



CMS Higgs Search Results & Prospects

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Fermilab

CMS Collaboration

- ▶ Higgs production mechanism and decay channels at LHC
- ▶ Commissioning of Standard Model objects/processes
- ▶ Higgs results from analysis of 2010 data
- ▶ Prospects and sensitivity projections for 2011–12

Implications of EWSB Workshop, U. Wisconsin, May 7, 2011

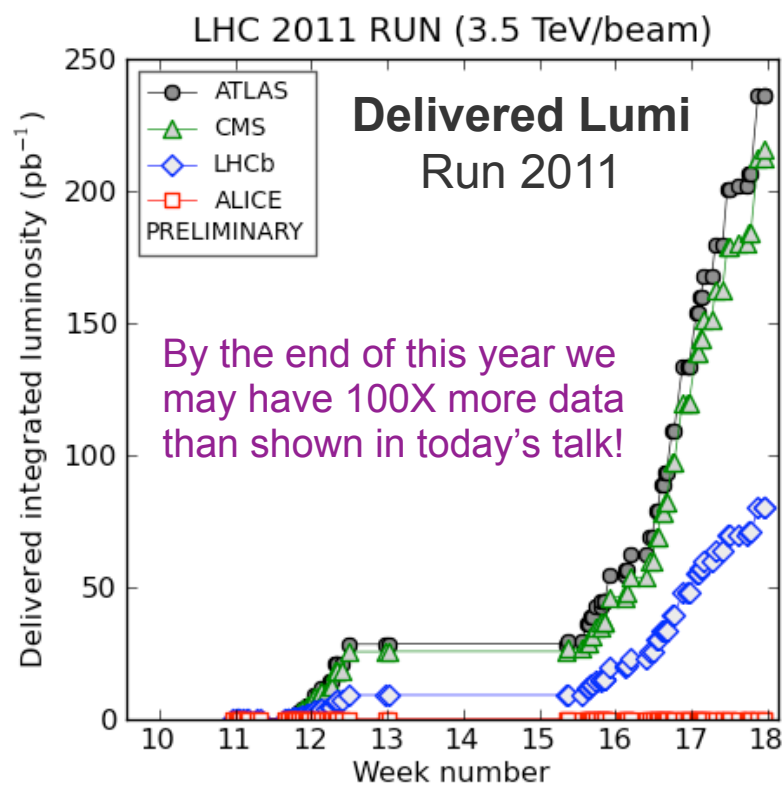
Outlook for 2011 data collection



Outlook is bright

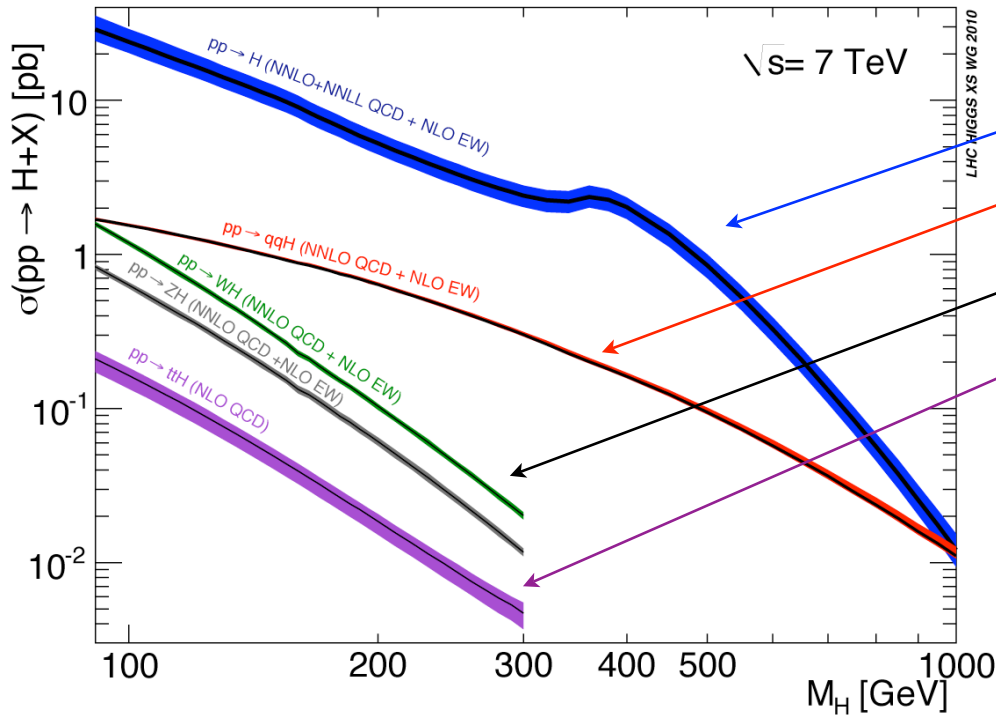
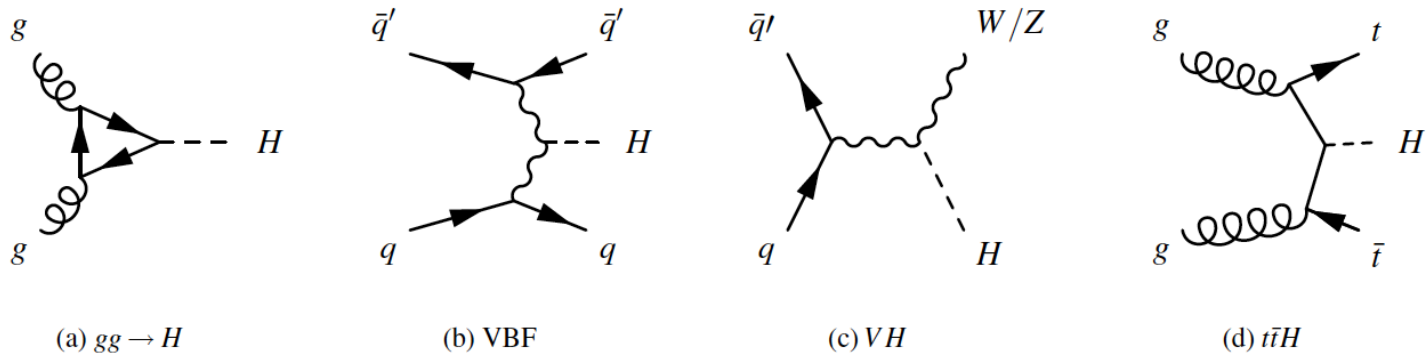
“Official” target:

Deliver at least 1 fb^{-1} per exp at $\sqrt{s} = 7 \text{ TeV}$ by year end. Likely to get lot more.



- **Breaking news:** LHC sets new world record luminosity: **$884 \mu\text{b}^{-1}\text{s}^{-1}$**
 - setting new world record ~every day
- On April 22nd LHC set a new world record for beam intensity at a hadron collider when it collided beams with a luminosity of $467 \mu\text{b}^{-1}\text{s}^{-1}$
 - this exceeded the previous world record of $402 \mu\text{b}^{-1}\text{s}^{-1}$, which was set by the Tevatron in 2010
 - Tevatron surpassed its own record last week: now **$417 \mu\text{b}^{-1}\text{s}^{-1}$**
- Moving to continuous physics running
 - short technical stop in December, then physics run until end of 2012
 - already delivered **0.3 fb^{-1}** per exp.

Higgs production at LHC

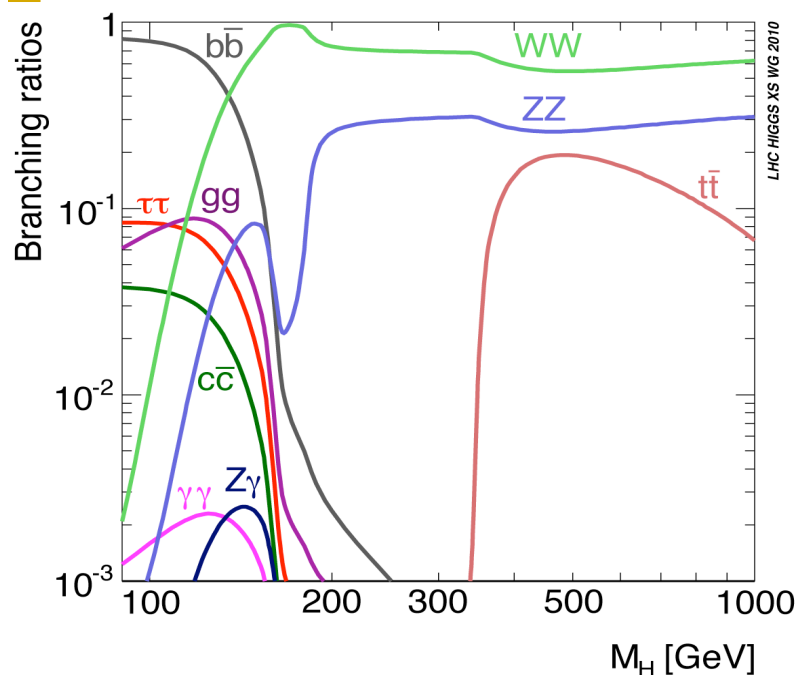


Gluon-gluon fusion
Vector boson fusion
 in association with W,Z
 in association with tt
gg → H is the dominant production mechanism

But this is only a part of the story of Higgs hunt



Higgs decay modes vs its mass



$H \rightarrow bb$ is the dominant if $m_H < 140$ GeV; $H \rightarrow WW, ZZ$ if $m_H > 160$ GeV

BR is the second part of Higgs story

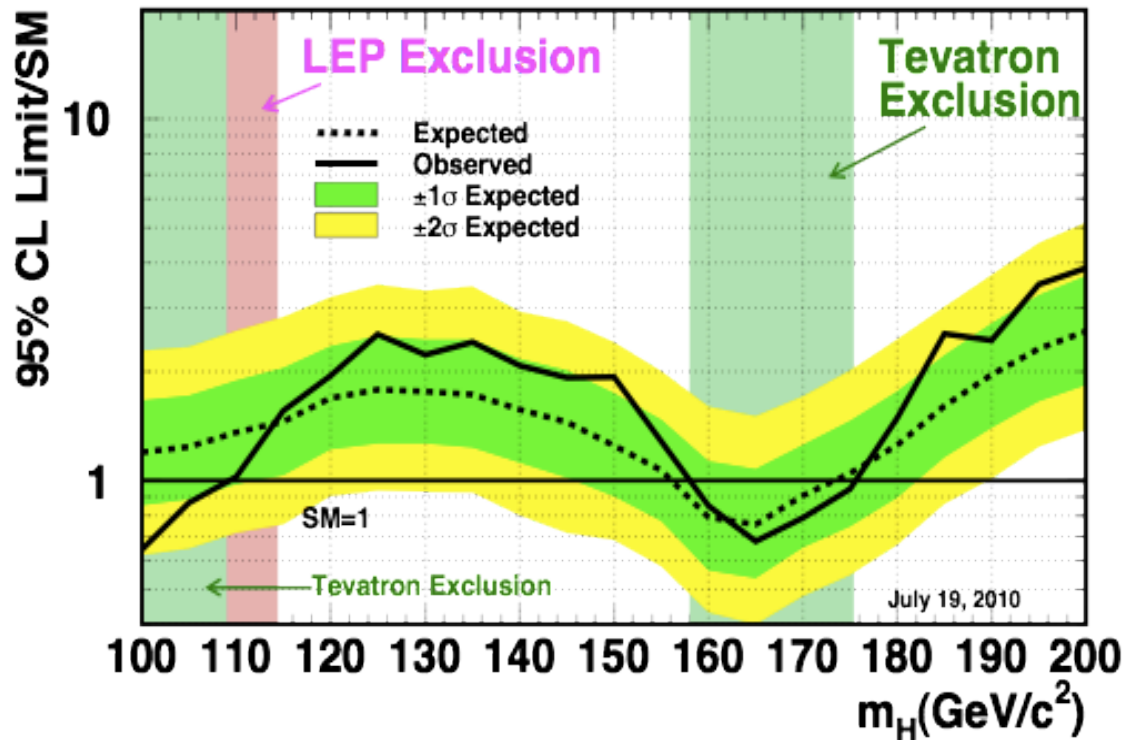
There is very important third part in the story: experimental background.

- ◆ $H \rightarrow bb$ has hopelessly high QCD background
 - only associated production mode (WH or ZH with $H \rightarrow bb$) can be used
 - even then life is tough. Several new ideas are being tried
 - this makes $H \rightarrow \gamma\gamma$ attractive for low mass Higgs ($m_H \approx 120$ GeV)
- ◆ On a contrary note, W/Z+jets background falls off rapidly with mass
 - this makes $H \rightarrow WW(l\nu jj)$ and $ZZ(l\nu\nu, lljj)$ more sensitive for high m_H

Current experimental limits on Higgs



Tevatron Run II Preliminary, $L \leq 6.7 \text{ fb}^{-1}$



The Higgs search landscape

Low Mass
($M_H \approx 120 \text{ GeV}$)

$H \rightarrow \gamma\gamma$
 $H \rightarrow WW$
 $qqH \rightarrow \tau\tau$
 $V+ H \rightarrow bb$
 $qqH \rightarrow bb$
 $V+ H \rightarrow WW$

Mid Mass
($\approx 160 \text{ GeV}$)

$H \rightarrow WW$
 $H \rightarrow ZZ$

High Mass
($\approx 400 \text{ GeV}$)

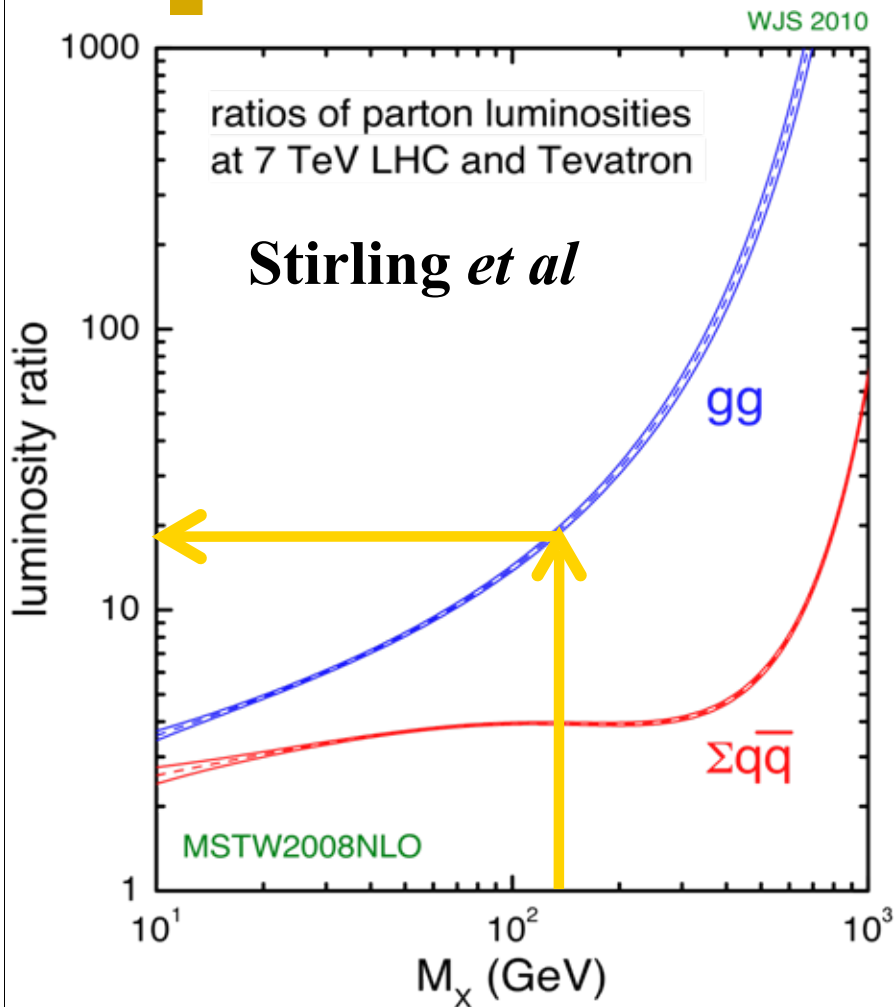
$H \rightarrow ZZ$
 $H \rightarrow WW$

95% CL Exclusions: $158 < M_H < 175 \text{ GeV}$; $100 < M_H < 109 \text{ GeV}$

Limit : $1.5x \sigma_{SM}$ for $M_H = 115 \text{ GeV}$

Note: Limits on non-SM Higgs are much weaker

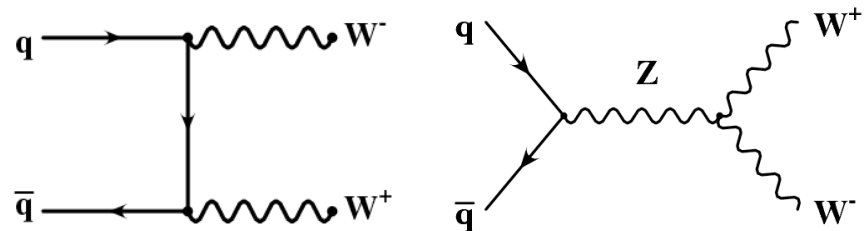
LHC vs Tevatron: partonic lumi helps $m_H > 140$



For $M_H > 140$ GeV

$gg \rightarrow H$ cross section at 7 TeV is >15 times that at 2 TeV

Irreducible backgrounds (WW,ZZ) originate from $q\bar{q}$ process which rises relative slowly (pp vs $p\bar{p}$)

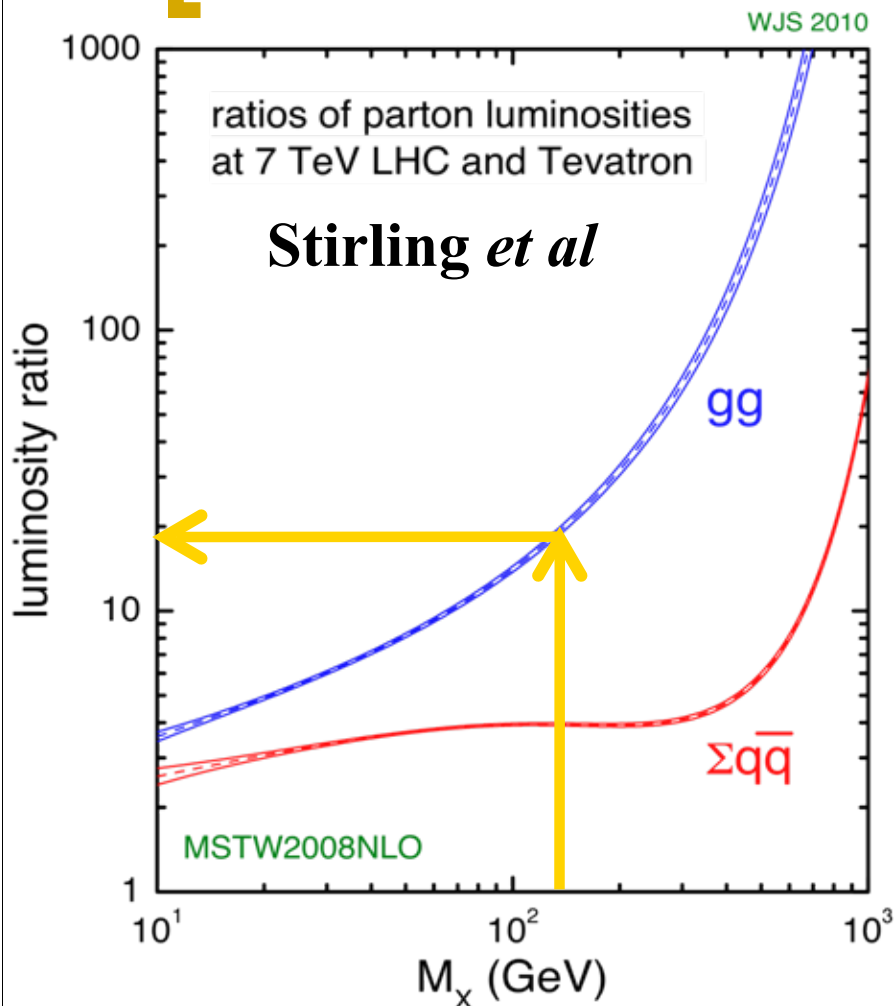


\Rightarrow Larger signal, better S/N

What about low m_H ? Well, Higgs is then produced in $q\bar{q}$ annihilation

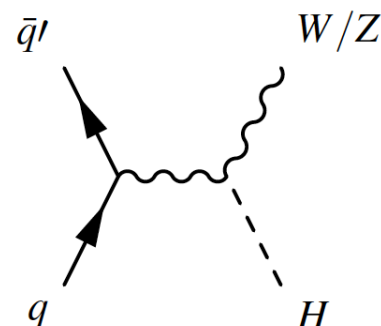


Higher partonic lumi doesn't help if $m_H < 130$



For $M_H < 130$ GeV

Modest rise in $q\bar{q}$ cross section at 7 TeV, $pp \rightarrow VH$ production only x3 larger than at 2 TeV



Major backgrounds are $W/Z + b\bar{b}$ & $t\bar{t}$ which rise sharply due to rise in qg and gg cross sections

⇒ Small signal, worse S/N

Need to get smarter: use jet sub-structure, pruning, ..., more new ideas

Basic building blocks for Higgs searches

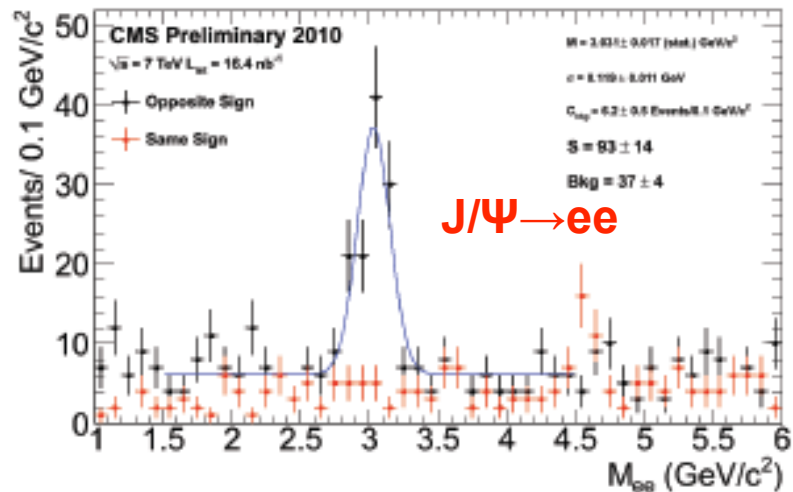
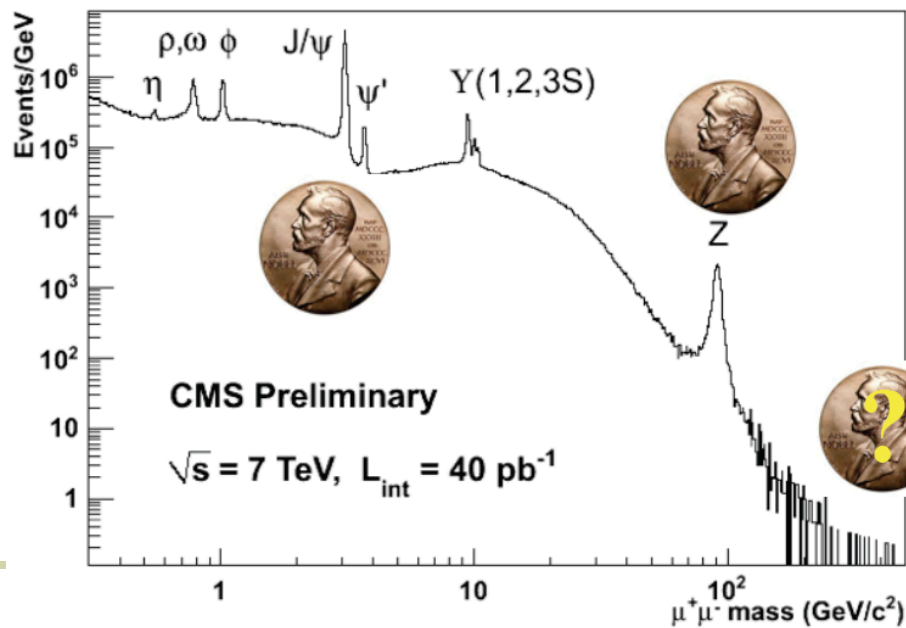
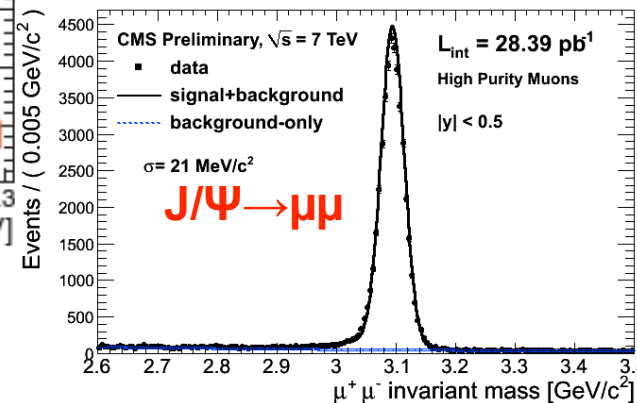
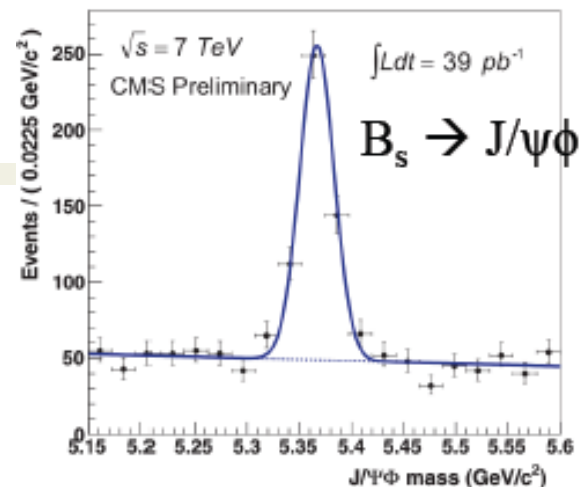
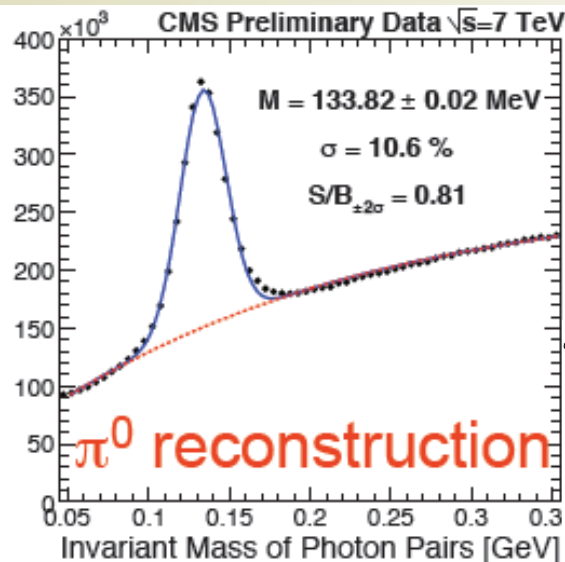
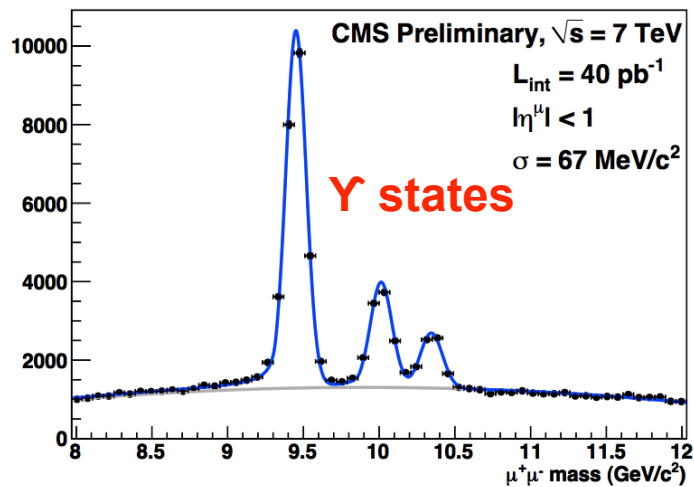


- Efficient Higgs search requires excellent performance from the entire detector and several reconstructed “objects”
- Key objects:
 - Electron, muon, photon, jet
 - Missing transverse energy (MET)
 - Tau
 - b quark-jet tagging (b-tag)
- Ability to reconstruct W, Z, top, W/Z+jets (including heavy flavor), and di-boson events and understand their production rates

2010 data has demonstrated excellent performance of CMS in reconstruction of these basic objects

Performance in data closely matches expectations based on simulations (MC) and sometimes exceeds it

A well calibrated detector



Jets and missing transverse energy

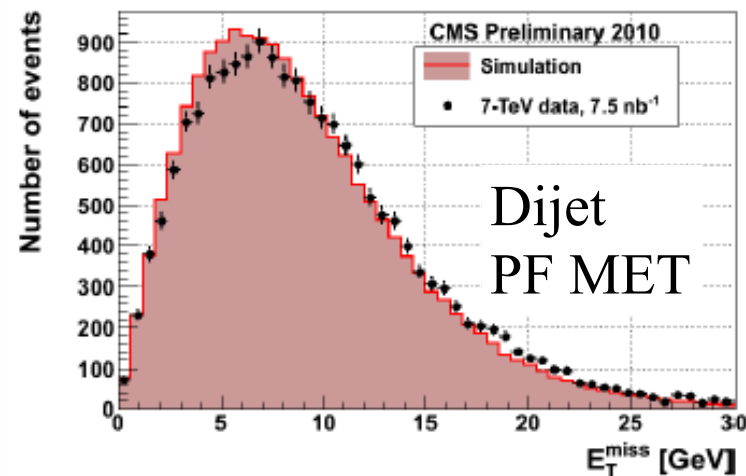
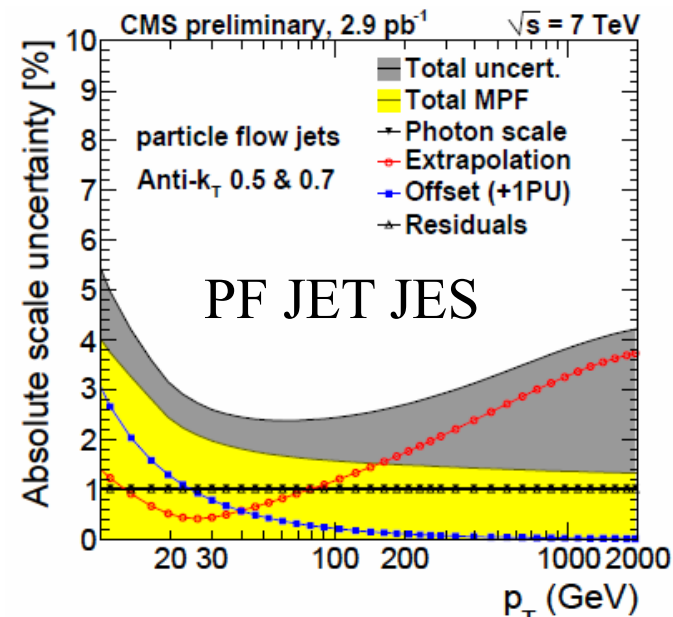


◆ Jet and Missing ET reconstruction uses **Particle Flow** (PF) technique:

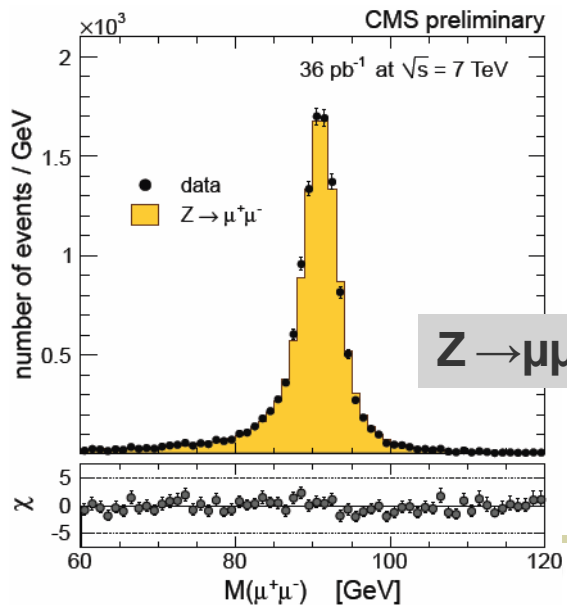
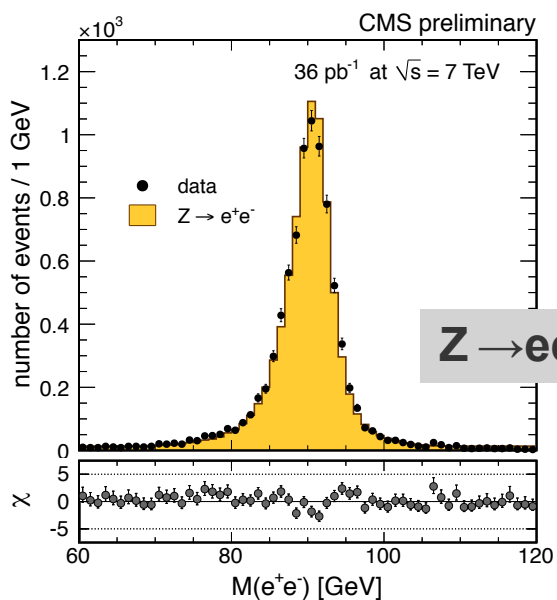
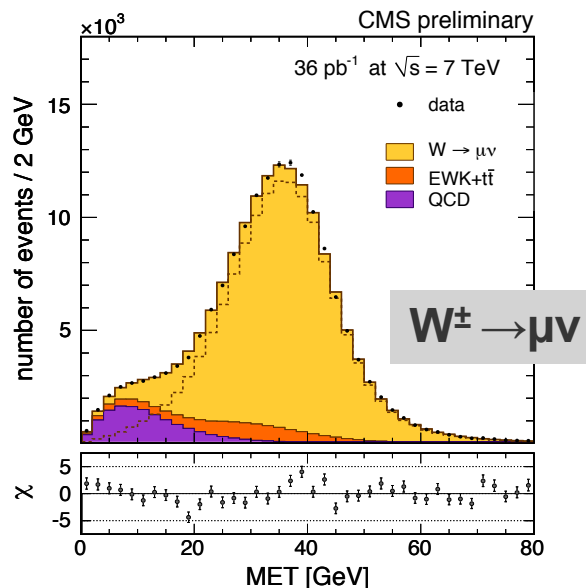
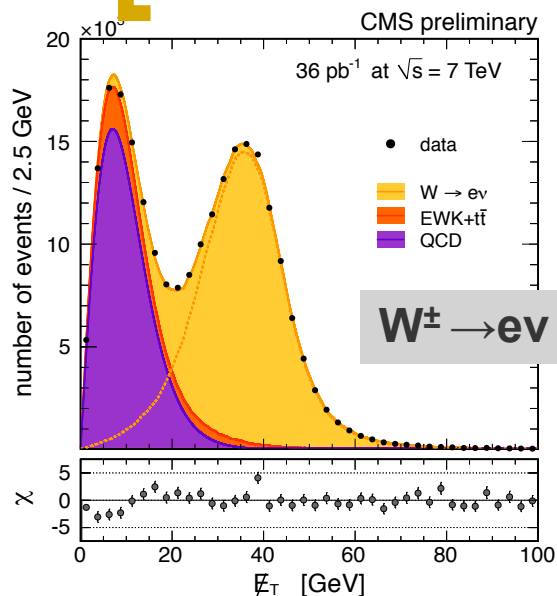
- All tracks/energy deposits sorted into charged/neutral hadron, electron, photon, or muon candidates
- Resulting set of corrected particles input to jet clustering, MET determination, H_T , M_T , etc.
- Significant improvement over traditional “CaloJets” for ~low-medium p_T jets with tracker coverage

◆ **Anti-k_T clustering with R=0.5** used everywhere here

- JES of PF jets known to 3–4%
- PF MET FWHM in dijets ~10 GeV



Leptons & MET: W and Z reconstruction



- ◆ Fully reco'ble, high purity
- ◆ MET well understood
-recoil modeling fine
- ◆ Lepton energy scale and resolution well measured
- ◆ Tiny experimental errors
-luminosity, theory dominate uncertainty

280000 W's

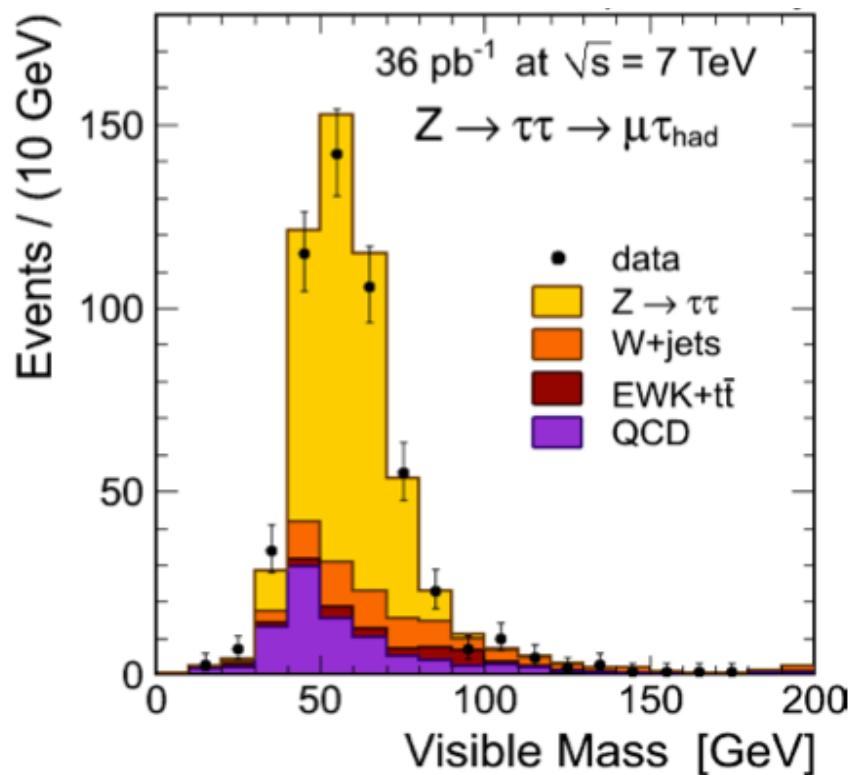
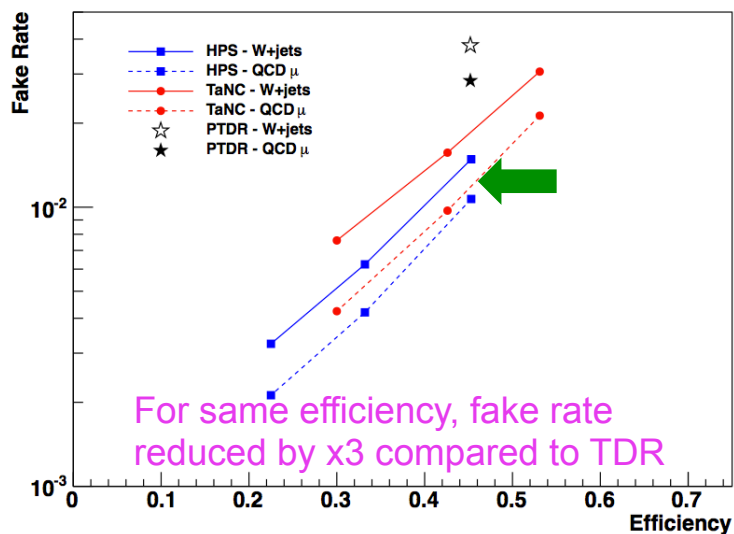
cross section x BR = 10.31 ± 0.02 (stat) ± 0.09 (syst) ± 0.10 (th.) ± 0.41 (lumi) nb

20000 Z's

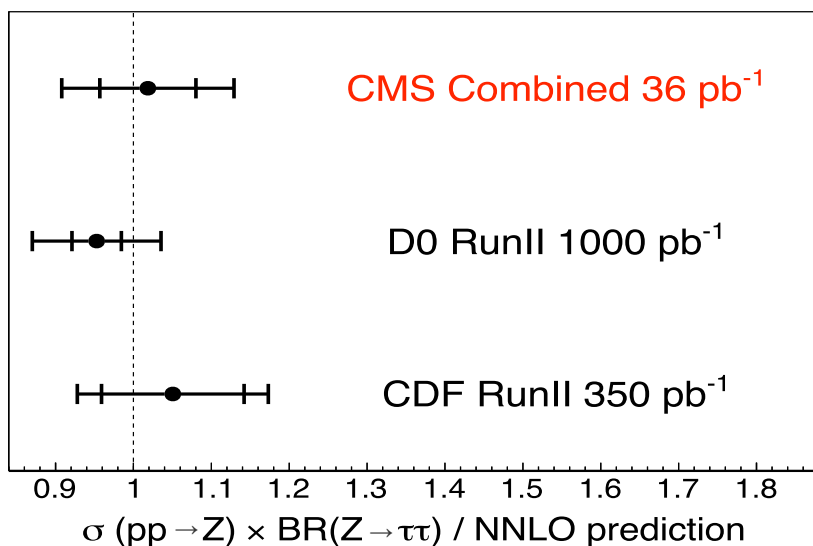
cross section x BR = 0.975 ± 0.007 (stat) ± 0.007 (syst) ± 0.018 (th.) ± 0.039 (lumi) nb



Tau reconstruction: excellent performance



Clean sample of Z → ττ



- ◆ Major background of tau searches
- ◆ Important control sample for tau ID, trigger, and reconstruction
- ◆ We can even trigger on hadronic tau !

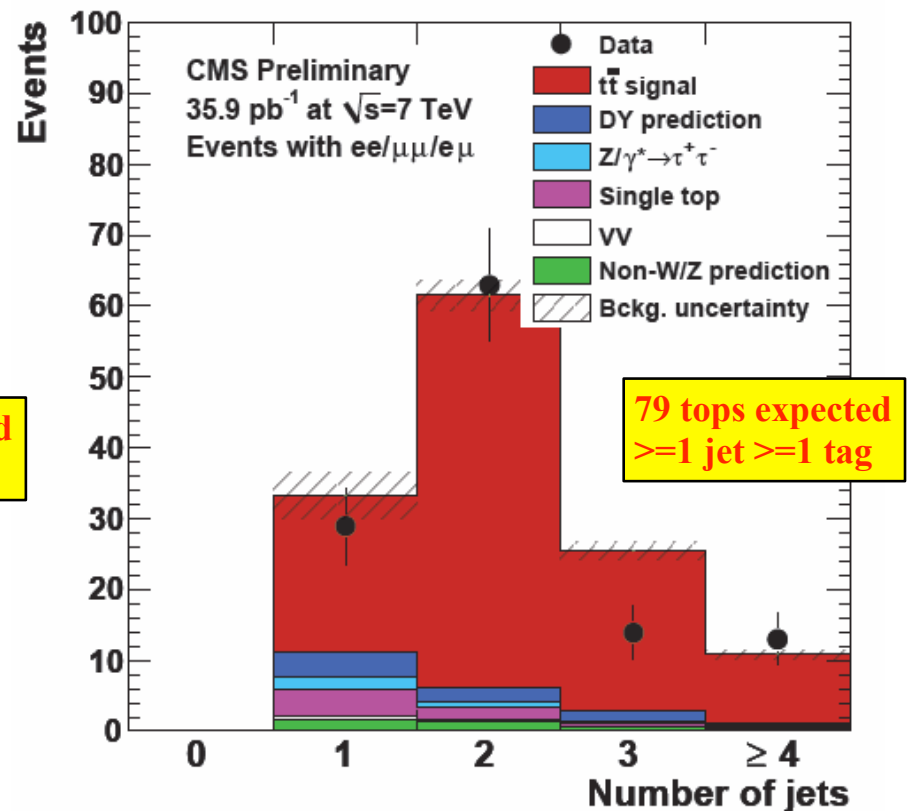
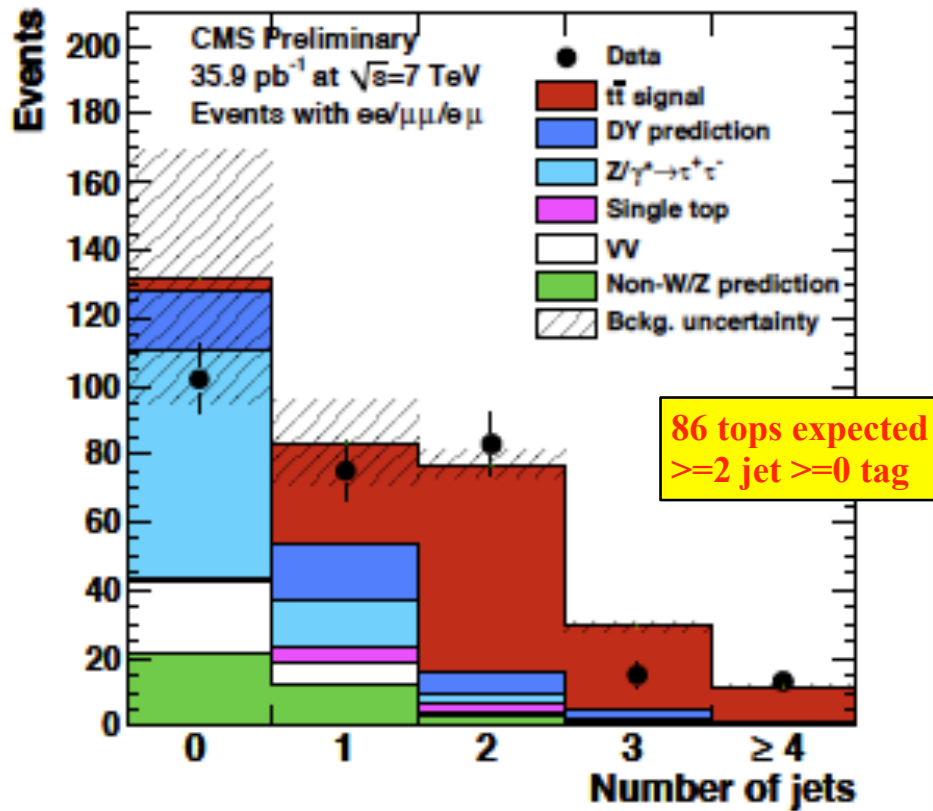
3rd generation: top and bottom



LHC top pair cross section is 160 pb, about **20X** Tevatron

MET >30 (50) GeV in ee/μμ for >2 (=1) jets, No MET cut in eμ; Z veto

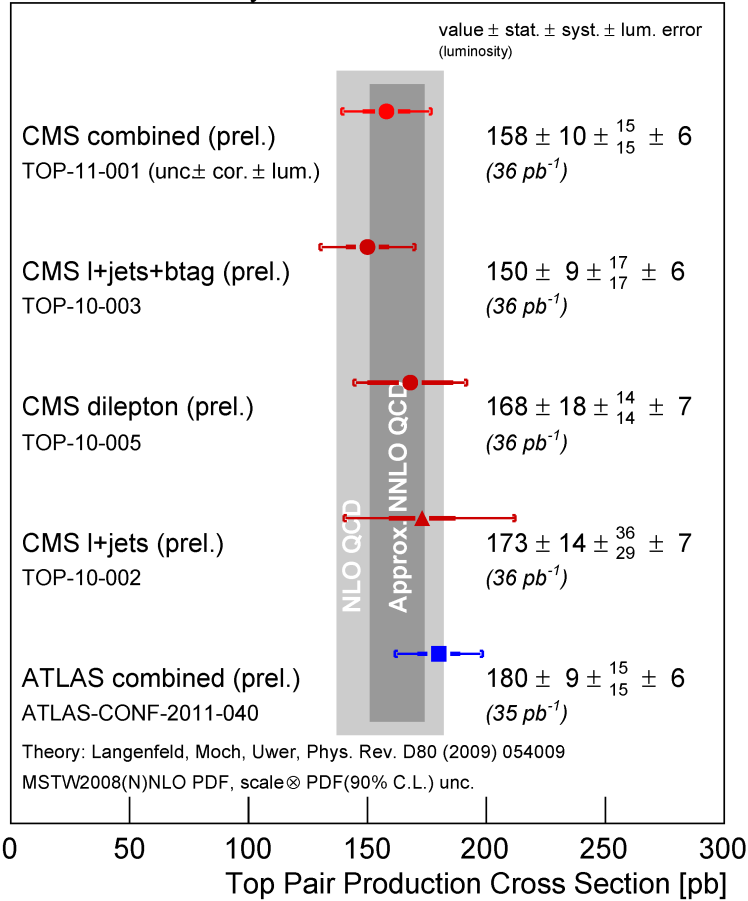
Simple counting experiment in N_{jet}/N_{tag} bins



$$\sigma(pp \rightarrow tt) = 168 \pm 18(\text{stat.}) \pm 14(\text{syst.}) \pm 7(\text{lumi.}) \text{ pb}$$

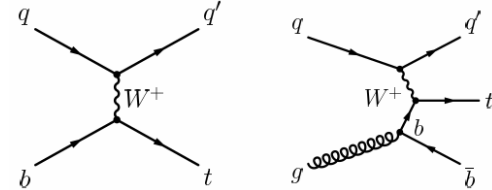
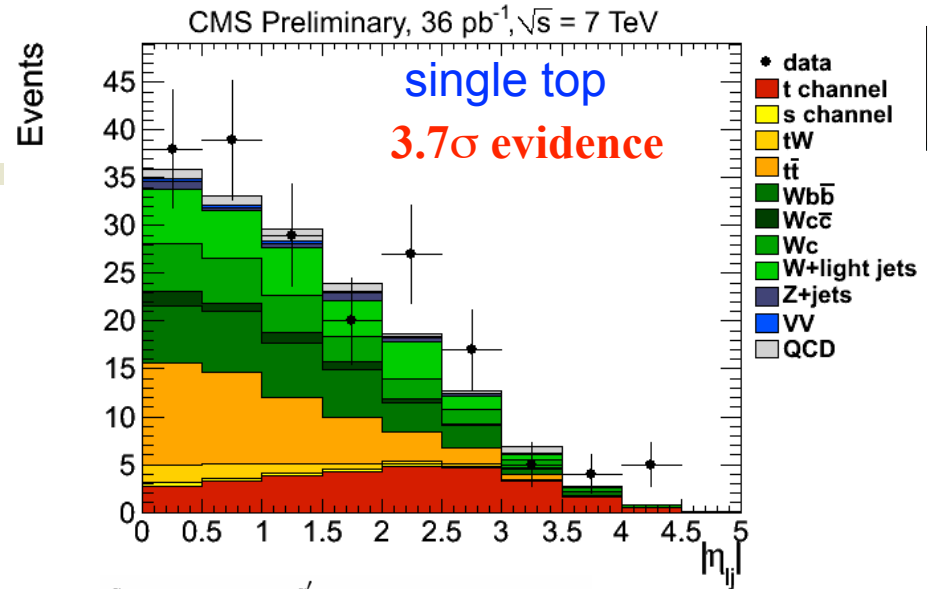
Top cross sections

CMS Preliminary, $\sqrt{s}=7$ TeV

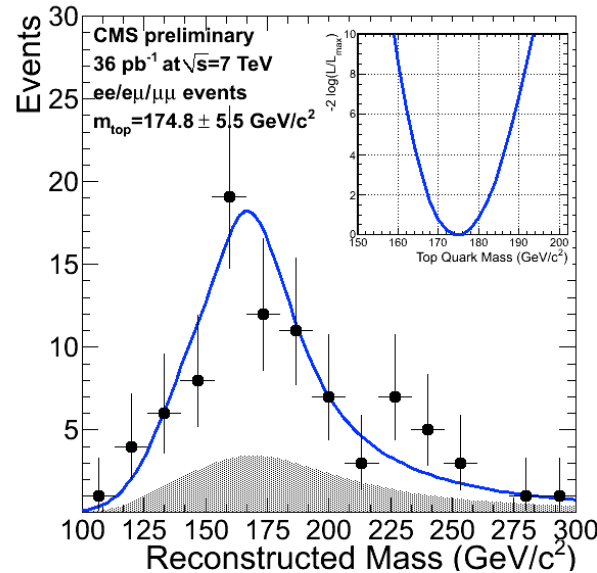


12% precision obtained. All measurements consistent with the SM and with each other

Kalanand Mi



$|\eta_{ij}|$ is rapidity of the recoil jet (signal is more forward)



First CMS top mass measurement!

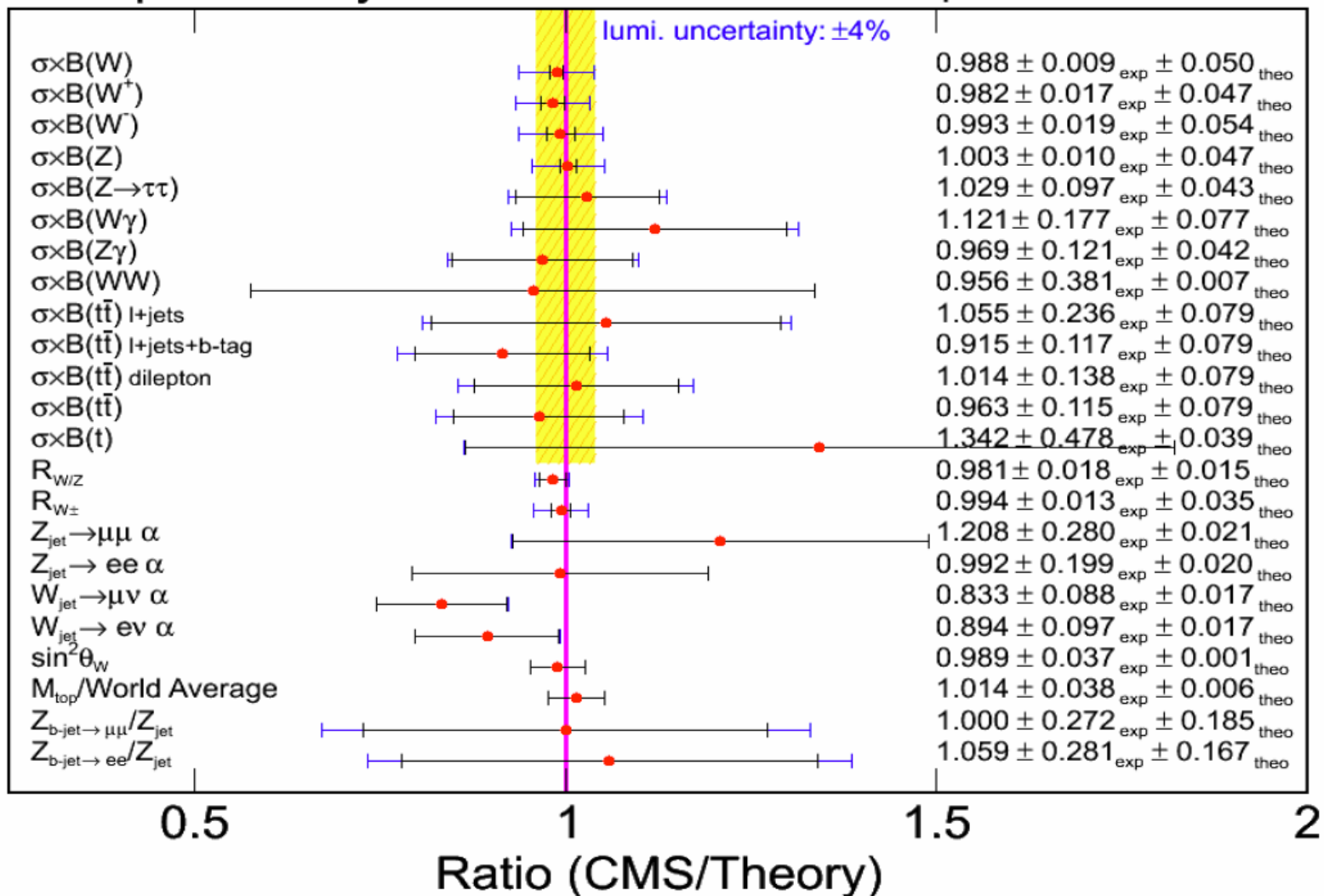
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The Standard Model: How am I



CMS preliminary

36 pb⁻¹ at $\sqrt{s} = 7$ TeV



Higgs search results from 2010 data



CMS published its first paper on the SM Higgs search using 36 pb^{-1} data

In the next slides I will focus on

- ☑ SM-like Higgs search in $H \rightarrow W(l\nu)W(l\nu)$ channel
 - WW production in di-lepton final state is well established
 - exclude Higgs boson with mass 144–207 GeV in an extension of Standard Model with 4-fermion generations
 - improve over the Tevatron limit

- ☑ Search for MSSM Higgs in $H \rightarrow \tau\tau$ channel
 - we again broke new ground here
 - improve over Tevatron limit for all values of Higgs mass and $\tan\beta$

- ◆ Other channels don't have enough sensitivity with 36 pb^{-1} of 7 TeV data
 - I will mention them briefly
 - CMS has dedicated people working on $H \rightarrow \gamma\gamma$, $H \rightarrow W(l\nu)W(jj)$, $H \rightarrow ZZ$, and associated production with vector boson modes
 - CMS has similar sensitivity to ATLAS in all channels

- ◆ We'll show you results on them when they get to the point of being interesting

H → WW → 2l2ν: work horse for 120 < m_H < 200



<http://arxiv.org/abs/1102.5429> Phys. Lett. B 699: 25-47 (2011)

◆ Signal: 2 isolated leptons with small $\Delta\phi$
+ MET + 0, 1, 2 jets

◆ Reduction of major backgrounds:

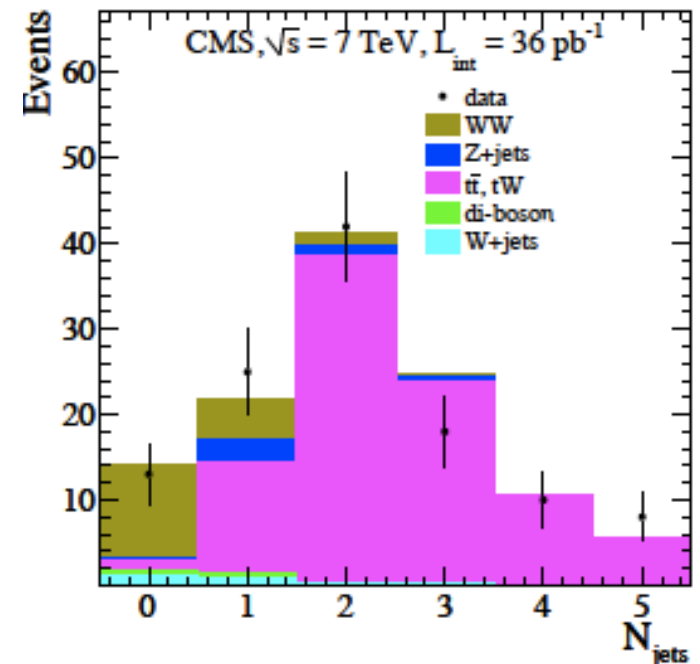
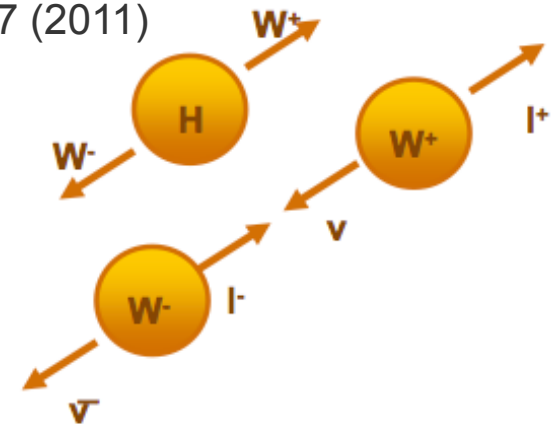
- **electroweak WW: $\Delta\phi$** ← main bkg for Higgs search
- ttbar: Central jet veto, $\Delta\phi$
- W+jets: tight lepton ID
- DY reduced by MET requirement
- WZ/ZZ: 2 leptons in final state, MET

◆ Higgs search used 2 counting methods:

- Cut on kinematic observables
- Cut on a BDT output & count
 - 15% higher eff for same bkgnd

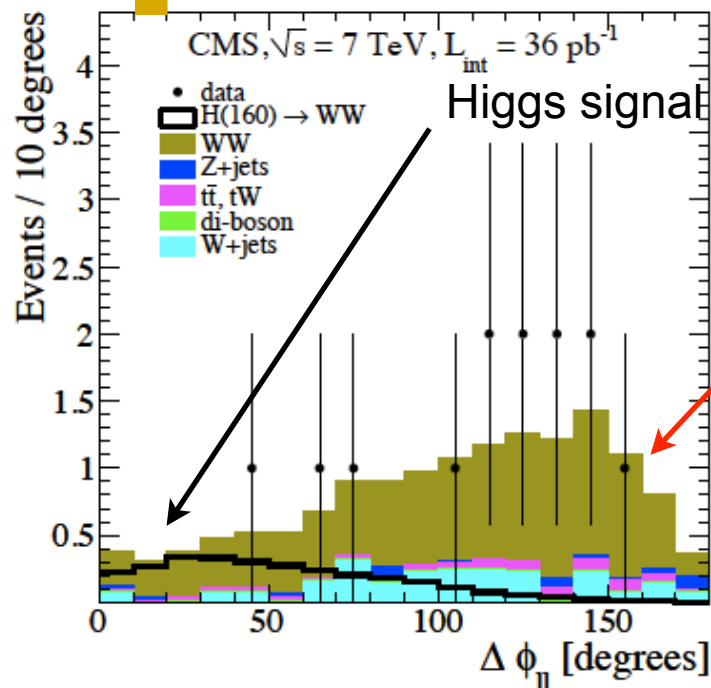
◆ Backgrounds are estimated using data

Different N_{jets} samples have different levels of signal purity. 0-jet is the purest. By optimizing N_{jets} samples independently we increase Higgs signal efficiency.





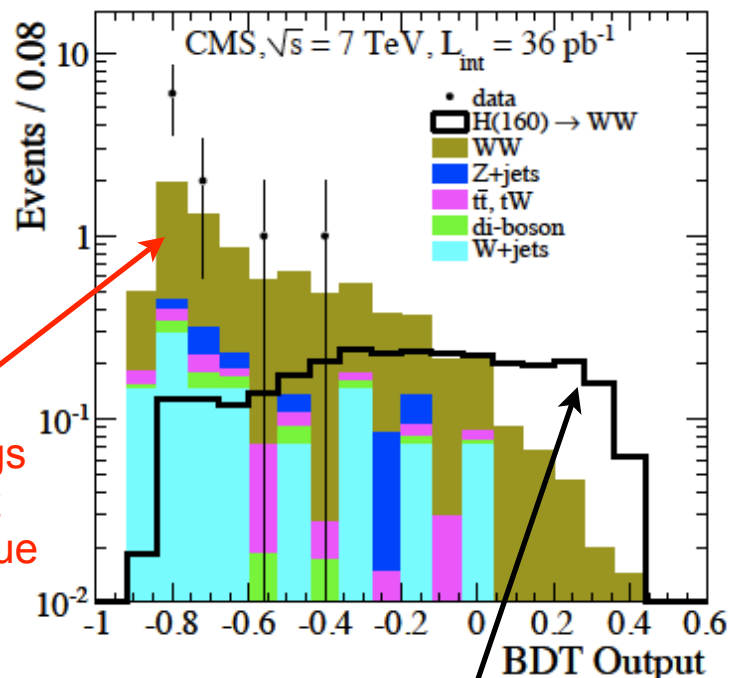
H → WW → 2l2ν: analysis details



Higgs signal peaks at low $\Delta \phi_{\parallel}$

SM WW peaks high

SM bkg peak at low value



Higgs signal has higher BDT output value

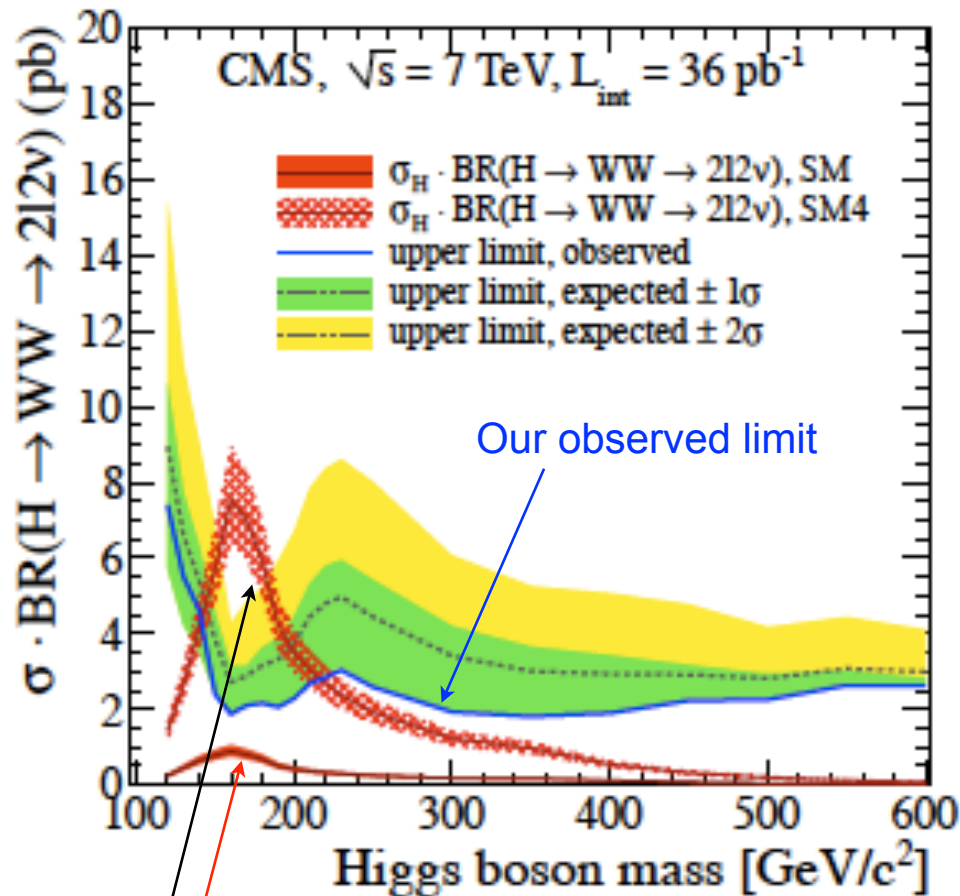
Observe **13** events: 2 in ee, 10 in eμ, 1 in μμ
 Estimate **3.29** ± 0.45 ± 1.09 events from bkg

Data is consistent with standard model electroweak di-boson WW production. We measure cross section for this process.

$\sigma_{WW} = 41.1 \pm 15.3 \text{ (stat)} \pm 5.8 \text{ (sys)} \pm 4.5 \text{ (lumi)} \text{ pb}$
 NLO prediction for SM WW = **43 ± 2 pb**

$$\frac{\sigma_{WW}}{\sigma_W} = (4.46 \pm 1.66 \pm 0.64) \cdot 10^{-4}$$

H → WW → 2l2ν: results



◆ 95% C.L. upper limit is a factor of 2 bigger than the Standard Model cross section for $H \rightarrow WW$ and $m_H = 160 \text{ GeV}$

◆ A Standard Model extension with 4 fermion generations predicts a factor of ~ 9 enhancement in the cross section
 - For this model we exclude Higgs in mass range from 144 GeV to 207 GeV

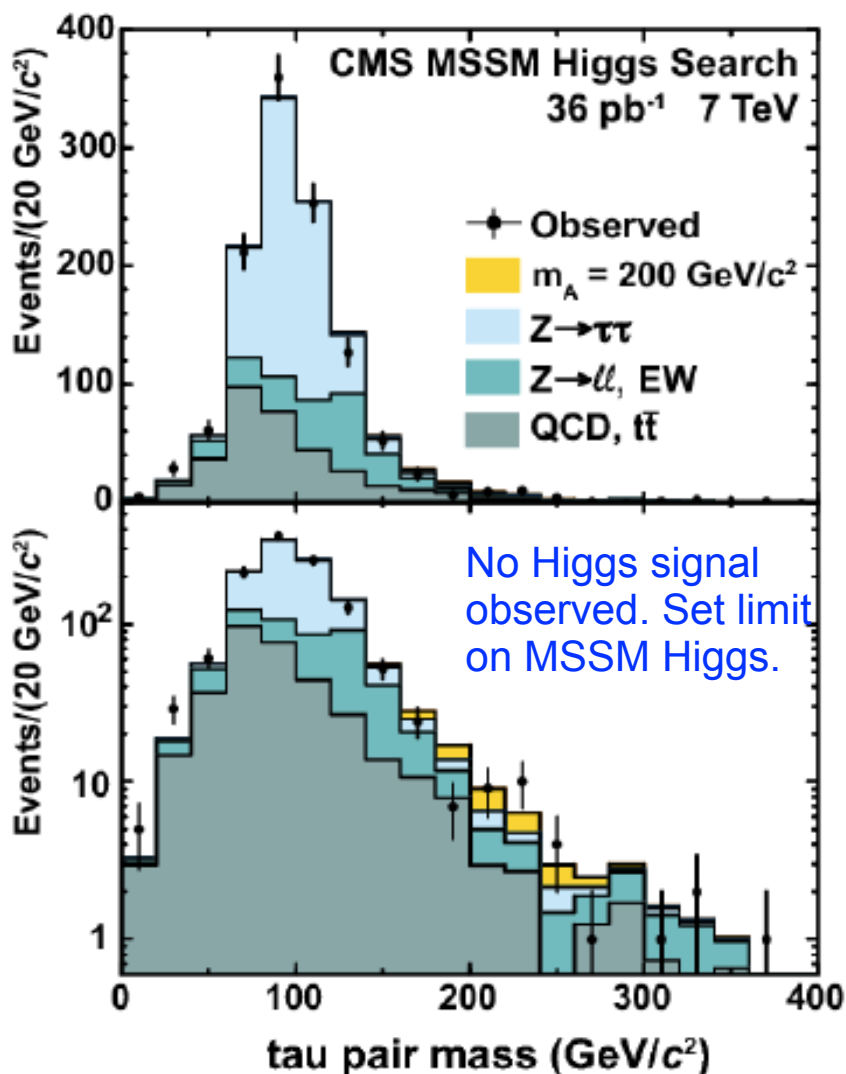
Better limit than CDF+DØ on 4g

ATLAS excludes $1.2 \sigma_{\text{SM}} @ M_H = 160 \text{ GeV}$

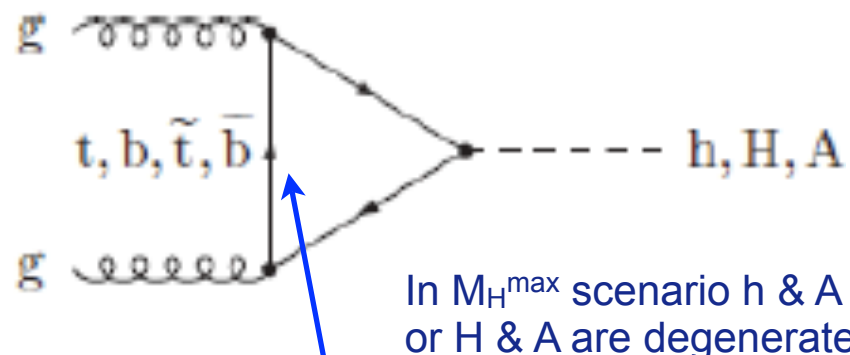
m_H (GeV/ c^2)	$\sigma \cdot \text{BR}$ SM (pb)	$\sigma \cdot \text{BR}$ 4th gen. (pb)	lim. obs. BDT-based (pb)
130	0.45	2.66	5.66
160	0.90	7.54	1.93
200	0.42	3.50	2.32
210	0.37	3.04	2.76
400	0.13	0.55	1.94



H → tau tau: limit on MSSM Higgs boson m_A



Not yet sensitive to setting limit on SM Higgs in $\tau\tau$ channel. However, we break new ground on excluding Higgs for a benchmark MSSM model

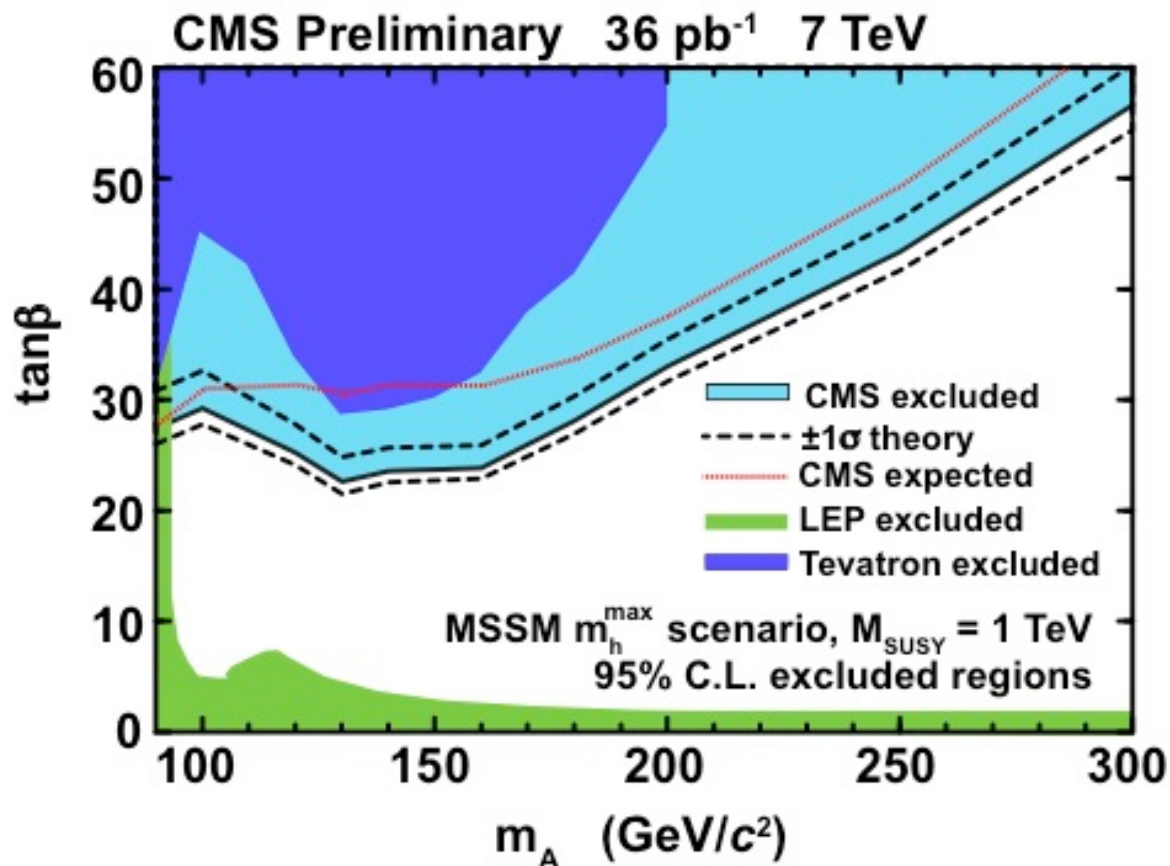


In M_H^{\max} scenario h & A or H & A are degenerate

- ◆ Can get large enhancement in Higgs production from **high $\tan\beta$**
- ◆ Enhancement due to contribution from third generation **squarks in the loop**
- ◆ $\text{BR}(A \rightarrow \tau\tau) = 10\text{--}15\%$



H \rightarrow tau tau: limit on MSSM Higgs boson m_A



With 10x more data on tape and 100x expected by the end of this year we will be able to set limit on SM Higgs in this channel also

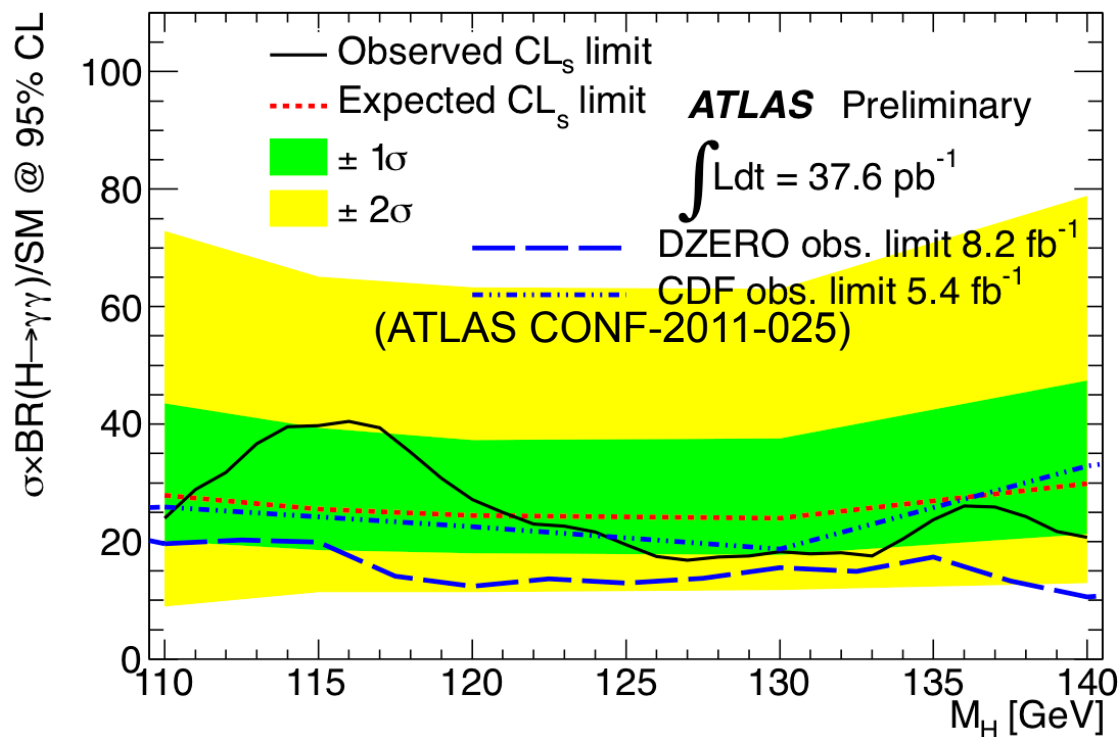
- ◆ For arbitrarily large value of $\tan\beta$ we exclude very heavy Higgs masses
-the plot range on x-axis goes all the way up to ∞
- ◆ Even for low values of $\tan\beta$ we improve substantially over Tevatron limit
-thus supersede Tevatron limits on m_A everywhere



H → γγ and other decay modes

LHC with 35 pb⁻¹ has ~ sensitivity as Tevatron's 5 fb⁻¹ (see CDF H → γγ C.L.)

Below I list some results from ATLAS to indicate the current sensitivity



H → WW → lvjj

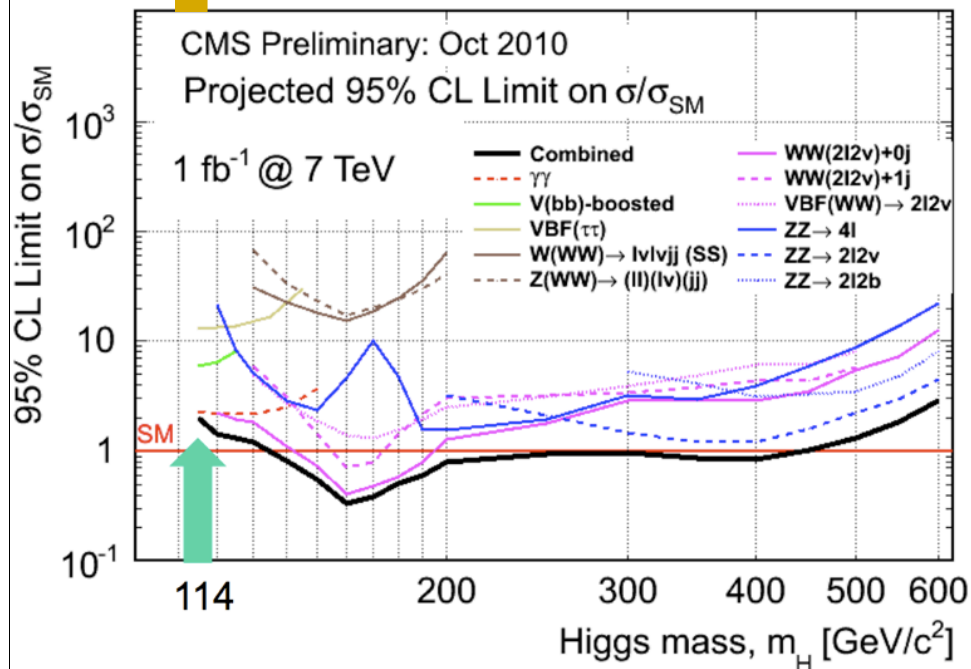
- Exclude 4–6 × σ_{SM} near m_H = 320 GeV and m_H = 480 GeV
- Exclude SM-4g near 320 GeV
- More sensitive for m_H > 250 GeV than any other channel

H → ZZ → llvv / lljj combined

- Exclude 4 × σ_{SM} near 260 GeV
- Sensitive to 4–10 × σ_{SM} in wide mass range in 200–400 GeV

- ◆ ATLAS excludes 40 × σ_{SM} at m_H = 115 GeV
- ◆ DØ excludes Higgs with 20 × σ_{SM} at m_H = 115 GeV

CMS Projected Exclusions with 1 fb^{-1} @ 7 TeV



Caveats:

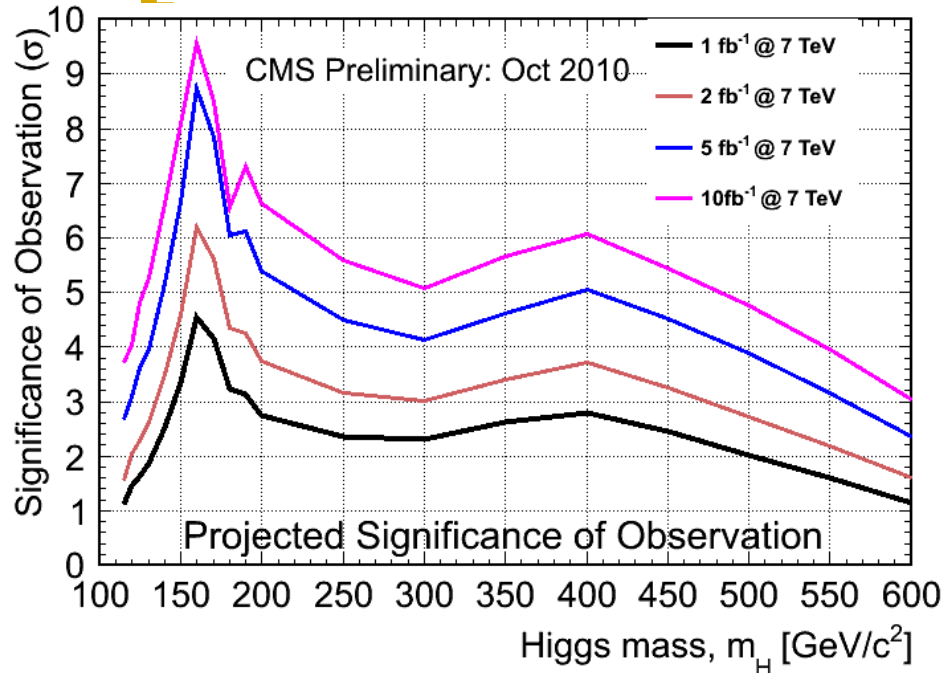
- Projections based on 2010 conditions
- LHC environment is much more aggressive in '11-'12
 - Instantaneous Luminosity $1\text{--}5 \text{ nb}^{-1}\text{s}^{-1}$
 - 50ns bunch crossing (was 75ns in '10)
 - Pileup ~ 10 per event
 - E_t^{miss} , lepton isolation, jet resolution all degraded

- ◆ With 1 fb^{-1} we will be able to exclude SM Higgs in a large mass range
 - starting at 120 GeV and going all the way up to 500 GeV
 - only the very low mass Higgs ($\approx 115 \text{ GeV}$) may remain elusive

- ◆ The projections are somewhat pessimistic in one respect: not all discriminating variables and data-driven techniques were exploited in this MC exercise

Projections are indicative not predictive !

SM Higgs sensitivity: 1, 2, 5, 10 fb⁻¹ @ 7 TeV



Some observations from this plot

- ◆ If SM Higgs exists with $m_H > 135$ GeV, we will start seeing hints after 1 fb⁻¹
- ◆ On the other hand, we'll not gain much territory in exclusion beyond 2 fb⁻¹ !
- ◆ A definitive evidence for SM Higgs is likely with 1–2 fb⁻¹

Summarizing it all

ATLAS + CMS ≈ 2 x CMS	95% CL exclusion	3σ sensitivity	5σ sensitivity
1 fb⁻¹	120 - 530	135 - 475	152 - 175
2 fb⁻¹	114 - 585	120 - 545	140 - 200
5 fb⁻¹	114 - 600	114 - 600	128 - 482
10 fb⁻¹	114 - 600	114 - 600	117 - 535

Conclusions



- ◆ The LHC Higgs era is upon us
 - Machine is performing spectacularly, and so are ATLAS and CMS
 - CMS published its first paper on the Standard Model Higgs searches using 36 pb^{-1} of data collected in 2010. Analyzing 2011 data.
- ◆ Higgs Boson, if it exists between masses of (114 – 600 GeV) will either be discovered or ruled out in \approx next two years



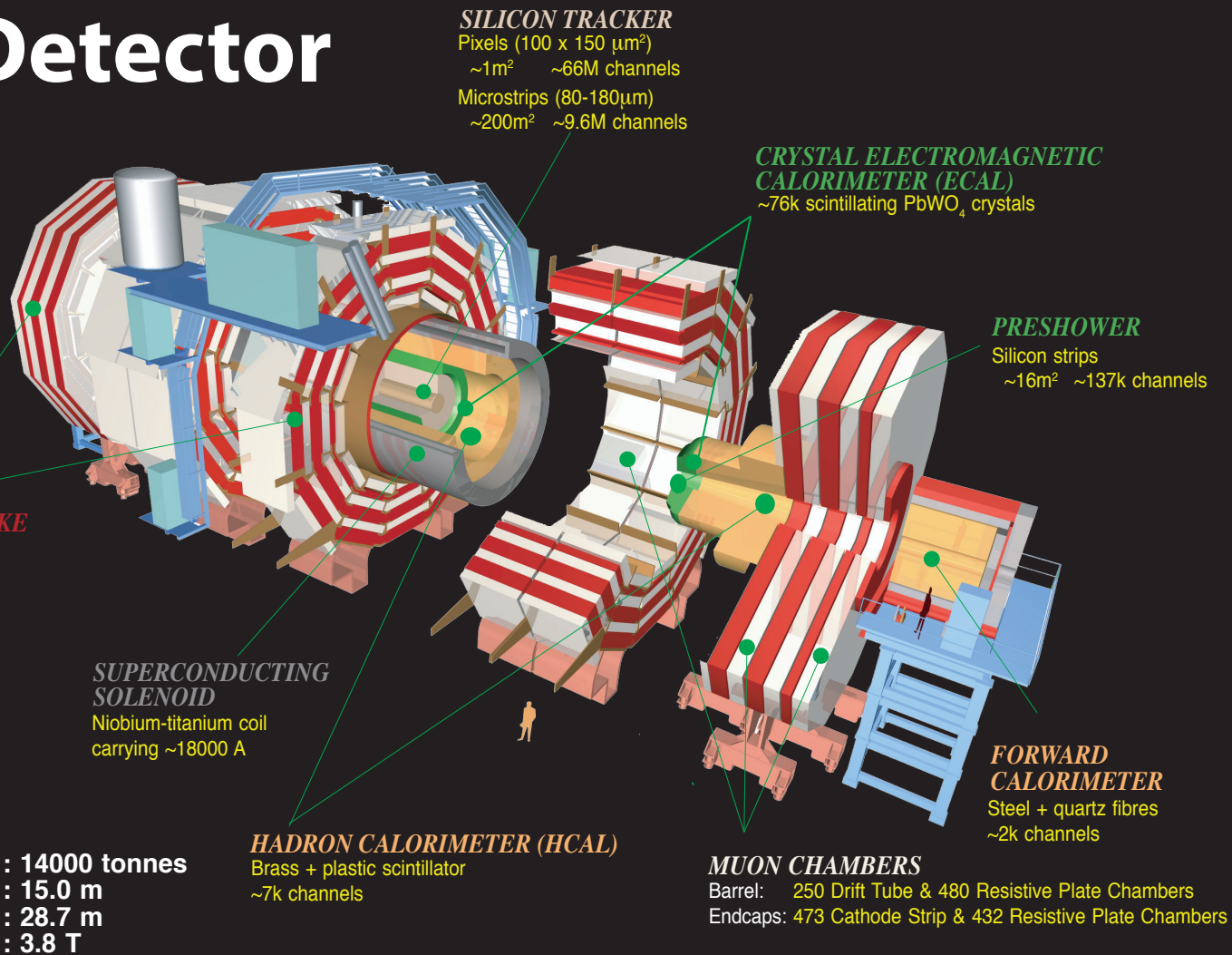
BACKUP SLIDES

Understanding CMS detector



CMS Detector

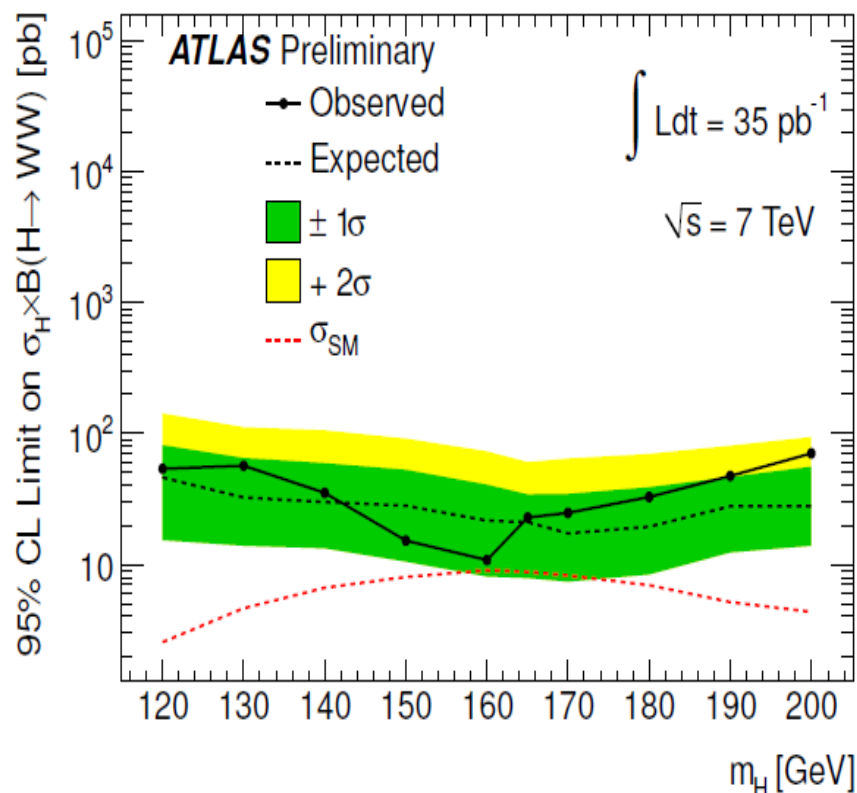
Pixels
 Tracker
 ECAL
 HCAL
 Solenoid
 Steel Yoke
 Muons





ATLAS $H \rightarrow WW \rightarrow l\nu l\nu$: Exclusion Limits

absolute limit on cross section

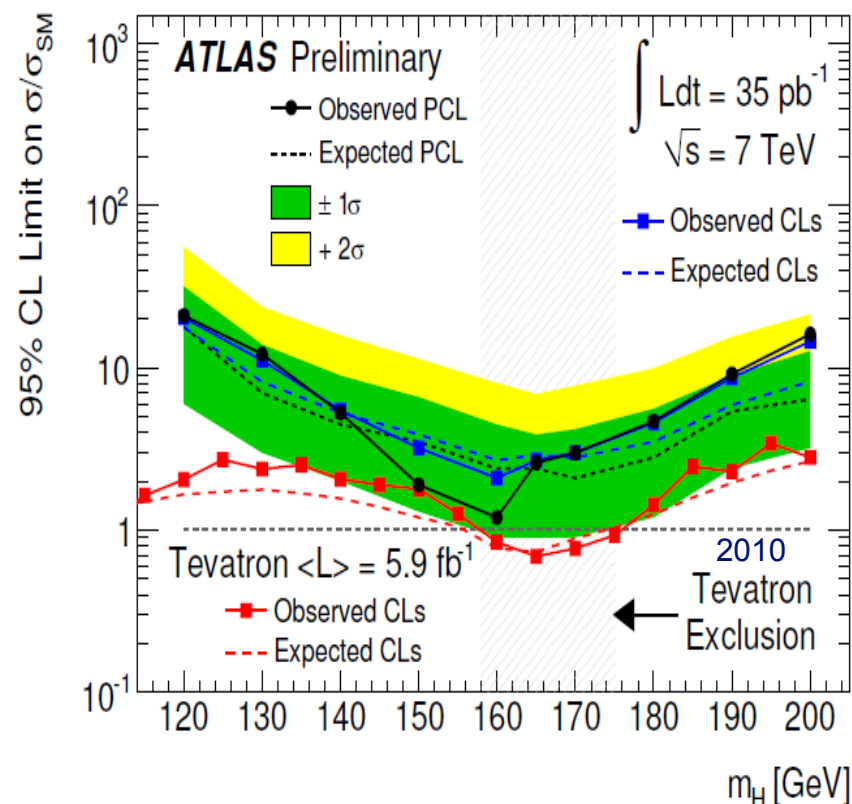


cross section limits:

54 (11,71) pb at $M_H=120$ (160,200) GeV

sensitivity dominated by gluon fusion

limit w.r.t. SM prediction

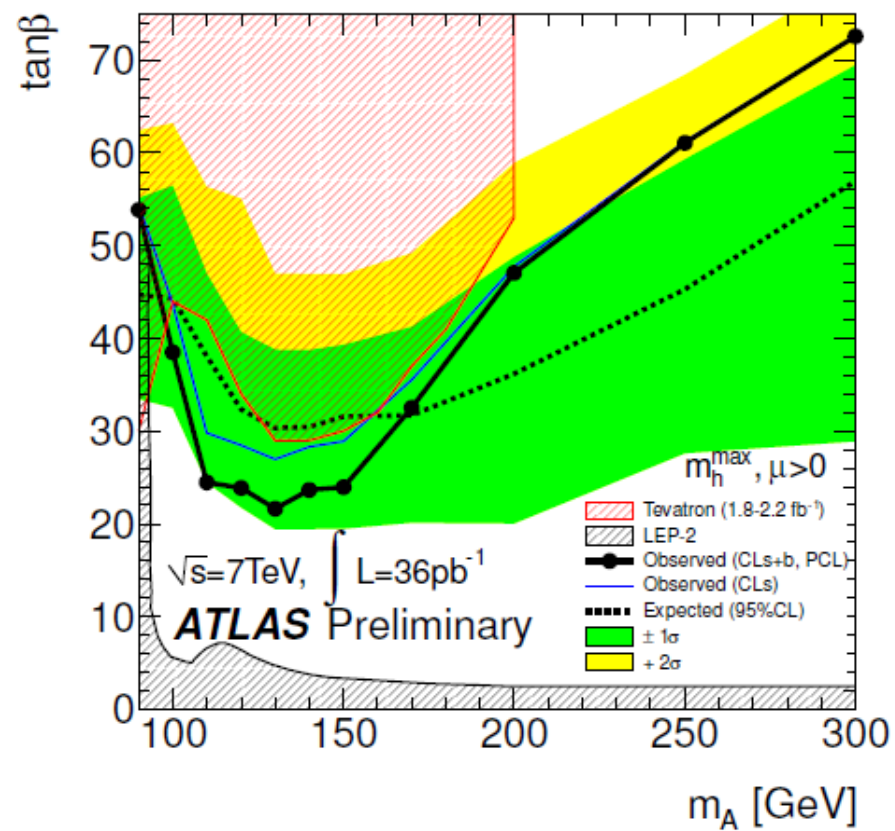
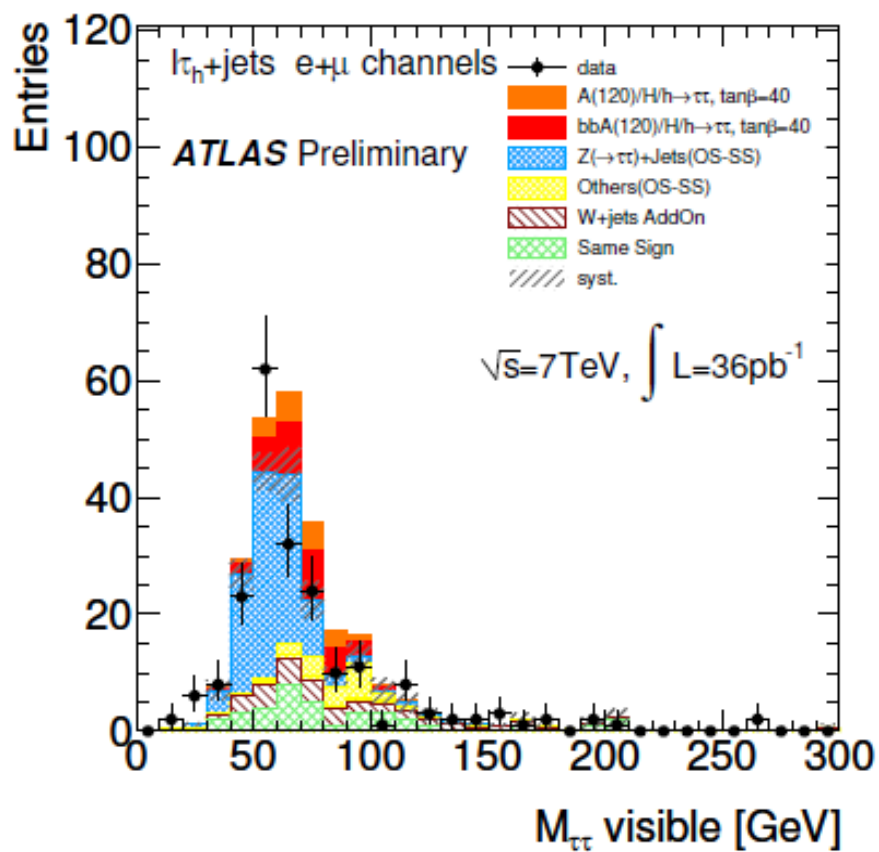


1.2 x SM cross section σ_{SM}

excluded at $M_H = 160$ GeV

M. Schumacher, Moriond EW 2011 talk

ATLAS $H \rightarrow \tau\tau$



M. Schumacher, Moriond EW 2011 talk

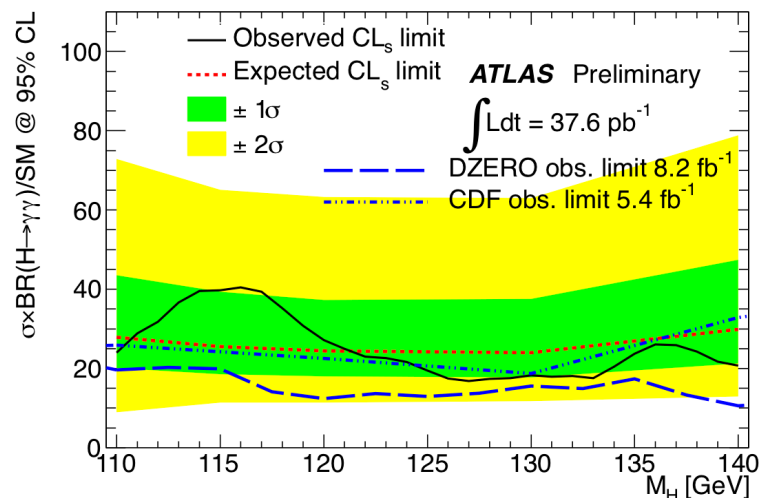
ATLAS: $H \rightarrow \gamma\gamma$, $H \rightarrow Z(\ell\ell) Z(\nu\nu)$, $H \rightarrow W(\ell\nu) W(jj)$



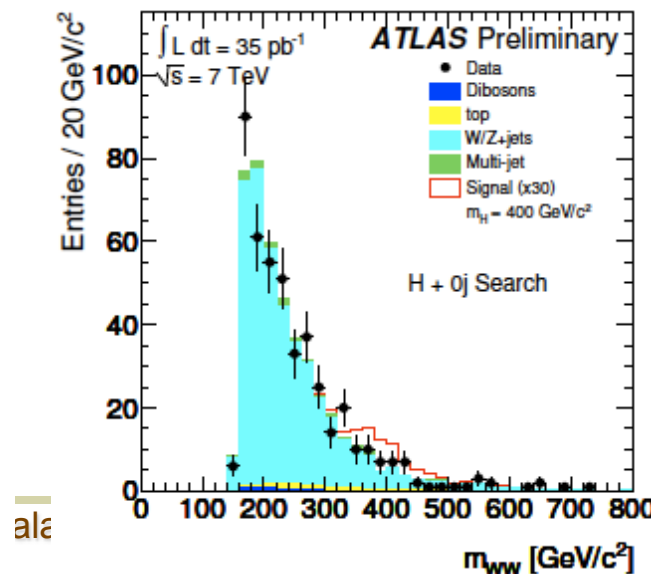
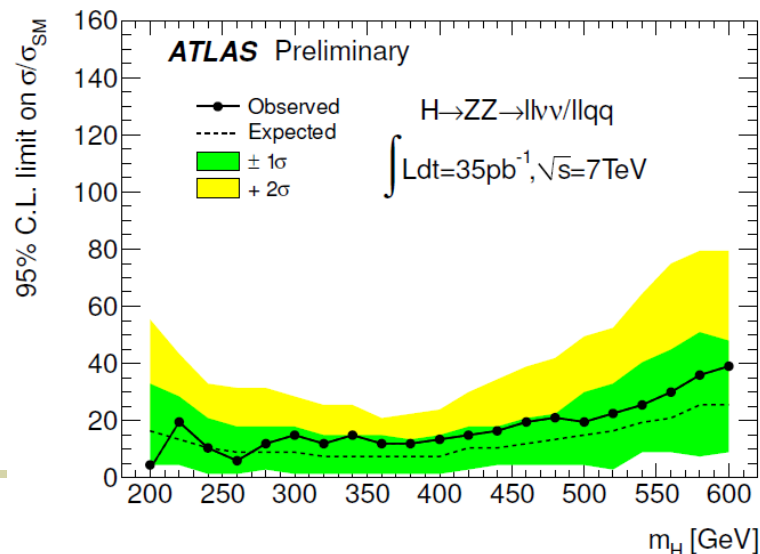
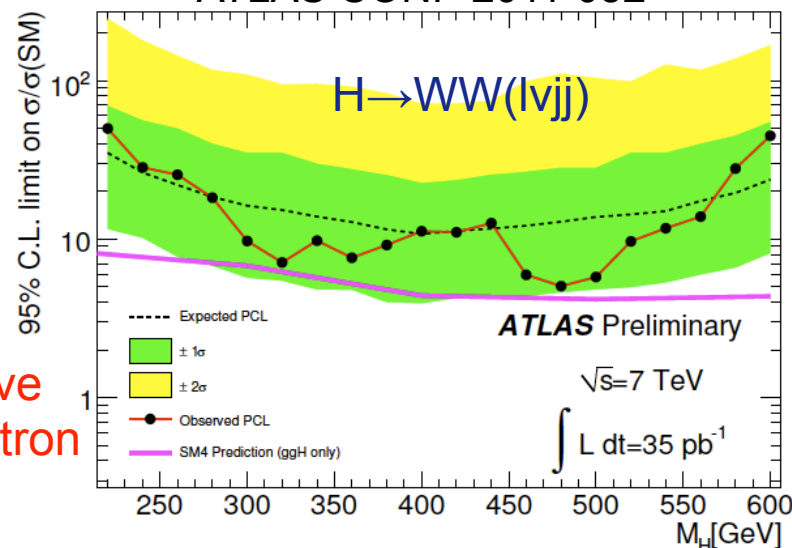
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LHC is competitive with Tevatron

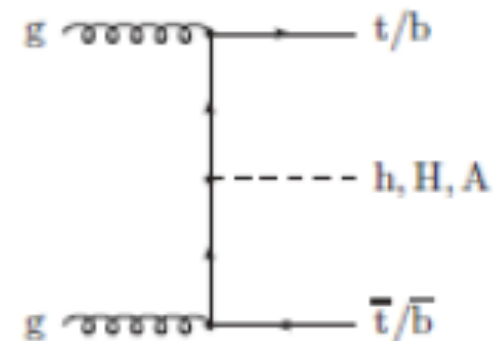
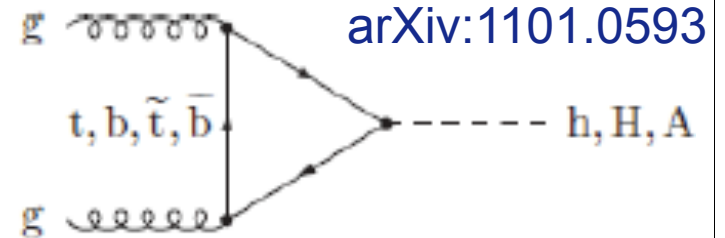


- ✓ BR is 6x larger than $l\nu l\nu$
- ✓ Fully reco'ble
- ✓ Most sensitive for $m_H > 200$ GeV
- But larger bkgd ...

MSSM Higgs boson search in M_H^{\max} scenario



- 2 Higgs doublets, 5 physical bosons
 - 2 CP-even h, H , 1 CP-odd A and 2 charged H^+, H^-
- at Born level 2 parameter: $\tan \beta, m_A$ ($m_h < m_Z$)
- large loop corrections from SUSY parameters
 - $m_h < 133$ GeV (for $m_{\text{top}} = 175$ GeV, $M_{\text{SUSY}} = 1$ TeV)
- corrections depend on 5 SUSY parameter:
 - $X_t, M_0, M_{2'}, M_{\text{gluino}}, \mu$
 - fixed in benchmark scenarios



Motivation for $H \rightarrow \tau^+ \tau^-$ search

For high values of $\tan \beta$:

- Cross section enhanced
- BR ($A \rightarrow \tau \tau$) = 10–15%
- h & A or H & A are degenerate