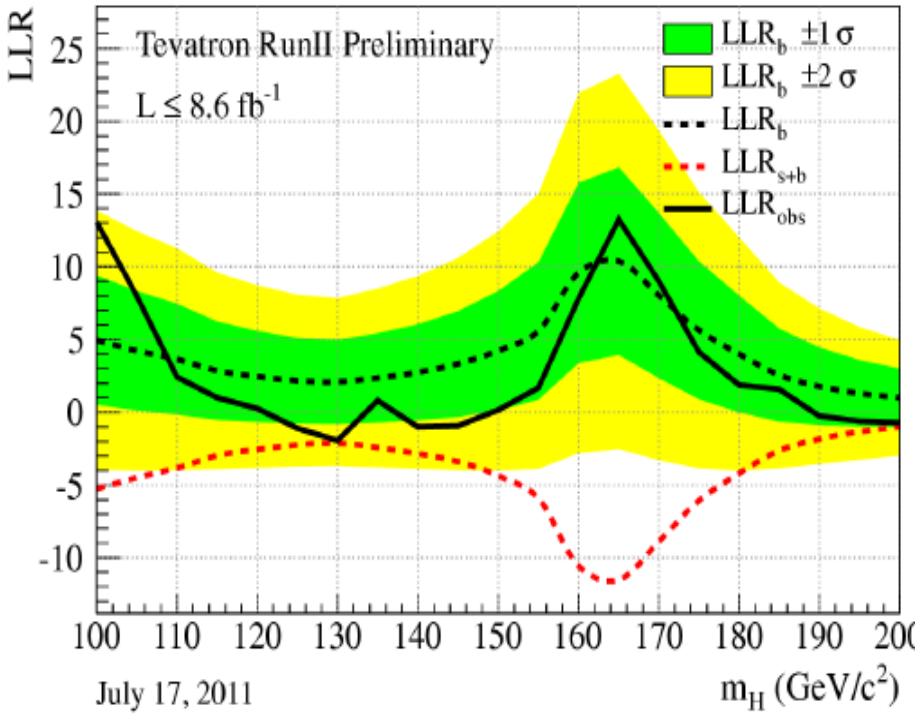
- Upper limits on Higgs production cross sections derived at 95% C.L. from a combination of relevant channels, assuming the SM prediction for ratio of cross sections and branching ratios.
- All experiments use
  - A "CL_s method" (a-la Tevatron or a-la LHC; see A. Read's talk)
  - State-of-art theoretical predictions and related uncertainties (for the most part)



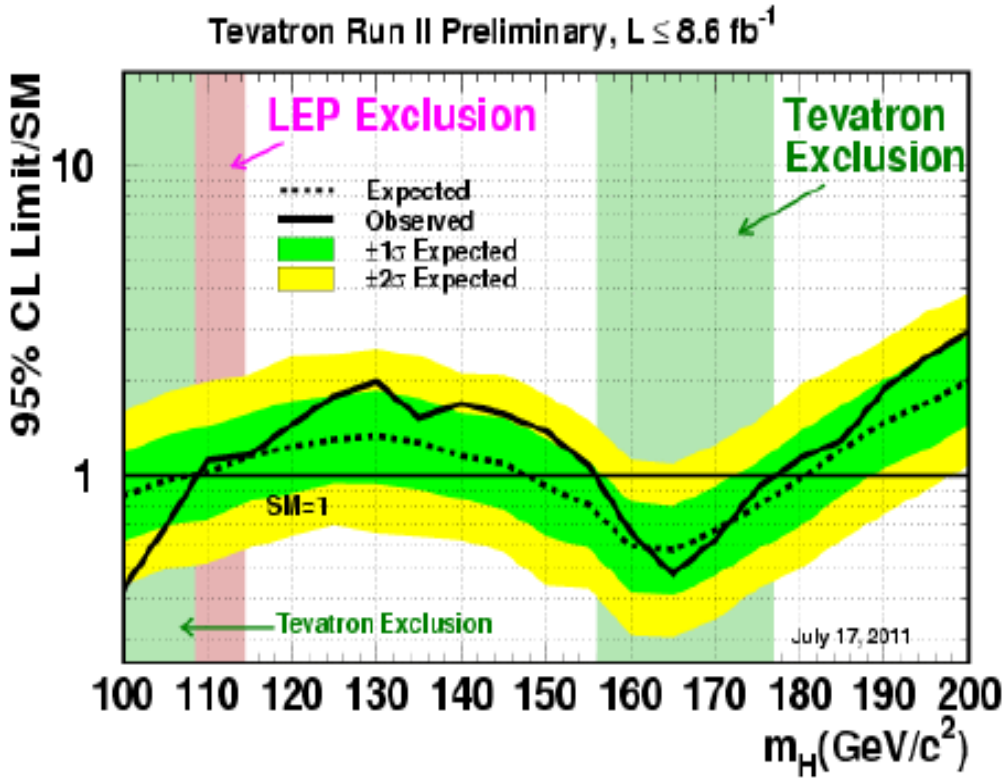


Tevatron Combination

B. Kilminster



G. Davies



- Most signal-like excess
  - Consistent with 130 GeV Higgs

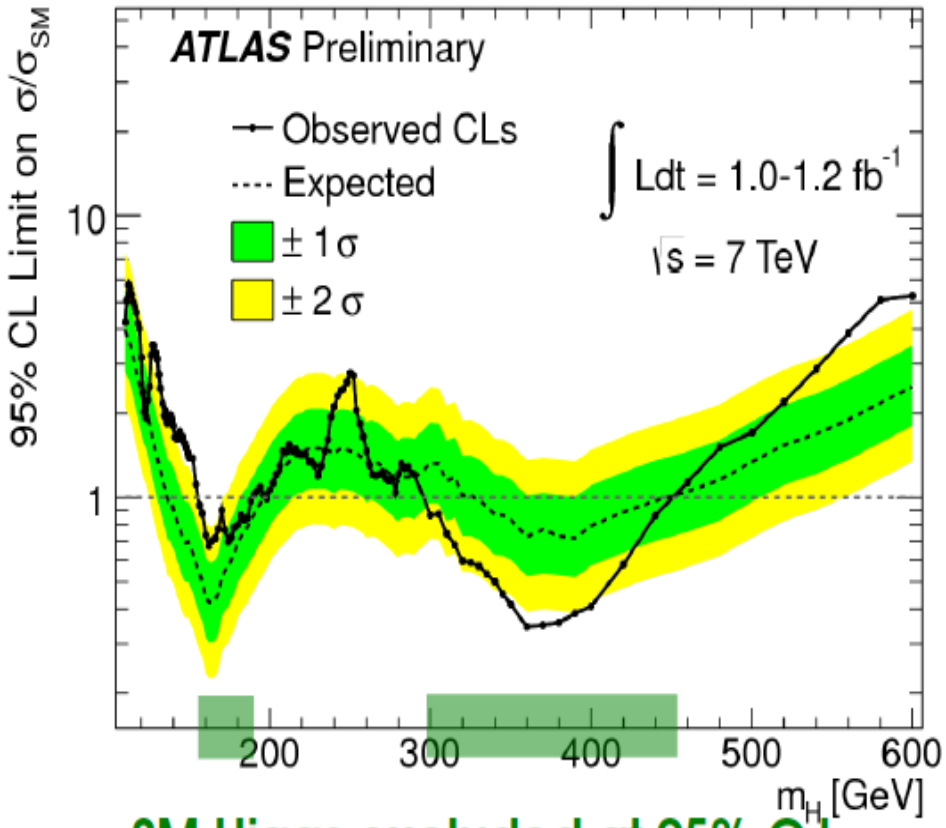
SM Higgs excluded @ 95% C.L.

$156 < m_H < 177$ GeV obs ($148 < m_H < 180$ GeV exp)

$100 < m_H < 108$ GeV obs ($100 < m_H < 109$ GeV exp)

LHC Combinations

A. Read

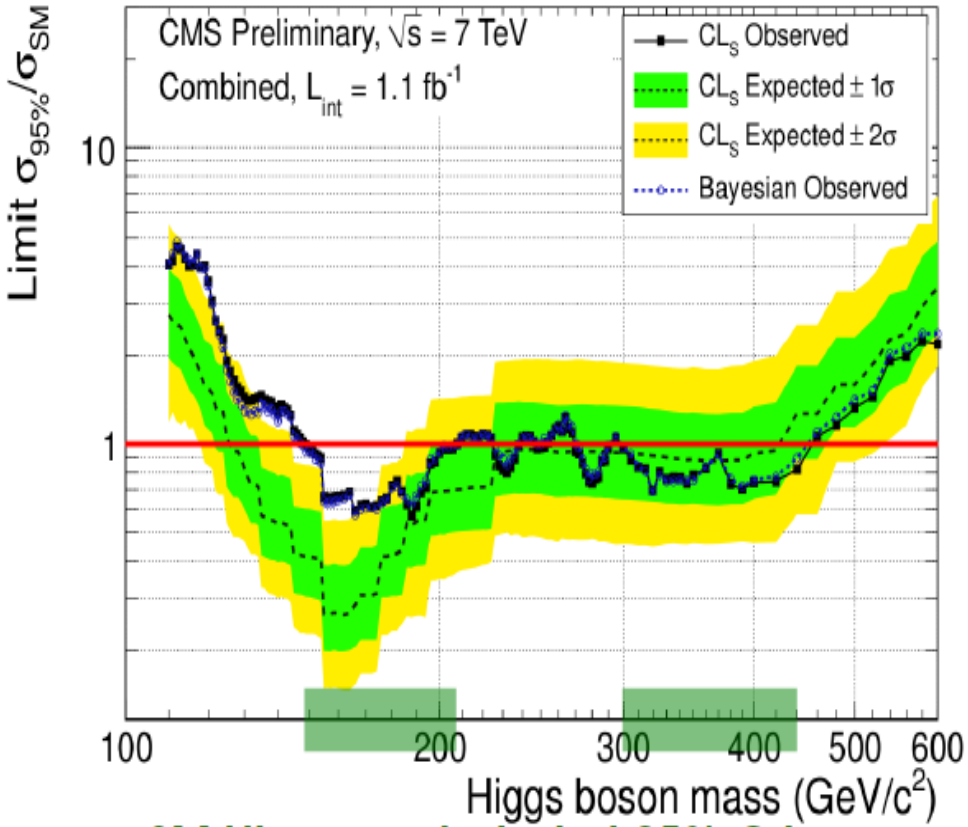


SM Higgs excluded at 95% C.L.

$155 < M_H < 190$ GeV

$295 < M_H < 450$ GeV

J.D. Olsen

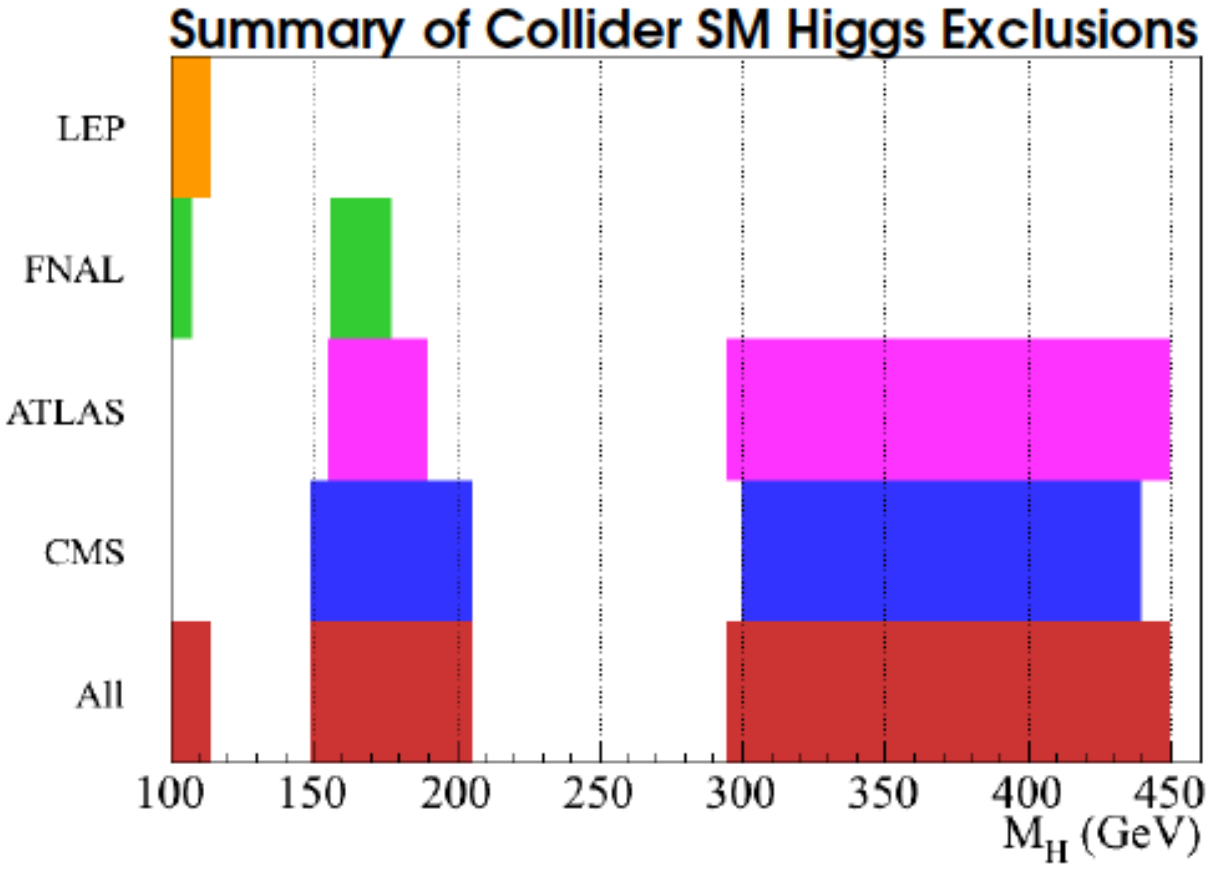


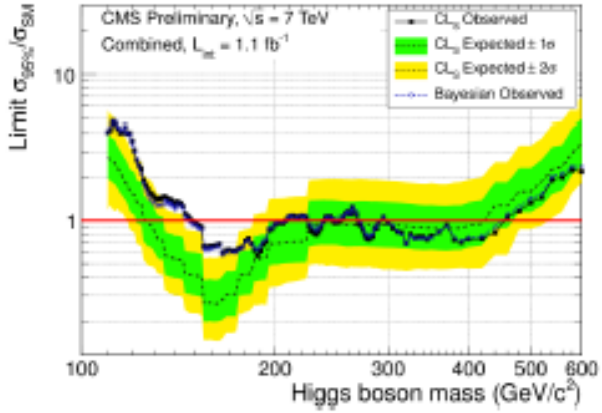
SM Higgs excluded at 95% C.L.

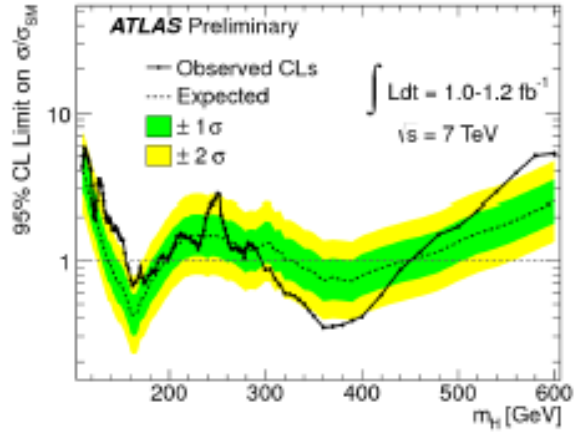
$149 < M_H < 206$ GeV

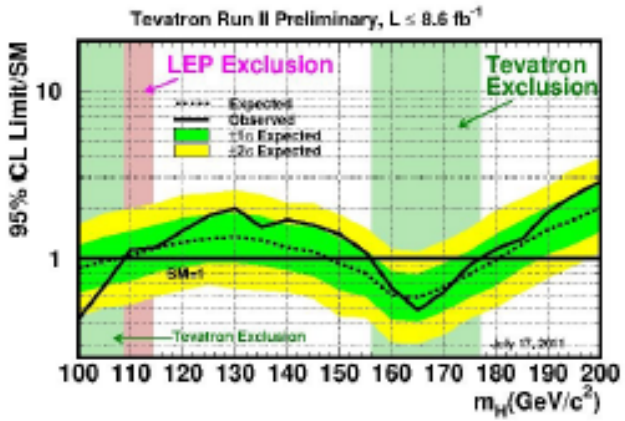
$300 < M_H < 440$ GeV

Summary of Current Limits

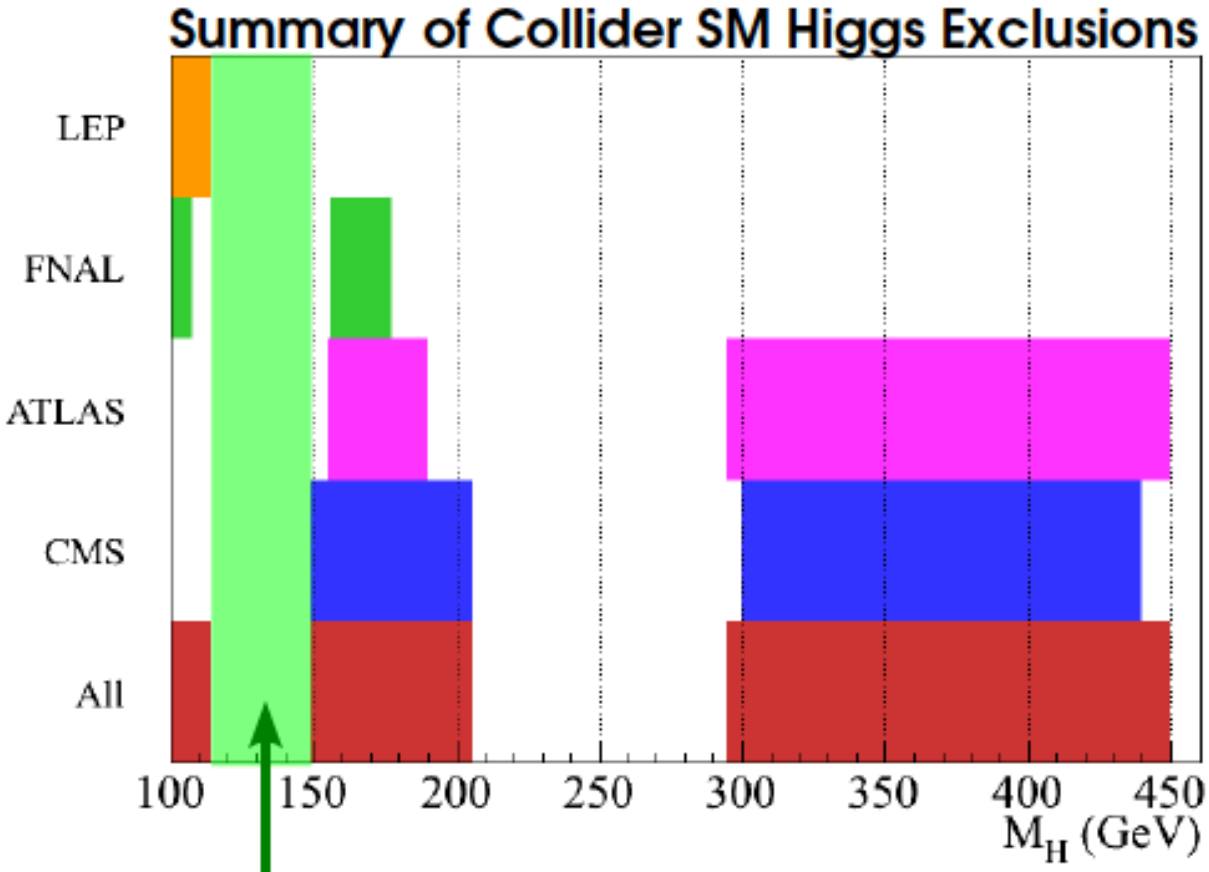




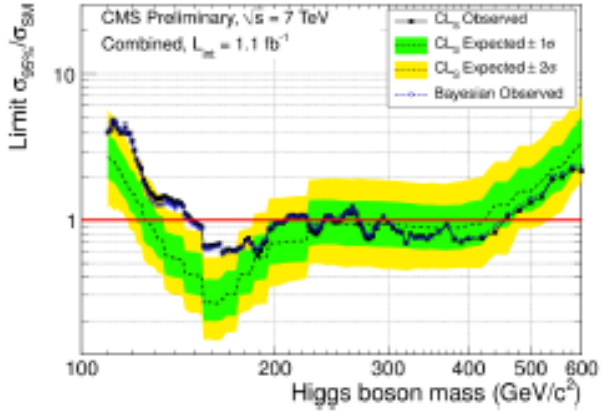


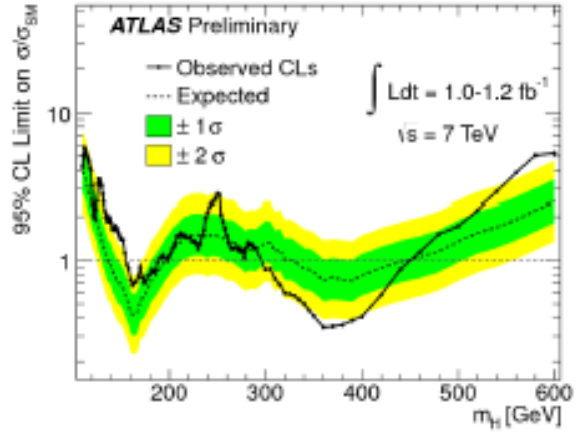


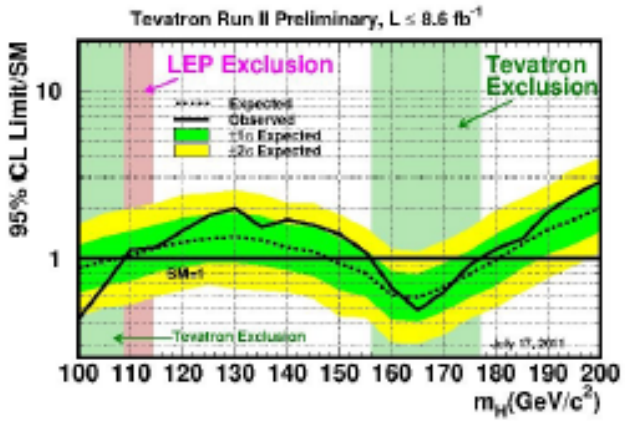
Summary of Current Limits



Region preferred by fit to precision EW data

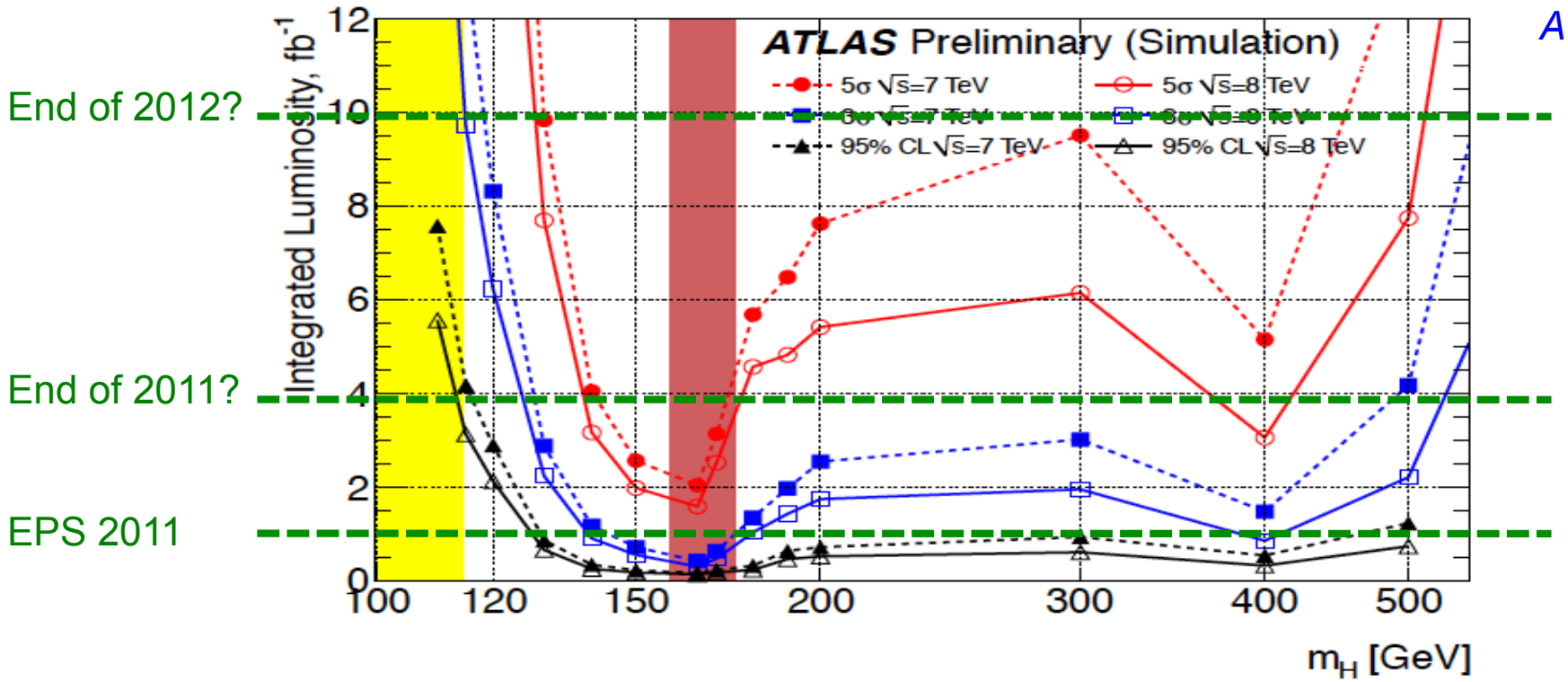






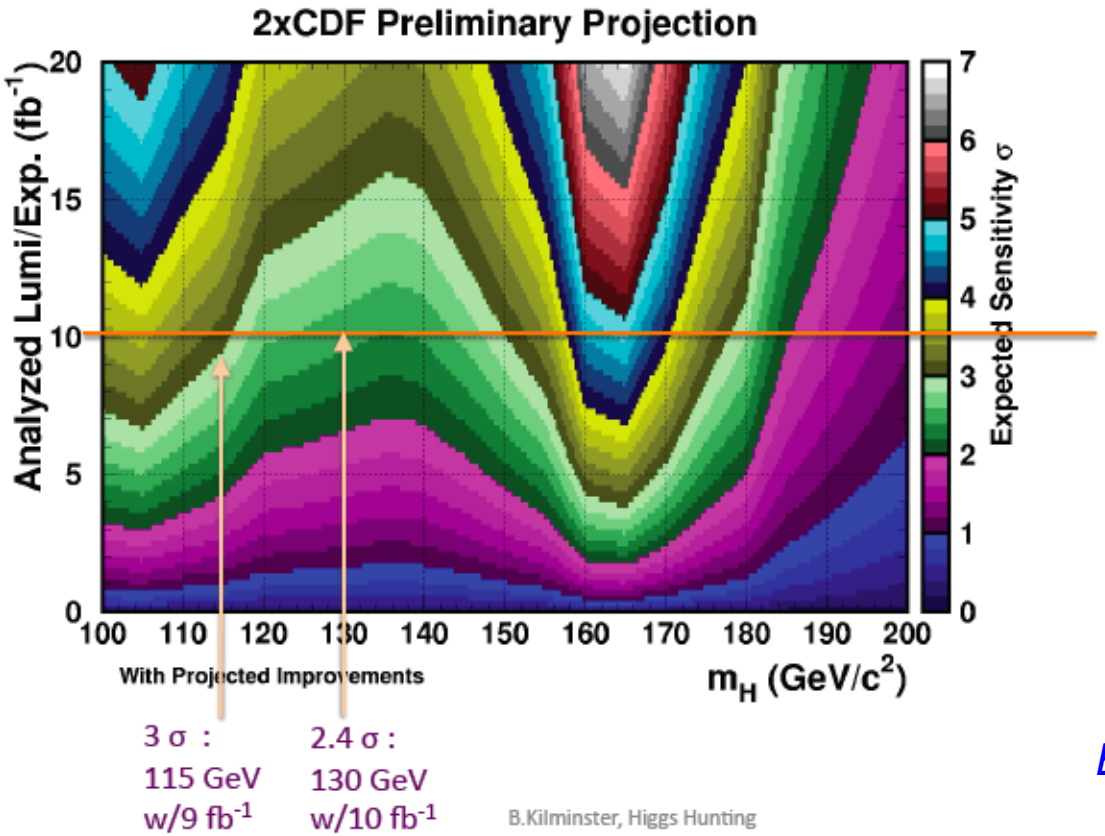
LHC Prospects

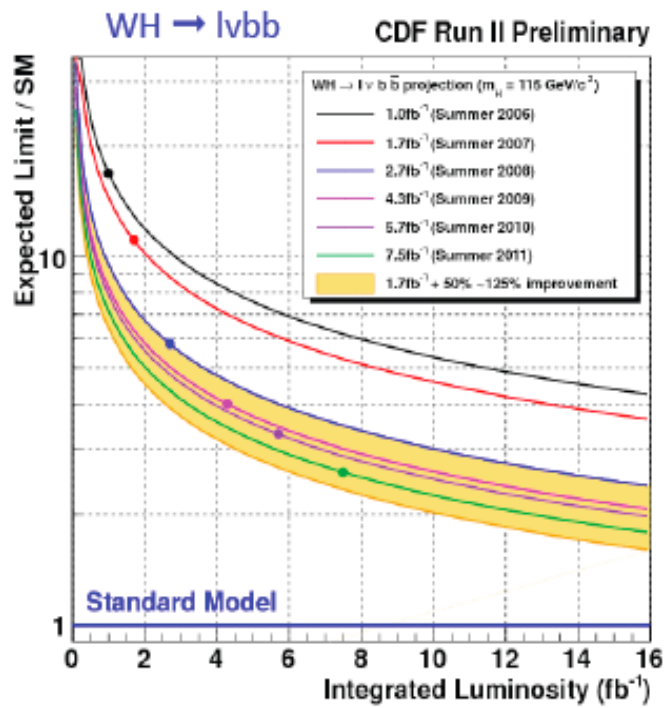
A. Mehta



- Limits can be improved by reducing systematics and optimizing selections
- Further gain can be made by adding more channels
- Biggest gain will be made by increased luminosity
- Futher improvements if LHC can run at higher beam energy
- Combining ATLAS and CMS should have a 5σ discovery potential with 10 fb^{-1} of data per experiment at $\sqrt{s} = 8$ TeV over entire mass range

Tevatron Prospects



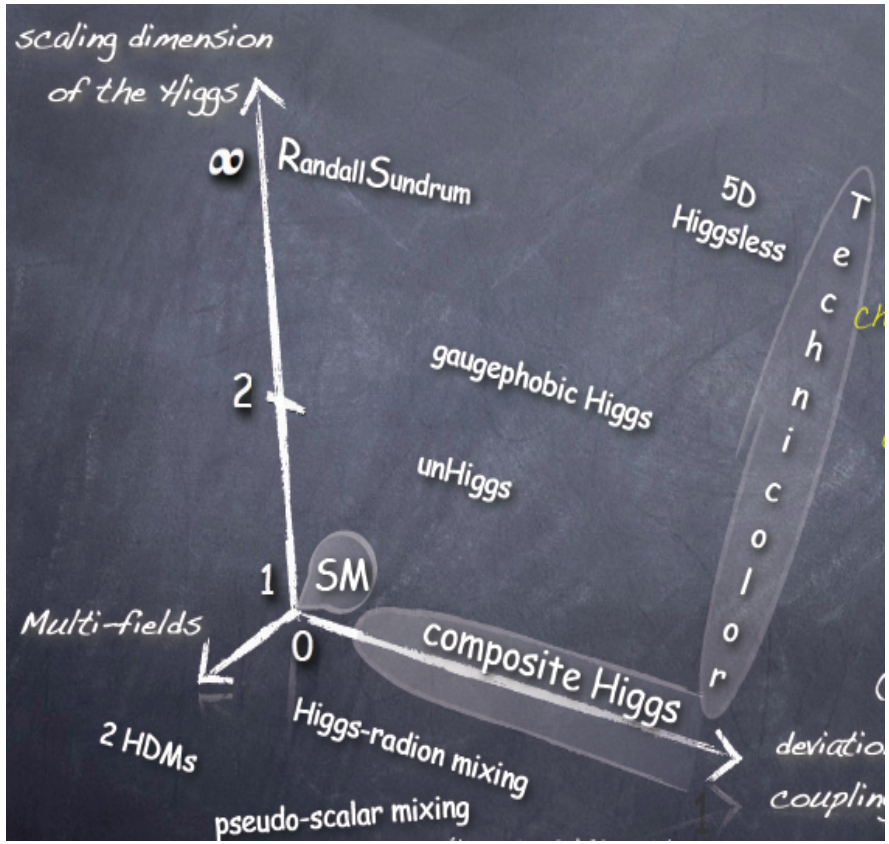


B. Kilminster

- Tevatron important at low mass 115 – 125 GeV
  - Best current limits at 115 GeV
  - Unique window to Higgs of H→bb
  - Sensitivity continues to improve
- Tevatron important in 130-140 GeV region
  - H→WW analyses sensitive to different signals and backgrounds than LHC
    - LHC – Tevatron agreement paints a consistent picture

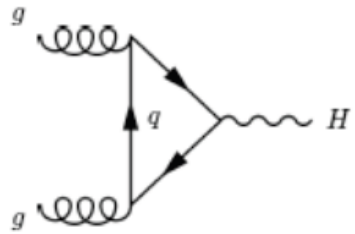
Full dataset including additional improvements should be analyzed by Spring/Summer 2012!

Beyond the SM Higgs



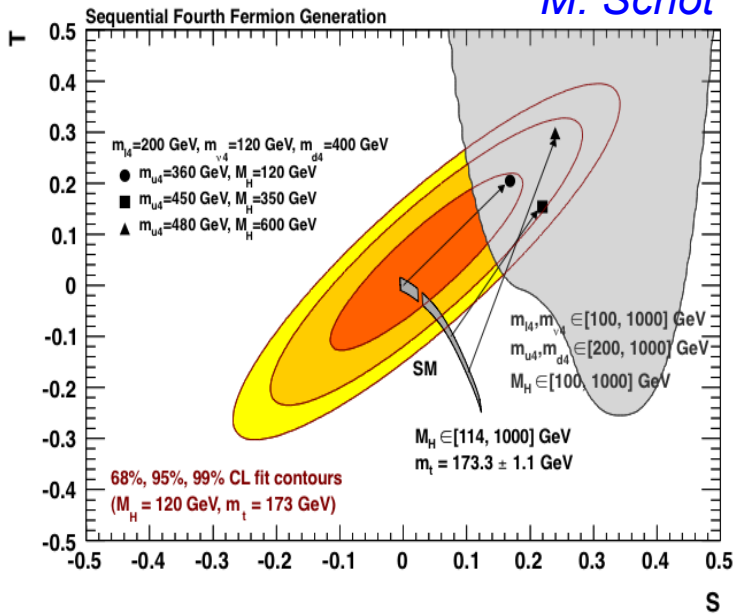
Higgs in 4th Generation Models

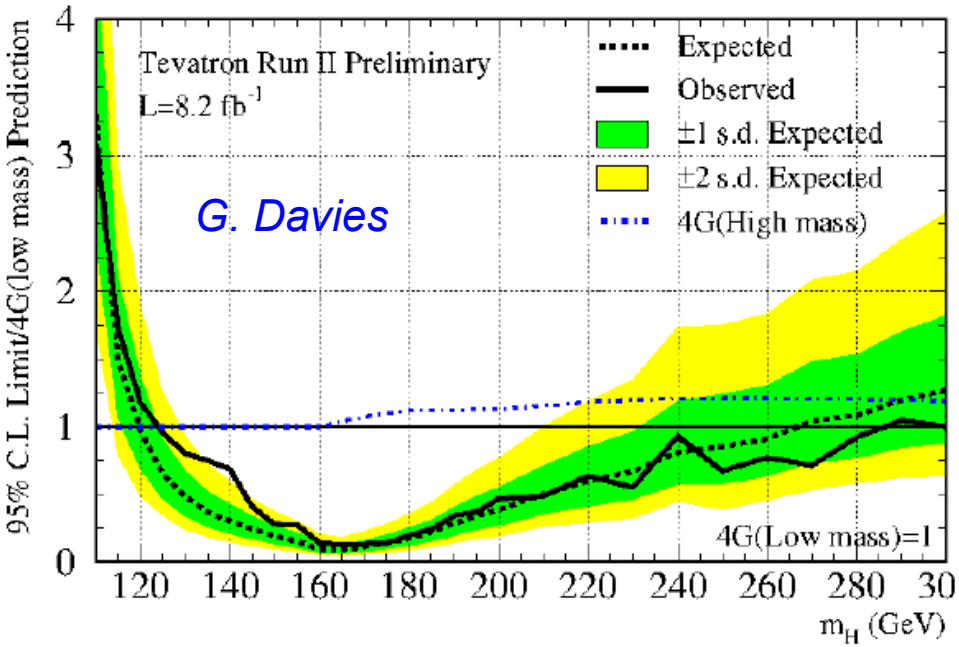
- Sequential 4th generation of fermions consistent with precision EW data. Higgs naturally heavy.
- Additional quarks enhance by x3 ggH coupling.

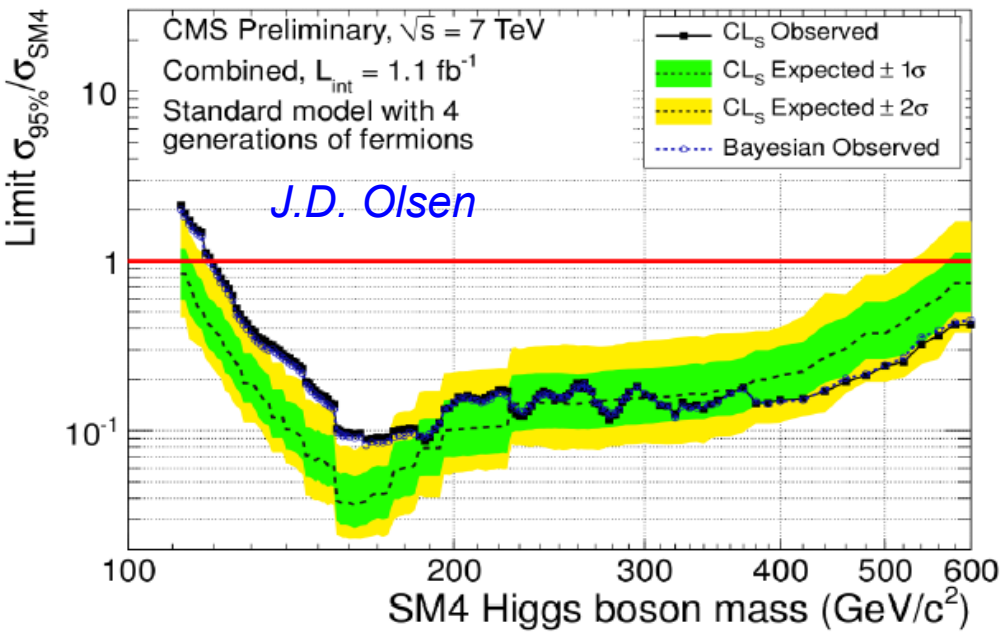


- Higgs production cross sections:
  - gg→H enhanced by ~x9-7 for m_H~ 100-300 GeV
  - VH and VBF remain at SM rate.

M. Schot



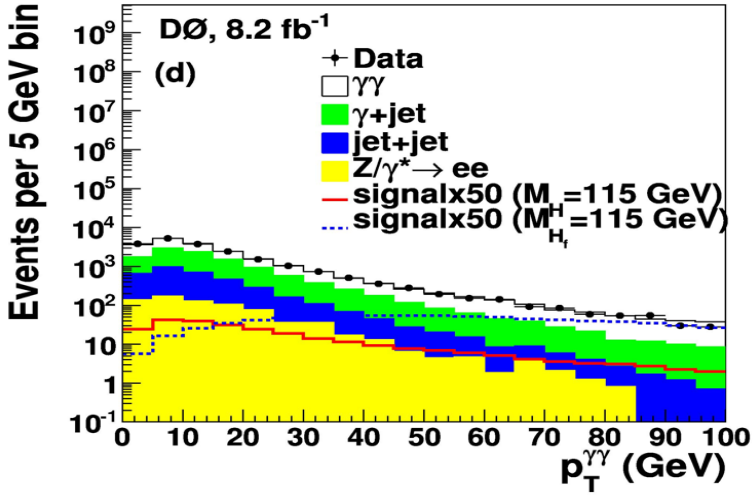


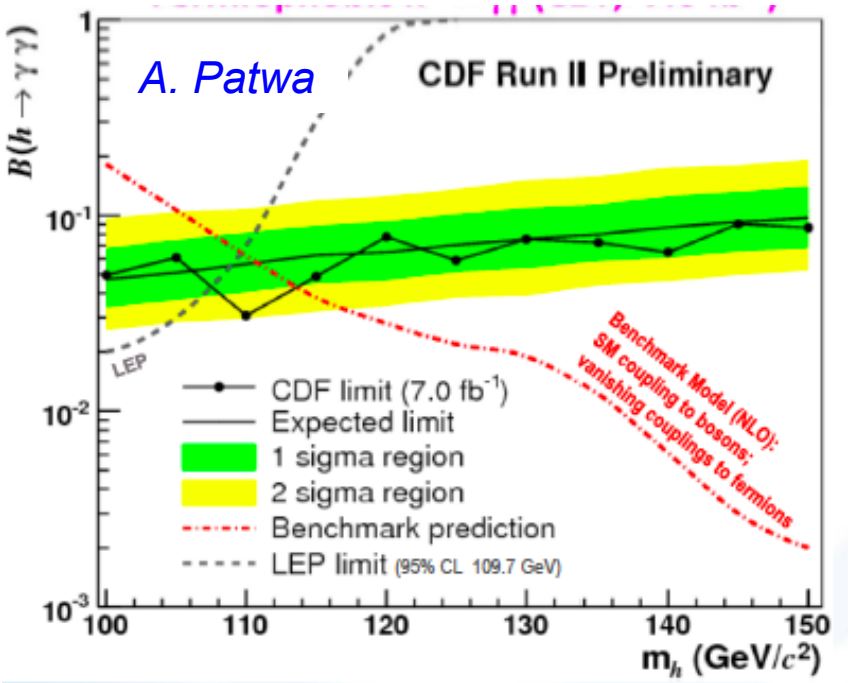


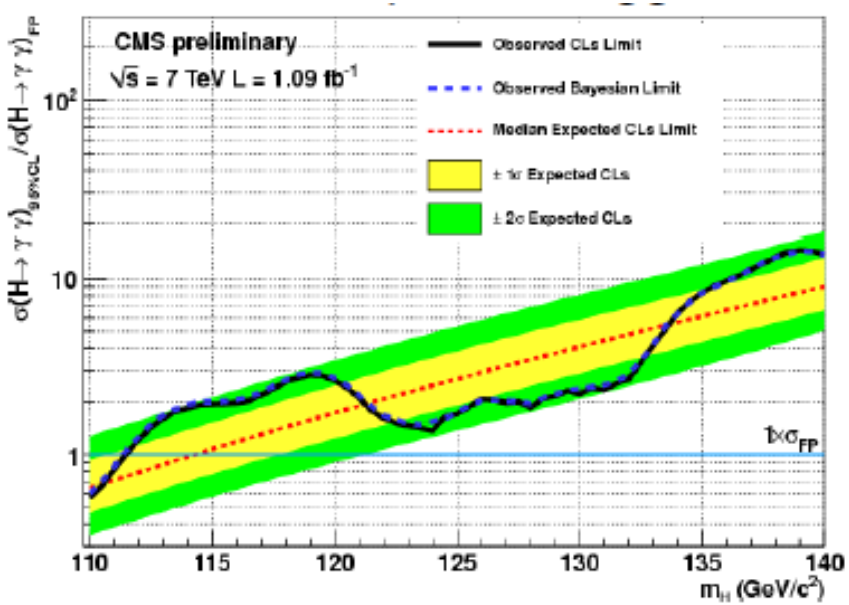
Fermiophobic Higgs (H→γγ)

- Couplings to fermions highly suppressed:
  - Only VH and VBF production
  - Large enhancement in B(H→γγ)

m_{h_f} (GeV)	100	110	120	130	140	150
$BR(H \to \gamma\gamma)$	0.0015	0.0019	0.0022	0.0022	0.0019	0.0014
$BR(h_f \to \gamma\gamma)$	0.18	0.062	0.028	0.019	0.0061	0.0020
$BR(h_f \to \gamma\gamma)/BR(H \to \gamma\gamma)$	120	33	13	9	3	1.4







M. Bluj

- Single experiments already exceeding LEP combined limit (M_{hf}>109.7 GeV @ 95% CL)

MSSM Higgs Bosons

- MSSM: extended Higgs sector (Type II 2HDM model)

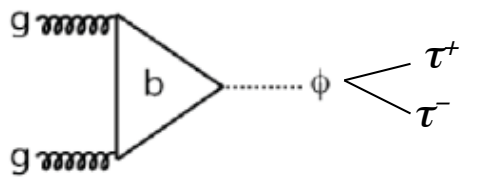
$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$$

  - After EWSB: four massive scalars (h^0,H^0,$H^\pm$) and one pseudo-scalar (A^0).
  - At tree level: parameterized in terms of M_A and $\tan\beta = v_u/v_d$
    Significant impact from radiative corrections on masses and couplings.

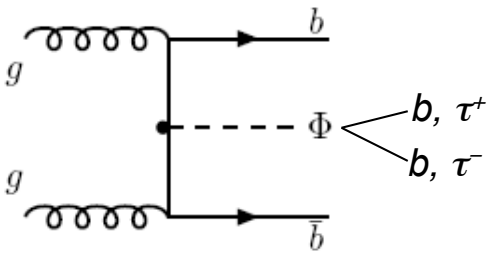
- Neutral Higgs bosons at high $\tan\beta$:
  - Φ^0={h^0/H^0,A^0} nearly degenerated in mass
  - Coupling to b, τ enhanced ($\propto\tan\beta$)

$\sigma_{\Phi+X} \sim 2 \times \tan^2\beta \times (\sigma_{\Phi+X})_{SM}$
$BR(\Phi^0\to bb)\sim 90\%$, $BR(\Phi^0\to\tau^+\tau^-)\sim 10\%$

  - Three complementary channels with comparable sensitivity:

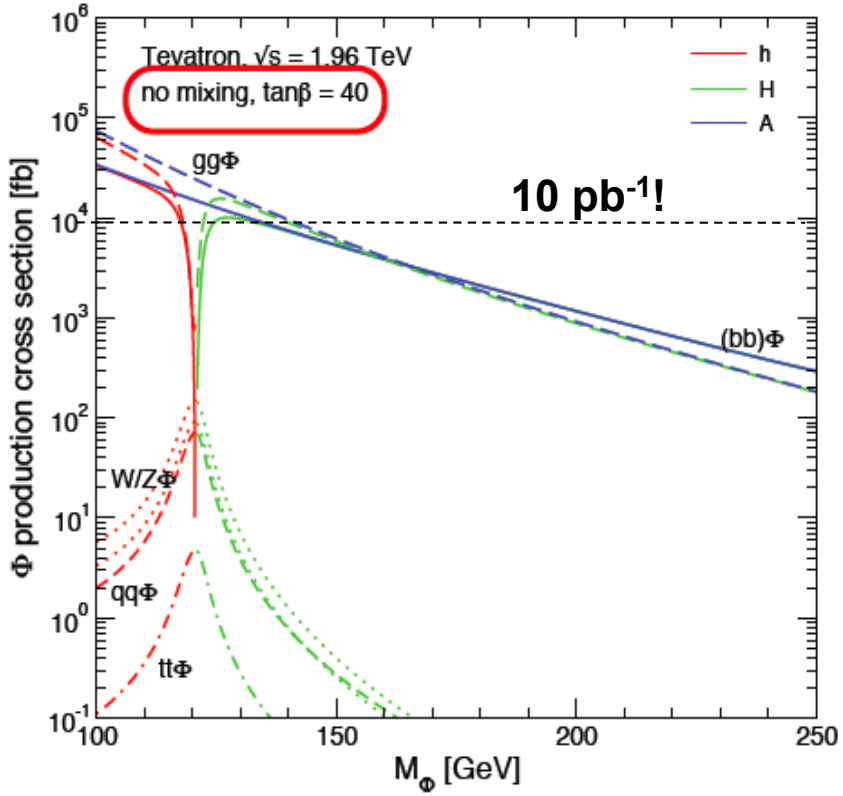


$\Phi^0\to\tau^+\tau^-$



$b(b)+\Phi^0\to bbb(b)$

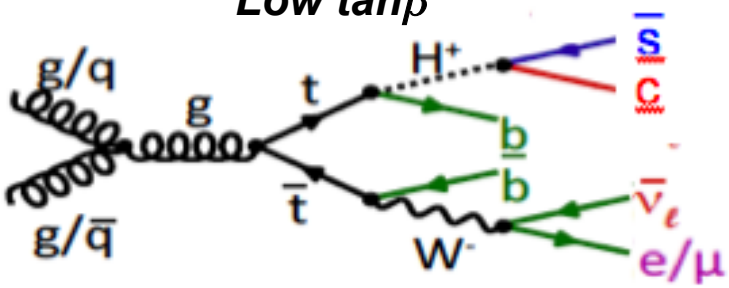
$b(b)+\Phi^0\to\tau^+\tau^-b(b)$



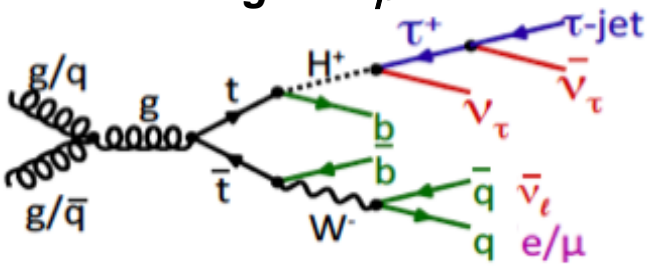
Charged Higgs

- For $m_{H^\pm} < m_t - m_b$, can have significant $B(t \rightarrow H^\pm b)$
  ➔ study kinematics and branching rations in tt events.

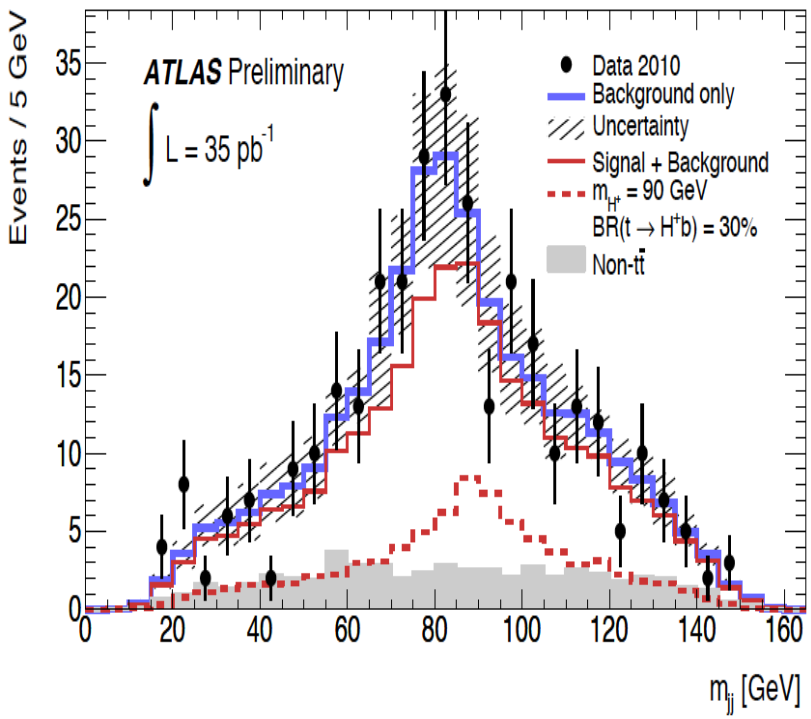
Low tanβ



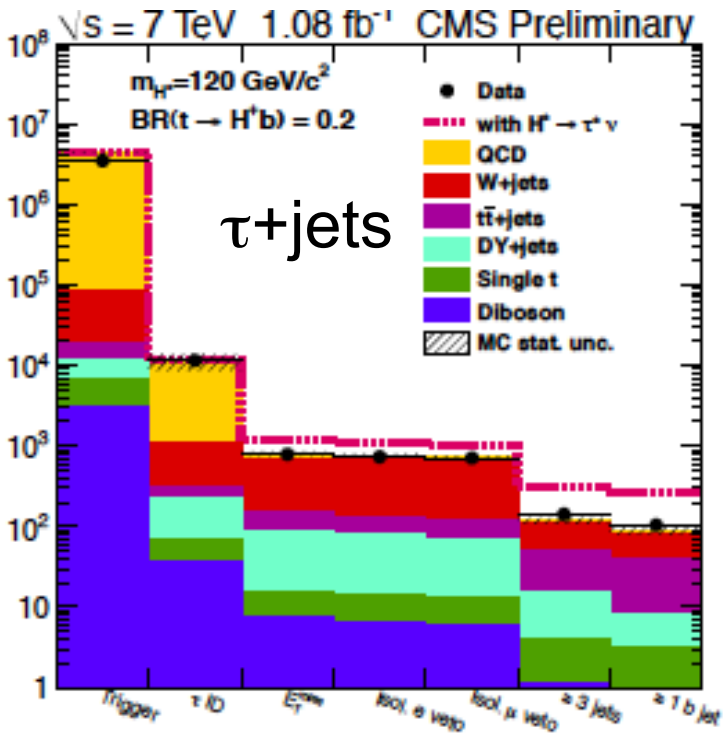
High tanβ



W.F. Mader



E. Friis



Charged Higgs

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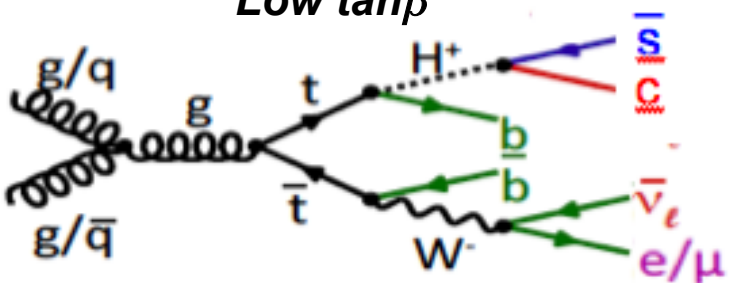
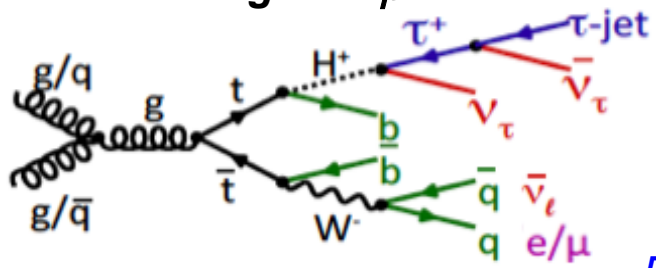
Low tanβ

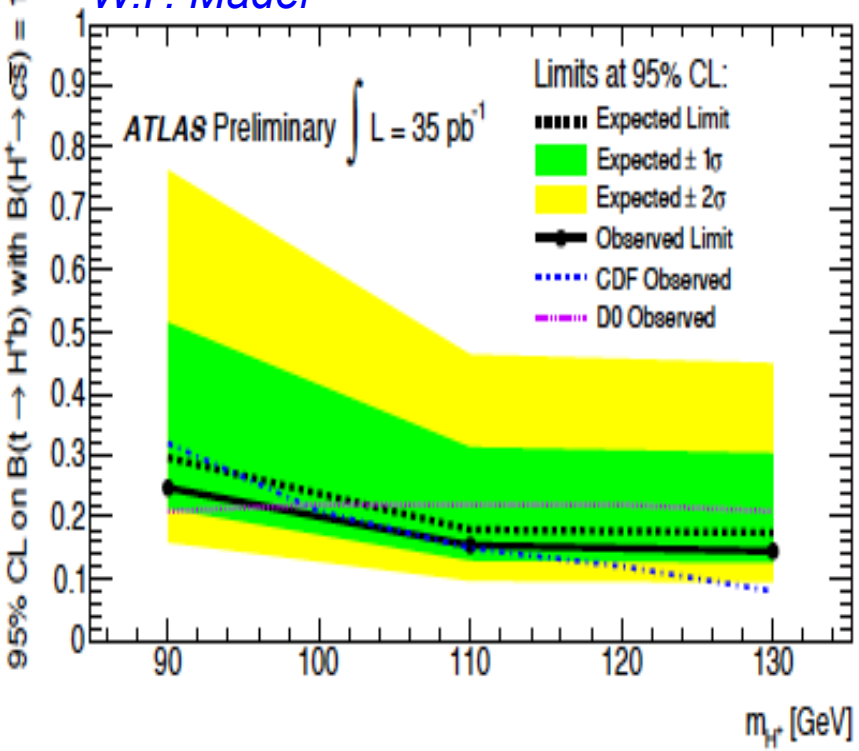


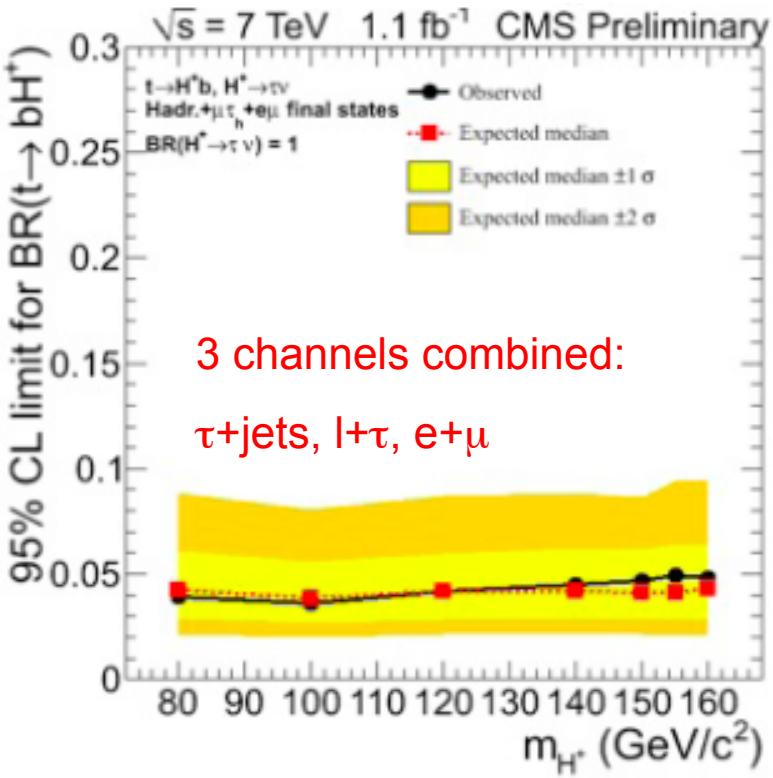
High tanβ



E. Friis

W.F. Mader

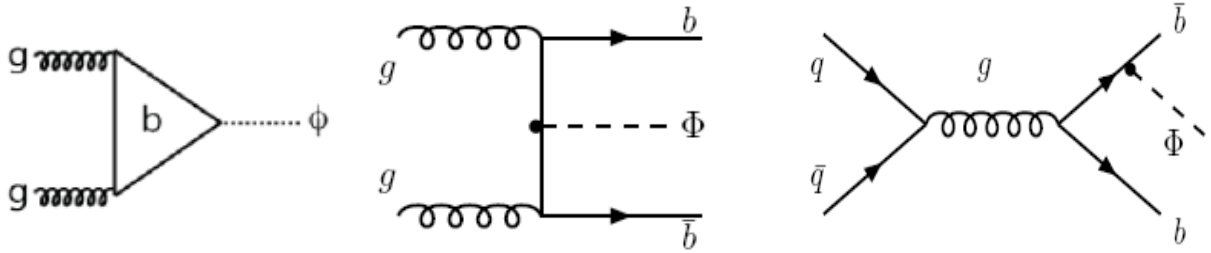




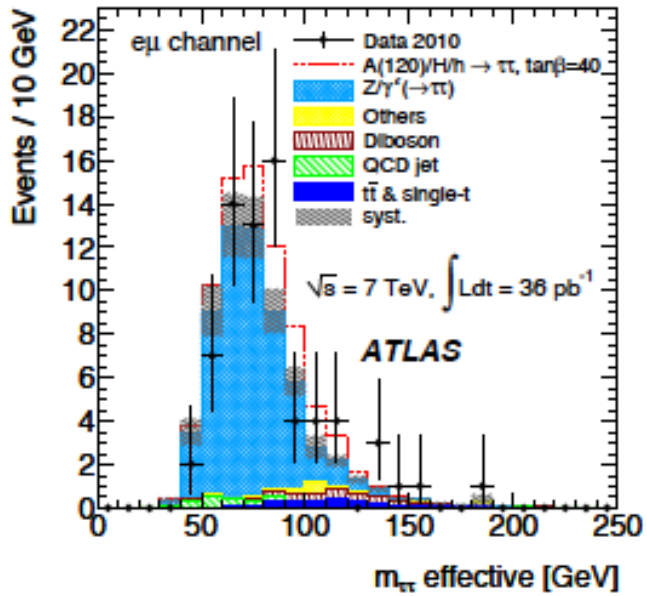
3 channels combined:

τ+jets, l+τ, e+μ

$(b)+\Phi^0 \rightarrow (b)\tau^+\tau^-$

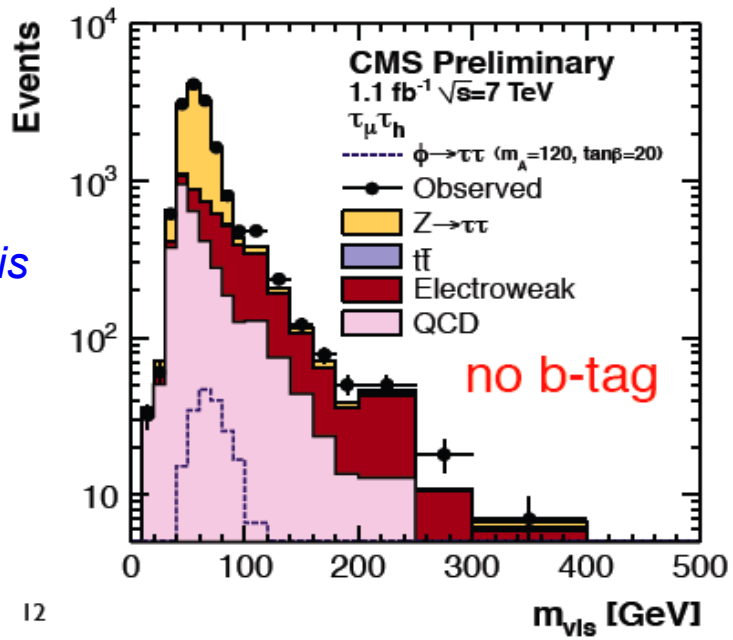


W.F. Mader

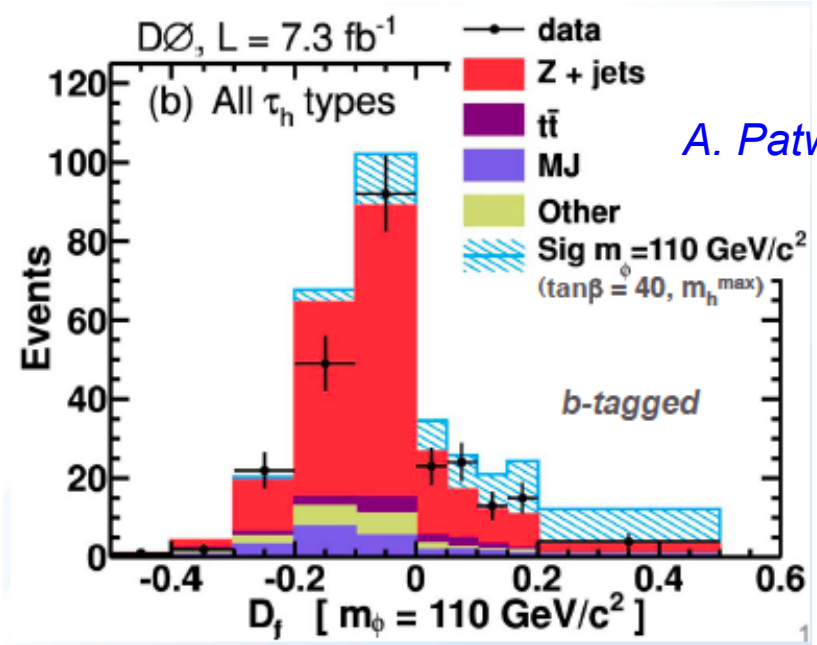


- Require ≥1 leptonic tau decays: $\tau_\mu\tau_{had.}$ $\tau_e\tau_{had,}$ $\tau_e\tau_\mu$, $\tau_\mu\tau_\mu$.
- Inclusive and exclusive (assoc. production) analyses involve different diagrams.
- Also differently sensitive to backgrounds:
  - No b-tag: $Z \rightarrow \tau\tau$ dominates
  - B-tagged: ttbar dominates

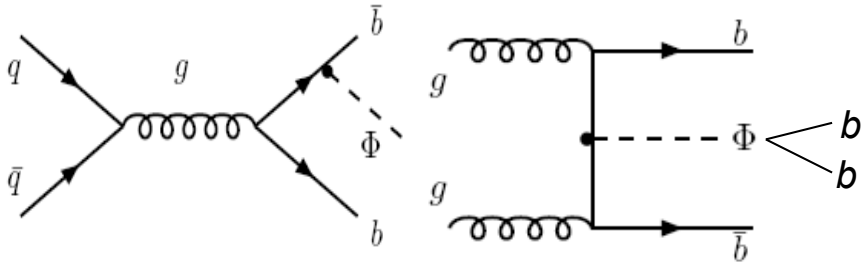
E. Friis

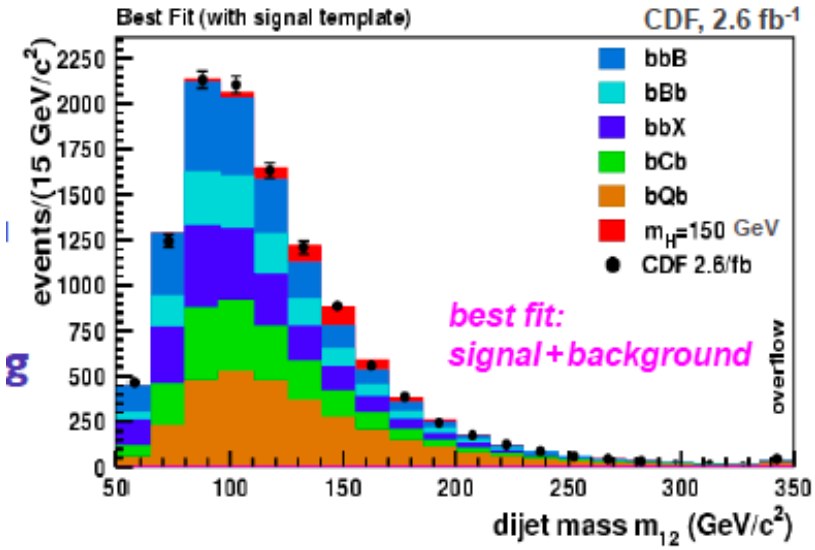


A. Patwa



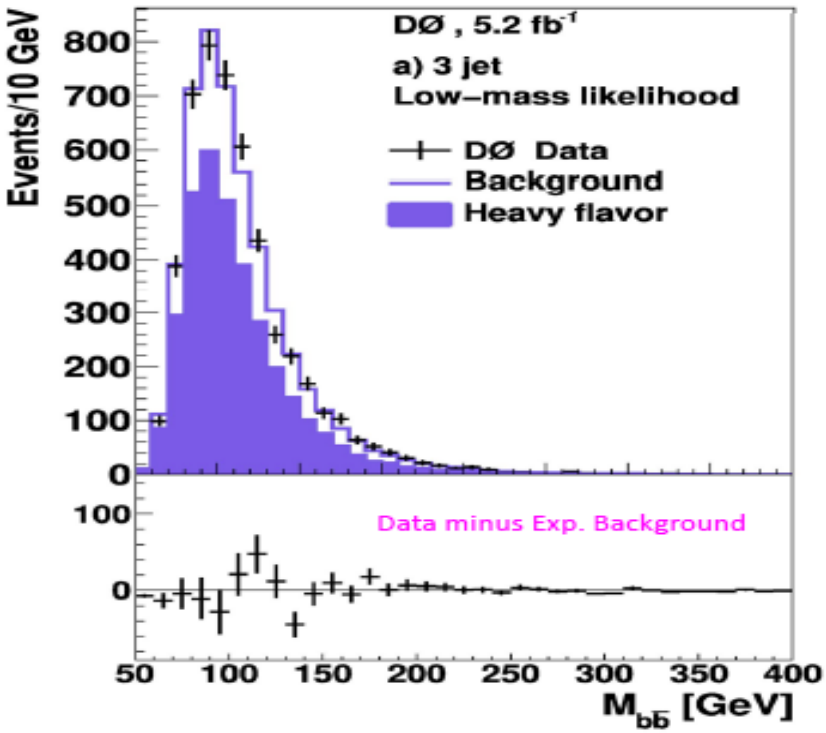
$b(b)+\Phi^0 \rightarrow bbb(b)$





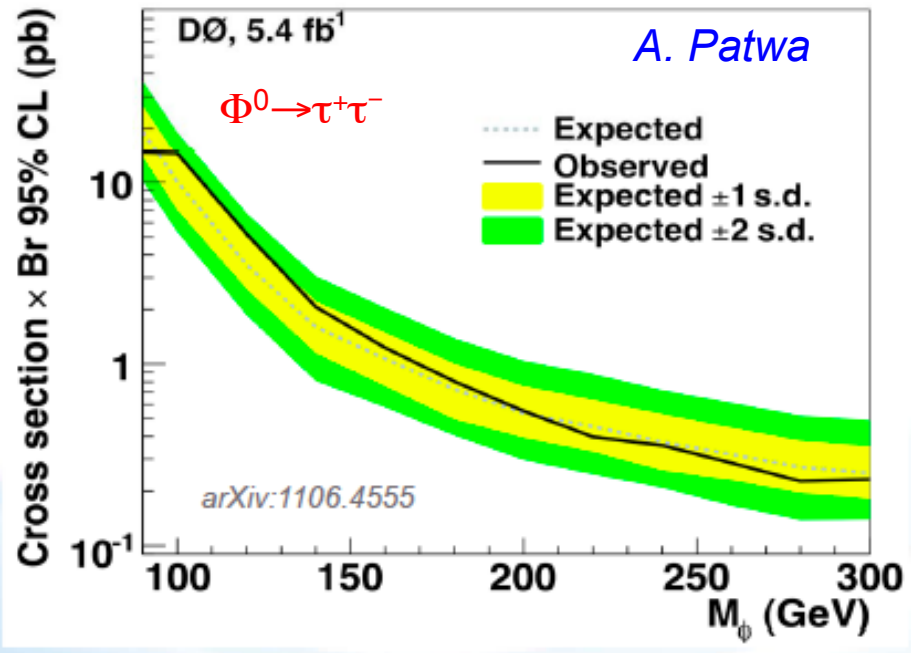
- Experimental signature:
  - 3, 4 or ≥5 jets; ≥3 b-tags
  - Invariant mass of leading two jets peaks at M_Φ

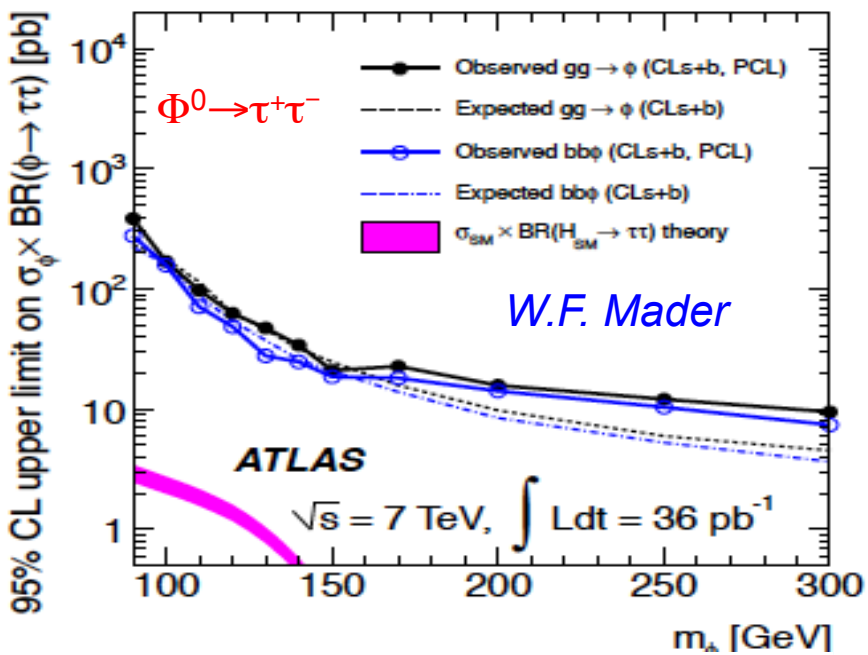
- Backgrounds dominated by heavy flavor-enriched QCD multijets:
  - Composition estimated from data
  - Shape extracted from 2-tag sample or MC simulation
  - Rate normalized outside the "signal region"

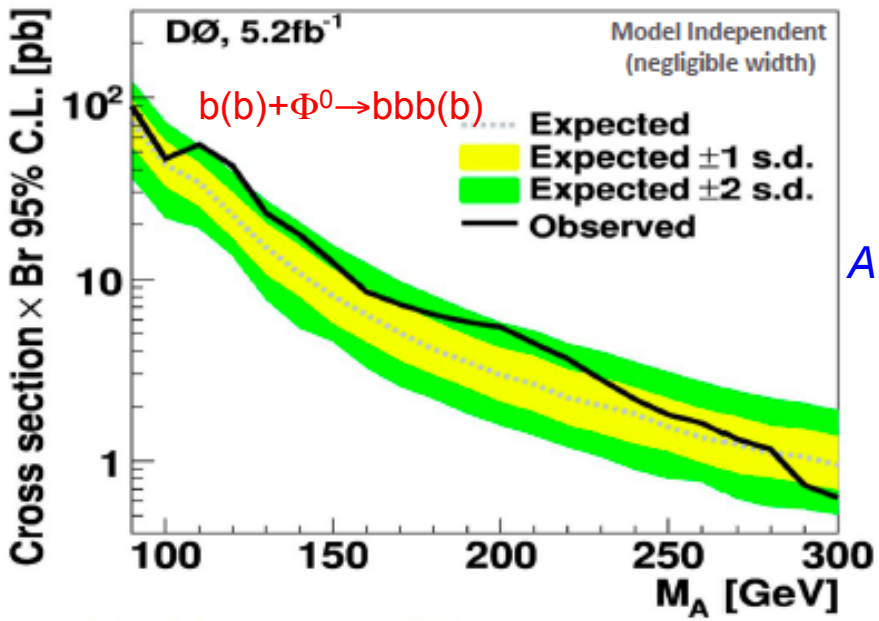


A. Patwa

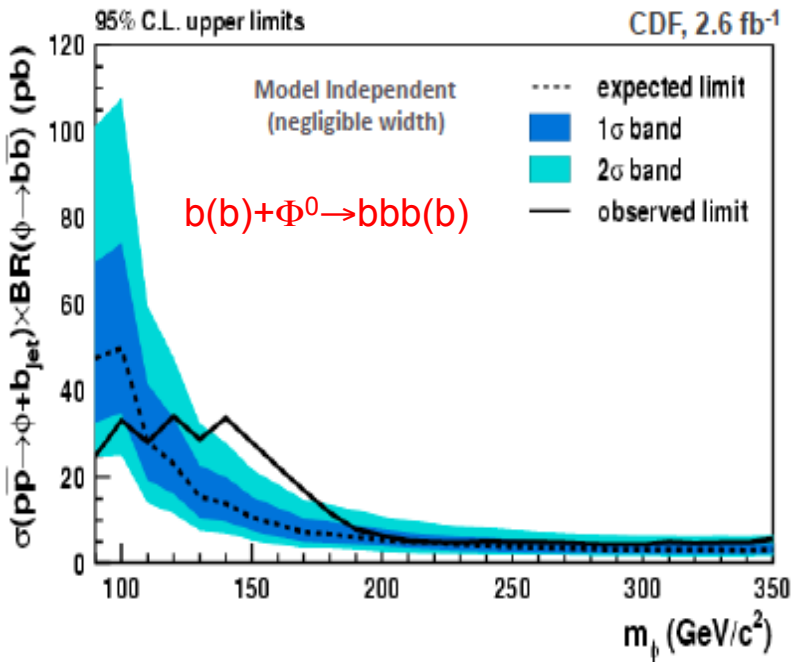
Quasi-Model Independent Limits



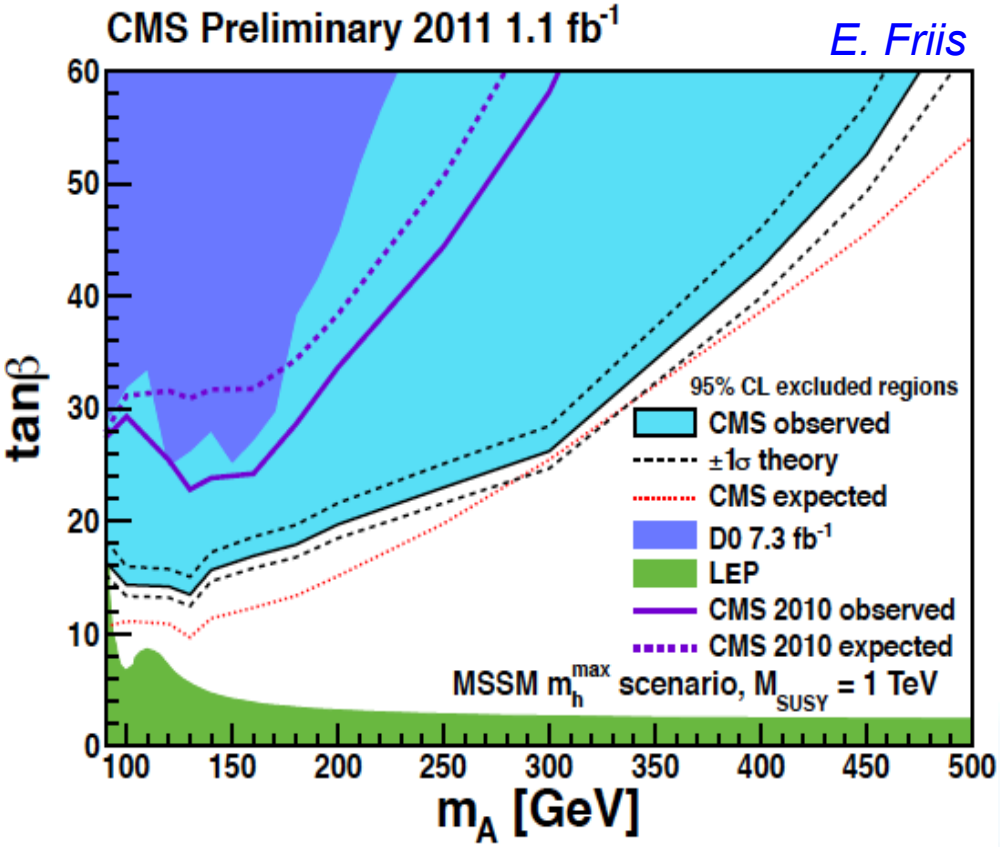




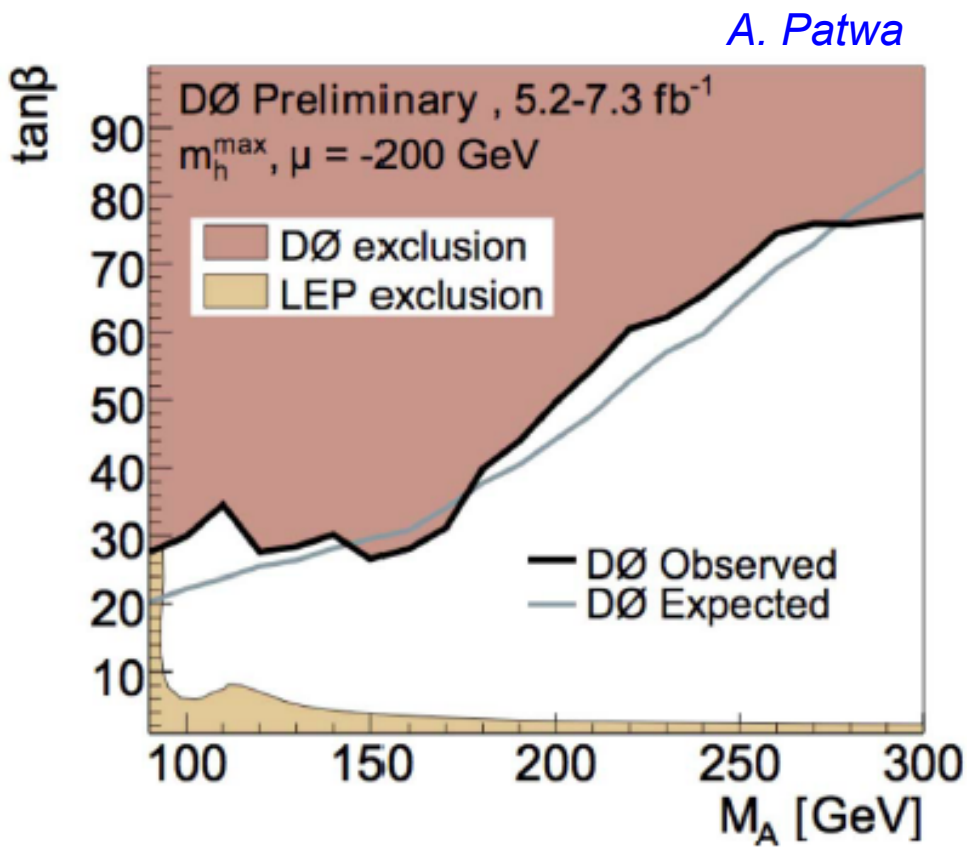
A. Patwa



Interpretations within MSSM



Combination of $H^{\pm}$ and $(b)\Phi^0 \rightarrow (b)\tau^+\tau$



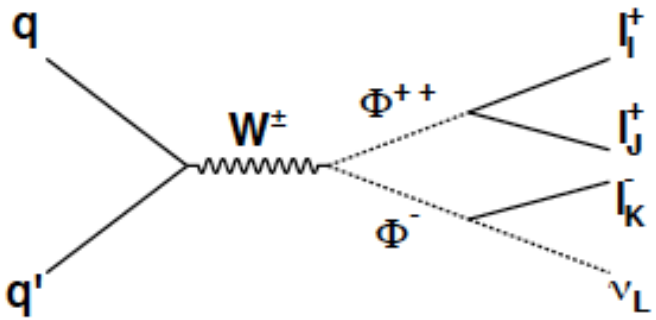
Combination of $b\Phi^0 \rightarrow b\tau\tau$ and $b\Phi^0 \rightarrow bbb$

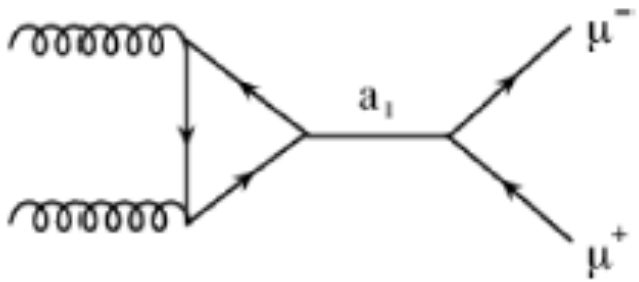
Already probing below "interesting" tanβ~30 region over wide mass range!

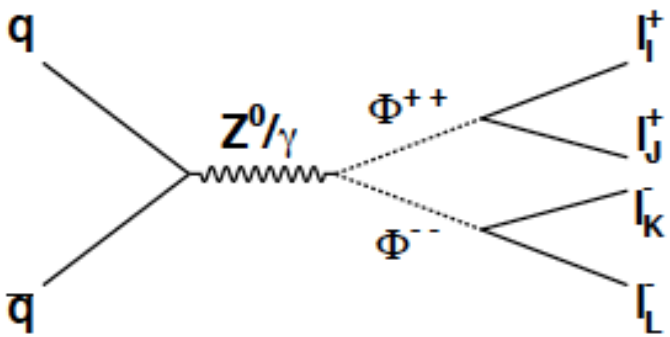
And Beyond the MSSM…

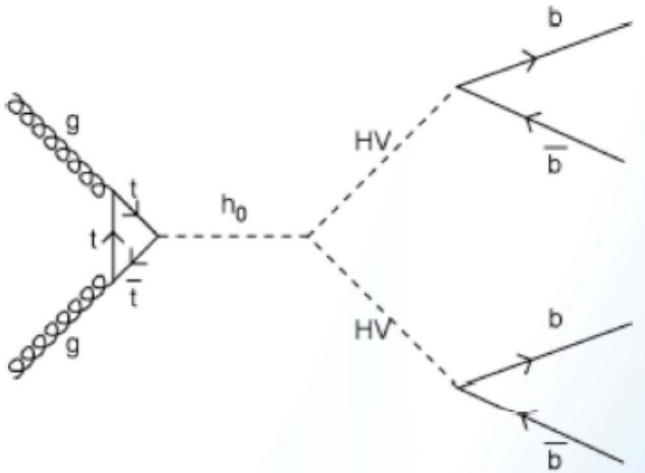
More exotic scenarios being probed ("leaving no stone unturned"):

- Doubly-charged Higgs (from Higgs triplet)
- Light CP-odd scalar (e.g. NMSSM)
- Higgs decaying to Hidden Valley pions
- …





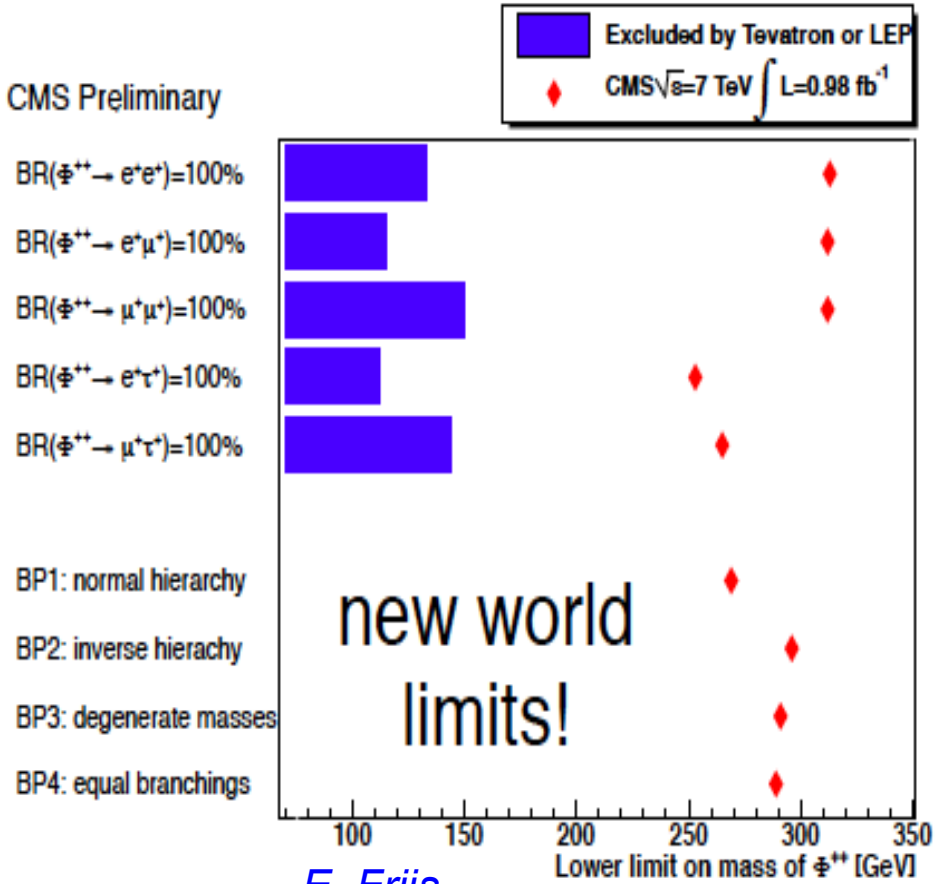




And Beyond the MSSM…

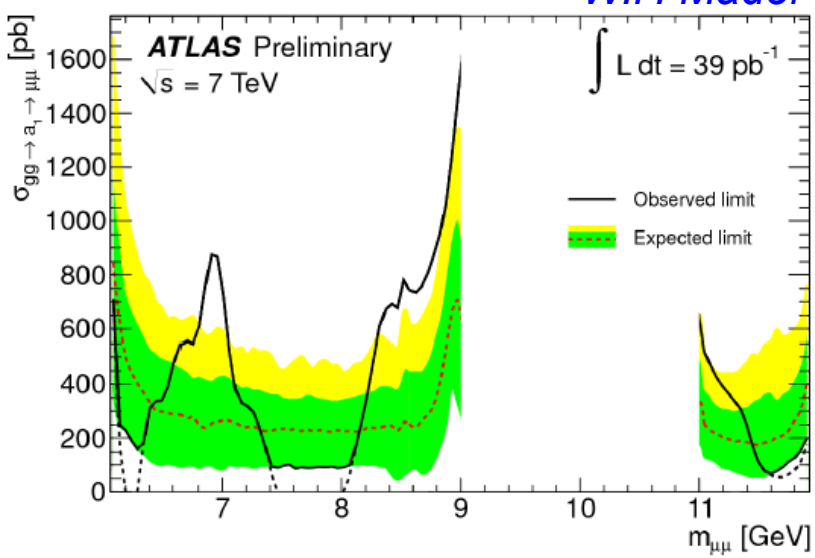
More exotic scenarios being probed ("leaving no stone unturned"):

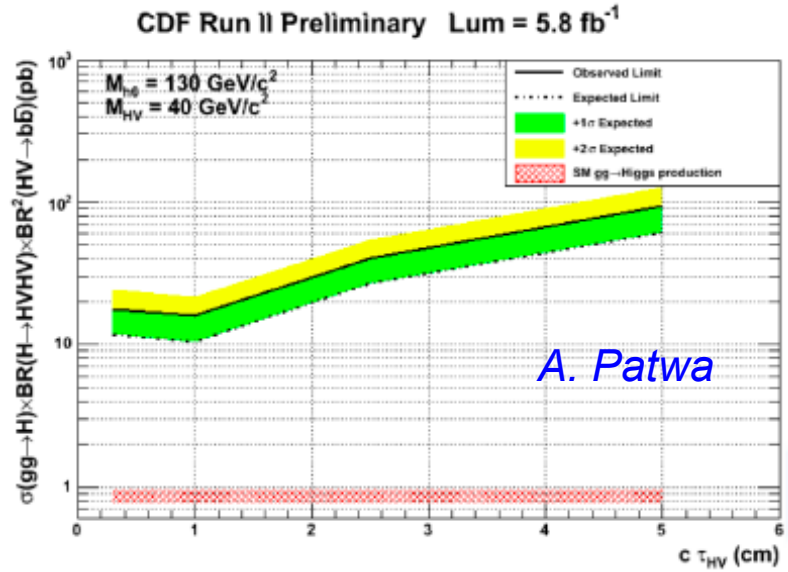
- Doubly-charged Higgs (from Higgs triplet)
- Light CP-odd scalar (e.g. NMSSM)
- Higgs decaying to Hidden Valley pions
- …



E. Friis

W.F. Mader





A. Patwa


What a Ride!

Conclusions

- Many thanks to the organizers for such a nice and productive workshop!
- Many thanks to the speakers for such high quality talks!
  - Fantastic presentations at the Young Scientist Forum!

Conclusions

But specially:

- Many congratulations to the experimental collaborations at the Tevatron and the LHC for the huge effort leading to these exciting results!

- Over the last year we have made major progress in our exploration of EWSB.
- Over the next year we expect to be able to make definite statements about the agent(s) responsible for it.

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But specially:

- Many congratulations to the experimental collaborations at the Tevatron and the LHC for the huge effort leading to these exciting results!

- Over the last year we have made major progress in our exploration of EWSB.
- Over the next year we expect to be able to make definite statements about the agent(s) responsible for it.
- Many of us are hoping it won't be what we were looking for, and we must be prepared not to miss it!