Higgs Searches

Bill Murray
RAL, STFC
Bill.Murray@stfc.ac.uk

Foz del Arelho
8th September 2011

- **Historical review**
- **ATLAS (LHC) search techniques**
- **Focus on results tomorrow**

Caveats

- For LHC I will often only show ATLAS
  - CMS is broadly similar
  - But I know ATLAS better
- Results are all at 7TeV;
  - Some illustrations taken from 14TeV
- Don't trust the numbers!
  - What is important is that you understand the principle rather than getting the right answer

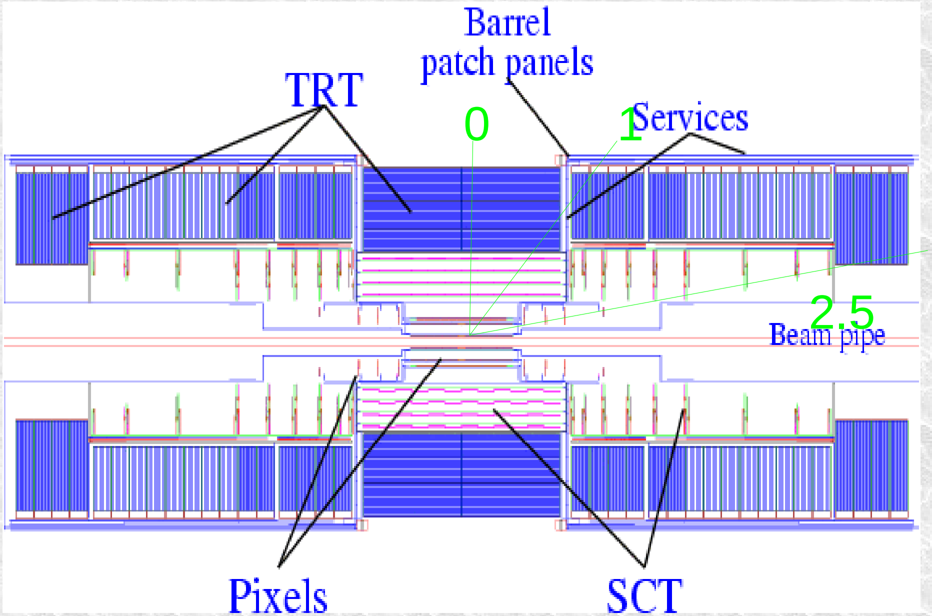
Who am I?

- I got a job in 1993 saying I wanted to look for the Higgs
- I worked on the LEP Higgs search
  - Especially in the lest year and excitement at 115GeV
- I have spent some time looking at a muon collider as a Higgs factory
- I am currently Higgs convenor of ATLAS

Science & Technology Facilities Council
Rutherford Appleton Laboratory

Co-ordinates

- pp ($p\bar{p}$) collisions are between partons
  - Proton remnants carry p_z down beampipe
  - Therefore z component of momentum is of reduced interest
- Tracker quotes p_T, calorimeter E_T
- Rapidity $y = \frac{1}{2}\log\frac{E+p_Z}{E-p_Z}$
- Pseudo-y $\eta = \log\tan(\theta/2)$
- Hadron colliders use not θ,φ but η,φ



ΔR

- y differences invariant under boost
- In massless aprox. y = η

- Jet finding is done using dR distances:

$$\Delta R^2 = \Delta\eta^2 + \Delta\varphi^2$$

- This has drawbacks for massive objects
  - Δy = Δη breaks down
  - Physical size of jets shrinks as η grows
- You can tell I am not happy with this...

Some Colliders

	LEP	LC	TeVatron	LHC
Collisions	e^+e^-	e^+e^-	$p\bar{p}$	pp
Years	1989-2000	2020??	1987-2011	2009-2018
Max E, GeV	208	?1000?	2000	14000
Integrated lumi.	$0.5fb^{-1}$	Large	$10fb^{-1}$	$300fb^{-1}$
Higgs reach	0-115	0-800+	Hard	100-1000

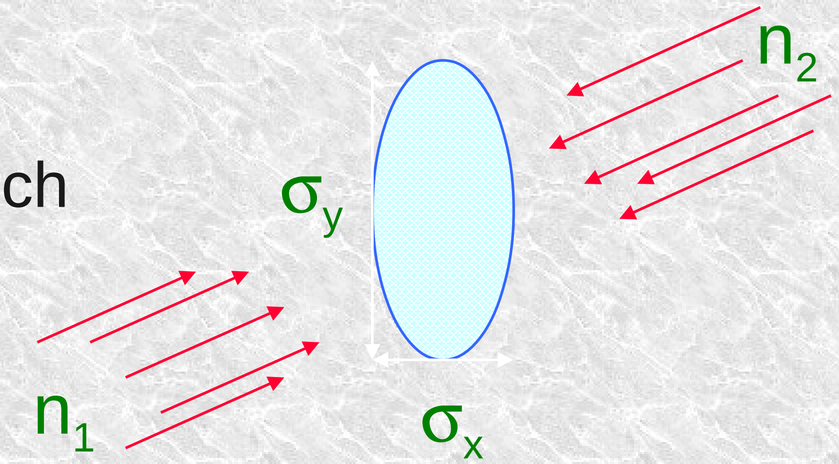
Luminosity

- Define: $R = l\,\sigma$
  - Interation rate is luminosity times cross-section

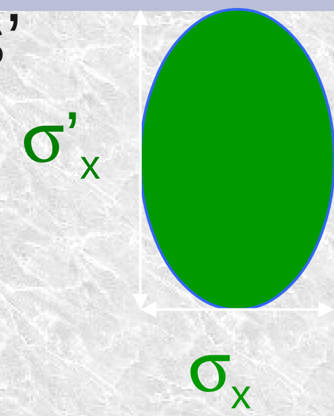
- For a circular machine

$$l = f\,\frac{n_1 n_2}{4\pi\,\sigma_x \sigma_y}$$

  - $f = n_b c/2\pi r$ is interaction rate,
  - n the number of particles / bunch
  - σ the beam size



Emittance

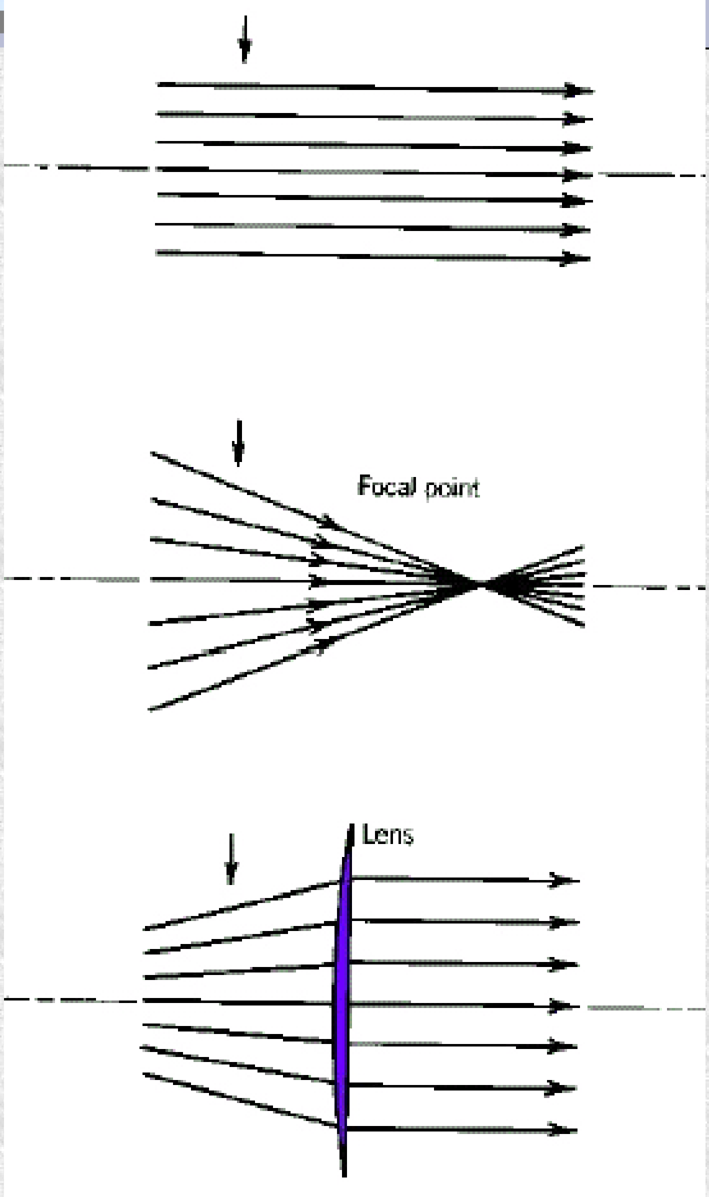


$1/\varepsilon$ = brightness

- Envelope of beam particles'
  - units m x Rad
- $\varepsilon_x = \pi \sigma_x \sigma'_x$:
  - Assumes uncorrelated
- Higher dimensional emittance
  - The 6-dimensional particle correlation x,y,z,x', y', z'
  - ε a conserved quantity (Liouville's theorem):
    - Reduce one σ, other grows
  - ε_T is almost a conserved quantity – is what LHC quotes
    - LHC has round beams: $\varepsilon_x = \varepsilon_y$
- Normalised emittance: $\epsilon_N \equiv \overline{\beta\gamma}\,\epsilon$
  - This is invariant under acceleration
  - It is so useful, it is often called emittance.

Emittance examples

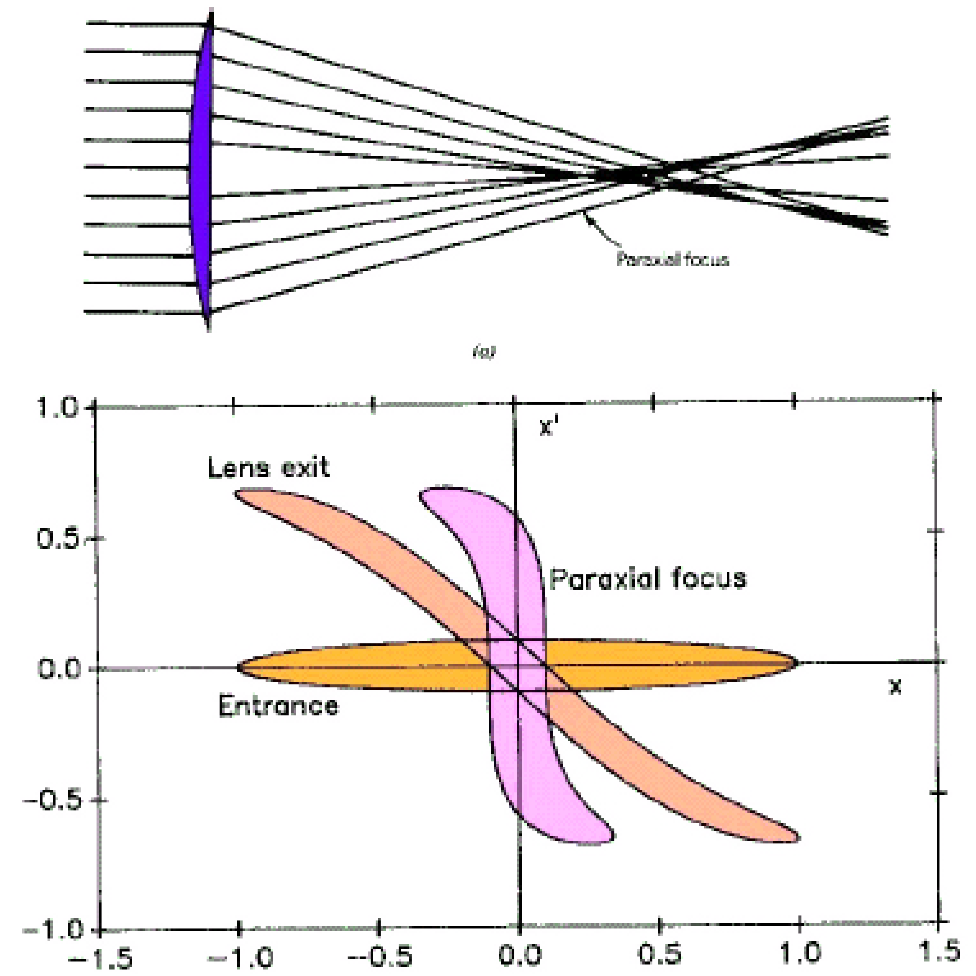
- All these have zero emittance



More Emittance examples

- Finite emittance
- Initially x' small
- Lense correlates x,x'
- Drift to focus makes x small.

- Area is conserved



Luminosity and Emittance

- Define β^* as σ_x/σ'_x,
- This is the strength of the focusing magnets
  - 'Low Beta quads'

$$l = f\frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

$$l = f\frac{n_1 n_2}{4\sqrt{\epsilon_x\beta^*_x\epsilon_y\beta^*_y}}$$

Beam Emittance

- e^+e^- rings set by synchrotron radiation
  - Electron machines `have no memory'
- pp machines limited by beam preparation
  - Stochastic cooling
  - emittance growth is cumulative
    - Beam beam effects reduce LHC emittance during fill
- For linear accelerators preparation and beam blowup contribute.

Luminosity Optimisation

$$l = f \frac{n_1 n_2}{4\sqrt{\epsilon_x \beta_x^* \epsilon_y \beta_y^*}}$$

- Increase f
  - Bunch separation, power constraints
- Increase n_i
  - Space charge, power, particle availability, pileup
  - But quadratic gain in rate...
- Decrease β^*
  - Strong Quads inside detectors apparatus, blowup, beam aperture limitations, bunch length
- Decrease ε
  - ‘colder beams’ improve performance
  - But too small and you have blowup issues

Other Luminosity limits

- Beam beam interaction:
  - Each beam feels field of the other: Disruptive if beams very small (linear v circular collider)
- Accelerating power
  - Available watts of RF power limit currents – not LHC
- cooling power
  - Limit may be keeping accelerator cold
- Electron cloud
  - Positive beam can pull electrons off wall
    - They can amplify when they collide with wall
  - LHC needs scrubbing to reduce this
- pile-up
  - LHC designed for 25 collisions per bunch crossing – much more would swamp detectors

Luminosity - practical example

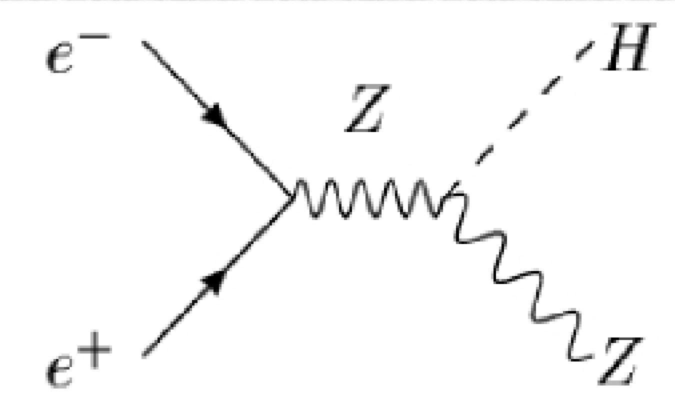
- LHC best fill:
  - 1.35×10^{11} p/bunch
  - 2×10^{-6} normalised transverse emittance
  - 1320 colliding bunches, 27km circumference
  - β^* 1.5m
- Peak Instantaneous luminosity 2.4 10^{33}cm^{-2}s^{-1}
  - Use 10^7 seconds in a year (4 months working)
  - 2.4 10^{40}cm^2/year
  - 1b = 10^{-28}m^2
  - 24fb^{-1} per year
  - Drop ~ factor 5-10 for filling, breakage, average-to-peak

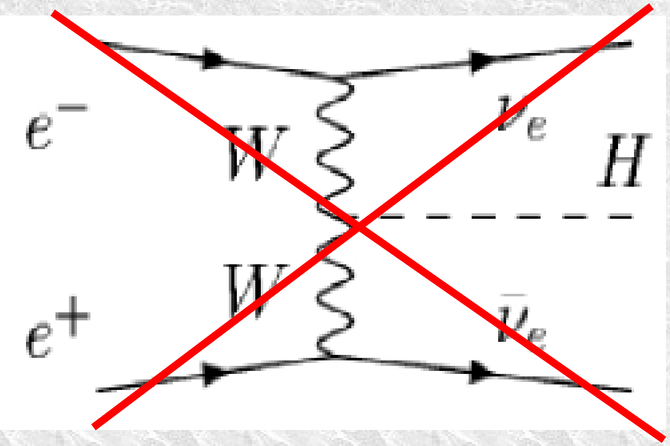
http://lpc.web.cern.ch/lpc/lumi.html

The Standard Model Higgs

LEP results

LEP Higgs production





- Production via Higgstrahlung
  - W boson fusion kinematically suppressed (<10%)
  - But included in cross-section calculations
- Established first extensive Higgs limits
- Either initial or final Z boson is off mass-shell
- Z boson decays characterise state

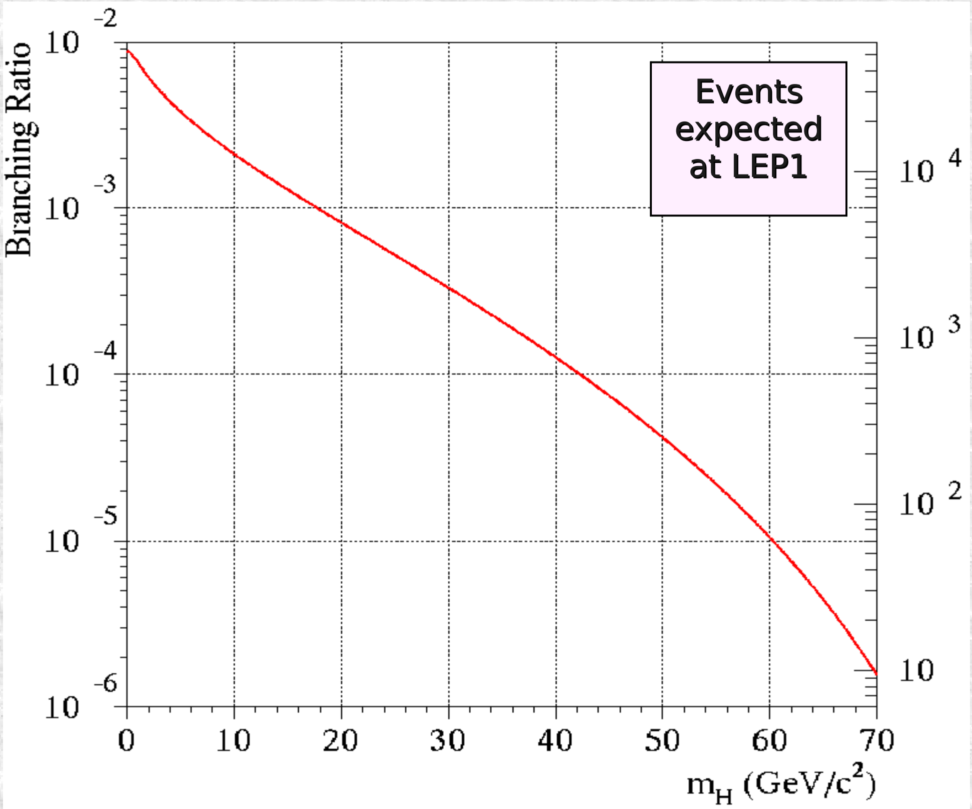
Search at LEP I - E_{CMS}=91GeV

- Great effort - which I have no time to describe
- Many modes:

    Stable,γγ,ee,μμ,ππ,ττ,bb

- Clean Z decays (ll, νν) used
- Prior to LEP only some patchy constraints

The mass range from 0 to ~65 excluded, no holes.



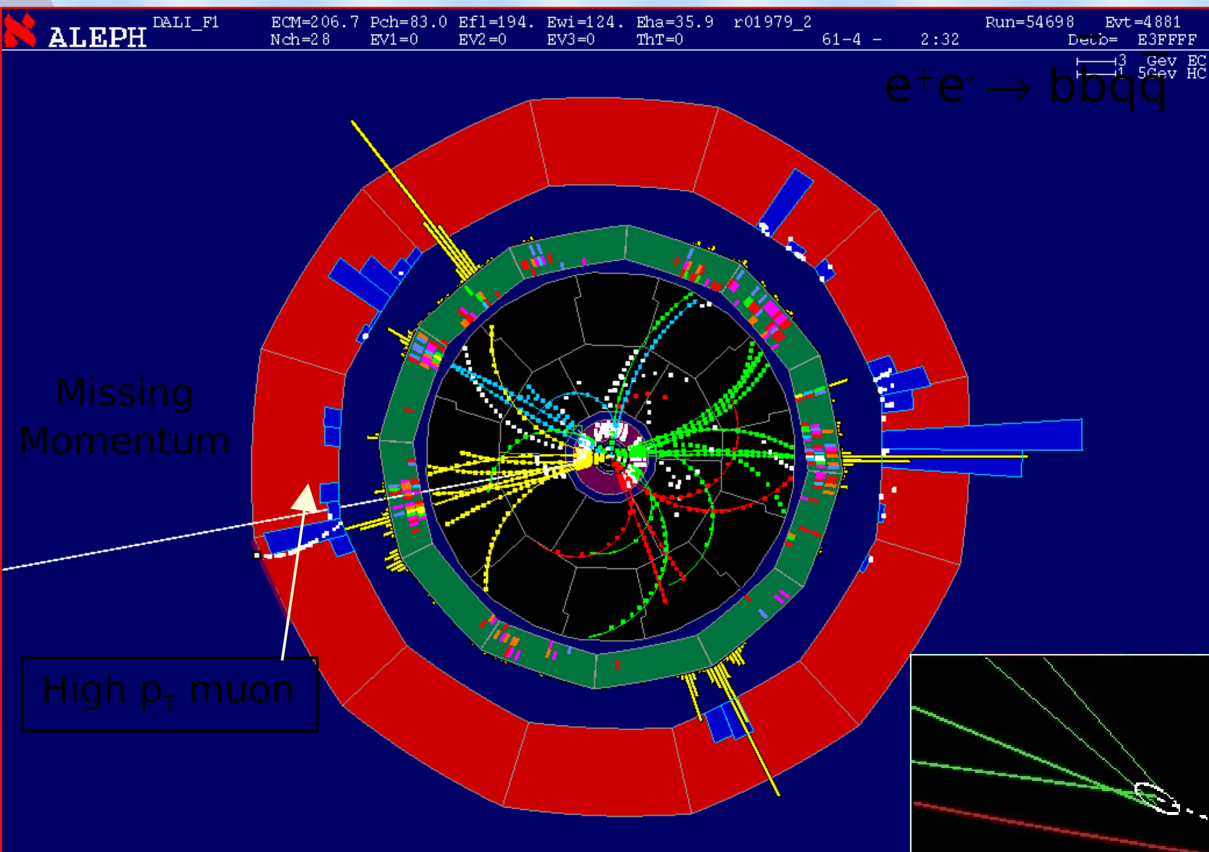
LEP 2: 200+ GeV

- Energy raised in steps from m_Z to 208 GeV
- Around $0.5fb^{-1}$ of data
- Sensitive to $Z^* \rightarrow ZH$
- Therefore approximate reach:

$$E_{CoM} - m_Z - 2$$

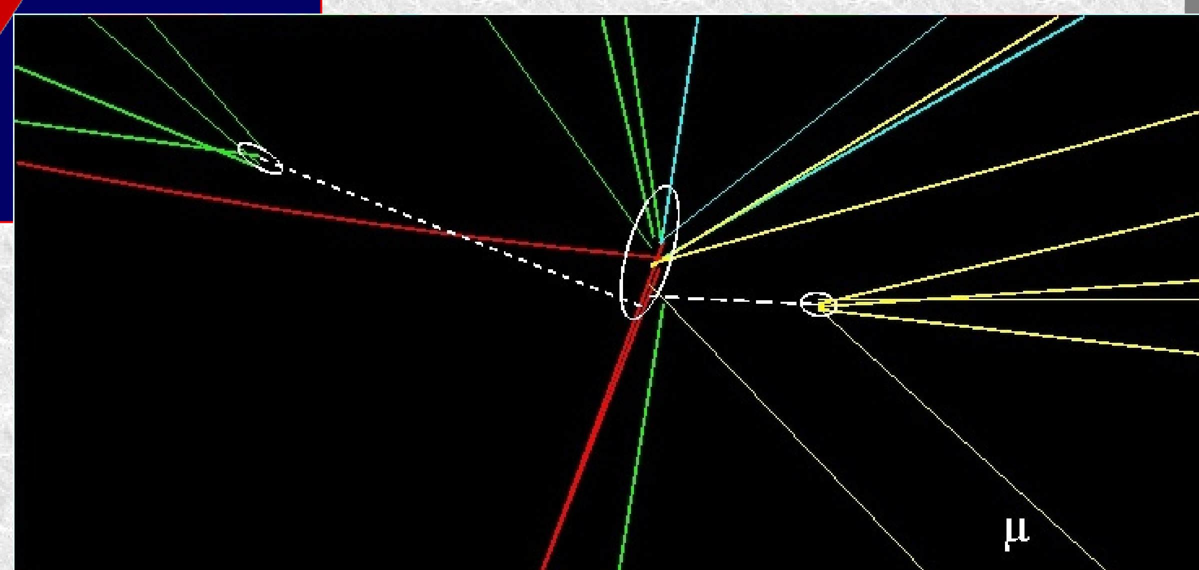
- Or $115 GeV/c^2$ at 208.
- In final year energy was raised to 206 then 208.

The best candidate, ALEPH



(14-Jun-2000, 206.7 GeV)

The purest candidate event ever

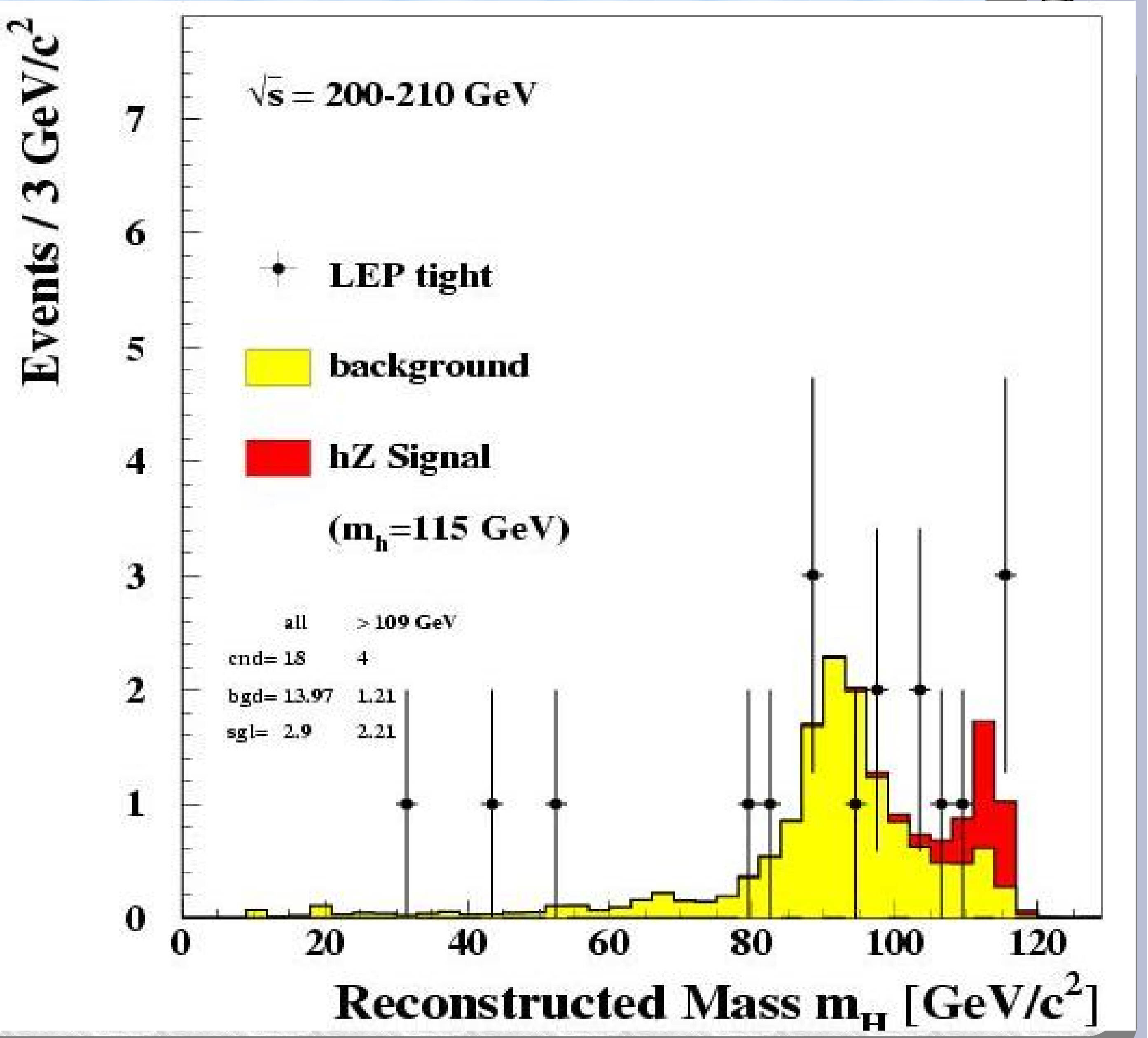


Sum of four experiments:

Distribution of the reconstructed Higgs boson mass with a Higgs boson of mass 115 GeV/c²

Yellow is background

Red is Higgs, if it weighs 115GeV

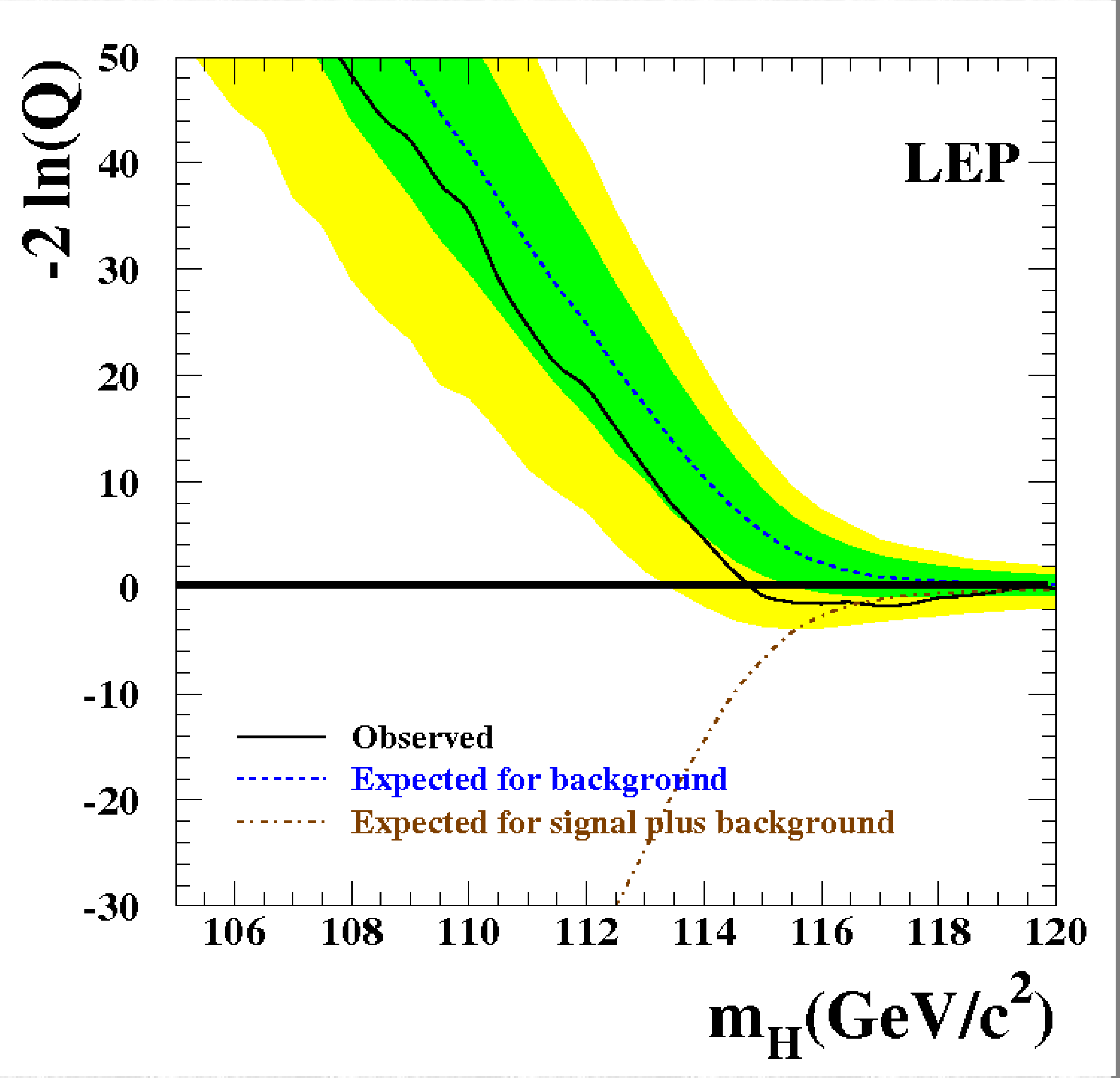


Higgs then: LEP SM Higgs

- Final LEP result:

M_H>114.4GeV
(95%CL)

Excess at 115GeV would happen in 9% cases without signal
But signal remains the best fit

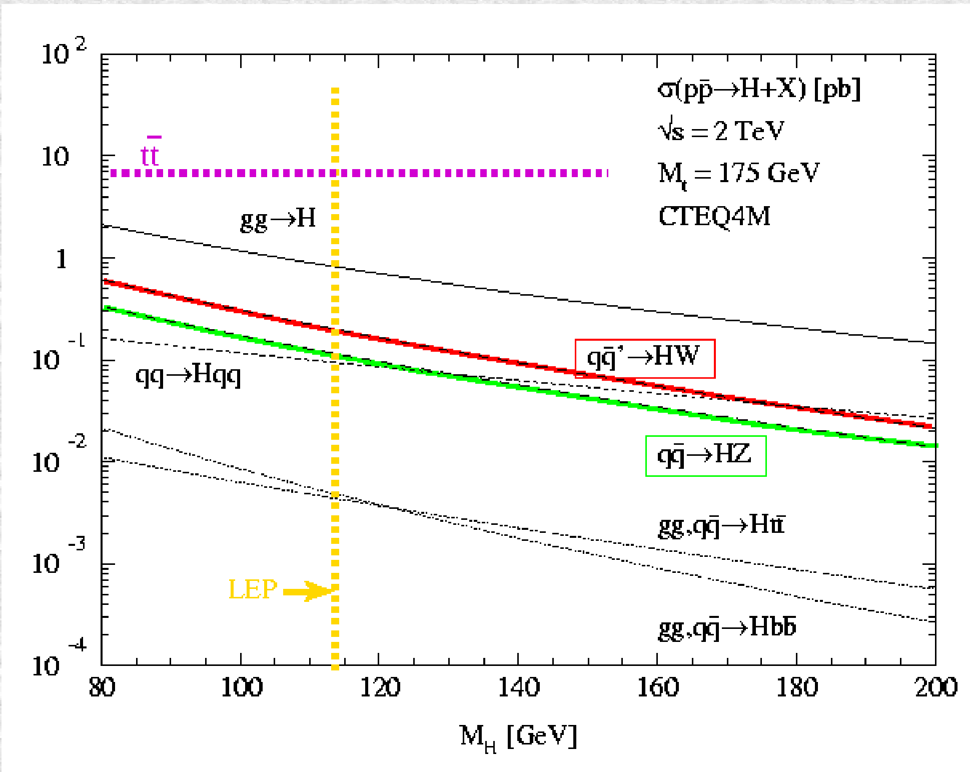


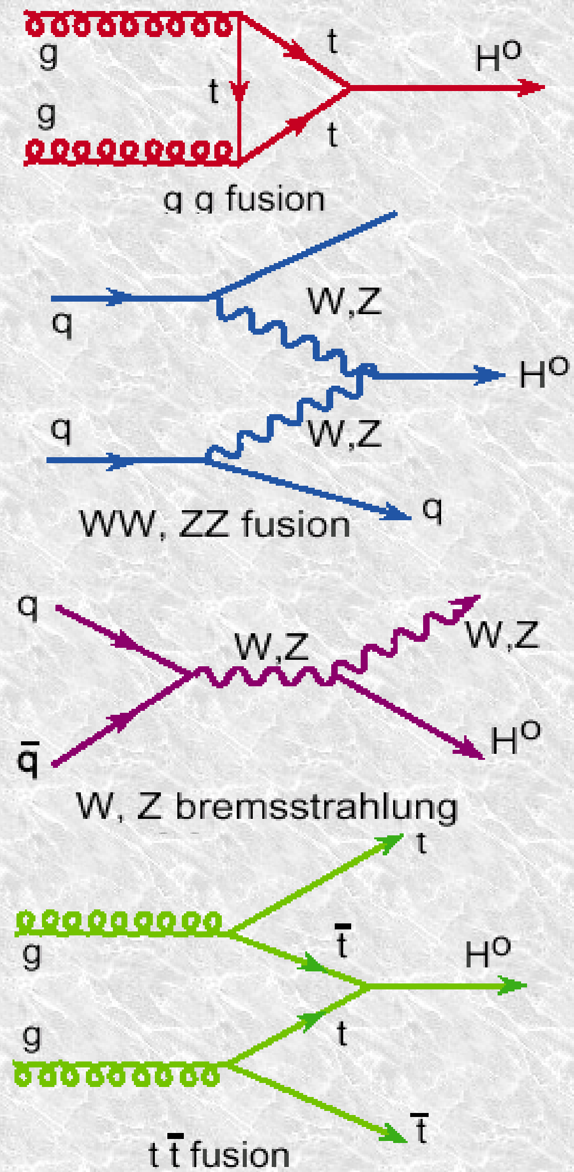
Science & Technology Facilities Council
Rutherford Appleton Laboratory

TeVatron results

Thanks to Gregorio Bernardi, for his LP-09 talk hours early

TeVatron Higgs production

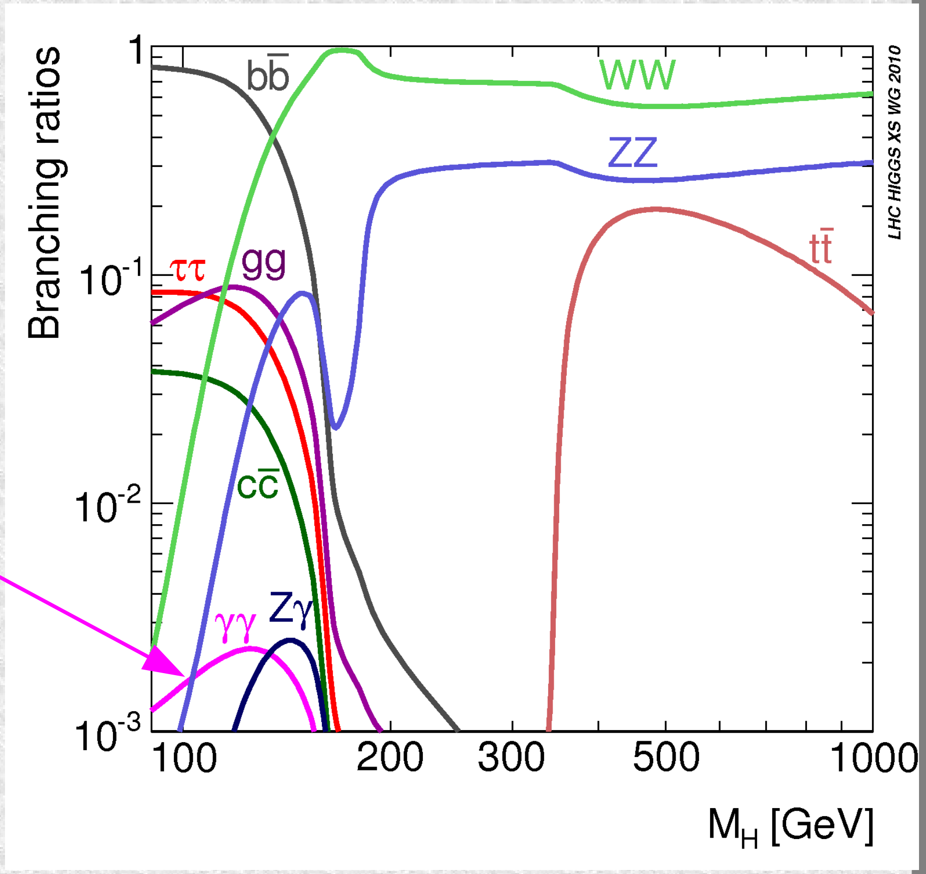




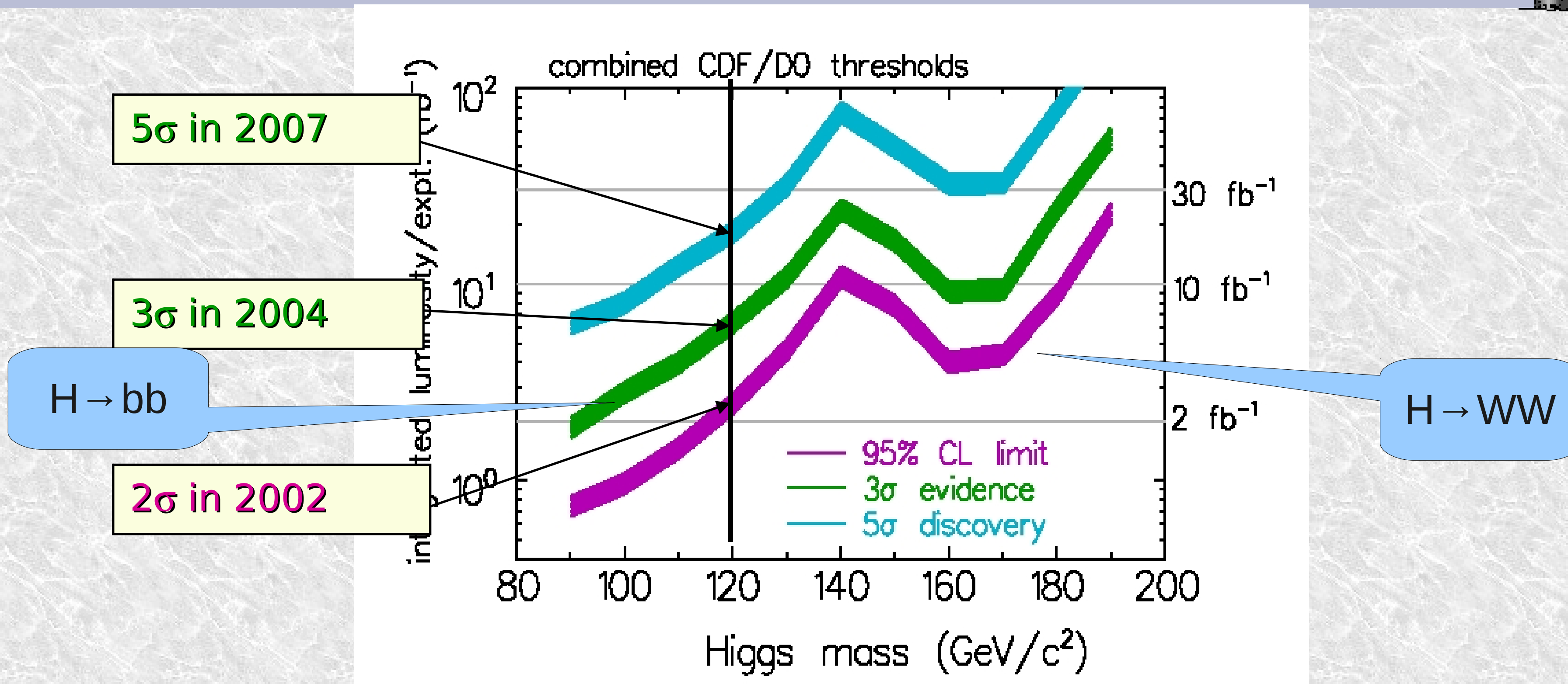
- Cross-sections of order pb
- $10fb^{-1}$ data gives thousands
- But the background are large

Tevatron analyses Channels

- H → WW
  - WW → lνlν: Most sensitive
- H → bb
  - tt̄H, WH, ZH useful but hard
- H → γγ
  - Rare, best for low mass
- H → ττ
  - Good s/b, low mass,rare
- H → ZZ
  - ZZ → llll: Cleanest mode but low rate

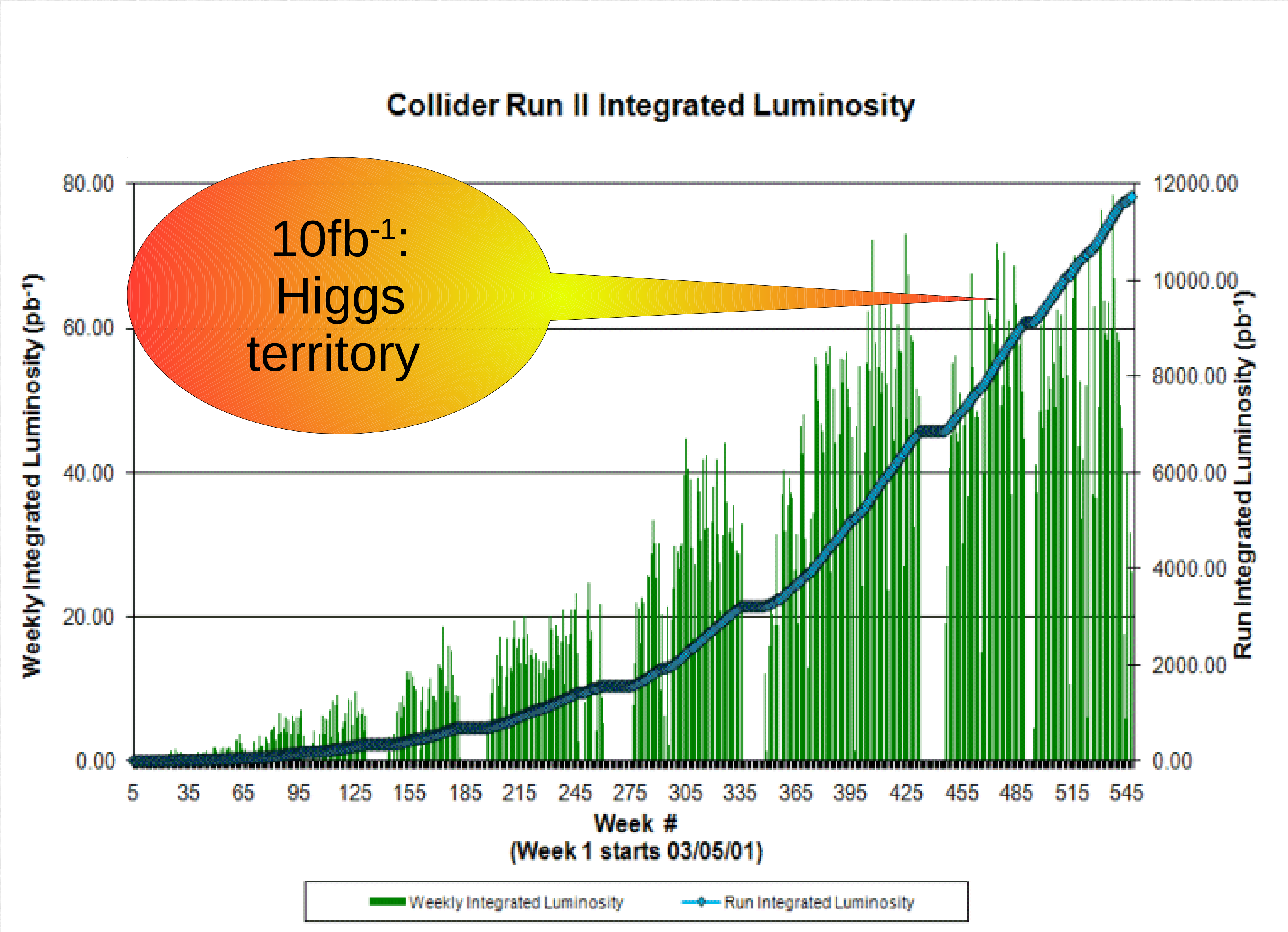


TeVatron pre-run expectation

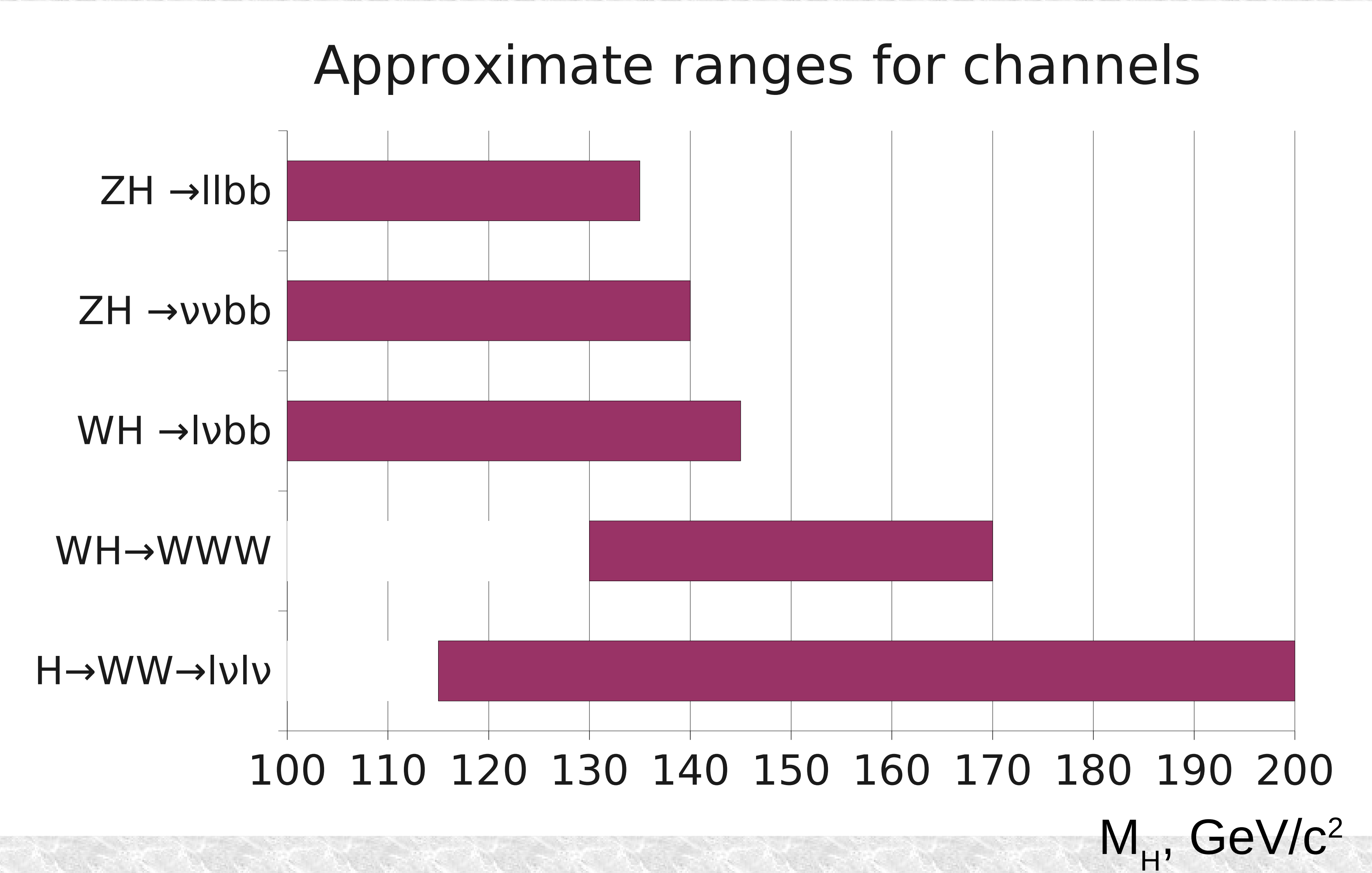


- Luminosity has been slower coming than hoped
  - LHC may have the same problem
- Planned silicon upgrade was not purchased
  - Hurts the $H \to b\bar{b}$ channels

Higgs now: The Tevatron

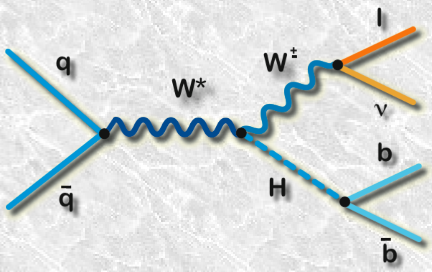


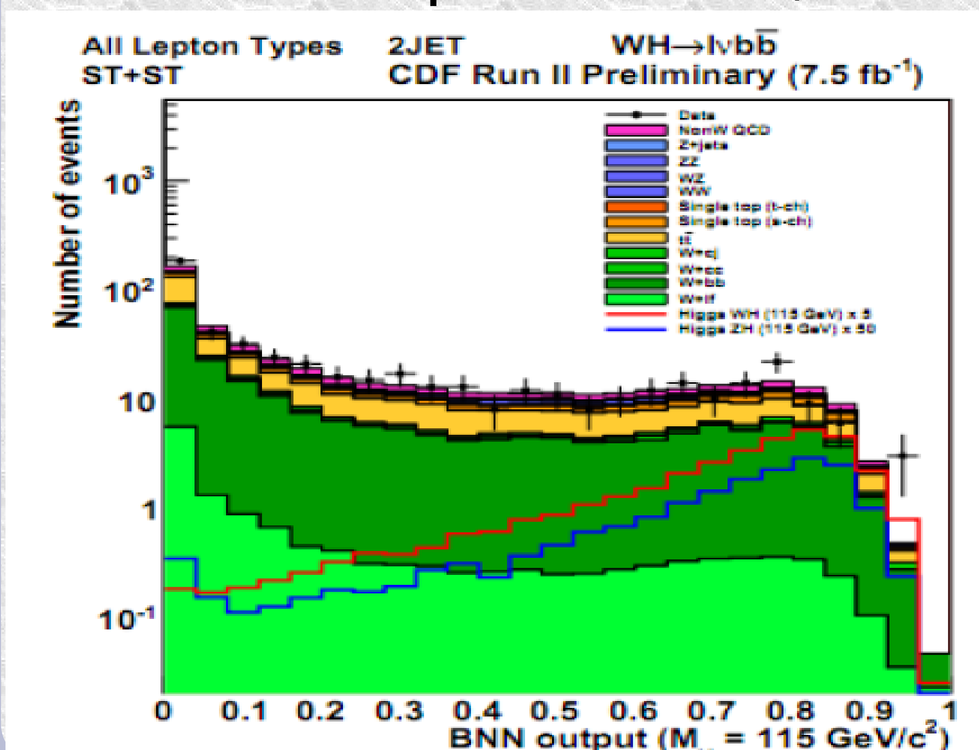
Tevatron Major channels

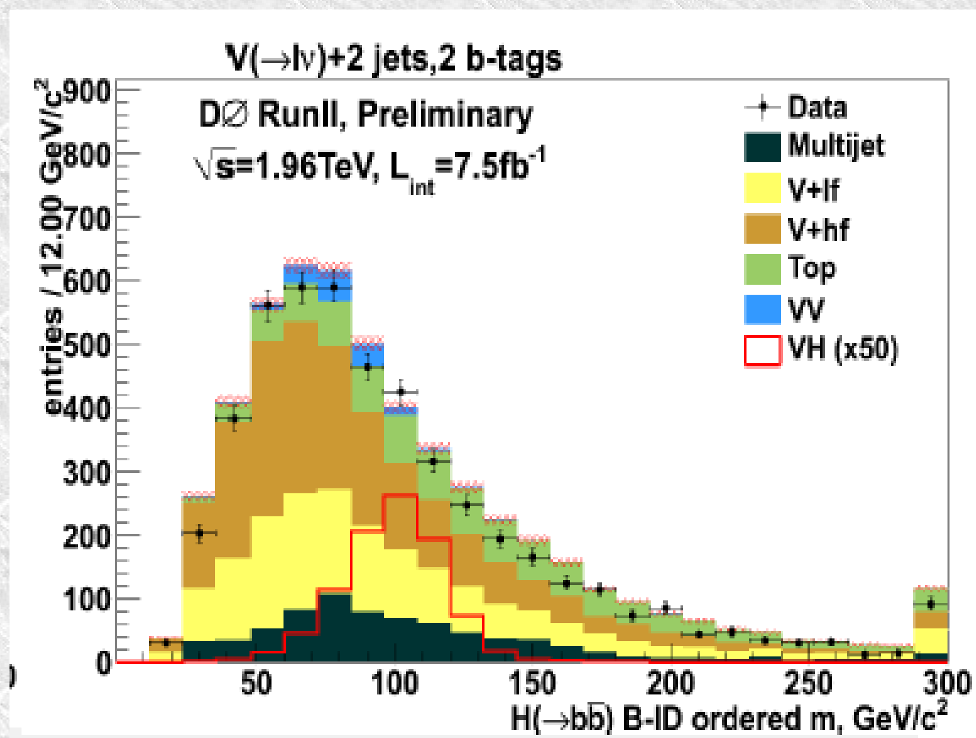


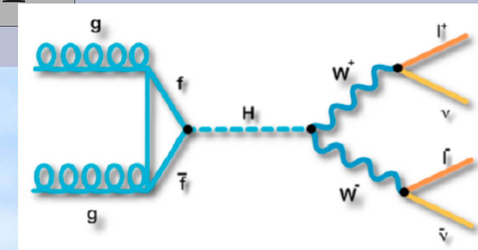
SM Higgs: WH→lνbb

- Signature: high p_T lepton, MET and b jets
  - Backgrounds: W+bb, W+qq, single top, Non W(QCD)
  - Key issue: estimating W+bb background
    - Shape from MC, normalization from data



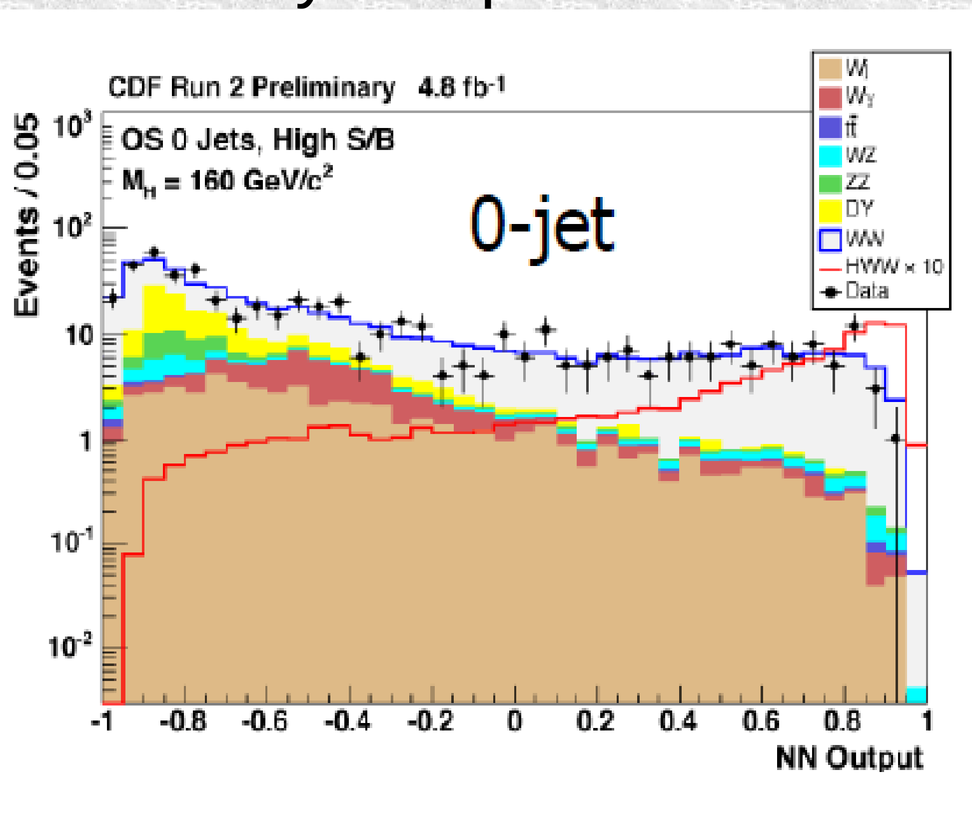


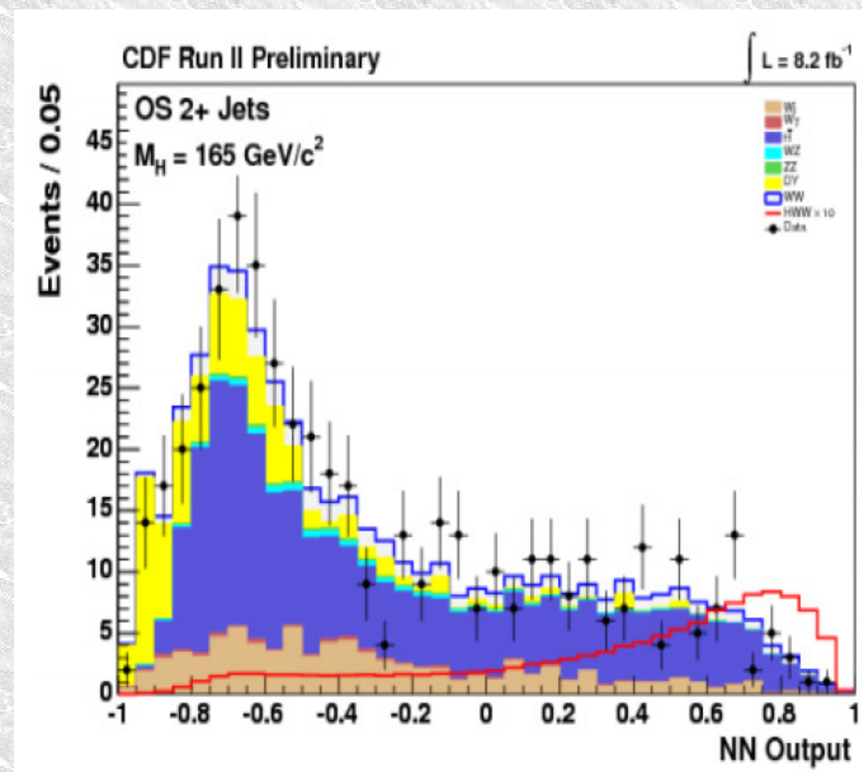




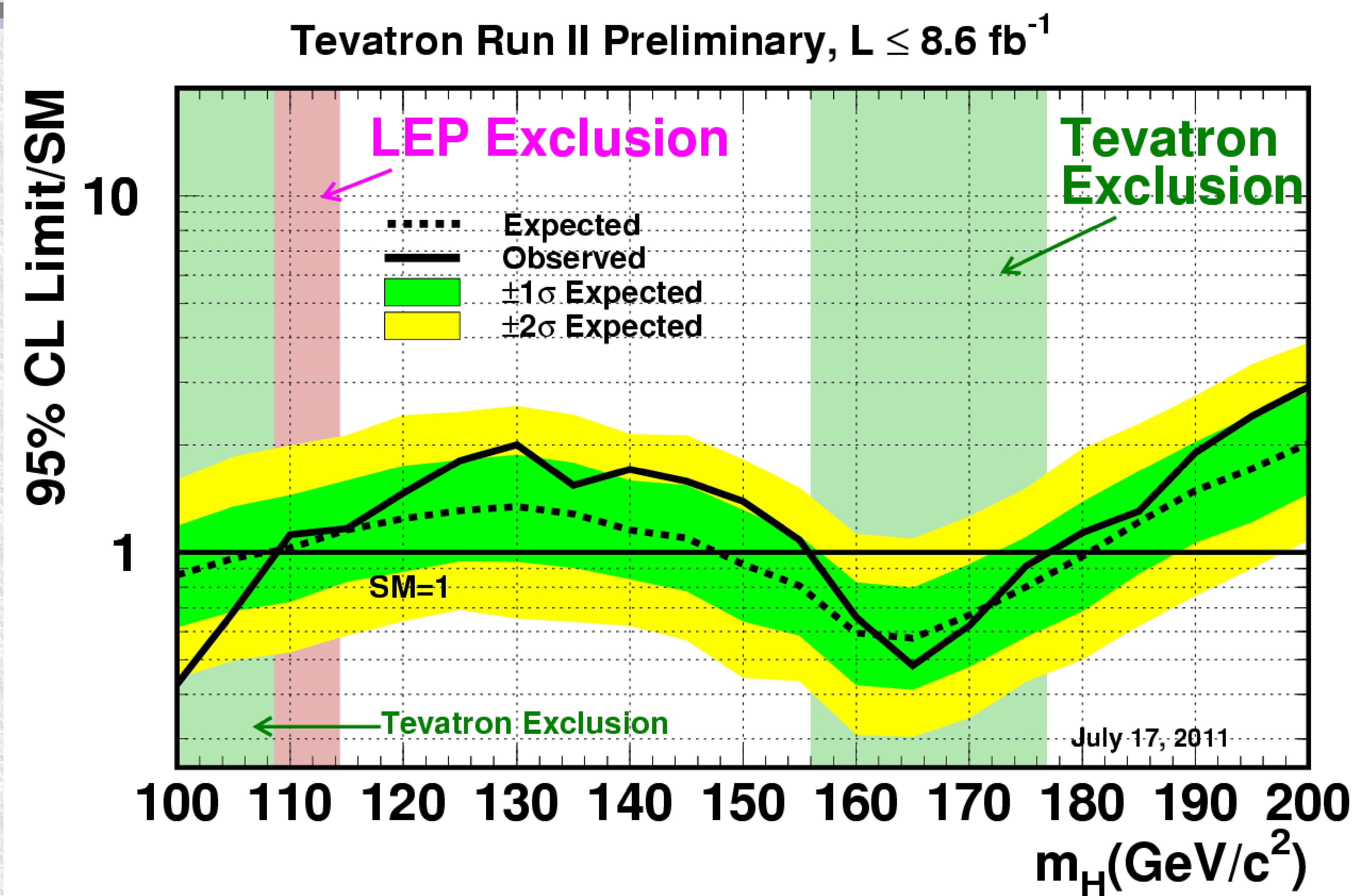
SM Higgs: H→WW

- H→WW→lνlν - signature: Two high p_T leptons and MET
  - Primary backgrounds: WW and top in di-lepton decay
  - CDF and D0 both using NN on many kinematic quantities
  - Many independent channels (n_{jets}, lepton quality)

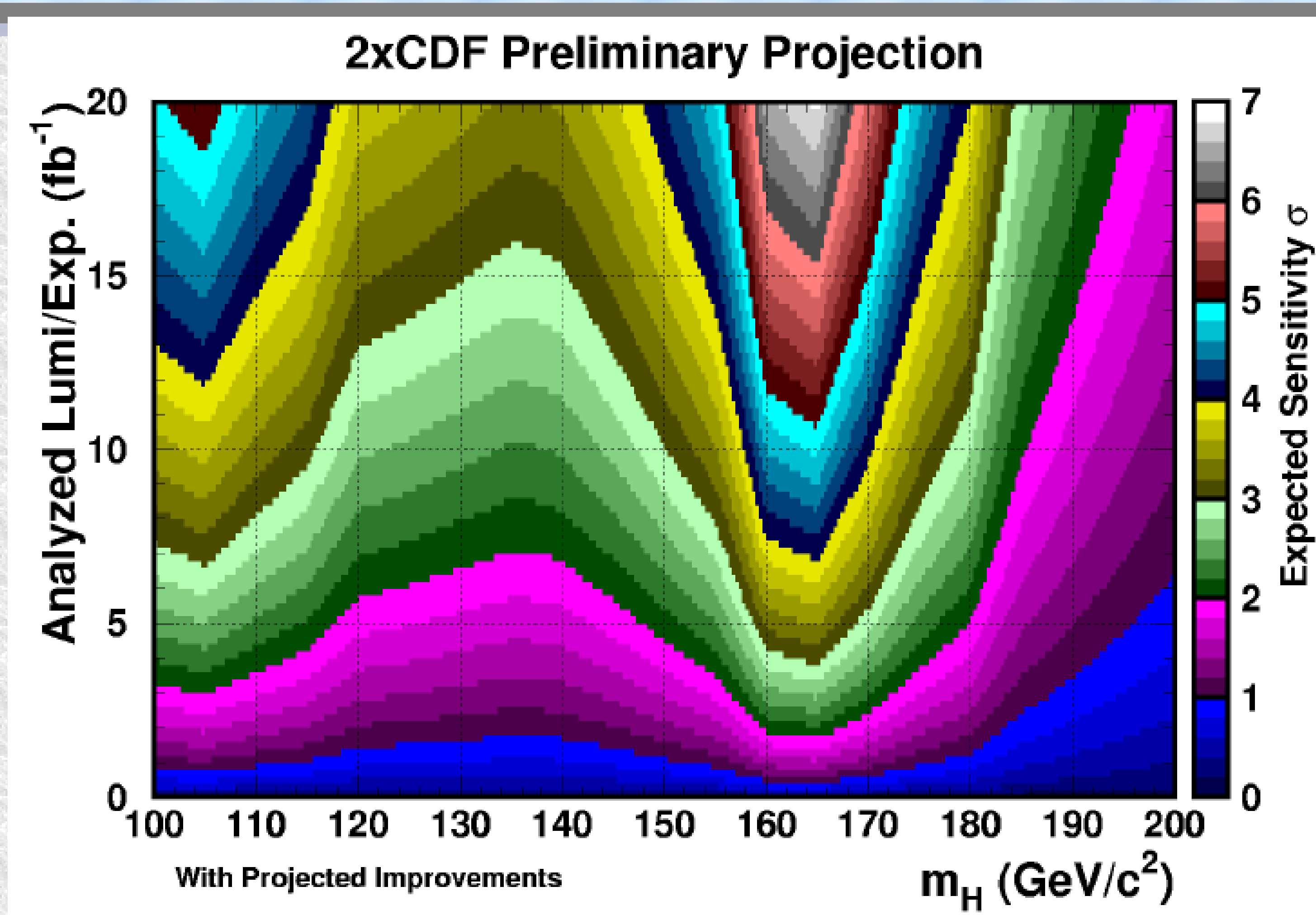




Tevatron Higgs Combination



TeVatron Outlook



- Claim >2.4σ for 100<m_H<185GeV with 10fb^{-1}
- Requires significantt improvements – under way

LHC results

The LHC situation

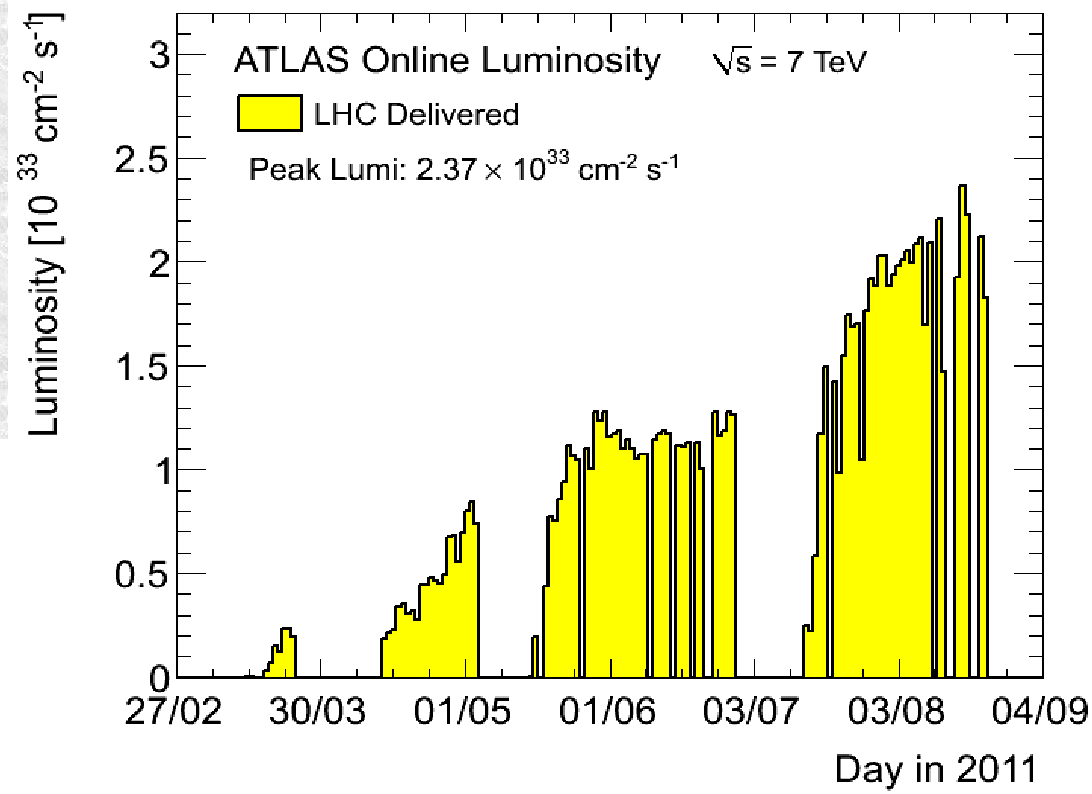
- The 7TeV pp energy raises the Higgs cross section
  - Factor 10 c/f 2TeV Tevatron
- Designed for 10^{34} luminosity
  - 2.4 10^{33} achieved
    - Hope for 5 10^{33} this year
  - c/f 4 10^{32} at Tevatron
- Decades of preparation continue
  - 50pb^{-1} delivered 2010
  - 2.5fb^{-1} in 2011 so far

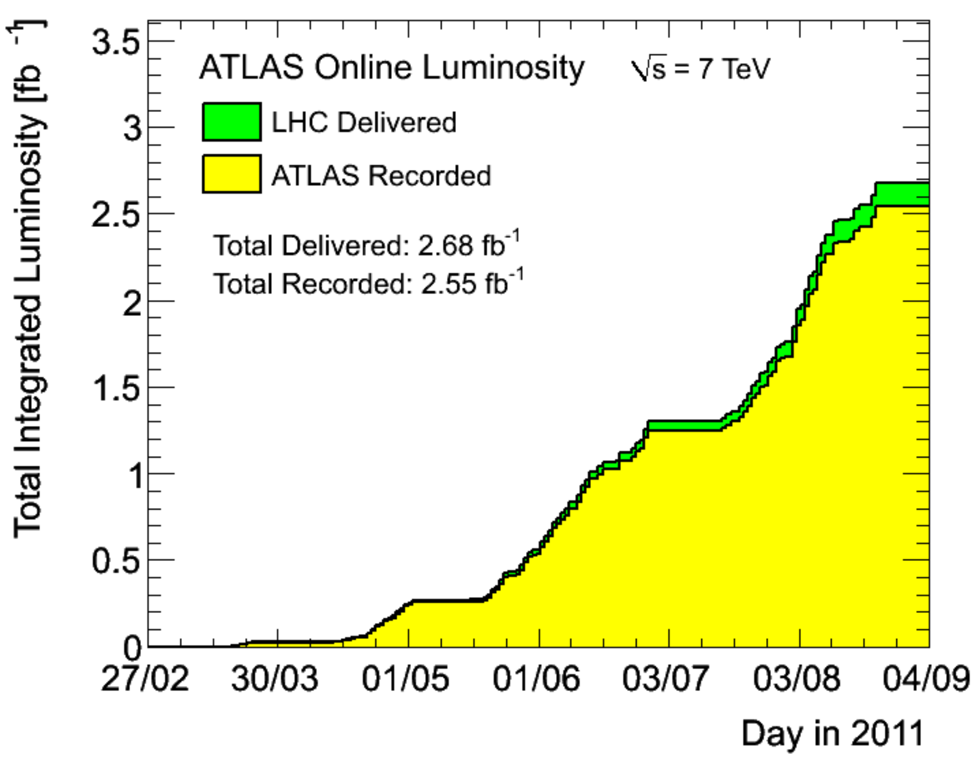
Science & Technology Facilities Council
Rutherford Appleton Laboratory

ATLAS

Data taking in 2011

- Peak Luminosity rising all the time
- Improvements coming

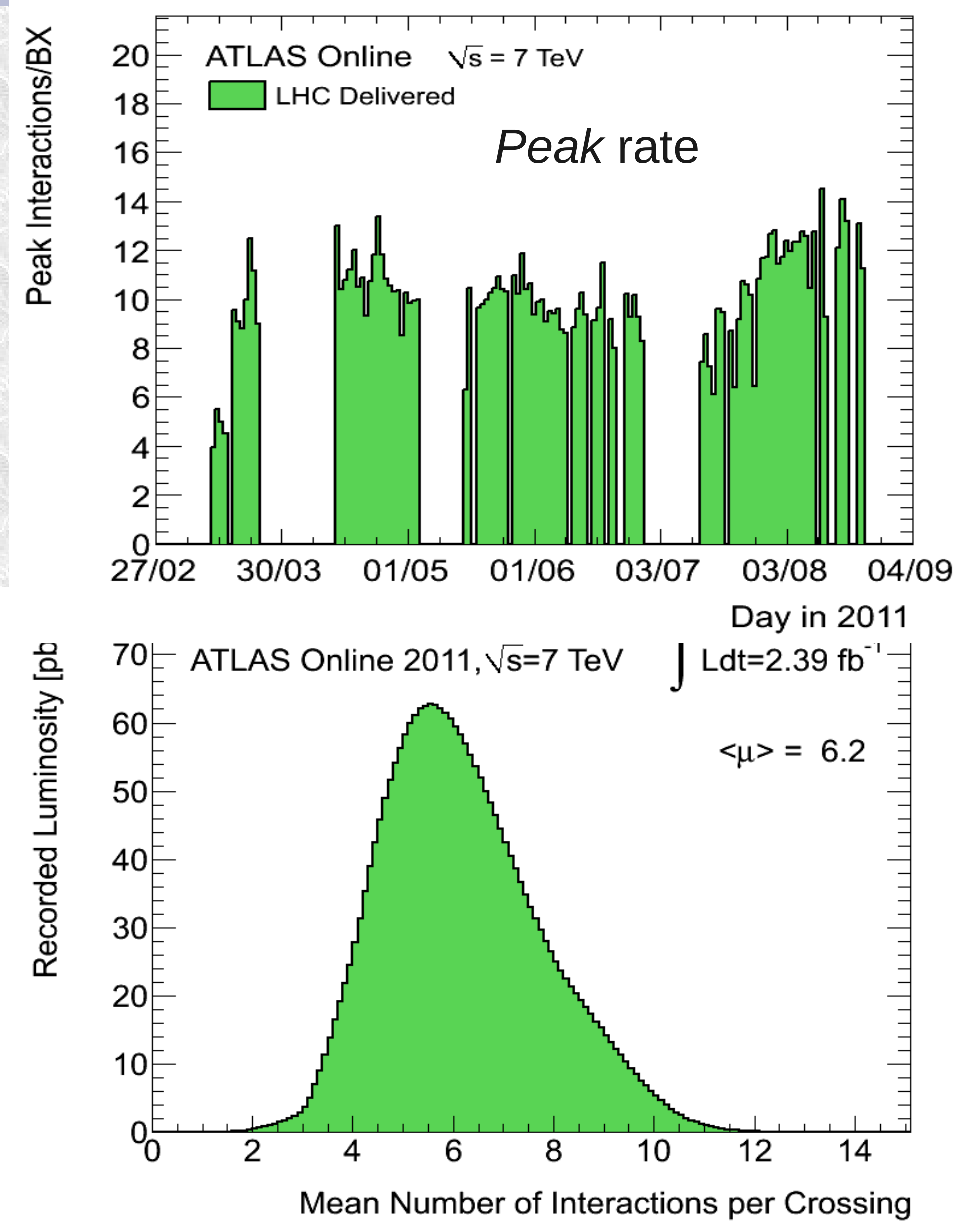




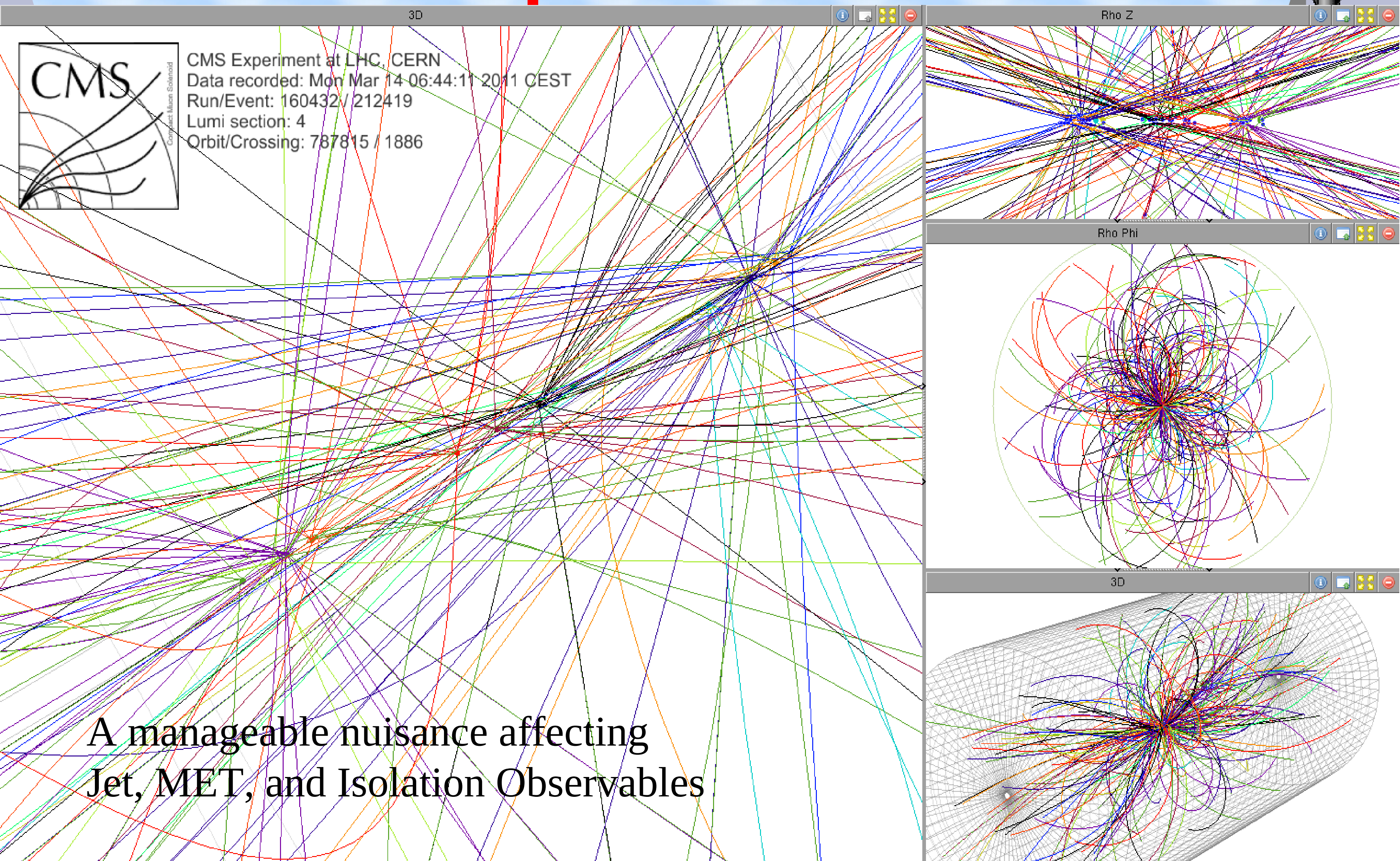
- Recording efficiency 95%
  - But up to 10% bad data by subdetector

Pileup

- Serious at LHC
  - Fairly stable so far
  - But 19.4 on 7th Sept
- 6 interactions per event
- 50ns bunch trains
  - So pileup also from previous *and subsequent* interactions
  - Affects calorimeters more than trackers
- Simulation difficult as rates must be measured
  - Need to reweight spectra



Pileup: 13 vertices

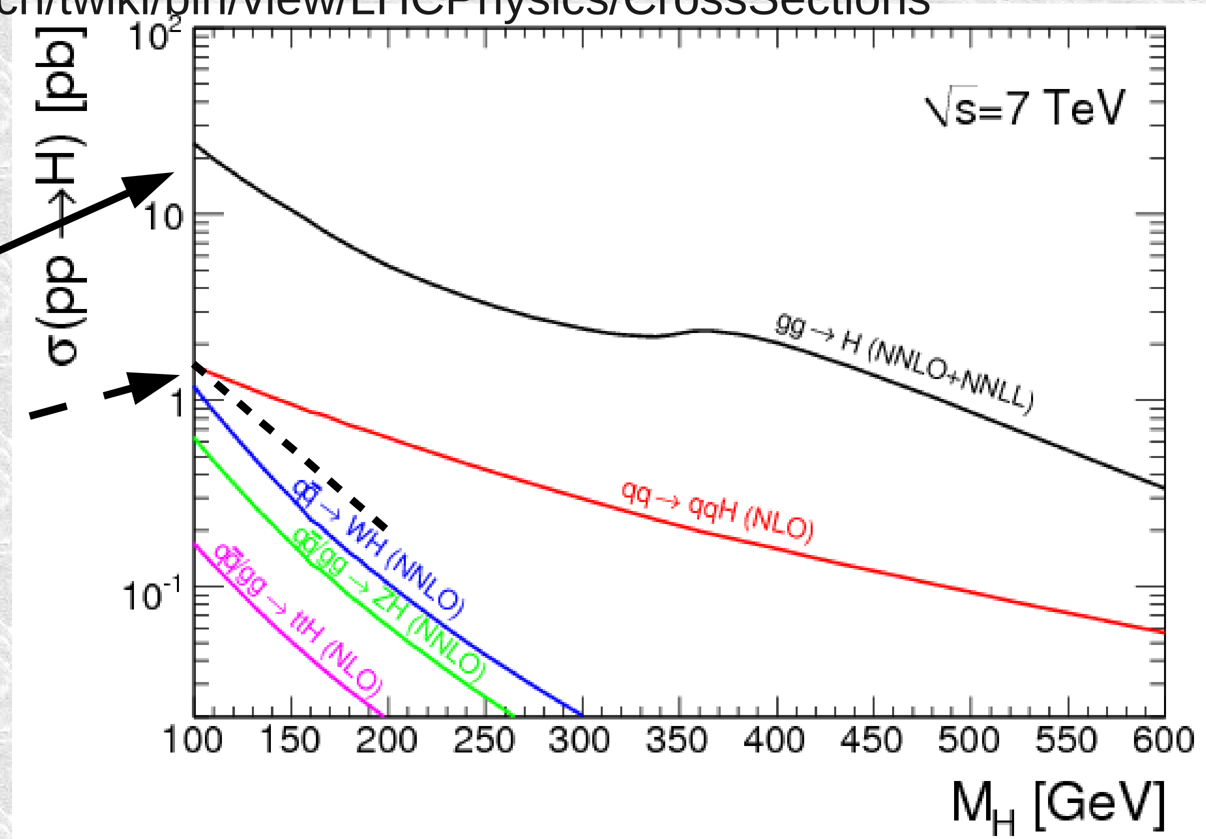


A manageable nuisance affecting
Jet, MET, and Isolation Observables

Higgs production

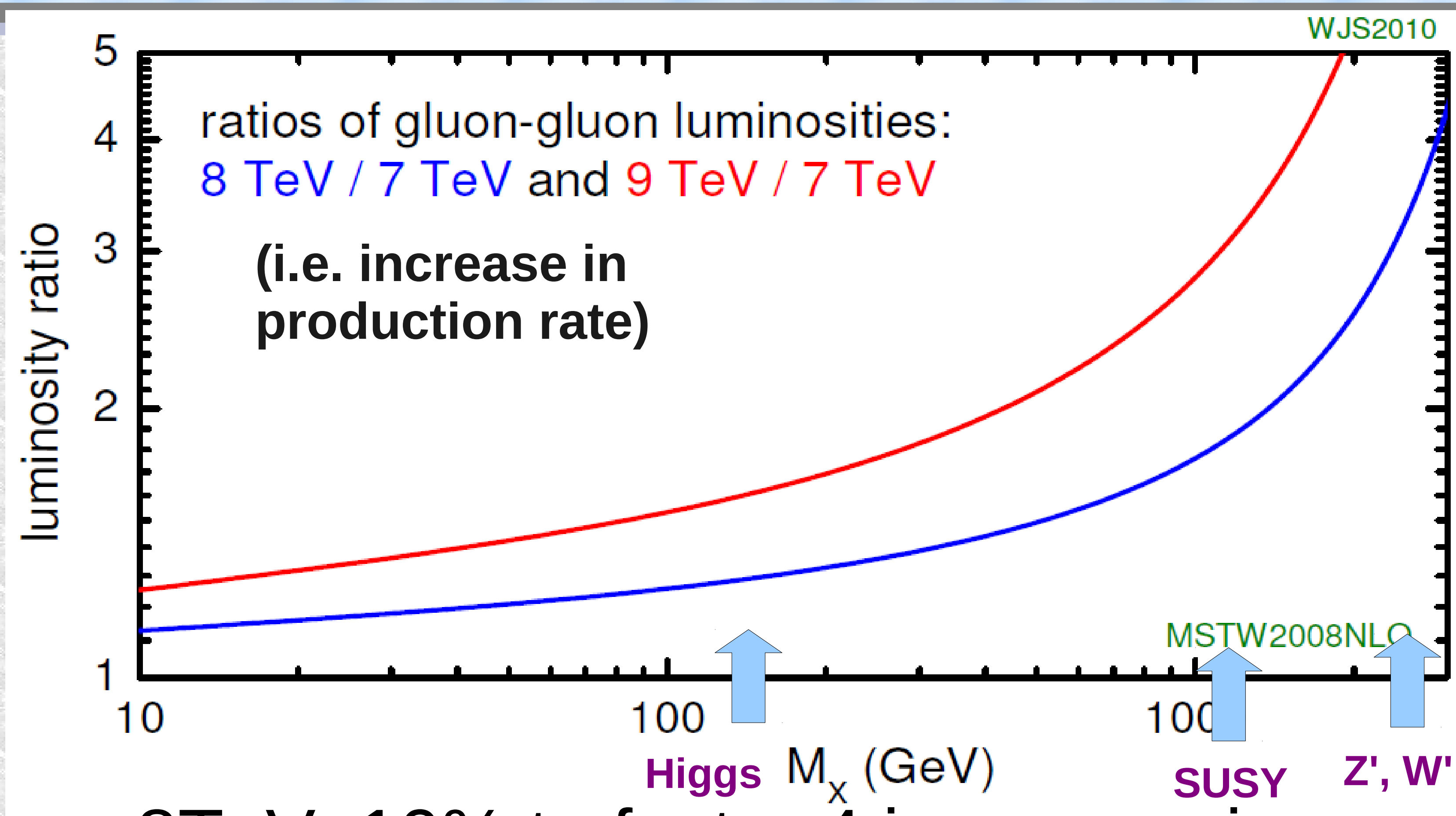
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

- Higgs cross-sections for gluon fusion
  —— LHC
  - - - - TeVatron
- At least a factor 10 advantage



- Backgrounds to WW,γγ are q$\bar{q}$ annihilation
  - pp collider supresses these c/f p$\bar{p}$
  - Effect is small at 7TeV

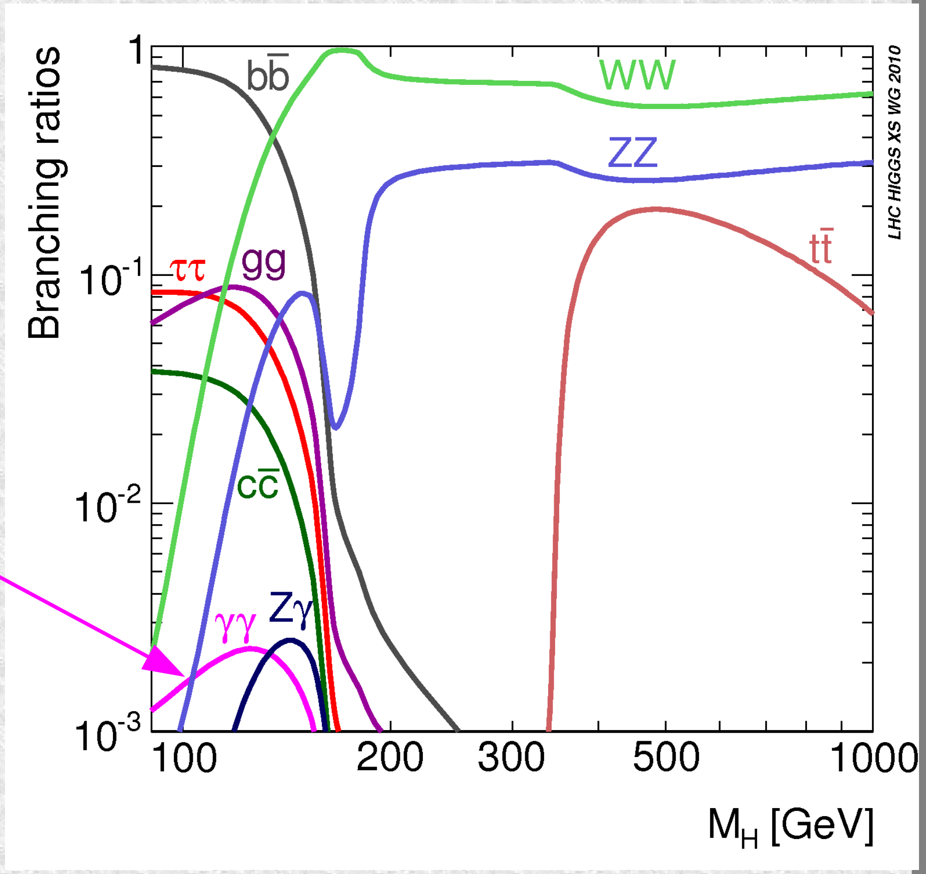
Reminder: Gain from E_{CMS}



- 8TeV: 10% to factor 4 increases in σ
  - Higgs increased by 30%
- Emittance shrinks by 8/7 as well
  - Luminosity may be slightly easier

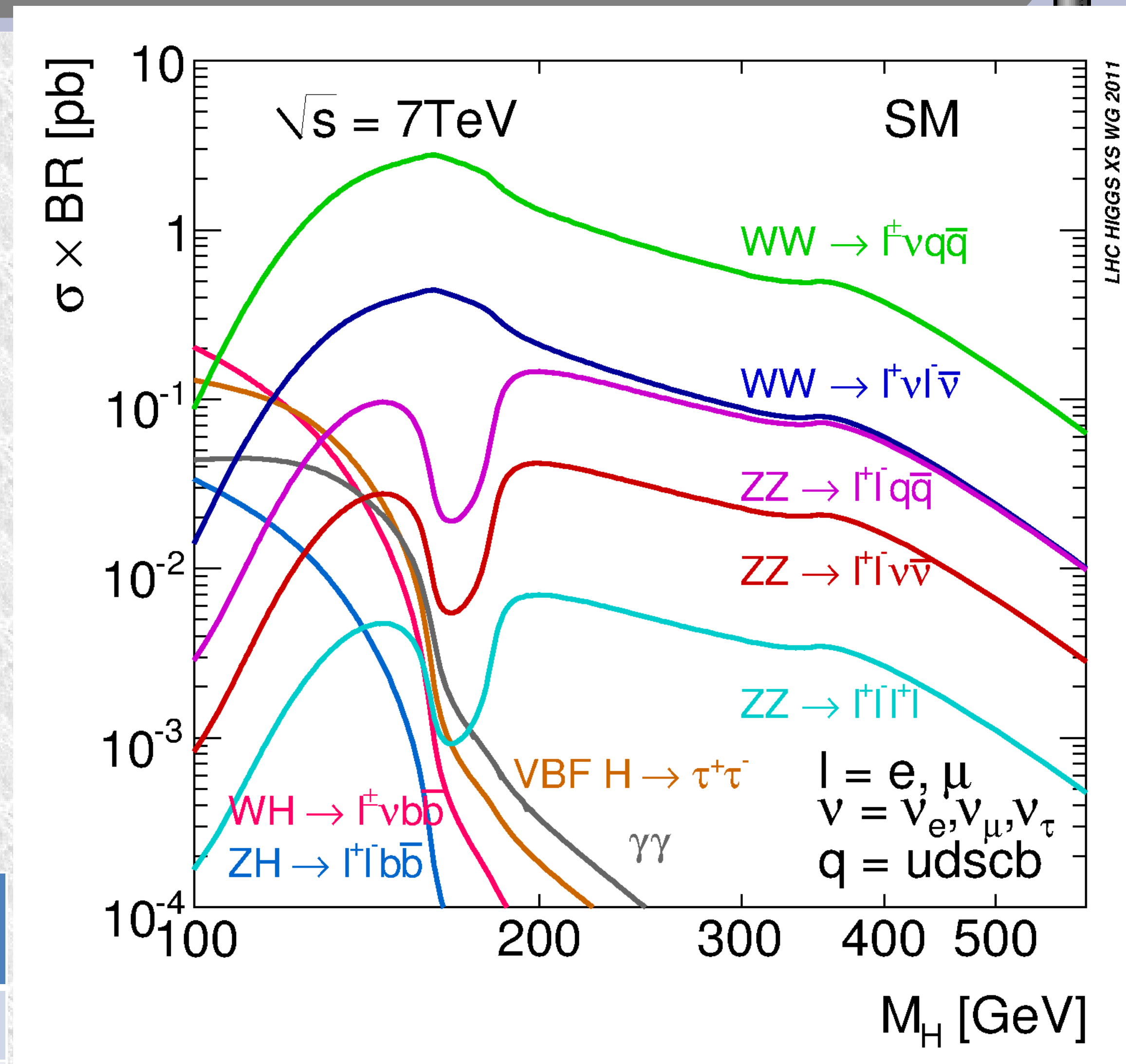
LHC analyses Channels

- H → ZZ
  - ZZ → llll: Golden mode
  - ZZ → llνν: Good High mass
  - ZZ → llbb: Also high-mass
- H → WW
  - WW → lνlν: Most sensitive
- H → γγ
  - Rare, best for low mass
- H → ττ
  - Good s/b, low mass,rare
- H → bb
  - $t\bar{t}$H, WH, ZH useful but hard



SM Higgs modes used

- Higgs decays to Bosons
  - Coupling structure favours it
  - Kinematics forces quark decays below 140GeV



mH, GeV	WW→lνlν	ZZ→4l	γγ
120	127	1.5	43
150	390	4.6	16
300	89	3.8	0.04

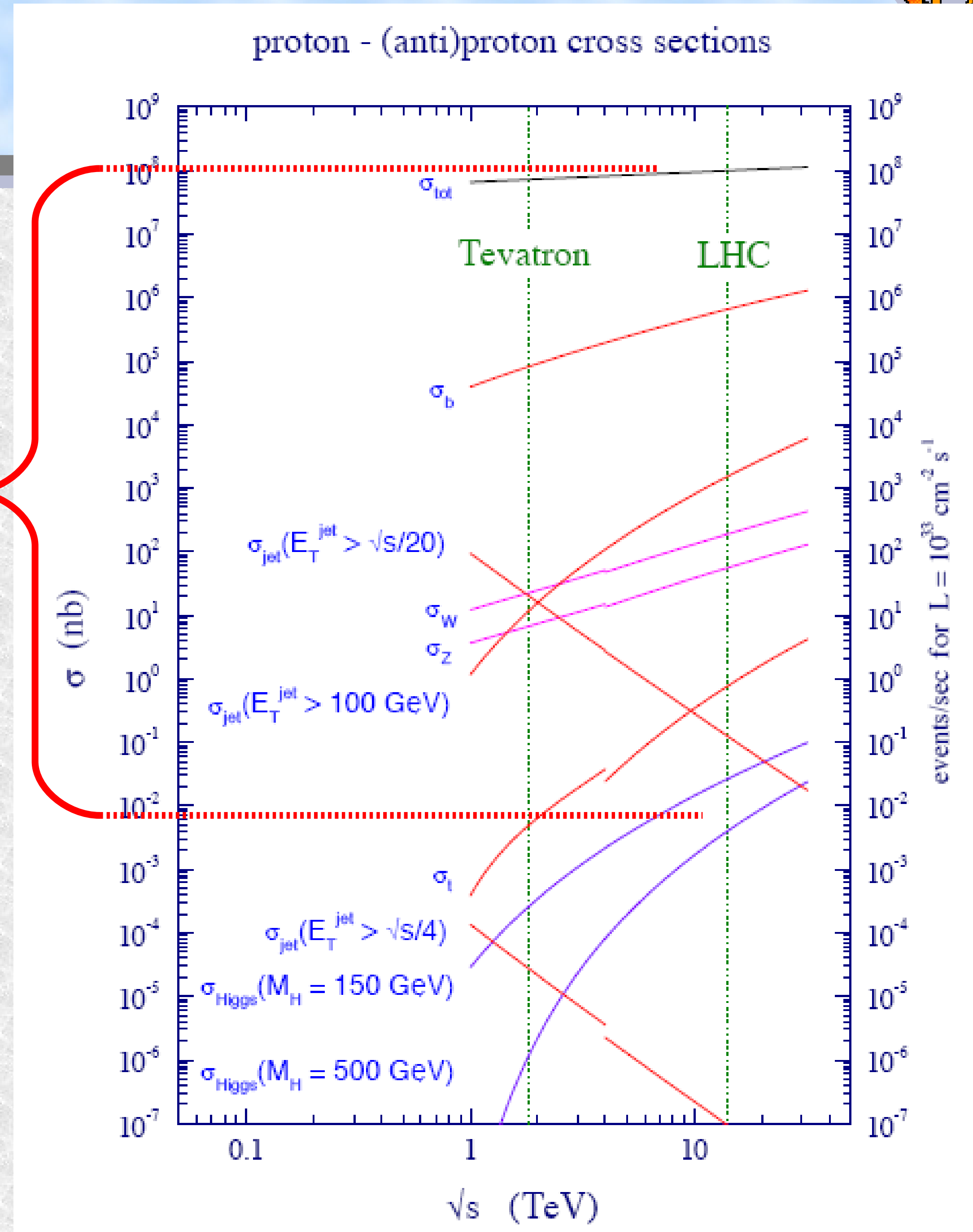
Rates?

- LHC backgrounds!

10^{10}

Every event at a lepton collider is physics; every event at a hadron collider is background

Sam Ting

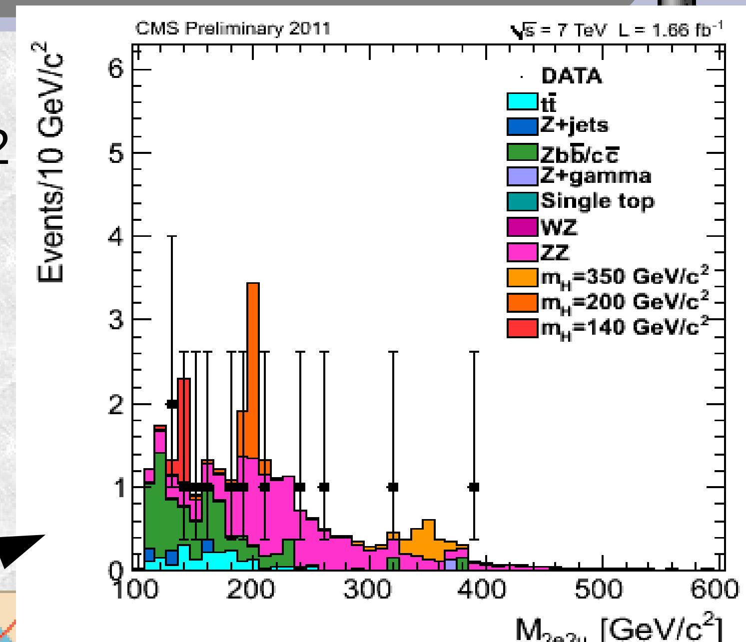


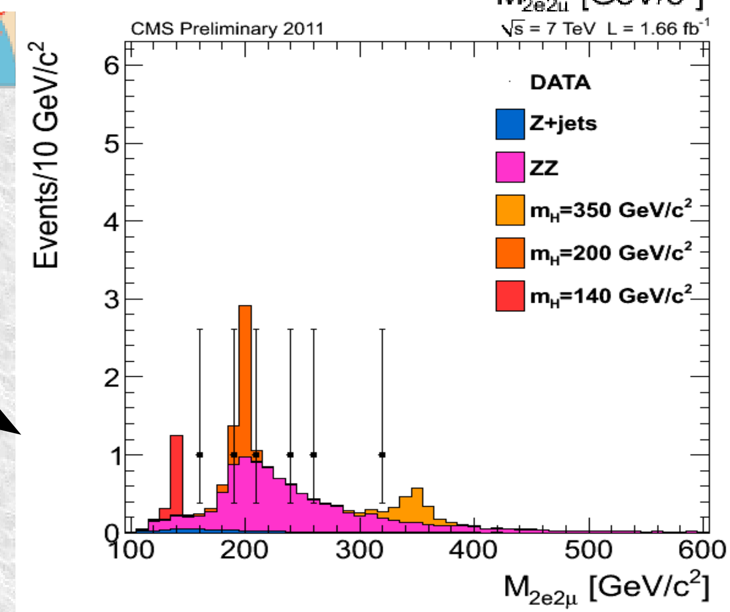
How to find the thing

- If Higgs boson is heavy (>140GeV/c^2)
  - Serious decays to WW, ZZ
  - These have clear leptonic decay modes
  - ZZ→4l is frankly nicer, but WW→lνlν more common
  - The discovery is fairly straightforward.
- If Higgs boson is light (<140GeV/c^2)
  - (and it is)
  - WW/ZZ still important, but rarer
  - Use H→γγ
  - Or VBF H→ττ – can trigger leptons
  - H→bb is dominant mode – can we find it?
    - Not without something to make it stand out
    - Z/W+H, ttH

$H \rightarrow ZZ \rightarrow l^+l^-l^+l^-$

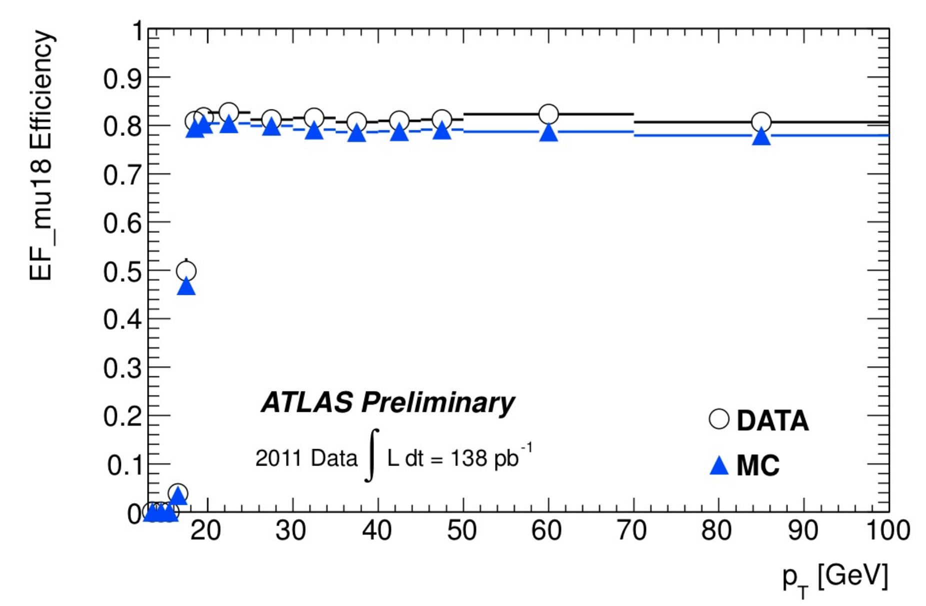
- Golden channel m_H>190GeV/c^2
  - Above ~200 two real Z's
  - Useful window ~ 140 GeV
- Good mass resolution, trigger
- Backgrounds:
  - Irreducible QCD ZZ to llll
  - Reducible Zbb, tt

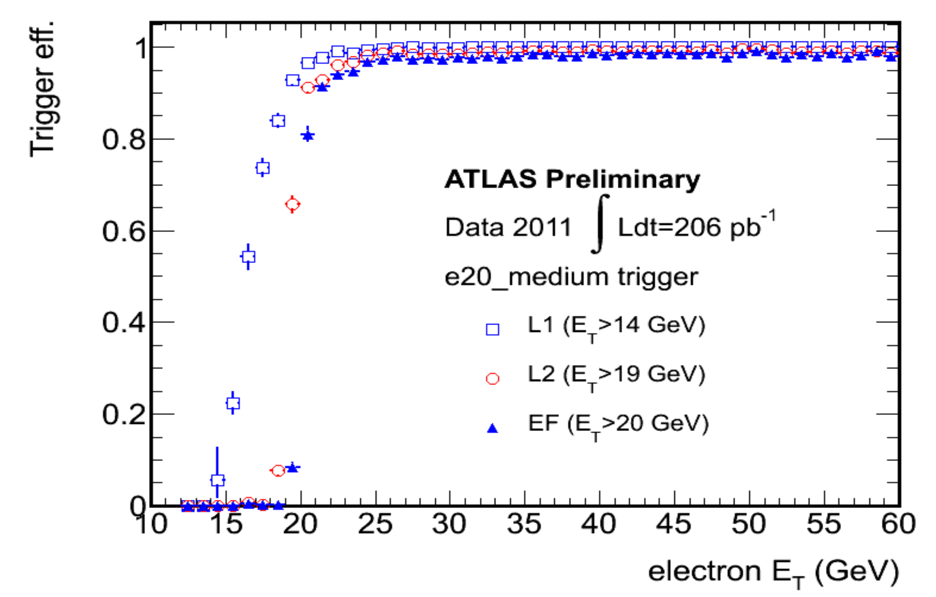




Trigger efficiencies (ATLAS)

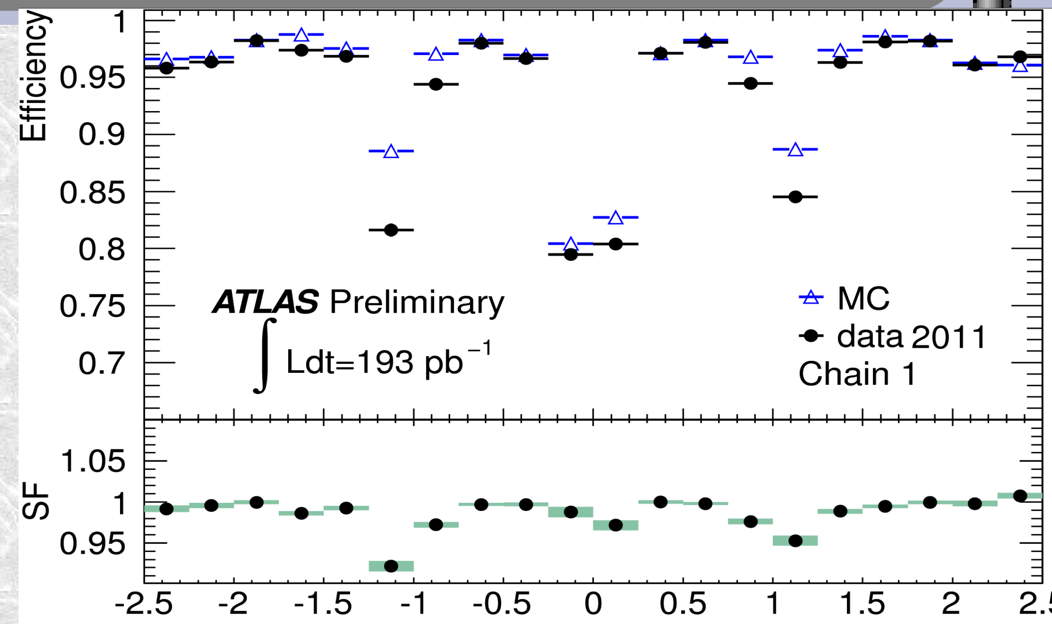
- Crucial to a hadron collider – the trigger
  - Most channels use single lepton ~20GeV p_T
- 3 level trigger system
  - L1: 2µs, local objects
  - L2: 'ROI' complete information
  - EF: full reconstruction
- Efficiency plateau
  - 80% µ efficiency
    - Multi-leptons give good total
  - ~98% electron efficiency

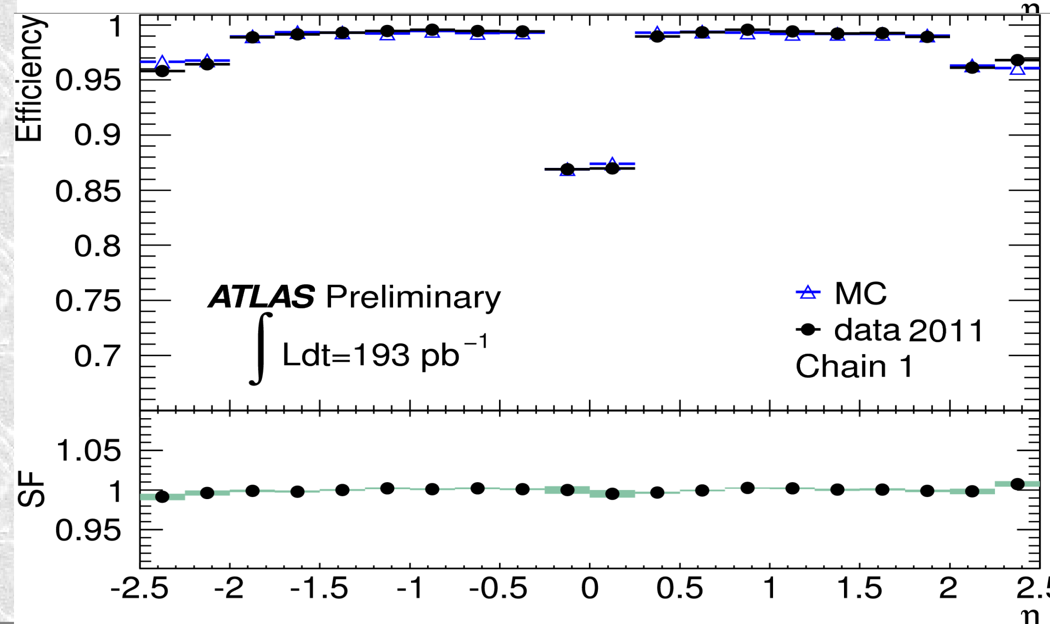




Muon reconstruction (ATLAS)

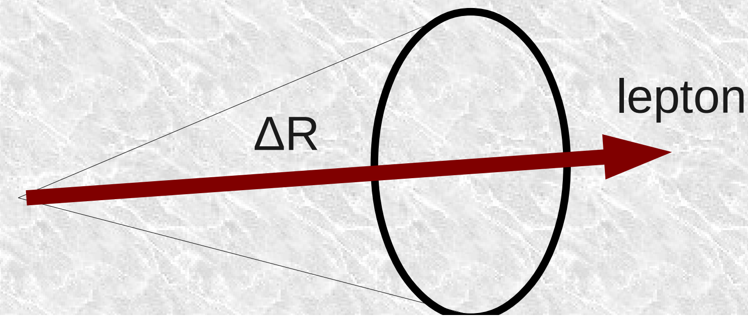
- Combined muons (top)
- Combined + segment tagged (bottom)
- Final efficiency good
- Difficulties:
  - η=0 (no muon chambers)
  - η=1.2 (barrel/forward transition)
- Could use 'stand alone' to improve to 2.7

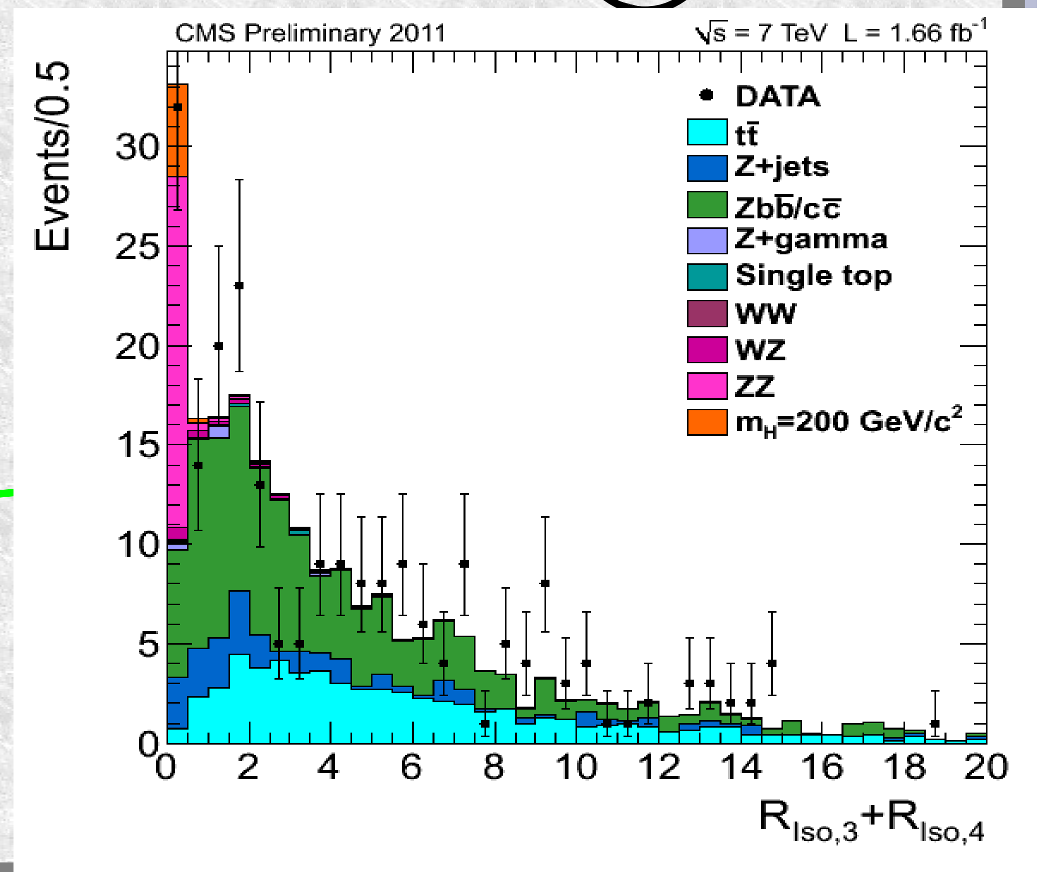




Isolation effects

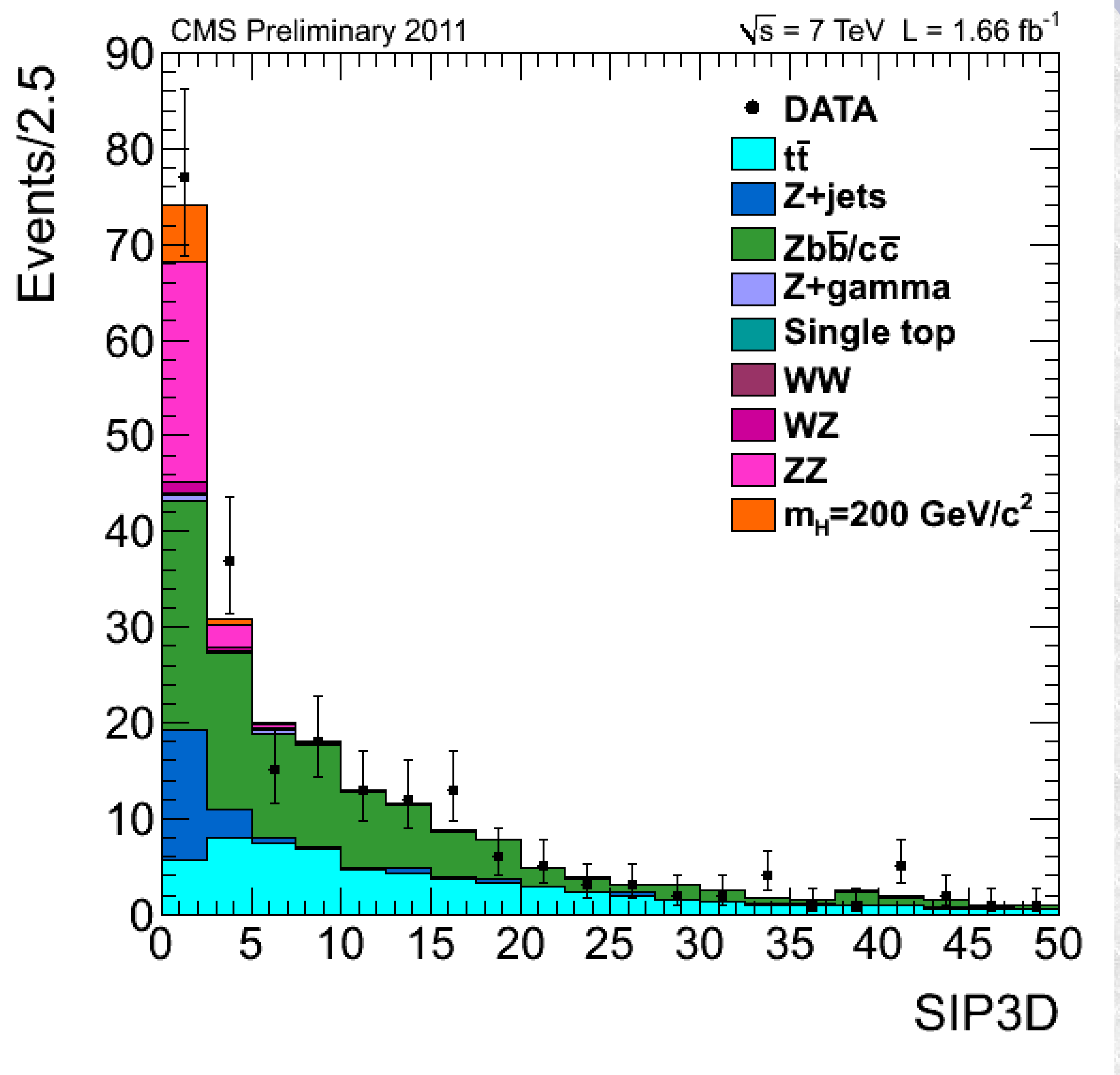
- Reducible background involves e/μ from b/c quarks
- Is there a jet here?
  - Define cone around lepton, size ΔR
  - Sum energy in cone
  - Require $E_{cone}/E_{lept}<X$
  - Need to optimise selection
    - Measure efficiency
    - And Background





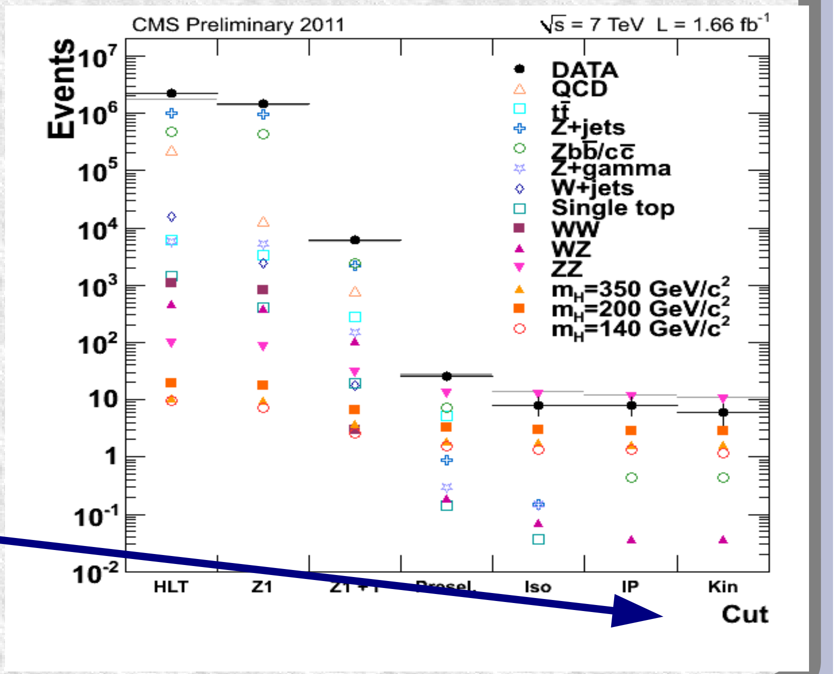
Impact parameters

- Suppression of b quarks with impact parameters
  - Lepton closest approach to proton collision
  - H → ZZ → llll have no decay length
  - lepton from b quarks have ~100µm impact
- Plotted is larger SIP for l3, l4



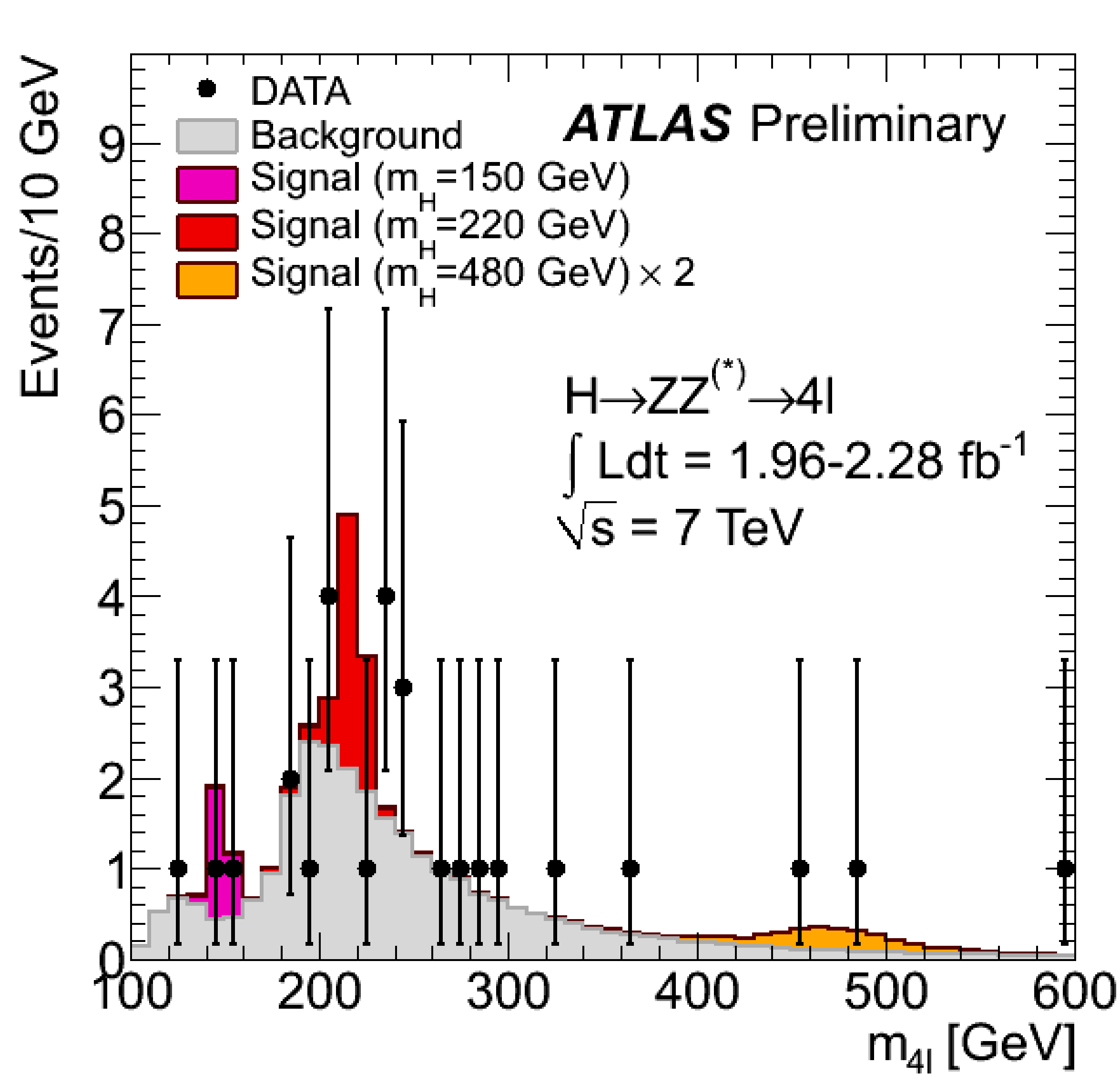
Analysis steps

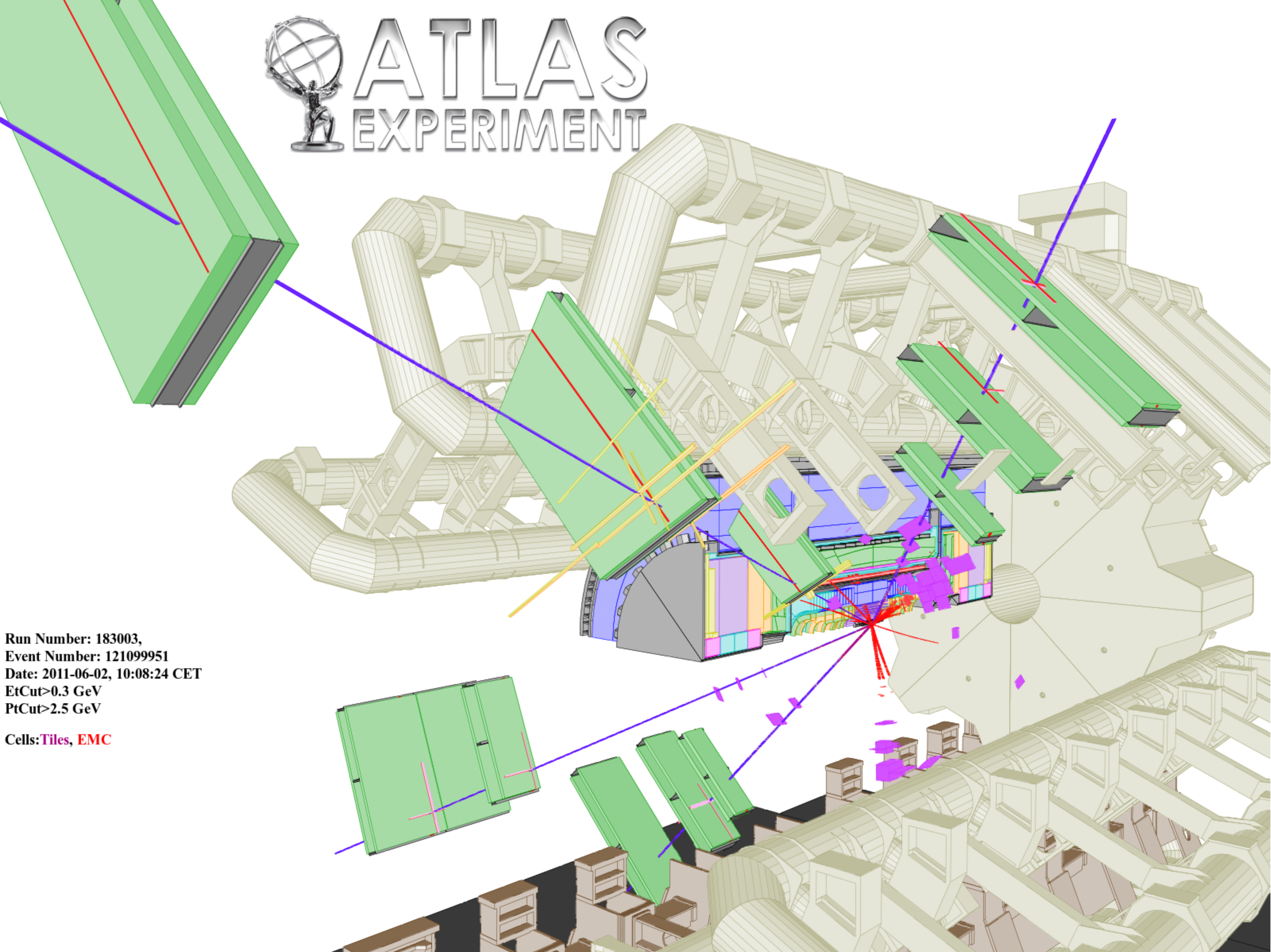
- Require 4 leptons ($e\bar{e}e\bar{e}$, $e\bar{e}\mu\bar{\mu}$, $\mu\bar{\mu}\mu\bar{\mu}$)
- Identifiy a good Z candidate
  - Mass within 15GeV on nominal, isolated.
- Study second pair
  - Request they are isolated
  - They must have small impact parameters
  - Require some consistency with Z mass
    - In a window if m_H>200
    - Above a threshold m_H<200
- Must have good control of final sample purity



Mass resolution

- A function of m_H, detector performance, lepton type etc
- Of order 2GeV for mass below 200
- Dominated by natural width above




ATLAS EXPERIMENT
Run Number: 183003,
Event Number: 121099951
Date: 2011-06-02, 10:08:24 CET
EtCut>0.3 GeV
PtCut>2.5 GeV
Cells:Tiles, EMC

CMS rates: 1.7fb^{-1}

	baseline		
	$4e$	4μ	$2e2\mu$
ZZ	4.05 ± 0.26	6.02 ± 0.40	9.87 ± 0.66
Z+jet	0.48 ± 0.08	0.09 ± 0.02	0.61 ± 0.11
$Zb\bar{b}/c\bar{c}, t\bar{t}$	0.01 ± 0.01	0.05 ± 0.01	0.06 ± 0.01
WZ	0.009 ± 0.009	0.009 ± 0.009	0.04 ± 0.02
All background	4.54 ± 0.27	6.12 ± 0.40	10.52 ± 0.67
$m_{\mathrm{H}} = 140\,\mathrm{GeV}/c^2$	0.45	0.82	1.19
$m_{\mathrm{H}} = 200\,\mathrm{GeV}/c^2$	1.20	1.71	2.80
$m_{\mathrm{H}} = 350\,\mathrm{GeV}/c^2$	0.70	0.93	1.63
Observed	5	10	6

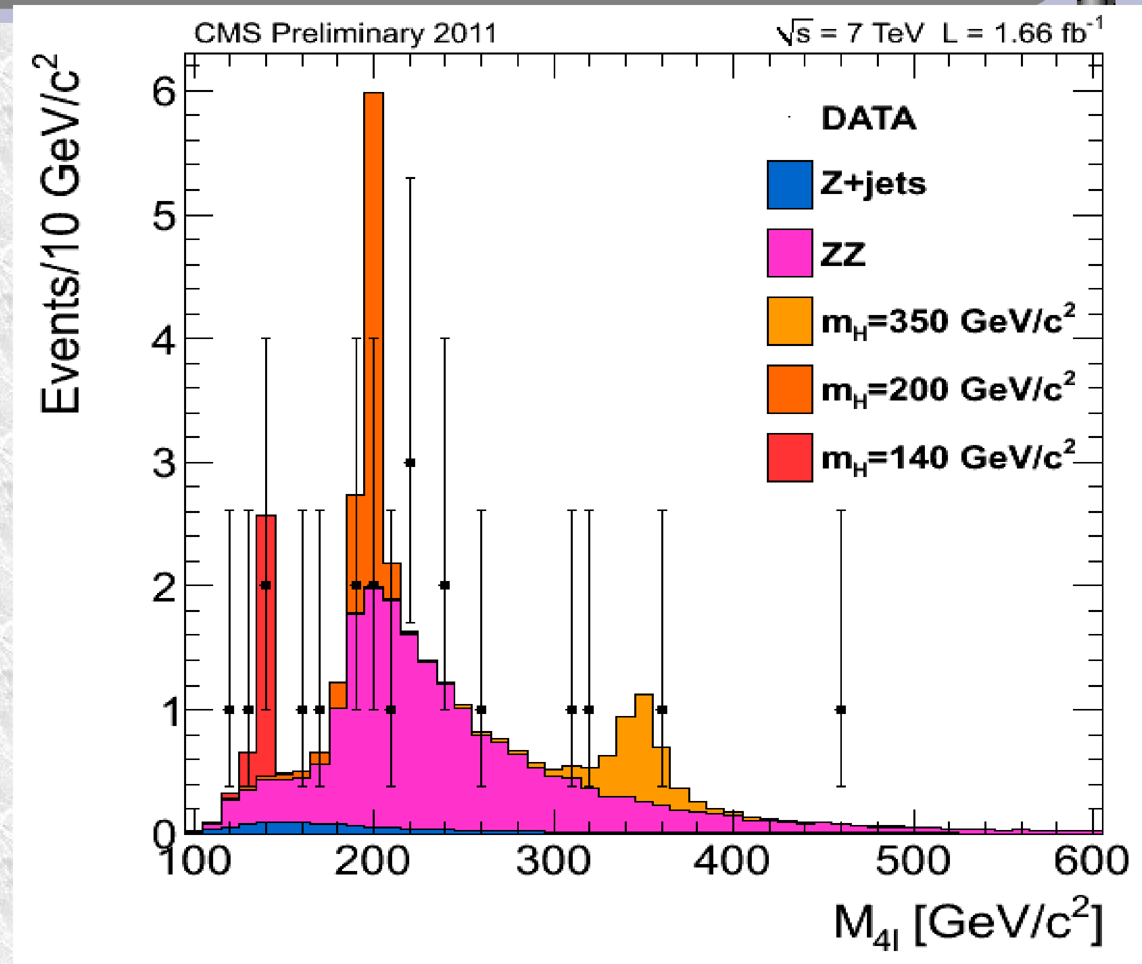
- Only a few signal expected in ZZ channel now
- Background fractions low
  - 10% in eeee
  - 2% in μμμμ
- Overall good agreement with expected rates

Lepton thresholds

- We wish to explore towards m_H=115GeV
- M_Z=91, so little energy for Z*
- Therefore important to use leptons of low p_T
  - 7GeV threshold used
    - (5GeV for muons in CMS)
- Need to understand eff, background
  - Tag and probe used normally
    - W, Z must be extended with $J/\psi \rightarrow \ell\ell$
- Backgrounds get more accute at low p_T.

Interpreting the distribution

- Need a model of background
  - CMS use analytic functions for background
  - ATLAS use MC distributions
- Use s,b densities to define ln LR for each candidate
  - Sum these
  - Compare with expectation



Statisitical interpretation

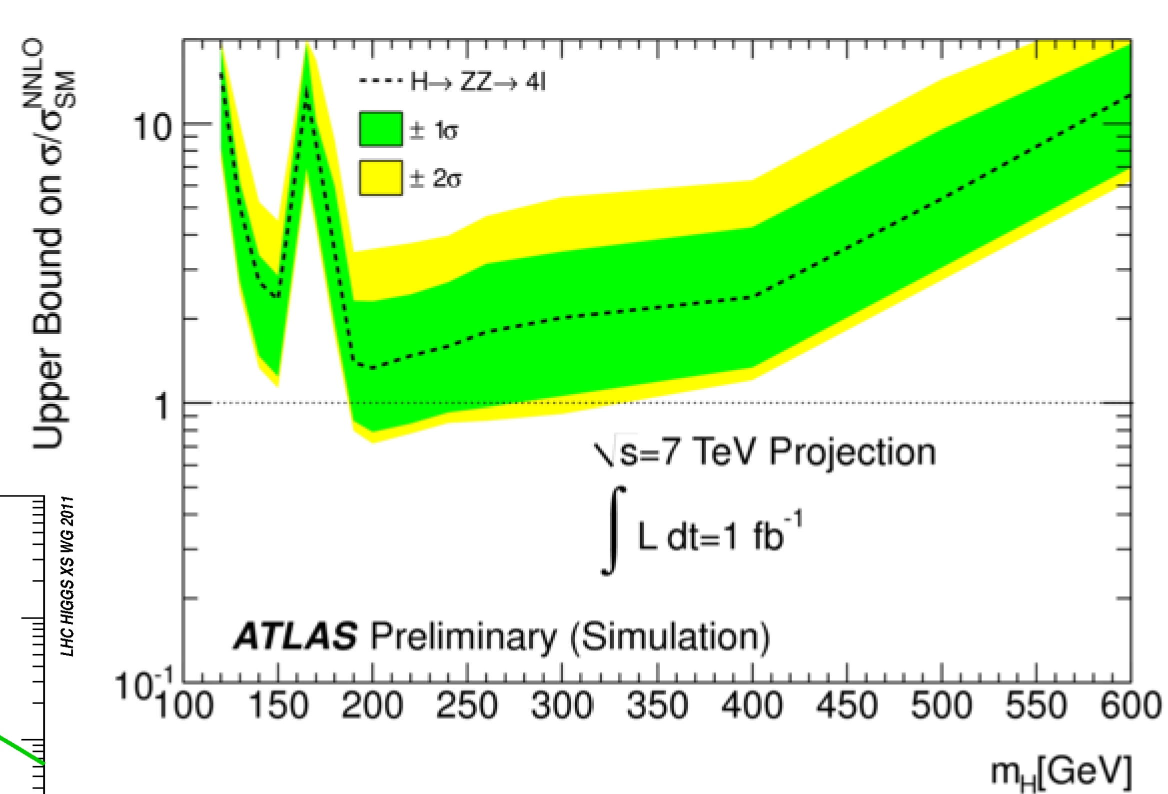
- Non-trivial business, with Frequentist and Bayesian methodologies
- For now ATLAS+CMS quote 'Cls' results
  - Derived as a compromise, acceptable to both schools
- Consult your statistics forum for local procedures
- A useful approximation for low rate counting experiments with negligible systematic errors:

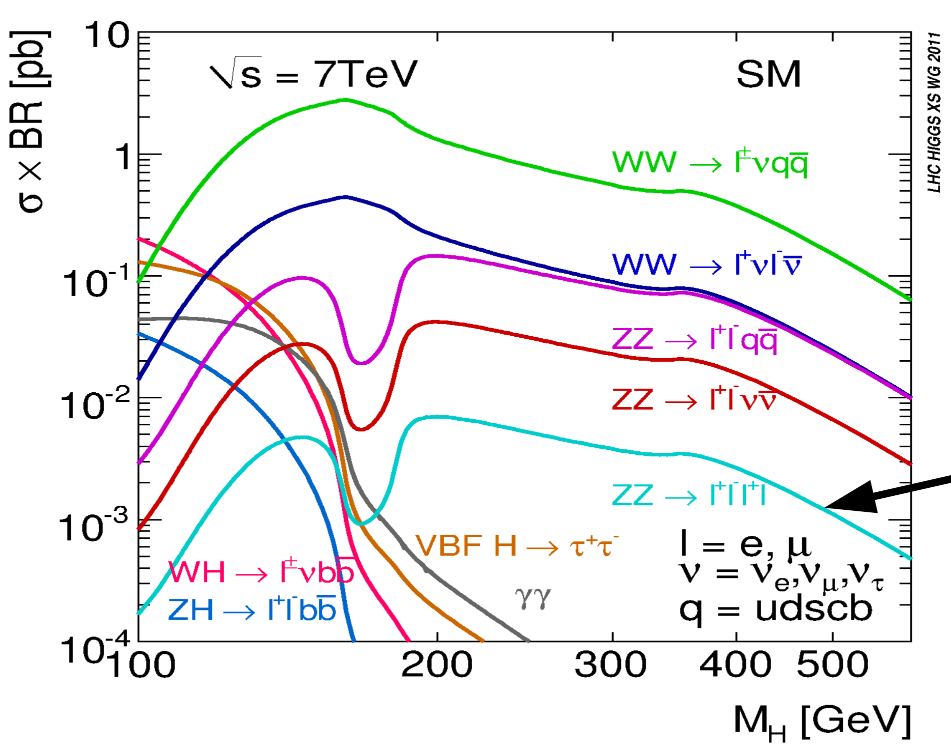
$$\langle Z_W \rangle = \sqrt{\left(2\left(\left(s+b\right)\ln\left(1+s/b\right)-s\right)\right)}$$

- This is much better than s/√b in the case of low numbers
  - Can be used to optimise analyses

Expected limits

- Expected upper limit from $1fb^{-1}$
- Before seeing data





- Shape reflects the H to llll expected event rate

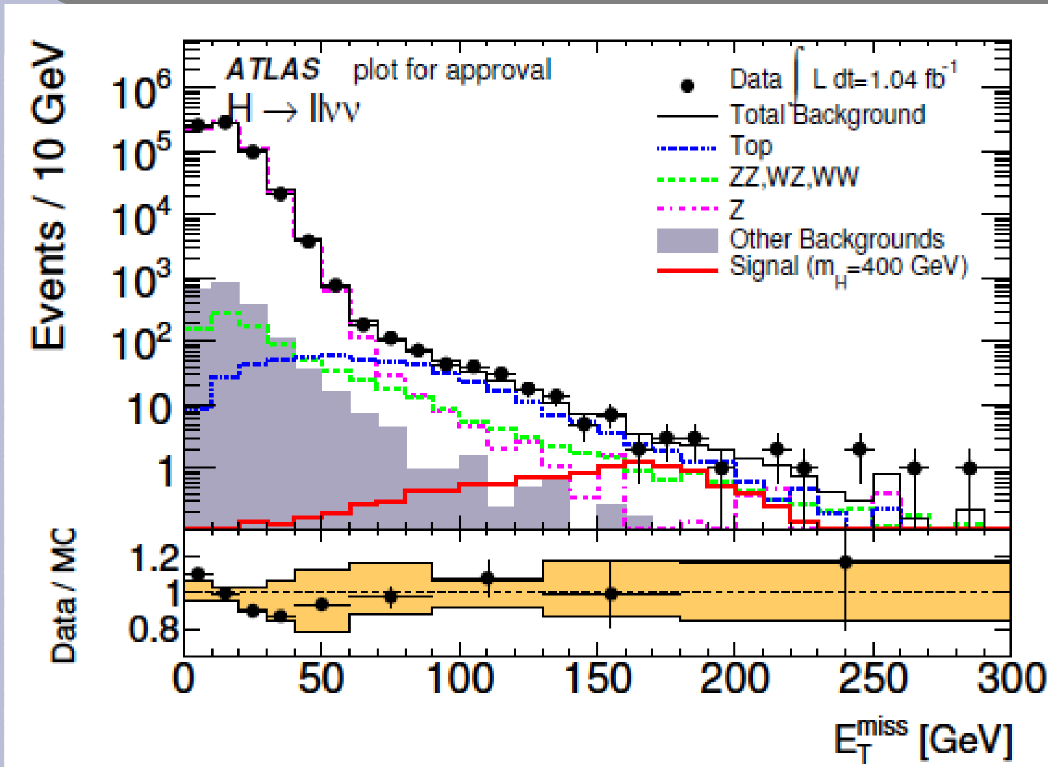
ZZ→llνν

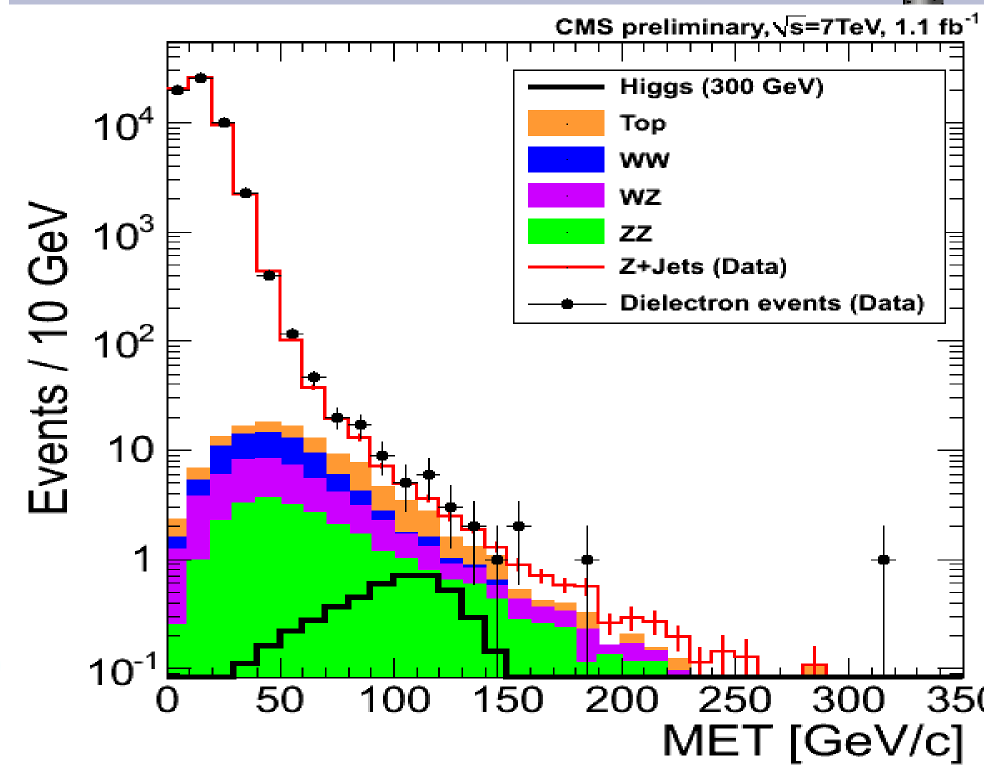
- Fully leptonic but rate 6xllll
- However mass reconstruction is not possible
  - Two missing neutrinos means too much is lost
  - 4-vector of the Z→ll, p_T of Z→νν available

$$m_T^2 \equiv \left[\sqrt{m_Z^2 + |\vec{p}_T^{\,\ell\ell}|^2} + \sqrt{m_Z^2 + |\vec{p}_T^{\,\mathrm{miss}}|^2}\right]^2 - \left[\vec{p}_T^{\,\ell\ell} + \vec{p}_T^{\,\mathrm{miss}}\right]^2$$

- Works best for m_H>300
  - Higgs is wide, so mass reconstruction less useful
  - Zs are boosted, so Z→νν has measurable p_T^{miss}
- E_t^{miss} needed for background rejection and signal

ZZ→llνν missing E_T

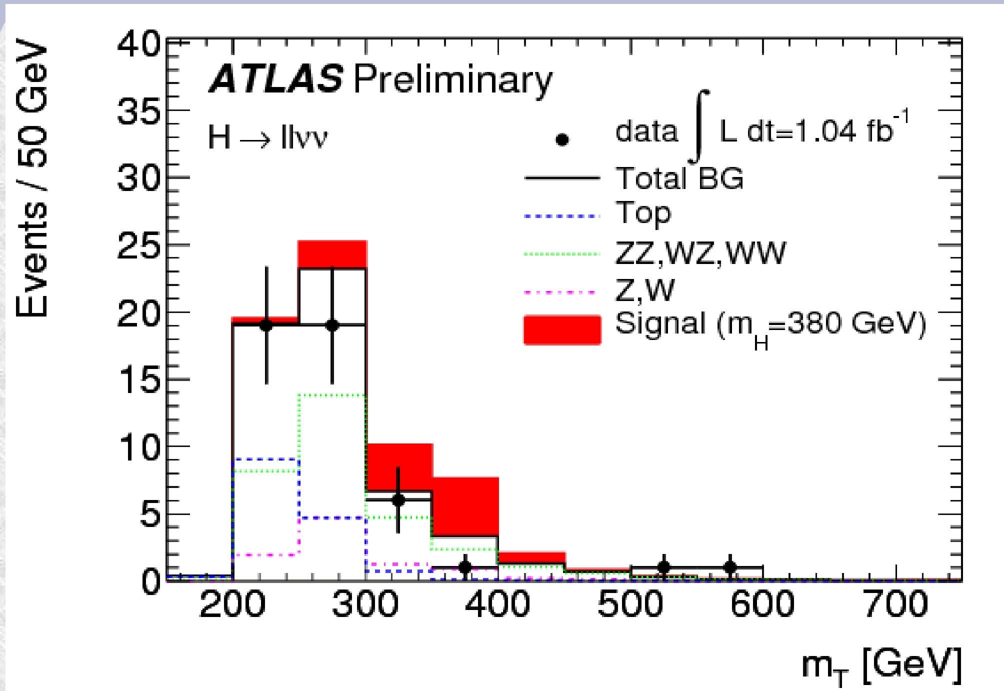


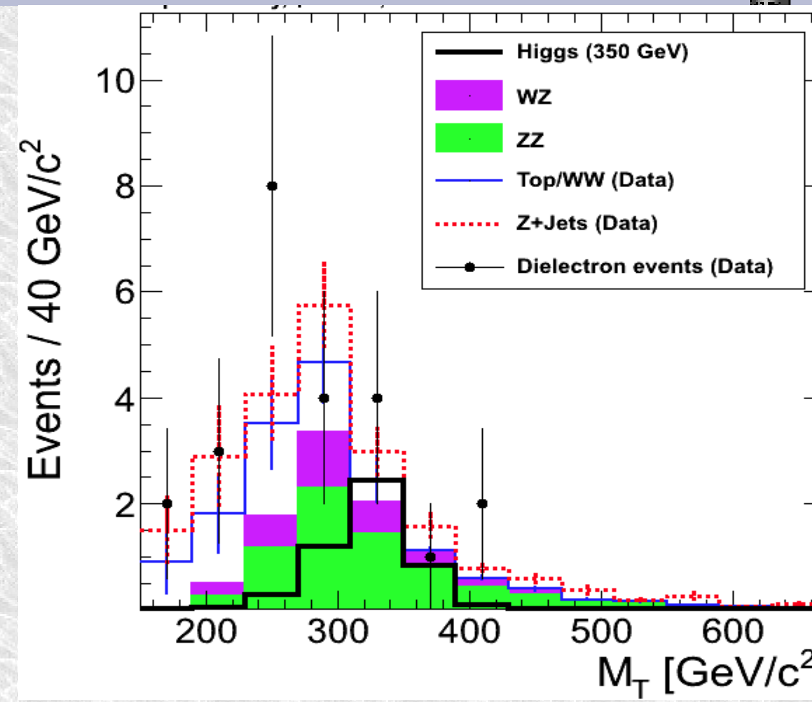


- For 150GeV ATLAS find Z with MET is minor
  - But ATLAS take this from simulation
- CMS have larger Z with MET component
  - Taken from gamma plus MET studies

Science & Technology Facilities Council
Rutherford Appleton Laboratory

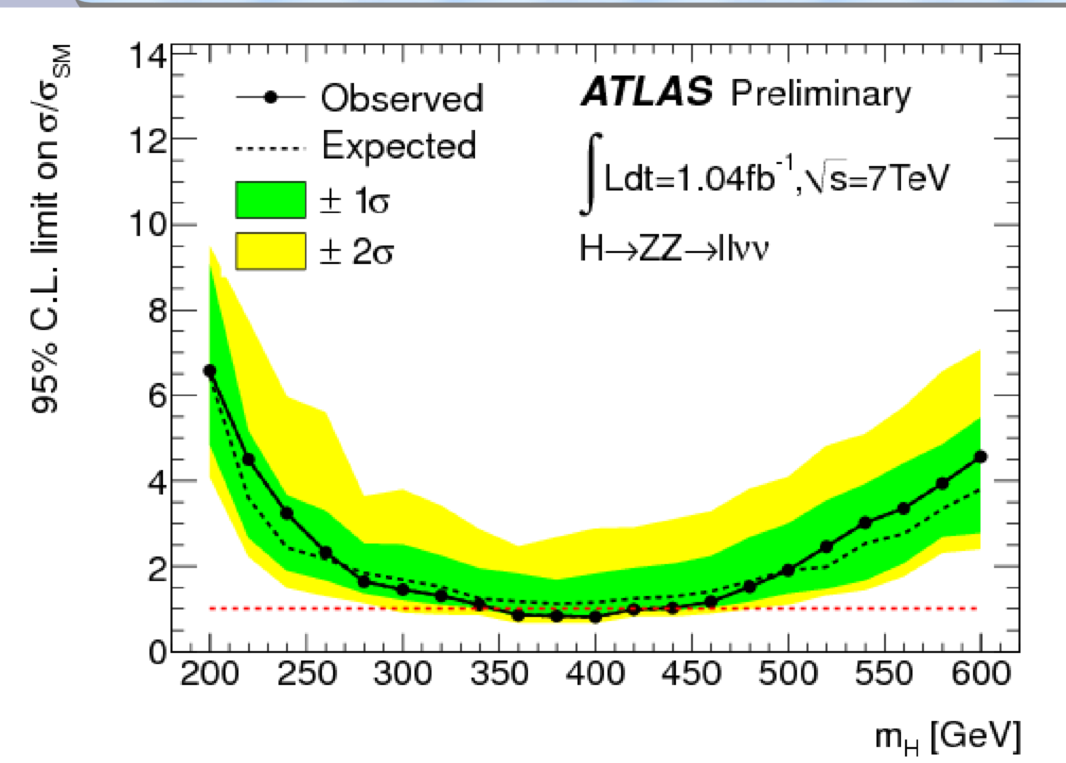
ZZ → llνν

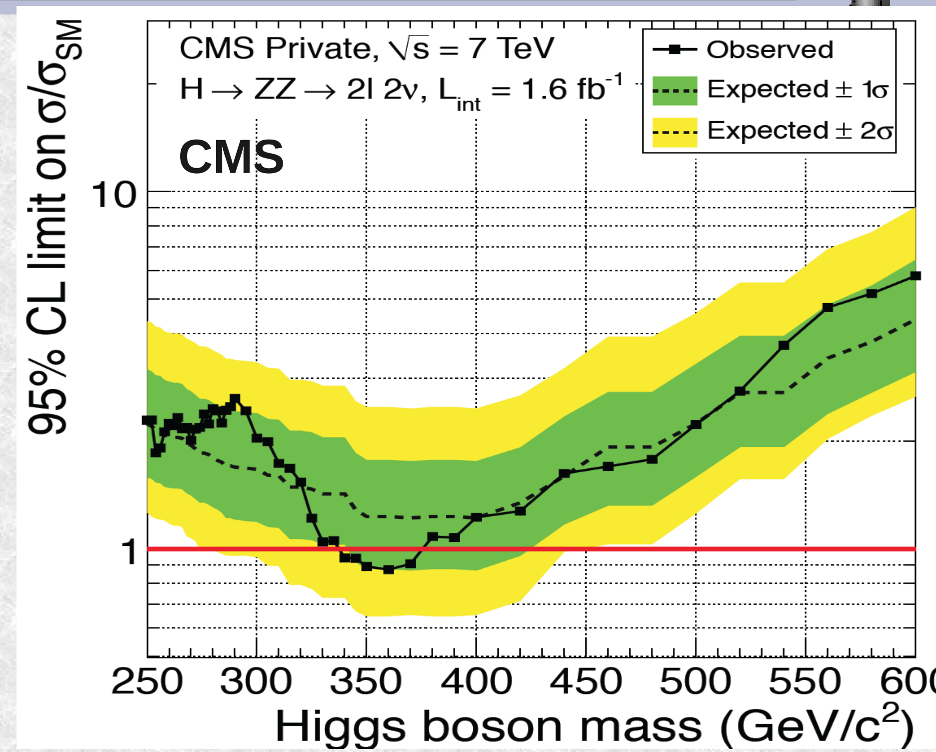




- ATLAS (left) and CMS (right)
- Harder E_T^{miss} and δφ cuts at high mass
- Each of these excludes the mass shown

$ZZ \to ll\nu\nu$



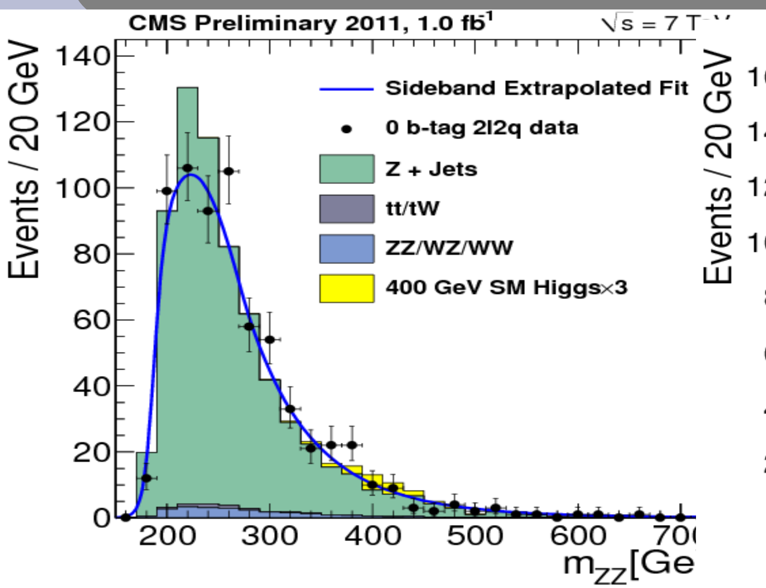


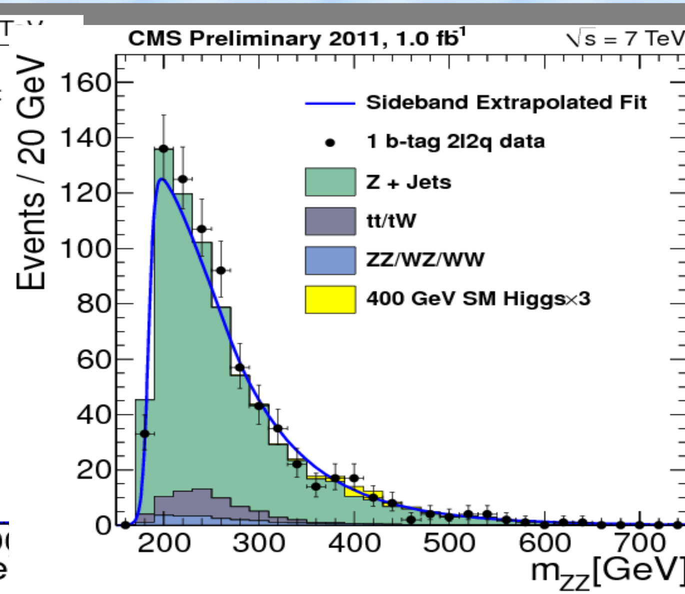
- ATLAS (left) and CMS (right)
- These searches exclude 100GeV wide region
- Both searches best sensitivity ~1.5xSM
  - Both got lucky

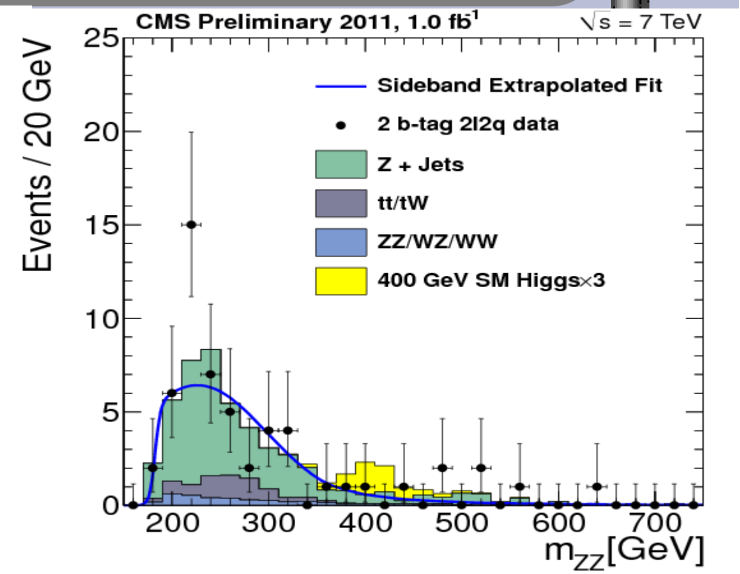
ZZ→llqq

- Highest rate for a ZZ process
  - Leptons provide 'easy' trigger
  - Need both Zs on shell so m_H over 200GeV
    - Work going on to bring this to low mass region
- Background reduction
  - Double constraint reduces tt contamination
  - Further reduced by MET veto
  - Z plus jets background dominant
- Use 2/3 subchannels:
  - Z to light quarks
    - CMS use quark v gluon tagging to enhance signal
  - Z to b quarks
- CMS use decay angles directly

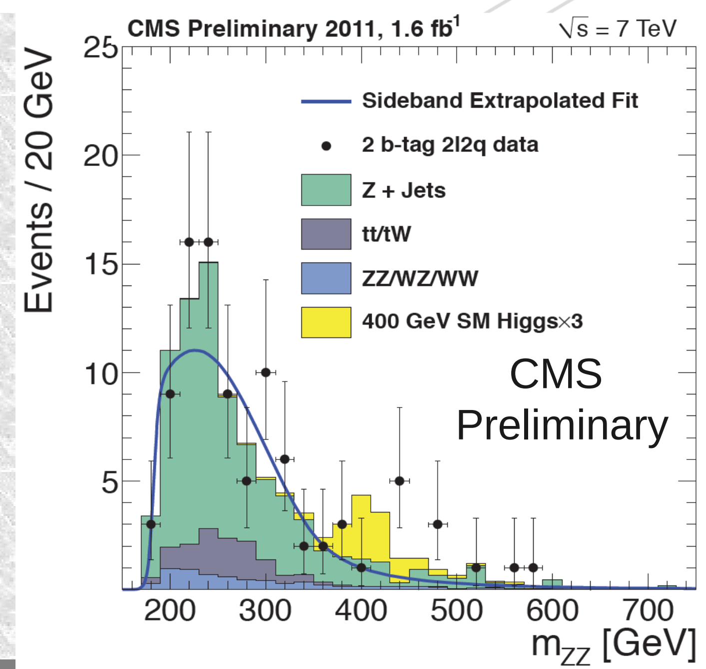
ZZ → llqq



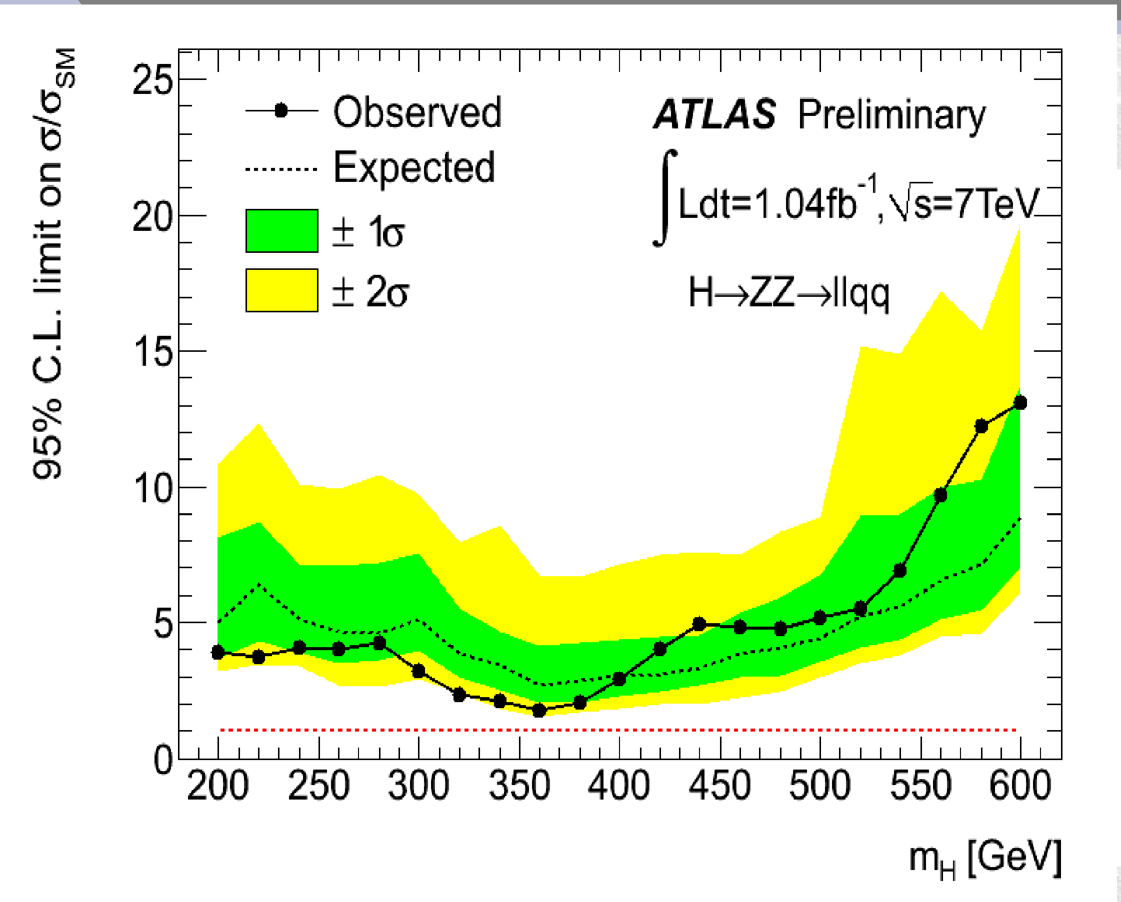


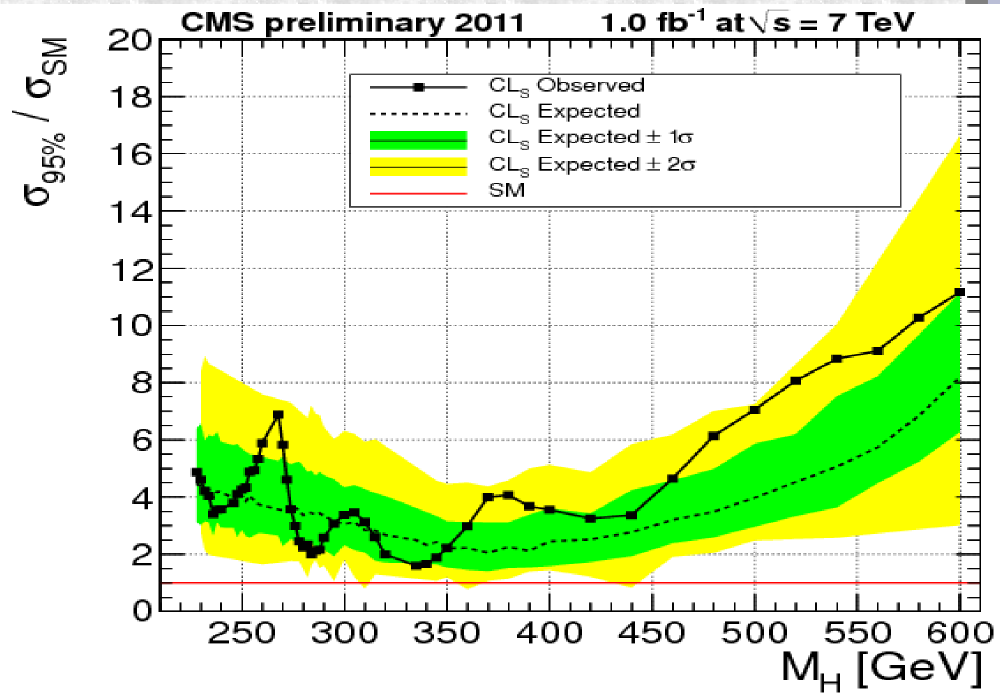


- Most backgrounds from data sidebands
  - Eg tt from $m_{ll}<m_Z-15$ or $m_{ll}>m_Z+15$
  - Z+jets use $m_{qq}<m_Z-15$ or $m_{qq}>m_Z+15$
- Small EW from simulation



llqq





- CMS sensitivity 2xSM, ATLAS 3xSM at 350-400
- Fluctuations never up to 2σ

H to WW

- Dominant decay mode in m_H>130 GeV
- lνlν
  - All leptonic mode allows suppression of background
    - Even when one W is off mass shell
  - Good rate
  - Non-resonant WW and tt are major backgrounds
  -
  - But ultimately it is a counting experiment; delicate
- lνqq
  - Highest rate final state
  - Only one neutrino allows mass reconstruction
    - But only if both W's on shell
  - Ferocious W+jets background

$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$

- W^+W^- to $l^+\upsilon l^-\bar{\upsilon}$ has assorted backgrounds:

Background	Reduced with	Estimated using
D-Y (l+l-) production (inc. $\tau\tau \rightarrow e\mu$)	Missing E_{Tr}^{el}	ABCD method
WW non-resonant	$d\Phi_{ll}$, M_T cuts	Rate in control region
$t\bar{t}$ and single top	B tag, jet binning	Rate in control region
W+jets	Isolation, IP cuts	Loose lepton fake rate
QCD	Same as above	As above

$H \to WW \to l\nu l\nu$

- Lepton thresholds

	e-e	μ-μ	e-μ
pT leading, GeV	25	25	25
pT subleading, GeV:ATLAS	20	15	e:15, μ:20
pT subleading, GeV:CMS	10	10	10
ETmissrel	40	40	25

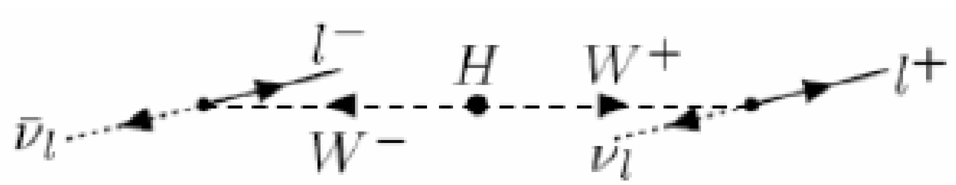
- MET

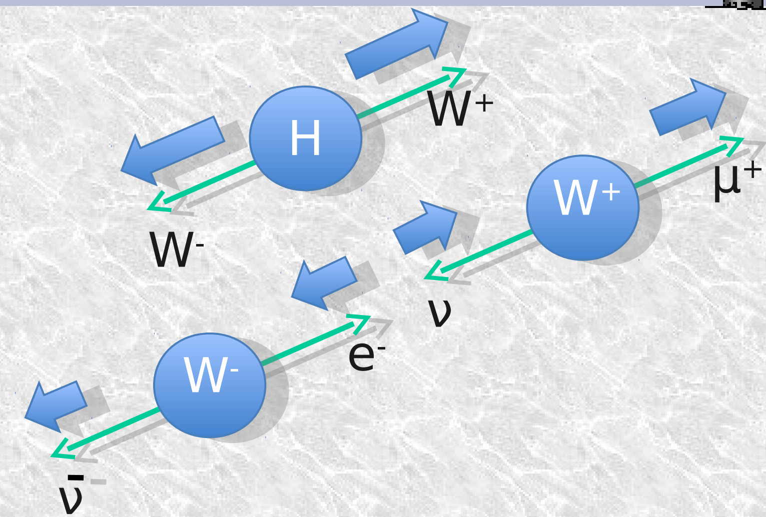
$$E_{\mathrm{T,rel}}^{\mathrm{miss}} = \begin{cases} E_{\mathrm{T}}^{\mathrm{miss}} & \text{if } \Delta\phi \geq \pi/2 \\ E_{\mathrm{T}}^{\mathrm{miss}} \cdot \sin\Delta\phi & \text{if } \Delta\phi < \pi/2 \\ & \Delta\phi = \min(\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \ell),\ \Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, j)) \end{cases}$$

- M_T

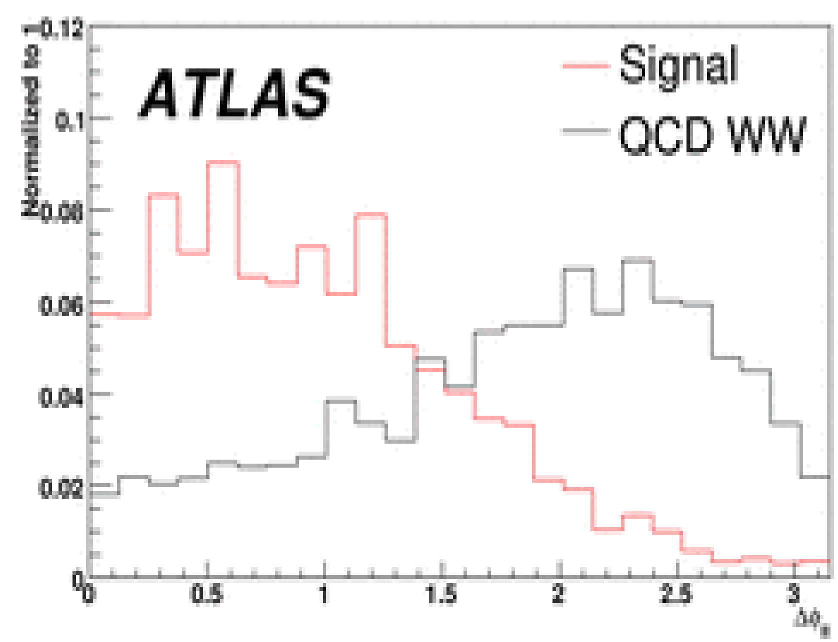
$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\mathbf{P}_{\mathrm{T}}^{\ell\ell} + \mathbf{P}_{\mathrm{T}}^{\mathrm{miss}})^2},$$

Spin correlation in H→WW(*)





- Spin 0 nature of Higgs differentiates from QCD WW
  - WW's spin opposite
  - Therefore decays correlated
- Cut on Δφ to select signal
- Normalise WW background from rejected region



Spin correlation issue

- Background is mostly qq→WW
  - But gg→WW also contributes
  - With different spin structure
  - Enhanced by cuts – but only 3%
- Or is it?
  - qq is NLO
  - gg is LO
  - K factor?
- We have no way to measure this

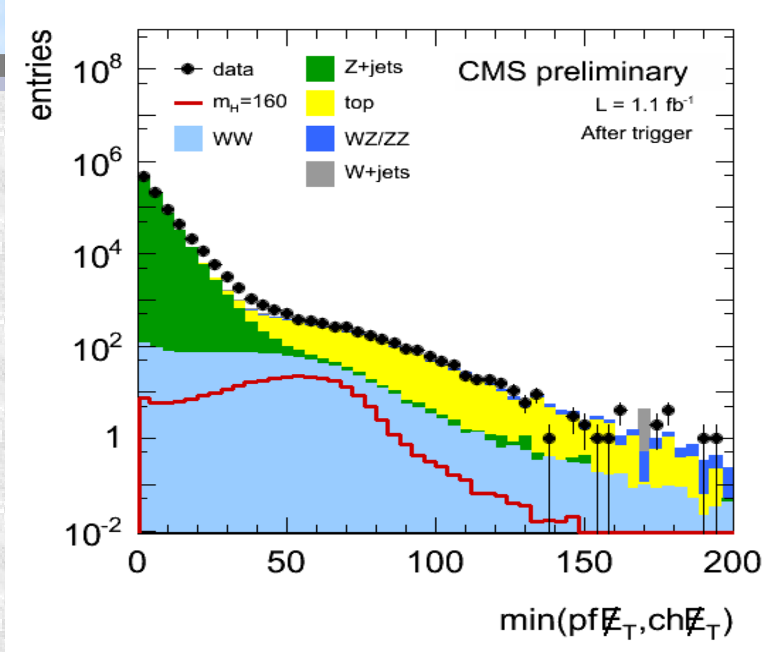
ArXiv: hep-ph/0503094

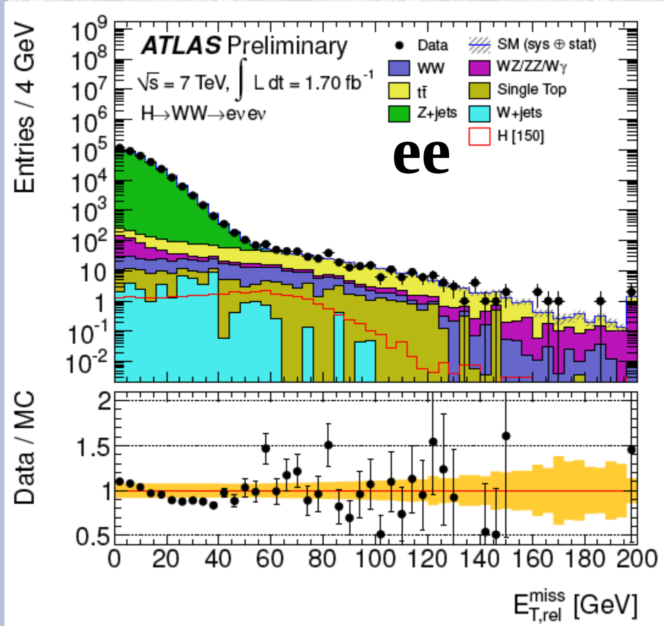
T. Binoth, M. Ciccolini, N. Kauer, M. Krämer

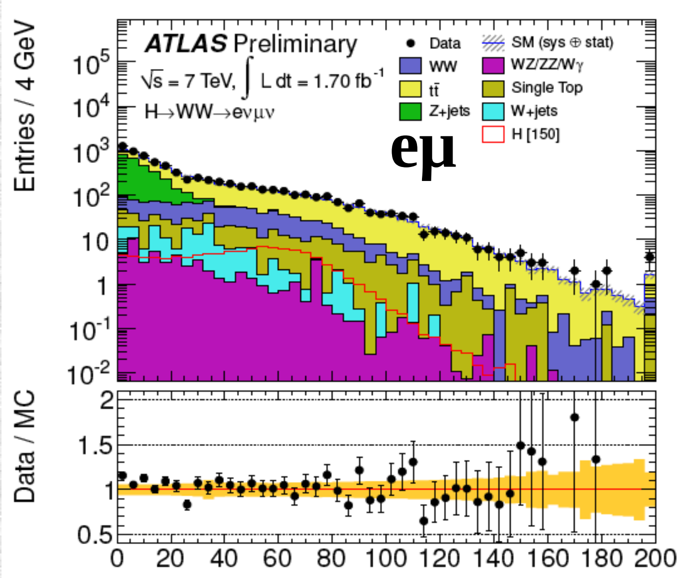
	$\sigma(pp \to W^*W^* \to \ell\bar{\nu}\bar{\ell}'\nu')$ [fb]				
	gg	$q\bar{q}$ LO	$q\bar{q}$ NLO	$\frac{\sigma_{\rm NLO}}{\sigma_{\rm LO}}$	$\frac{\sigma_{{\rm NLO}+gg}}{\sigma_{\rm NLO}}$
σ_{tot}	$53.61(2)^{+14.0}_{-10.8}$	$875.8(1)^{+54.9}_{-67.5}$	$1373(1)^{+71}_{-79}$	1.57	1.04
σ_{std}	$25.89(1)^{+6.85}_{-5.29}$	$270.5(1)^{+20.0}_{-23.8}$	$491.8(1)^{+27.5}_{-32.7}$	1.82	1.05
σ_{bkg}	$1.385(1)^{+0.40}_{-0.31}$	$4.583(2)^{+0.42}_{-0.48}$	$4.79(3)^{+0.01}_{-0.13}$	1.05	1.29

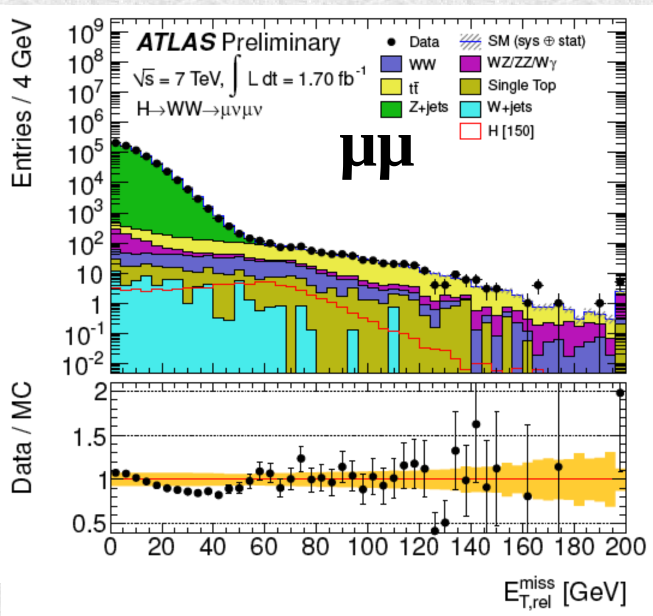
WW → lνlν

- Missing E_T
  - Vital tool against Z+jets events
    - costs in signal rate
  - Rate of Z+jets controlled using ABCD method

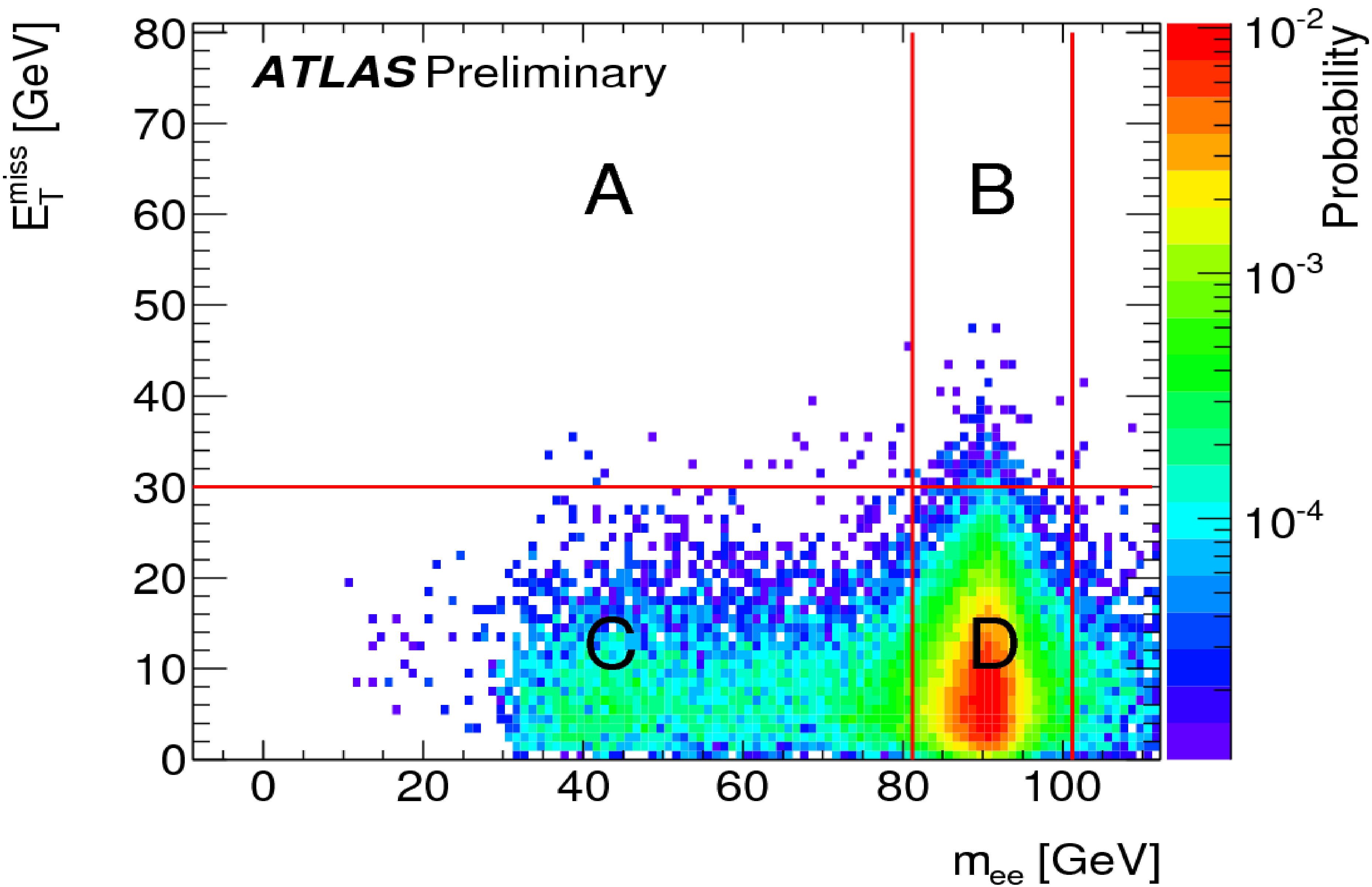






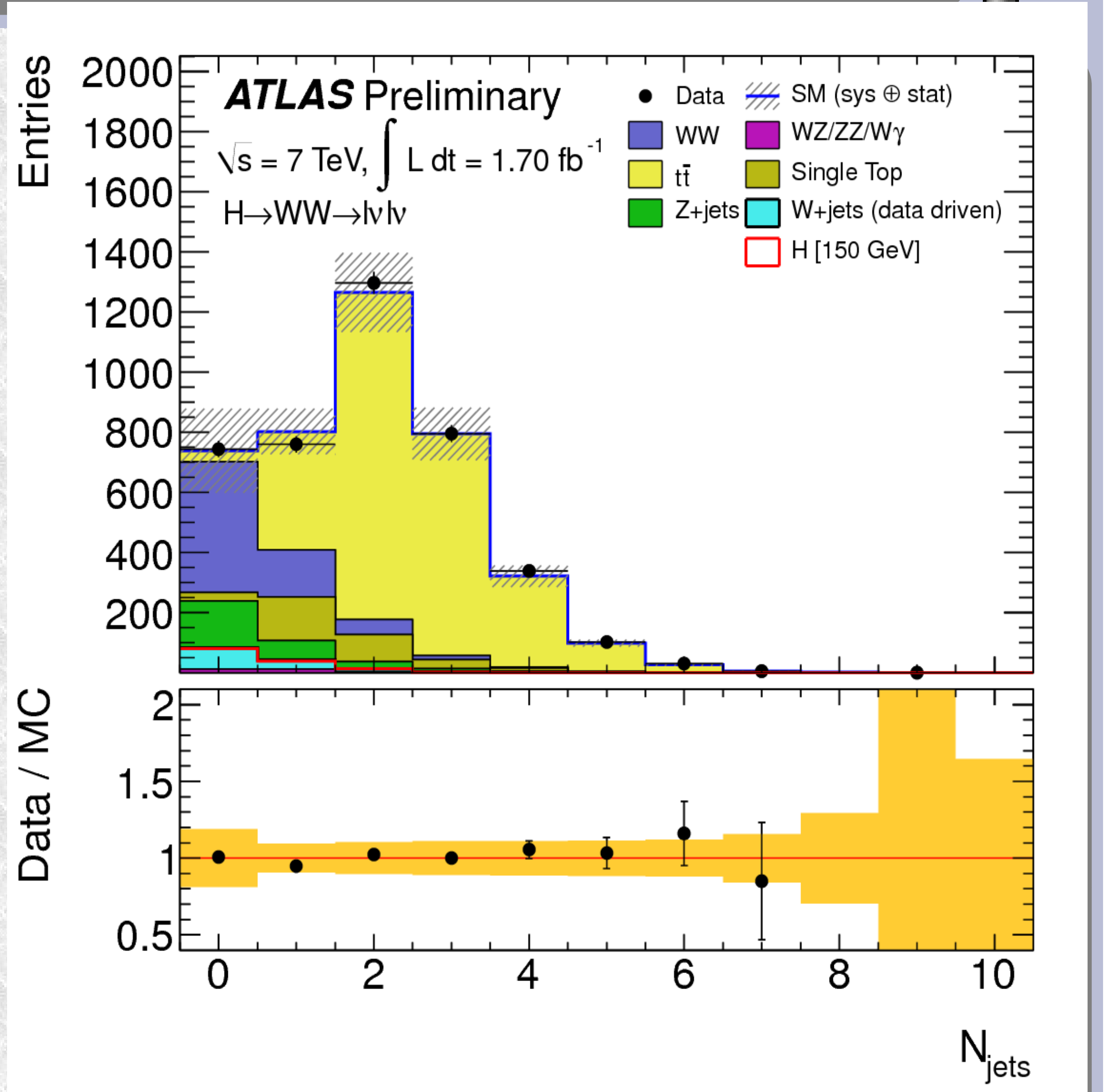


Z+jets background



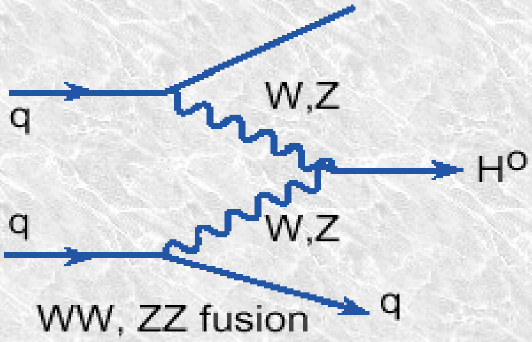
Jet binning

- The top background is dealt with by binning:
  - 0 jets
    - Very small top
  - 1 jet
    - B-veto jet
  - 2 jets
    - Used tag jets for VBF
- Top control: 1-jet with b-tag
  - Same leptons cuts as signal
    - acceptance from data

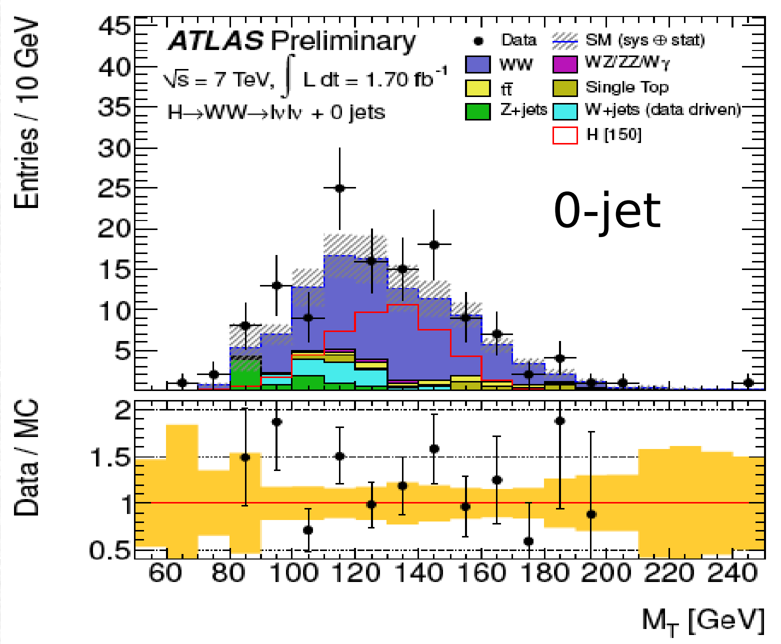


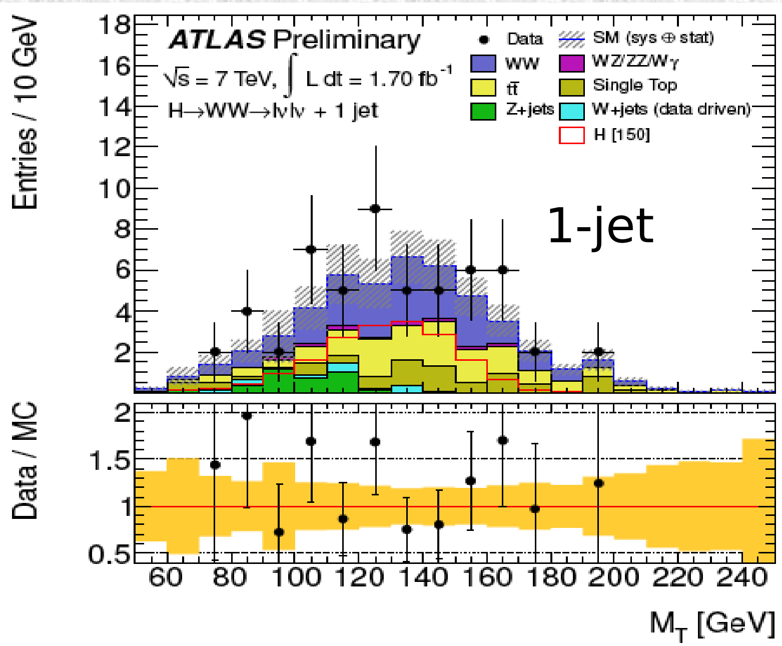
H→WW$^{(*)}$ via VBF

- VBF Higgs production gives two 'tag' jets
  - Reduced rate, but enhanced signal to background
    - If the central jet veto is applied
  - Requiring these jets gives additional complementary search
- Central Jet veto?
  - Issue here is reliability of efficiency calculation
  - No good estimation of this in data – more theoretical reliance
  - CMS did not apply jet veto
  - ATLAS did not use this channel



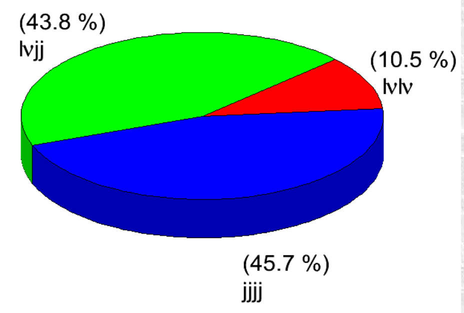
H→WW(*) transverse mass





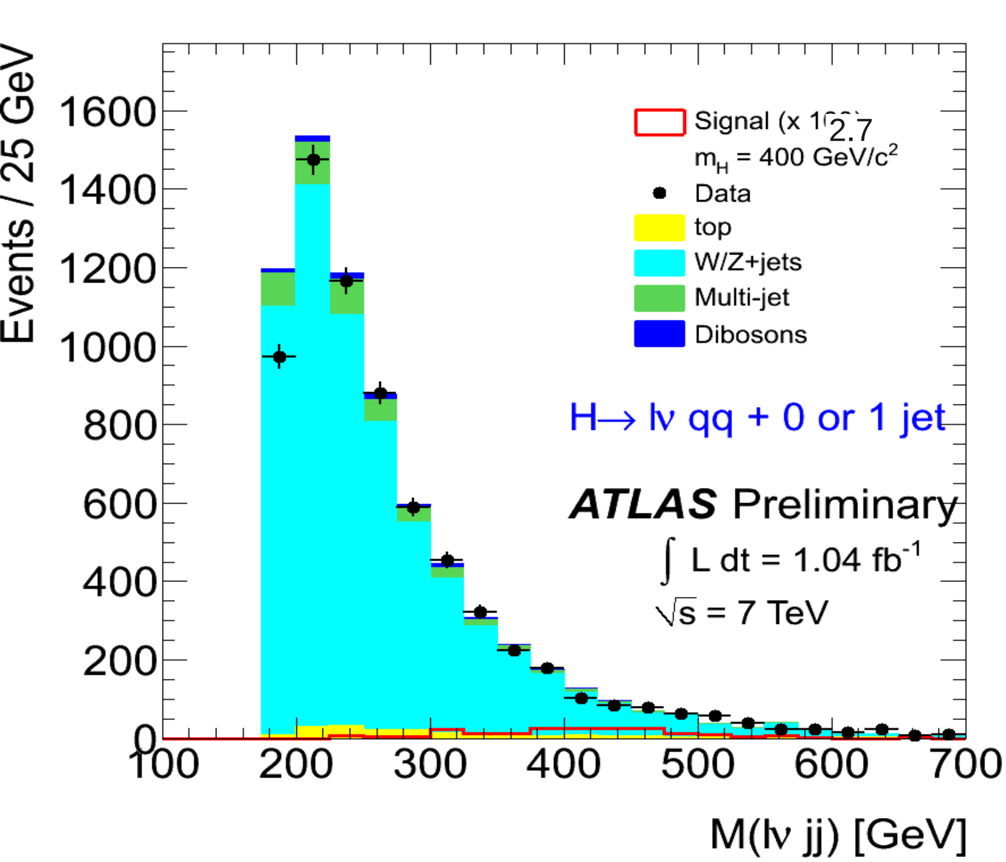
- M_T distributions have small excess
  - A signal?
  - Statistics?
  - Systematic problems?
- I will return to results tomorrow

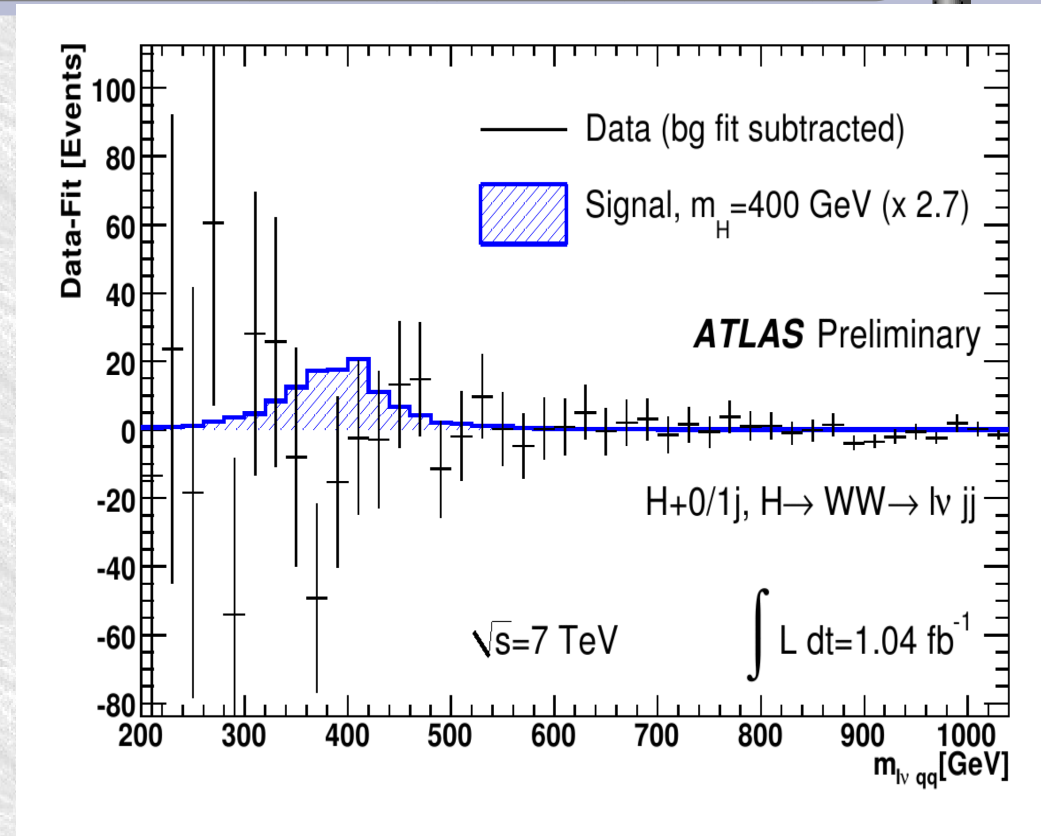
WW → lνqq



- Largest Higgs BR for high mass
- Presence of charged lepton gives QCD rejection
- But, like in $t\bar{t}$, semileptonic mode allows mass reconstruction
  - Missing p_T and m_W are 3 constraints
  - Obtain p_Z^{ν} from roots of quadratic
    - Only take real solutions
    - Take lower p_z option
- Suffers from LARGE background from W+jets
  - But smooth background
  - Signal is a bump
  - Analysis is relatively straightforward

WW → lνqq

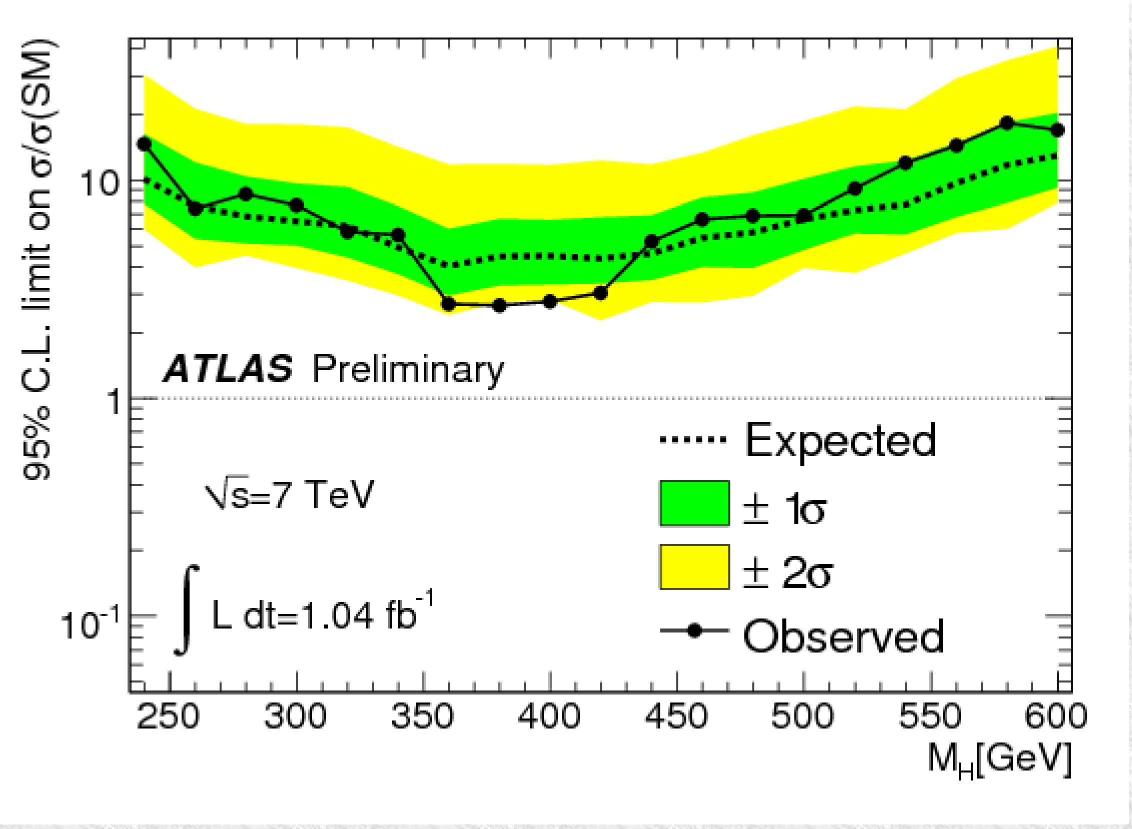




- $M_{l\upsilon qq}$ raw (left) and background-subtracted (right)
  - Fit with double exponential
    - Simulation only for signal distribution
  - Sum over the 0 and 1 extra jet searches

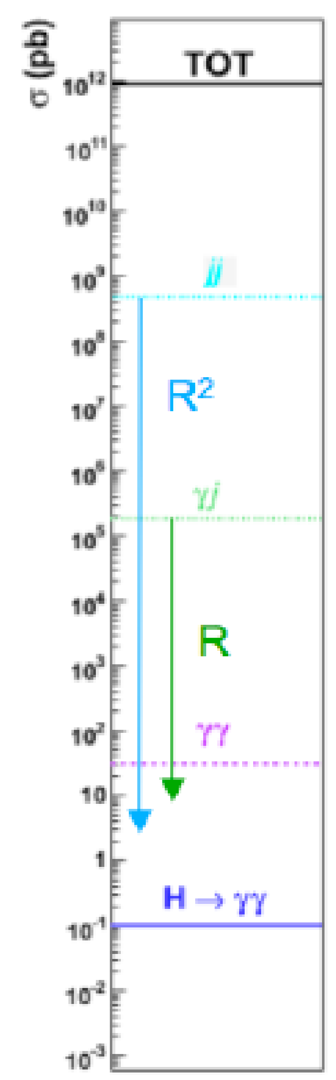
WW → lνqq

- Sensitive to five to ten times SM cross-section
- Limits 'lucky' around 400GeV
  - Exclude 2xSM
- No excess anywhere
- Future work:
  - Use decay angles
  - MVA approach?



H → γγ

- Rare (2×10^{-3}) decay mode – top loop
- But trigger, mass resolution are good
- Large backgrounds of γγ, γ-jet and jet jet
  - Need $O(10^4)$ jet rejection
  - Both detectors provide this
- Low rate means emphasis on efficiency
- Background prediction have large errors
  - But can be taken from data in bump-hunt

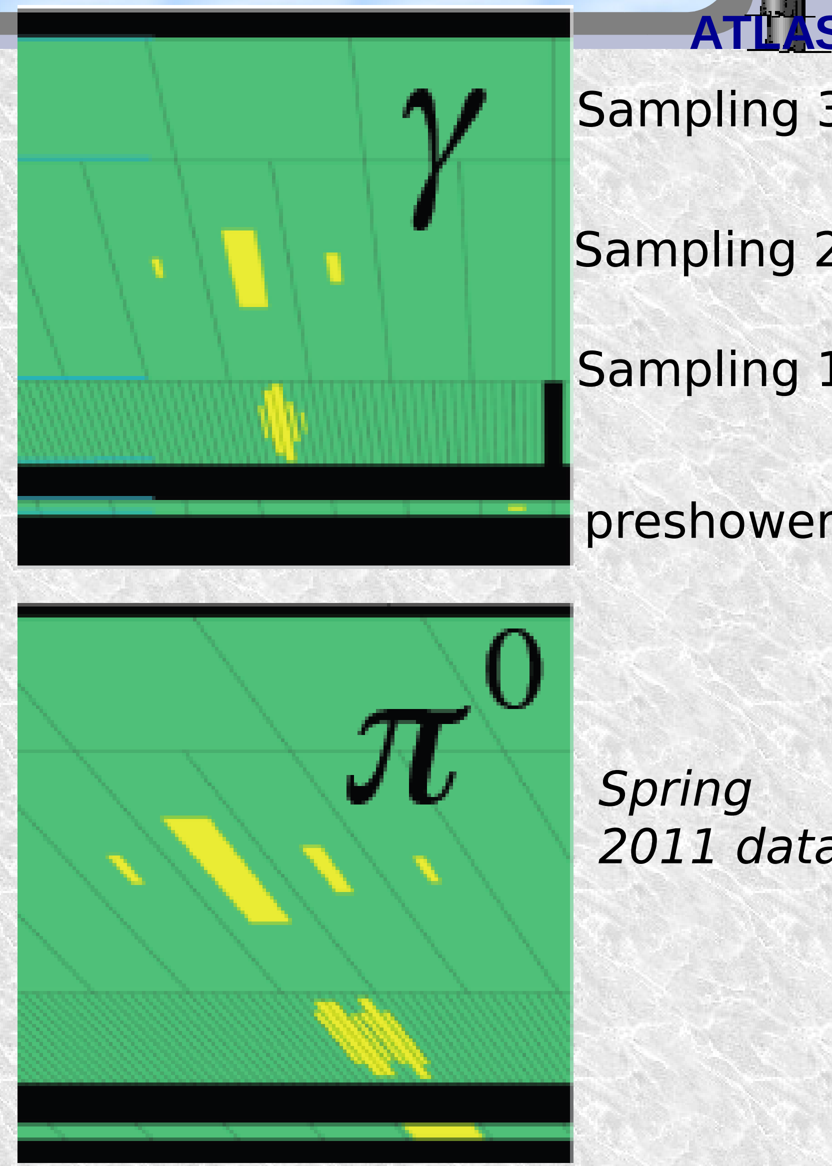


R ~ O(8000)

H to yy event selection

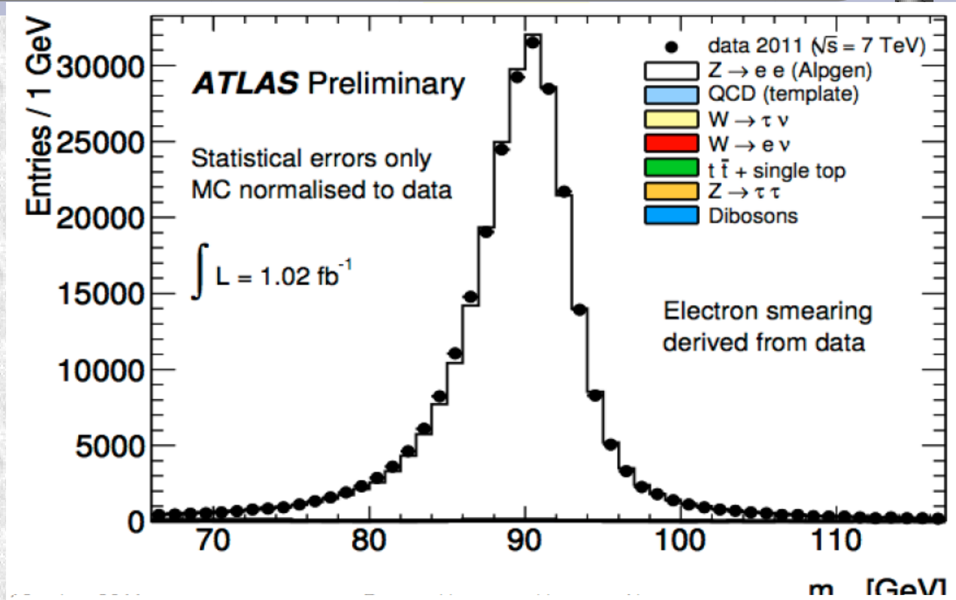
Very simple signature (and analysis)
Photon identification based both on lateral and longitudinal segmentation of the Electromagnetic calorimeter
Two high-quality isolated high-pT photons

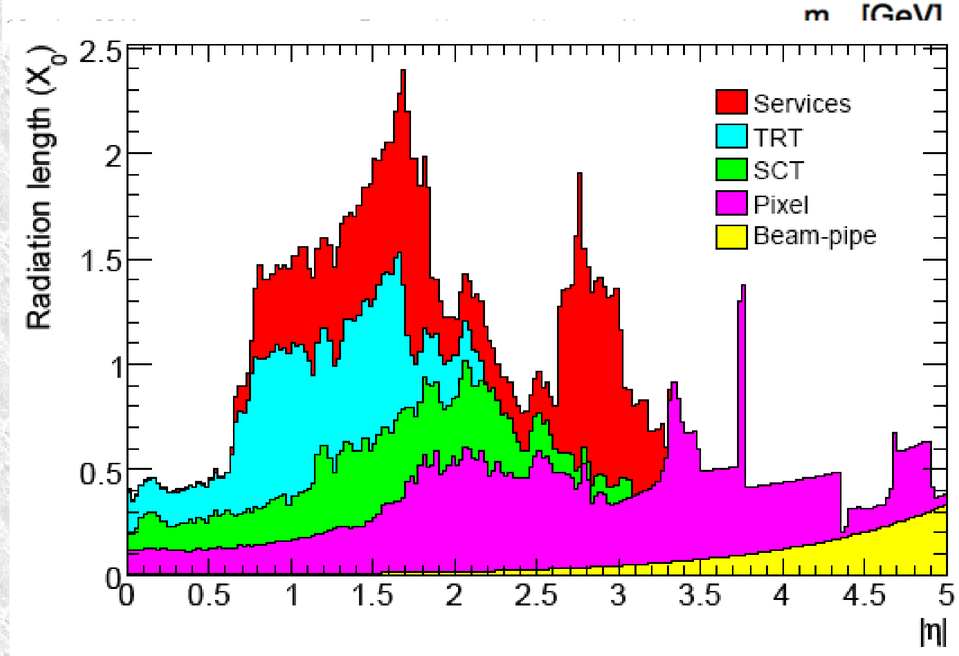
- $pT1 > 40$ GeV; $pT2 > 25$ GeV
- $|\eta12| < 1.37$ and $1.52 < |\eta12| < 2.37$



H → γγ

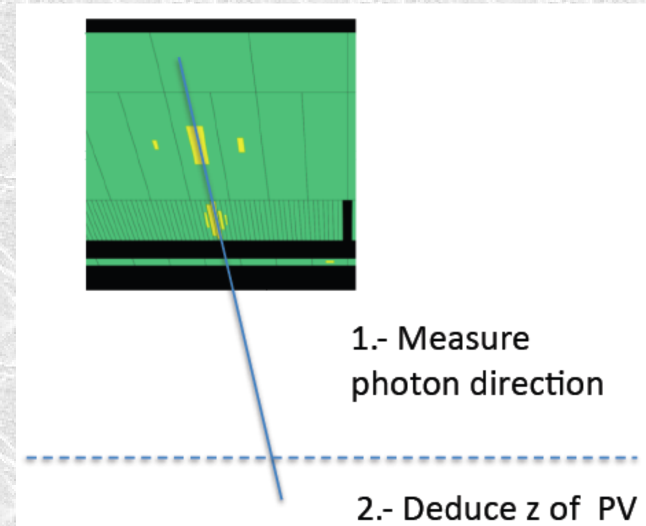
- Electron resolution checked using the Z peak
- Need to transport to photon with MC
- Different e/γ response in MC largest systematic uncertainty

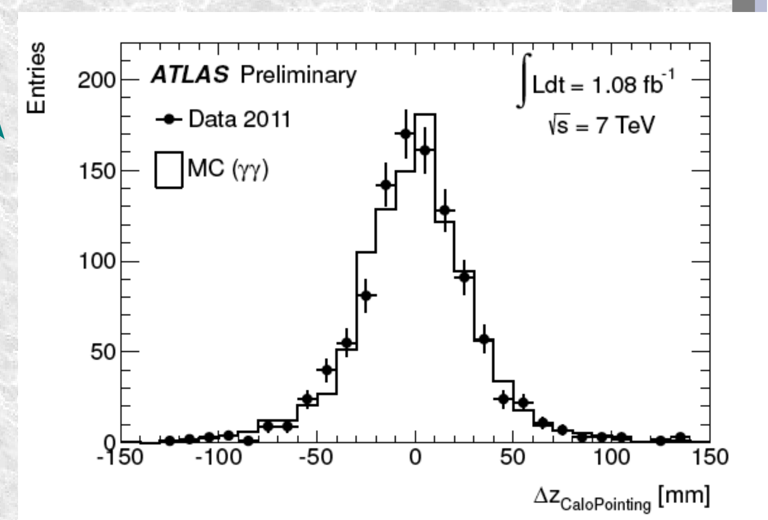




Primary Vertex

- Finding energy in a calorimeter does not tell you the photon momentum
  - You need to know the primary vertex position too
- Problem: pileup gives many
- ATLAS uses pointing from calorimeter to identify correct
- CMS photon conversion tracks, vertex p_T, vertex sum p_T



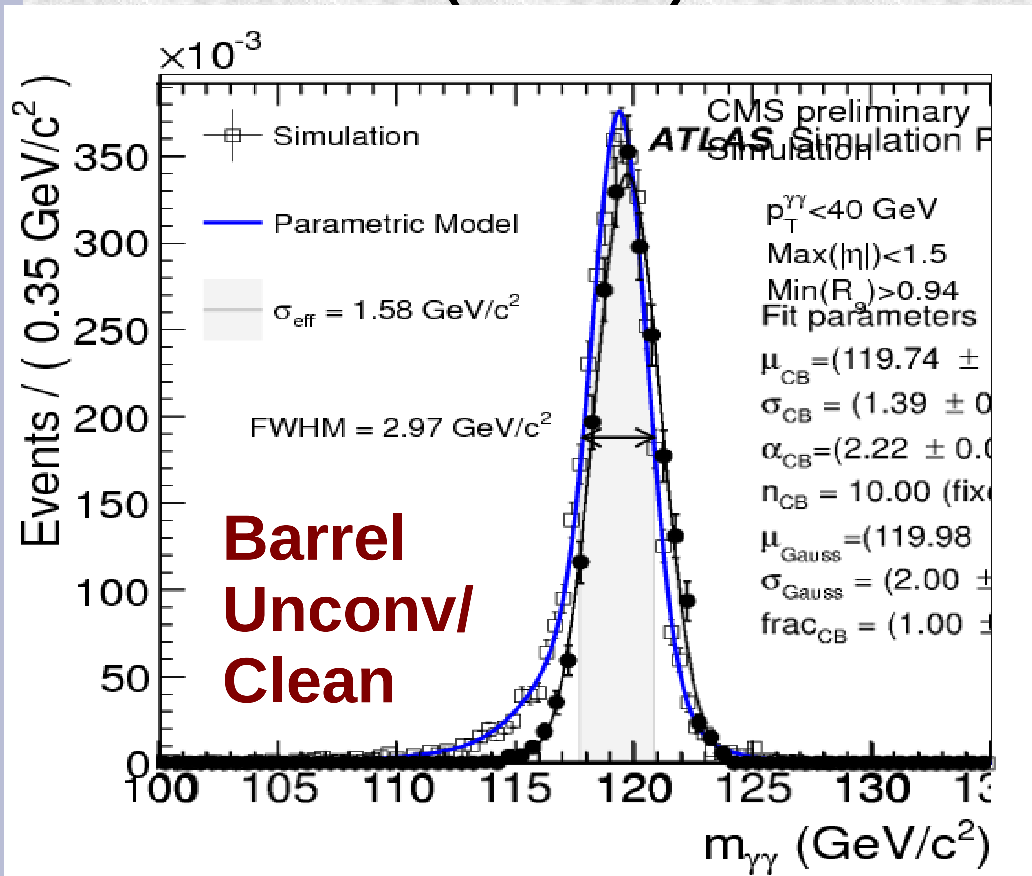


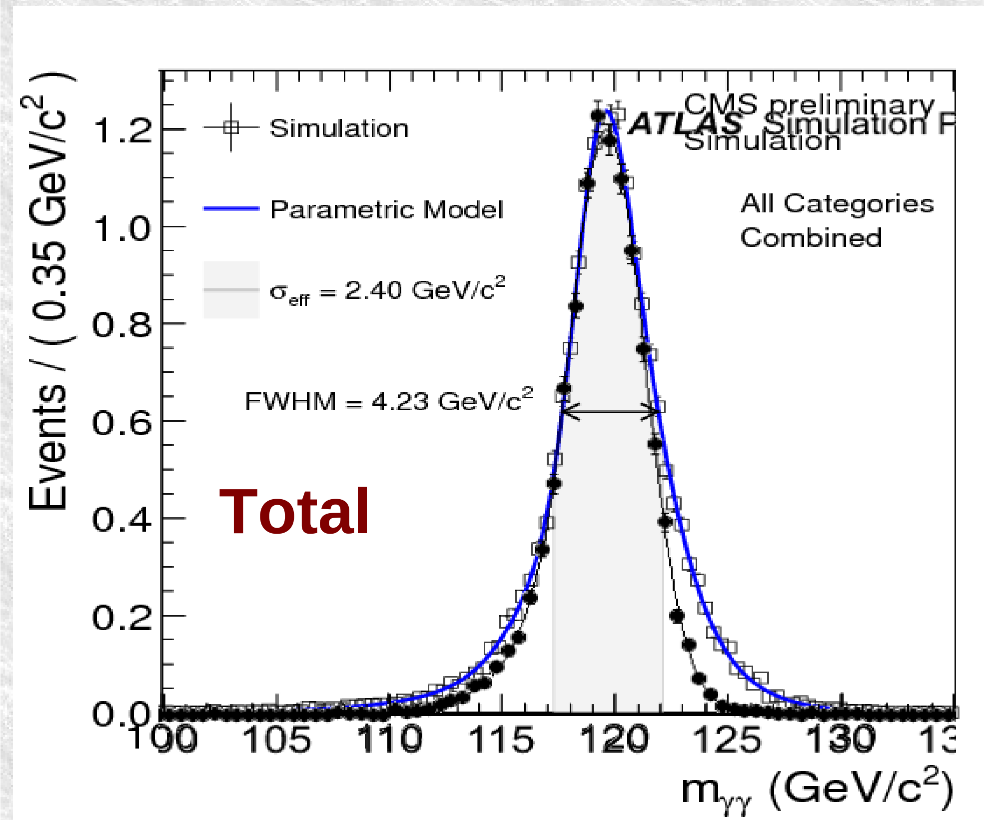
$\Delta z12 = z\gamma1 - z\gamma2$; $\Delta z12 \approx 3$ cm;

$\delta z\gamma\gamma \approx 1.5$ cm;

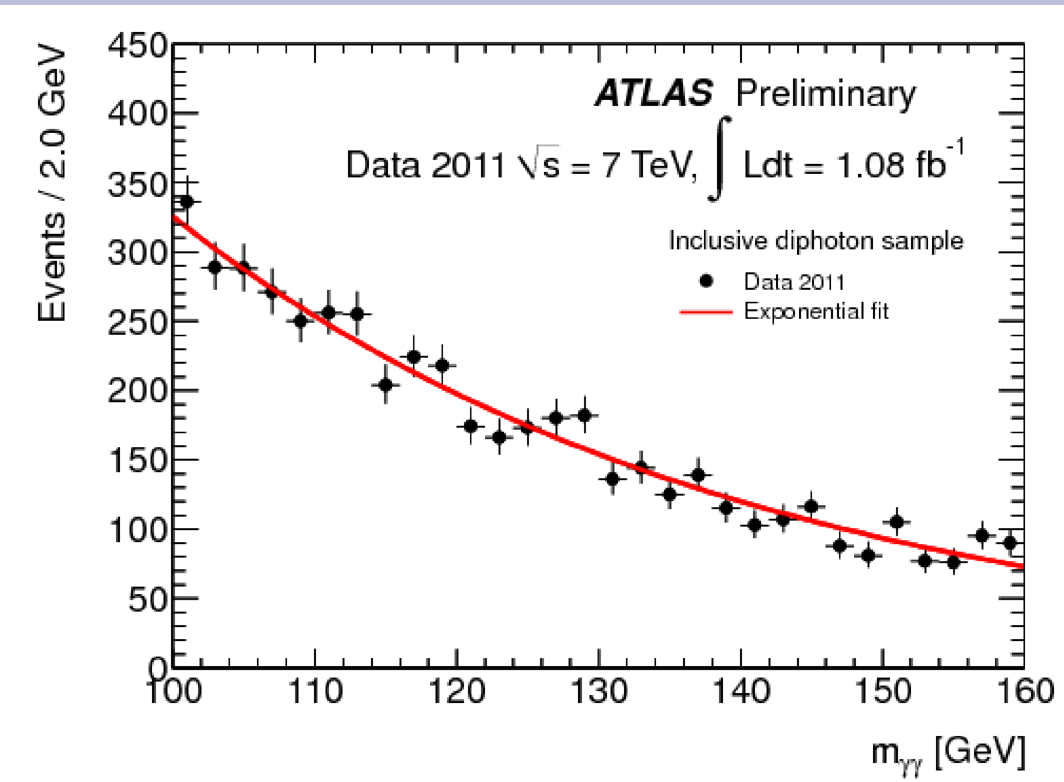
Higgs mass resolution

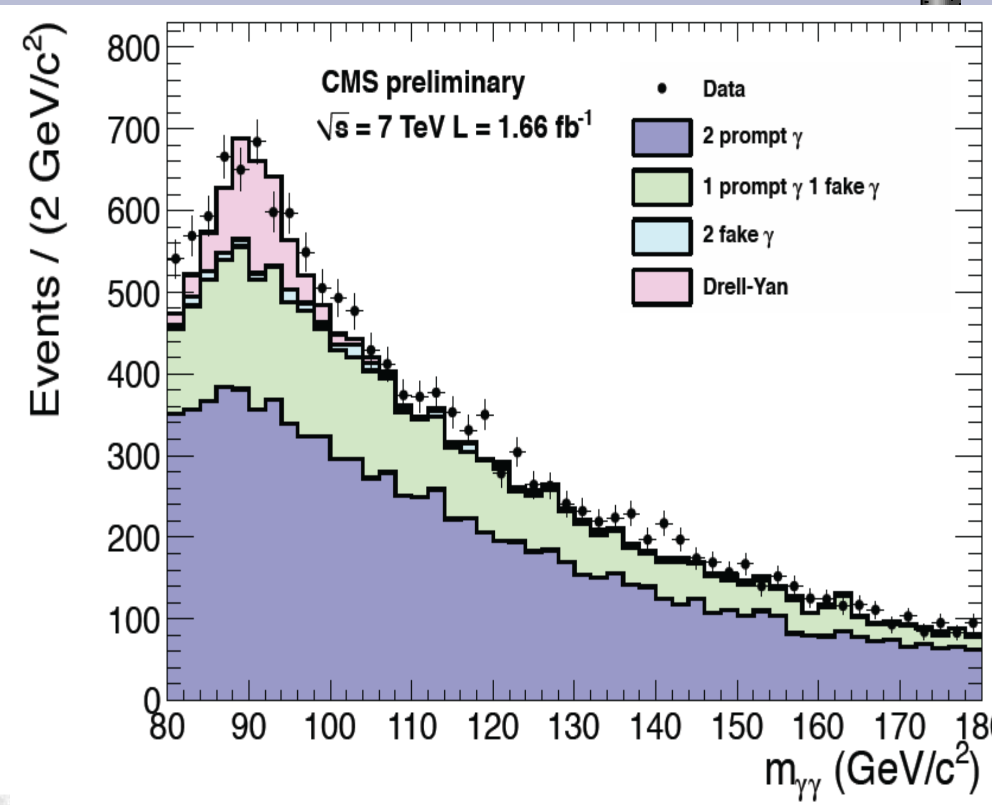
- No good calibration in data
  - Until we find Higgs!
  - Has to be simulated
- ATLAS (black) and CMS (blue) compared





$H \rightarrow \gamma\gamma$





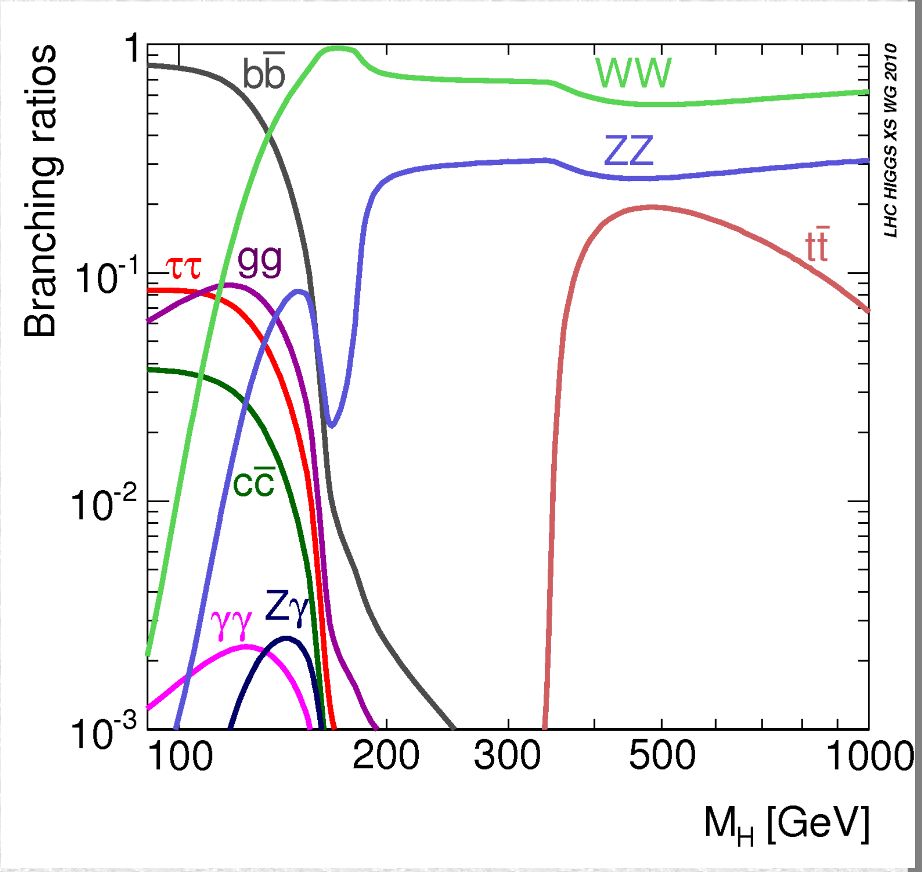
- Invariant mass spectra similar
  - Real γγ events dominant for both experiments
- Fit to this spectrum, looking for sharp peak
  - Both divide events into quality categories

H $\rightarrow \gamma\gamma$ improvements?

- Mass resolution is a key issue
  - Calorimeter calibrations can be improved
  - Potential big gain for CMS
- Use of production mode
  - Gluon fusion dominates
  - 0,1,2 jets improve s/b
  - W,Z,tt associated also improve in future...
    - rates very low
    - But they will be useful if light Higgs exists

H → Zγ

- No experiment shows this
  - Old studies found it hard
- But if M_H ~ 140 it could be retried
- 50x less than ZZ
  - But 15x better B.r., so only 3x down
  - Similar mass resolution
- Zγ background worse than ZZ
- Spin structure helps.
  - Spin zero H and massless γ so Z is transverse polarised

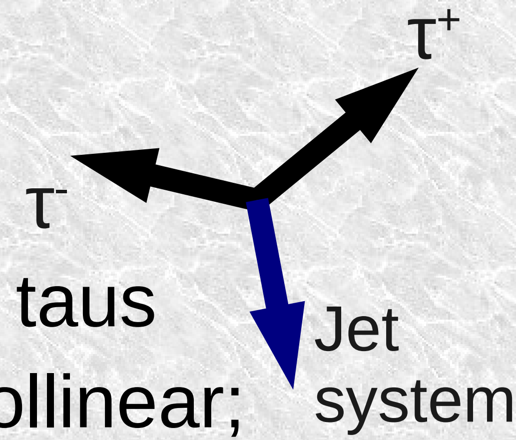


H → ττ

- Production mode
  - Before data taking, VBF mode assumed
  - Inclusive search has been used by both experiments
  - CMS do do the VBF too
- Trigger:
  - One/both tau decay gives trigger lepton
  - Or hadronic tau triggers for hh mode
- Mass of H done many ways:
  - collinear approximation
  - Visible mass
  - 'Missing Mass Calculator'
- Z → ττ main background

$H \rightarrow \tau^+\tau^-$ mass

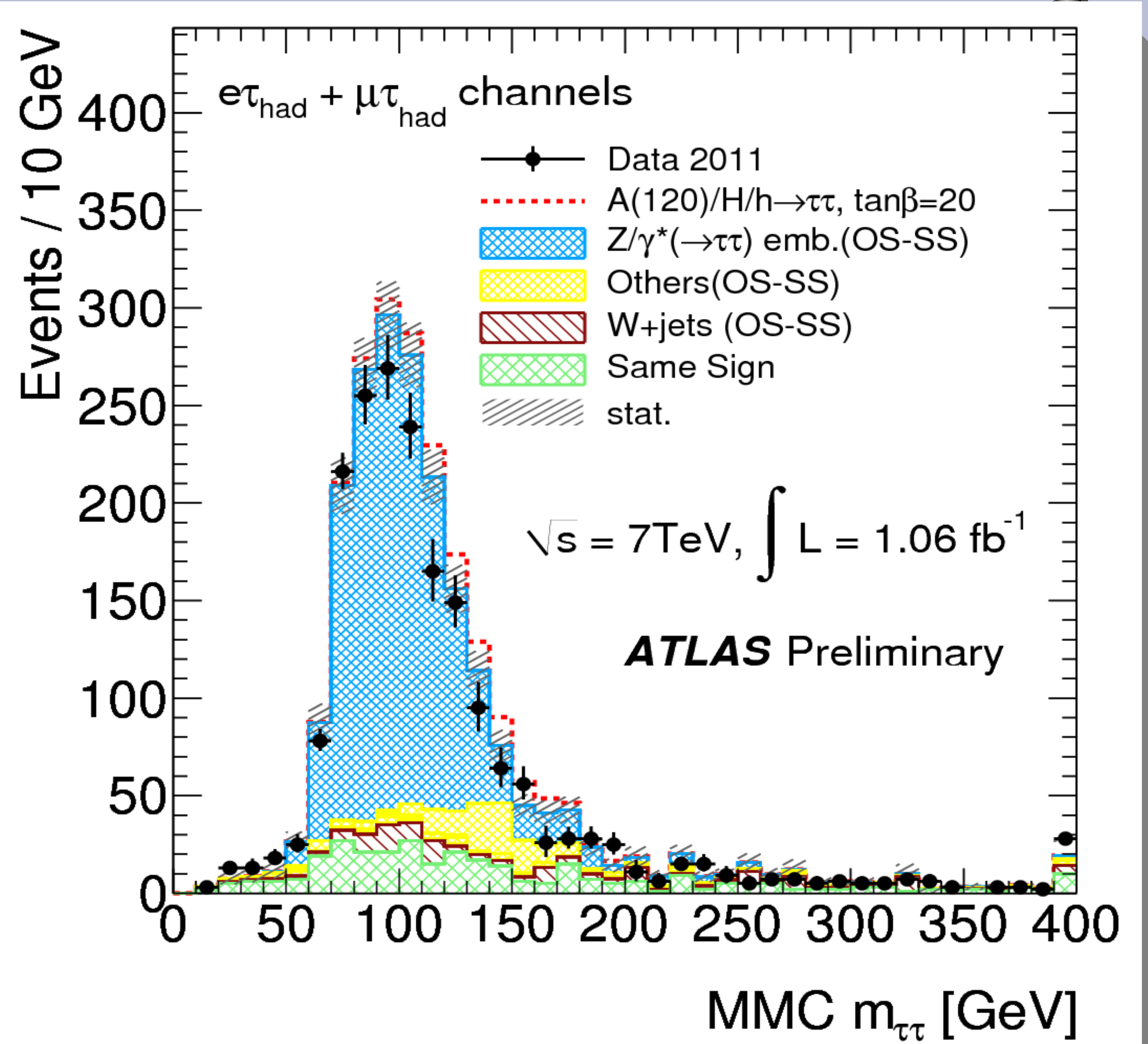
- 'Collinear approximation'; i.e. leptons follow tau direction
  - Impose p_T balance on system
  - Gives 2 constraints $\Sigma p_x=0$, $\Sigma p_y=0$
  - Solve for 2 unknowns: the p_T of the two taus
  - NB This does not work if the taus are collinear; need some p_T in the Higgs



- Visible mass: Sum observed
- Missing mass calculator
  - Multi-dim maximisation of probability of observed system given m_H

Inclusive tautau

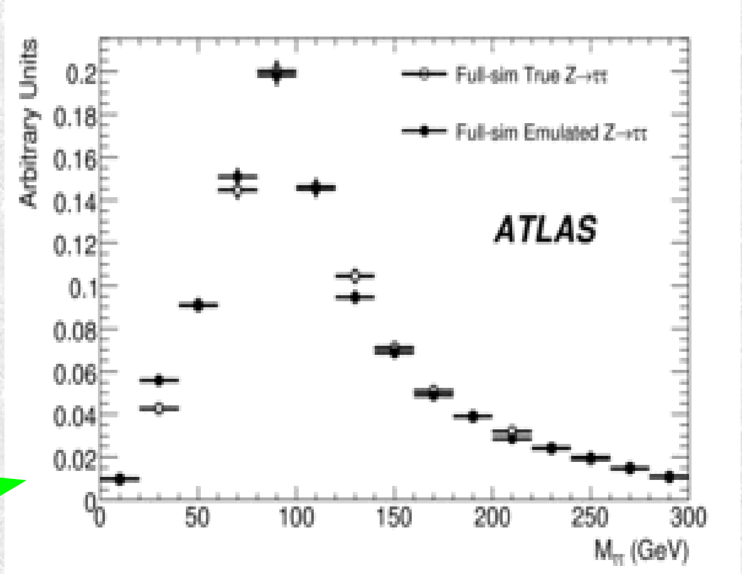
- ATLAS use lh inclusive
- Background based on like sign rate
- opposite sign corrections partly from data
- $Z \rightarrow \tau\tau$ from 'embedding' MC tau in data



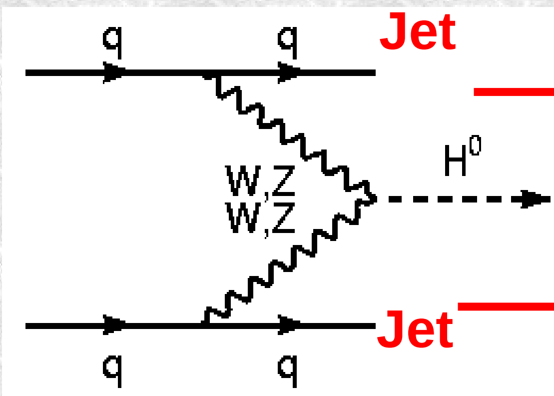
H → $\tau^+\tau^-$ background

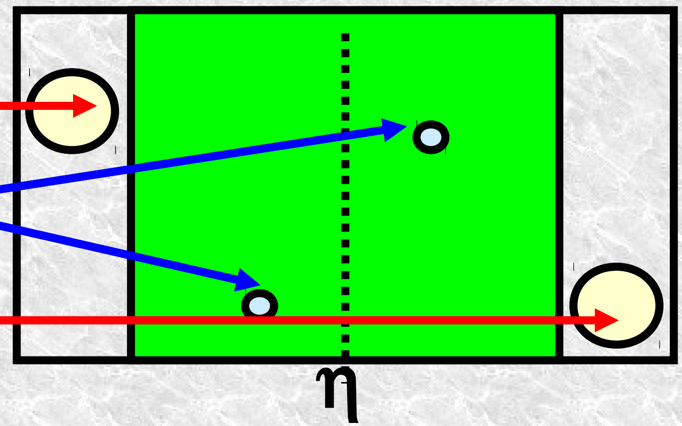
- Two major backgrounds:
- Z to tau tau
  - Found using real Z to μμ
  - Remove μ, convert into a tau, use as input to simulation
  - Replace simulated tau into original event

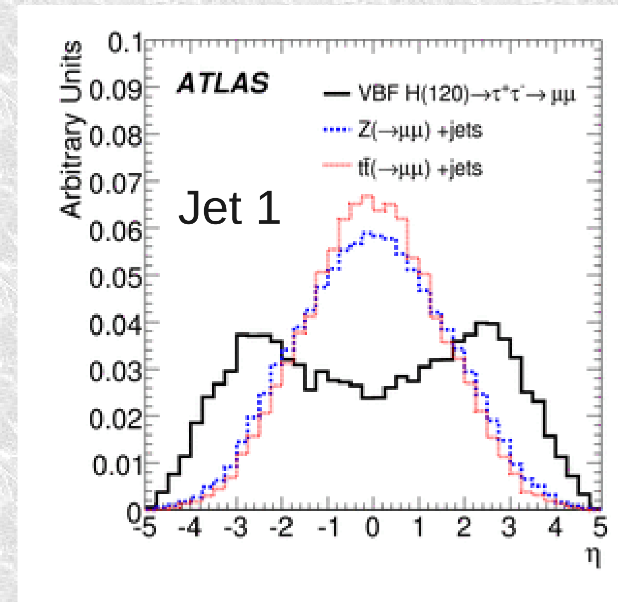
(Apologies - old slide)

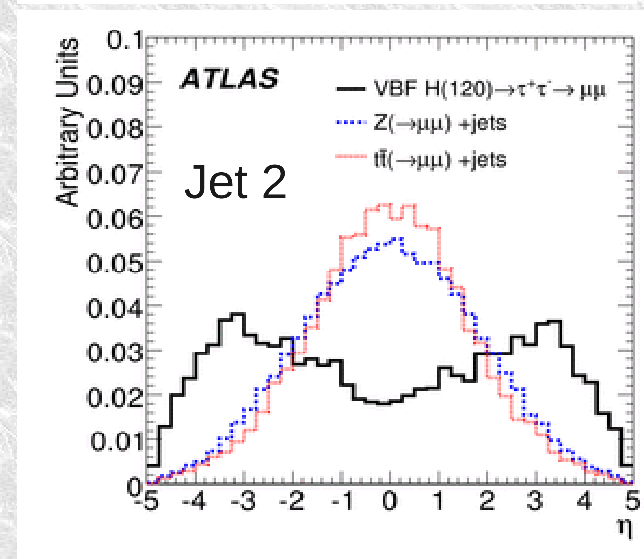


VBF: $qq \rightarrow qqH \rightarrow \tau\tau$







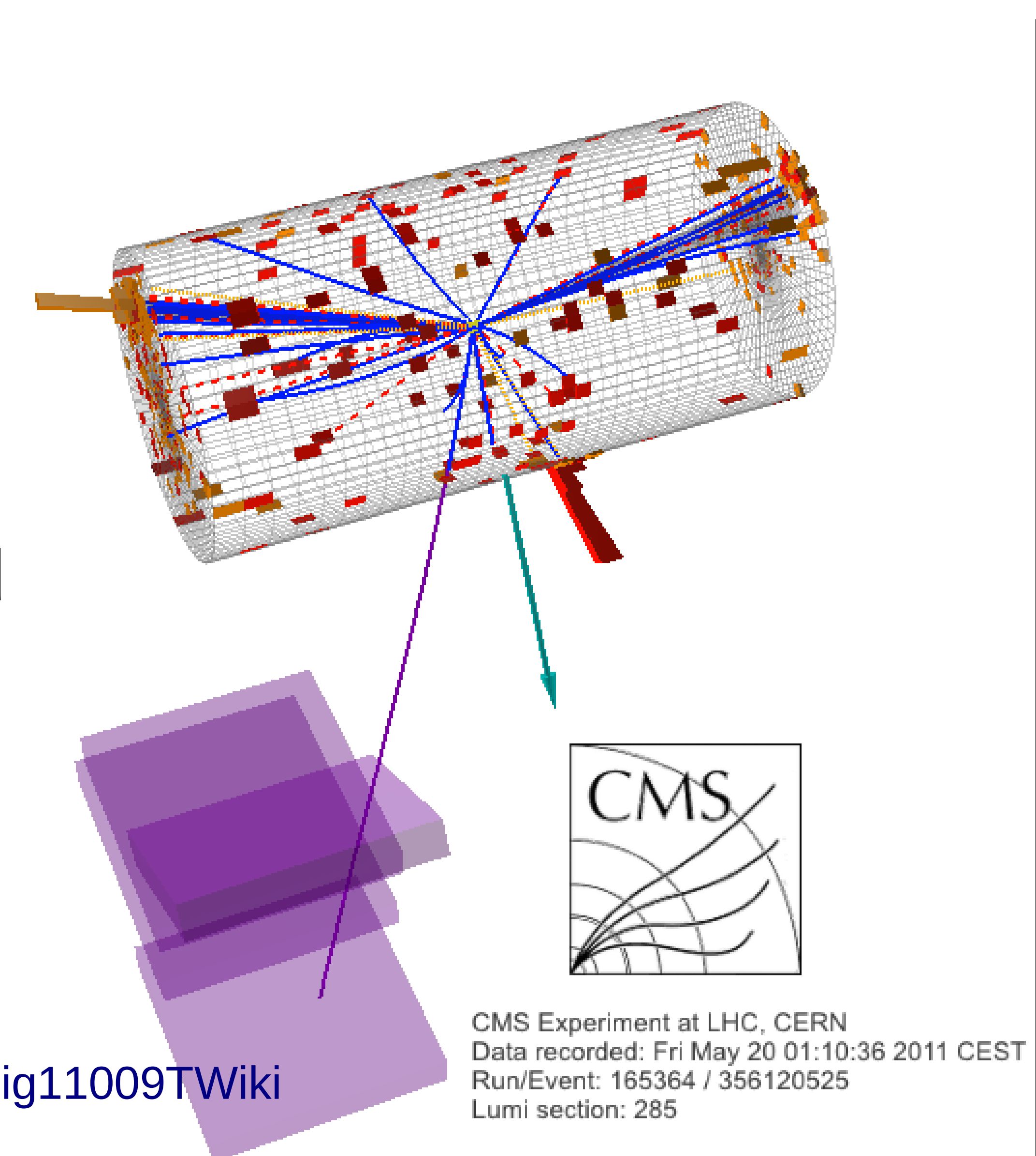


- Two forward jets, P_T of order $M_W/2$
- Higgs products central
- No colourflow → suppressed central jets

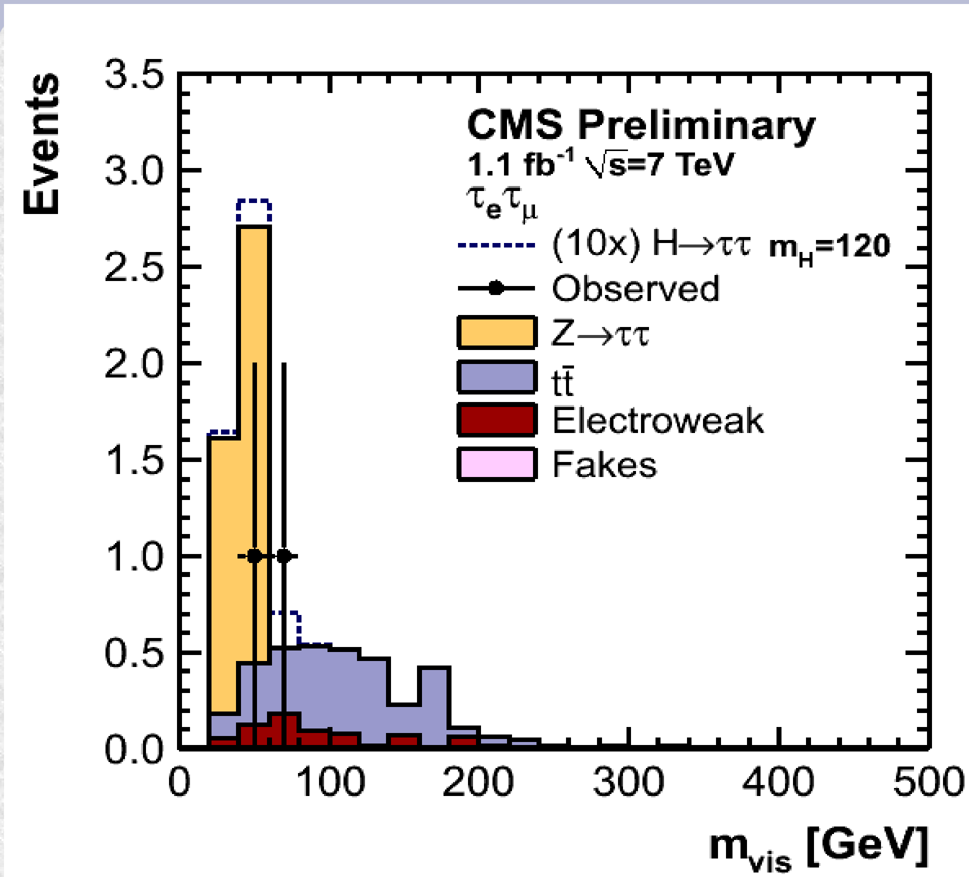
H $\rightarrow \tau\tau$

- CMS use many modes
- Including VBF search
  - With a beautiful picture
    - μ-τ candidate
    - Two forward jets
      - Mass 580GeV
    - Little central activity
  - Looks just as advertised
- e-μ, μ-μ, μ-τ, e-τ channels studied
- Details are here:

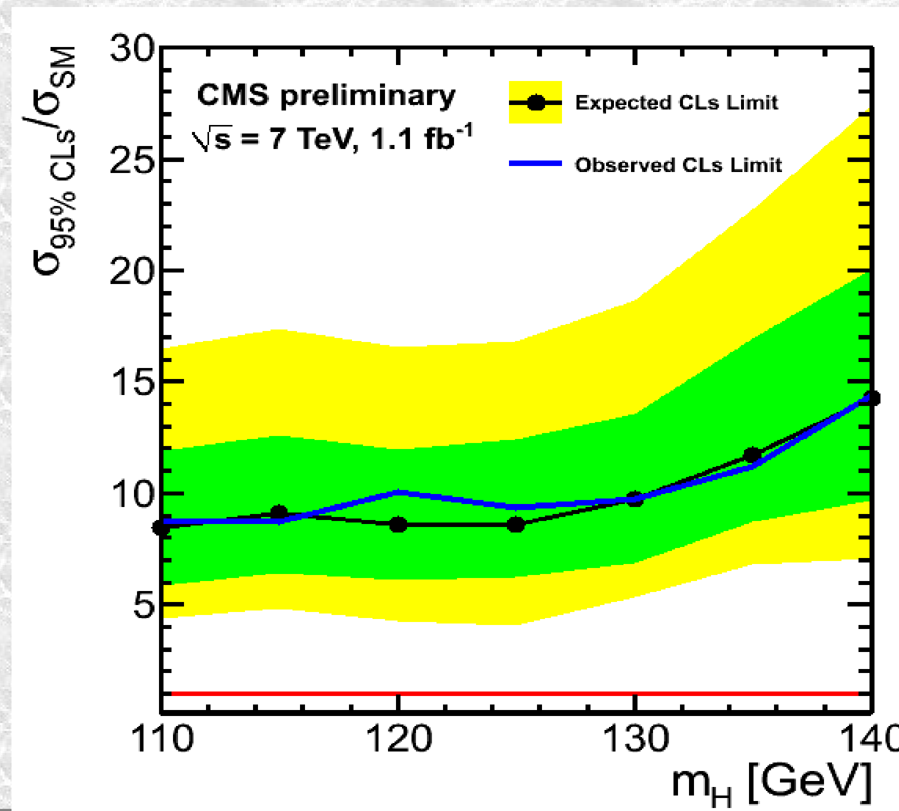
https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig11009TWiki



H →ττ results



- e-μ VBF channel (left) is cleanest
  - Mass calculation can improve



- Limits around 9xSM
  - At 115-125 (where we need this most)

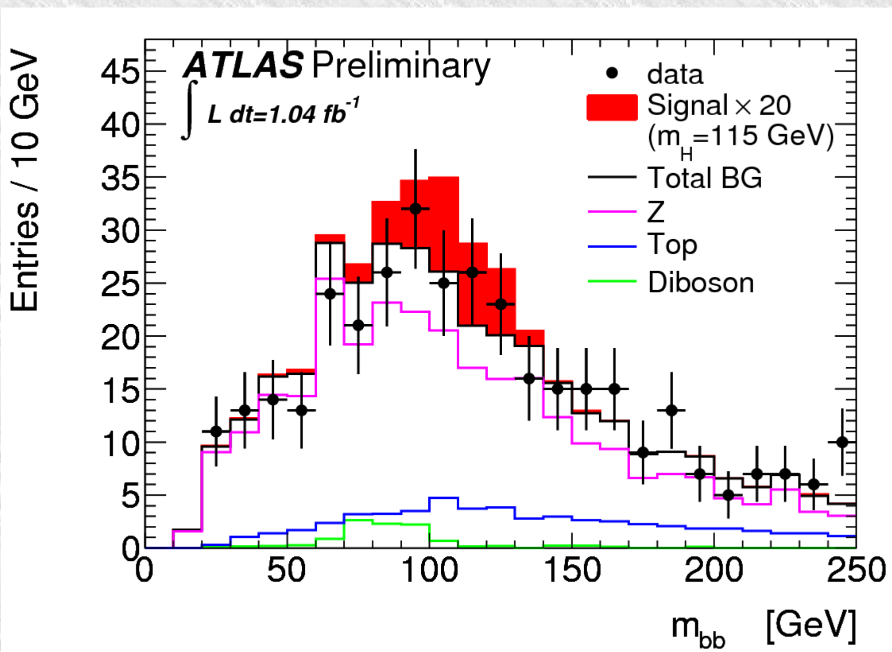
$H \to b\bar{b}$

- Dominant decay mode for m_H<130GeV
  - Gluon fusion is buried under background
  - VBF might be accessible
    - Trigger is hard.
    - Suggestion of photon associated?
      - ??
  - WH/ZH are best modes at Tevatron
    - Inclusive & boosted approaches at LHC
  - ttH is tough – many jets
    - Too much QCD radiation
    - Rate suppressed at 7TeV

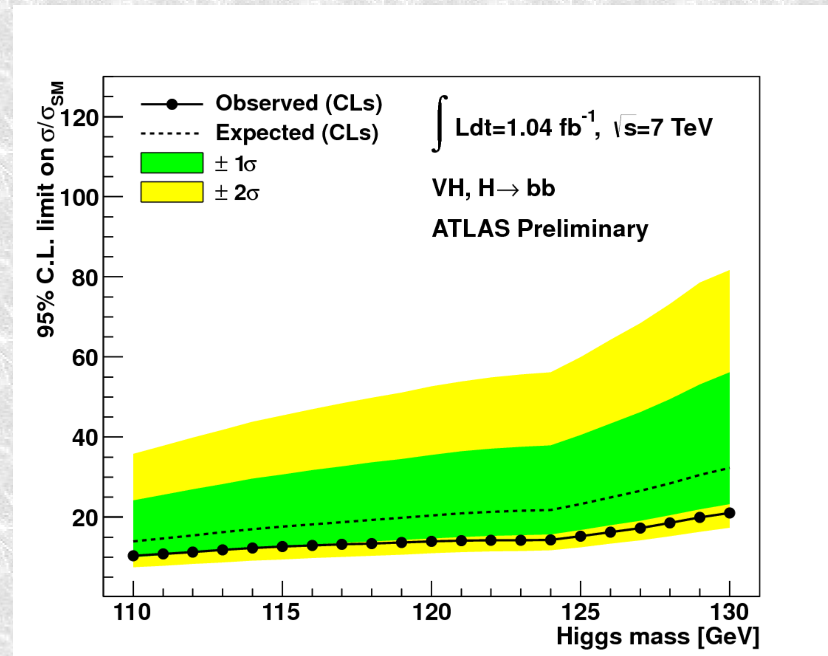
W,Z+H → b$\bar{\text{b}}$

ATLAS

Select events with Z or W boson in the leptonic final state (used also to trigger the event), and with exactly two jets b-tagged with pT>25 GeV
Backgrounds:
W+jets, Z+b-jets, top, QCD jets



The invariant mass, m_{bb}, for ZH→llbb, for mH=115 GeV; The signal distribution enhanced by a factor of 20 for visibility.



Expected (dashed) and observed (solid line) exclusion limits for the VH,H→bb channels combined, expressed as the ratio to the Standard Model

Improve the sensitivity to H→bb decays by looking to events with boosted jet pairs

Boost VH → bb

Best option: qq → VH; H → bb

Major backgrounds are V+jets, VV, ttbar

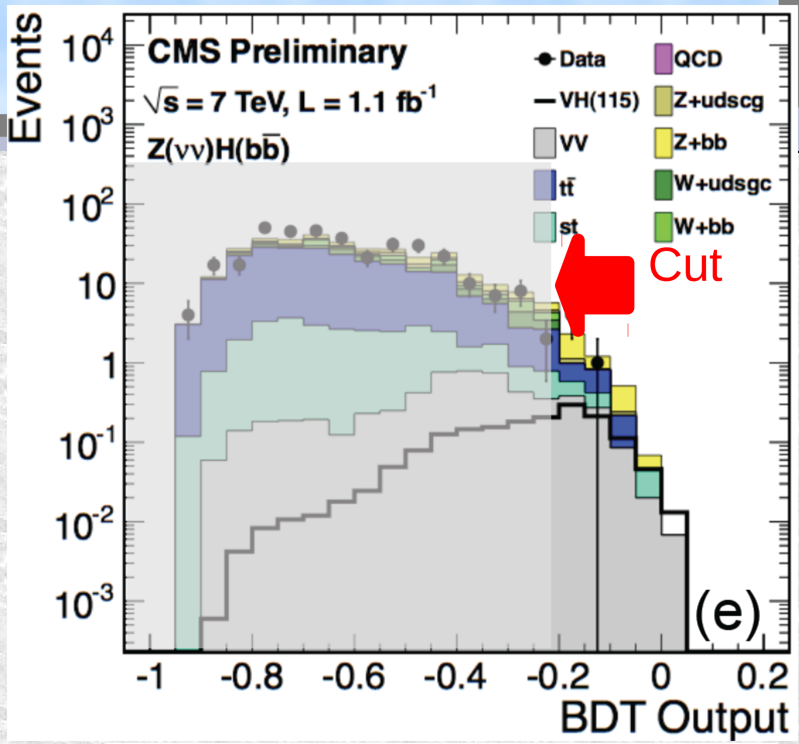
Use

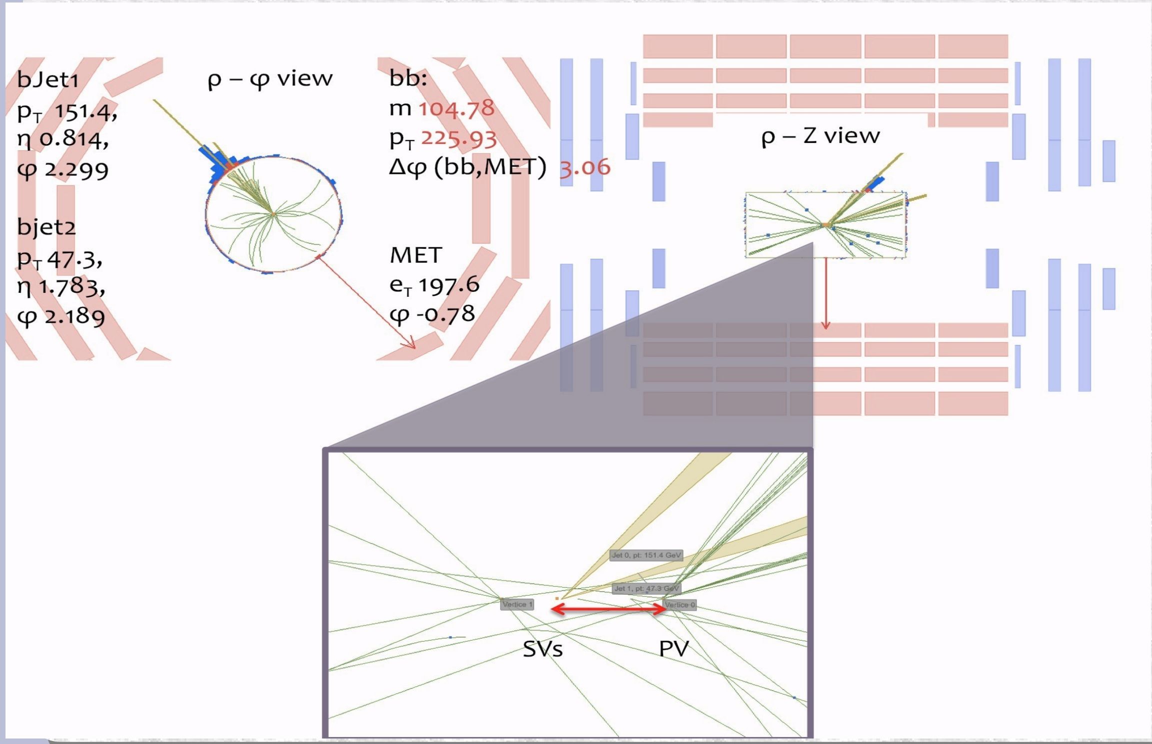
VH topology : ΔΦ(V,H) > 3

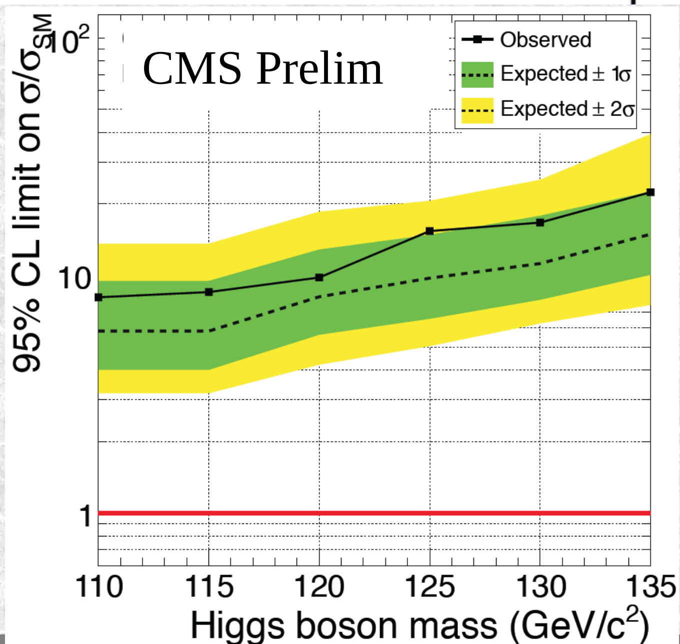
PT(V)> 100-160 GeV (boosted W/Z)

Tight b-tagging & MET quality

Backgrounds estimated from control data

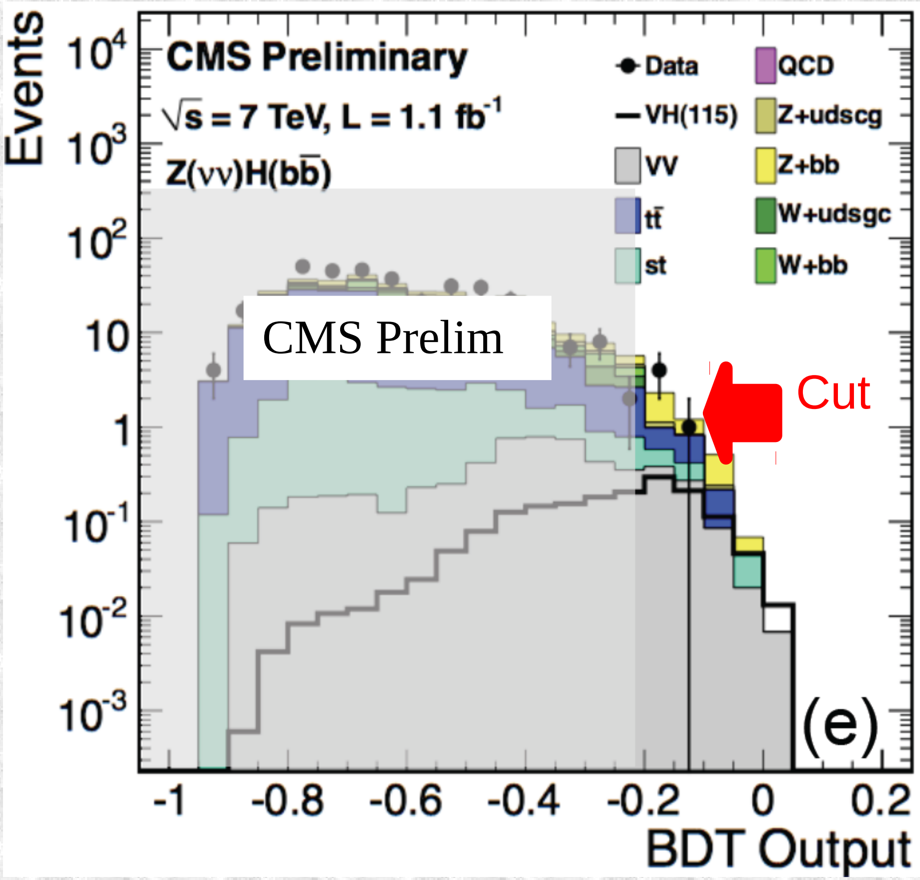






$VH \rightarrow b\bar{b}$

- Vbb has big backgrounds
  - Has harder p_T spectrum than most
  - So request high p_T
- Three modes used
  - ννbb :
    - p_T>150GeV to trigger events
  - lνbb :
    - p_T>165GeV to remove $t \rightarrow Wb$ contribution
  - llbb:
    - p_T>100GeV to supress Zbb

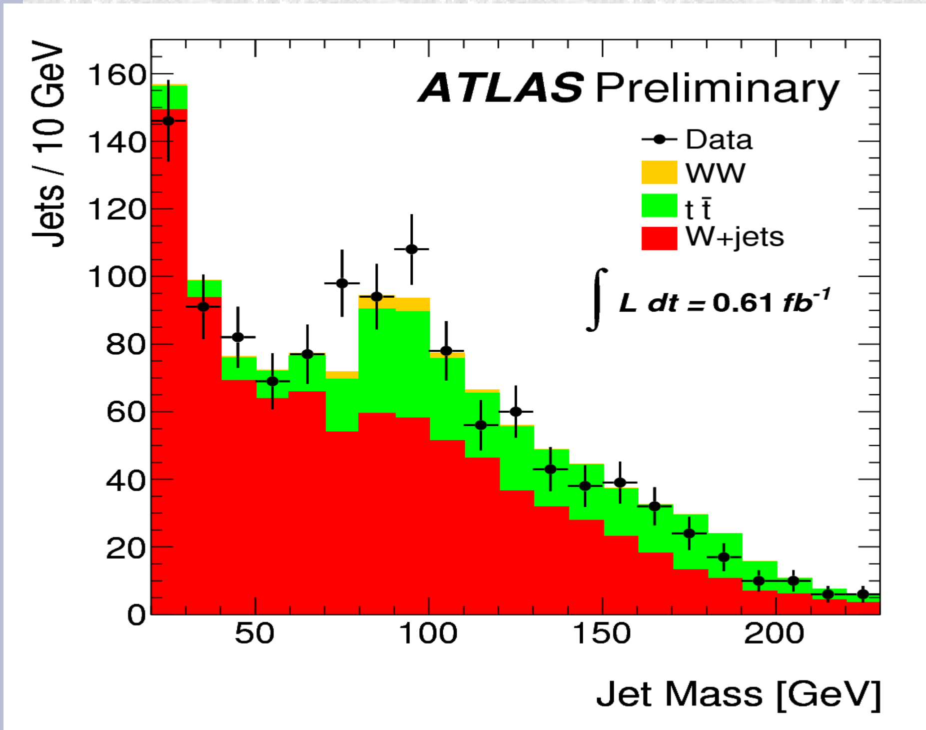


VH, H→bb compared

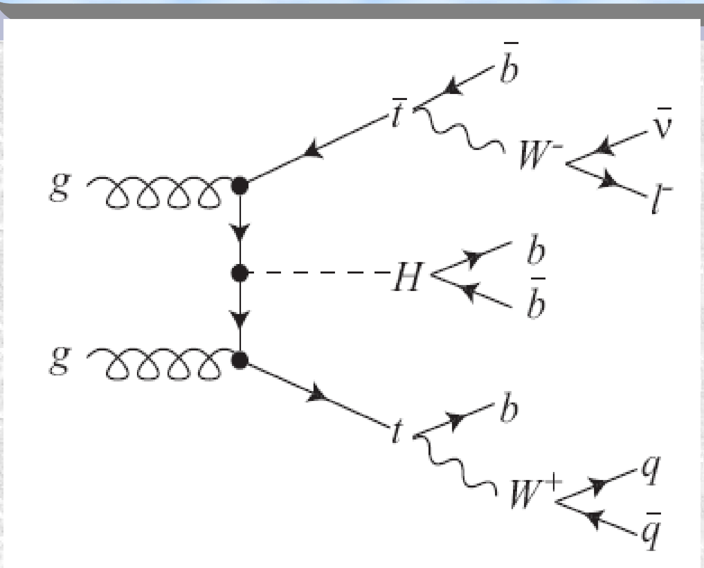
- Boosted analysis 3x more sensitive
- Includes ZH→ννbb channel
  - Only H mode with charged lepton!
  - Needs missing pT trigger
- But boost improves s/b
  - Signal decreased factor 15
    - ATLAS m_H=120 4.5 signal
    - CMS m_H=120 0.3 signal
  - Background a factor 200
    - ATLAS ~500
    - CMS 2.4
  - Better s/b helps with systematic errors
    - These are major in unboosted analysis

Subjet analysis

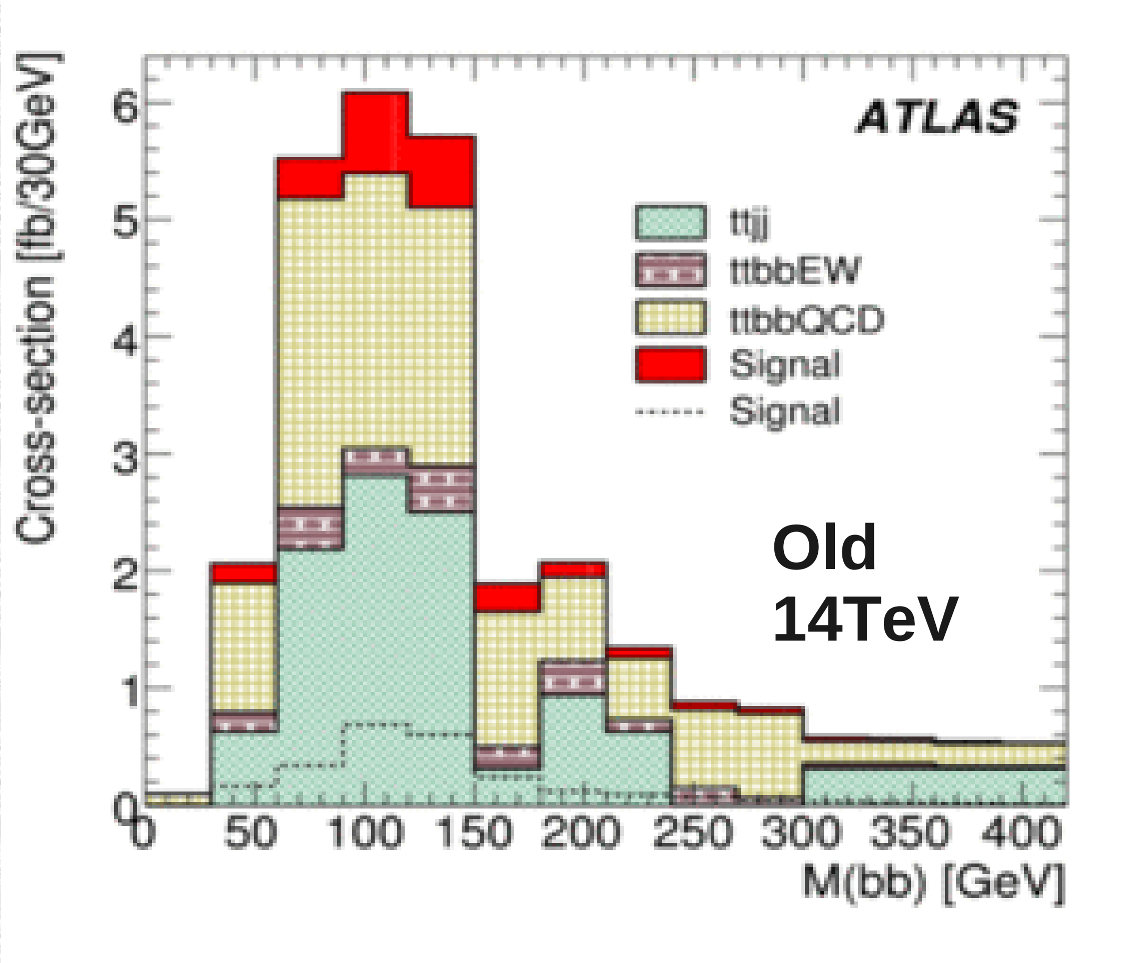
- Subjet analysis should help
  - W+'fatjet' studies suggest W to qq from $t\bar{t} \rightarrow WbWb$ seen
  - Ready to search for H to bb



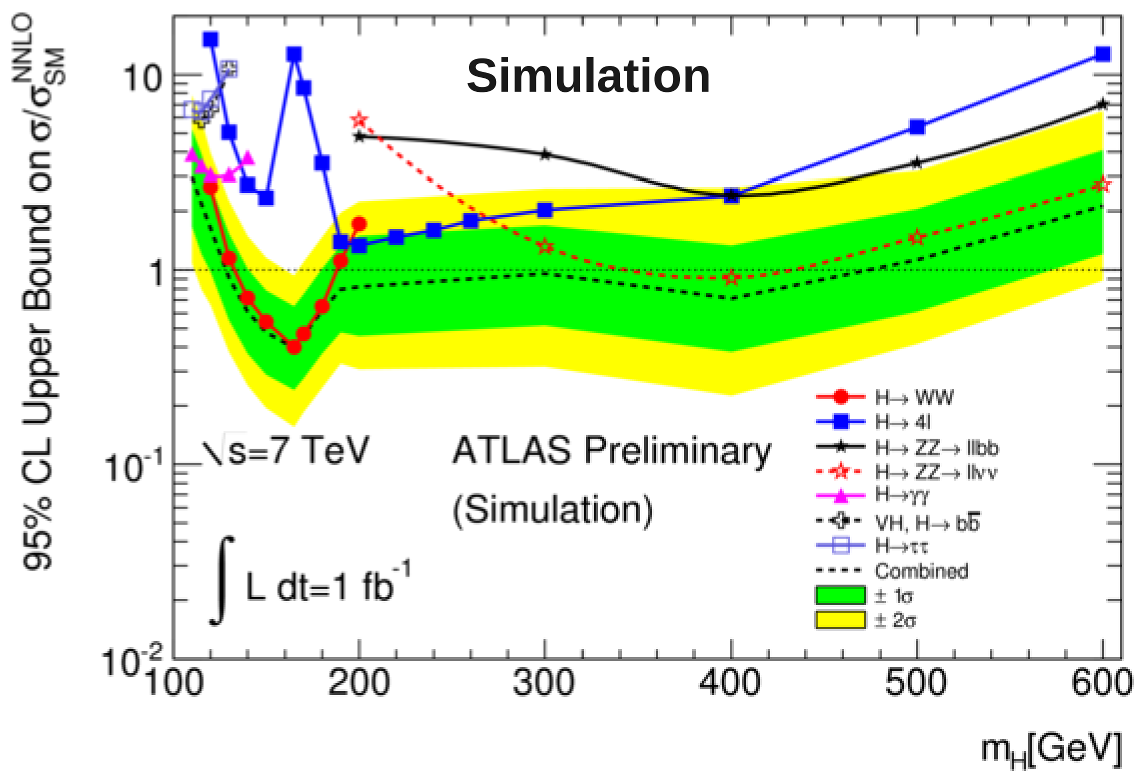
ttH, H to bb

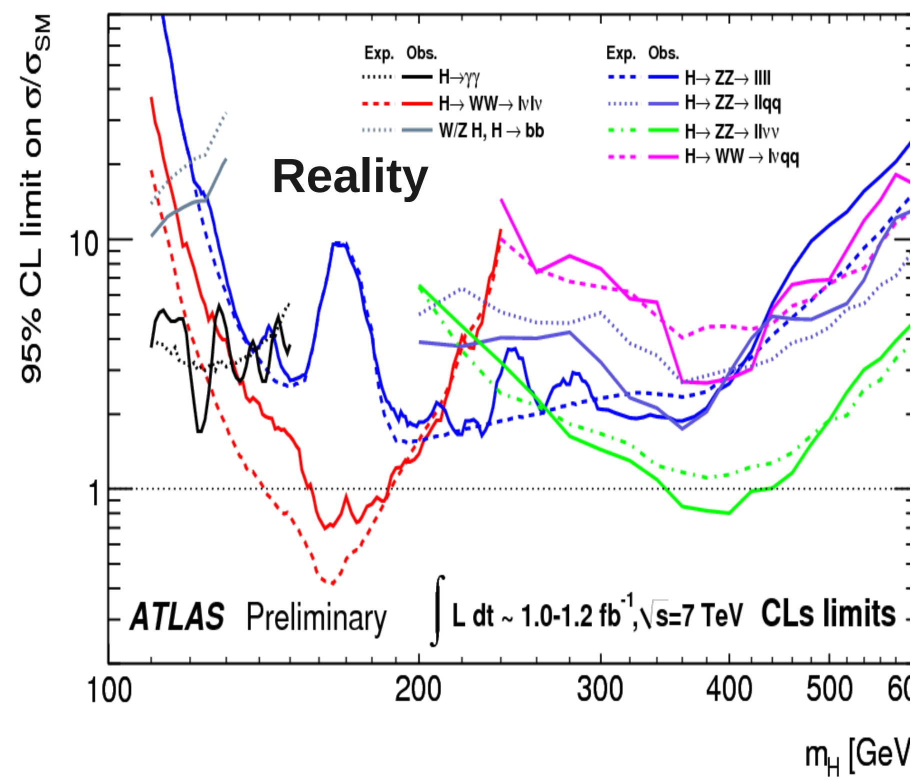


- Gluon radiation complicates 6 jet states!
- s/b poor
- This will need enthusiasm
  - Useful for MSSM



Accuracy of projections

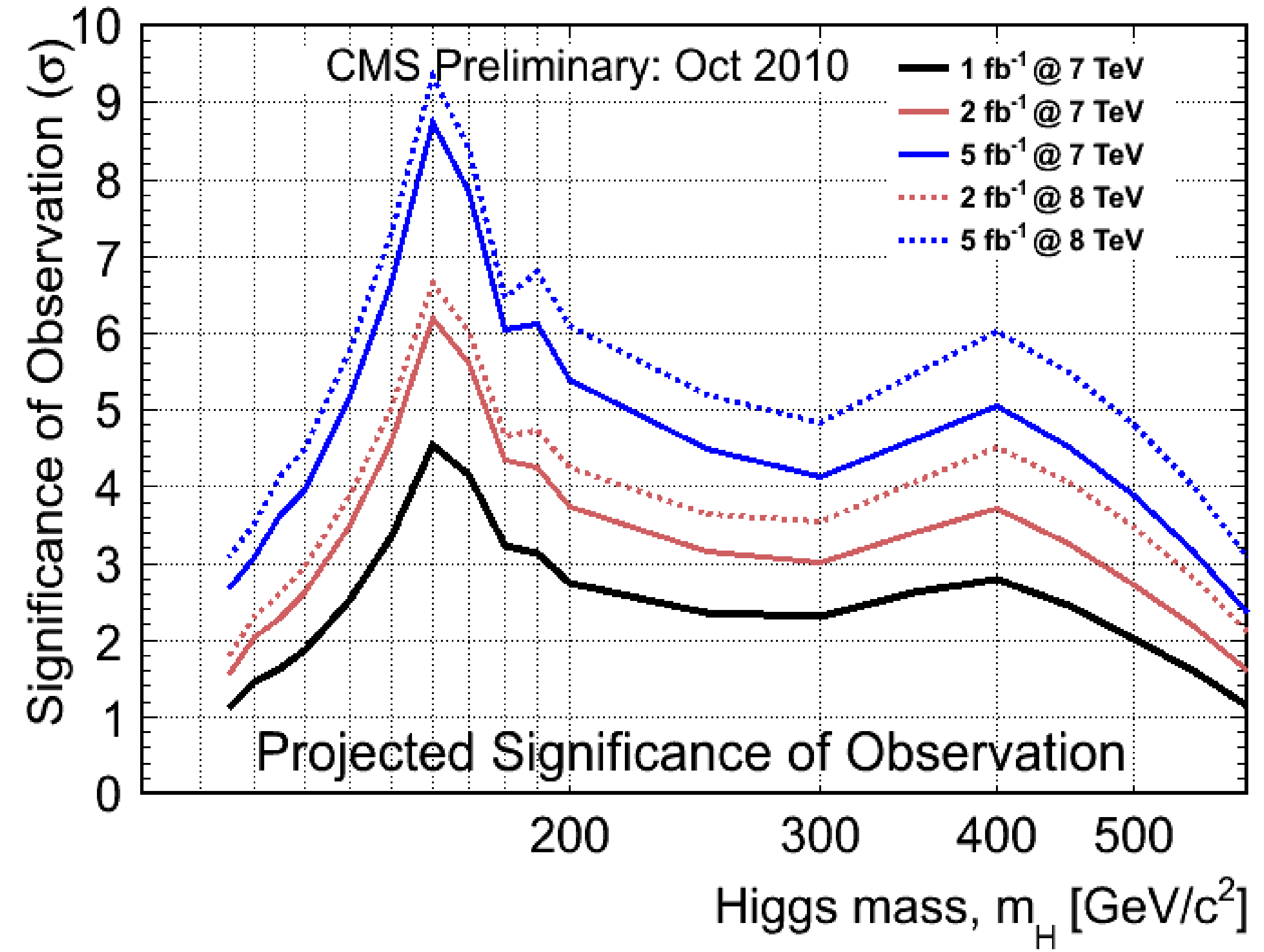




- Predictions very close – maybe 10% optimistic
  - H→bb here used non-boosted analysis
  - No VBF H→ττ from ATLAS yet
- CMS predictions similarly close

Signal significance

- $5fb^{-1}$ gives either experiment large sensitivity
- Projections optimistic at 115
  - Need work on γγ
  - Or bb,ττ



LHC-HCG

- Group set up to combine ATLAS+CMS Higgs
  - Double data set – more science possible
- Combination of EPS (July) data was made
  - But by LP (August) it was unhelpful
  - Individual experiments had big increases in data
  - Results did not confirm excess seen in July
- Machinery is oiled
  - Common (theory) assumptions/systematics
  - Definitions and procedures for interpretation
  - Software (roostats) for handling mathematics &data
- Ready to be used when required

Conclusion

- Tevatron still interesting, especially for m_H~115
  - But would 2σ exclusion of SM satisfy?
- A conclusive discovery requires LHC
- At least 2σ across 115-500 available in 2011
- Where we have got to I address tomorrow