CMS Electroweak and Higgs Results and Prospects for 2011–12

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Fermilab

CMS Collaboration

- Commissioning of Standard Model objects/processes
- Precision electroweak measurements, asymmetry, W/Z+jets ...
- Higgs results from analysis of 2010 data
- Prospects and sensitivity projections for 2011−12

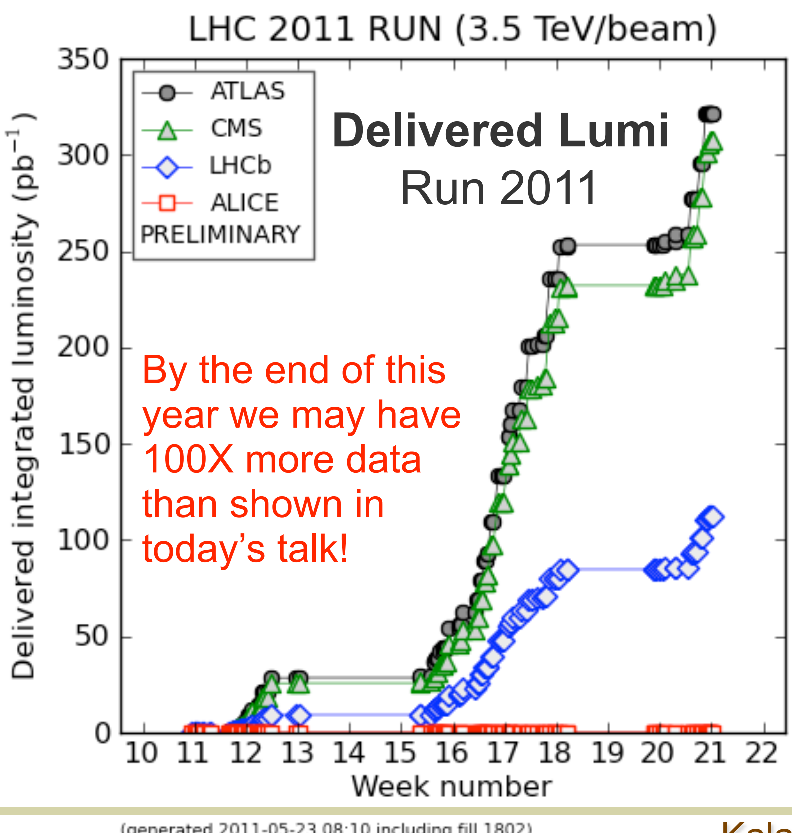
University of Oregon, May 23, 2011

Outlook for 2011 data collection

Outlook is bright

"Official" target:

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



- Breaking news: LHC sets new world record luminosity: **1.08** $nb^{-1}s^{-1}$ (i.e., 1E33)
  - 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 $\mu b^{-1}s^{-1}$
  - this exceeded the previous world record of 402 $\mu b^{-1}s^{-1}$, which was set by the Tevatron in 2010
  - Tevatron surpassed its own record three weeks ago: now **417** $\mu b^{-1}s^{-1}$
- Moving to continuous physics running
  - short technical stop in December, then physics run until end of 2012
  - <u>already delivered **0.4** fb^{-1} per exp.</u>

W and Z production at LHC

✦W and Z production at LHC happens at first order from collisions of a valence quark (u,d) and a sea antiquark (Q≈100 GeV):

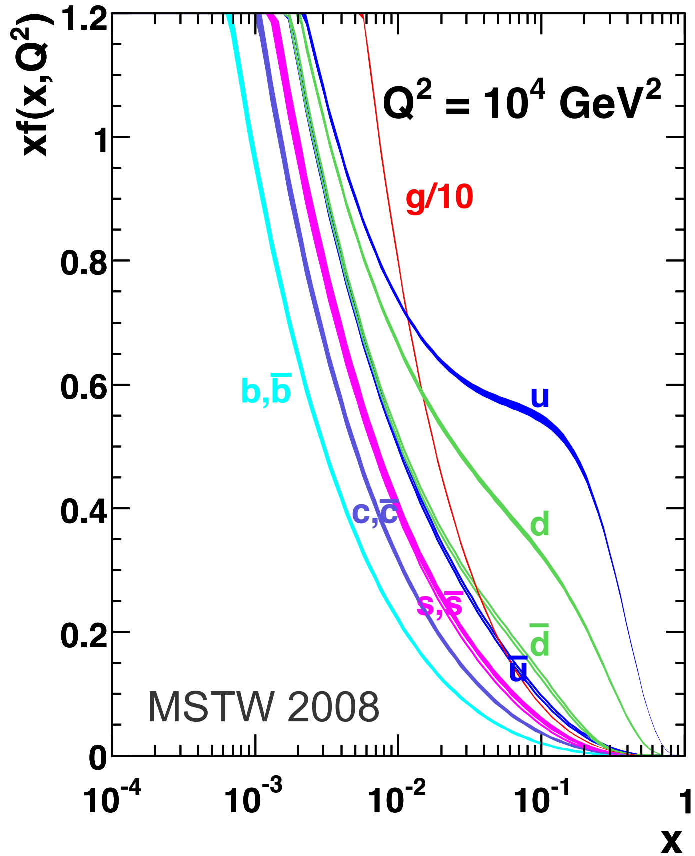
$$u+\bar{d}(\bar{s})\rightarrow W^{+} \qquad u+\bar{u}\rightarrow Z$$
$$d+\bar{u}(\bar{c})\rightarrow W^{-} \qquad d+\bar{d}\rightarrow Z$$

✦Parton fractions are typically $10^{-3} < x < 10^{-1}$:
-sea-sea qq contributions are also important

✦W production in pp collisions is globally charge asymmetric:
- pp has 2X more ud than du collisions due to uud valence quark content of p
-sea quark-sea quark charge symmetric production dilutes W^{+}/W^{-} ratio from 2 to ~1.4

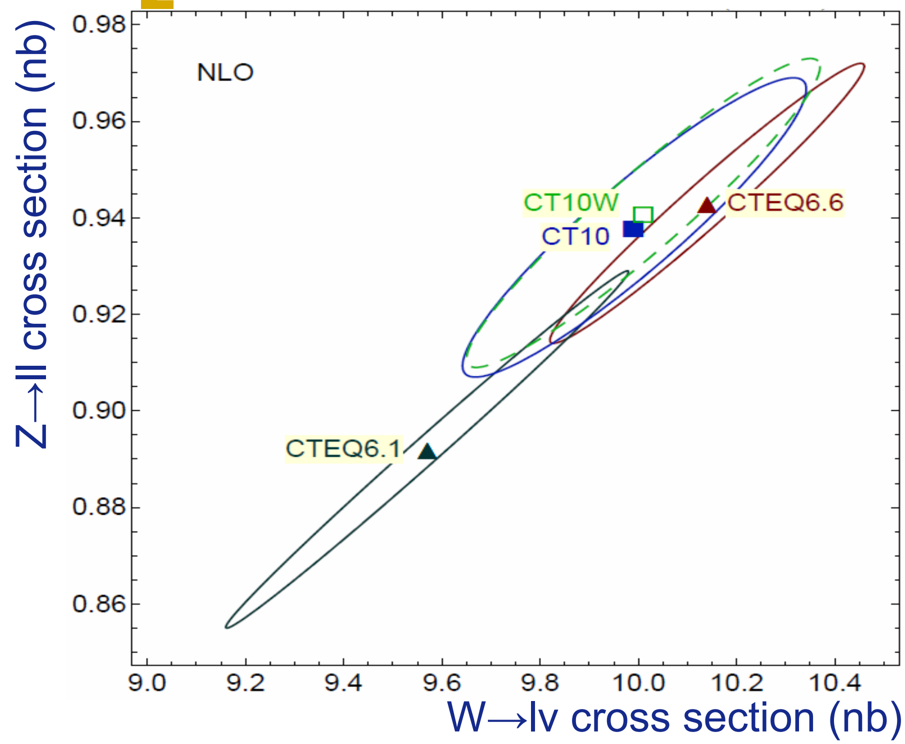
✦Theory uncertainties at few percent level

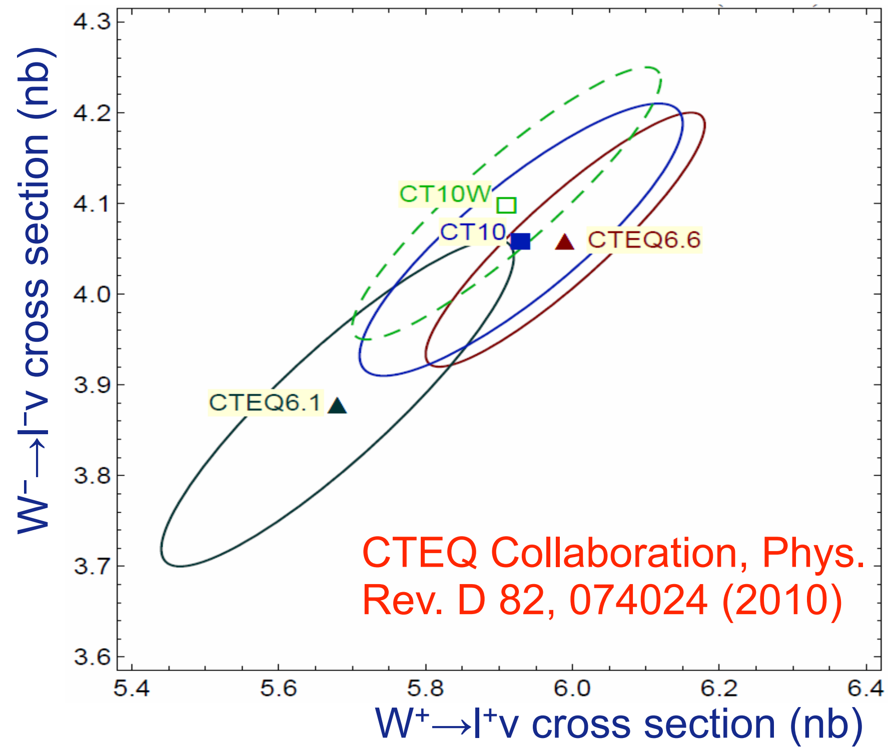
> 10^5 W→lv and > 10^4 Z→ll events in 2010 data !!

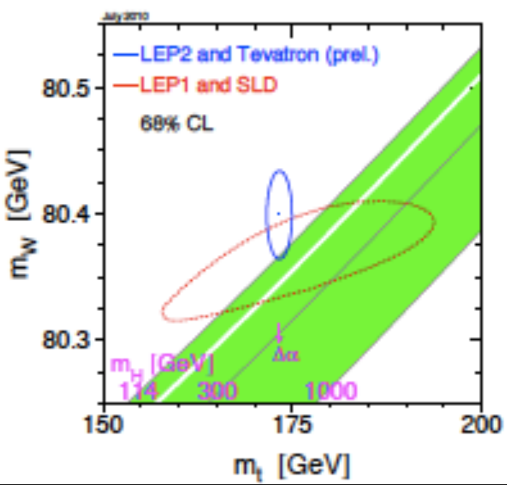


Cross sections = 4X Tevatron
W σxBR(W→lν) ~10 nb each l
Z σxBR(Z→ll) ~1 nb each l

Connection with the PDF







Ratios: W^+/W^- and W/Z production cross sections

- are insensitive to luminosity and other sources of uncertainties (2% precision)
- therefore provide precision test of perturbative QCD and proton PDFs
- inputs to constraining Higgs couplings, new physics models

Basic building blocks for EWK, Higgs analysis

- Requires excellent performance from the entire detector and several reconstructed "objects"

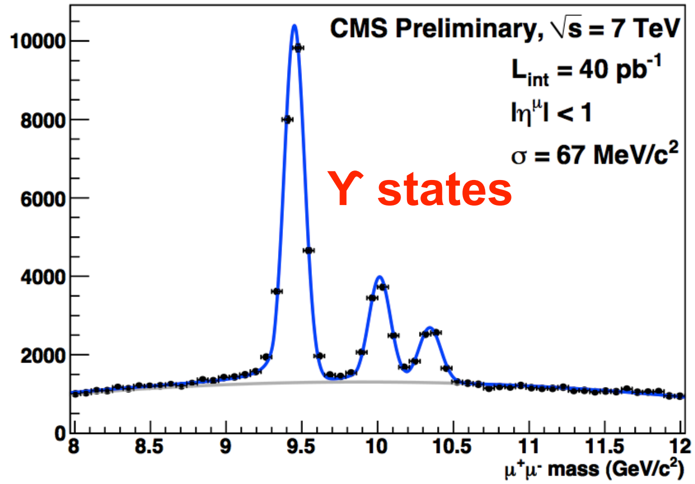
- Key objects:
  - ☑ Electron, muon, photon, jet
  - ☑ Missing transverse energy (MET)
  - ☑ Tau
  - ☑ b quark-jet tagging (b-tag)

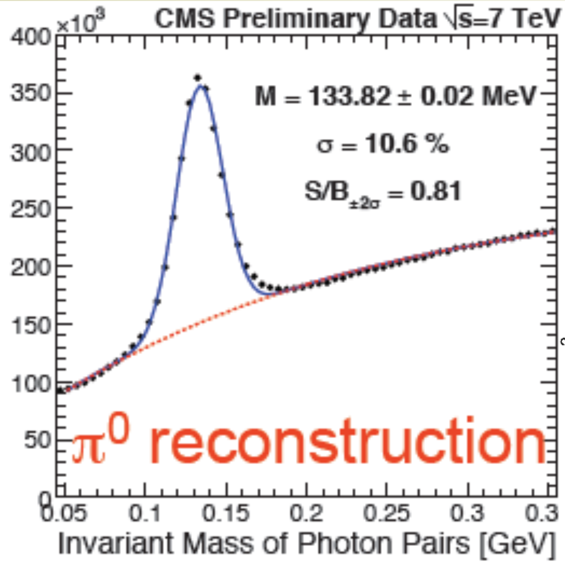
- Ability to reconstruct W, Z, top, W/Z+jets (including heavy flavor), and di-boson events and understand their production rates

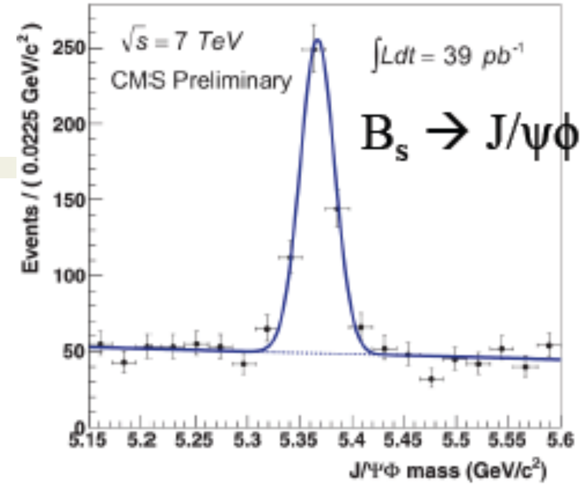
2010 data has demonstrated excellent performance of CMS in reconstruction of these basic objects

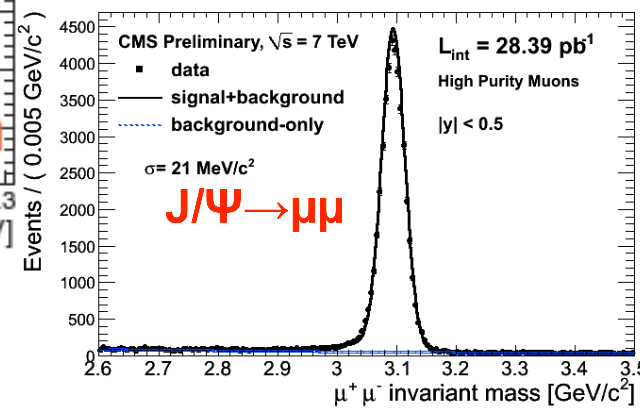
Performance in data closely matches expectations based on simulations (MC) and sometimes exceeds it

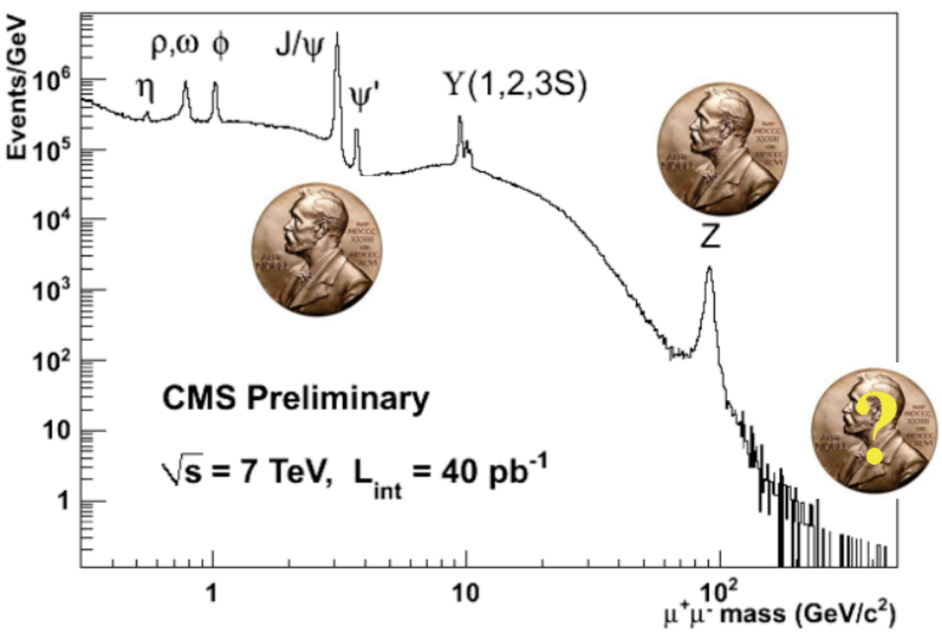
A well calibrated detector

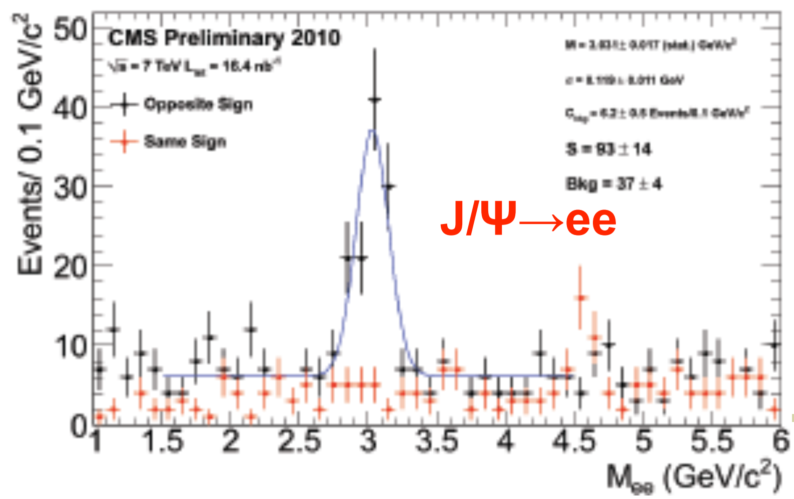








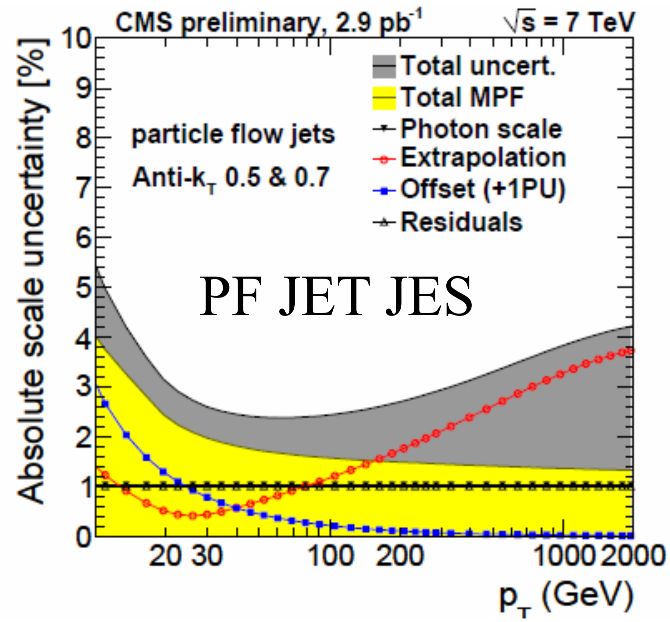




Jets and missing transverse energy

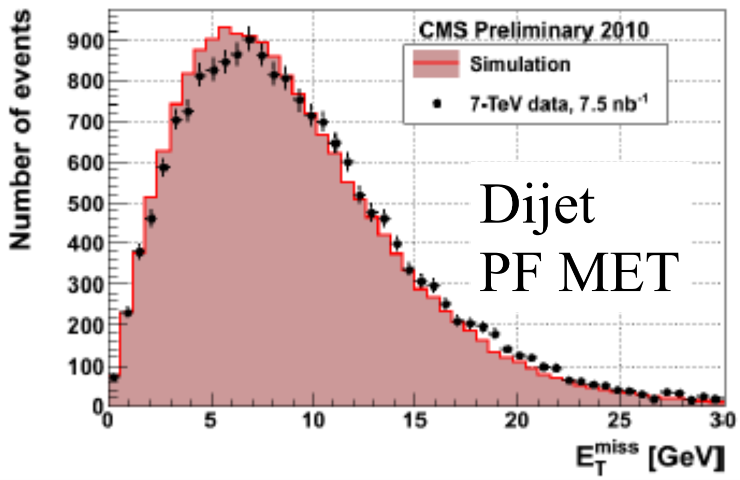
✦Jet and Missing ET reconstruction uses **Particle Flow** (PF) technique:

- -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

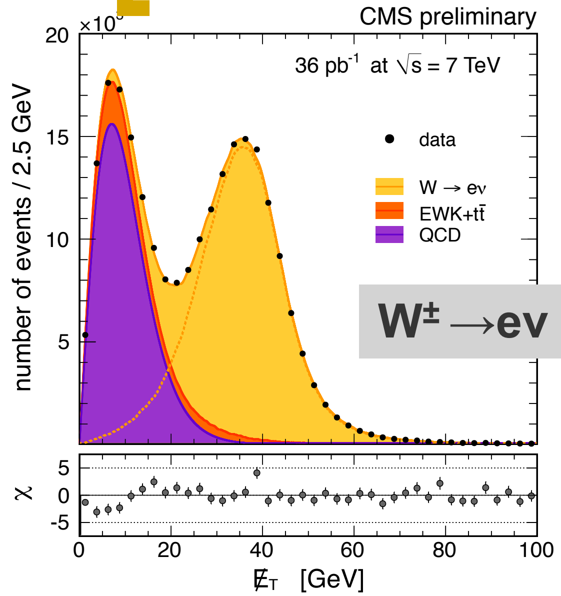


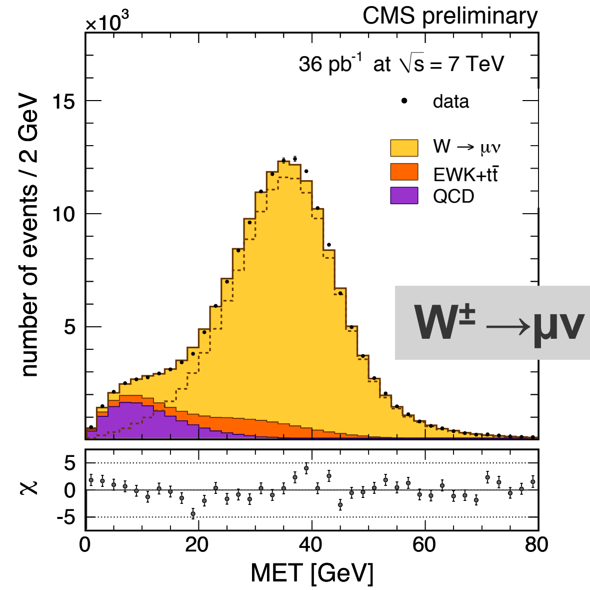
✦**Anti-kT clustering with R=0.5** used everywhere here

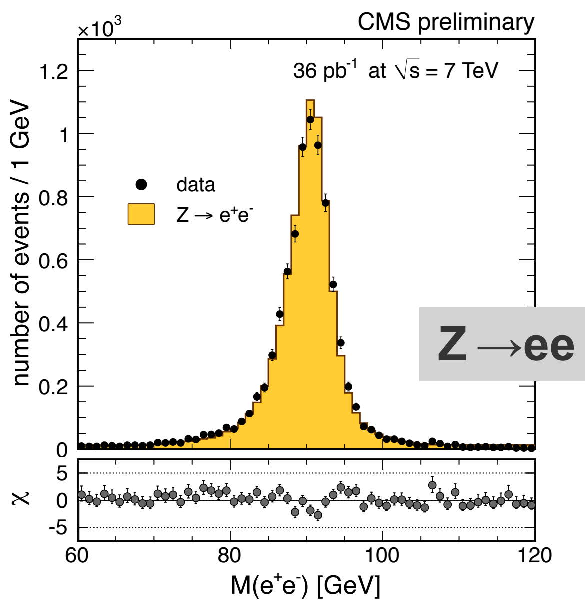
- -JES of PF jets known to 3−4%
- -PF MET FWHM in dijets ~10 GeV

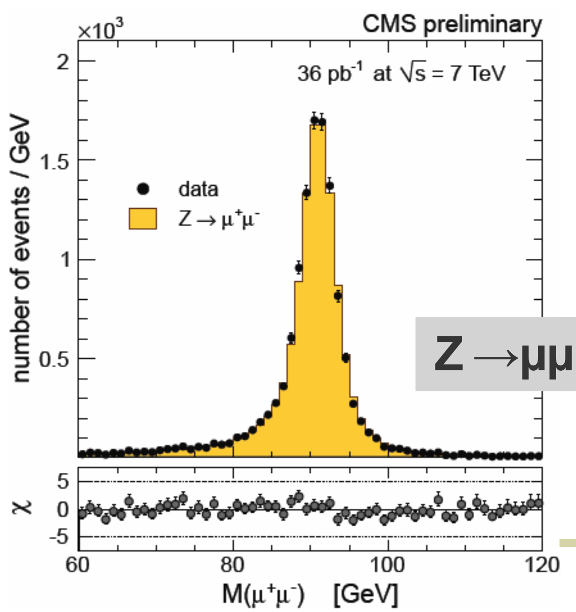


Leptons & MET: W and Z reconstruction









- ✦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

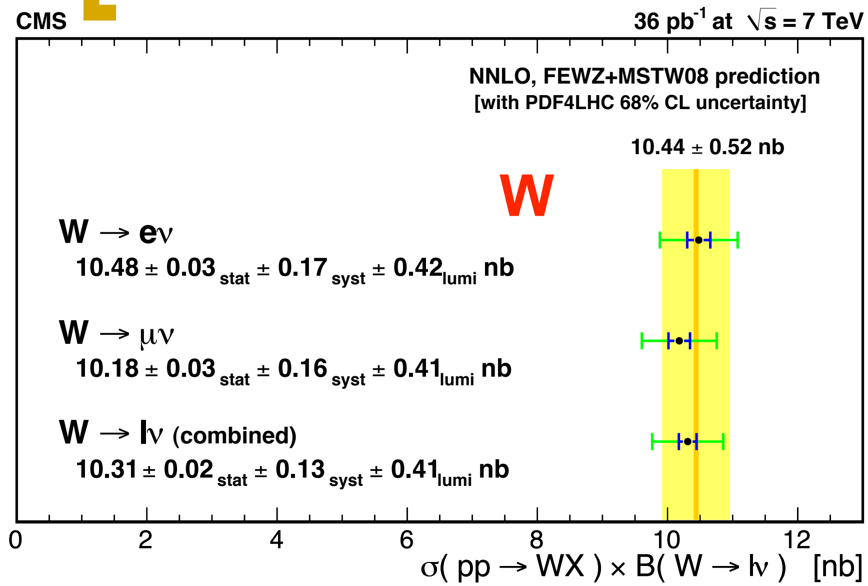
280000 W's

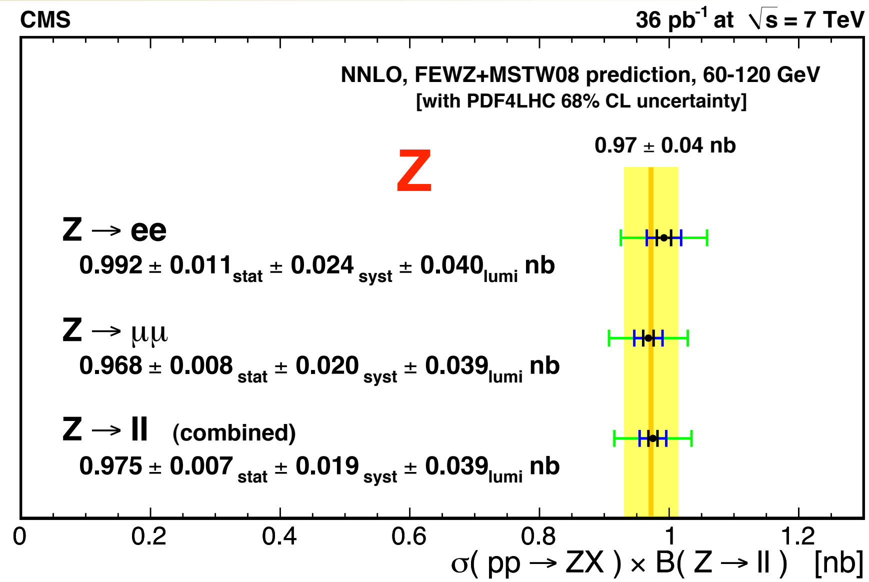
cross section x BR = 10.31 ± 0.02 (stat) ± 0.09 (syst) ± 0.10 (th.) ± 0.41 (lumi) nb

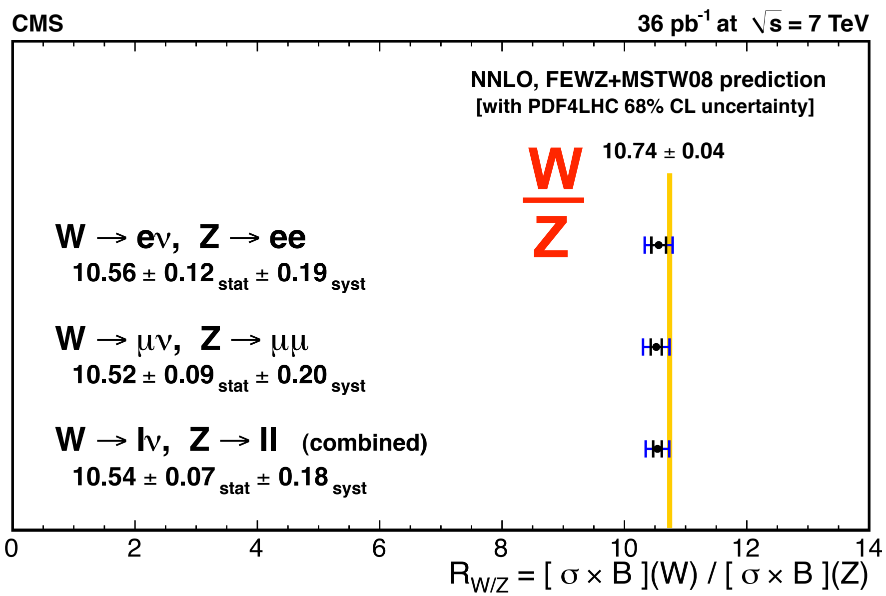
20000 Z's

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

W, Z cross section: precision measurements



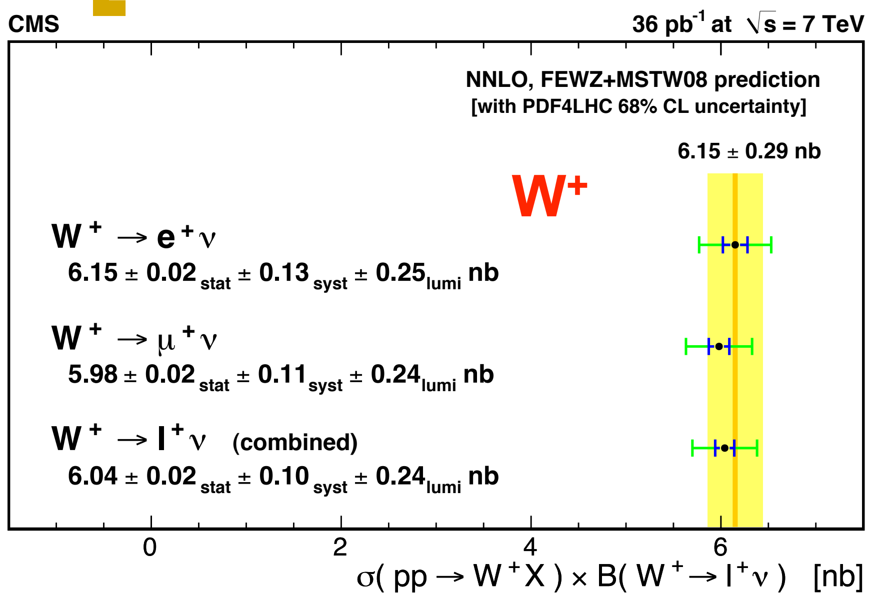


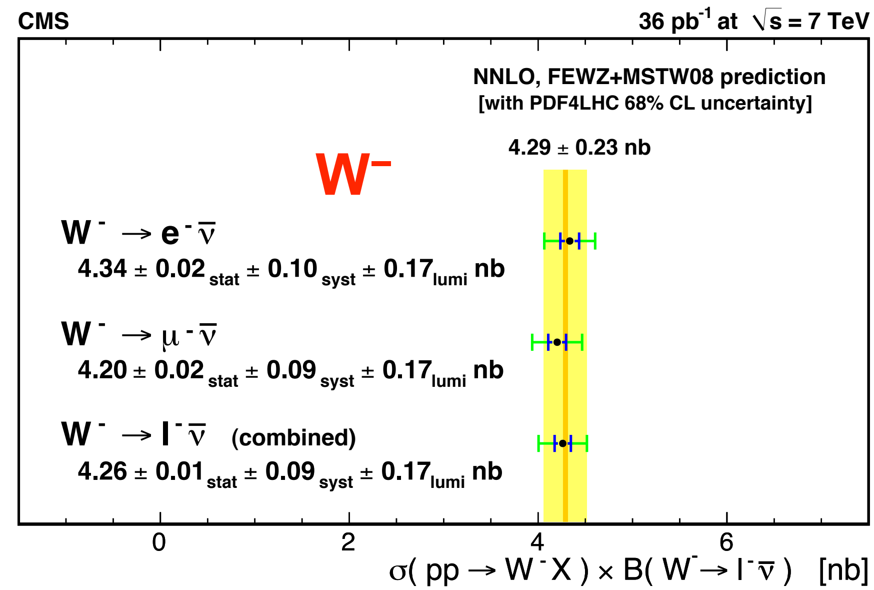


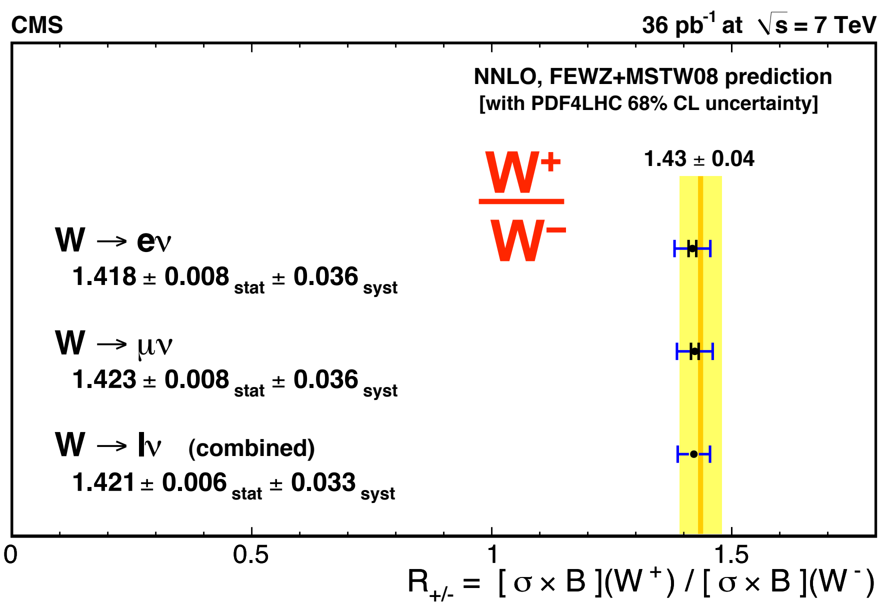
- Uncertainty in theory prediction
- Statistical uncertainty
- Systematic uncertainty
- Luminosity uncertainty (4%)

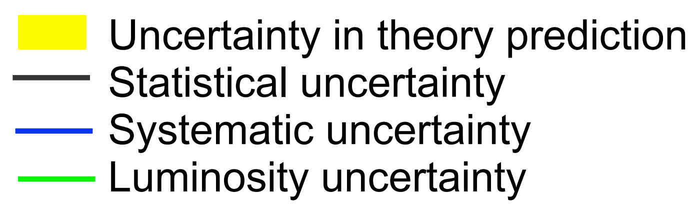
- W cross section non-lumi error **1.6%**
- Z cross section non-lumi error **2%**
- W/Z ratio total error **2%**
- Internally consistent across channels
- Everywhere systematics limited

W^+ and W^- cross section and their ratios



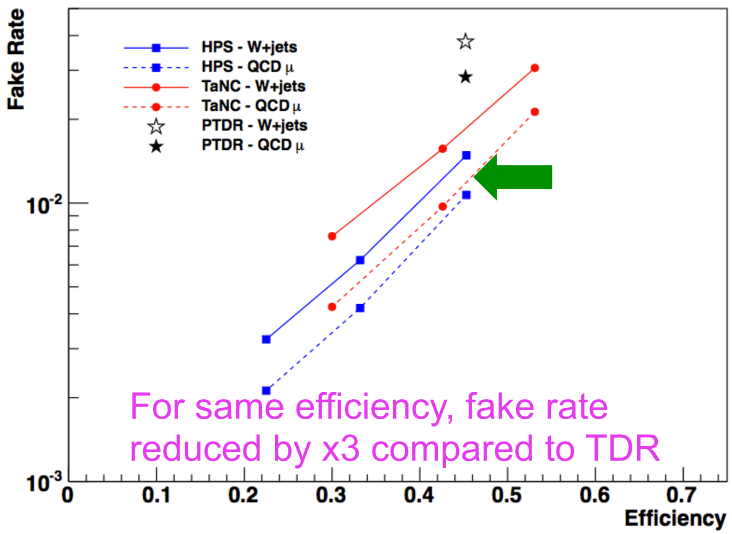


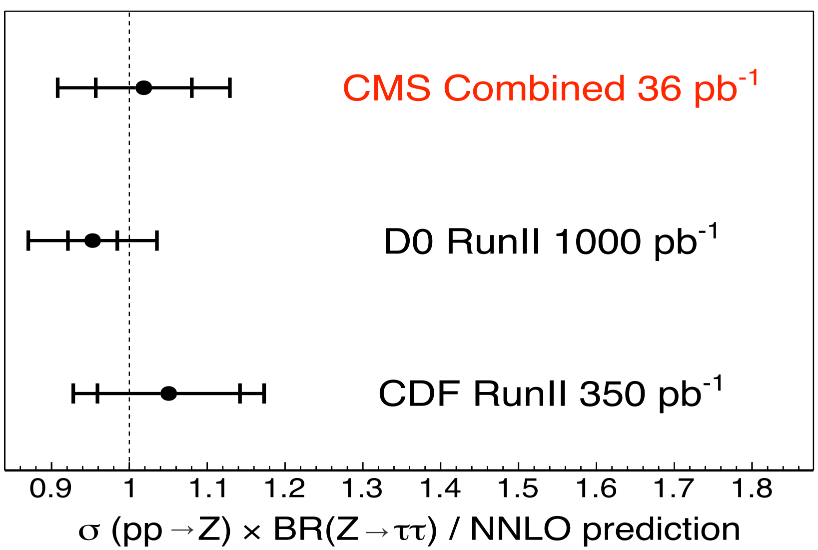


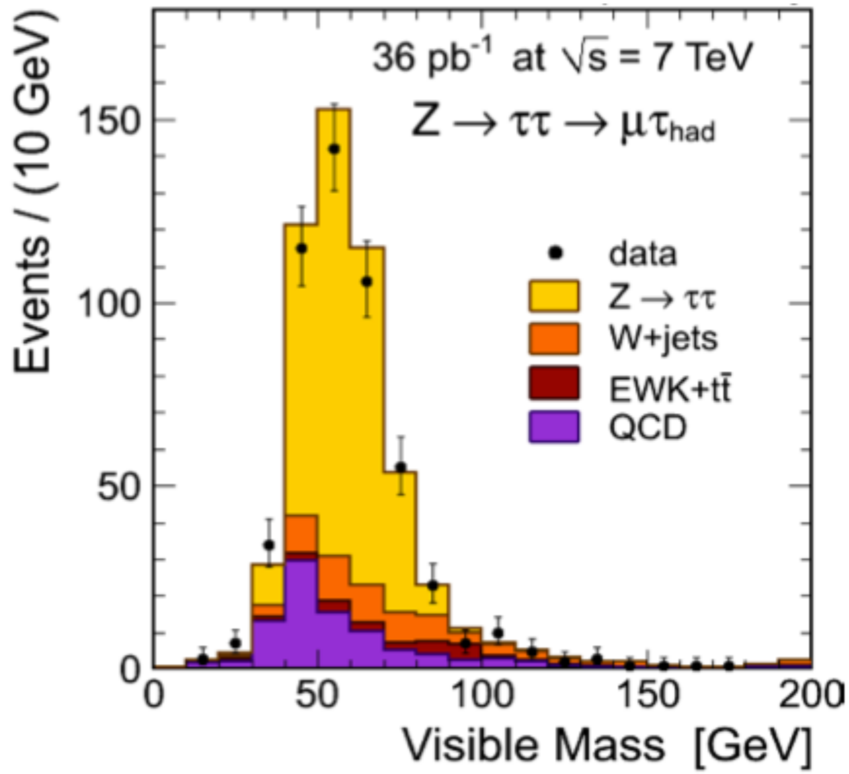


W^+ and W^-, and the ratio are consistent with PDF expectations. We measure the ratio within 2.5% uncertainty.

Tau reconstruction: excellent performance



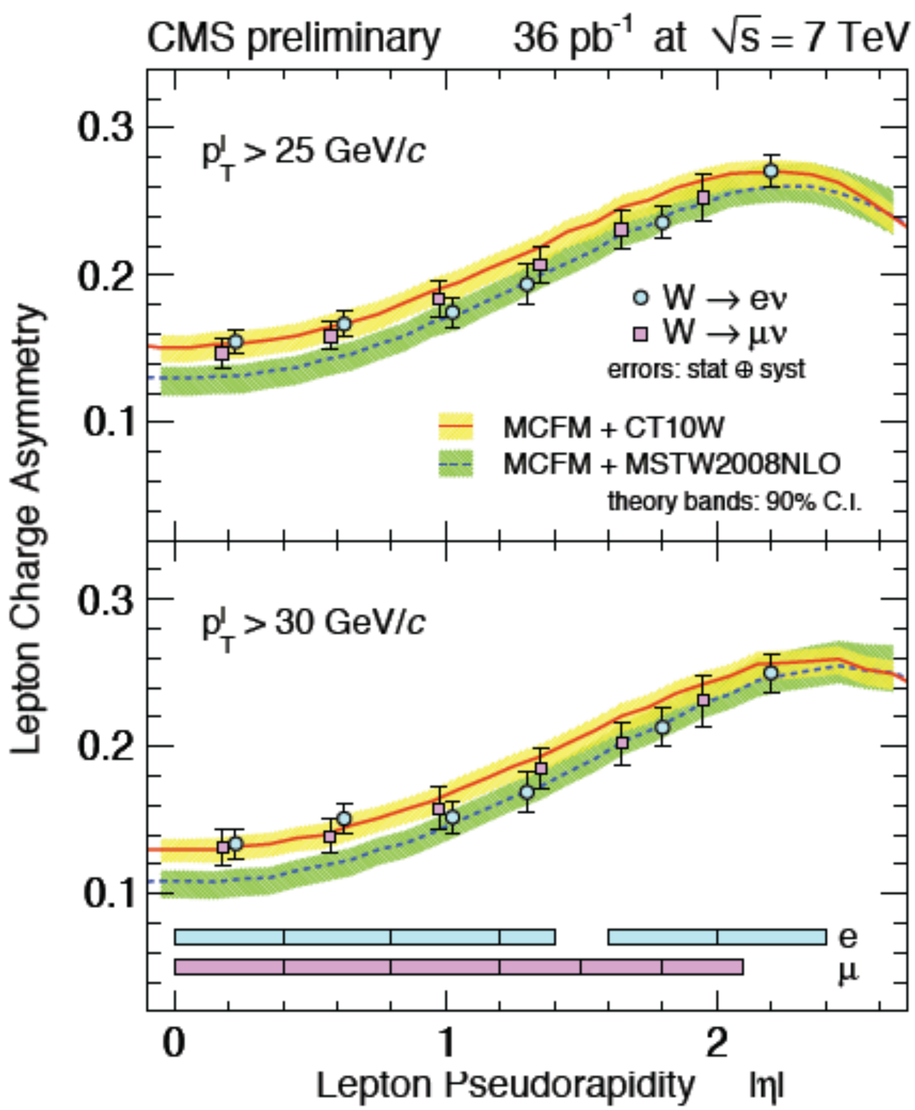




Clean sample of $Z \to \tau\tau$

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

Other precision EWK results: $W^{\pm}$ asymmetry



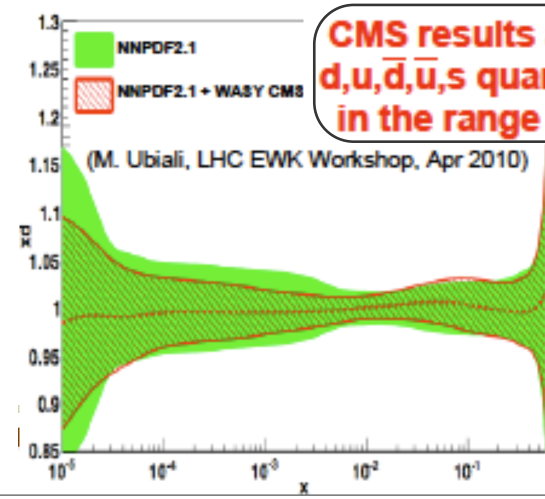
Measure W charge asymmetry like shown before but in bins of lepton rapidity

✦This is the first measurement of W charge asymmetry (binned) at LHC

- -Electron & muon channels are in good agreement with each other

✦Neither of the two most-used NLO PDFS describe the data well

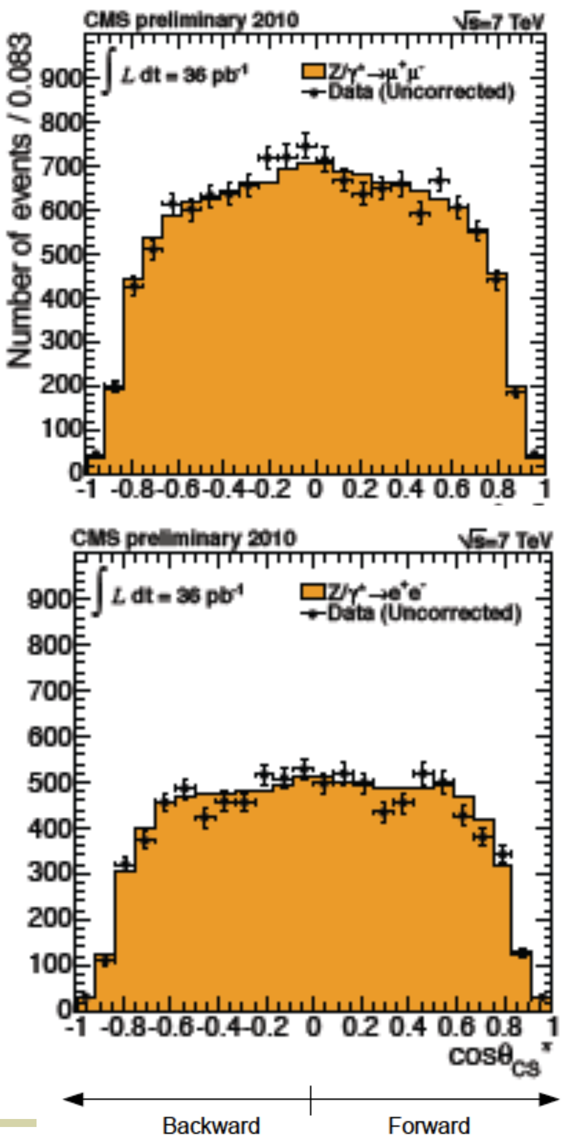
- -precision of the measurement is significant enough to provide new inputs to the PDF global fits.



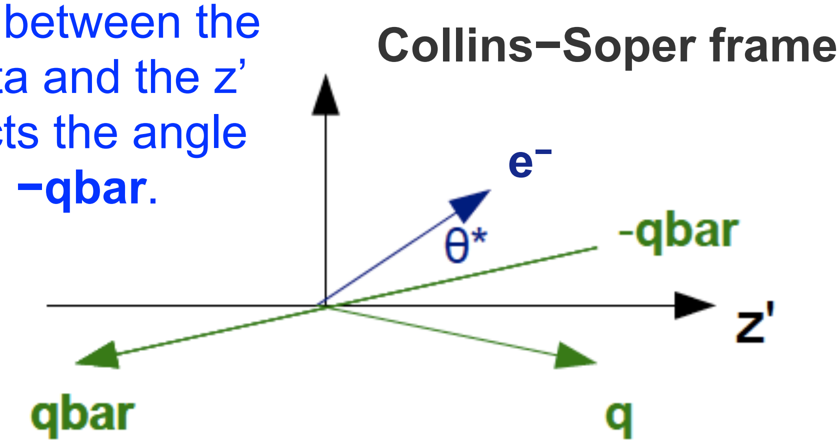
CMS results already improve d,u,$\bar{d}$,$\bar{u}$,s quark PDFs by >40% in the range $10^{-3} < x < 10^{-2}$!!!

potential to improve by a factor 3

Z production topology: cosine θ*



θ* is the angle between the lepton momenta and the z' axis that bisects the angle between **q** and **−qbar**.



J.C. Collins and D.E. Soper, Phys. Rev. D 16, 2219 (1977)

- **Forward** events ($\cos\Theta^*>0$)
- **Backward** events ($\cos\Theta^*<0$)

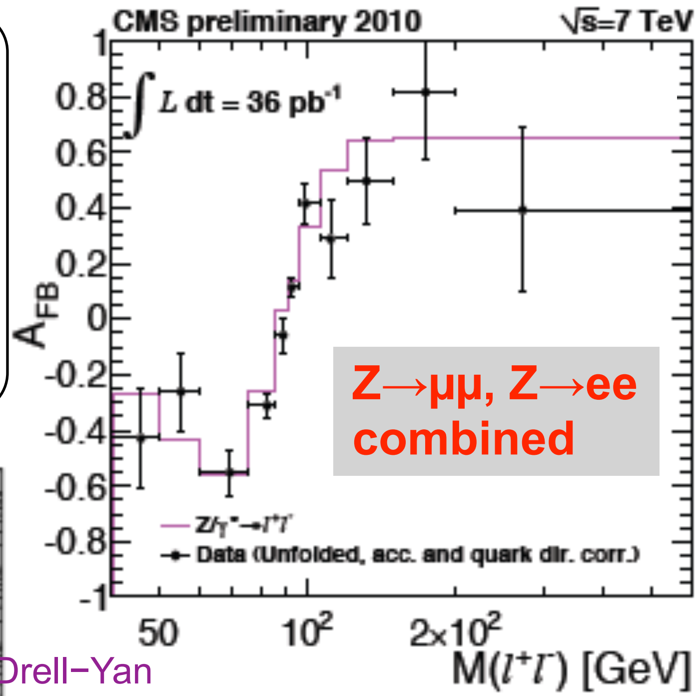
✦Z−γ* interference gives rise to forward−backward asymmetry in production
✦But the knowledge of initial quark direction is diluted at LHC

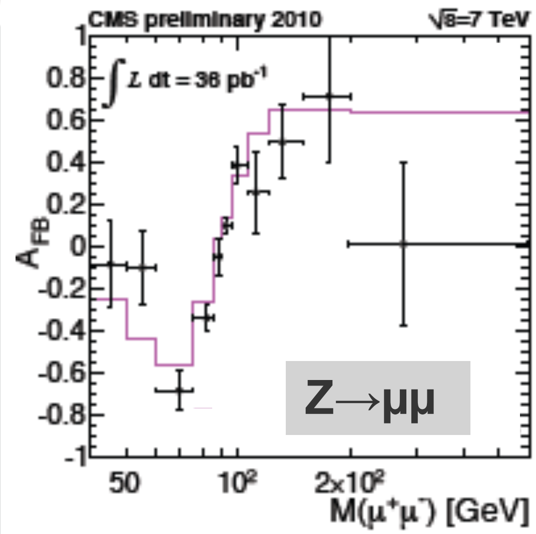
Z forward-backward asymmetry

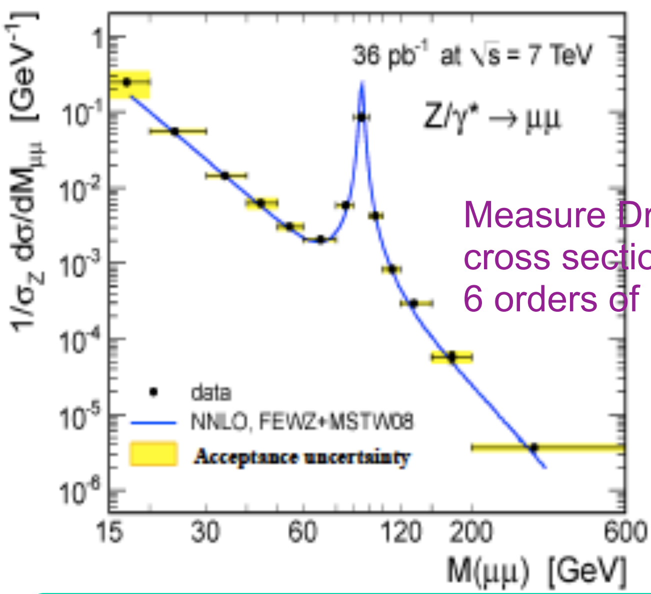
This is a measurement sensitive to $\overline{\sin^2\theta_W}$ parameter in the SM

$$\frac{d\sigma}{d\cos\theta^*} = \frac{3}{8}(1+\cos^2\theta^*) + A_{FB}\cos\theta^*$$

A_{FB} depends on the quark type (u,d) and on $\overline{\sin^2\theta_W}$



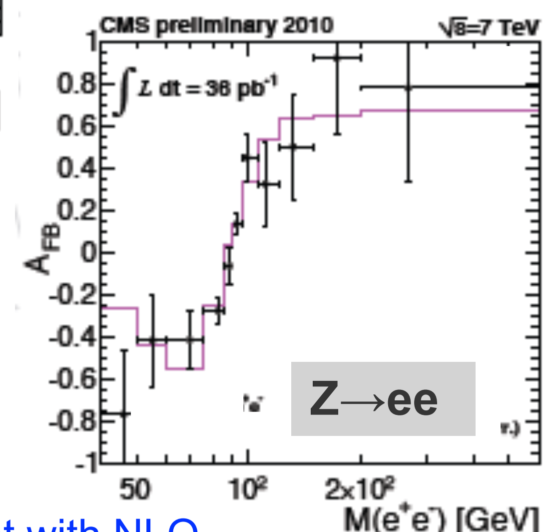




Measure Drell−Yan cross section drop by 6 orders of magnitude

In each Z mass bin, we compute asymmetry

$$A_{fb} = \frac{(N_f - N_b)}{(N_f + N_b)}$$

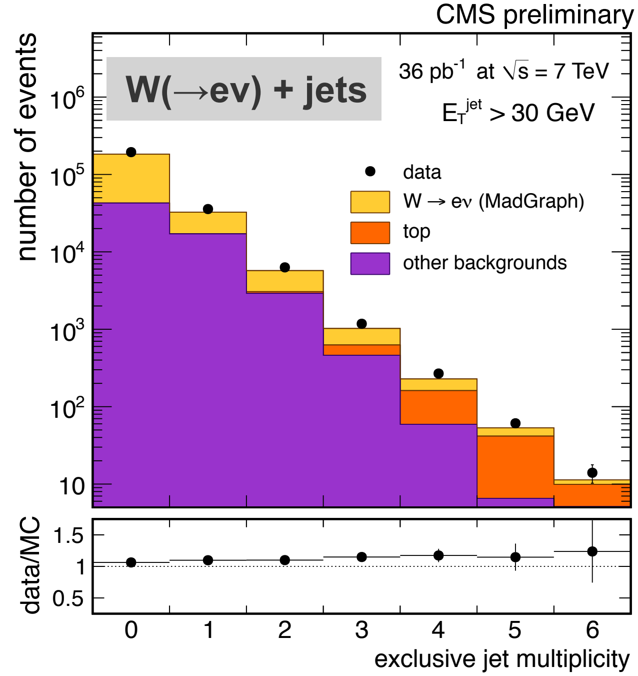


$$\sin^2\theta_{\rm eff} = 0.2287 \pm 0.0077({\rm stat.}) \pm 0.0036({\rm syst.})$$

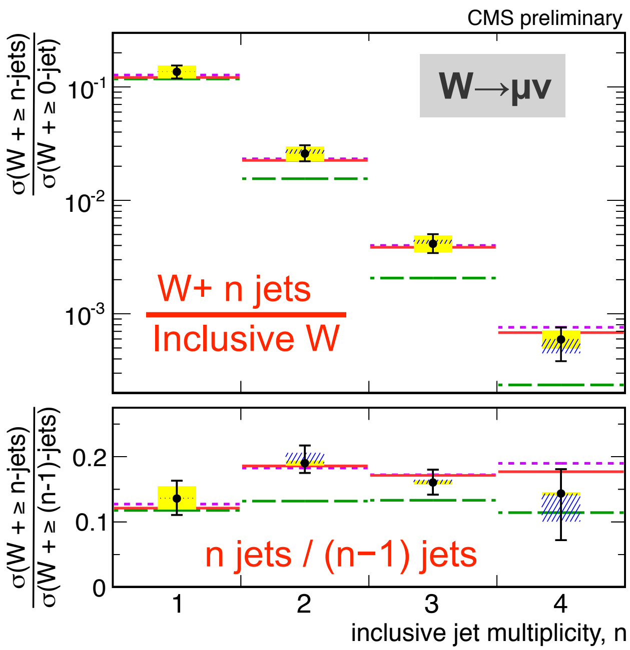
Consistent with NLO

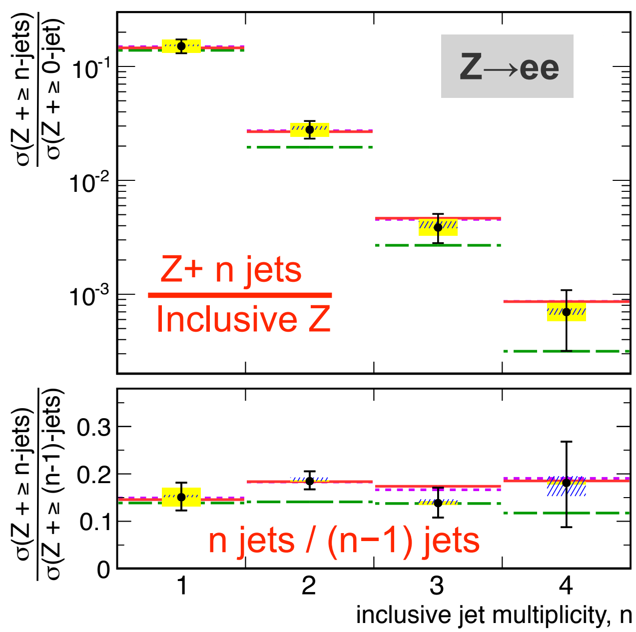
W,Z production in assoc. with jets

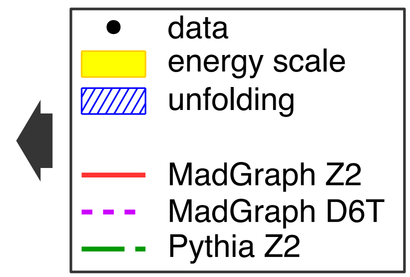
- Key background for most new physics searches
- Standard strategy: a) LO matrix element calculations for each jet multiplicity, b) interface with parton shower MC using specific matching recipe (AlpGen, MadGraph, Sherpa)
- Despite difficulty some NLO calculations appeared recently



Results agree with expectations from MadGraph. Pythia doesn't agree with data (only expected to describe up to 1 hard jet + soft/collinear radiation (LO+ME reweighting)







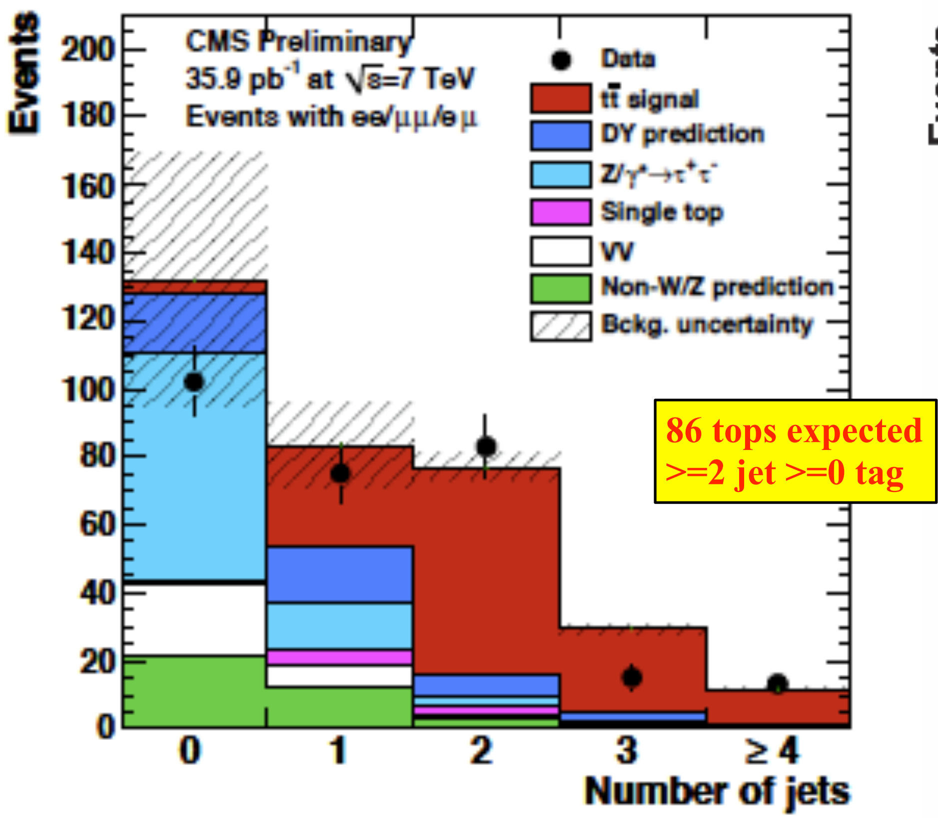
These are important processes to understand for LHC physics program. Need close collaboration with theorists.

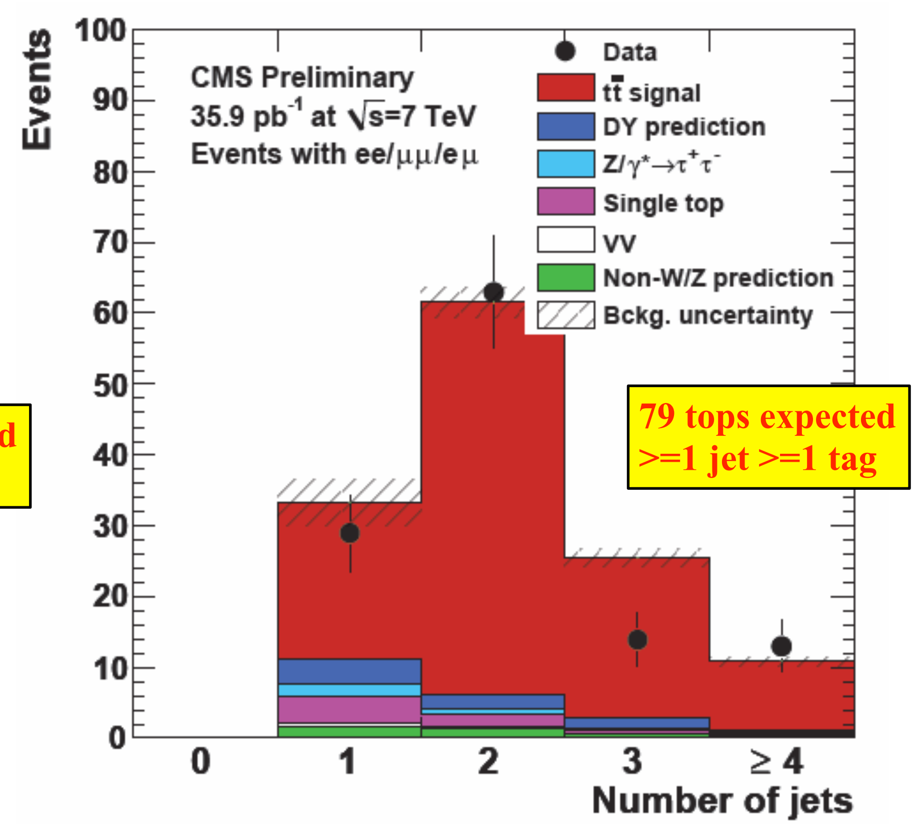
Commissioning 3rd generation: top and bottom

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

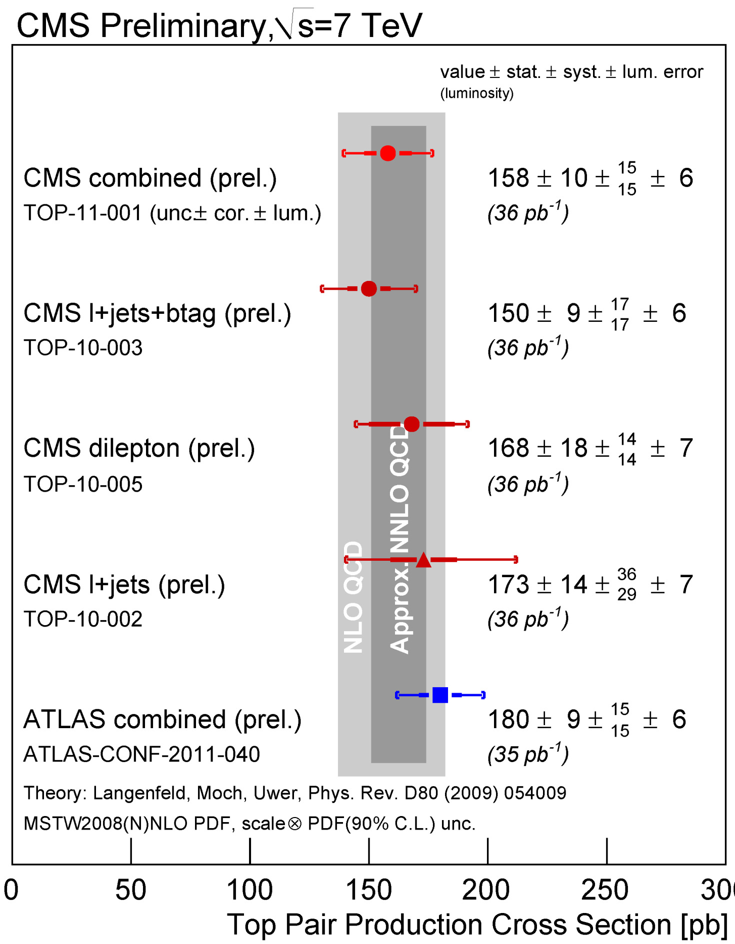
Simple counting experiment in Njet/Ntag bins



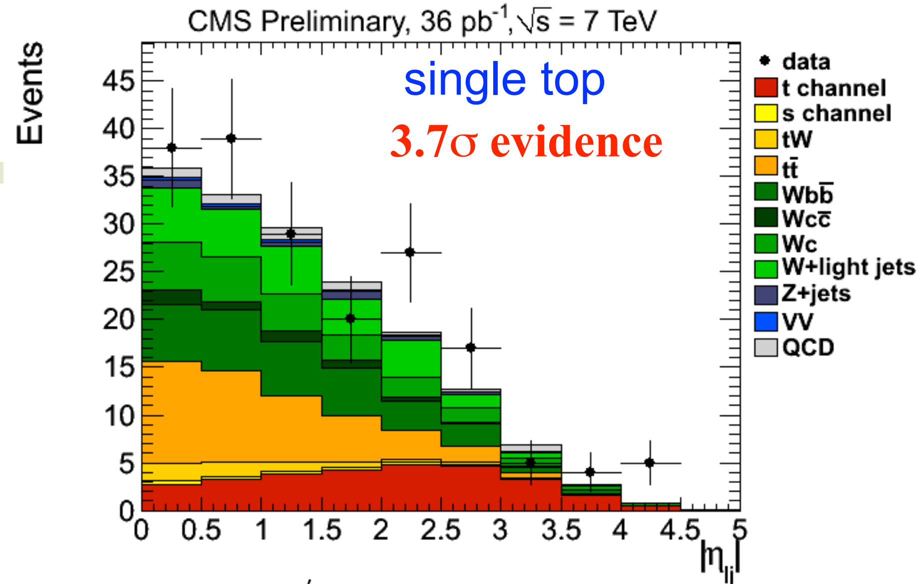


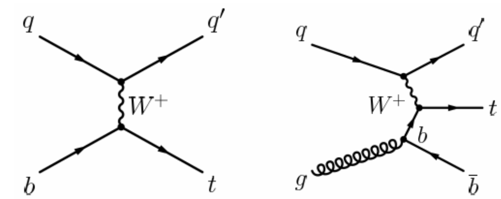
$\sigma(pp \rightarrow tt) = 168 \pm 18(\text{stat.}) \pm 14(\text{syst.}) \pm 7(\text{lumi.})$ pb

Top cross sections

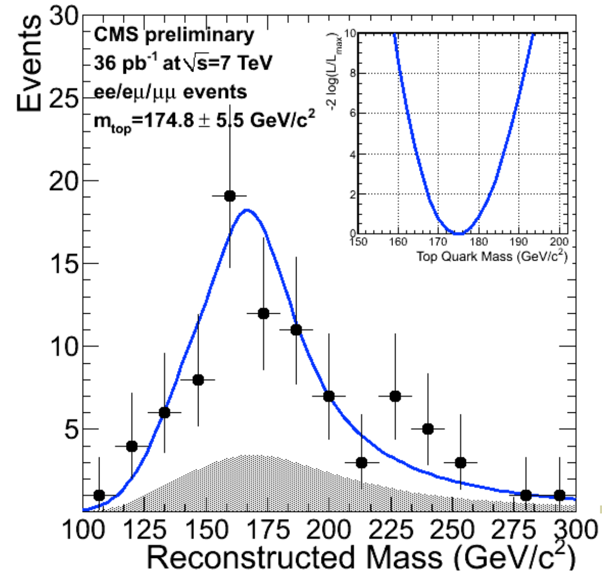


12% precision obtained. All measurements consistent with the SM and with each other



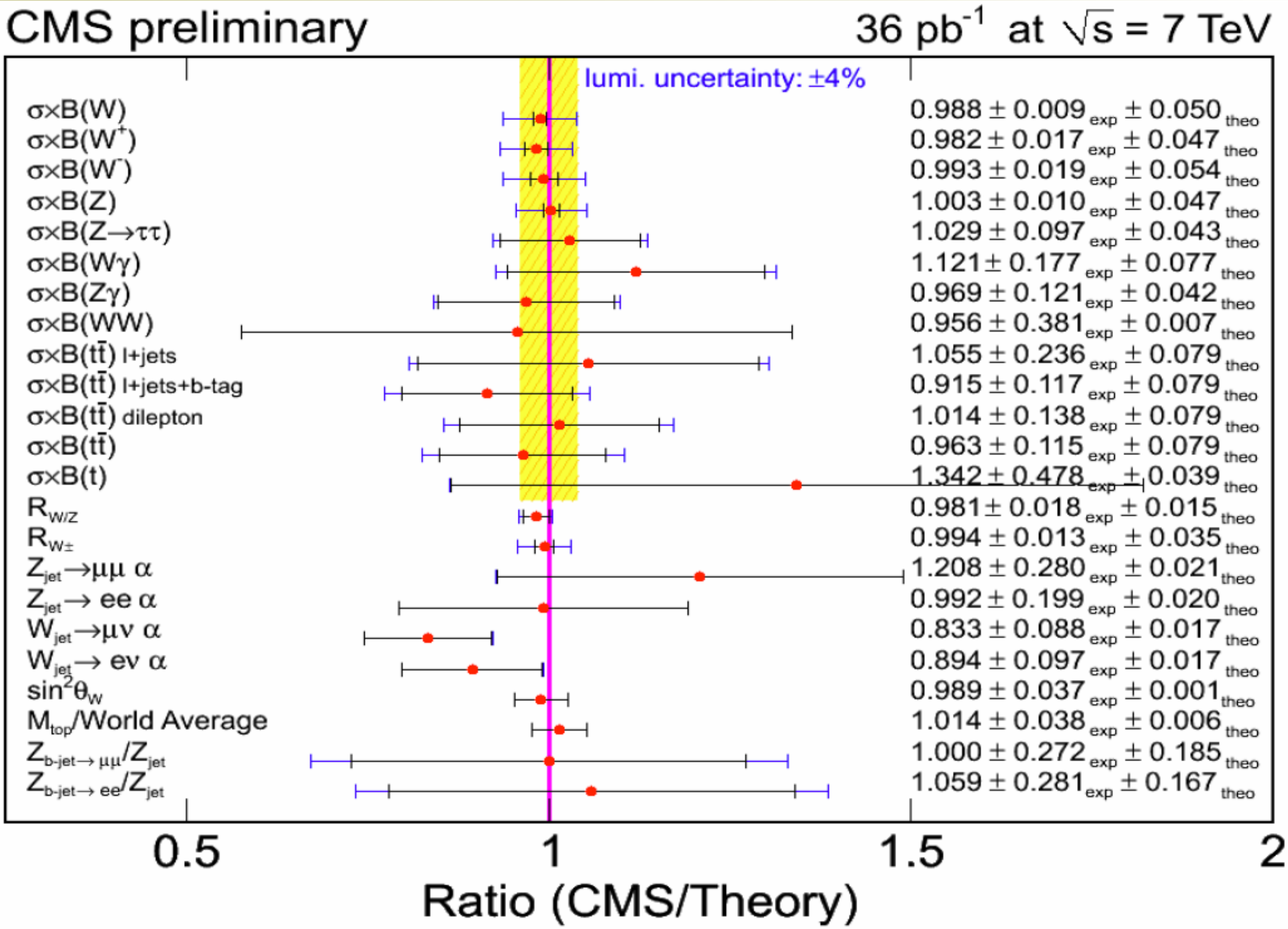


$|\eta_{lj}|$ is rapidity of the recoil jet (signal is more forward)

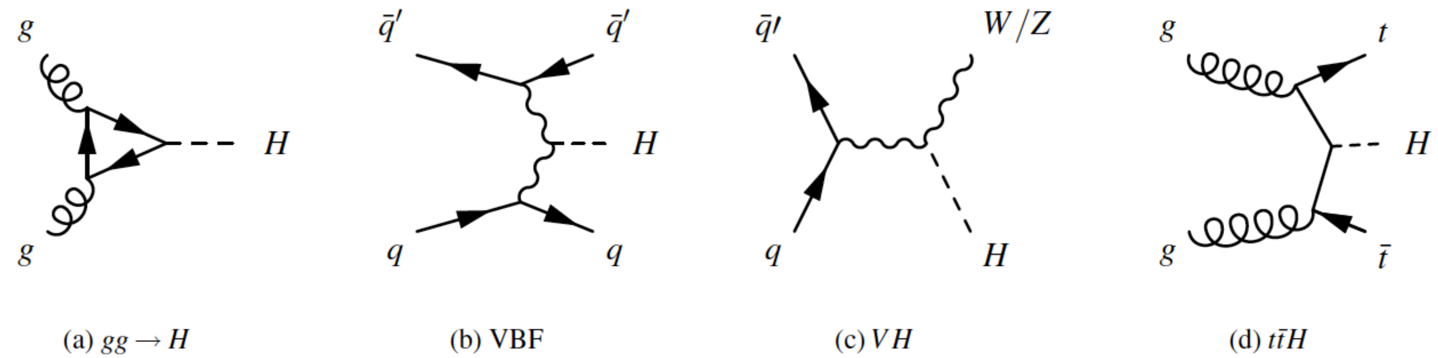


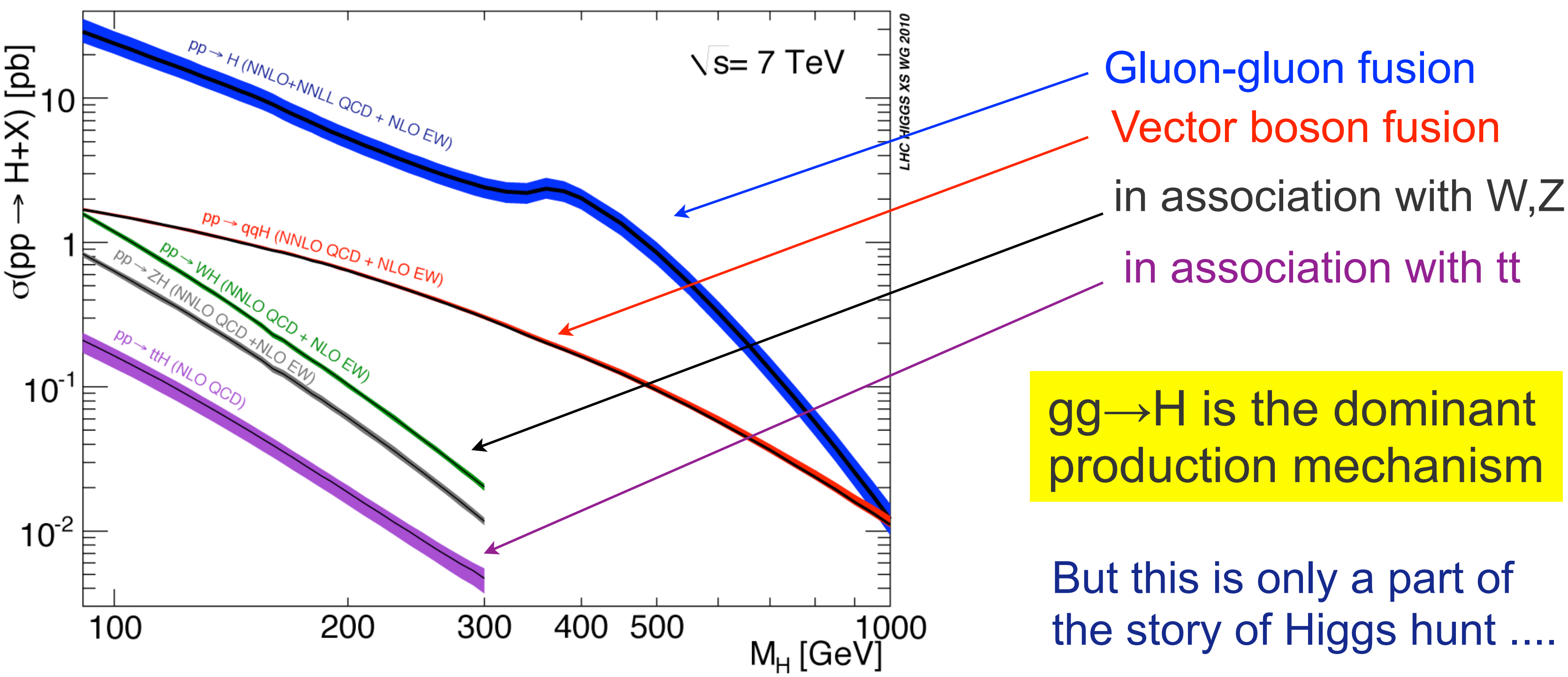
First CMS top mass measurement!

The Standard Model: How am I



Higgs production at LHC

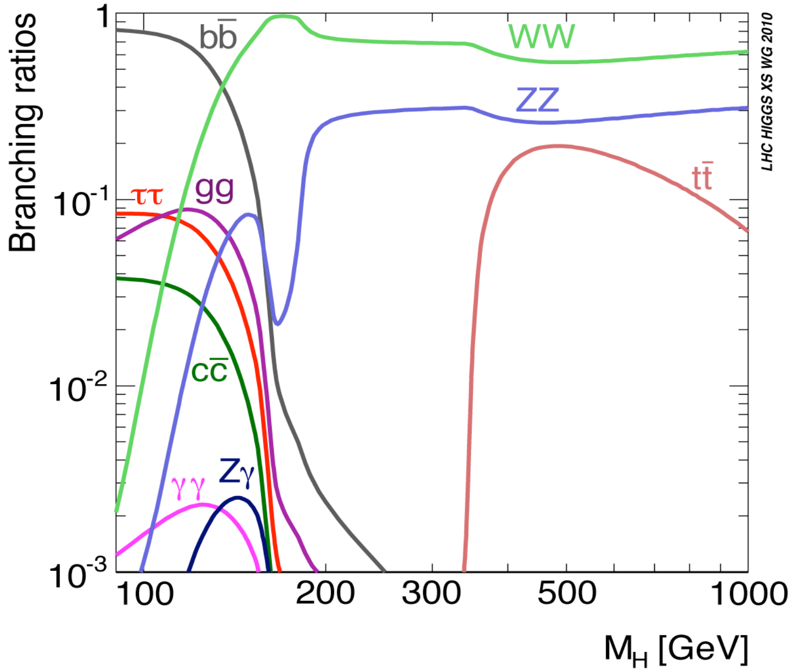




gg→H is the dominant production mechanism

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

Higgs decay modes vs its mass



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

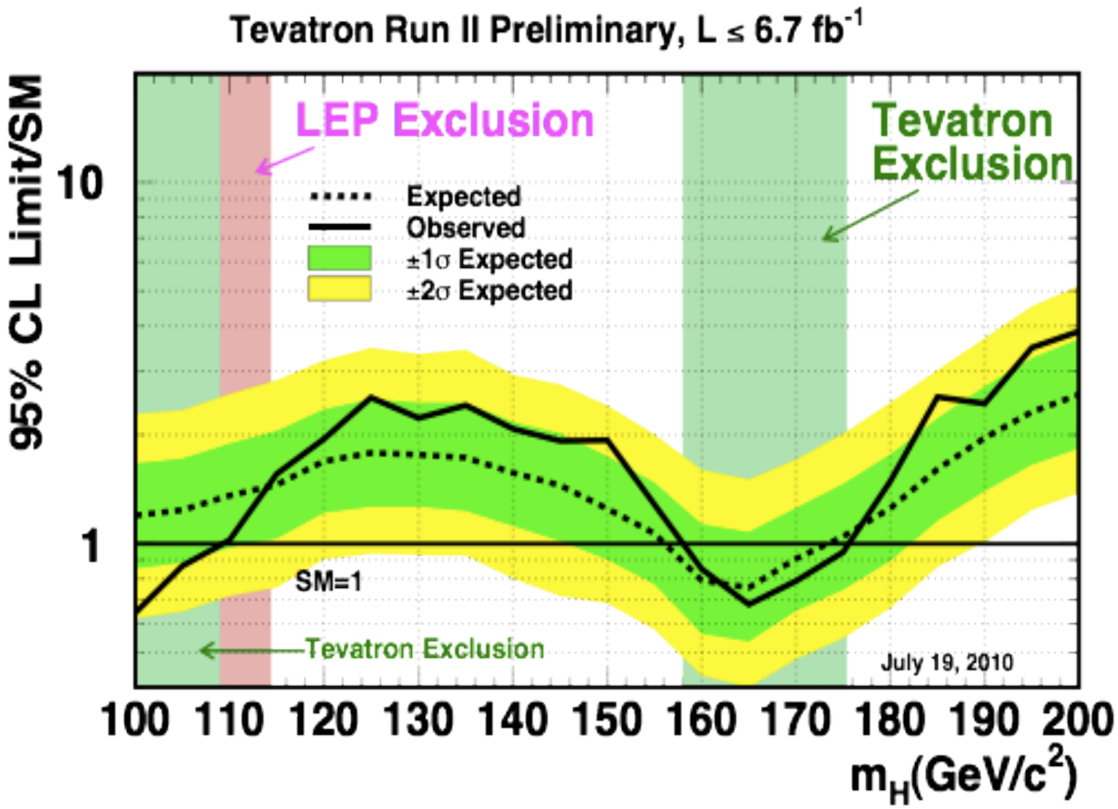
BR is the second part of Higgs story

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

- ✦H→bb has hopelessly high QCD background
  - -only associated production mode (WH or ZH with H→bb) can be used
  - -even then life is tough. Several new ideas are being tried
  - -this makes H→γγ attractive for low mass Higgs (m_H ≈ 120 GeV)

- ✦On a contrary note, W/Z+jets background falls off rapidly with mass
  - -this makes H→WW(lvjj) and ZZ (llvv, lljj) more sensitive for high m_H

Current experimental limits on Higgs



The Higgs search landscape

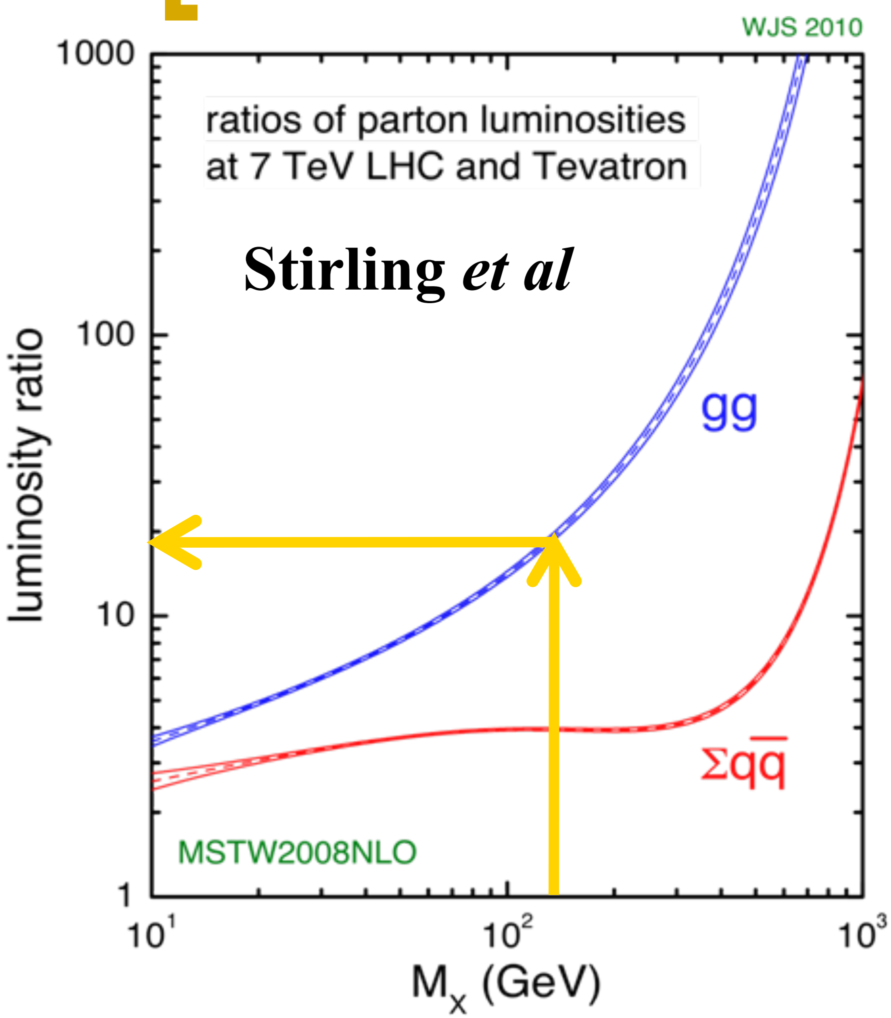
Low Mass ($M_H \approx$ 120 GeV)	Mid Mass (≈ 160 GeV)	High Mass (≈ 400 GeV)
$H \to \gamma\gamma$	$H \to WW$	$H \to ZZ$
$H \to WW$	$H \to ZZ$	$H \to WW$
$qqH \to \tau\tau$		
$V + H \to bb$		
$qqH \to bb$		
$V + H \to WW$		

95% CL Exclusions: 158 < M_H < 175 GeV ; 100 < M_H < 109 GeV

Limit : 1.5x σ_{SM} for M_H = 115 GeV

Note: Limits on non-SM Higgs are much weaker

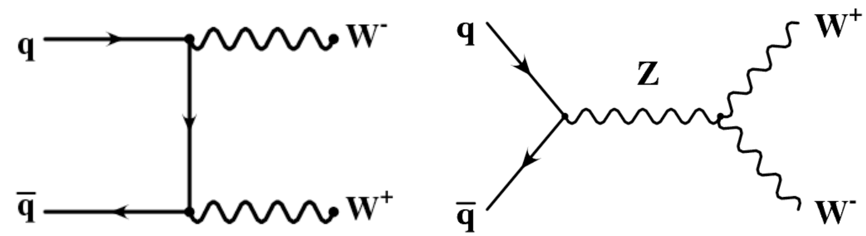
LHC vs Tevatron: partonic lumi helps $m_H > 140$



For M_H > 140 GeV

gg → H cross section at 7 TeV is >15 times that at 2 TeV

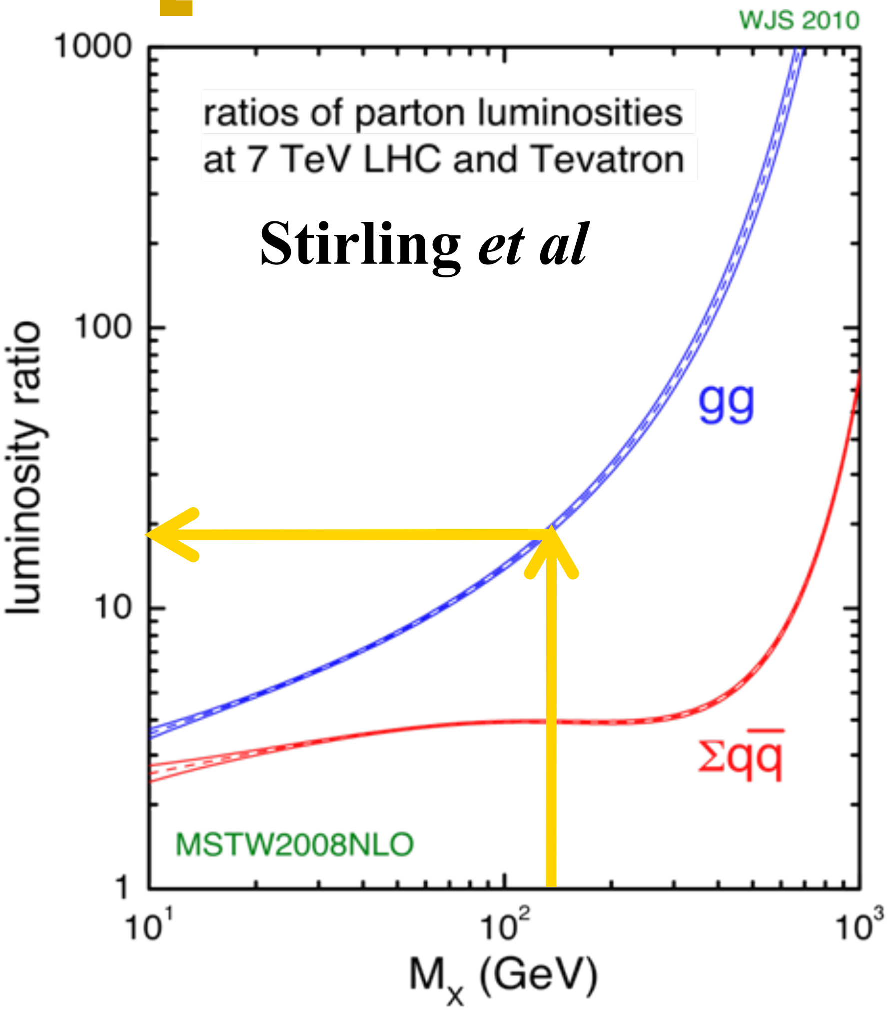
Irreducible backgrounds (WW,ZZ) originate from $q\bar{q}$ process which rises relative slowly (pp vs $p\bar{p}$)



⇒ Larger signal, better S/N

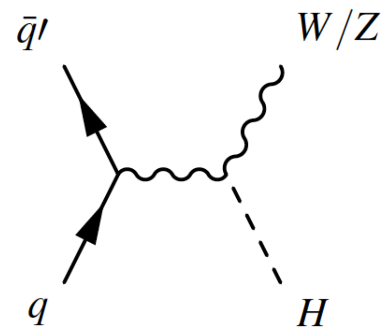
What about low m_H ? Well, Higgs is then produced in qq annihilation ....

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 → 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

$\Rightarrow$ Small signal, worse S/N

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

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 $H \to W(l\nu)W(l\nu)$ 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

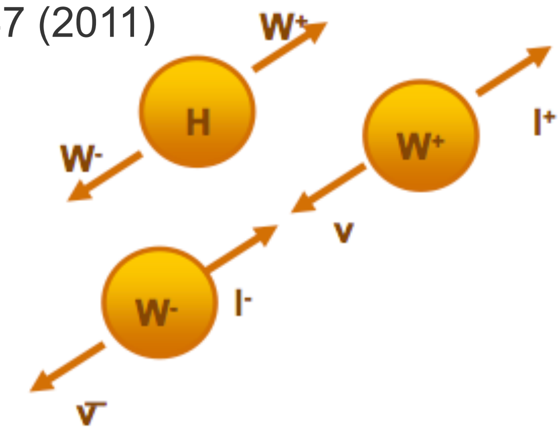
- ☑ Search for MSSM Higgs in $H \to \tau\tau$ channel
  - -we again broke new ground here
  - -improve over Tevatron limit <u>for all values of Higgs mass and tanβ</u>

- ✦ 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 $H \to \gamma\gamma$, $H \to W(l\nu)W(jj)$, $H \to ZZ$, and associated production with vector boson modes
  - -CMS has similar sensitivity to ATLAS in <u>**all**</u> channels

- ✦ We'll show you results on them <u>when they get to the point of being interesting</u>

$H \to WW \to 2l2\nu$: 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

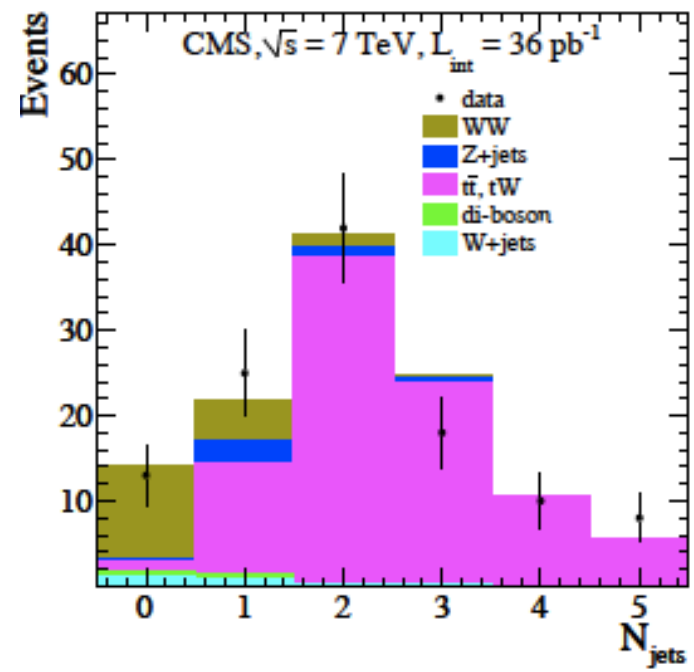
✦Reduction of major backgrounds:

- **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:

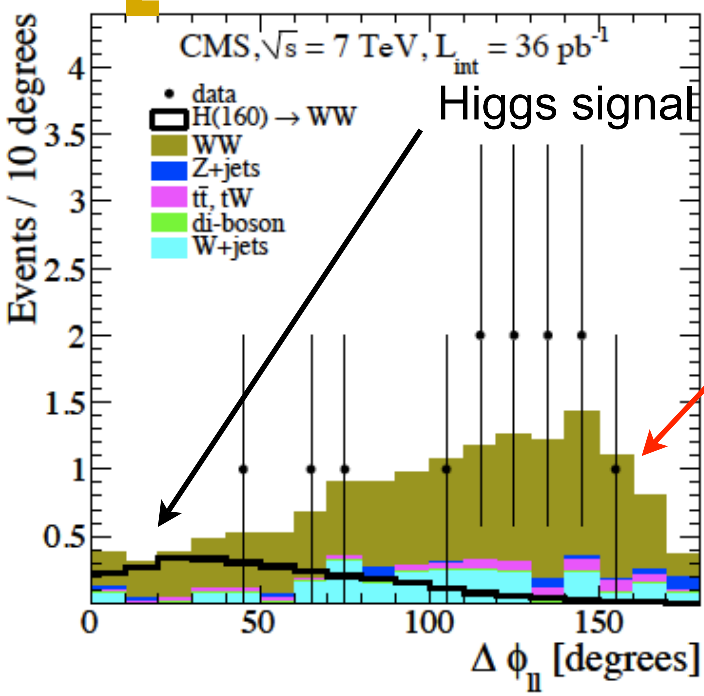
- Cut on kinematic observables
- Cut on a BDT output & count
  - 15% higher eff for same bkgnd

✦Backgrounds are estimated using data



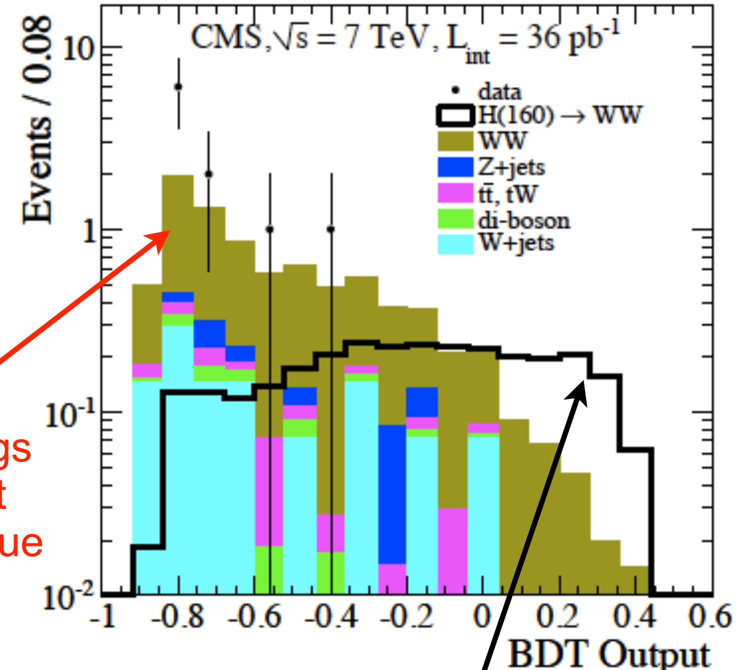
Different N_{jets} samples have different levels of signal purity. 0−jet is the purest. By optimizing N_{jets} samples independently we increase Higgs signal efficiency.

H→WW→2l2ν: analysis details



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

SM WW peaks high



SM bkgs peak at low value

Higgs signal has higher BDT output value

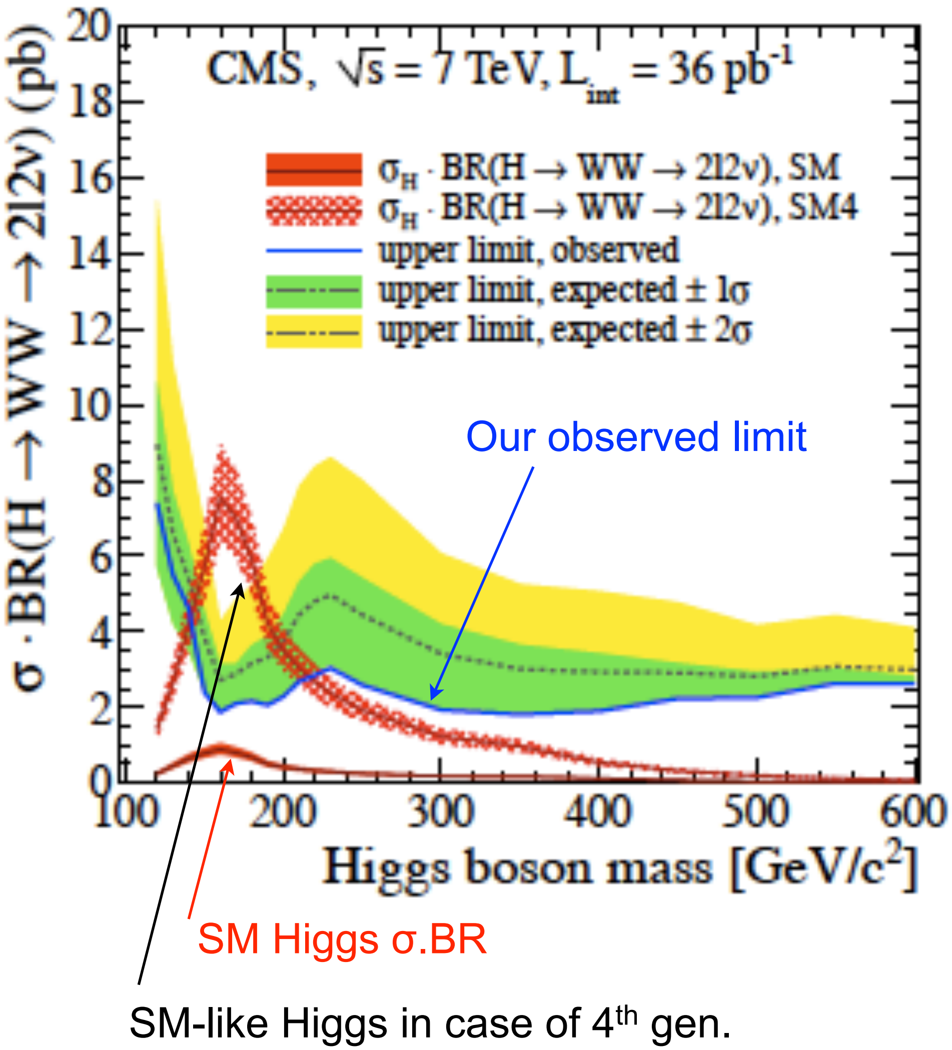
Observe **13** events: 2 in ee, 10 in eμ, 1 in μμ
Estimate **3.29** ± 0.45 ± 1.09 events from bkg

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

σ_{WW} = 41.1± 15.3 (stat) ± 5.8 (sys) ± 4.5 (lumi) 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



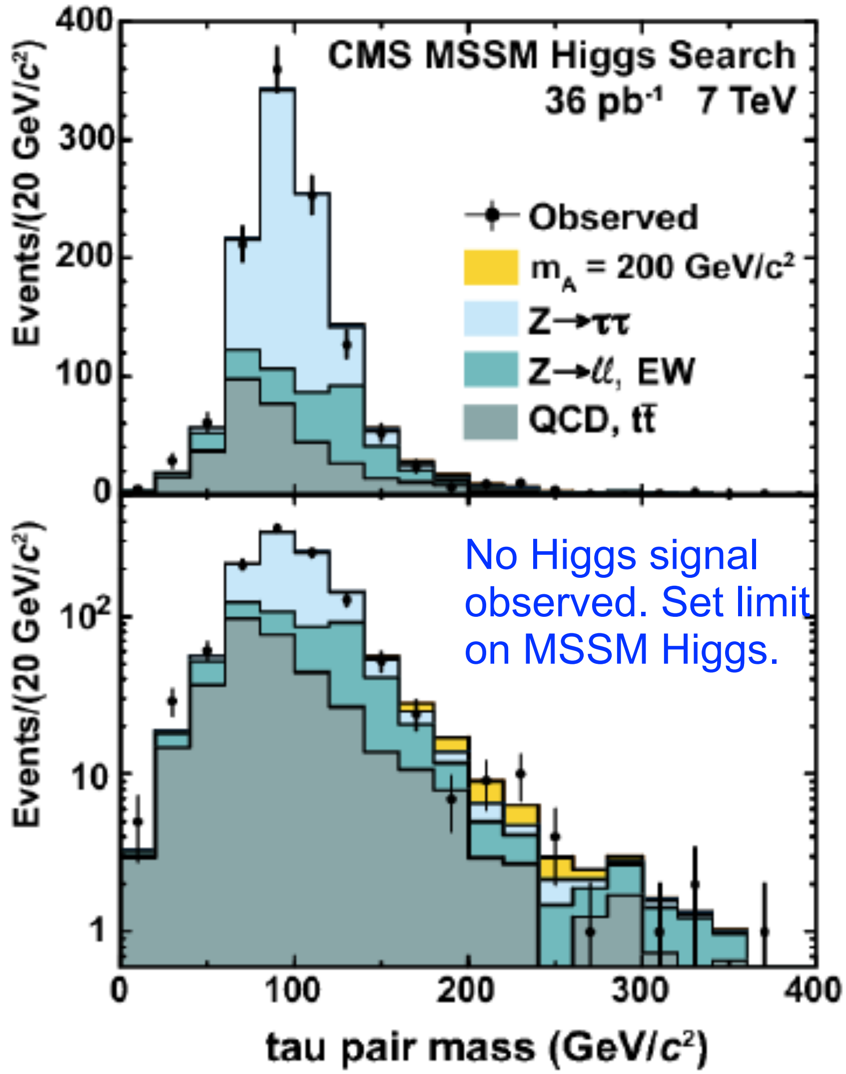
- 95% C.L. upper limit is a factor of 2 bigger than the Standard Model cross section for H→WW and m_H = 160 GeV
- A Standard Model extension with 4 fermion generations predicts a factor of ~9 enhancement in the cross section
  - -For this model we exclude Higgs in mass range from 144 GeV to 207 GeV

  Better limit than CDF+D∅ on 4g

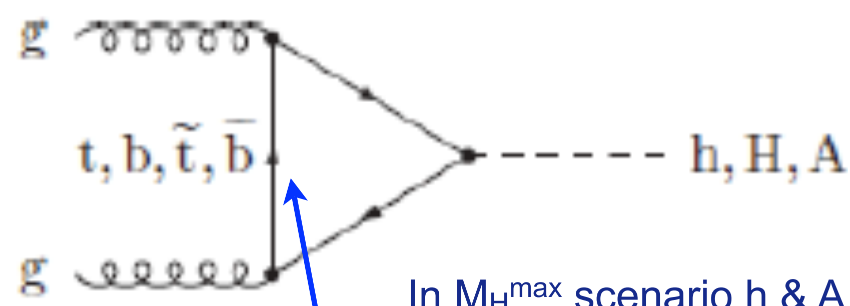
ATLAS excludes 1.2 σ_{SM} @ M_H=160 GeV

m_H (GeV/c^2)	$\sigma \cdot BR$ SM (pb)	$\sigma \cdot BR$ 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



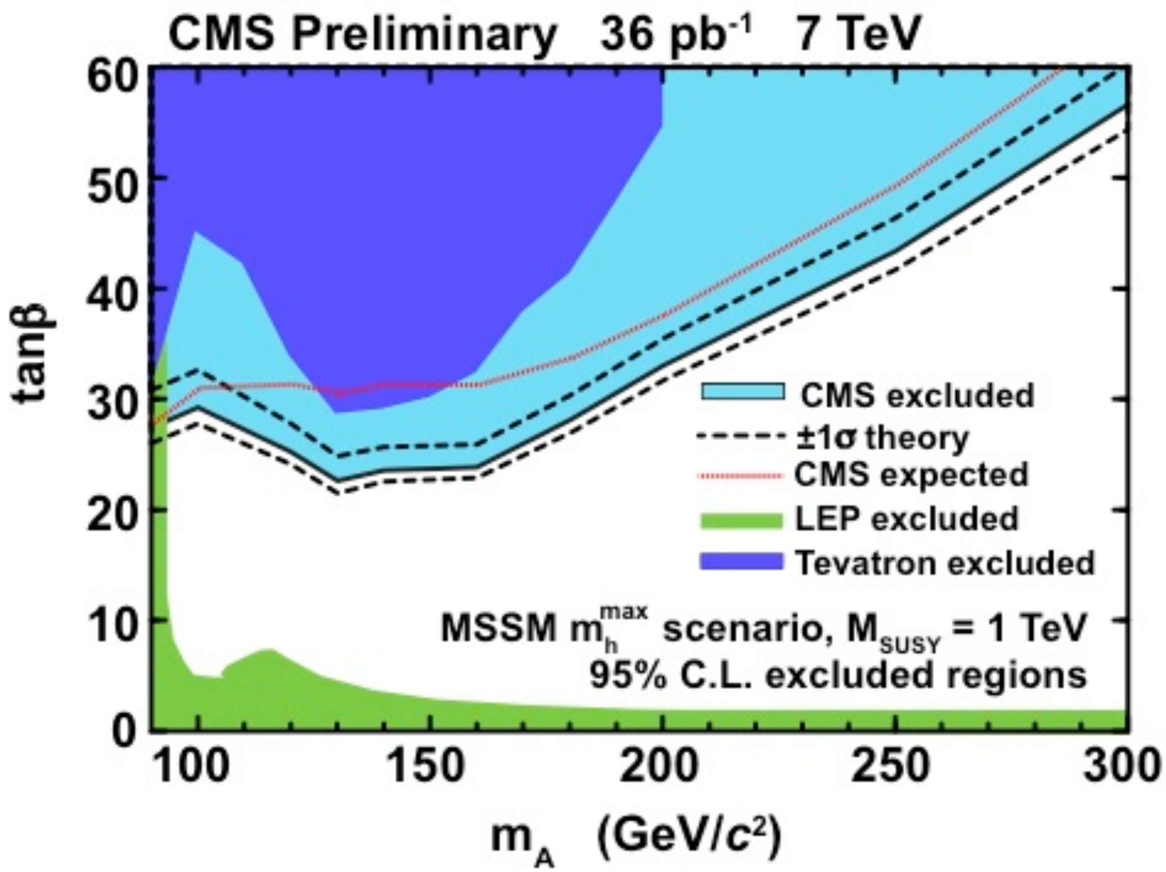
Not yet sensitive to setting limit on SM Higgs in ττ channel. However, we break new ground on excluding Higgs for a bench mark MSSM model



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

- ✦Can get large enhancement in Higgs production from high tanβ
- ✦Enhancement due to contribution from third generation squarks in the loop
- ✦BR (A→tau tau) = 10−15%

H→tau tau: limit on MSSM Higgs boson m_A



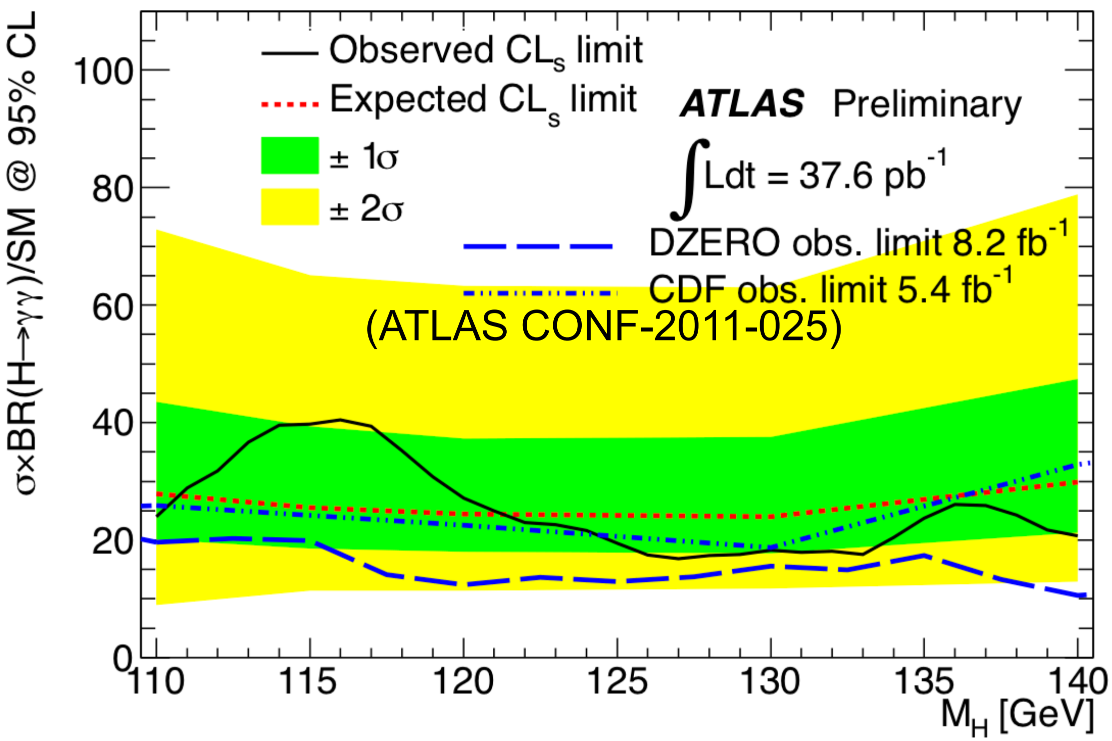
With 10x more data on tape and 100x expected by the end of this year we will be able to set limit on SM Higgs in this channel also

- ✦For arbitrarily large value of tanβ we exclude very heavy Higgs masses
  - -the plot range on x-axis goes all the way up to ∞
- ✦Even for low values of tanβ 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→lνjj

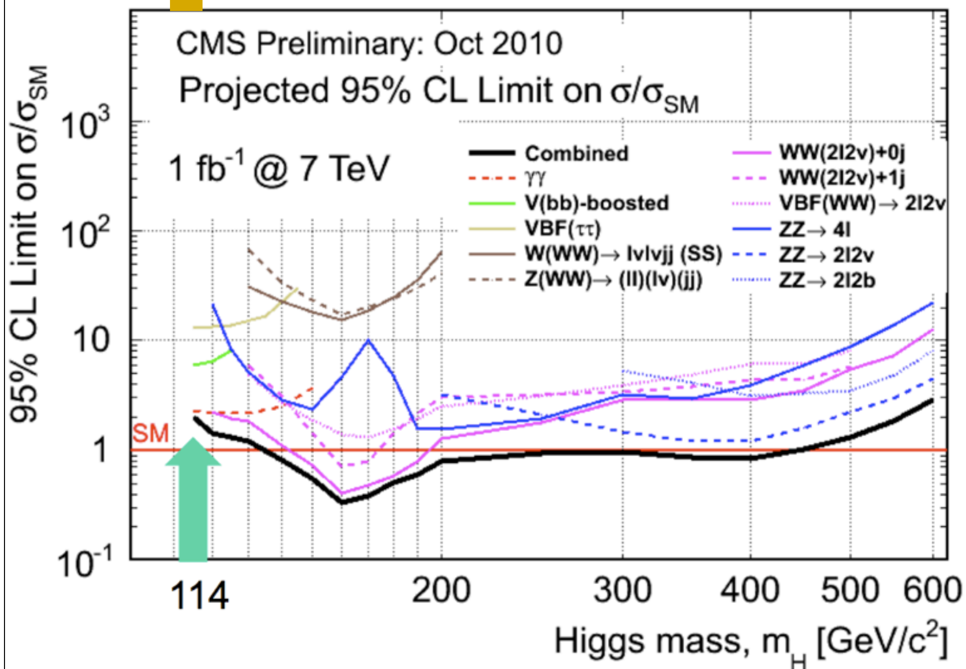
- Exclude 4−6 x σ_{SM} near m_H = 320 GeV and m_H = 480 GeV
- Exclude SM-4g near 320 GeV
- More sensitive for m_H>250 GeV than any other channel

H→ZZ→llνν / lljj combined

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

✦ATLAS excludes 40 x σ_{SM} at m_H = 115 GeV
✦D∅ excludes Higgs with 20 x σ_{SM} at m_H = 115 GeV

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



Caveats:

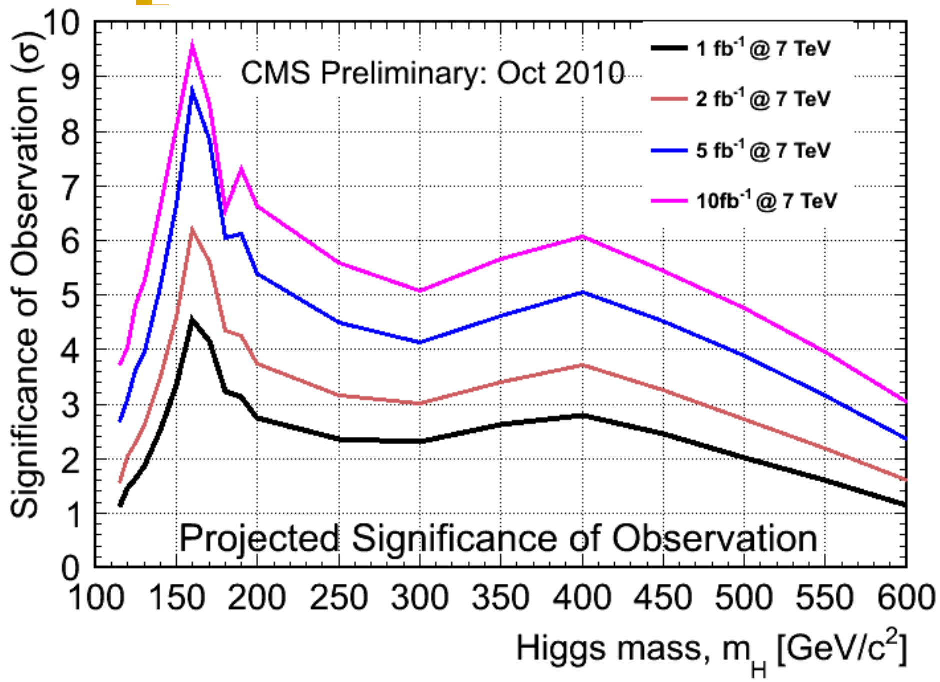
- Projections based on 2010 conditions
- LHC environment is much more aggressive in '11−'12
  - –Instantaneous Luminosity 1−5 $nb^{-1}s^{-1}$
  - –50ns bunch crossing (was 75ns in '10)
  - –Pileup ~10 per event
  - –E_t^{miss}, lepton isolation, jet resolution all degraded

✦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 (≈115 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

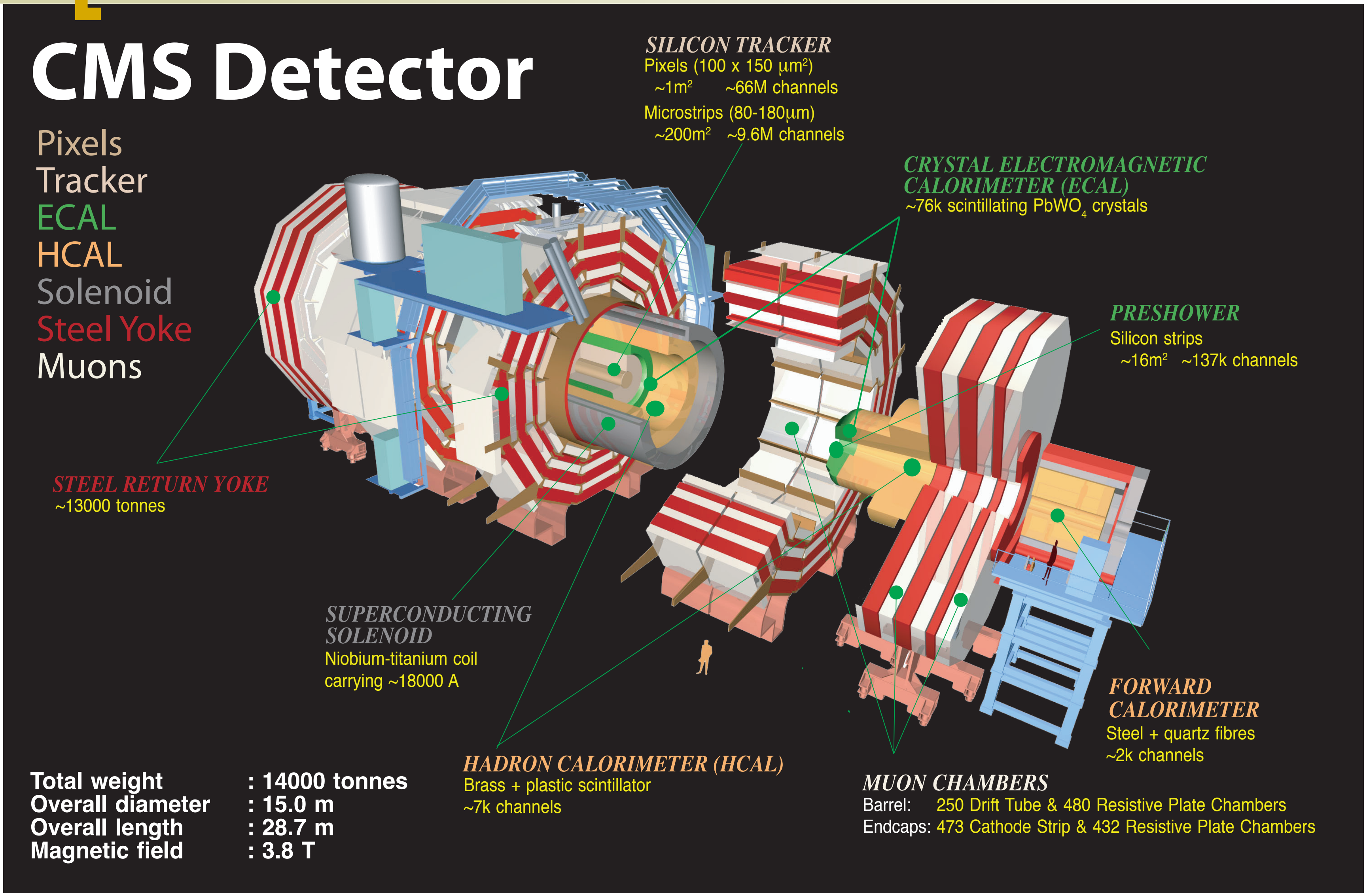
✦The LHC era is upon us

- Machine is performing spectacularly, and so are ATLAS and CMS
- Within months achieved 2% precision tests of electroweak physics
- Published first paper on the Higgs searches using 36 pb^{-1} of data collected in 2010. Broke several new grounds. Analyzing 2011 data.

✦Higgs Boson, if it exists between masses of (114 − 600 GeV) will either be discovered or ruled out in ≈ next two years

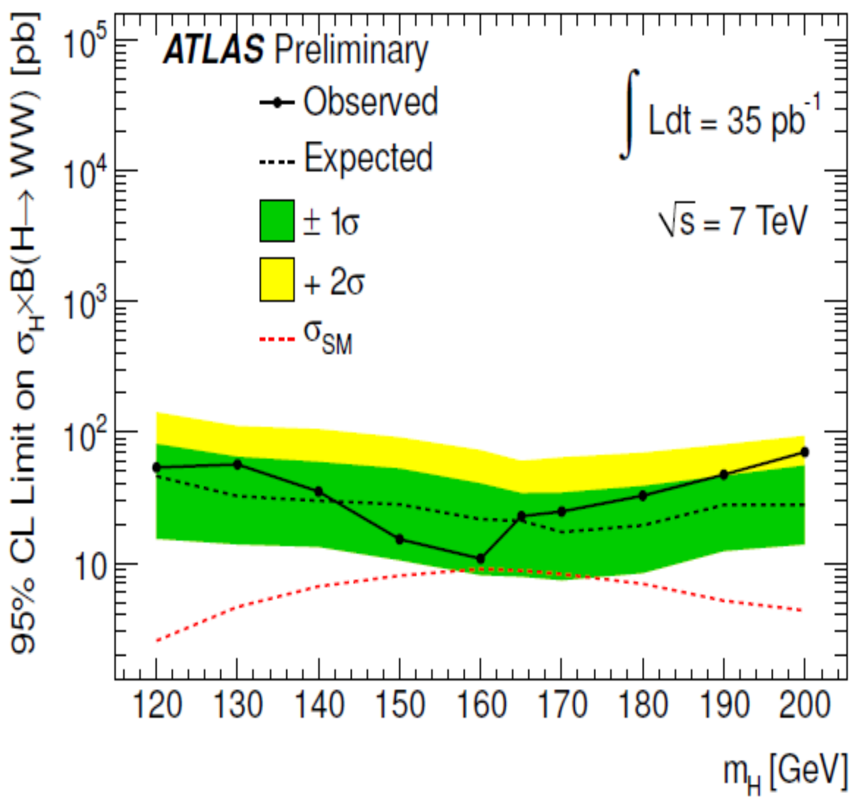
BACKUP SLIDES

Understanding CMS detector



ATLAS H→WW→lνlν: Exclusion Limits

- absolute limit on cross section

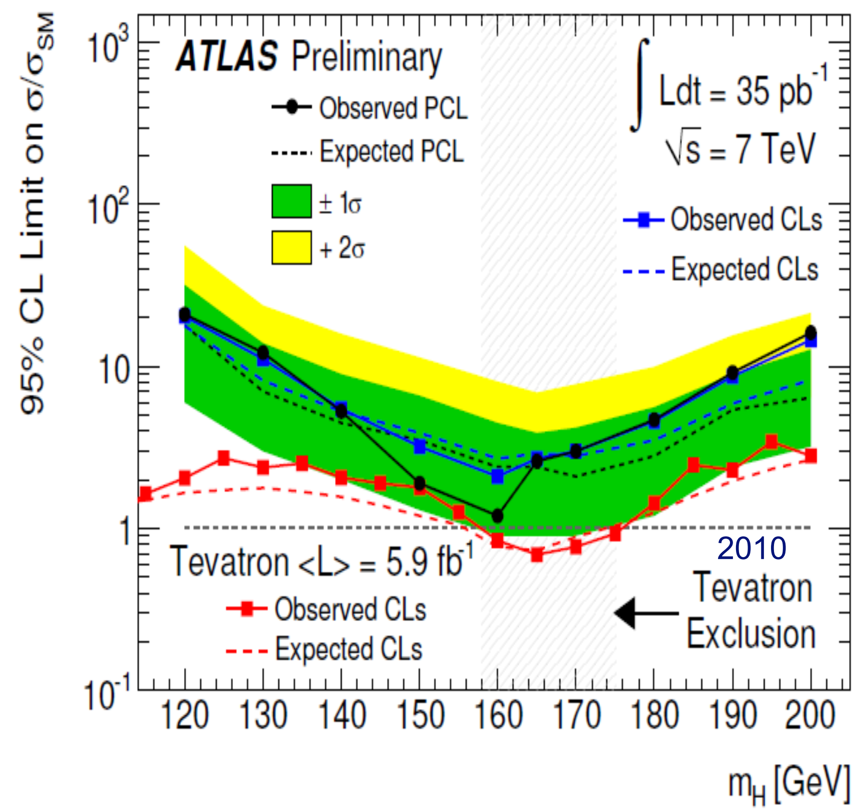


cross section limits:

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

sensitivity dominated by gluon fusion

- limit w.r.t. SM prediction

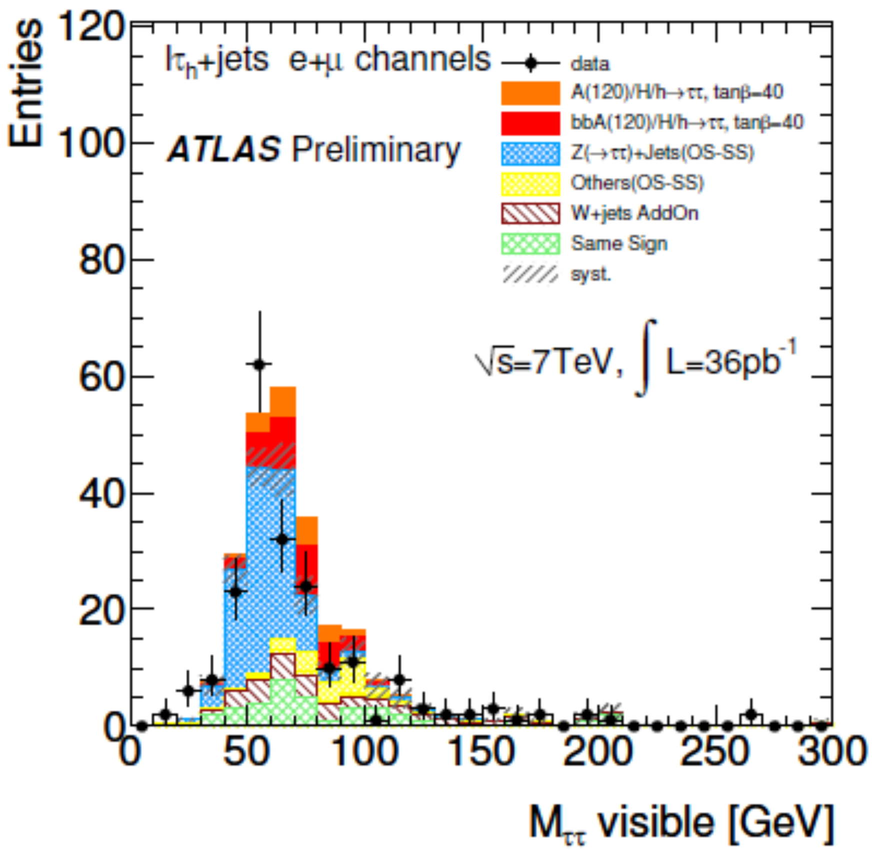


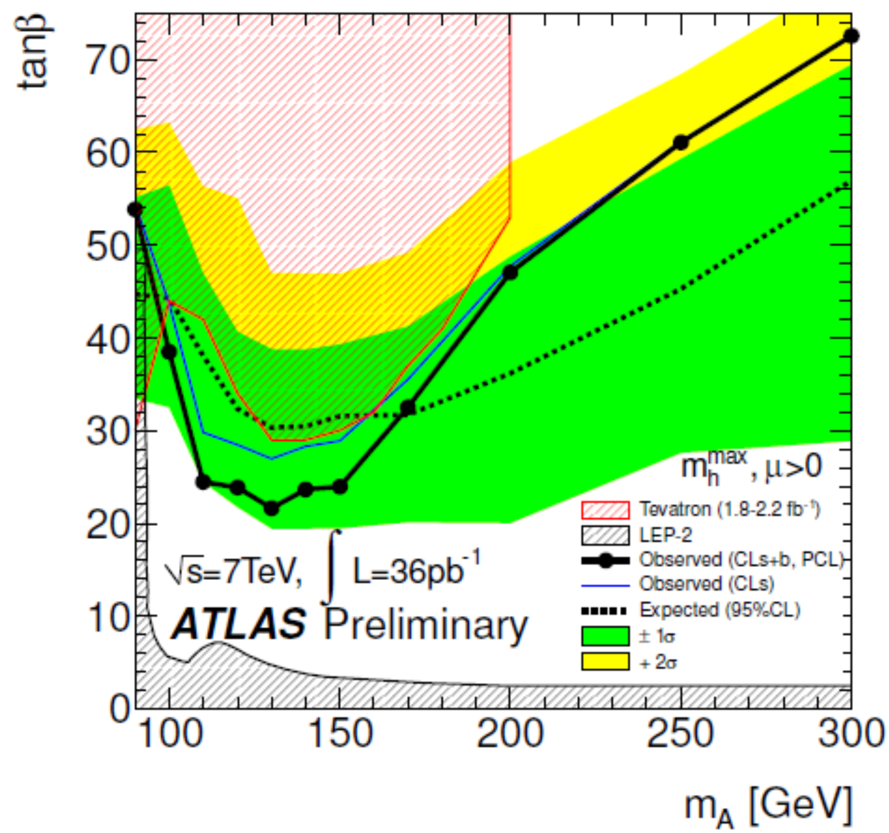
1.2 x SM cross section σ_{SM}

excluded at M_H = 160 GeV

M. Schumacher, Moriond EW 2011 talk

ATLAS H→ tau tau



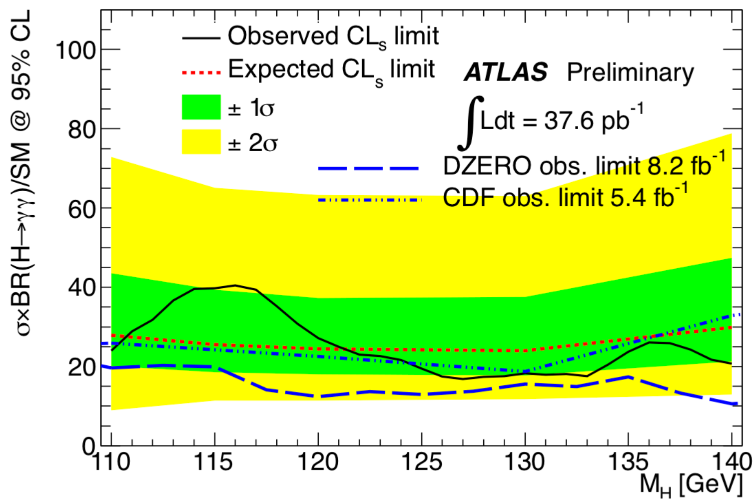


M. Schumacher, Moriond EW 2011 talk

ATLAS: H→γγ, H→Z(ll) Z(νν), H→W(lν) W(jj)

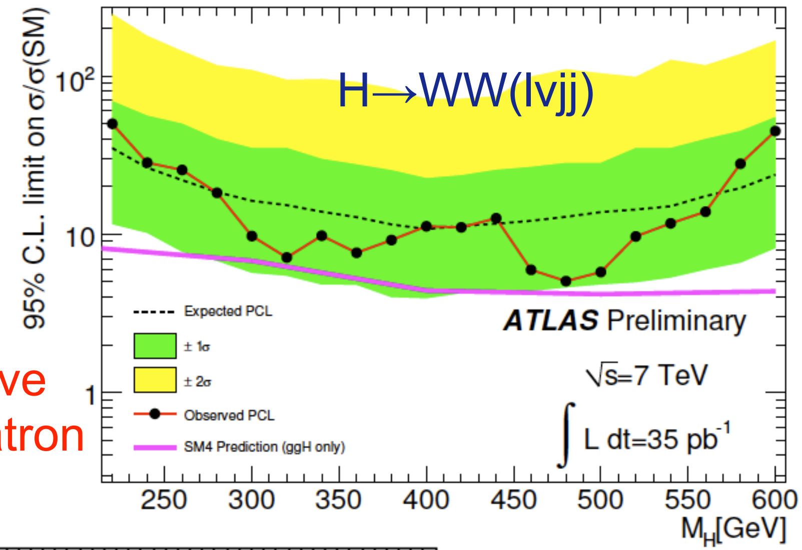
M. Schumacher, Moriond EW 2011 talk

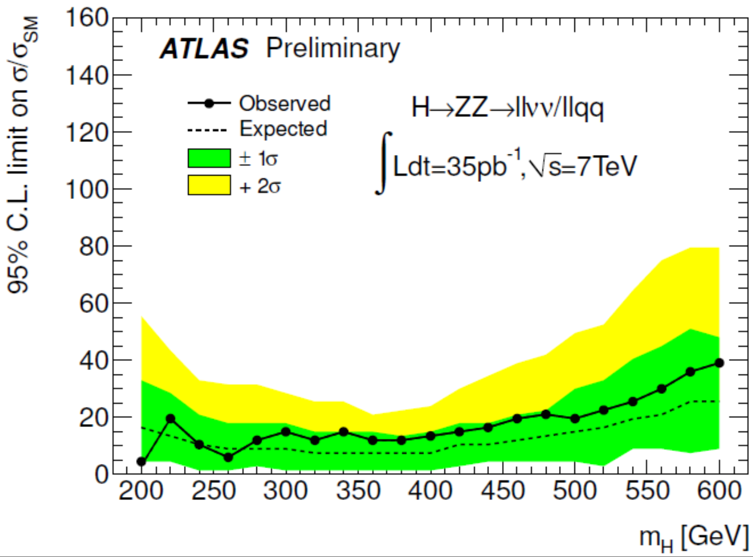
ATLAS CONF-2011-025 D0 Note 6177-CONF



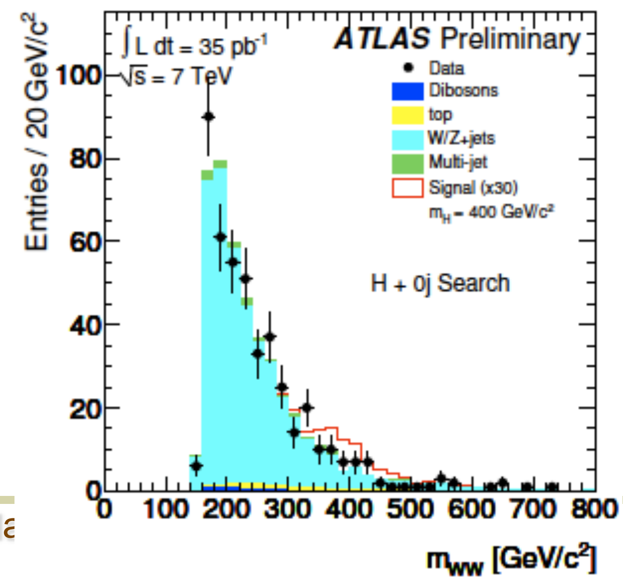
LHC is competitive with Tevatron

ATLAS CONF-2011-052





ala

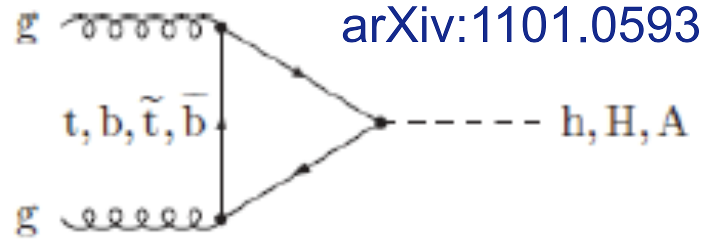


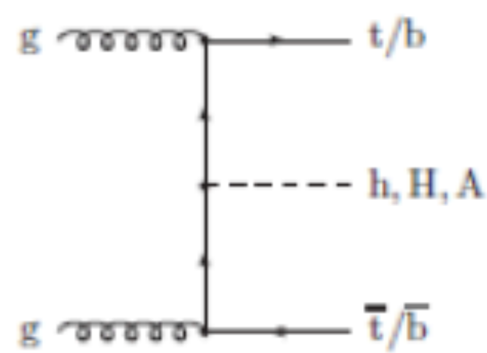
- ✓BR is 6x larger than lvlv
- ✓Fully reco'ble
- ✓Most sensitive for m_H>200 GeV
- -But larger bkgd ...

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 β, m_A ($m_h < m_Z$)
- large loop corrections from SUSY parameters
  - m_h < 133 GeV (for m_{top} = 175 GeV, M_{SUSY} = 1 TeV)
- corrections depend on 5 SUSY parameter:
  - X_t, M_0, M_2, M_{gluino}, μ
  - fixed in benchmark scenarios

arXiv:1101.0593





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

For high values of tanβ:
-Cross section enhanced
-BR (A→tau tau) = 10−15%
-h & A or H & A are degenerate