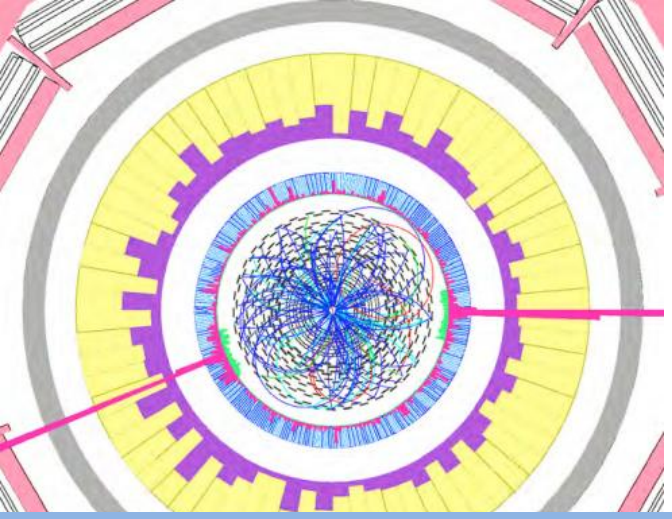
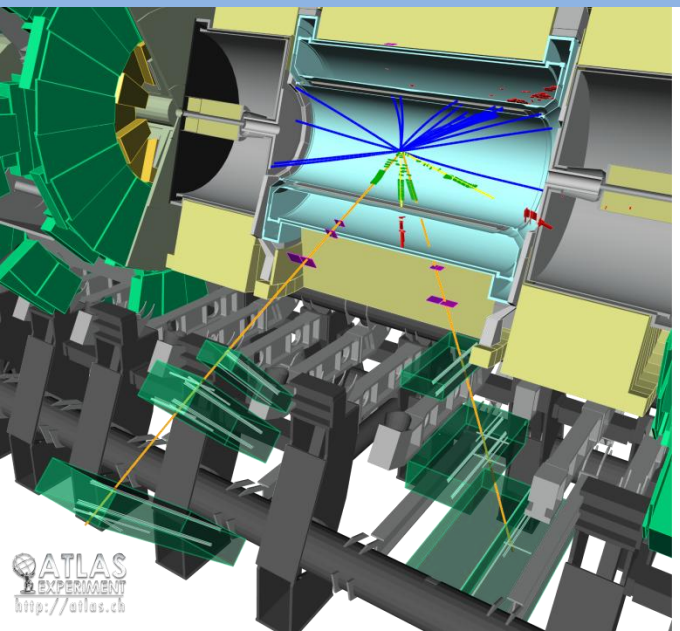


Royal Holloway University of London

Pedro Teixeira-Dias

Higgs Overview



UK HEP Forum – Cosener's House, 20/9/2010

Overview

LHC data taking at high energy started in 2010

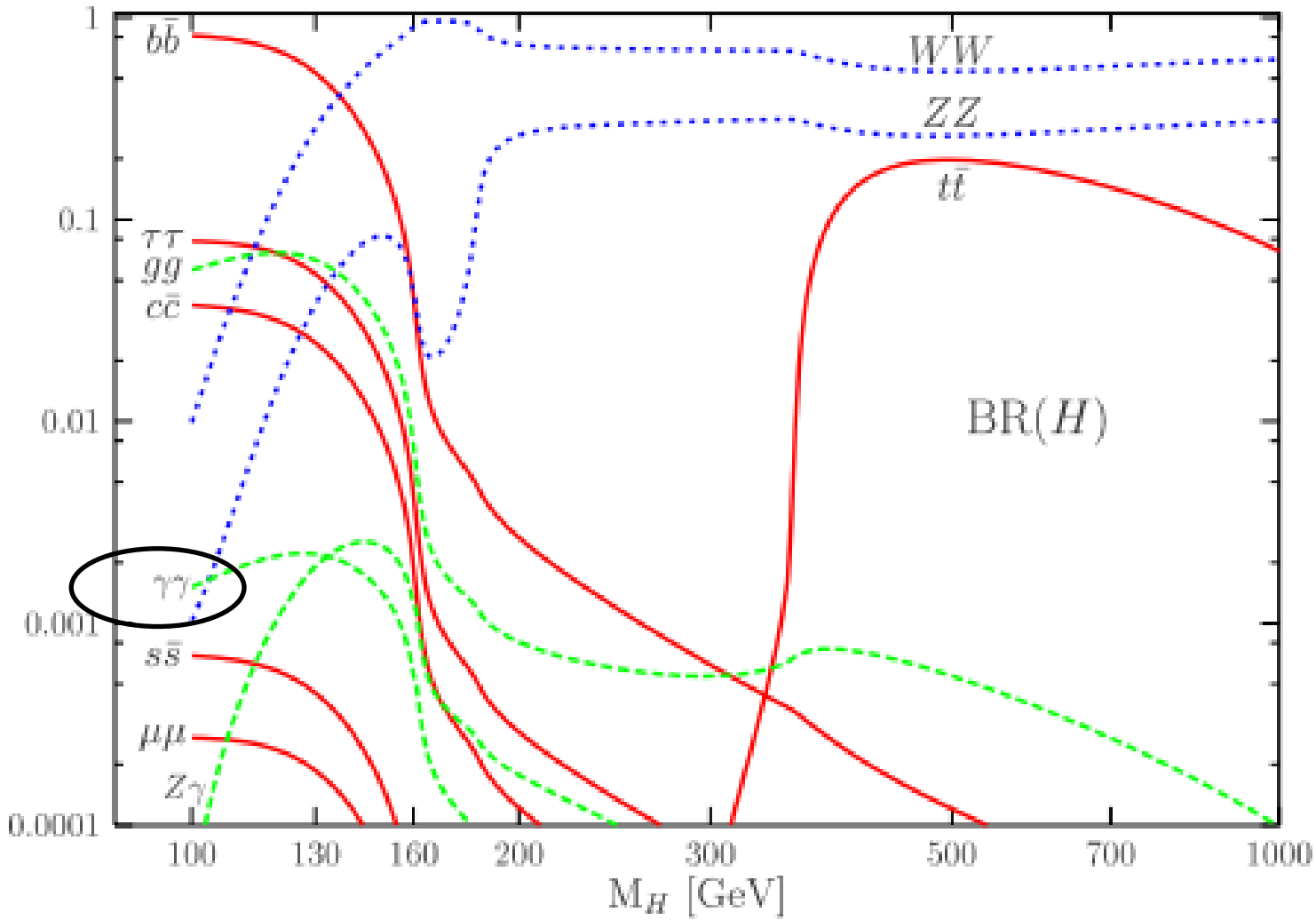
First results presented this summer at

- ICHEP 2010, 22-28 July
- Higgs Hunting, 29-30 July

In this talk I will review recent Higgs developments and projections for the near future:

- Introduction: SM Higgs production and decay
- SM Higgs searches at the TeVatron
- Theoretical interlude
- LHC: operations at 7 TeV
- SM Higgs sensitivity (and MSSM Higgs, too)
- Conclusions

SM Higgs decays: branching ratios

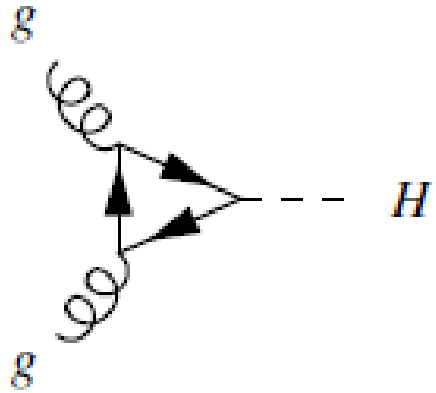


Main decays used in Higgs searches:

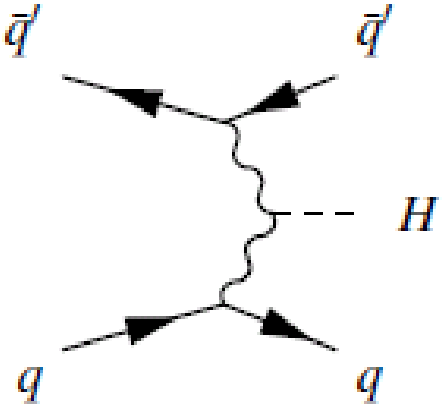
- $m_H < 140$ GeV: bb, $\tau\tau$, and $\gamma\gamma$
- $m_H > 140$ GeV: WW dominates, with ZZ a distant 2nd

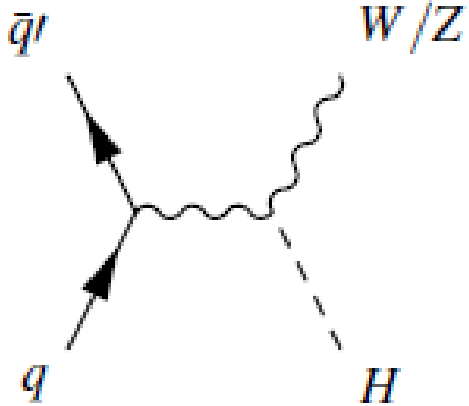
SM Higgs production

Gluon fusion (GF)
Dominant production mode

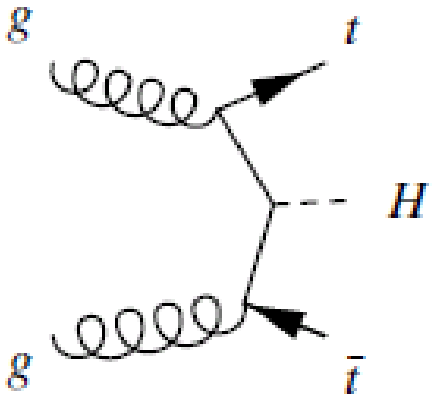


Vector boson fusion (VBF)
Characteristic "tag jets" signature





Higgsstrahlung

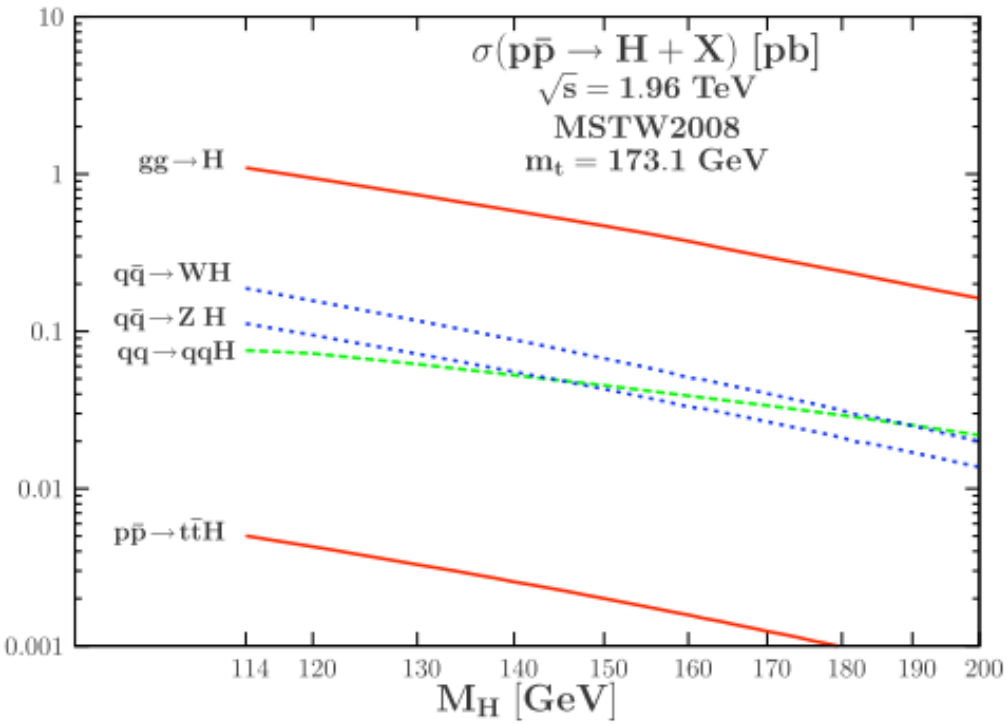


Associated production
with a pair of top-quarks

HIGGS HUNTING AT THE TEVATRON

Higgs at the TeVatron

Higgs boson production cross-sections



Overall search strategy

Low Higgs mass

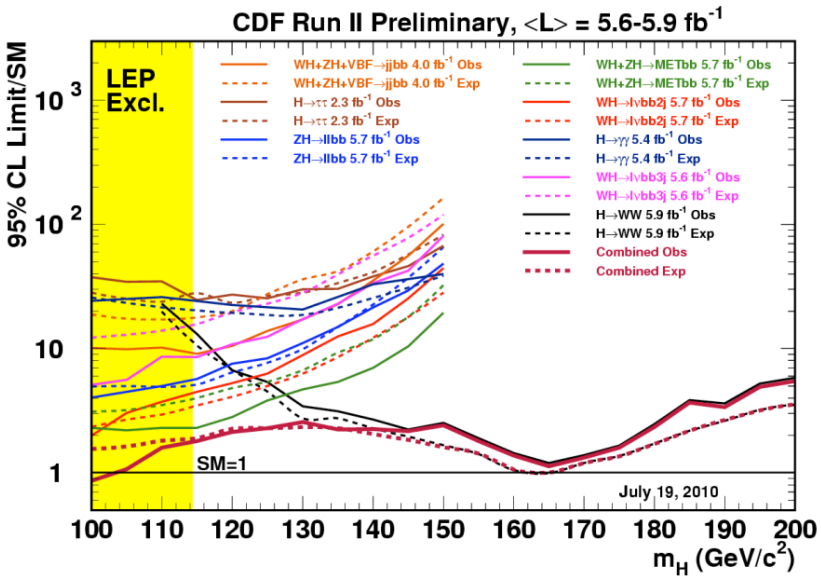
- H→bb decay dominates (…can't use GF)
- pp→WH,ZH→ℓνbb, ννbb, ℓℓbb
- Main backgrounds are W+jets, Z+jets

High Higgs mass

- H→WW is main decay (→leptons!)
- gg→H→WW most important (m_H>125 GeV)

Analysis of most channels is divided into sub-channels for improved s/b

Higgs at the TeVatron

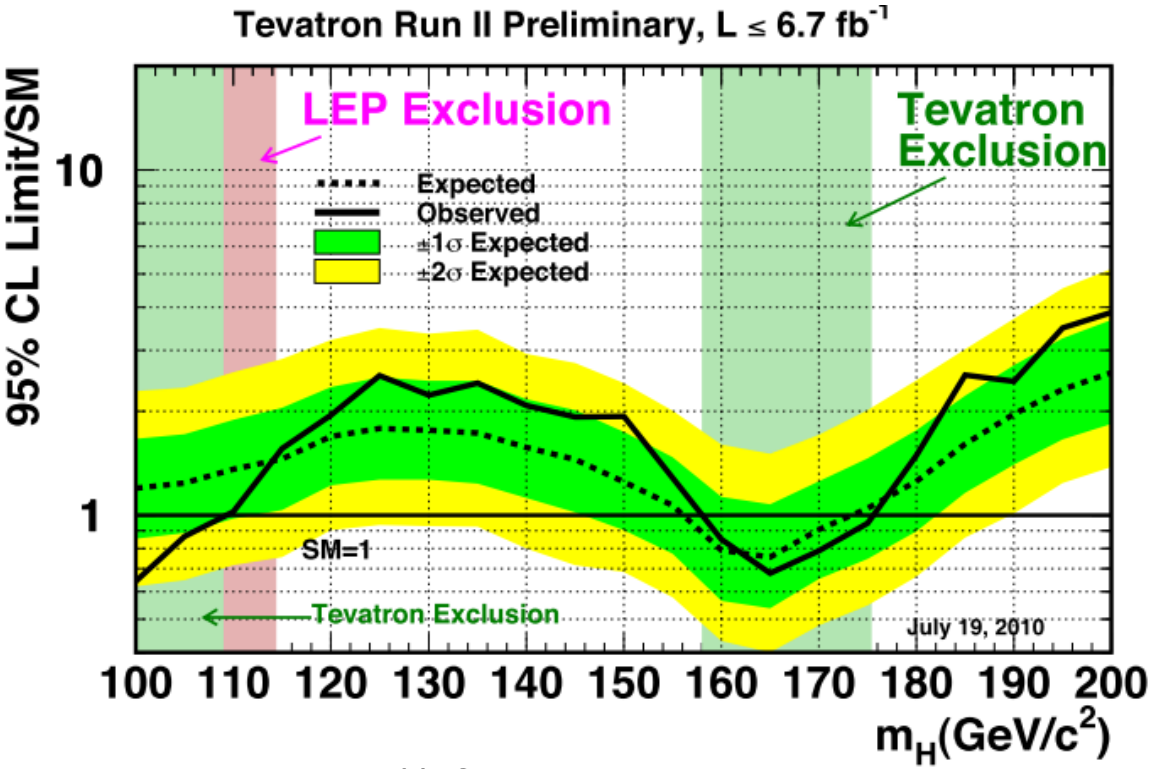


Channel	Expt	Dataset now	Increase since Nov. 2009 combination
H → WW	D0	6.7	24%
H → WW	CDF	5.9	23%
WH → lνbb	CDF	5.7	30%
WH → lνbb	D0	5.3	6%
ZH/WH→METbb	CDF	5.7	60%
ZH/WH→METbb	D0	6.4	23%
ZH → llbb	CDF	5.7	40%
ZH → llbb	D0	6.2	45%
H → γγ	CDF	5.4	New!
H → γγ	D0	4.2	0%
H → ττ	CDF	2.3	15%
H → ττ	D0	4.9	0%
ZH/WH→qqbb	CDF	4	100%
ttH	D0	2.1	0%

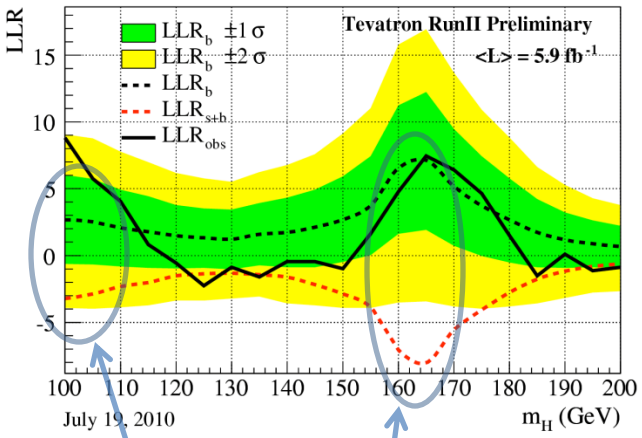
Ben Kilminster, ICHEP 2010

- But in practice have expanded list of searches: *"no channel too small"*
- H→ττ, H→γγ also included
- D0 even includes tt(H→bb) !

Higgs at the TeVatron



Log likelihood ratios: b, s+b



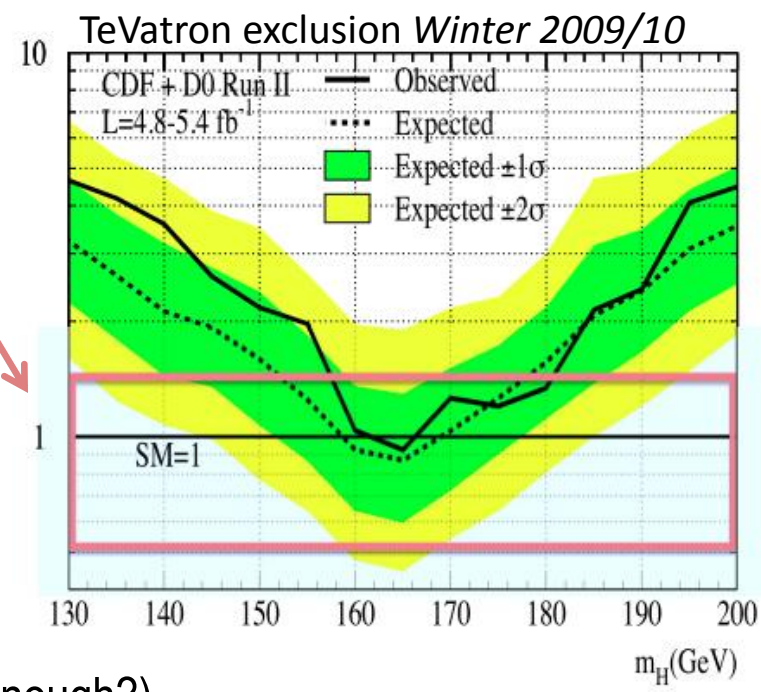
Larger sensitivity

- Excluded at 95% CL
  - 158 < m_H < 175 GeV (4x previous exclusion)
  - In the absence of signal: expect 156 < m_H < 173 GeV
  - At m_H=115 GeV: 1.5 x $\sigma_{SM\ Higgs}$
- Approved to end 2011. Request 3 more years ("Run III")

THEORETICAL INPUTS

Theoretical input to searches

SM Higgs limits are not purely experimental…
eg input of $\sigma_{SM\ Higgs}$ (line at R="1")



- "Predictions for Higgs production at TeVatron and associated uncertainties"
  (Baglio & Djouadi, [hep-ph] 1003.4266, 1009.1363)
- Bottom line: authors estimate unctty. in $\sigma(gg \rightarrow H)$ (~40%) is twice as large as what was used in latest TeVatron combination
- Main issues:
  - Uncertainty from scales μ_R, μ_F (variation not large enough?)
  - PDF uncertainties, and incorporation of uncertainties on both $\alpha_S^{th} + \alpha_S^{exp}$
  - how to combine above errors
- Over the Summer, work has been done by both sides to discuss + address issues… but debate still rages on
- LHC 7 TeV is also being given the "Baglio & Djouadi treatment" ($\Delta\sigma/\sigma \approx$ -25% $\leftrightarrow$ +30%)

Theoretical input to searches

Theoretical inputs (event generators, PDFs, cross-sections for signals and backgrounds , Higgs BRs, etc) are crucial to searches

↓

vital that theorists and experimentalists work together on this

LHC Higgs "Cross Section" Working Group

Meetings: April 2010 (Freiburg), July 2010 (CERN), November 2010 (Bari)

https://twiki.cern.ch/twiki/bin/view/LHCPhysics

LHC Higgs WG

LHC Higgs Cross Section Working Group

MC Group
MC4LHC

PDF4LHC

Creation announced in January 2010.
Kickoff meeting on February 3, 2010.
Preparatory workshop in Torino Nov. 23-24, 2009
Inauguration workshop in Freiburg April 12-13, 2010

Task: SM and MSSM Higgs Cross Section and BRs
Compute and agree on cross sections and Brs
Use the same Standard Model input parameters
Strategy on uncertainties (scale, a_s, PDF, etc.)
Monte Carlo at NLO for the signal
Define pseudo-observables
Cross sections of background SM processes

SM Cross Section Task Force

Beyond SM and MSSM?
Other SUSY scenario NMMSM,
Invisible Higgs, Higgsless, etc.

Statistics Forum

R Tanaka

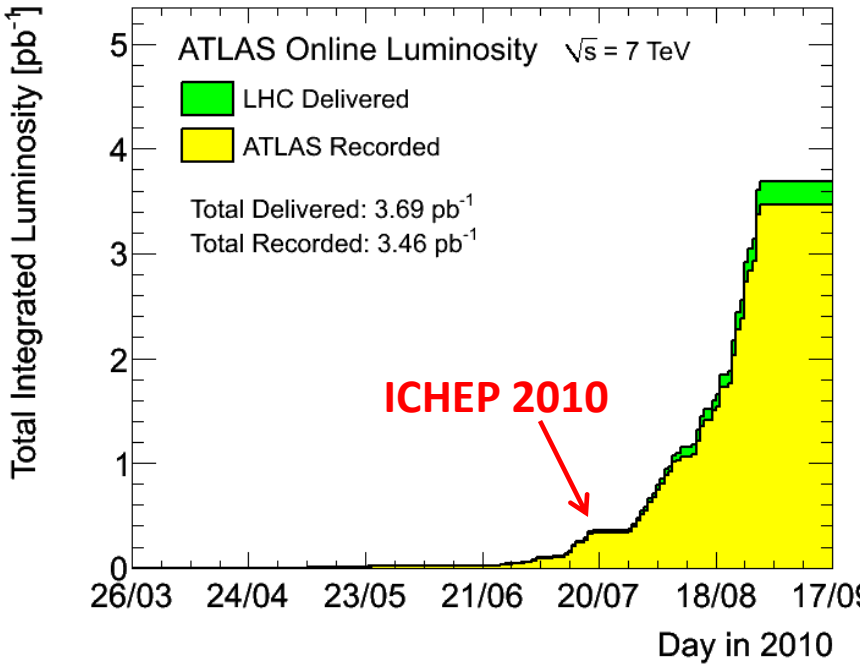
LHC

LHC operations in 2010

LHC operations: impressive so far

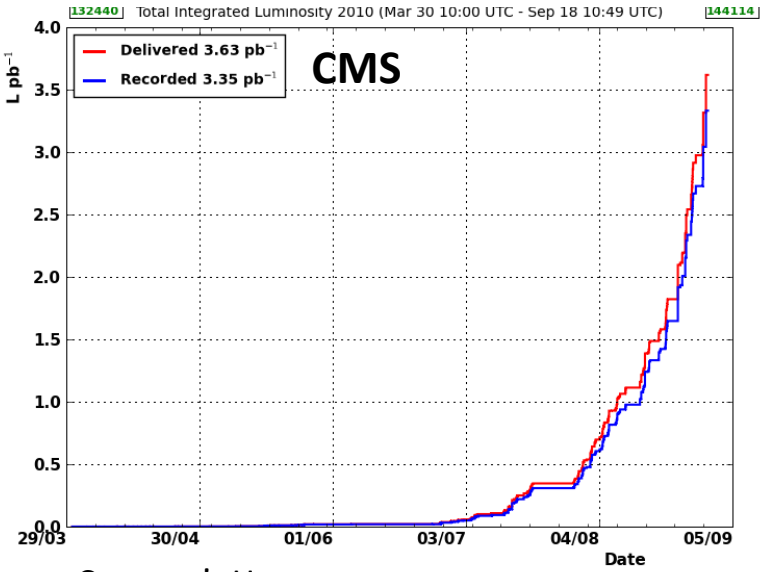
2010

- Start of 7 TeV pp collisions: end of March
- L = ~~10^{27}~~, ~~10^{28}~~, ~~10^{29}~~, ~~10^{30}~~, 10^{31} $cm^{-2}s^{-1}$
- Already attained max p/bunch: 10^{11}
- Late August: collided 36 x 36 bunches (delivering ~0.5 /pb/day)
- Target: 10^{32} $cm^{-2}s^{-1}$ < end of year



ATLAS + CMS

- data collection and detector commissioning going impressively well
- each experiment now has ~3.5 /pb of high quality data



2011: aim for $L_{int} \geq 1$ /fb /expmt

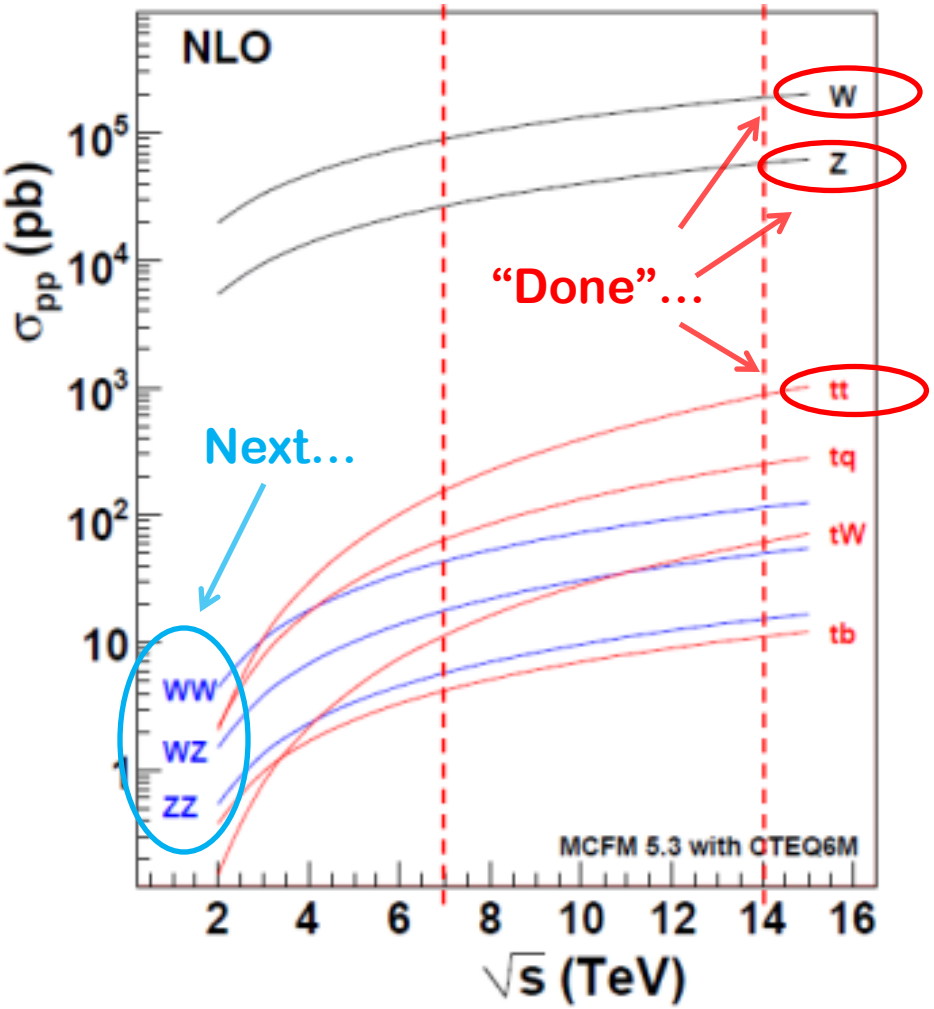
2012: shutdown

2013: collisions at 14 TeV

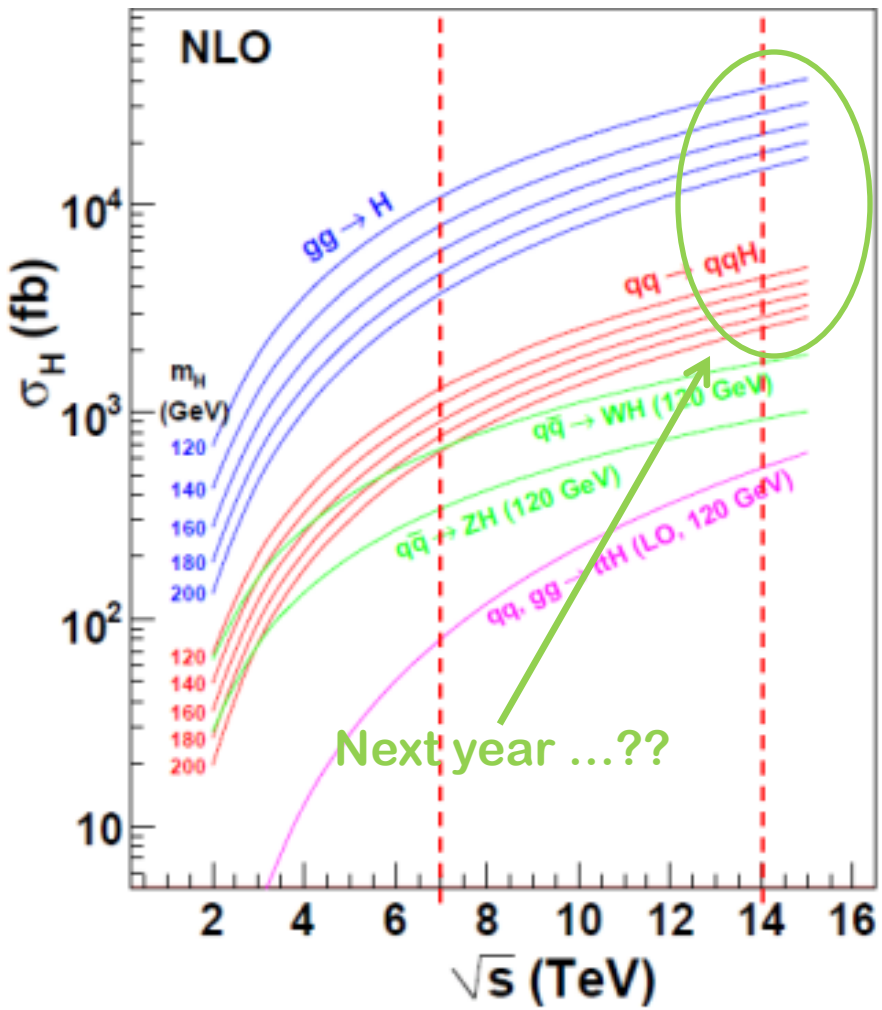
LHC production cross-sections

Rediscovering the Standard Model

SM processes (pb)

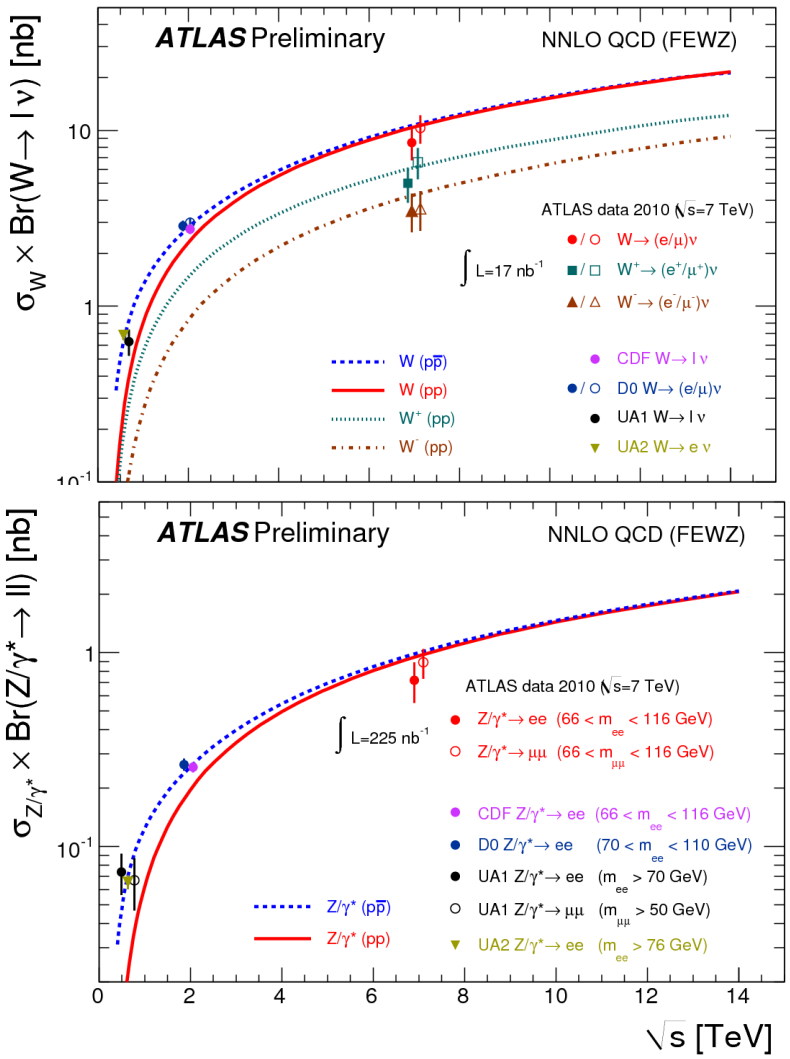


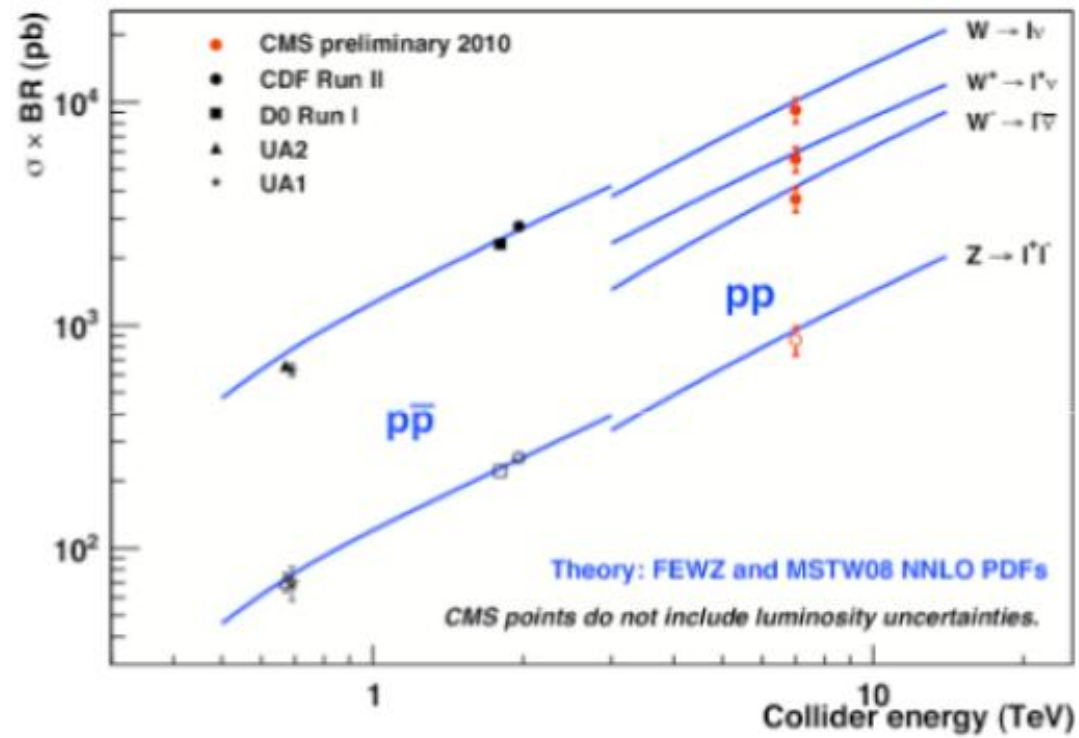
SM Higgs (fb !)



W & Z cross-sections measurement

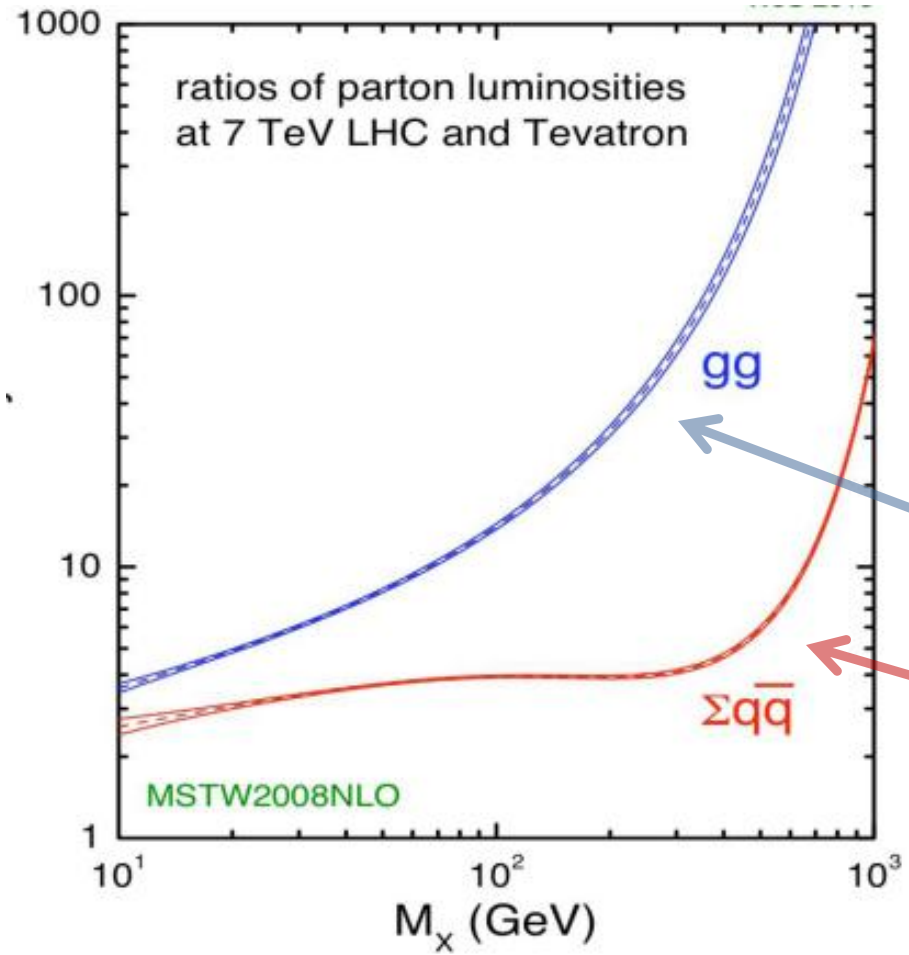
Detector commissioning going very well (and rapidly) on all fronts: tracking, calorimetry, particle id, jets, missing E_T, b-tagging.





Higgs: from the TeVatron to the LHC

Clearly, the 7 TeV LHC should be a significant step up in Higgs sensitivity



Parton luminosities for gg/qq → X

For M_X >140 GeV, the gg luminosity is > 15 times larger at LHC: good news for gg→H→WW/ZZ.

In addition, dominant backgrounds are produced via qq.

gg→H→WW/ZZ

qq→WW/ZZ

LHC 7 TeV: Higgs sensitivity

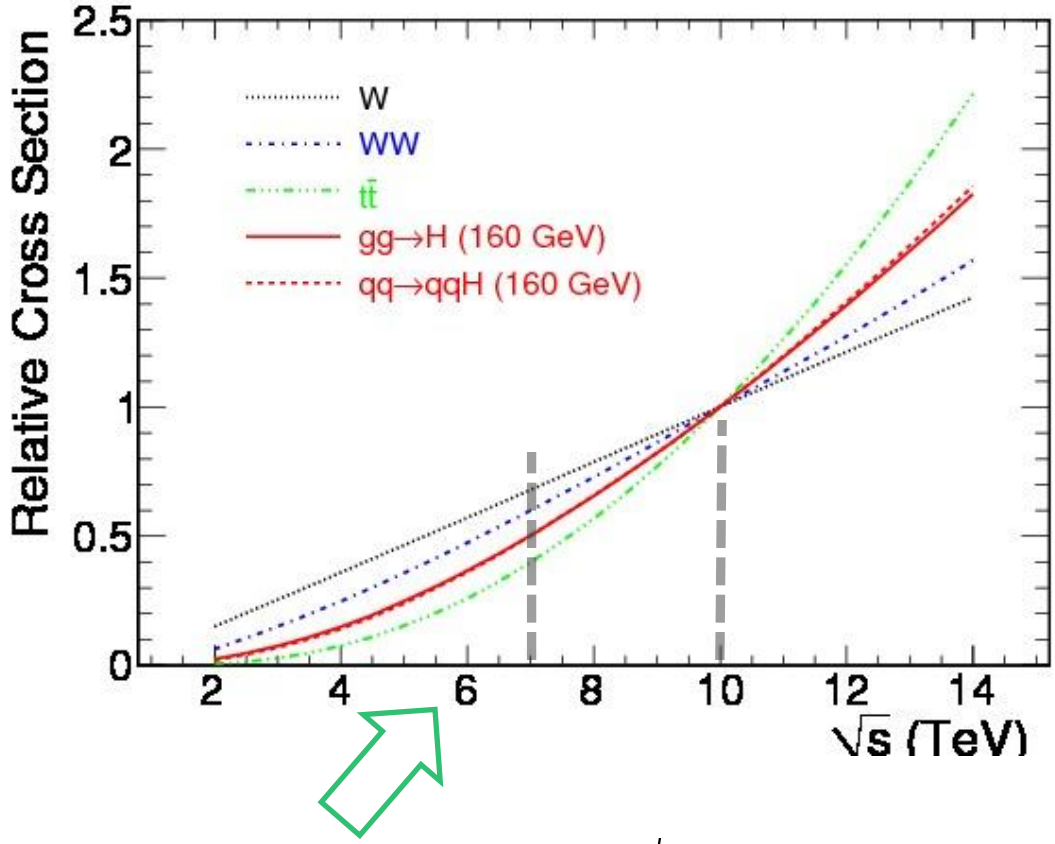
Projected Higgs exclusion sensitivity for 1/fb of data at 7 TeV LHC

- Method used by ATLAS + CMS:
  - No new analyses developed for $\sqrt{s}$=7 TeV
  - Instead rely on full simulation studies at $\sqrt{s}$=10/14 TeV and rescale signal and background cross-sections to $\sqrt{s}$=7 TeV.
  - ATLAS uses GF NLO; CMS uses GF NNLO (~30% higher)
  - Acceptances, efficiencies unchanged (verified to be the same – or even slightly higher – at 7 TeV)
  - Errors rescaled/re-evaluated for 7 TeV and 1/fb
  - 10/14 TeV studies optimised for discovery, instead of exclusion: room for improvement
  - Limit setting (incorporating uncertainties) using profile likelihood method (ATLAS) and CL_S method (CMS)

- References: ATL-PHYS-PUB-2010-009, CMS NOTE 2010/008

Effect of 10/14 TeV → 7 TeV

Some signal and background cross-sections as function of √s, normalised to √s=10 TeV

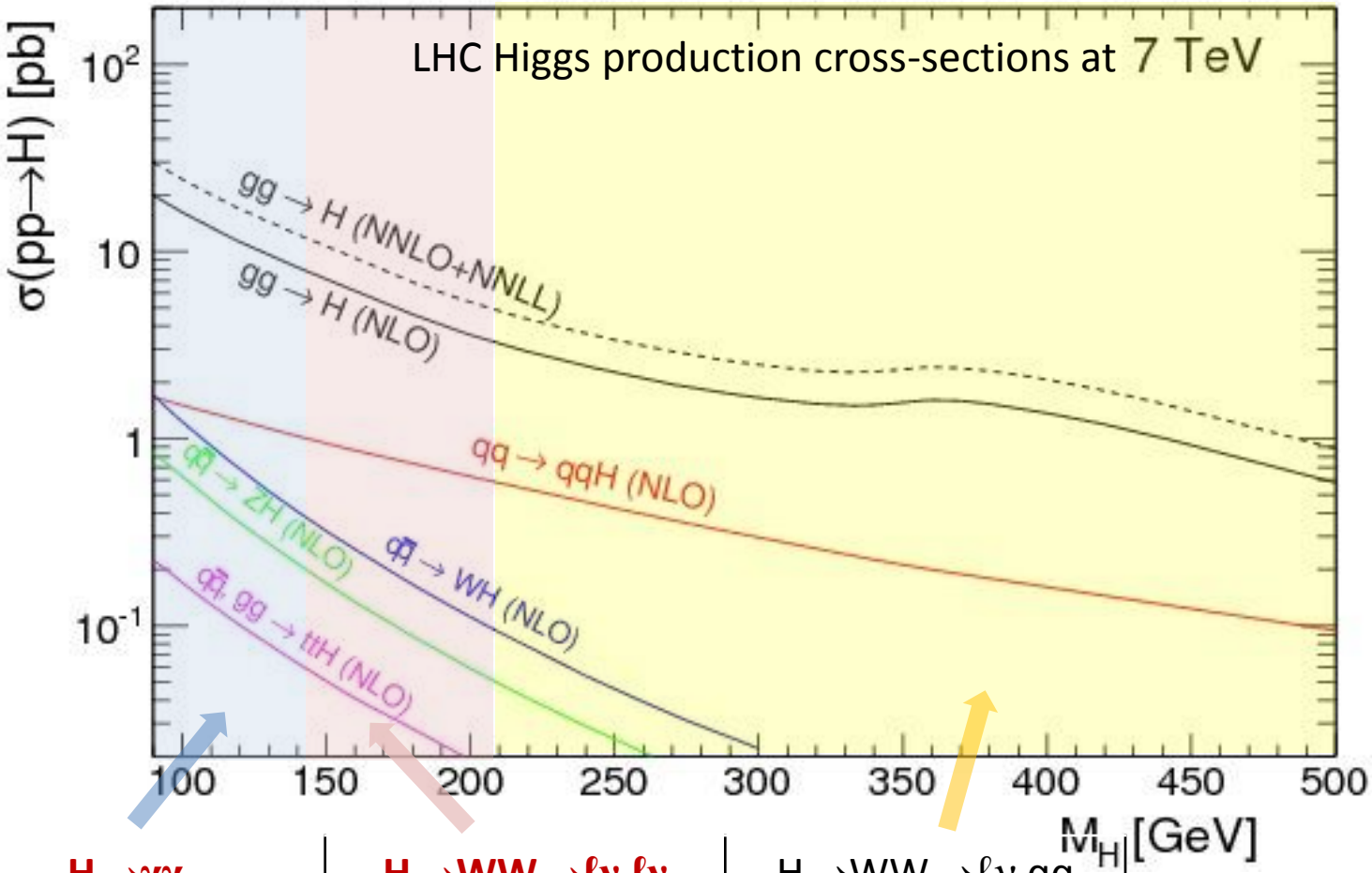


Cross sections depend strongly on √s…:

e.g., from 10 ⟶ 7 TeV

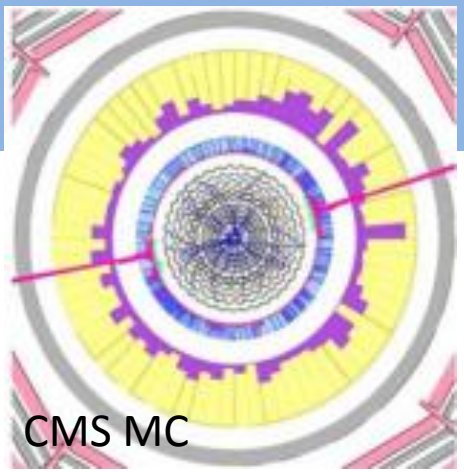
- GF + VBF signals (m_H=160 GeV) drop to 50%
- tt, WW and W backgrounds drop to 30-60%

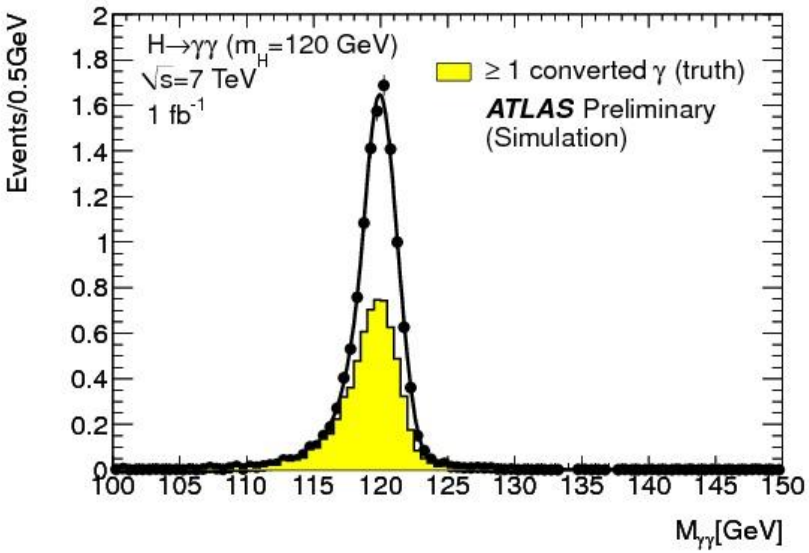
LHC Higgs search strategy



H→γγ	**H→WW→ℓν ℓν**	H→WW→ℓν qq
qq(H→ττ)	**H→ZZ→ℓℓ ℓℓ**	
tt(H→bb)	H→ZZ→ℓℓ νν	H→ZZ→ℓℓ bb/qq
W/Z(H→bb)		

H→γγ





- very clear signature
- excellent mass resolution: CMS 0.7% - ATLAS 1.1%

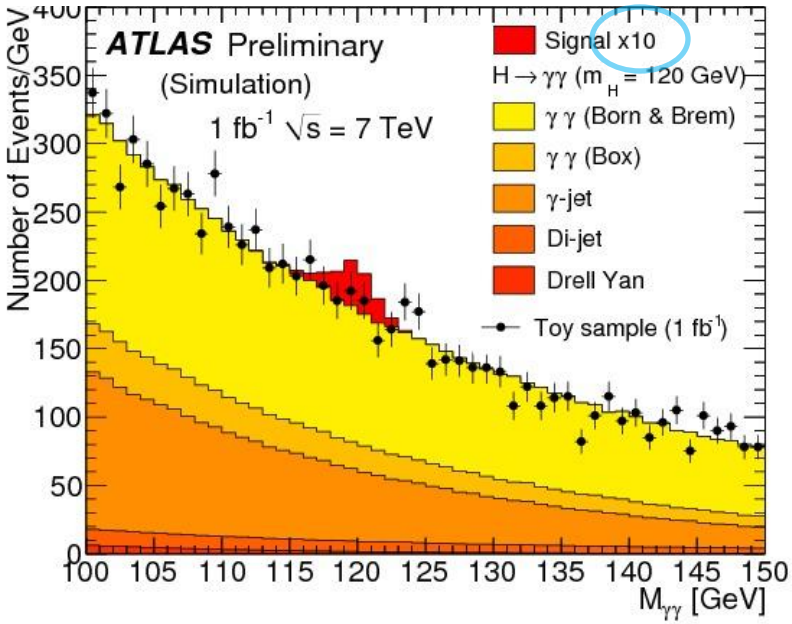
→ narrow di-photon resonance

BUT

- low signal yield: B(H→γγ) ~ 10^{-3}
- high background rate (γγ, γj)

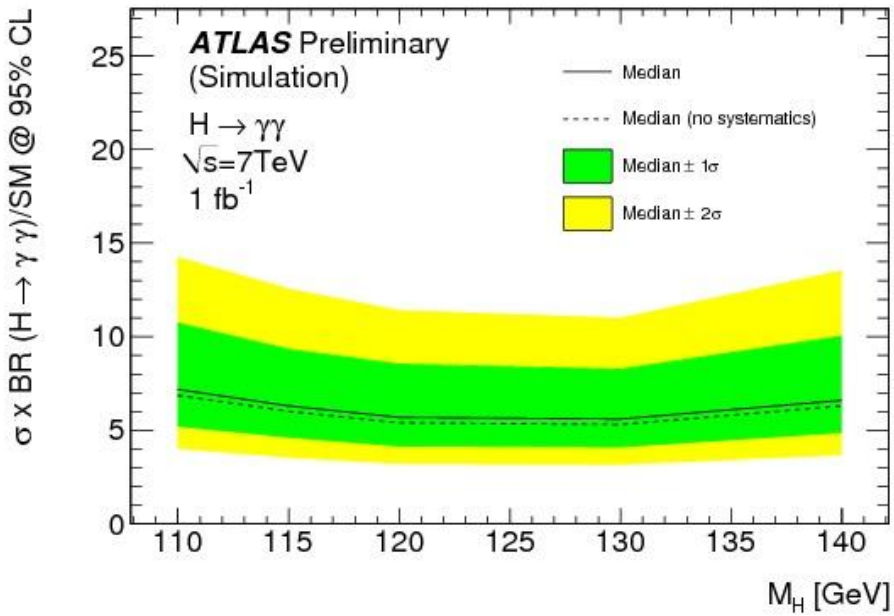
NEED

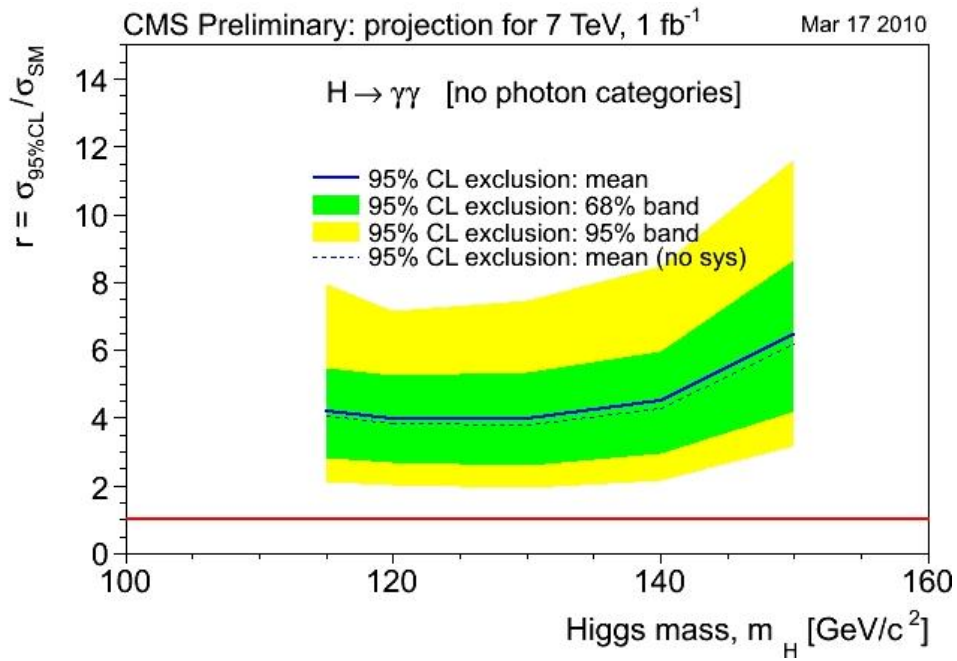
- excellent ECAL calibration
- high γ identification efficiency
- γ conversion recovery
- γ/jet discrimination



H→γγ

Ratio of 95% CL upper limit on σ x B(H→γγ) and the SM rate





- No exclusion with this channel stand-alone
- Limits are better than current H →γγ TeVatron limits (~ 20 x SM)

$H \rightarrow WW \rightarrow \ell\nu\ell\nu$

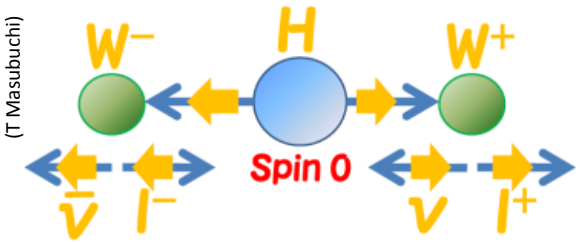
Powerful channel: $H \rightarrow WW$ has largest BR around $m_H \sim 2m_W$

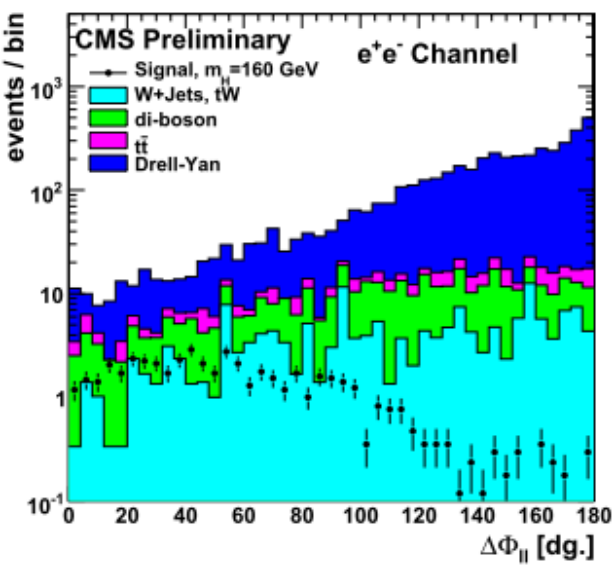
- di-lepton signature (include ee + $e\mu$ + $\mu\mu$) and missing E_T
- ATLAS analyses H+0/1/2jets (GF+VBF)
- CMS uses a multivariate method
- backgrounds are WW, top (tt, single t, Wt), and W+jets
- no Higgs mass peak, due to νs!
  - systematics very important
  - detailed understanding of backgrounds is absolutely key: use sophisticated treatment of control regions; data-driven estimates

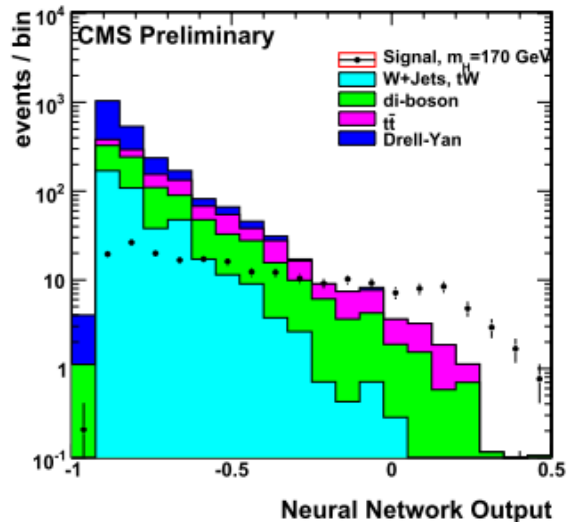
References: ATL-PHYS-PUB-2010-005 (10 TeV); CMS PAS HIG-08/006 (14 TeV)

H→WW→ℓν ℓν

Explore azimuthal di-lepton correlation, due to resonant *scalar* decay

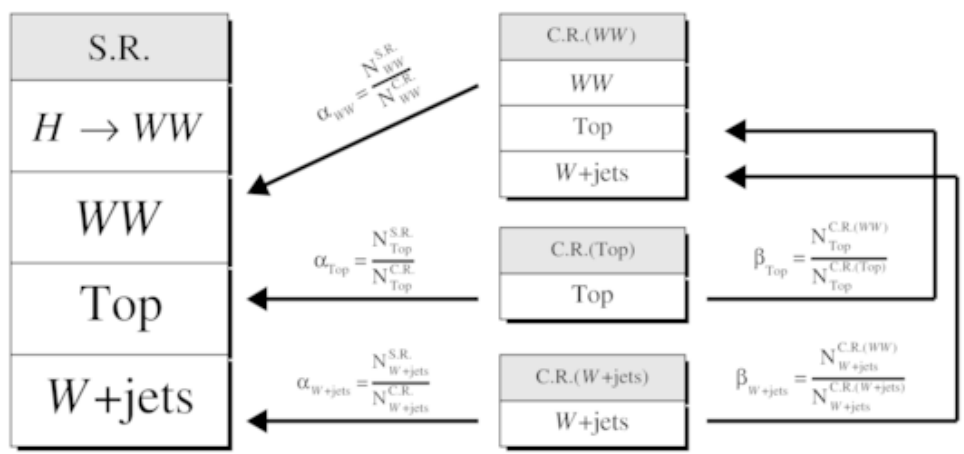






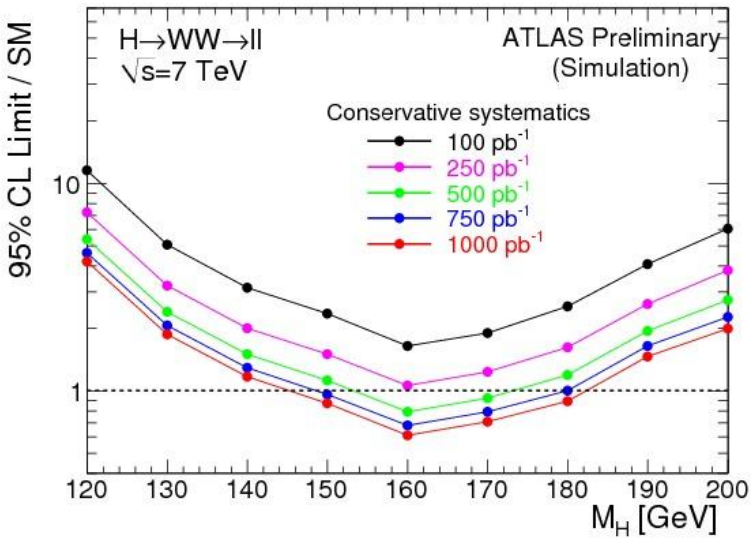
← CMS NN output

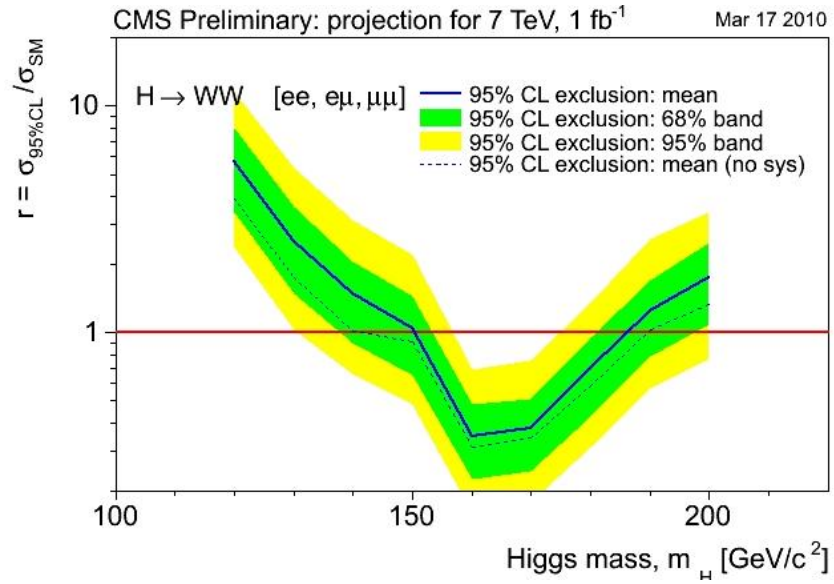
Determining background in signal region (ATLAS)



H→WW→ℓν ℓν

Ratio of 95% CL upper limit on σ x B(H→WW→ℓνℓν) and the SM rate



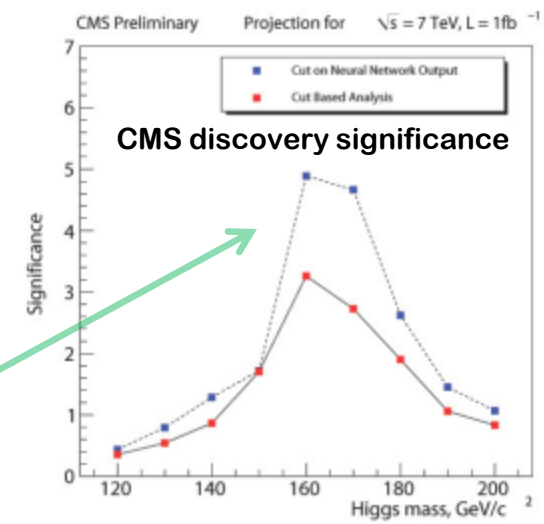


ATLAS

- sensitivity to SM starts with L = 250 /pb
- with L= 500 /pb would exclude same range as ICHEP 2010 TeVatron combination
- 145 < m_H < 180 GeV excluded (L=1 /fb)

CMS (L= 1 /fb)

- 150 < m_H < 185 GeV excluded
- discovery sensitivity (significance > 4.5σ): 160 < m_H < 170 GeV



$H \rightarrow ZZ \rightarrow \ell\ell\ \ell\ell$

Very clear signature, low bgd: effective over a wide m_H range

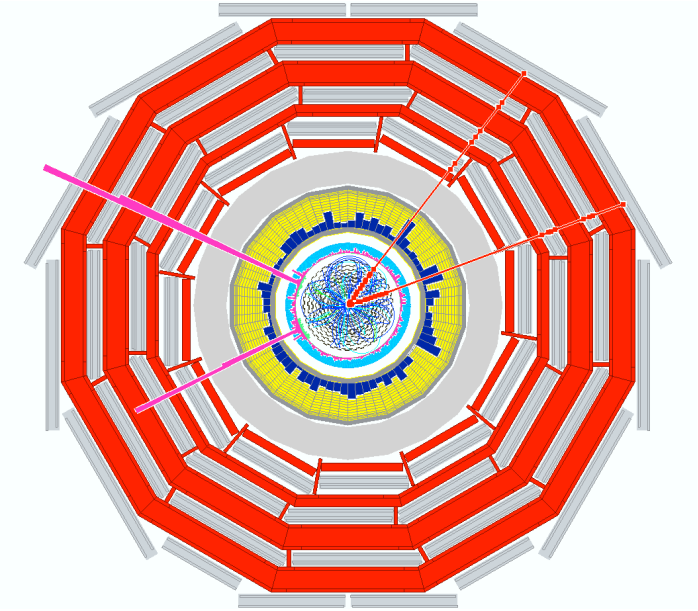
- Four isolated high p_T leptons (4e, 4μ,2e2μ)
- Reconstruct narrow 4ℓ mass peak (m_Z constraint helps)

BUT

- low signal yield: $B(H \rightarrow ZZ) \times B^2(Z \rightarrow \ell\ell) < 10^{-3}$
- backgrounds: $ZZ^{(*)}$ dominates; Z+jets, tt, Zbb

NEED

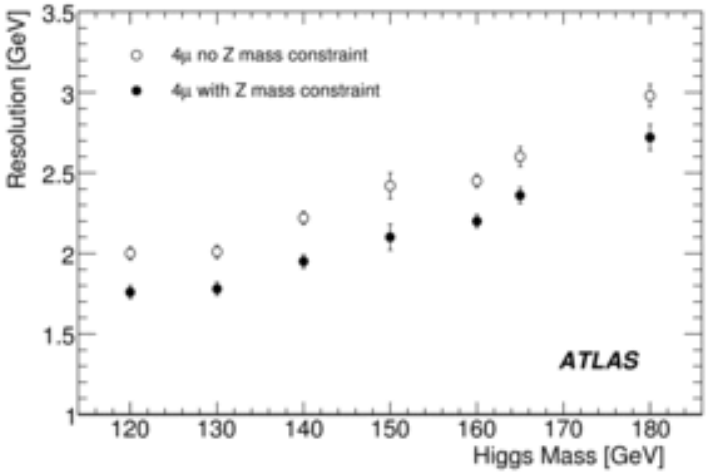
- high efficiency e/ reconstruction
- excellent lepton E and p resolution



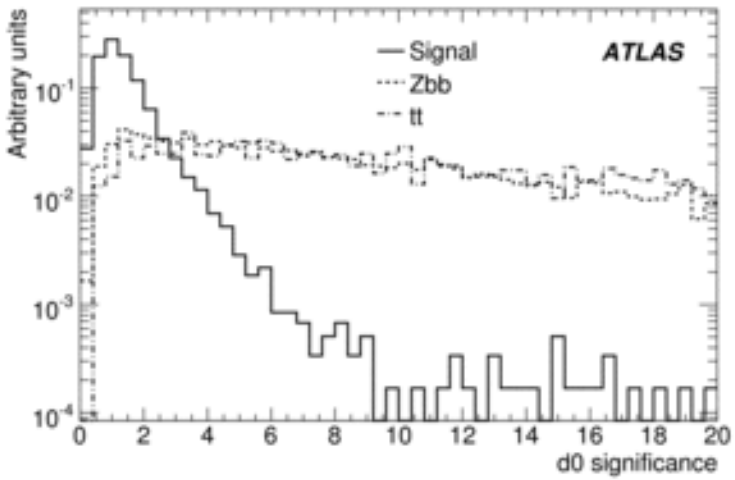
References: ATLAS CERN-OPEN-2008-020 (14 TeV); CMS PAS HIG-08/003 (14 TeV)

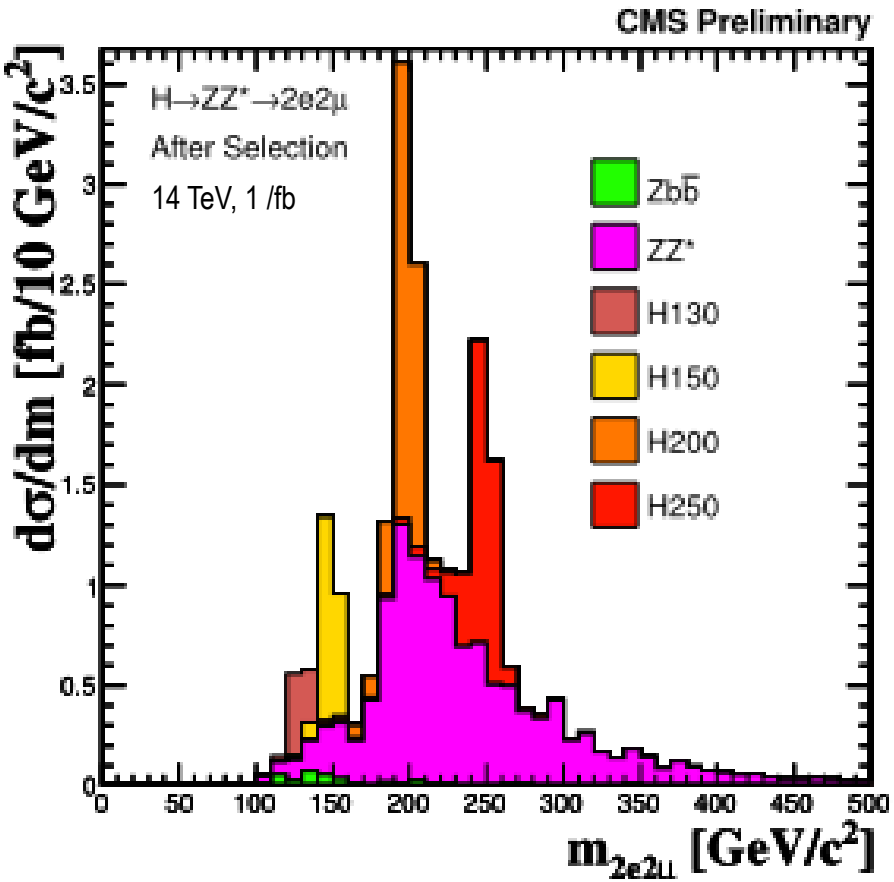
H→ZZ→ℓℓ ℓℓ

Z mass constraint:
improvement in mass resolution (10-20%)



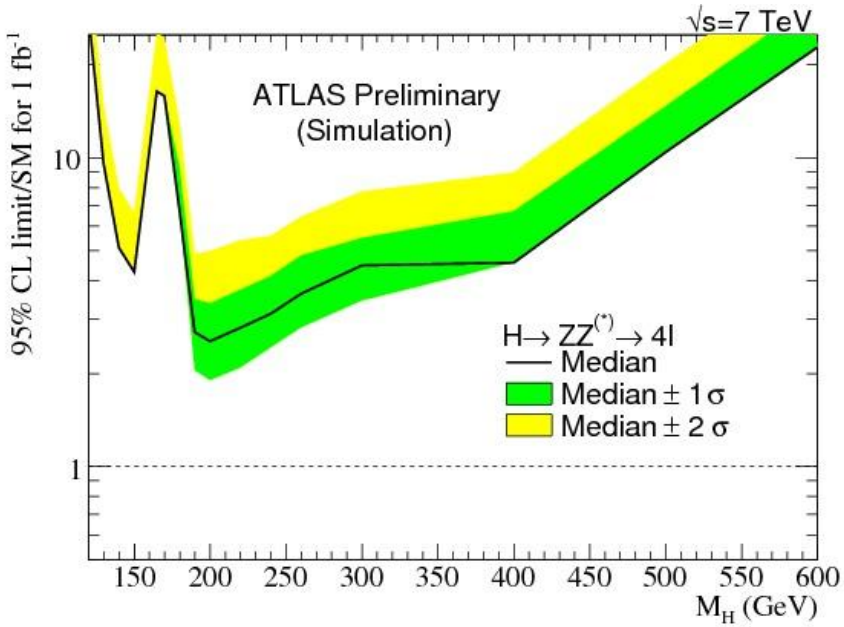
Impact parameter significance:
rejecting leptons from semi-leptonic B-decays

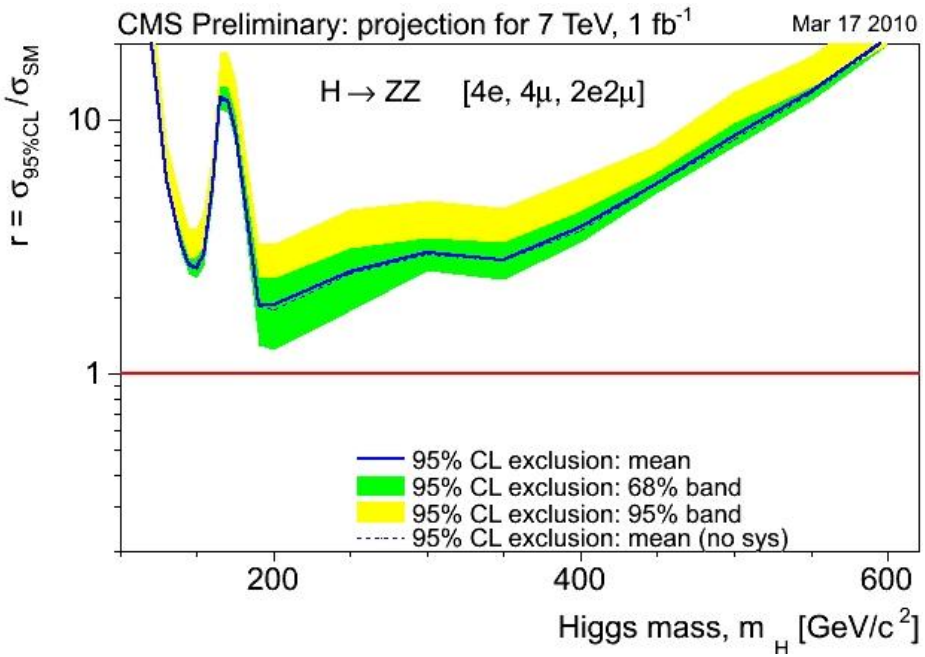




H→ZZ→ℓℓ ℓℓ

Ratio of 95% CL upper limit on σ x B(H→ZZ→ℓℓ ℓℓ) and the SM rate

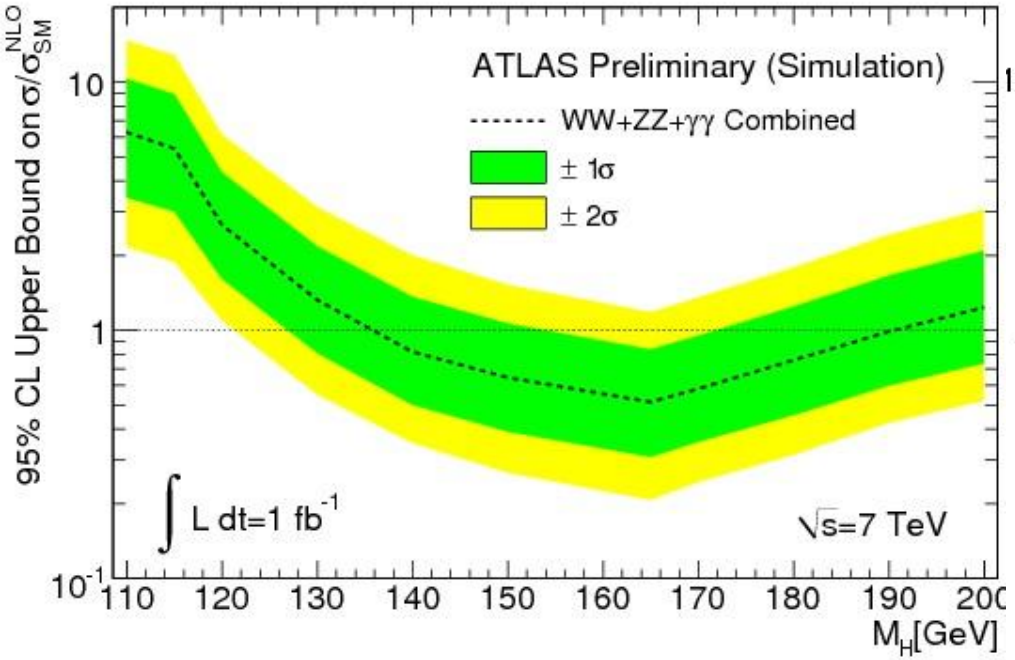


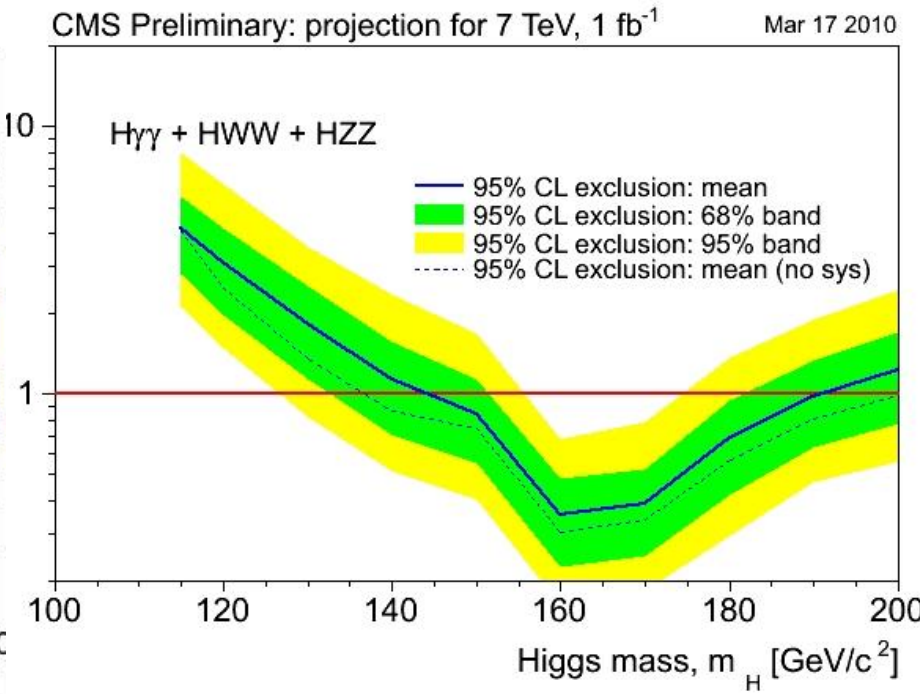


- No stand-alone exclusion
- But competitive sensitivity (< 4 x SM) in wide m_H region: 200 – 400 GeV

LHC 7 TeV combined results

95% CL upper bounds on cross-section (normalised wrt SM Higgs cross-section)
for 1/fb, and $H\rightarrow\gamma\gamma$ + $H\rightarrow WW\rightarrow\ell\nu\ell\nu$ + $H\rightarrow ZZ\rightarrow 4\ell$





$135 < m_H < 188$ GeV

$145 < m_H < 190$ GeV

- Both experiments combined (2 x CMS): **$140 < m_H < 200$ GeV** (95% CL excl.)
- Both experiments combined should exceed 5σ discovery potential for 160 – 170 GeV
- For low m_H will need more channels ($H\rightarrow bb$, $\tau\tau$), and higher √s

Subjets structure for Higgs search?

At the LHC: production of EW-scale particles (W,Z,H,t→jets) >> threshold
→ highly boosted/collimated decay products, with *measurable* **subjet structure;**
→ can be used to differentiate from QCD jets

Apply subjet analysis technique to WH+ZH (H→bb) at the LHC

- select events with very high p_T H and W,Z decay products
- cluster H decay products into a single fat jet
- iteratively decompose into **subjets** while checking for consistency with bbg
- two hardest subjets must b-tag
- subjets are "filtered" (cleanup contamination from underlying event)
- selected subjets are then used to reconstruct m_H: much improved mass resolution

- References: Butterworth et al, PRL**100** (2008)242001; ATL-PHYS-PUB-2009-088.

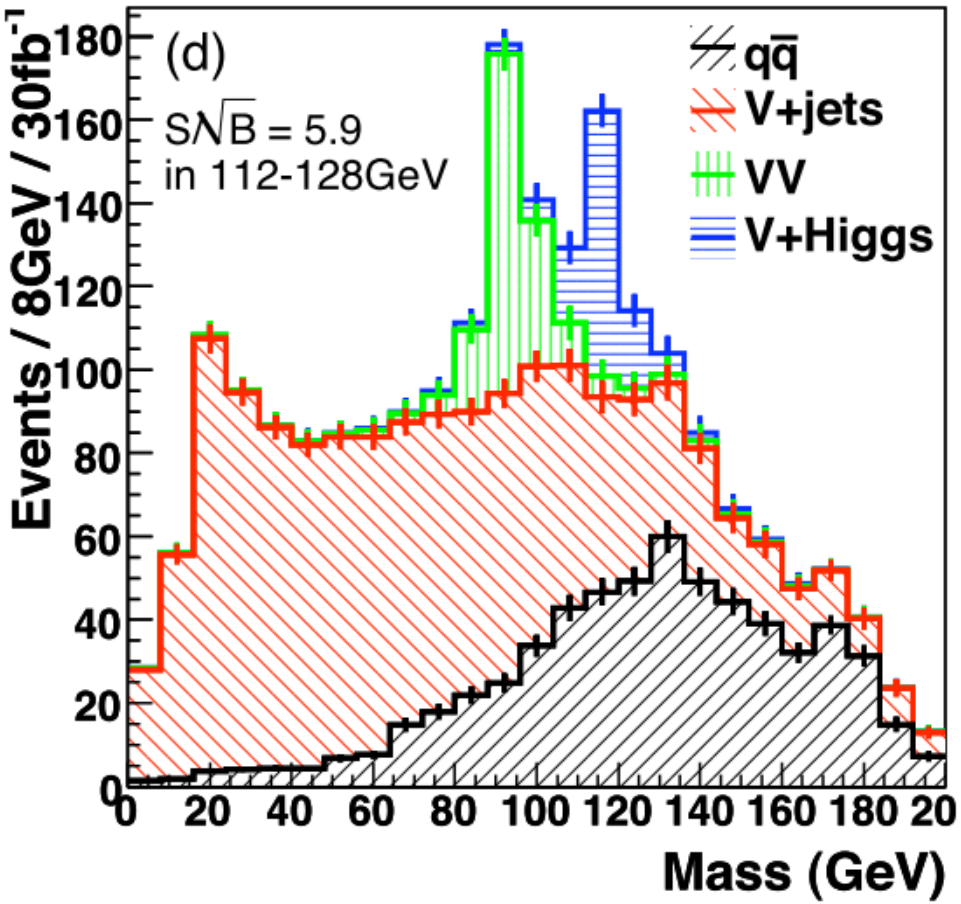
Subjets as Higgs search tool

LHC

(WH→ℓν bb + ZH→ℓℓ bb + ZH→νν bb)

Combined particle-level result

J Butterworth – *Higgs Hunting 2010*



- Note excellent Z peak for calibration
- 5.9 σ; potentially very competitive
- bb branching information critical for extracting Higgs properties
  - *"Measuring the Higgs sector" Lafaye, Plehn, Rauch, D.Zerwas, Duhrssen, arXiv:0904.3866 [hep-ph]*
- Studies within ATLAS are promising (14 TeV, ~4σ). 7 TeV nearly public.

HIGGS BEYOND THE SM

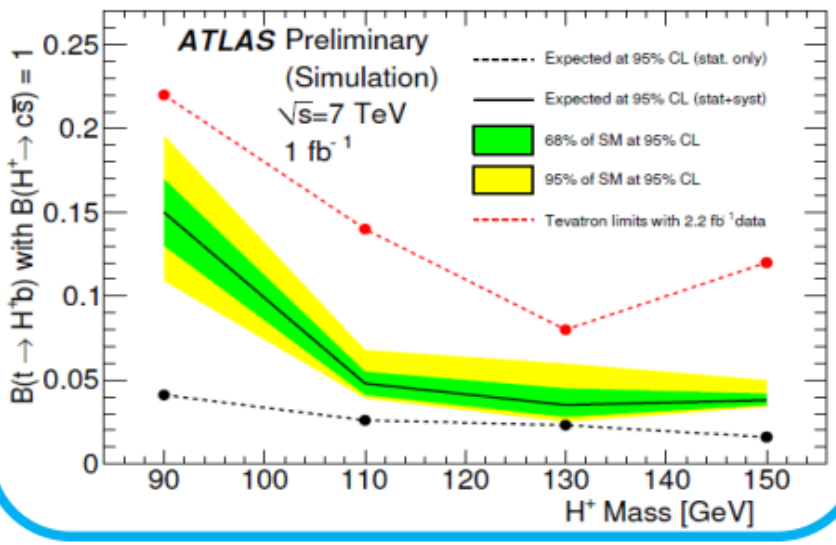
MSSM: $H^+ \rightarrow cs, \tau\nu$

ATLAS

- Light charged higgs ($m_{H+} < m_{top}$) can appear from top quark decay

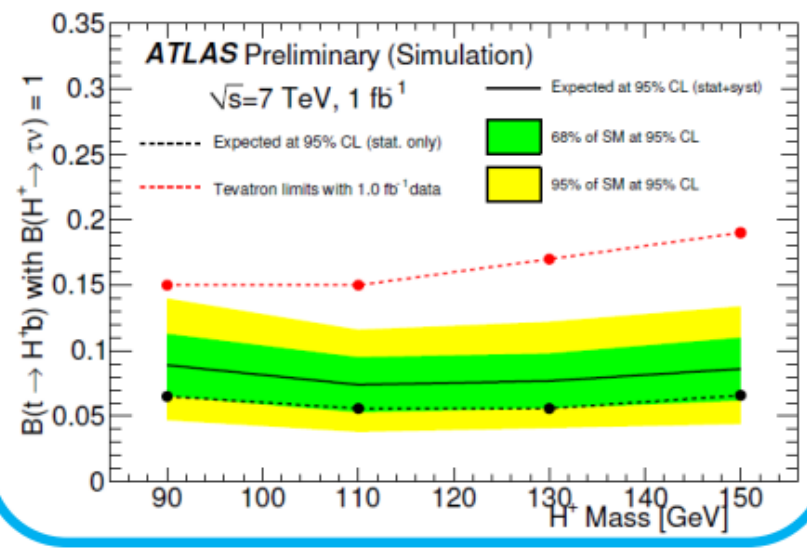
$H^+ \rightarrow c\bar{s}$ in semi-leptonic $t\bar{t}$ events

- lepton + MET + 4jets (with 2 b-tag)
- Reconstruct m_{H+} with 2 untagged jet
- Main background : ttbar (95%)
- Improve dijet mass resolution with leptonic W, top mass constraint



$H^+ \rightarrow \tau\nu$ in di-lepton $t\bar{t}$ events

- Use leptonic tau decay mode
- Two leptons + MET + 2 b-jets
- Main background : ttbar (90%)
- Look for excess close to -1 in helicity angle $\cos\theta_l^*$

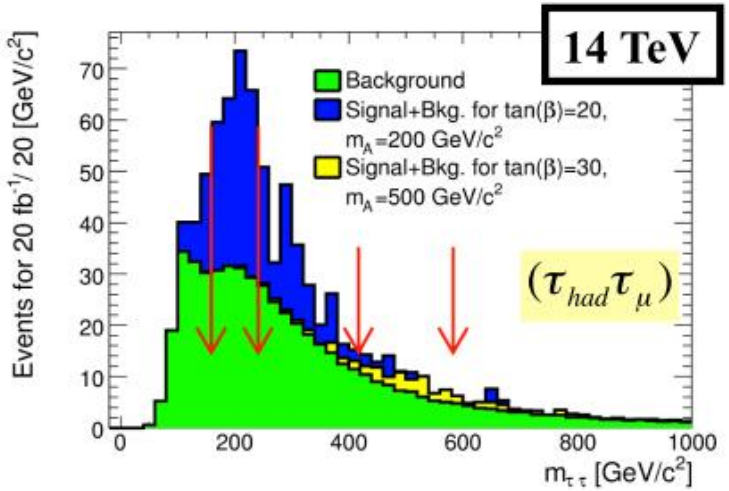


Better upper limit on branching ratio compared to current Tevatron results

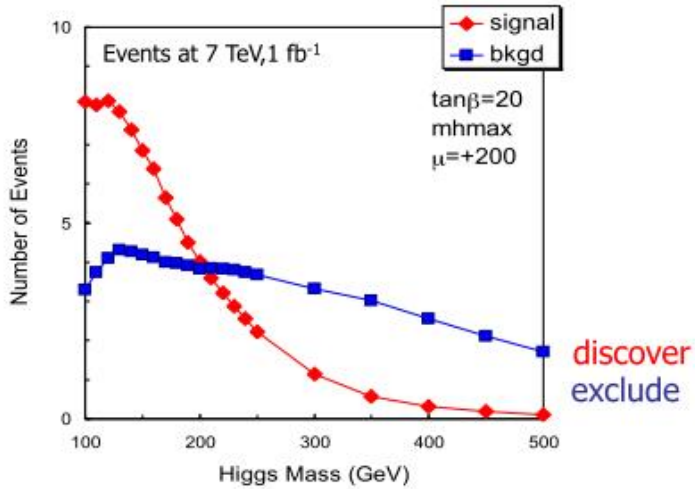
T Masubuchi – *ICHEP 2010*

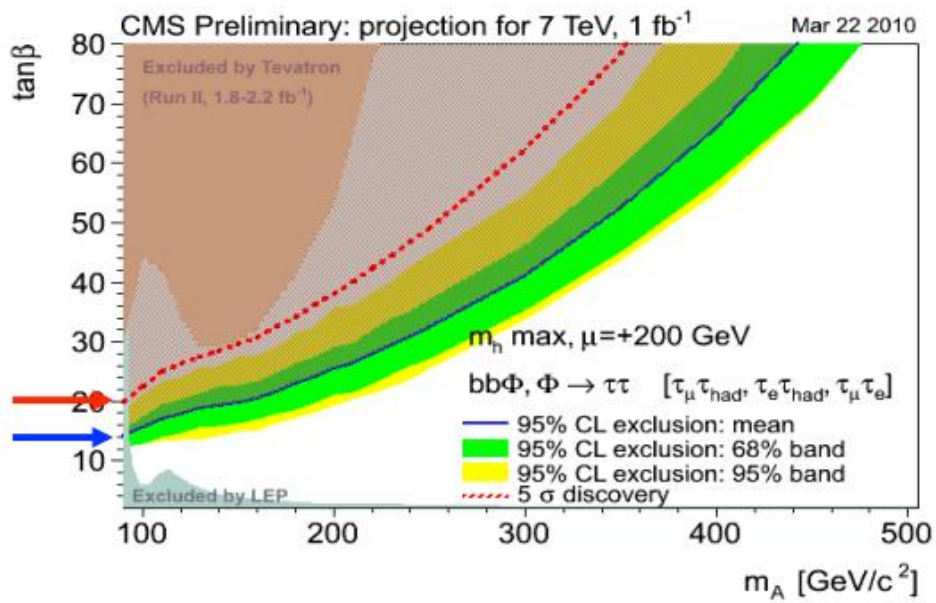
MSSM Higgs pp→bbφ; φ→ττ

CMS



- – Isolated pairs of $(\tau_{had}\tau_\mu),(\tau_{had}\tau_e),(\tau_\mu\tau_e)$
- – With MET, 1 tagged bjet, veto extra jets
- – Build $\tau\tau$-mass using collinear approx
- – Count events in sliding $\tau\tau$-mass window
- – Dominant backgrounds: $t\bar{t}$, $Z+b\bar{b}$ & $Z+c\bar{c}$
  - -- assessed from data





M Gataullin – *ICHEP 2010*

Conclusions and Outlook

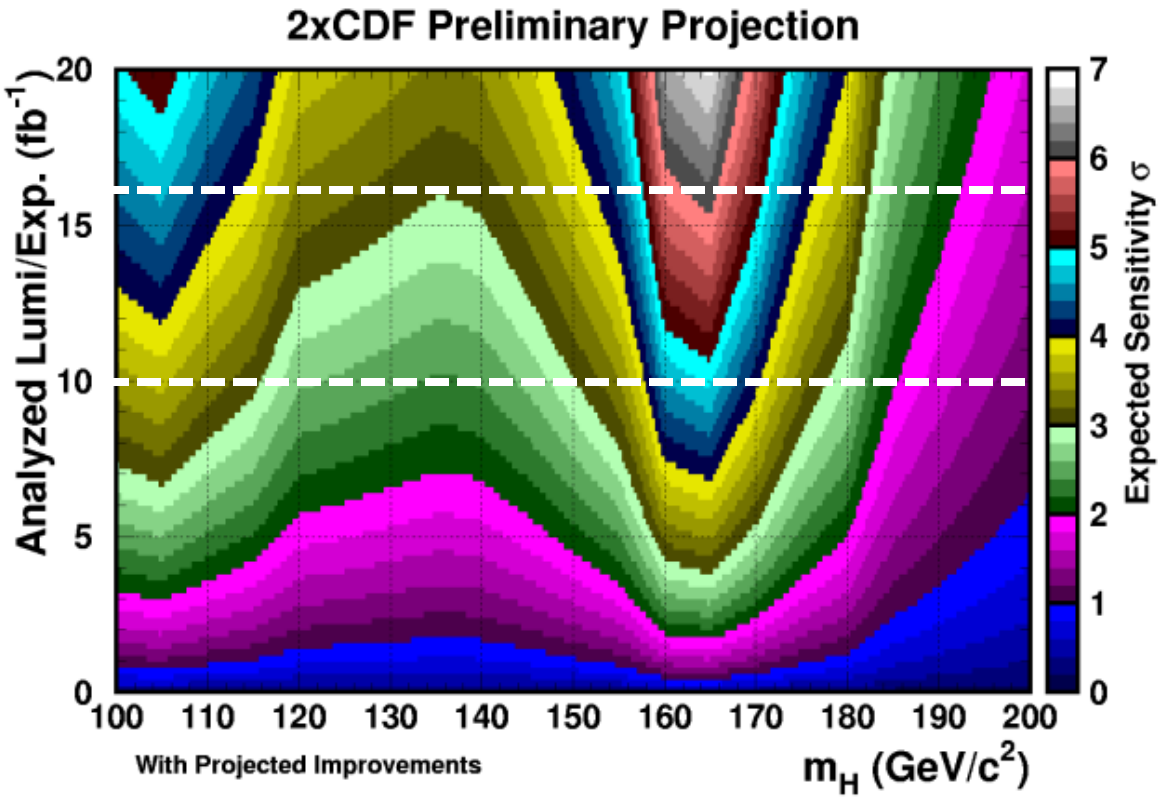
- **TeVatron Higgs:**
  - **pushing on, with an impressive list of sophisticated searches**
  - **extended running for 3 more years proposed ("Run III")**
- **LHC:**
  - **machine and detectors operating extremely well**
  - **off to a good start! …but some major milestones still ahead of us**
- **LHC initial sensitivity to Higgs: expected early in 2011**

This time next year we may have some real Higgs candidates… not just simulation!

Truly higgsciting times ahead!!

BACKUPS

TeVatron Higgs projections



Projections (based on 2 x CDF):

End 2011, 10 /fb

2.4σ expected across whole range

3σ at m_H=115 GeV

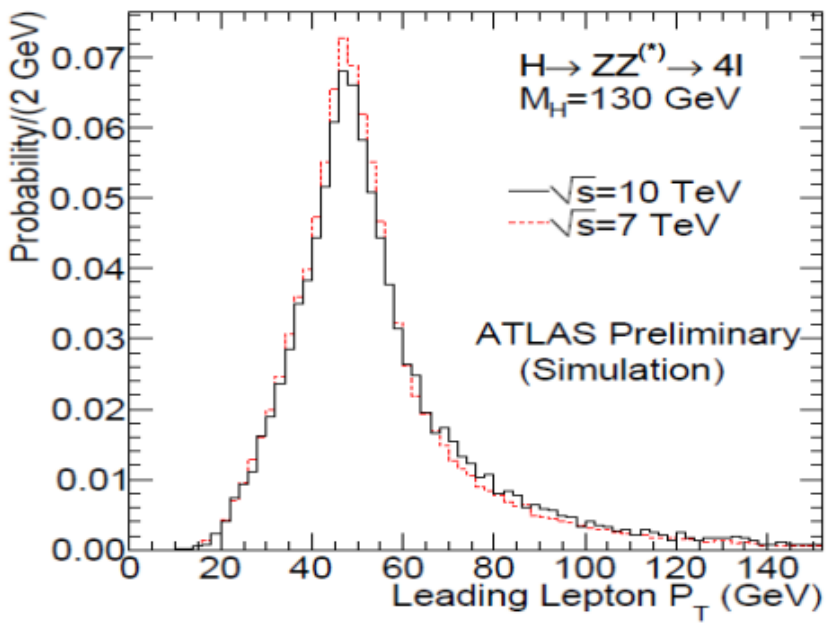
End 2014 (Run III), 16 /fb

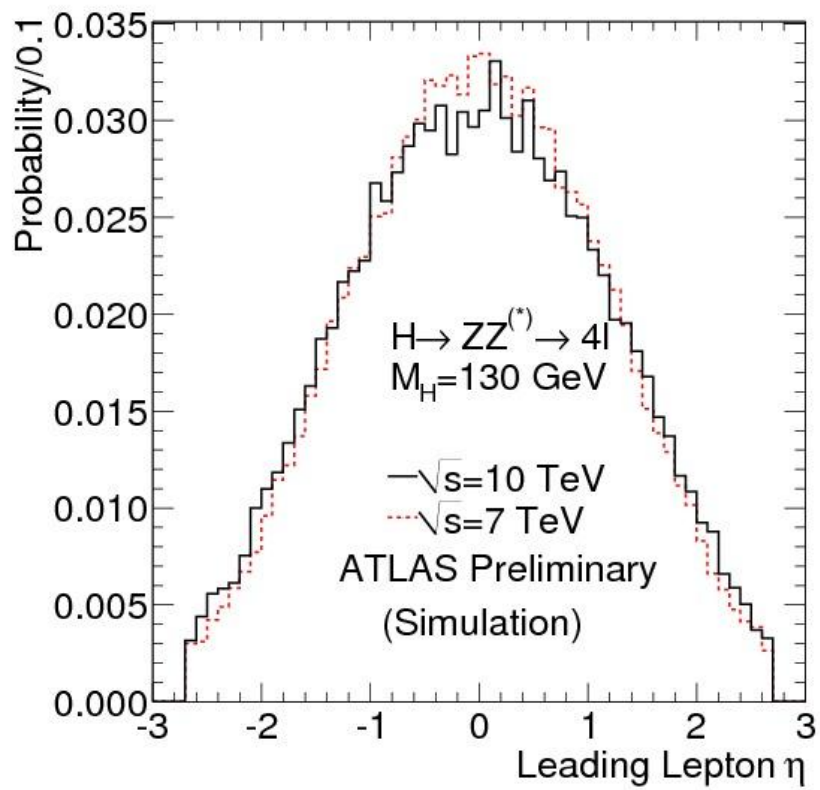
3σ expected across whole range

4σ at m_H=115 GeV

Rescaling effect on H→ZZ→ℓℓℓℓ

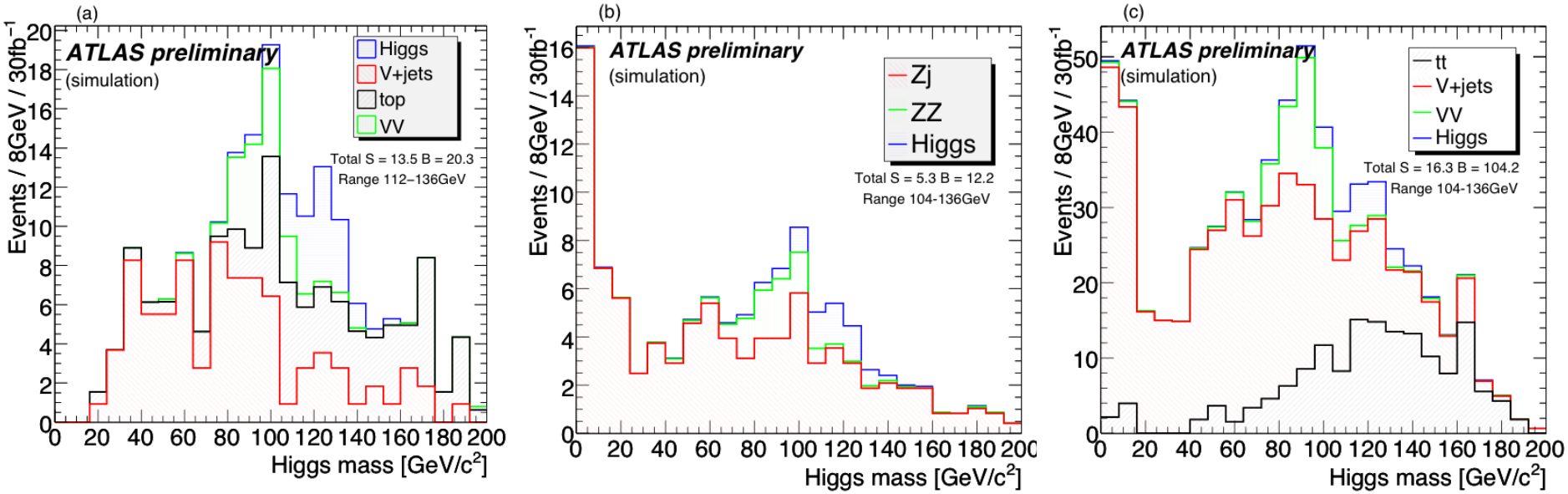
Acceptance of signal and irreducible ZZ background agree to within 2%





Fully simulated detector

- Included trigger, real ATLAS b-tagging algorithm, detailed tracking & calorimeter
- Also include Wt background omitted from initial study.
- Also included study of Wbb ME vs Wg->Wbb
- Slight degradation w.r.t particle level, but still very promising



Scale uncertainty

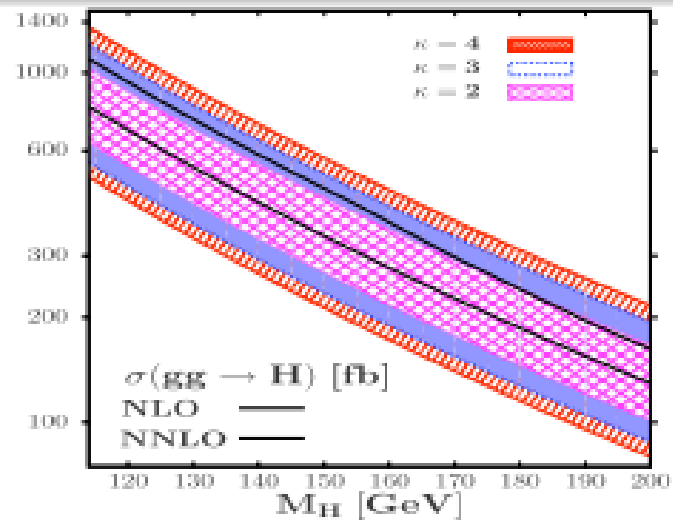
Higher orders (HO) guessed with μ_R, μ_F variation around central $\mu_0 = m_H$

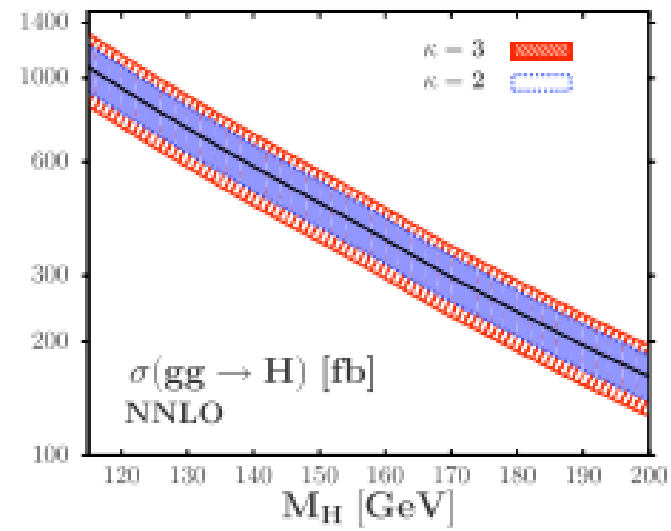
$$\frac{m_H}{\kappa} \leq \mu_R, \mu_F \leq \kappa m_H$$

Small HO $\Rightarrow \kappa = 2$ enough (ex. $q\bar{q} \to HV$)

Large HO in $gg \to H$ ($K_{HO} \simeq 3$)
guess scale domain from $\sigma_{\rm NLO}$:
NLO band catches $\sigma_{\rm NNLO}$
$\Rightarrow \kappa = 3$ needed (at least) according to our criterium
NNLO $gg \to H$: $\simeq$ **20% scale variation**

($\neq$ 10% assumed by CDF/D0)





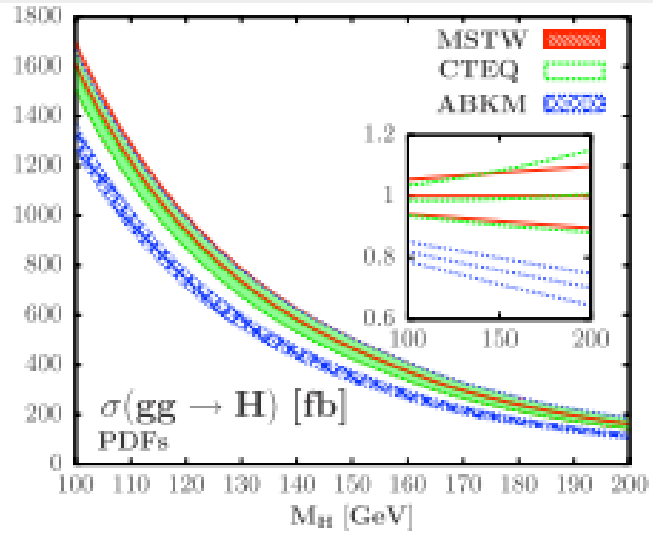
PDF and $\alpha_s^{\text{exp+th}}$ errors

Different sets of PDFs on the market

⇒ differents errors on individual PDF

+ different central values

All have $\sim 5-7\%$ error, but central ABKM is 25% smaller than MSTW/CTEQ !



Add PDF+α_s^{exp} correlated error (MSTW dedicated set)

⇒ $\alpha_s(M_Z) = 0.1171 \pm 0.0034$ (90%CL) error

Add $\Delta^{\text{th}}\alpha_s = 0.002$ error with central fixed–α_s MSTW PDF sets

⇒ ABKM is now consistent with MSTW/CTEQ

$\sim$ 20% final error $\gg$ 5% PDF alone