Higgs Searches

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- **Luminosity**
- **LEP/TeVatron results**
- **$H \rightarrow ZZ \rightarrow llll$**

Caveats

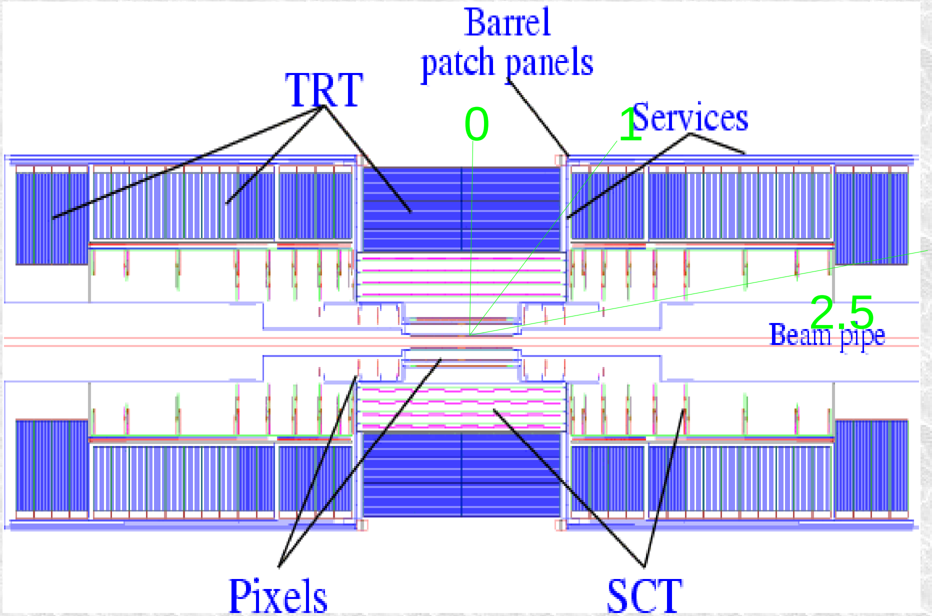
- For LHC I will often only show ATLAS
  - CMS is broadly similar
  - But I know ATLAS better
- Don't trust the numbers!
  - What is important is that you understand the principle rather than getting the right answer
  - If you want to check Higgs discovery, look at the papers

Who am I?

- I work at Rutherford Appleton Laboratory
  - Permanent since 1993
  - A post I got saying I wanted to look for the Higgs
- I worked on the LEP Higgs search
  - I am still DELPHI Higgs convenor!
- I have spent some time looking at a muon collider as a Higgs factory
- I was Higgs convenor of ATLAS up to end 2011

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. $y = \eta$
- Jet finding/isolation is done using dR distances:

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

- This has drawbacks for massive objects
  - $\Delta y = \Delta\eta$ breaks down
  - Physical size of jets shrinks as η grows
- There is no perfect solution
  - So continuous development

Some Colliders

	LEP	LC	TeVatron	LHC	
Collisions	e^+e^-	e^+e^-	$p\bar{p}$	pp	
Years	1989-2000	2020??	1987-2011	2010-2012	2015-2022
Max E, GeV	208	?1000?	2000	7000/8000	13000/14000
Integrated lumi.	$0.5fb^{-1}$	Large	$10fb^{-1}$	$30fb^{-1}$	$300fb^{-1}$
Higgs (125GeV)	1	100K+	10000	300000	10M
Higgs reach	0-115	0-800+	Hard	100-1000	100-1000

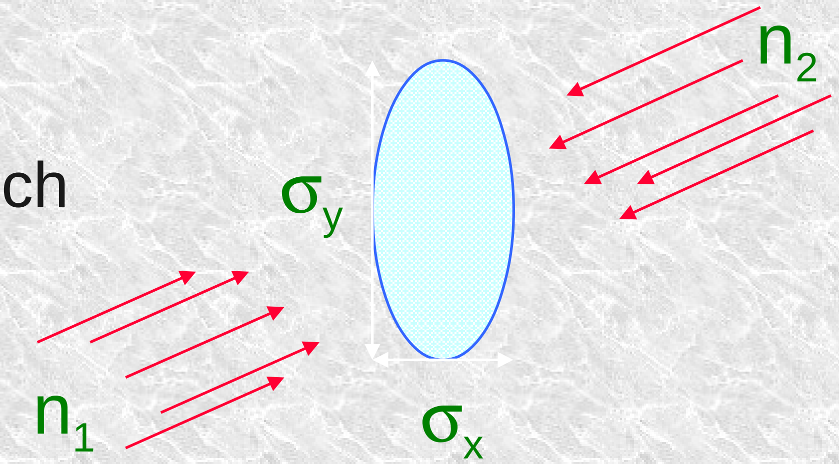
Luminosity

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

- For a circular machine

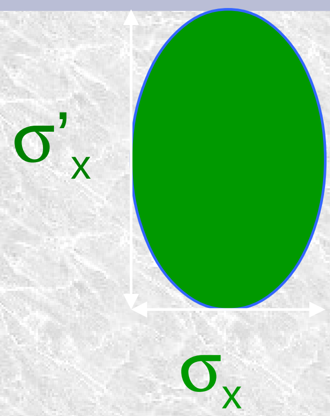
$$l = f\,\frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

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



Emittance

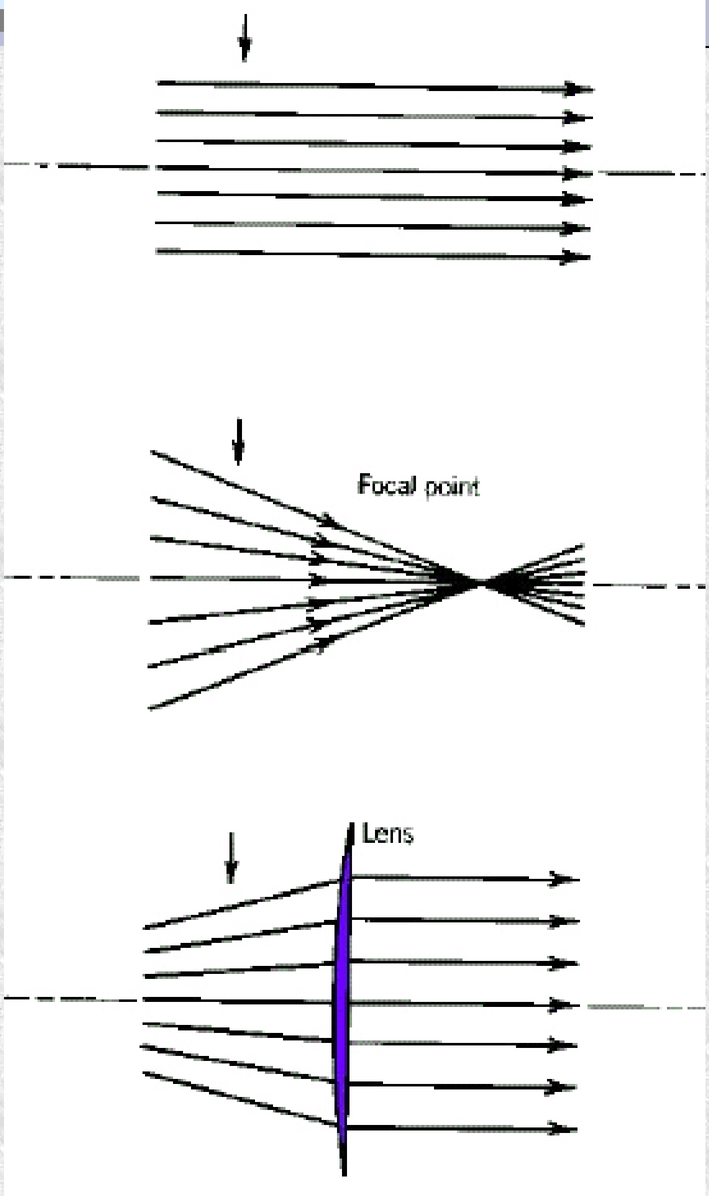
- Envelope of beam particles
  - units m x Rad
- $\varepsilon_x = \pi\sigma_x\sigma'_x$:
  - Assumes uncorrelated
- Higher dimensional emittance
  - The 6-dimensional particle correlation x,y,z,x', y', z'
  - ε a conserved quantity (Liouville's theorem):
    - Reduce one σ, other grows
  - ε_T is almost 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.



1/ε = brightness

Emittance examples

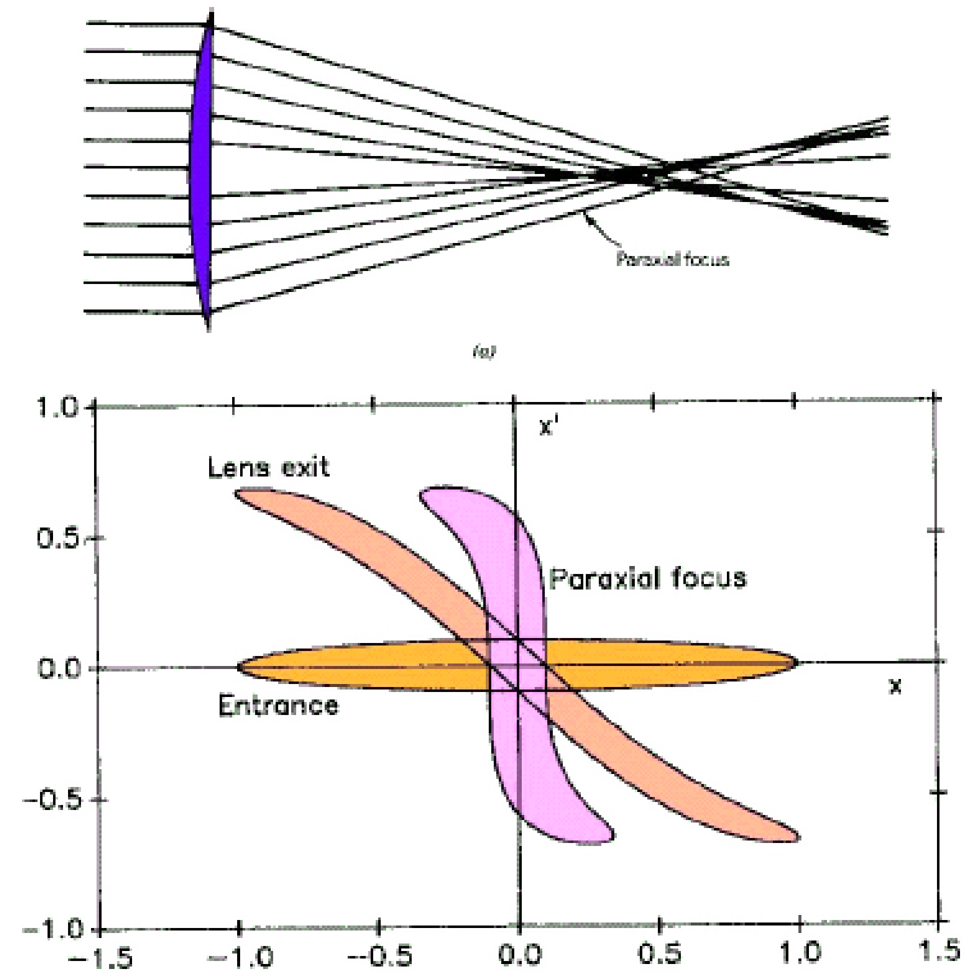
- All these have zero emittance



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 increase LHC emittance during fill
    - Actually LHC has some KeV synchrotron radiation
- For linear accelerators preparation and beam blowup contribute.

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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 beam-beam interaction destructive

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 will swamp detectors

Luminosity - practical example

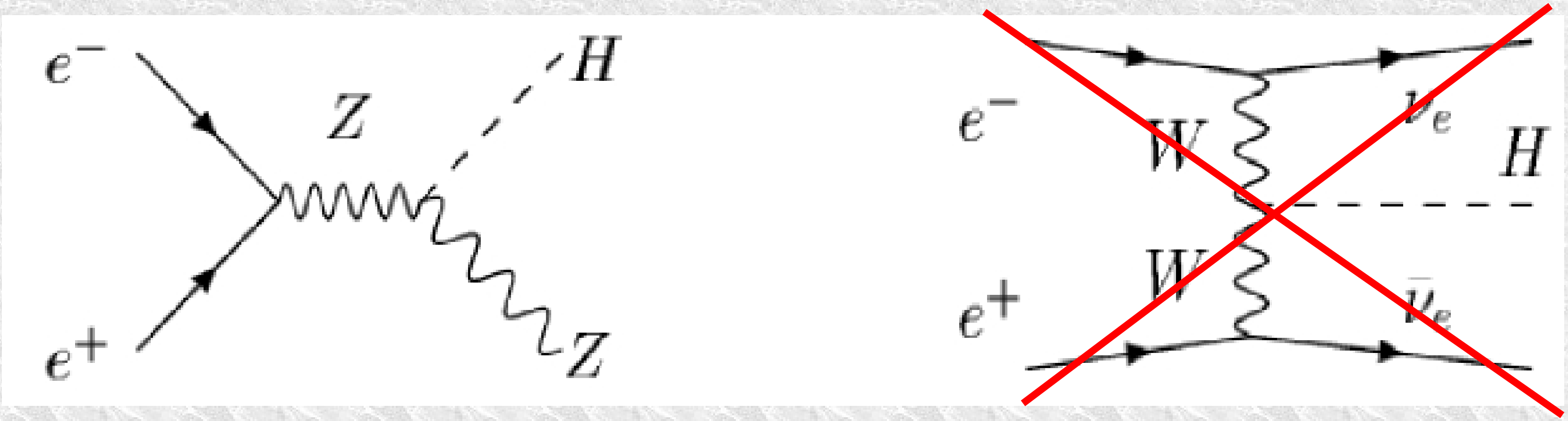
- Sample LHC 2011 parameters:
  - 1.35×10^{11}p/bunch
  - 2×10^{-6} normalised transverse emittance
  - 1320 colliding bunches, 27km circumference
  - β* 1.5m
- Peak Instantaneous luminosity 2.4 10^{33}cm^{-2}s^{-1}
  - Use 10^{7} seconds in a year (4 months working)
  - 2.4 10^{40}cm^{2}/year
  - 1b = 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

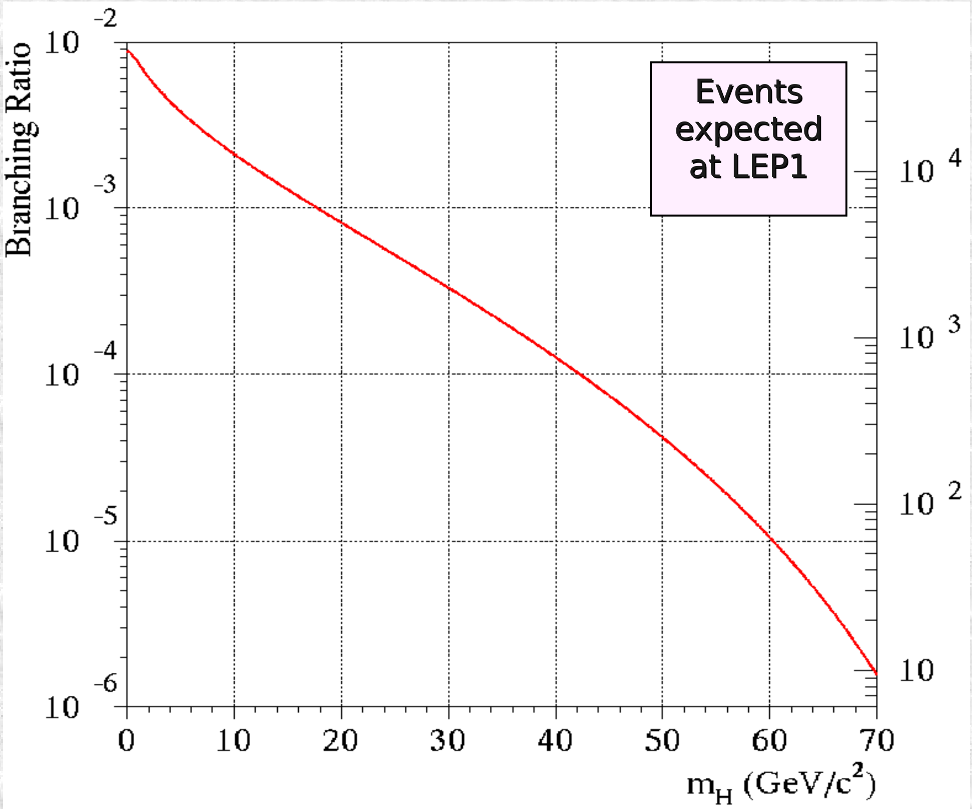
Search at LEP I - E_{CMS}=91GeV

- 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

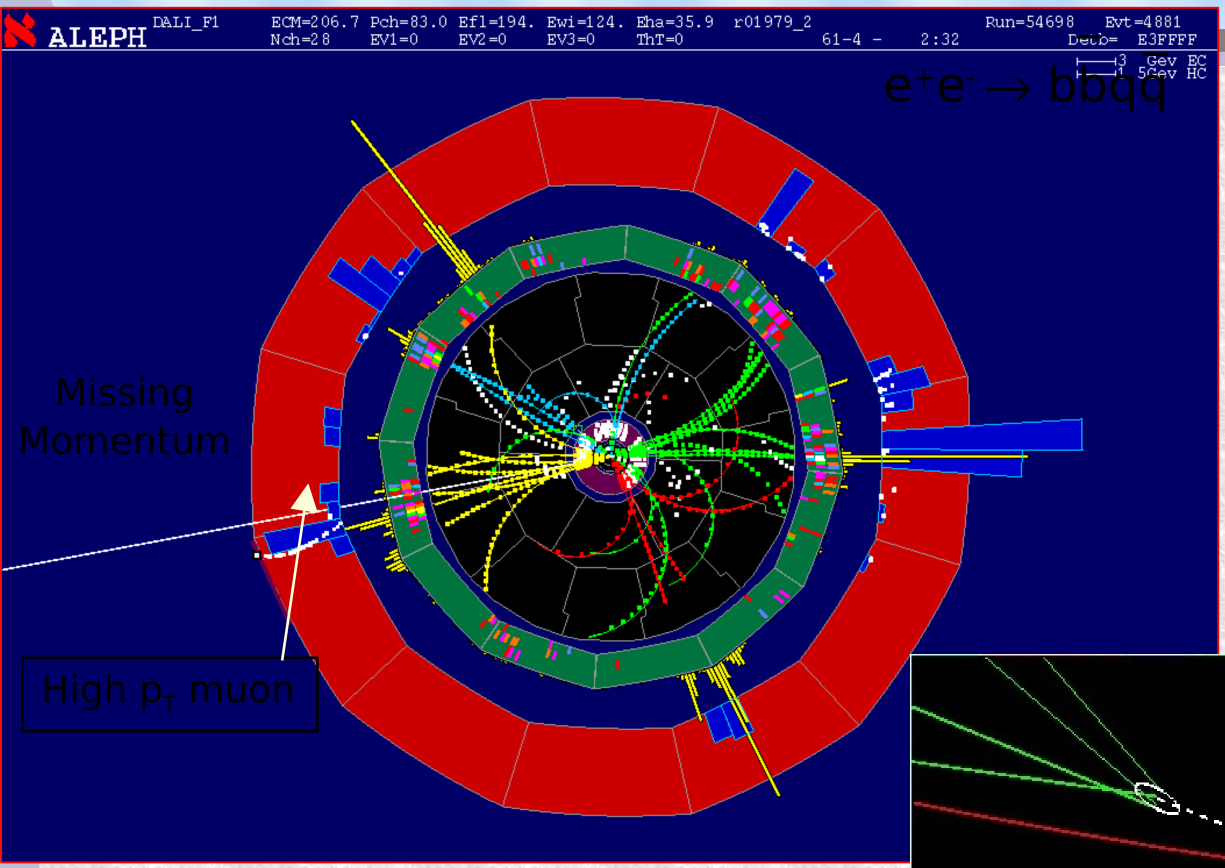
- Energy raised in steps from m_Z to 208 GeV
- Around $0.5 fb^{-1}$ of data
- Sensitive to $Z^* \rightarrow ZH$
- Therefore approximate reach:

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

- Or $115 GeV/c^2$ at 208.

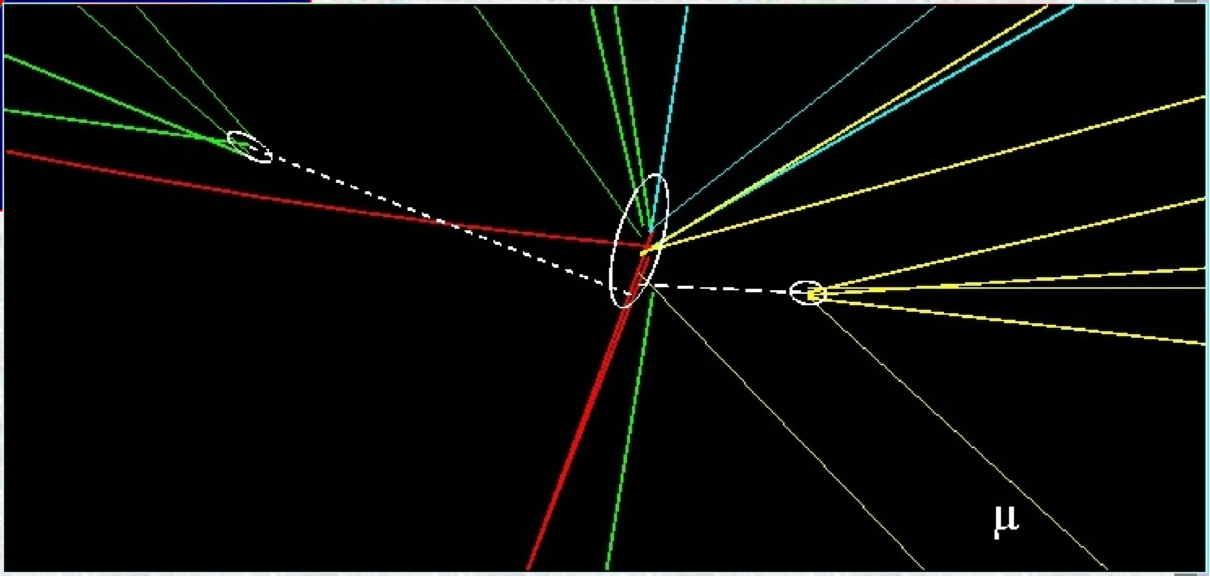
- In final year energy was raised to 206 then 208.

The best candidate, ALEPH



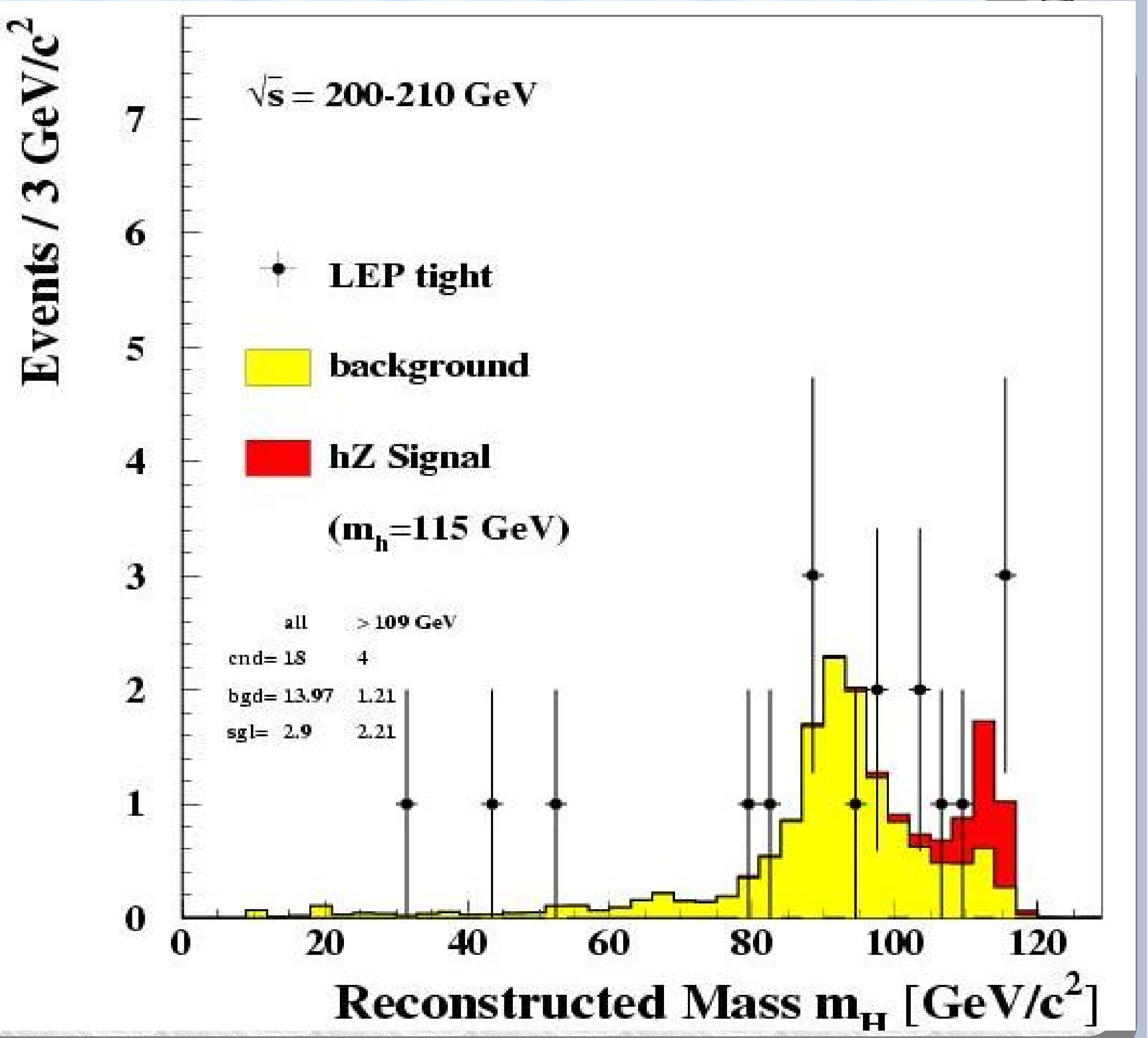
(14-Jun-2000, 206.7 GeV)

B jets well tagged plus muon



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

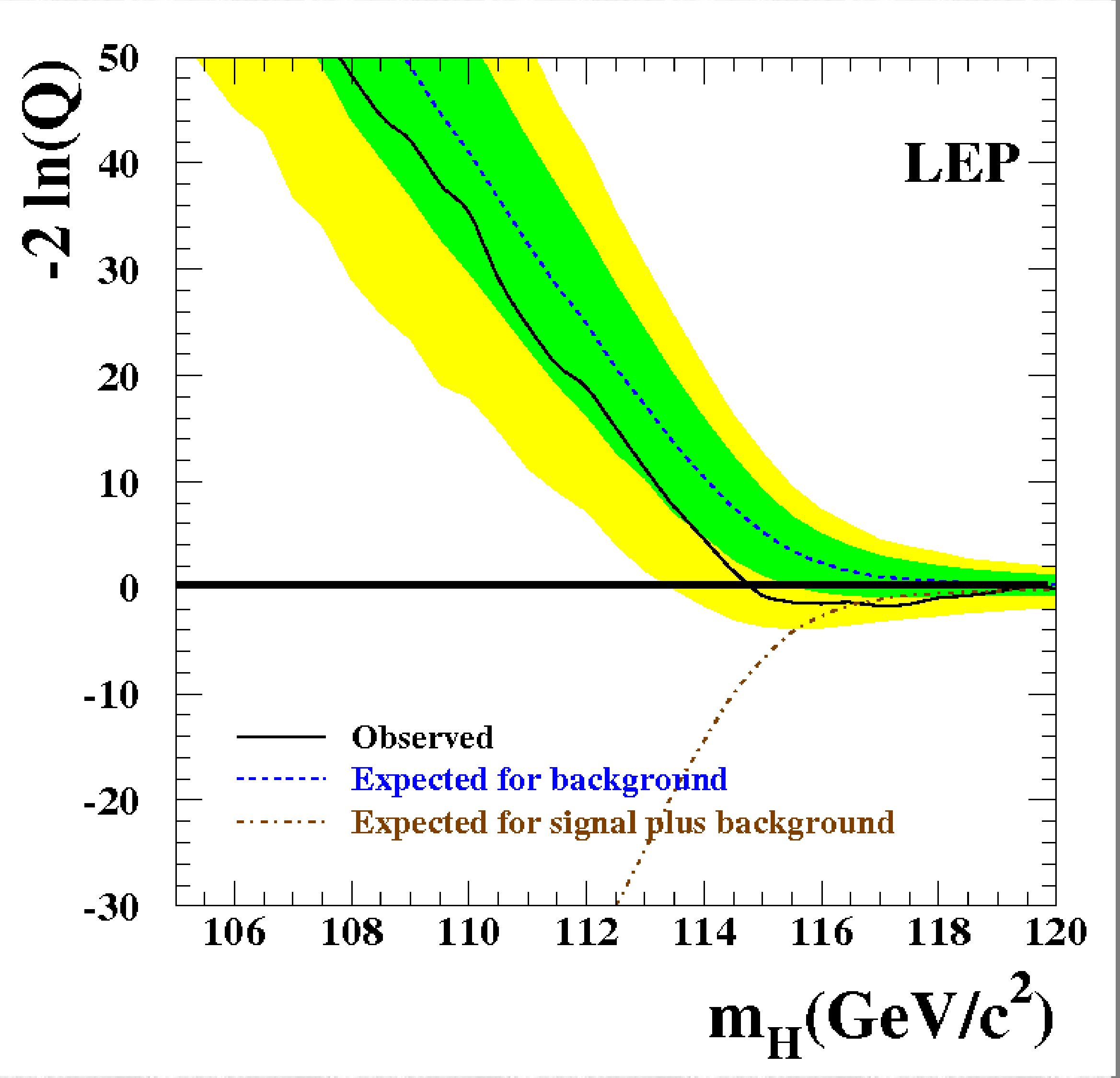
Higgs then: LEP SM Higgs

- Final LEP result:

M_H>114.4GeV

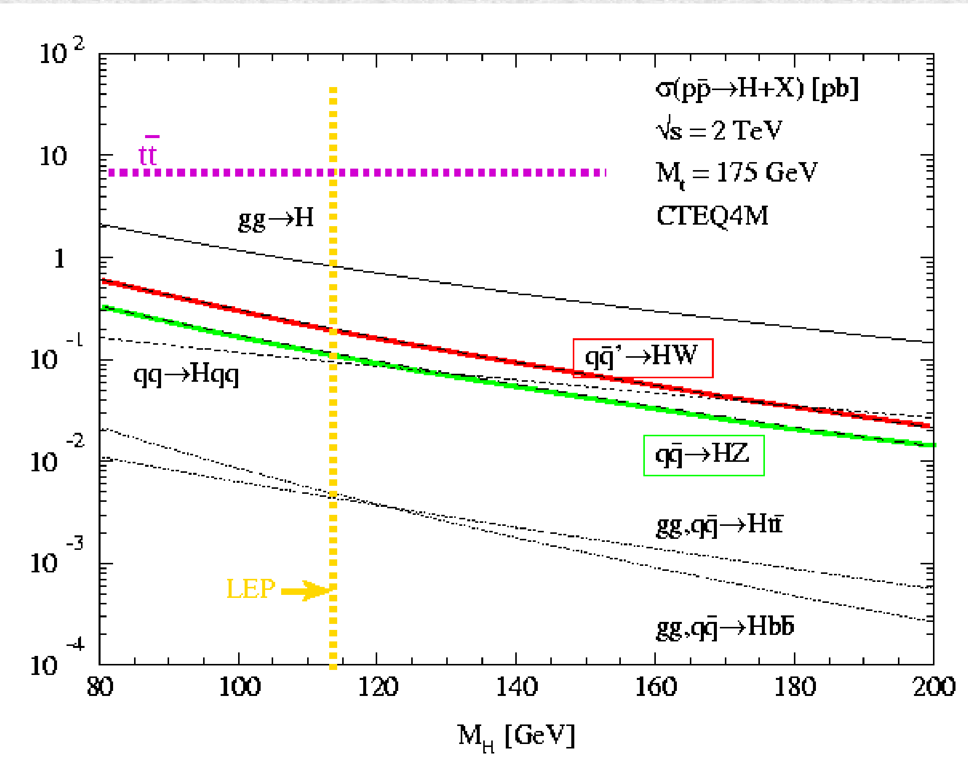
(95%CL)

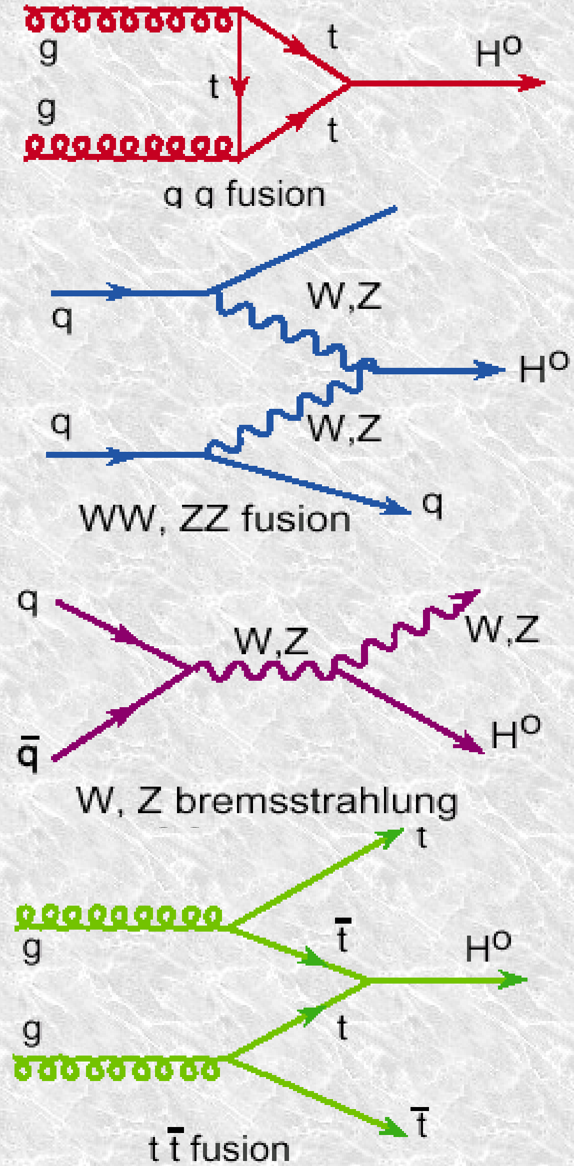
Excess at 115GeV would happen in 9% cases without signal



TeVatron results

TeVatron Higgs production





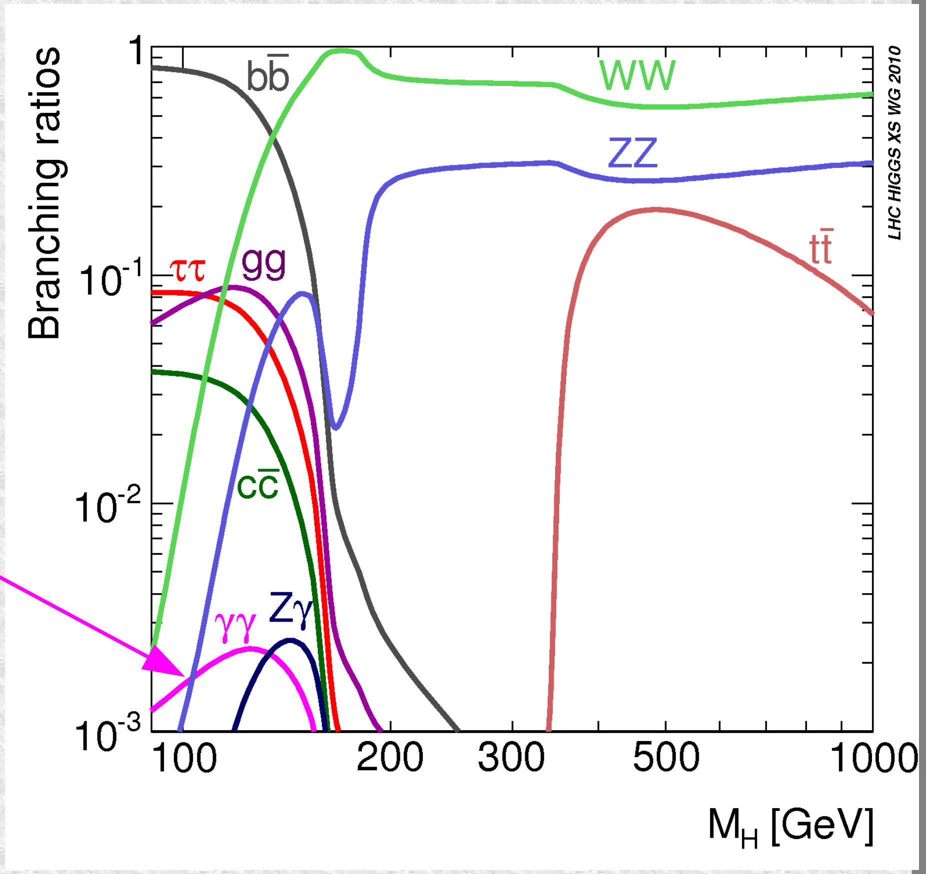
- Cross-sections of order pb
- 10fb^{-1} data gives thousands
- But the background are large

The Higgs problem

- Rates are low
  - So luminosities must be large
- One event in 10^{10} is signal
  - 10,000 events is tiny

Tevatron analyses Channels

- H → WW
  - WW → lνlν: Most sensitive
- H → bb
  - WH, ZH, ttH useful but hard
- H → γγ
  - Rare, helps for low mass
- H → ττ
  - Hard, low mass,rare
- H → ZZ
  - ZZ → llll: Cleanest mode but low rate



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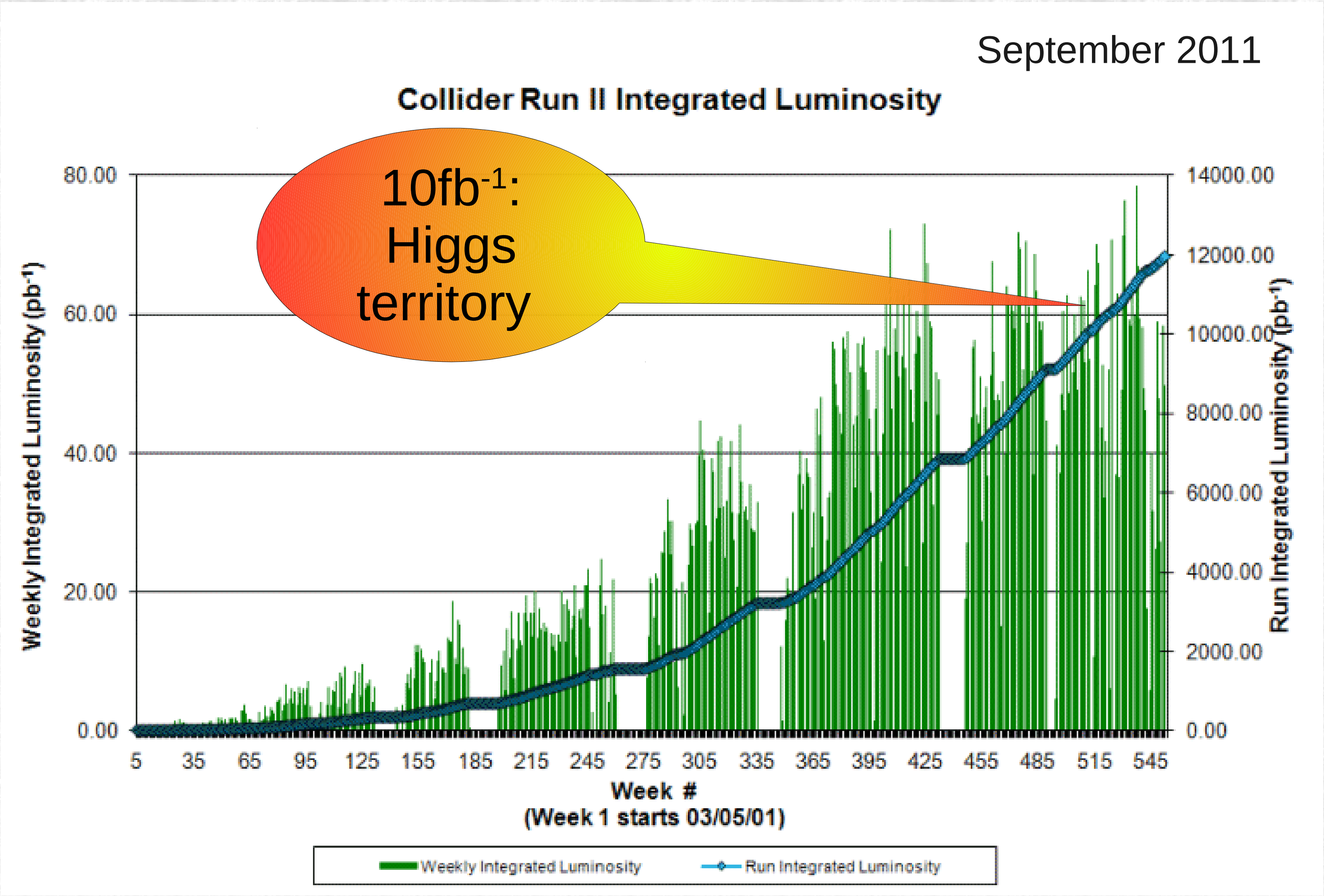
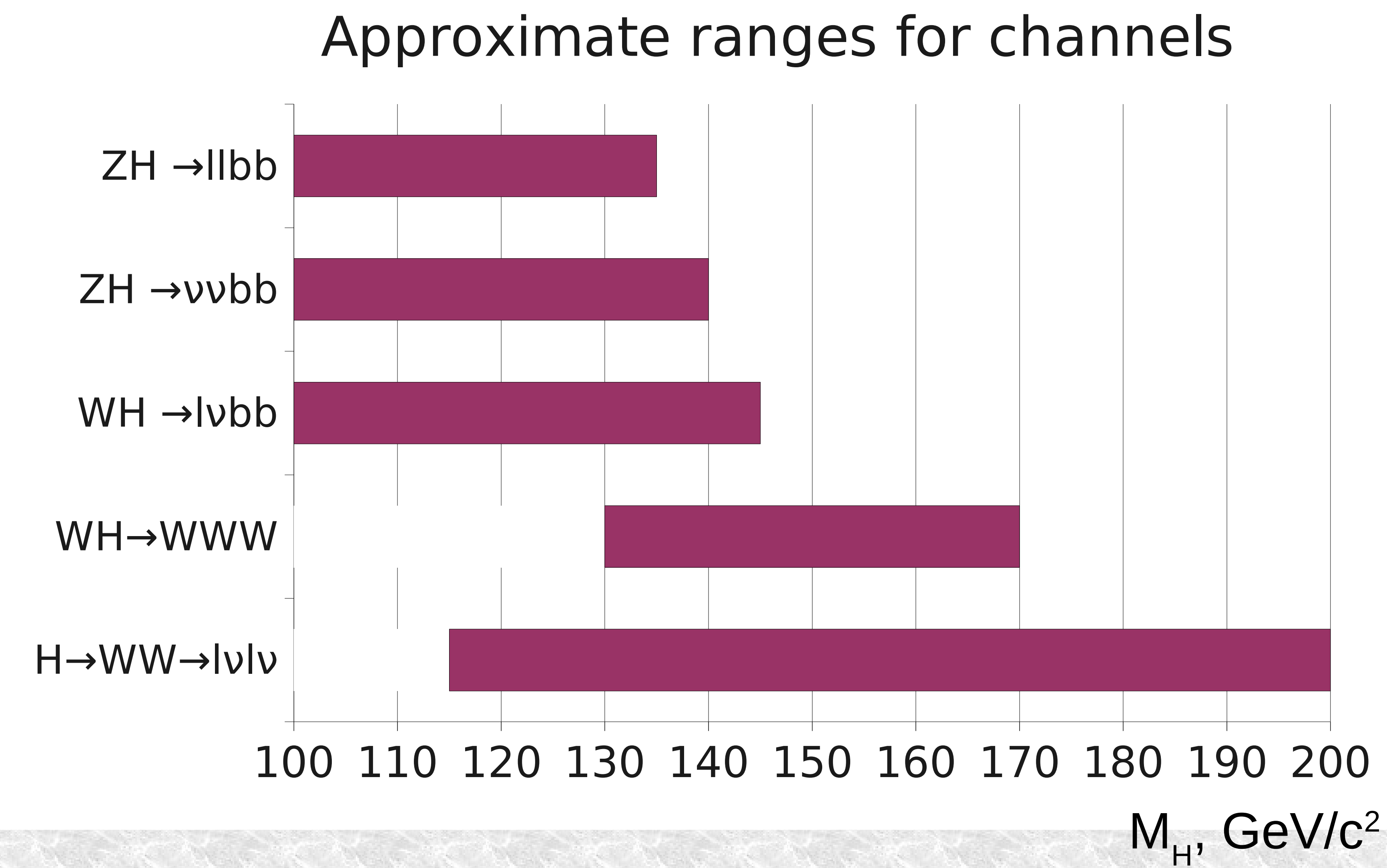
Tevatron dataset, $12fb^{-1}$

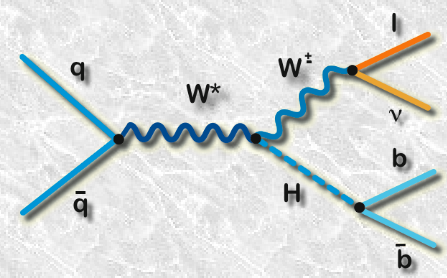


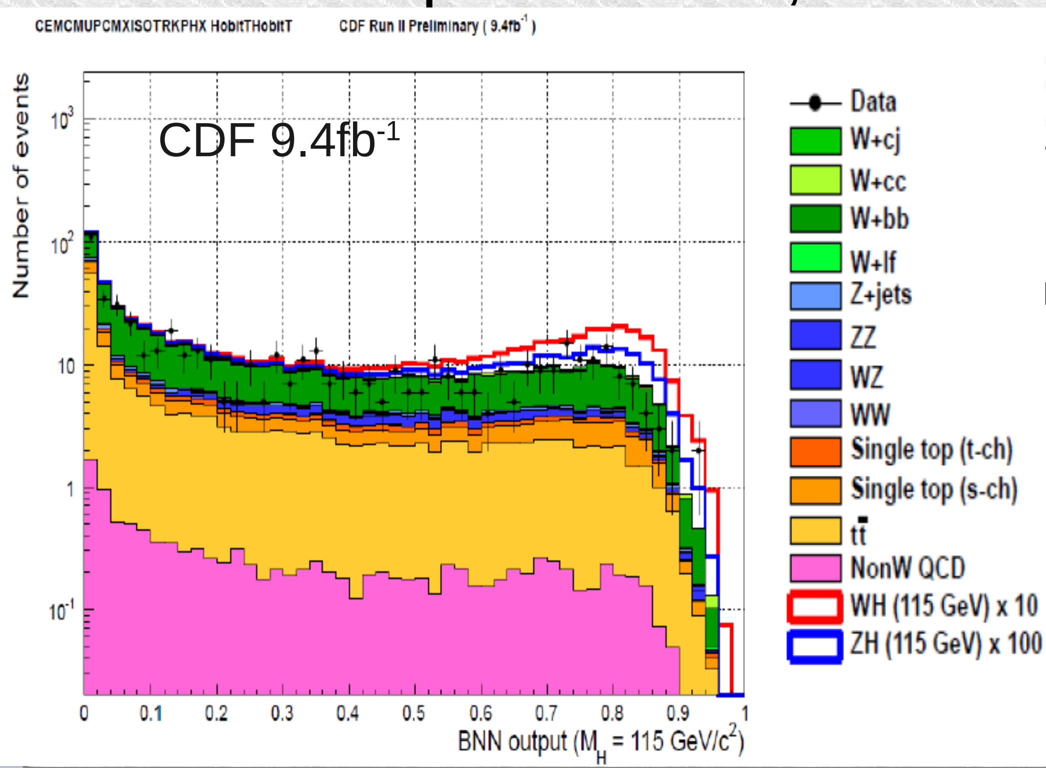
Tevatron Major channels

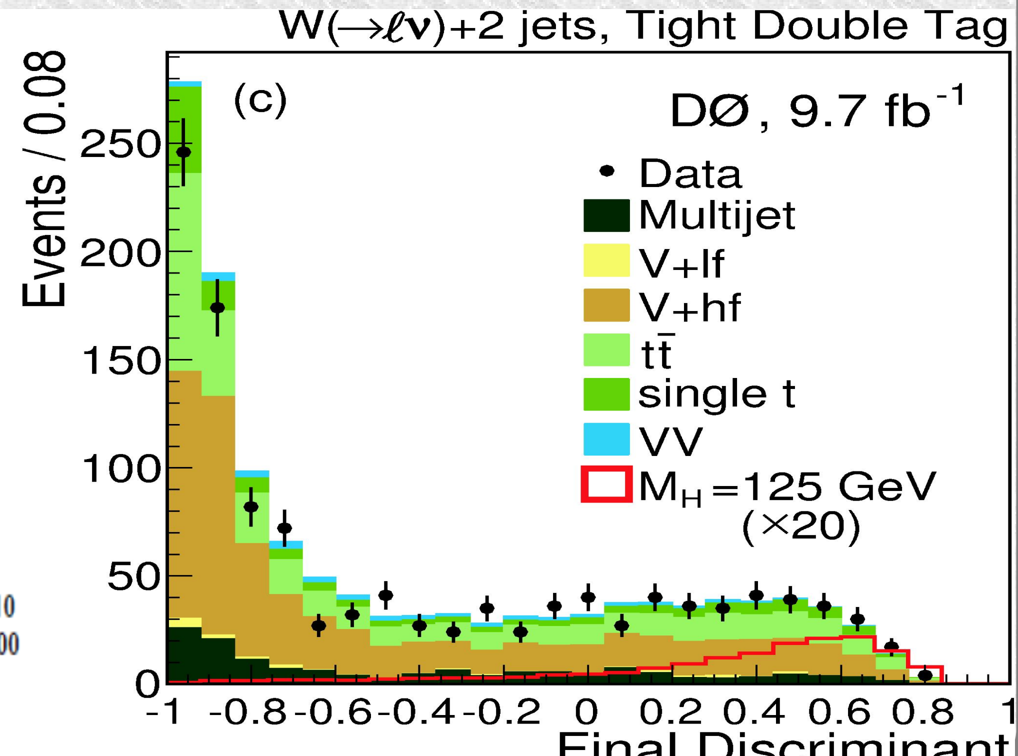


SM Higgs: WH→lνbb

- Signature: high p_T lepton, MET and b jets
  - Backgrounds: W+bb, W+qq, top/$t\bar{t}$, Non W(QCD)
  - Key issue: estimating W+bb background
    - Shape from MC, normalization from data

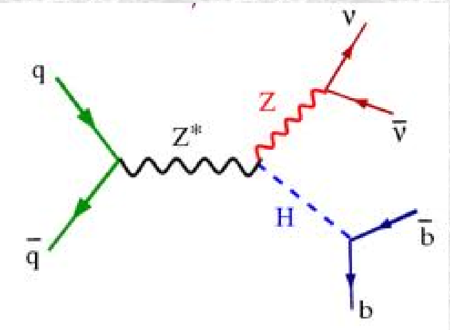


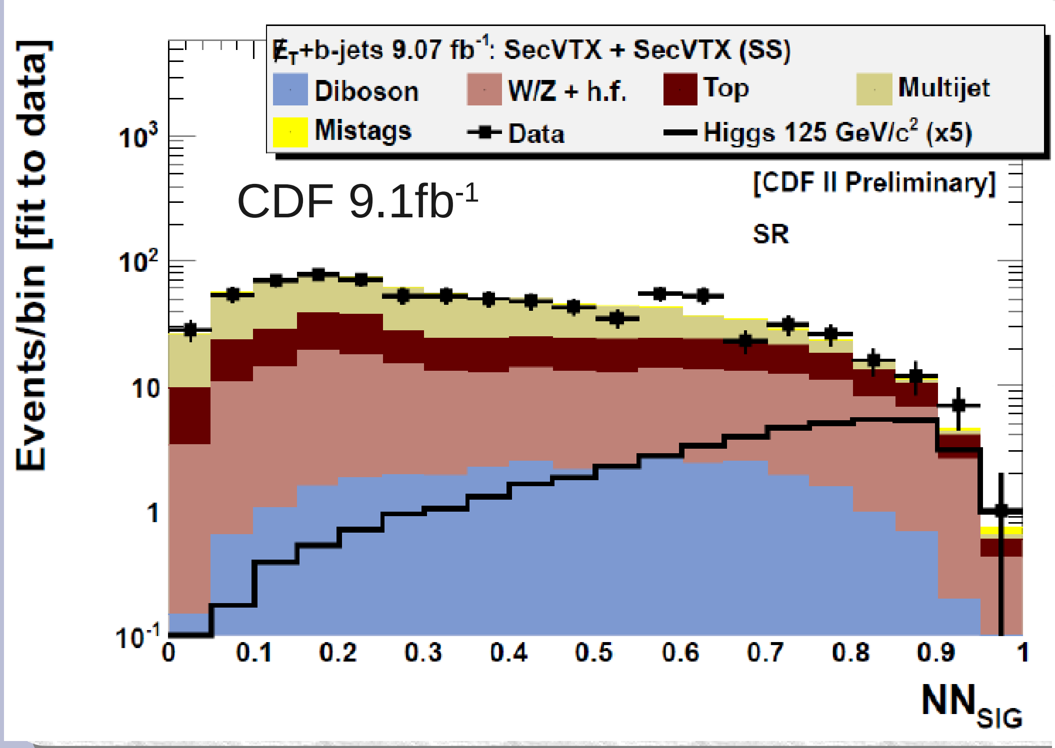


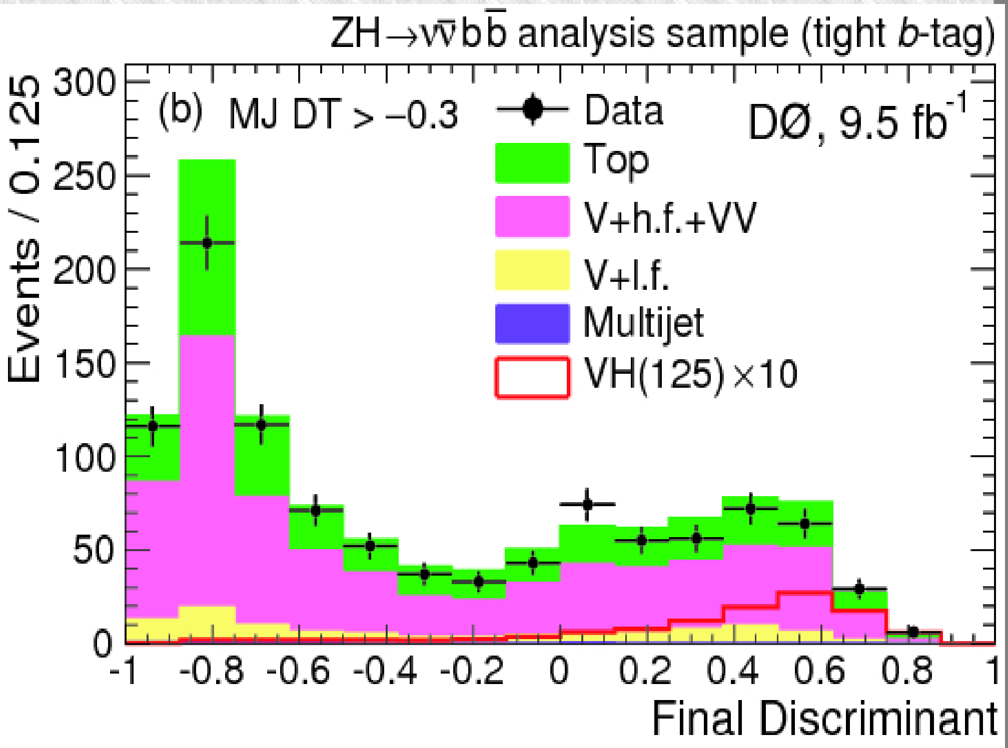


SM Higgs: ZH/WH→MET+bb

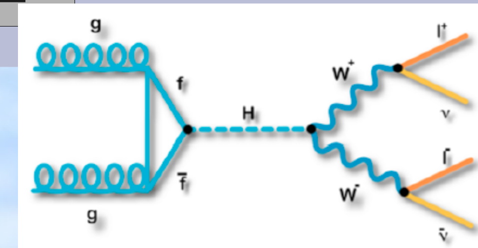
- Signature: MET and b jets
  - Backgrounds: Z+bb, Z+qq, top, QCD
  - Key issues: estimating W+bb background
    - Shape from MC, normalization from data



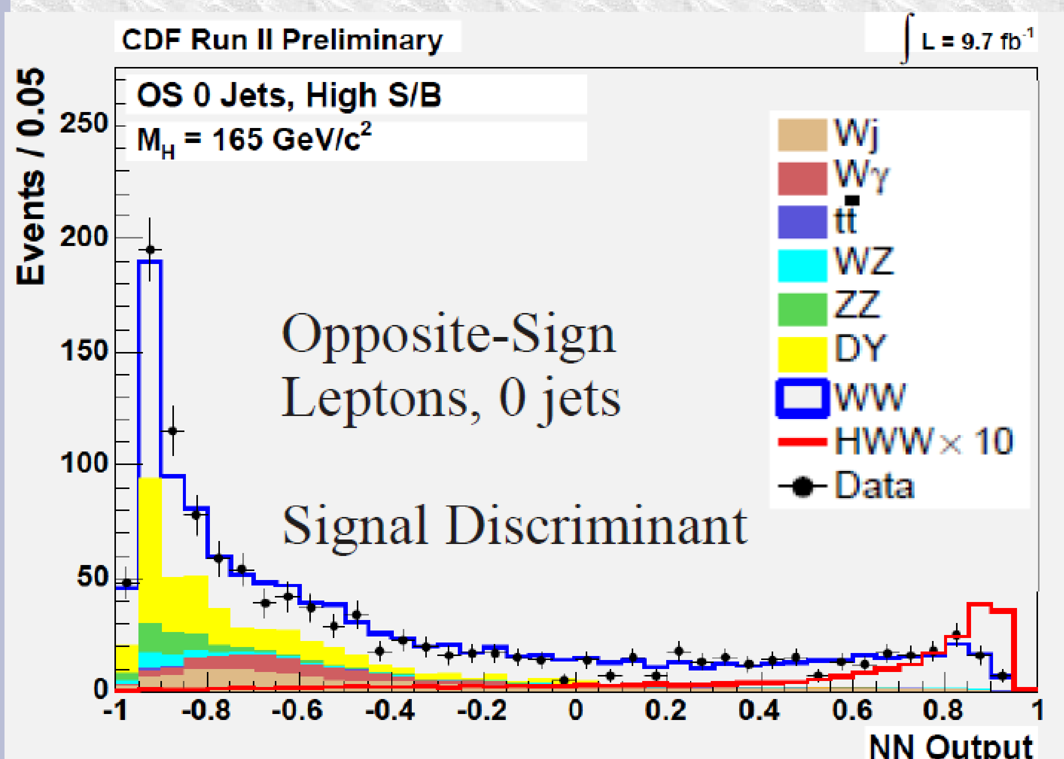


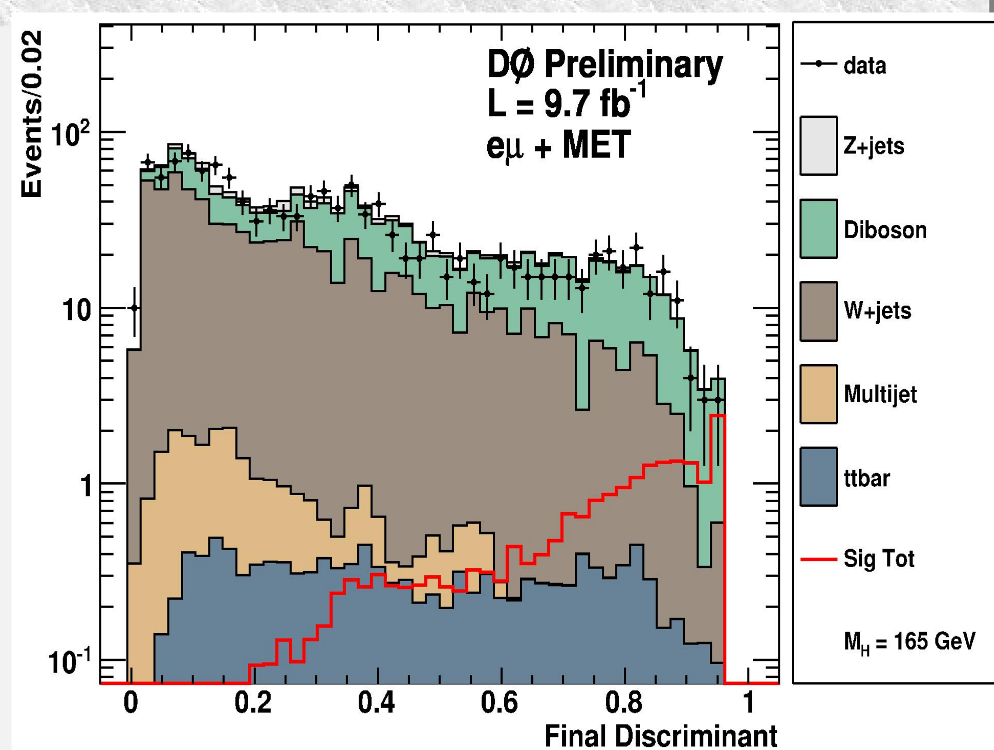


SM Higgs: H→WW

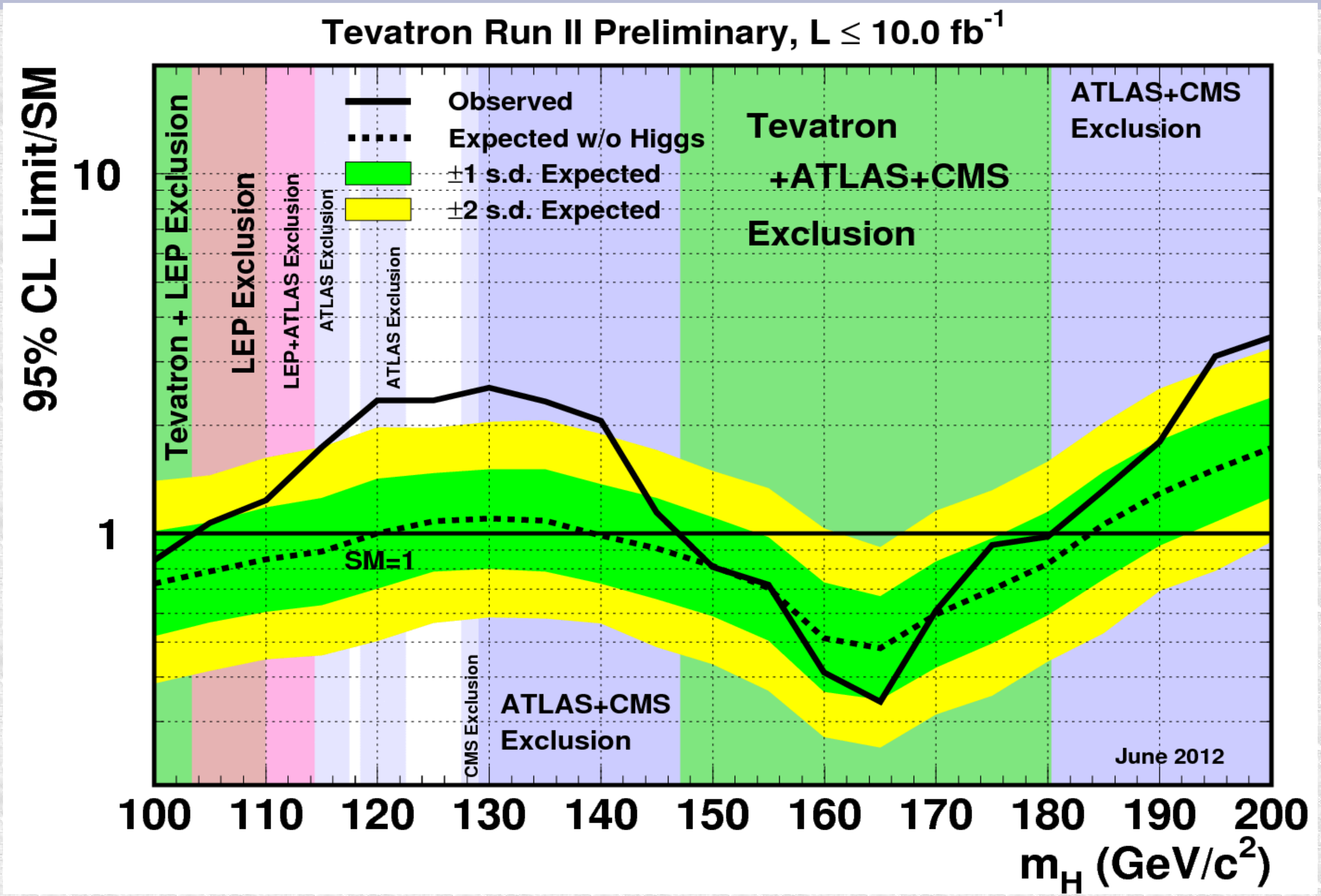


- H→WW→lνlν - signature: Two high p_T leptons and MET
  - Primary backgrounds: WW and top in di-lepton decay
  - CDF and D0 both using NN on many kinematic quantities
  - Many independent channels (n_{jets}, lepton quality)

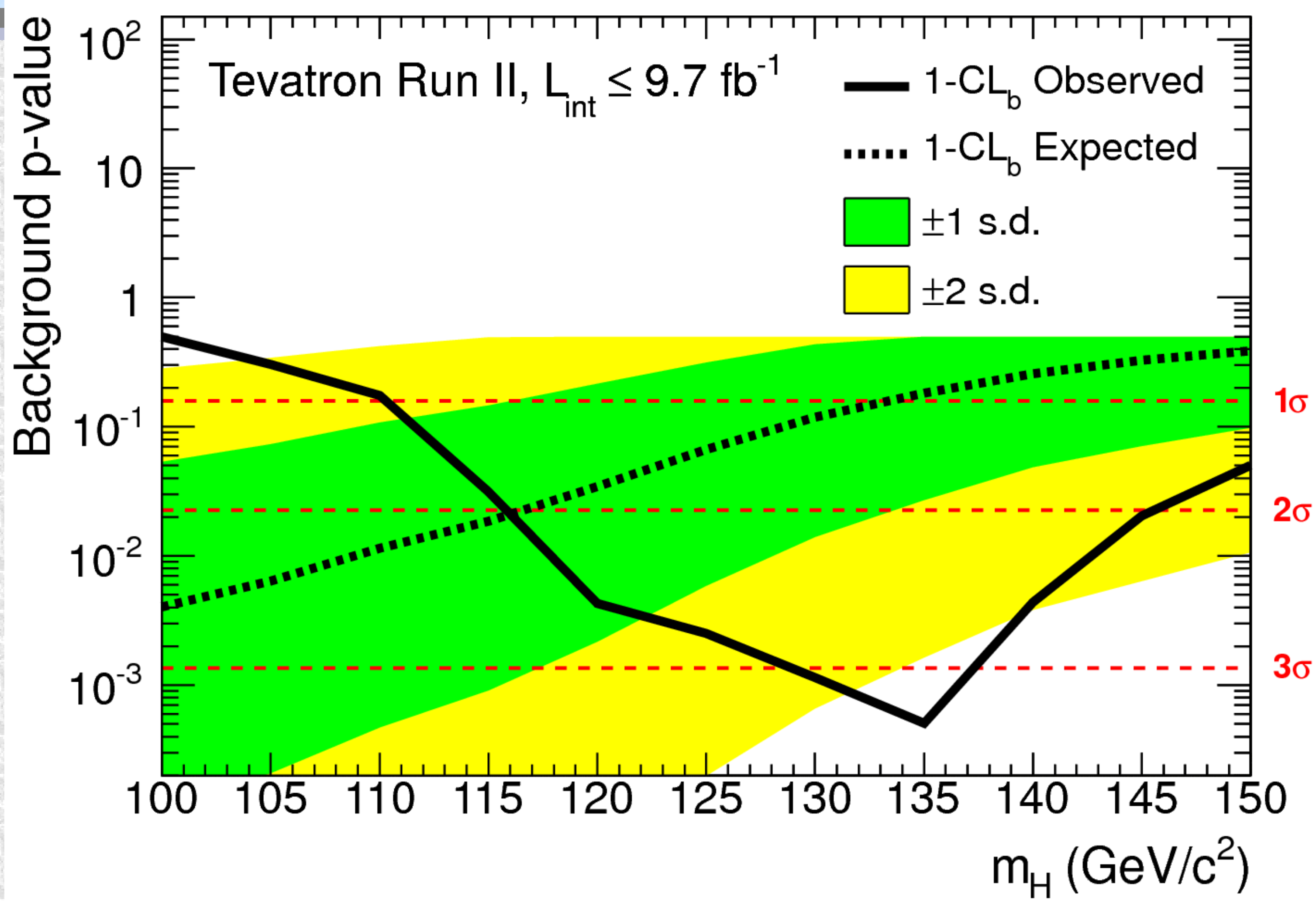




Tevatron Higgs Combination



Tevatron 'Evidence for'



- Observe >3.3σ for $m_{H\sim}$135GeV with 10fb^{-1}
- 3.1σ global significance

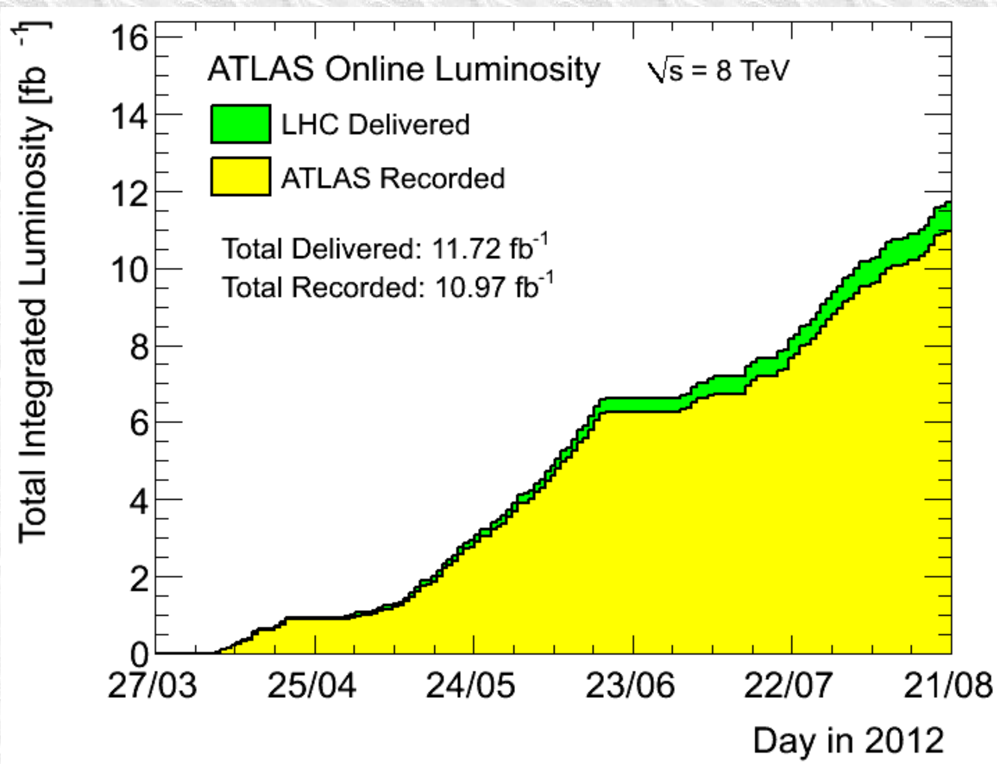
LHC results

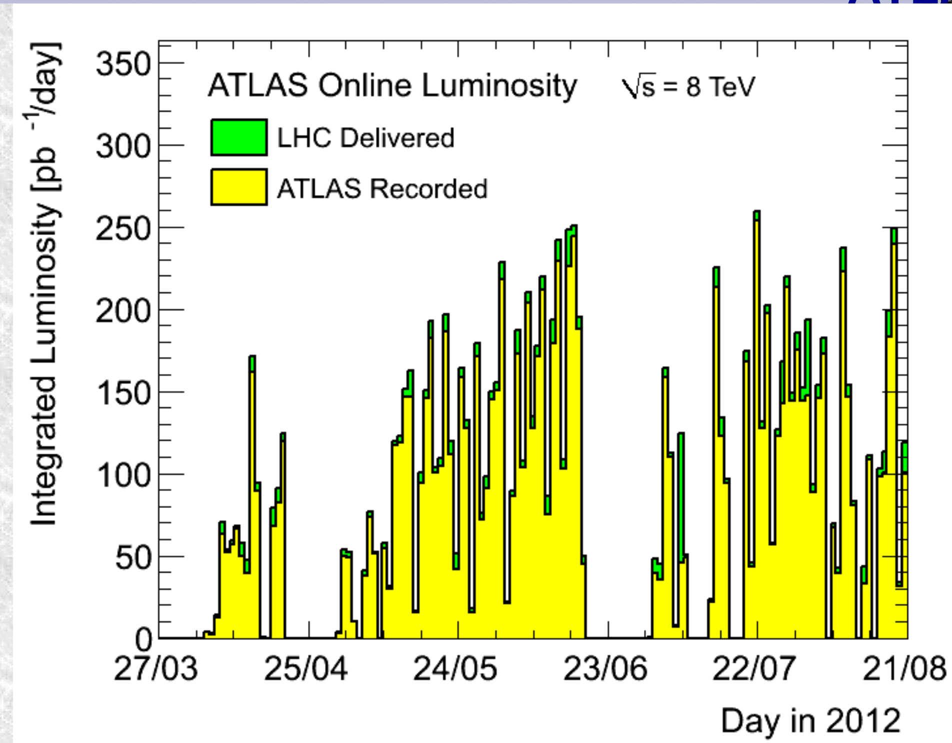
The LHC situation

- The 7/8TeV pp energy raises the Higgs cross section
  - Factor 10 c/f 2TeV Tevatron
- Designed for 10^{34} luminosity
  - 7 10^{33} achieved
  - c/f 4 10^{32} at Tevatron
- Decades of preparation continue
  - 0.05fb^{-1} delivered 2010
  - 5fb^{-1} in 2011
  - 12fb^{1} in 2012 so far

Data taking in 2012

- Peak Luminosity almost stable
- Improvements slow now



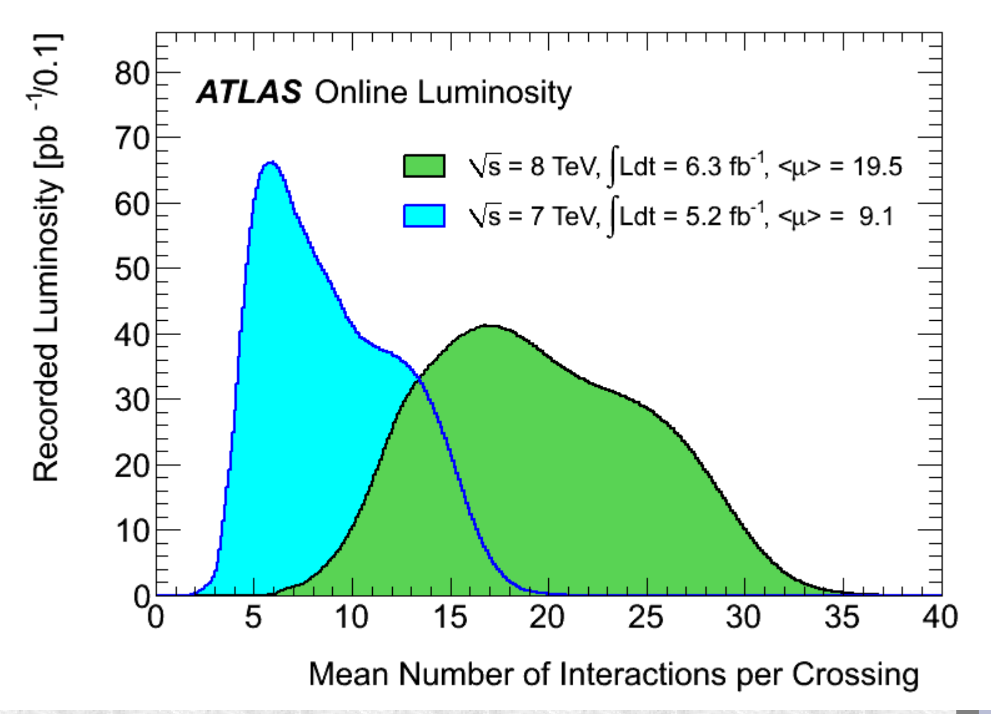


- Recording efficiency 93%
  - Less than 10% bad data by subdetector

Pileup

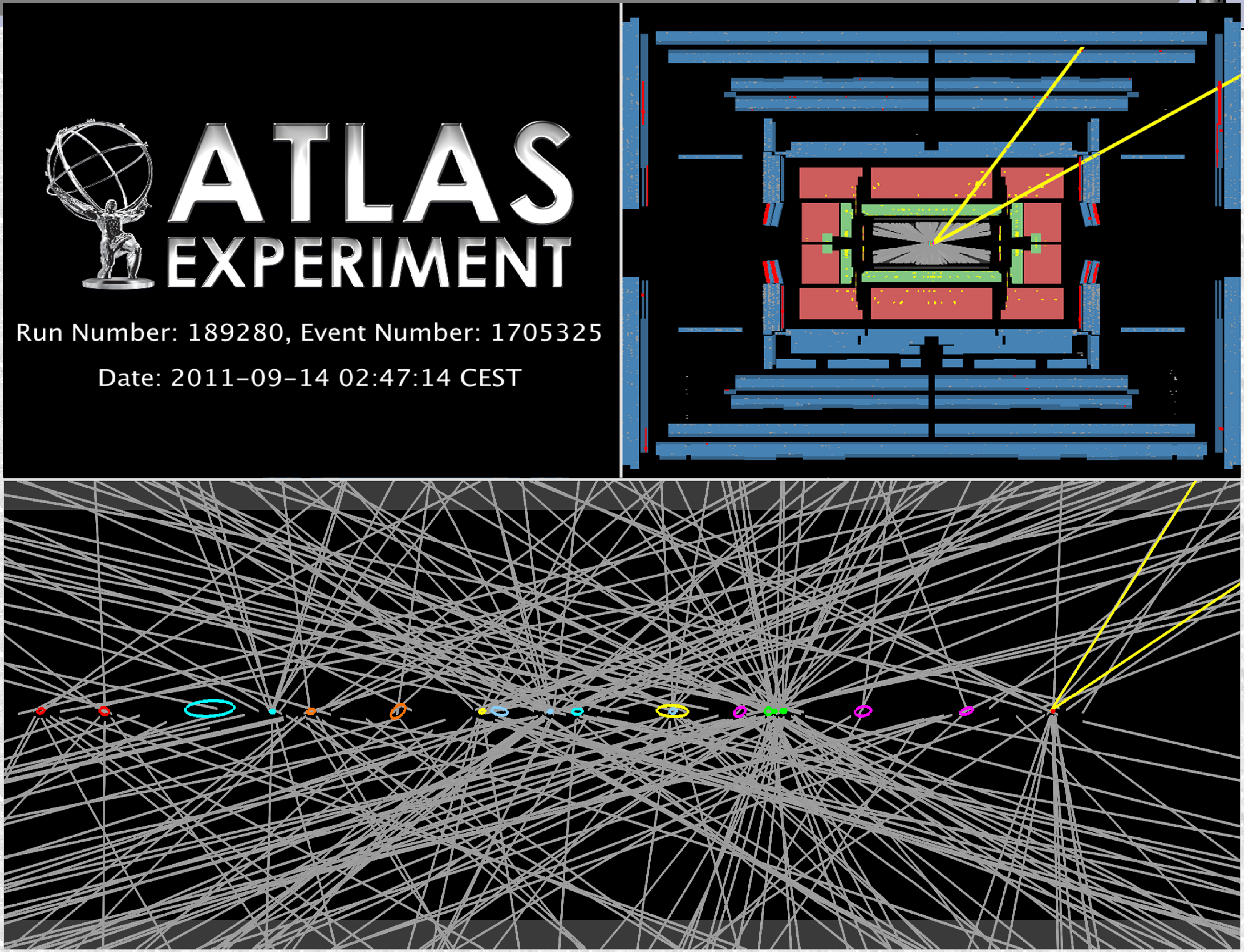
- Serious at LHC
  - Fairly stable so far
  - But double 2011
- 20 interactions per event
- 50ns bunch trains
  - So pileup also from previous *and subsequent* interactions
  - Affects calorimeters more than trackers
- Simulation difficult as rates must be measured
  - Need to reweight spectra

Peak rate



Z to μμ – plus pileup

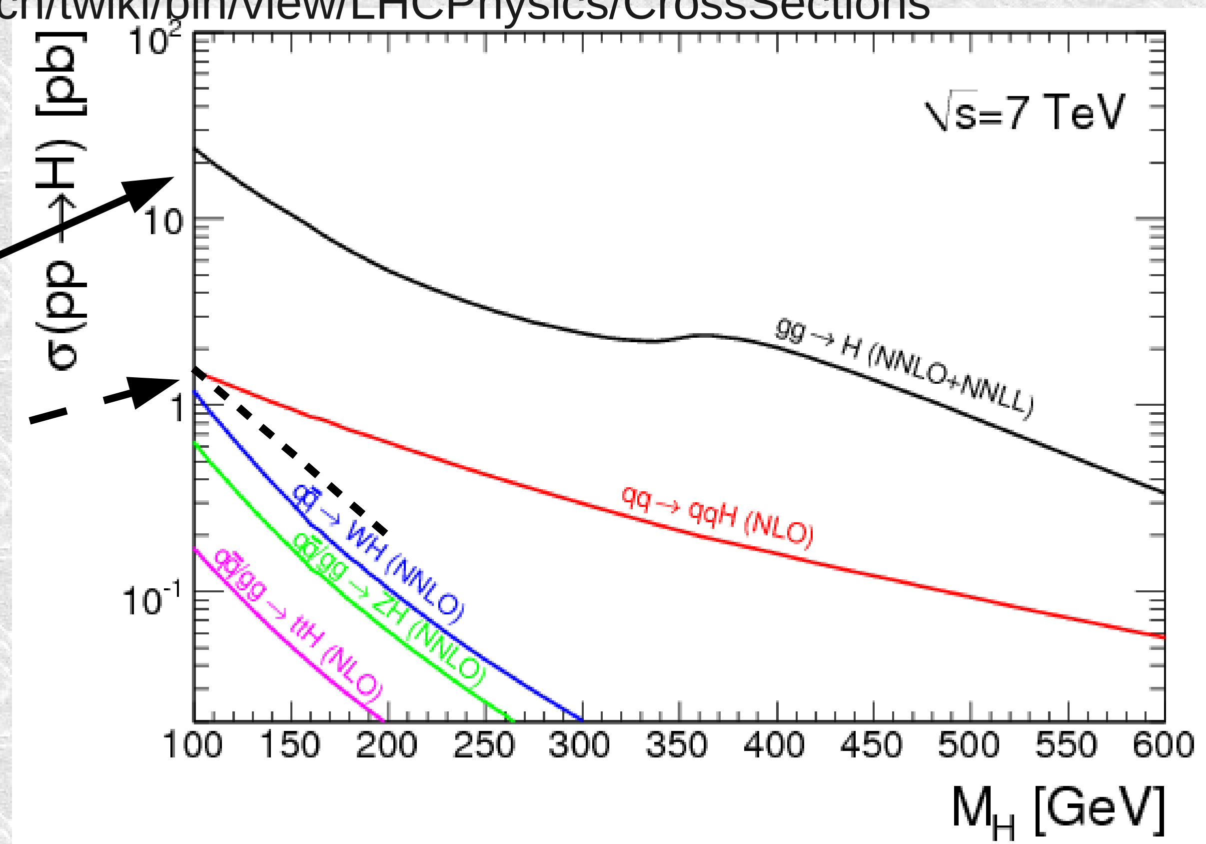
This 2011 event is pretty typical for 2012



Higgs production

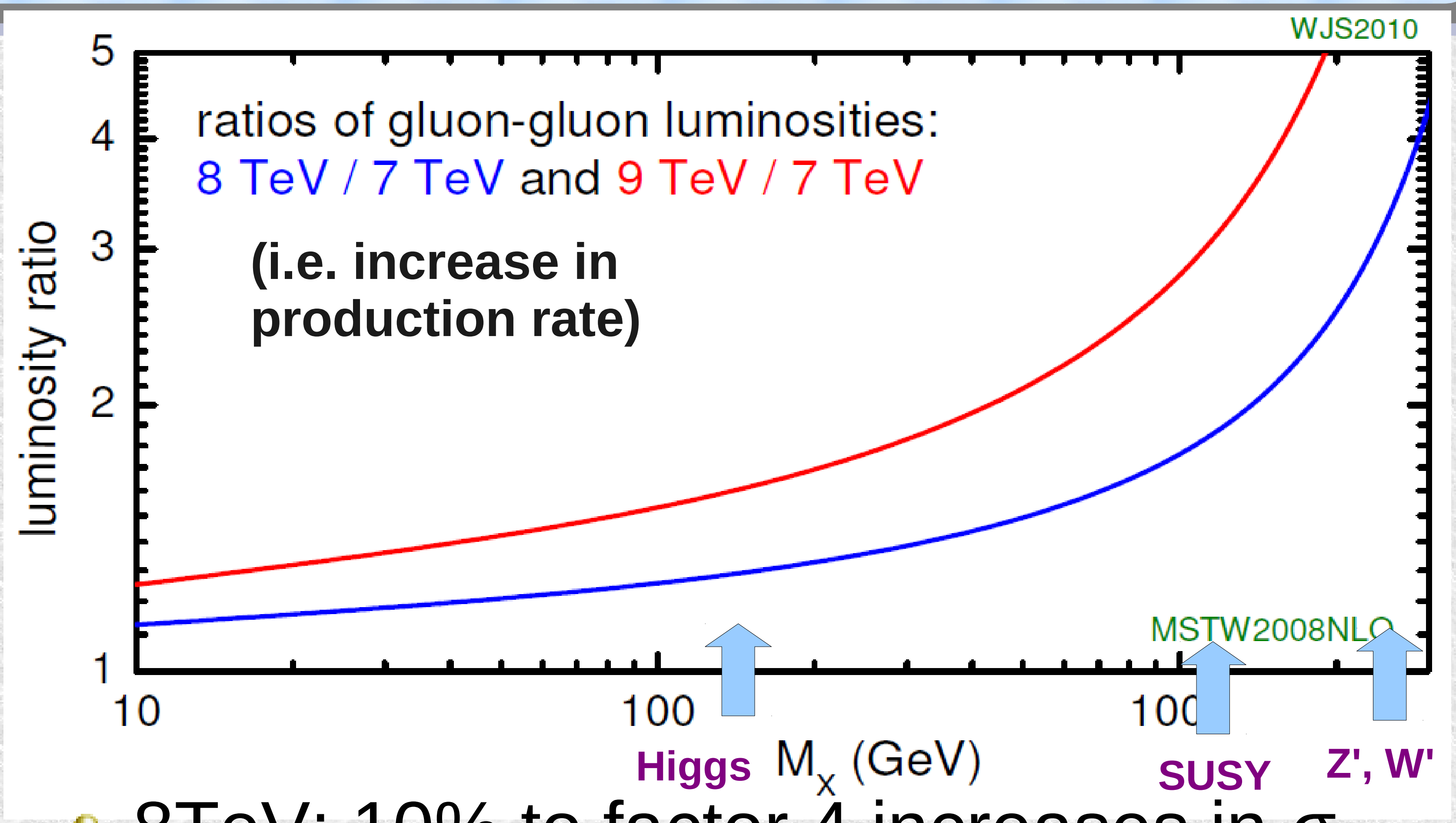
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

- 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

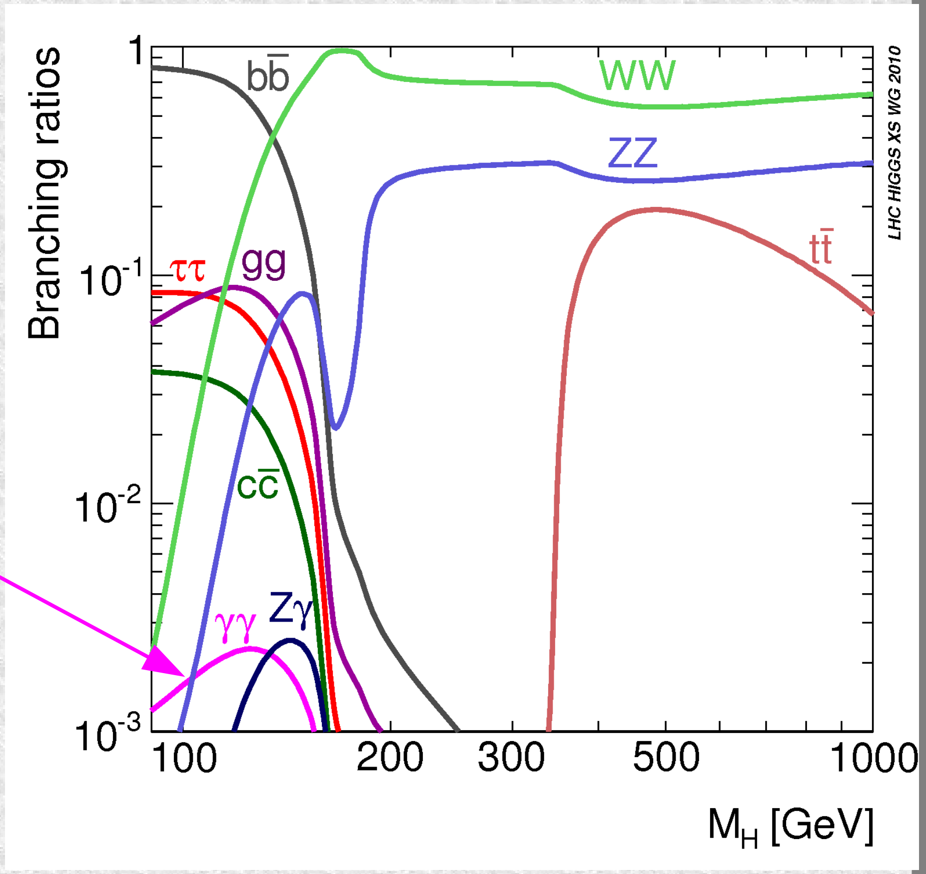
Reminder: Gain from E_{CMS}



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

LHC analyses Channels

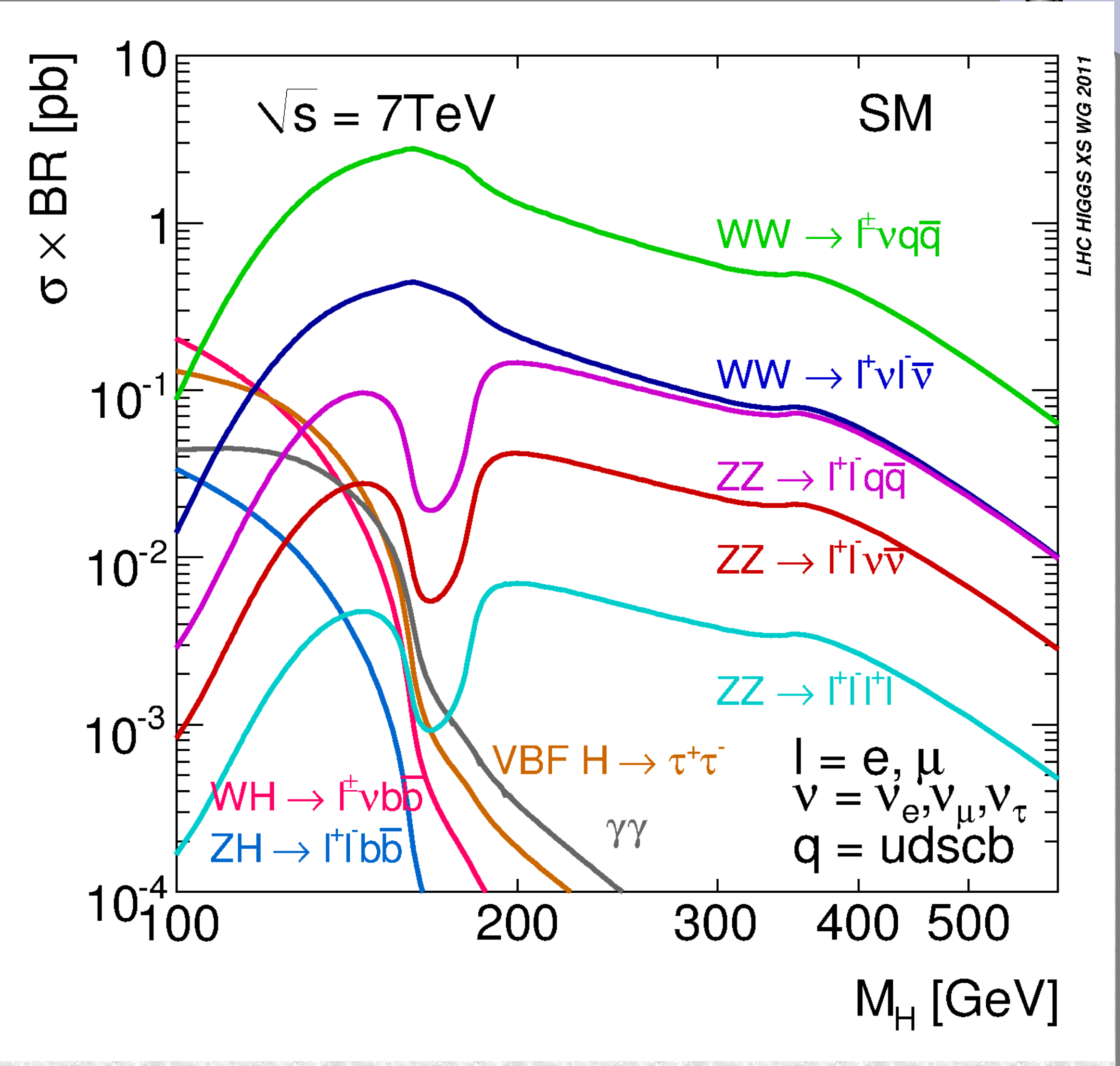
- H → ZZ
  - ZZ → llll: Golden mode
  - ZZ → llνν: Good High mass
  - ZZ → llbb: Also high-mass
- H → WW
  - WW → lνlν: Most sensitive
- H → γγ
  - Rare, best for low mass
- H → ττ
  - Good s/b, low mass,rare
- H → bb
  - t̄tH, WH, ZH useful but hard



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



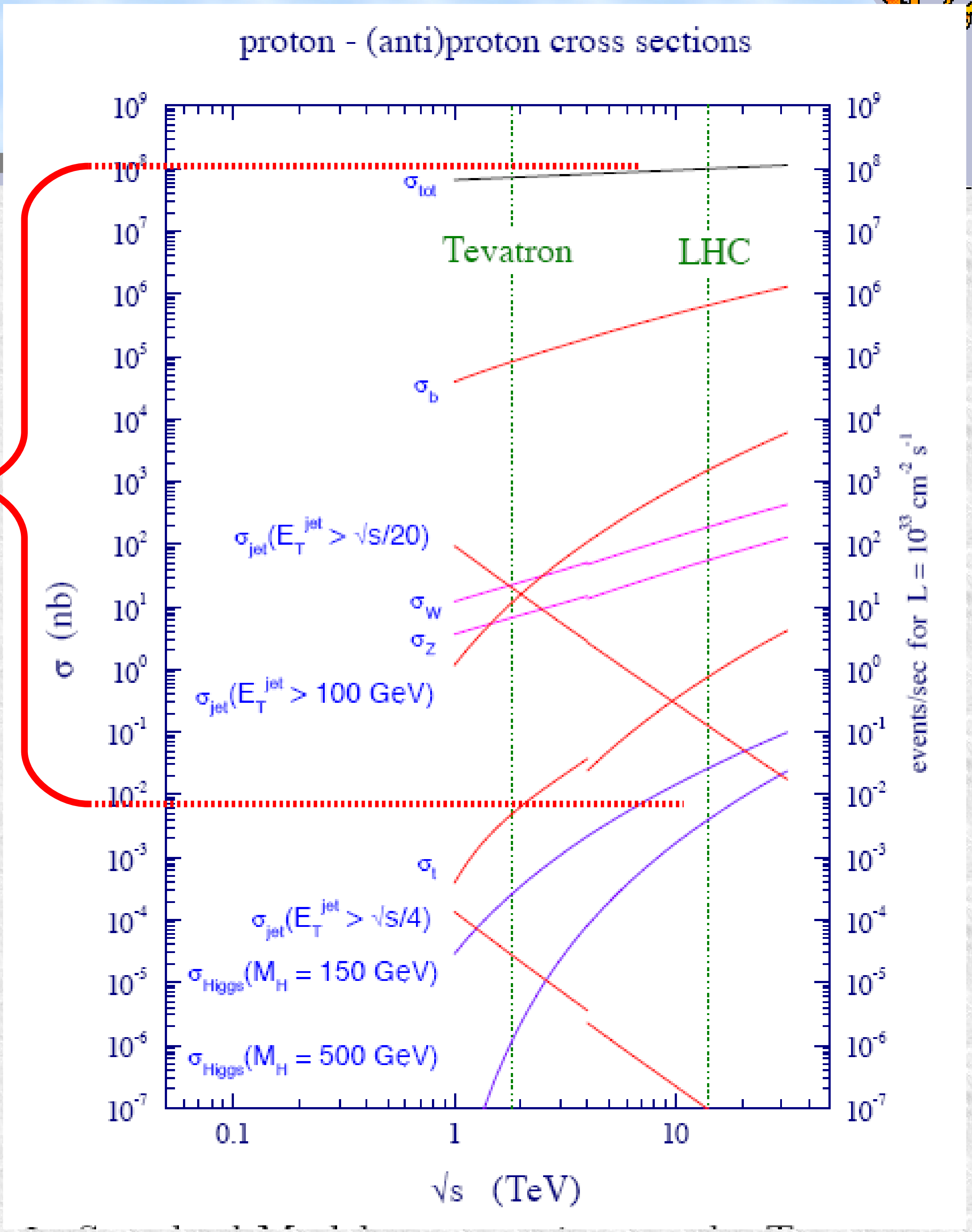
Rates?

- LHC backgrounds!

10^{10}

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

Sam Ting

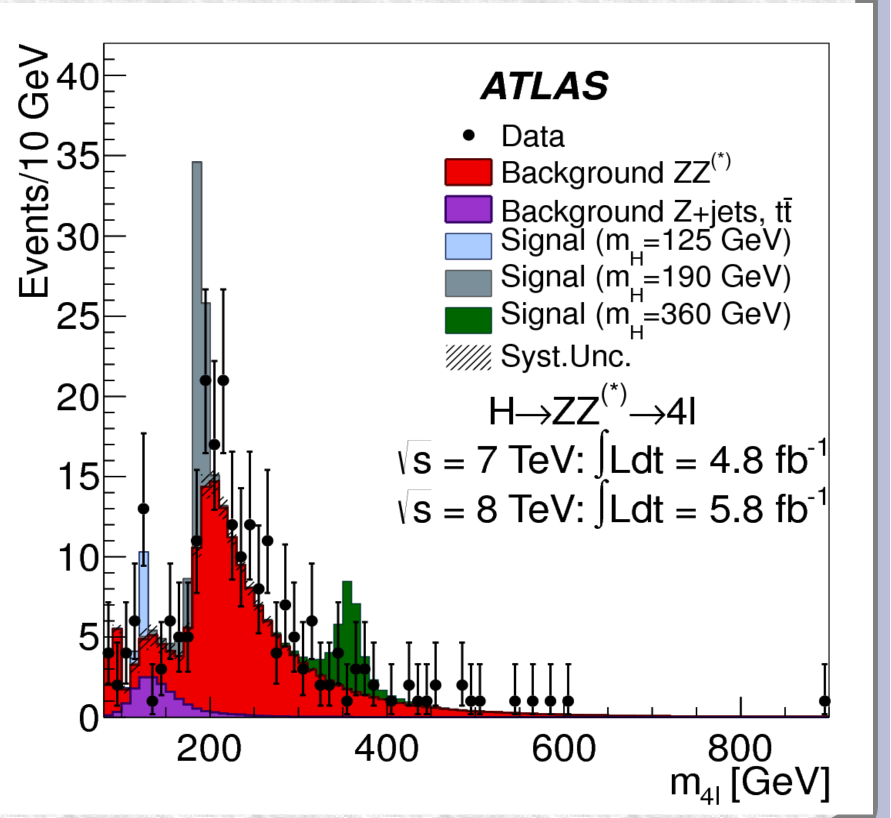


How we search for the thing

- If Higgs boson had been 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

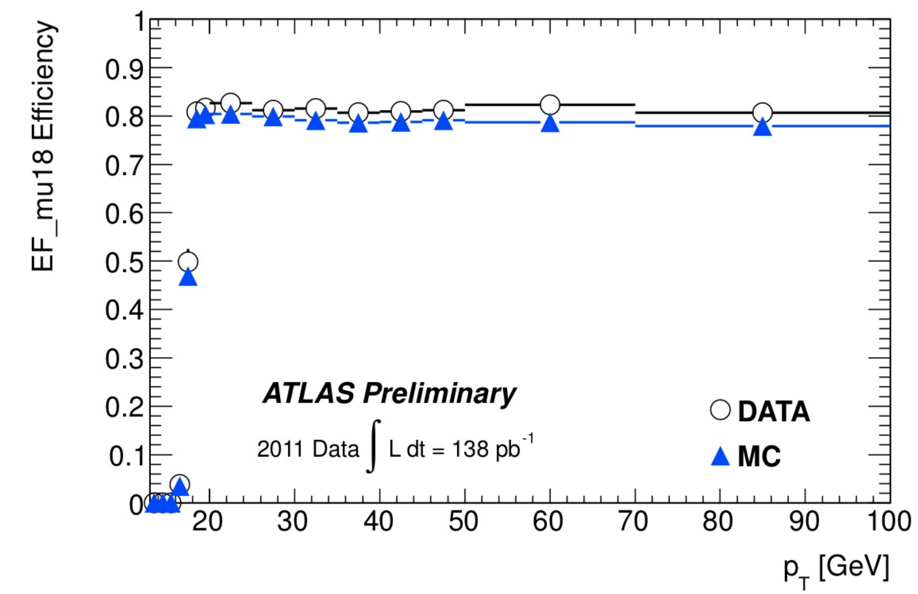
$H \rightarrow ZZ \rightarrow l^+l^-l^+l^-$

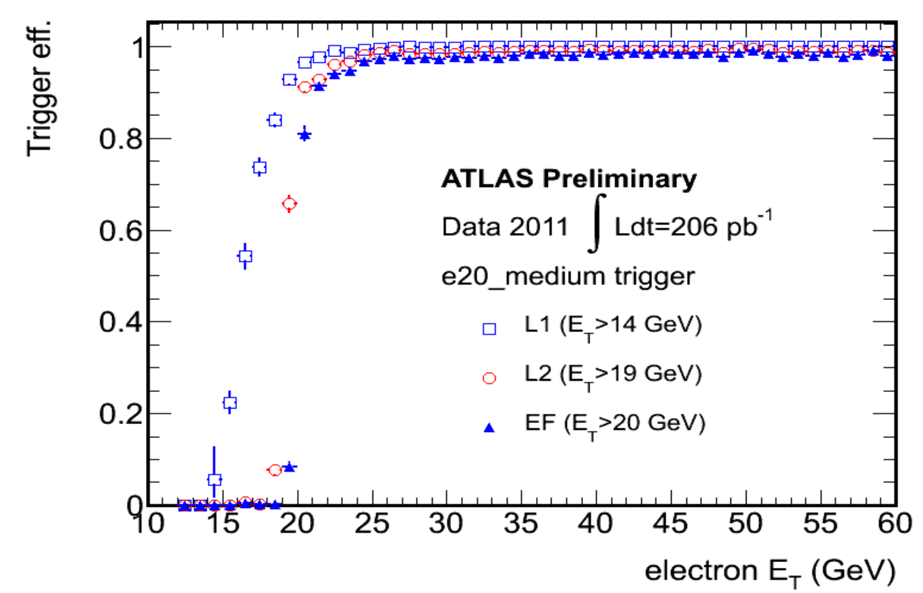
- Golden channel m_H>190GeV/c^2
  - Above ~200 two real Z's
  - Down by 125 ZZ*, 1 or even both off shell
- Good mass resolution, trigger
- Require 4 leptons
  - Isolated, prompt
  - One pair 50-106 GeV
  - The other variable
- Backgrounds:
  - Irreducible QCD ZZ to llll dominates
  - Reducible Zbb, tt especially for low masses



Trigger efficiencies (ATLAS)

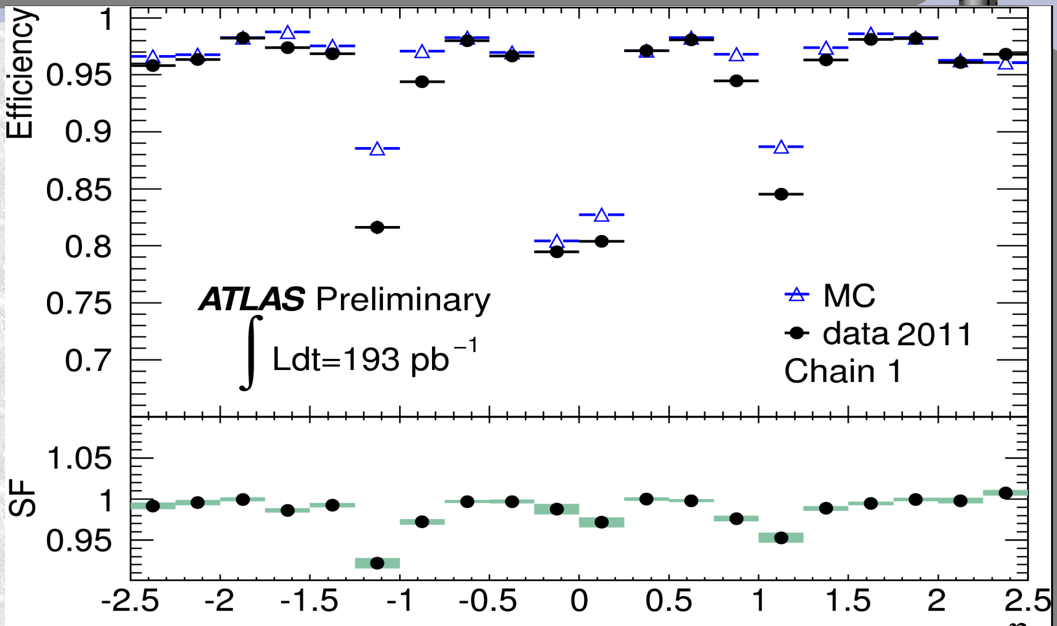
- Crucial to a hadron collider – the trigger
  - Most channels use single lepton ~20GeV p_T
- 3 level trigger system
  - L1: 2µs, local objects
  - L2: 'ROI' complete information
  - EF: full reconstruction
- Efficiency plateau
  - 80% µ efficiency
    - Multi-leptons give good total
  - ~98% electron efficiency
- Ultimately 99% efficient

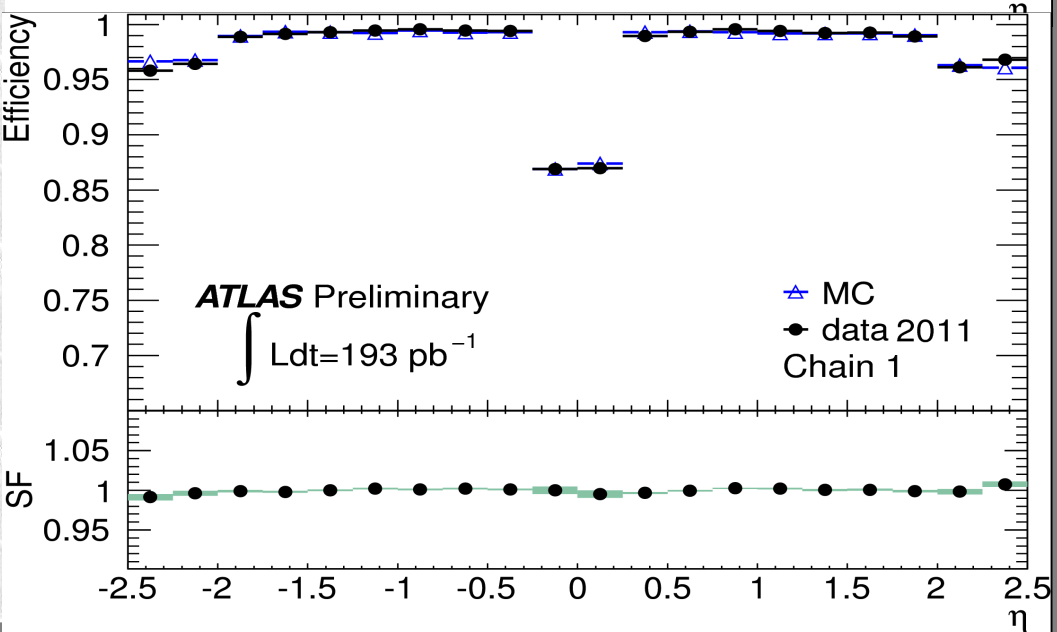




Muon reconstruction (ATLAS)

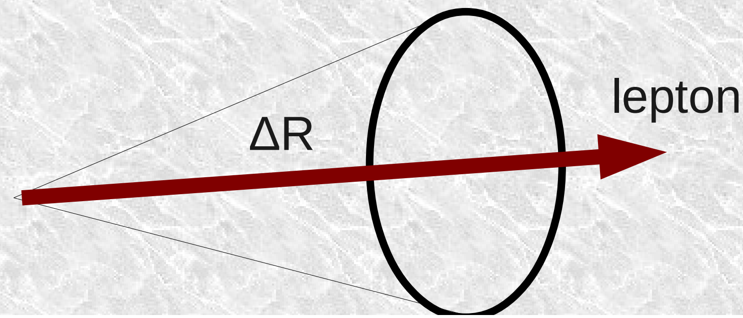
- Combined muons (top)
- Combined + segment tagged (bottom)
- Final efficiency good
- Difficulties:
  - η=0 (no muon chambers)
  - η=1.2 (barrel/forward transition)
- In 2012 use 'stand alone' to improve to 2.7

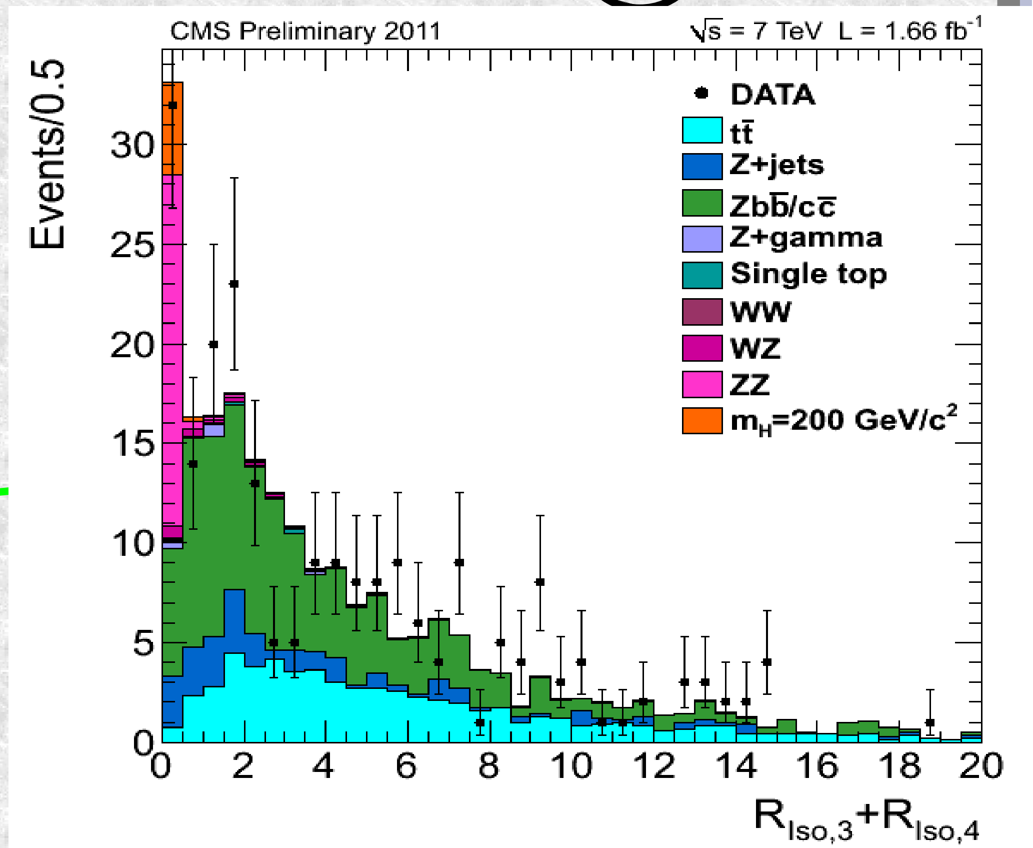




Isolation effects

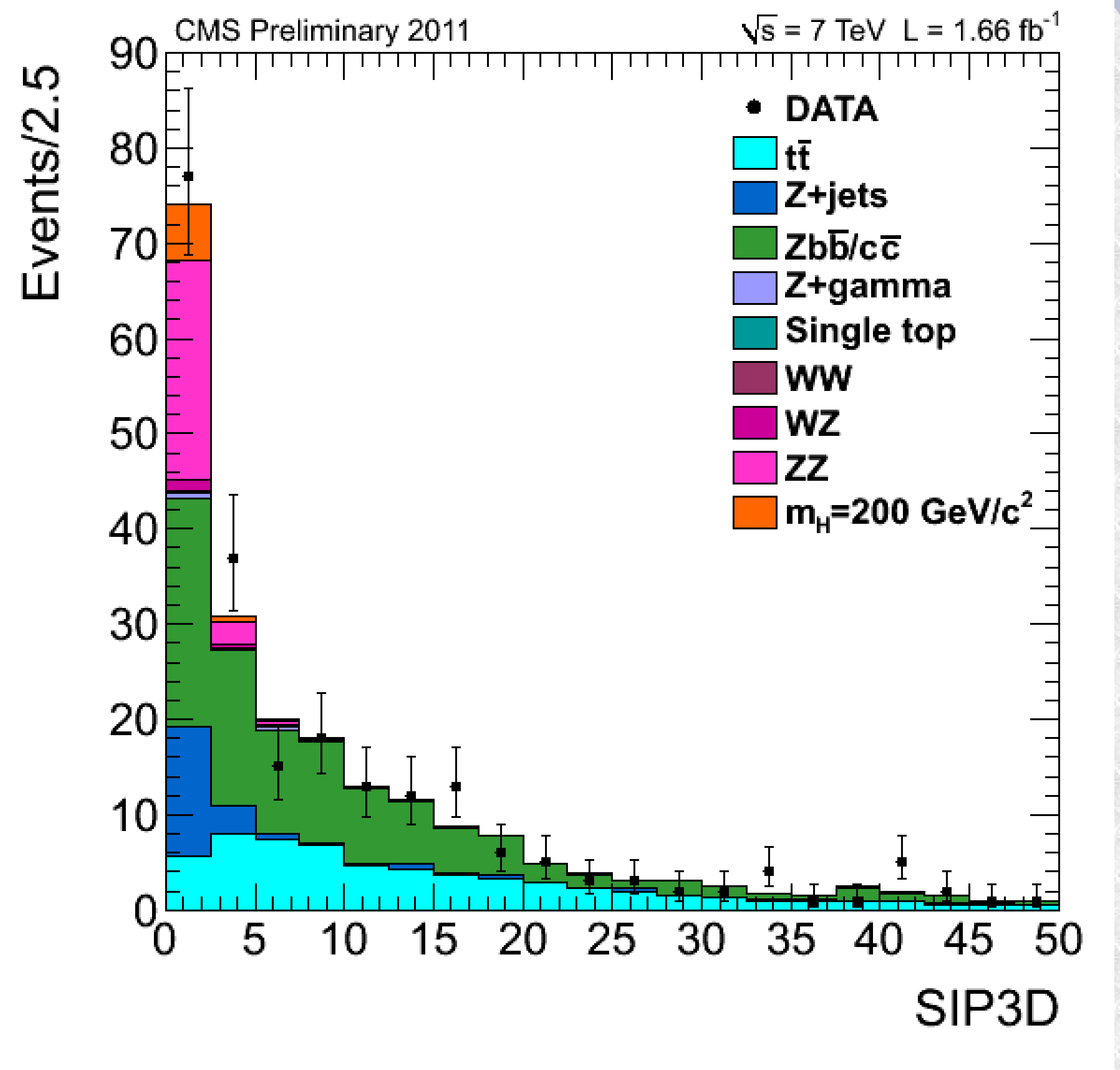
- Reducible background involves e/μ from b/c quarks
- Is there a jet here?
  - Define cone around lepton, size ΔR
  - Sum energy in cone
  - Require $E_{cone}/E_{lept} < X$
  - Need to optimise selection
    - Measure efficiency
    - And Background





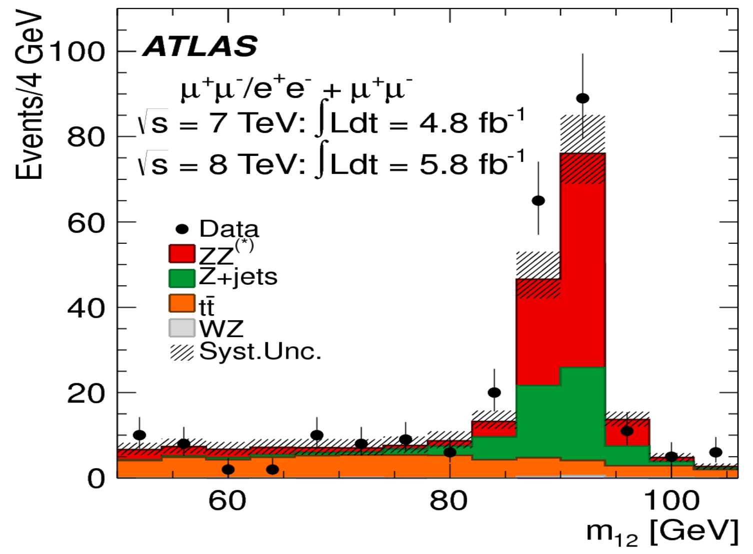
Impact parameters

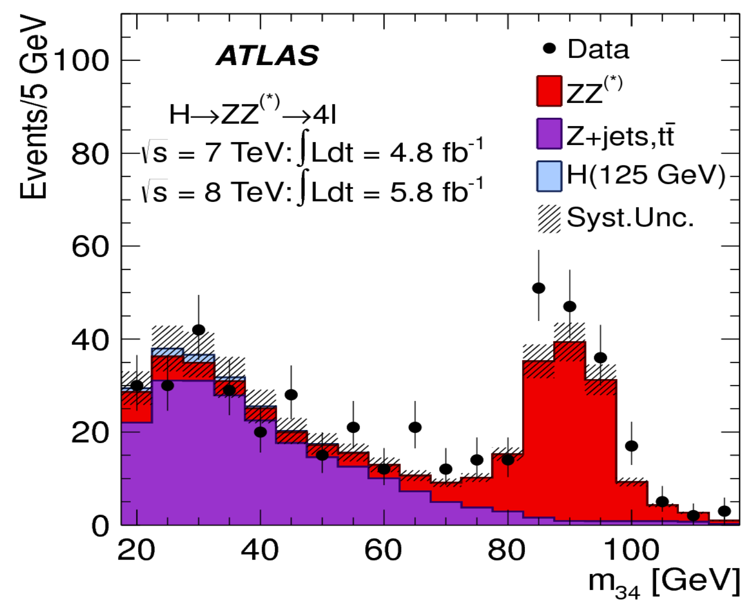
- Suppression of b quarks with impact parameters
  - Lepton closest approach to proton collision
  - H → ZZ → llll have no decay length
  - lepton from b quarks have ~100µm impact
- Plotted is larger SIP for l3, l4



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

- Estimation of background
- For ZZ:
  - Shape from MC (gg,qq)
  - Rate fitted to data with theory constraint
- For non Z+jets, tt:
  - Relax isolation cuts
    - More background
  - tt fitted to m_{12}
  - Z+jets fitted to m_{34}
  - Extrapolate to signal region



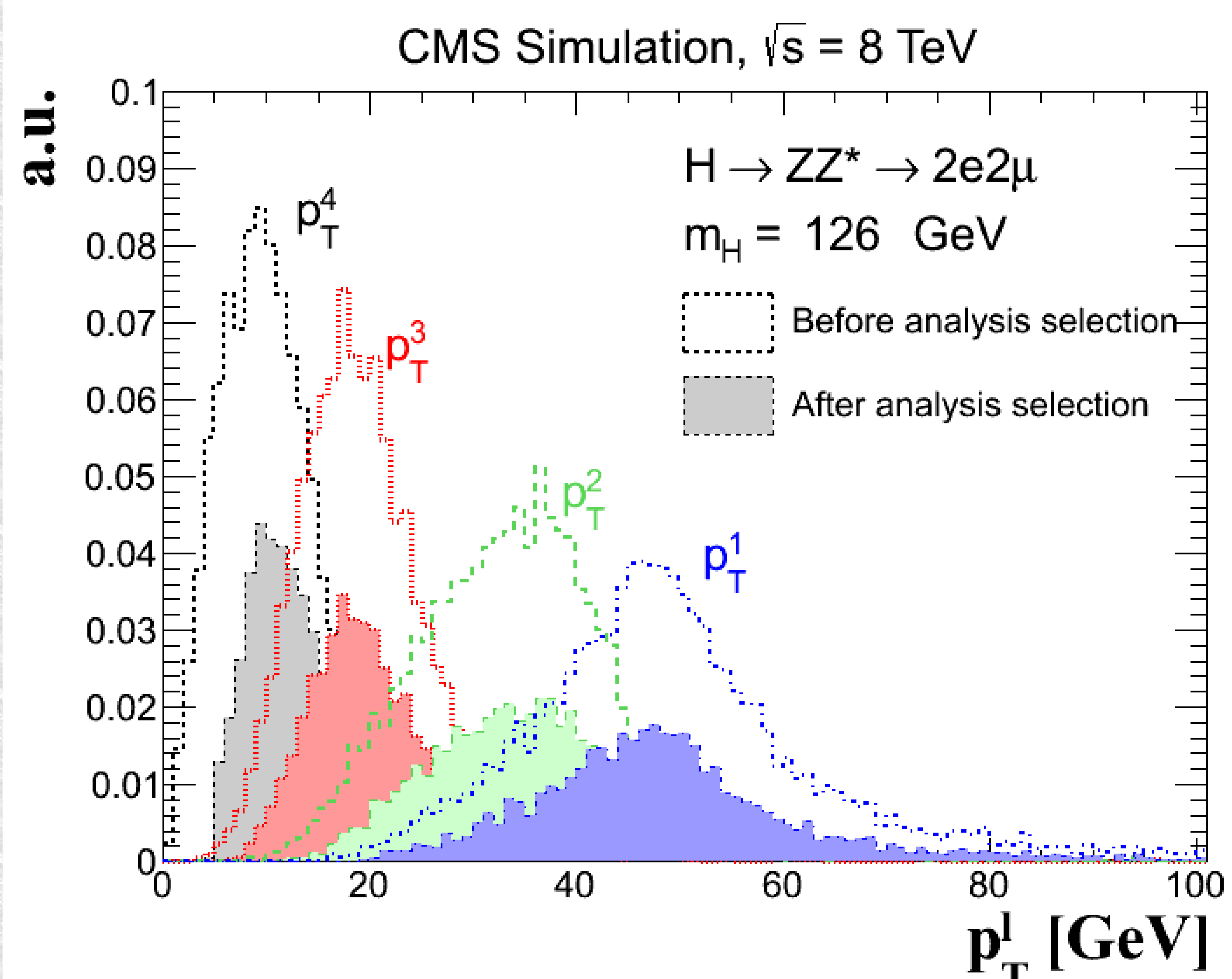


Lepton thresholds

- 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.

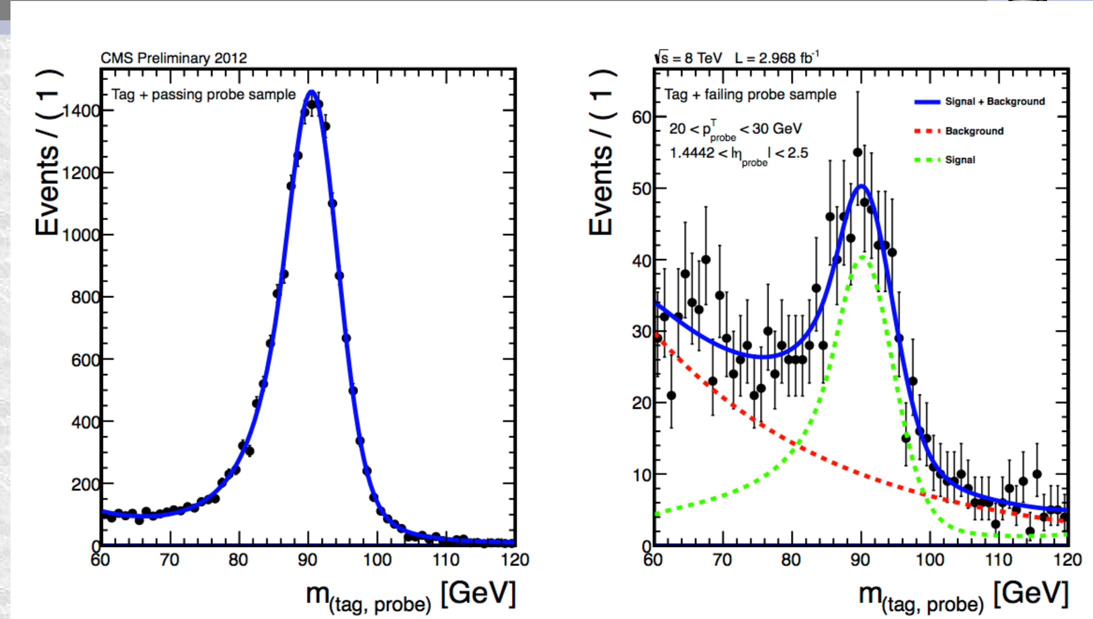
Lepton p_T distribution

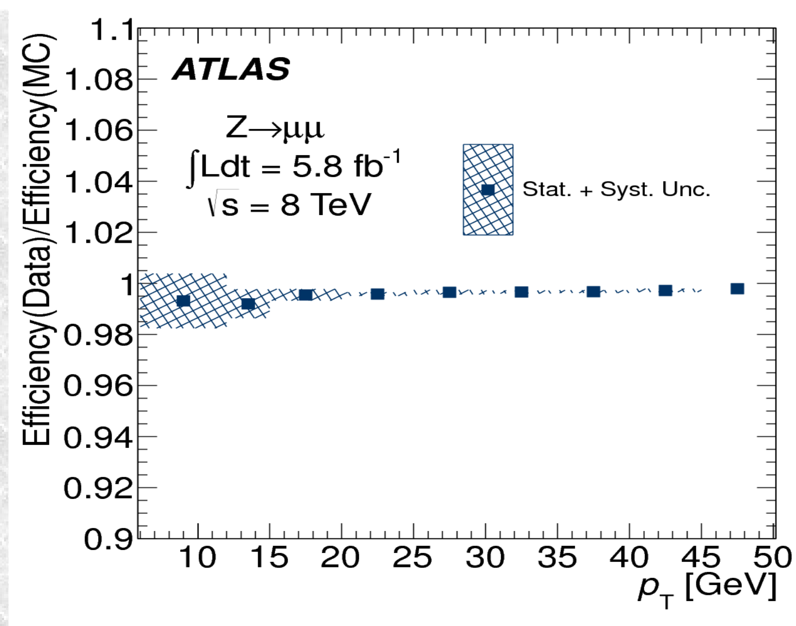
- $m_H << 2m_Z$
- The decay involves one Z being far from mass-shell
- The softest lepton is typically below 10GeV p_T
- Need to push lepton momentum range



Lepton isolation/impact pars

- Nothing in MC is trusted
- The efficiency of the isolation and impact parameter cuts is checked with data
- The Z → μμ peak allows efficiency measurement
  - But few Z produce leptons of only 7 GeV





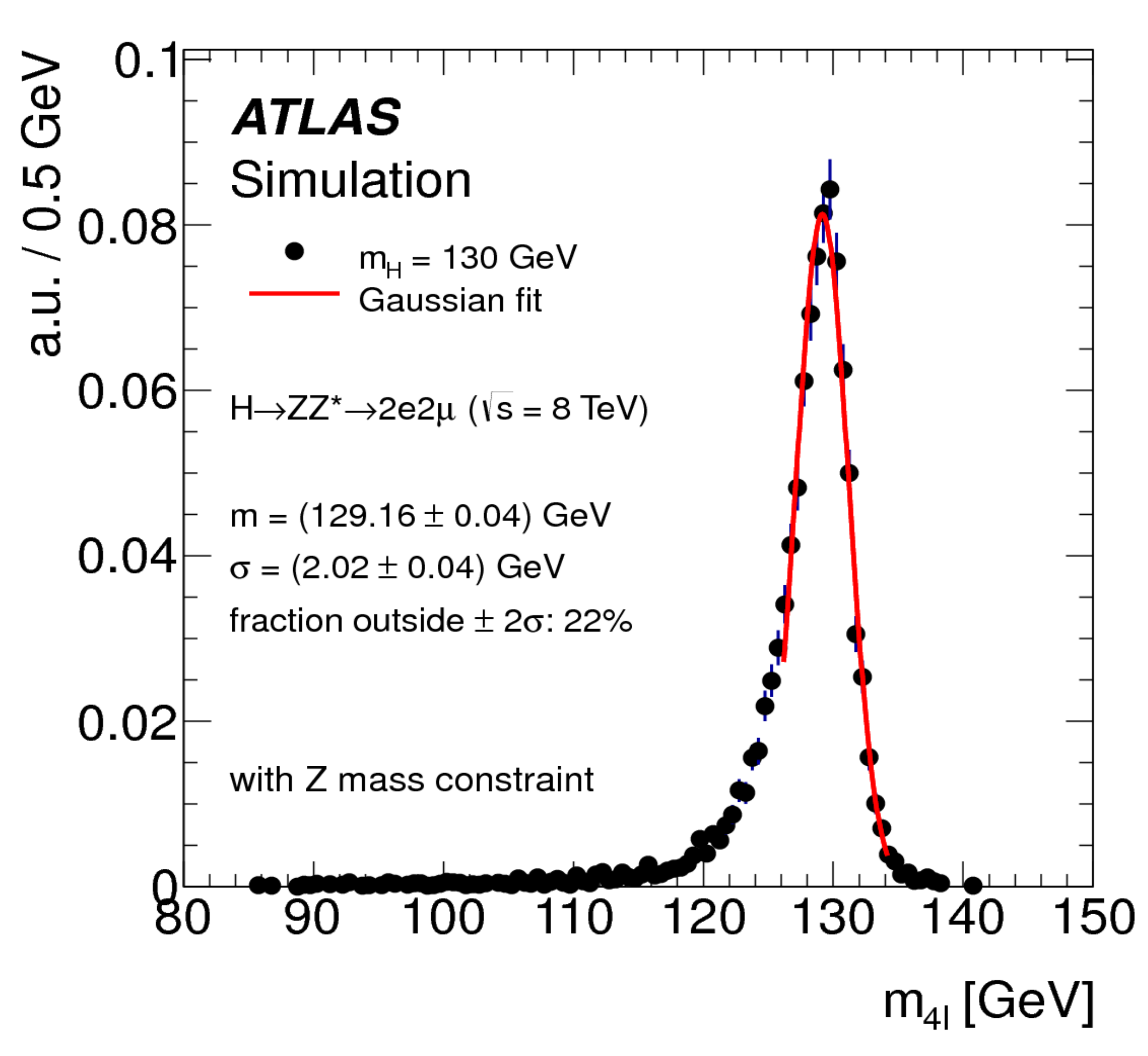
Selection methods

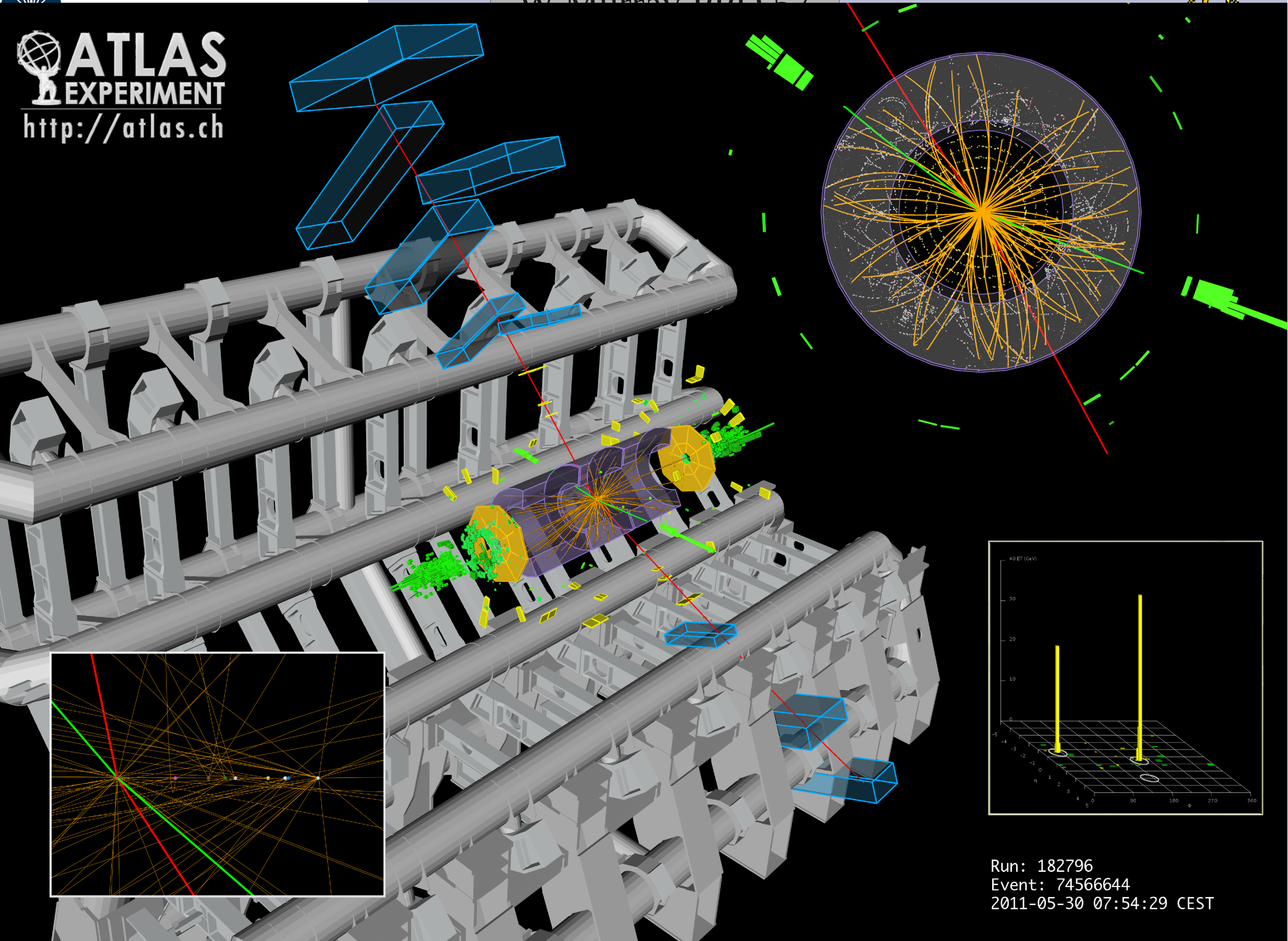
	ATLAS	CMS
Minimum lepton p_T	7Gev (e) / 6 GeV (μ)	7Gev (e) / 5 GeV (μ)
Mass Z_1	50 - 106	40 - 120
Mass, Z_2	17.5 - 115	12 - 120

- CMS cuts always a little looser, more efficient
  - ATLAS efficiency: 36%,21%,18% in μμμμ,eeμμ,eeee
  - CMS efficiency 40%,27%,18% in μμμμ,eeμμ,eeee
  - 10% higher efficiency in CMS
- Backgrounds similar despite different cuts:
  - ATLAS background expected (120-130): 4.9
  - CMS background (121.5 -130.5): 3.8
  - 10% less background in CMS per GeV
- CMS also uses 'matrix element'
  - Uses leptons angles & Z masses to separate sig. from back.

Mass resolution

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



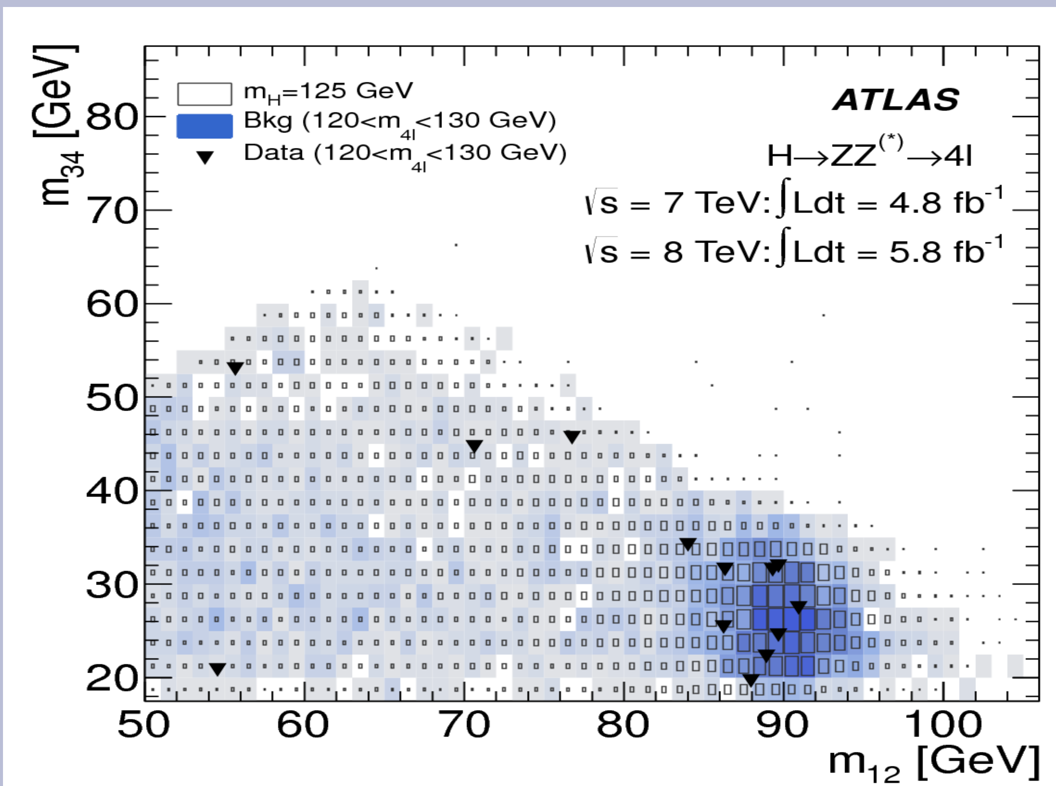

ATLAS
EXPERIMENT
http://atlas.ch
Run: 182796
Event: 74566644
2011-05-30 07:54:29 CEST

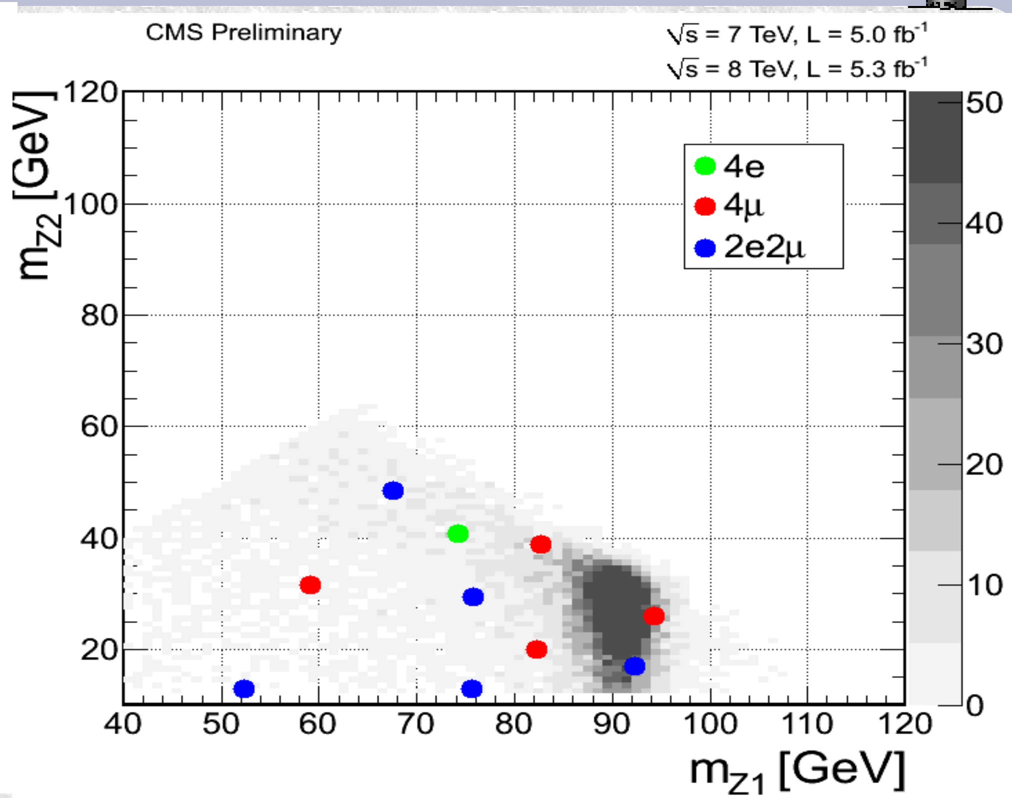
Event rates 120-130GeV

	Signal	$ZZ^{(*)}$	$Z+\text{jets}, t\bar{t}$	Observed
4μ	2.09±0.30	1.12±0.05	0.13±0.04	6
$2e2\mu/2\mu2e$	2.29± 0.33	0.80±0.05	1.27±0.19	5
$4e$	0.90±0.14	0.44±0.04	1.09±0.20	2

- Five signal expected in ZZ channel now
  - Twice the non-resonant ZZ background
- Non-ZZ Background small c/f sigal
  - 120% in eeee
  - 6% in μμμμ
  - The Z+ee is much dirtier than Z+μμ
- There is an excess, all channels

Candidate masses: m_1 v m_2



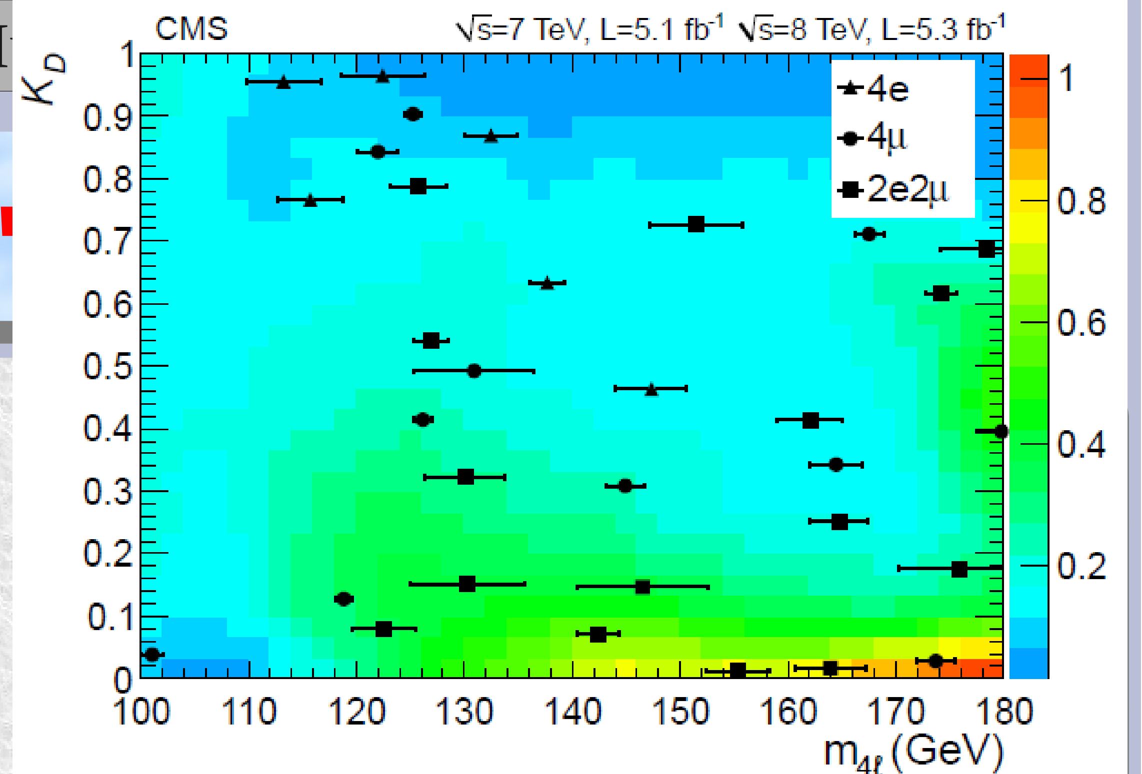


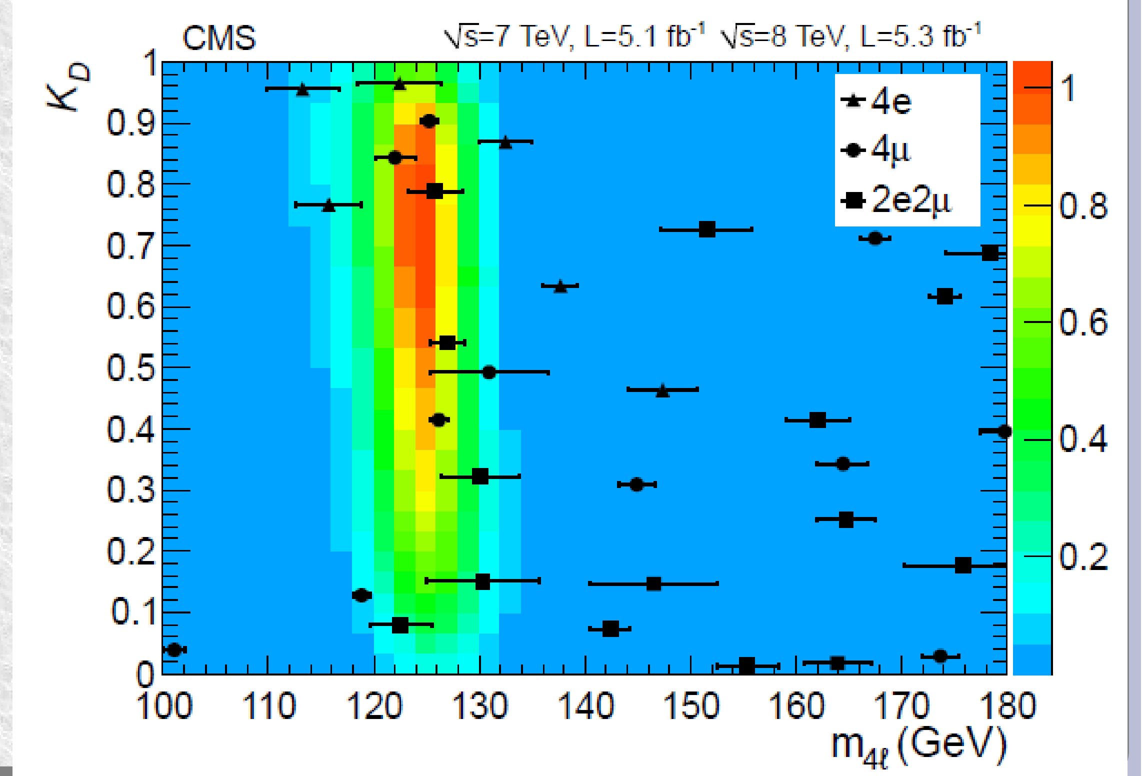
- CMS plot showed few events with m_{Z1} >90 GeV
  - Had sparked theoretical papers!
- ATLAS version is reassuring

W.M

CMS 'MELA'

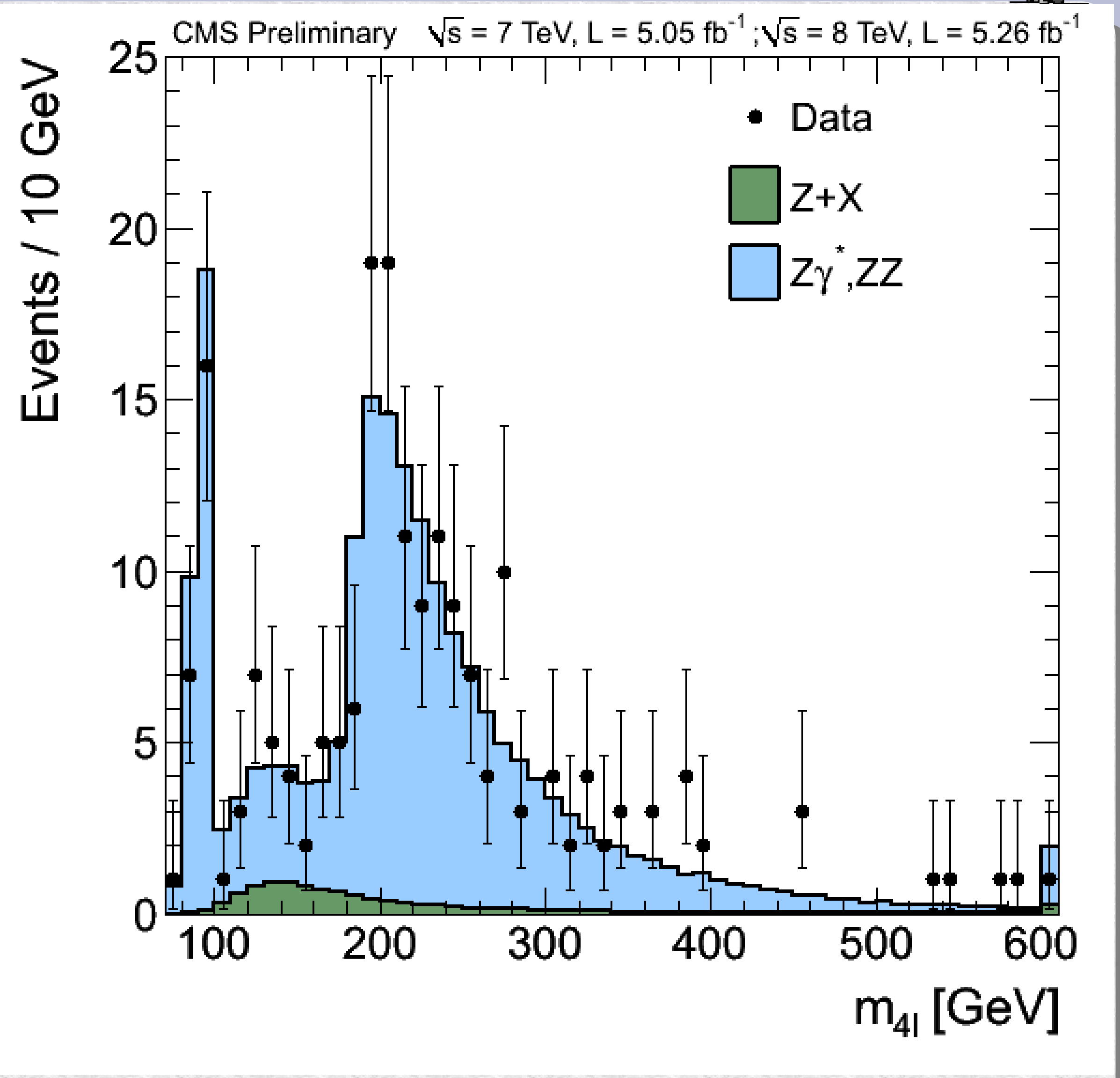
- Matrix element likelihood analysis
- Uses 5 angles and 2 Z masses of the $H \rightarrow ZZ \rightarrow llll$ system
- Background modelled as $ZZ^*/Z\gamma^*$
- Several events are 125 GeV are seen to have very high 'MELA' values, K_D





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



Statistical interpretation

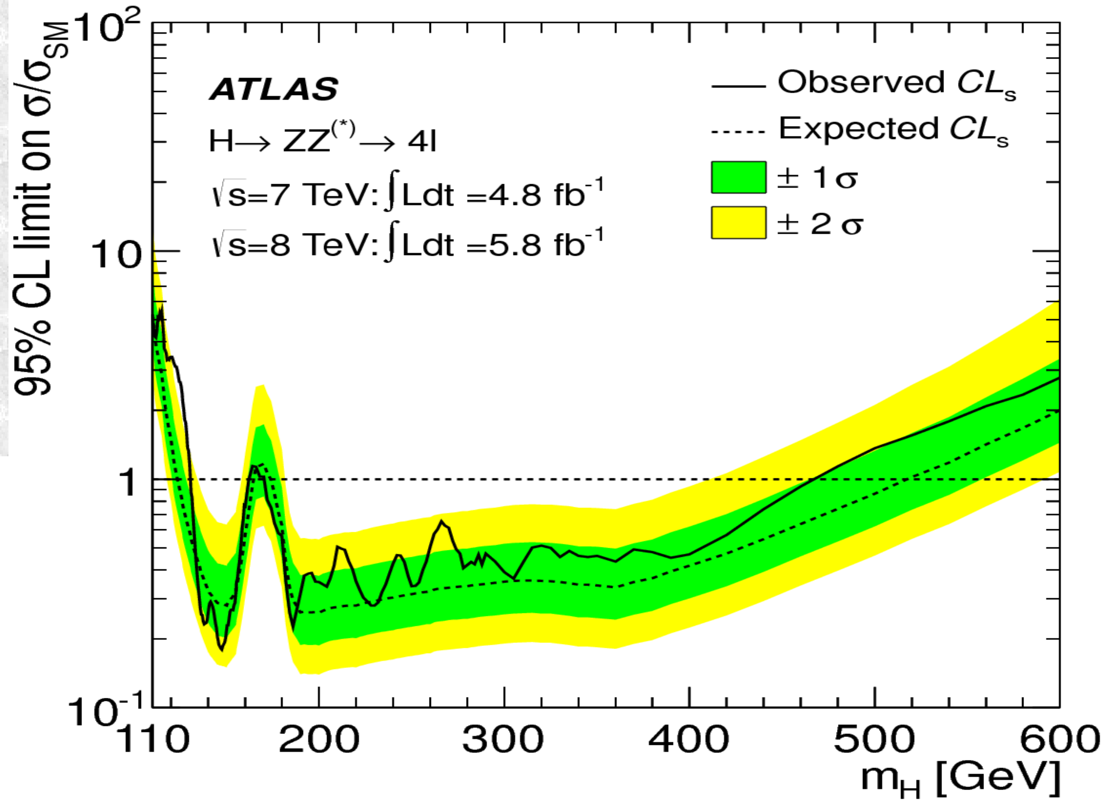
- Non-trivial business, with Frequentist and Bayesian methodologies
- For now ATLAS+CMS quote 'CLs' results
  - Derived as a compromise, acceptable to both schools
  - Glen must have discussed this
- A useful approximation for low rate counting experiments with negligible systematic errors:

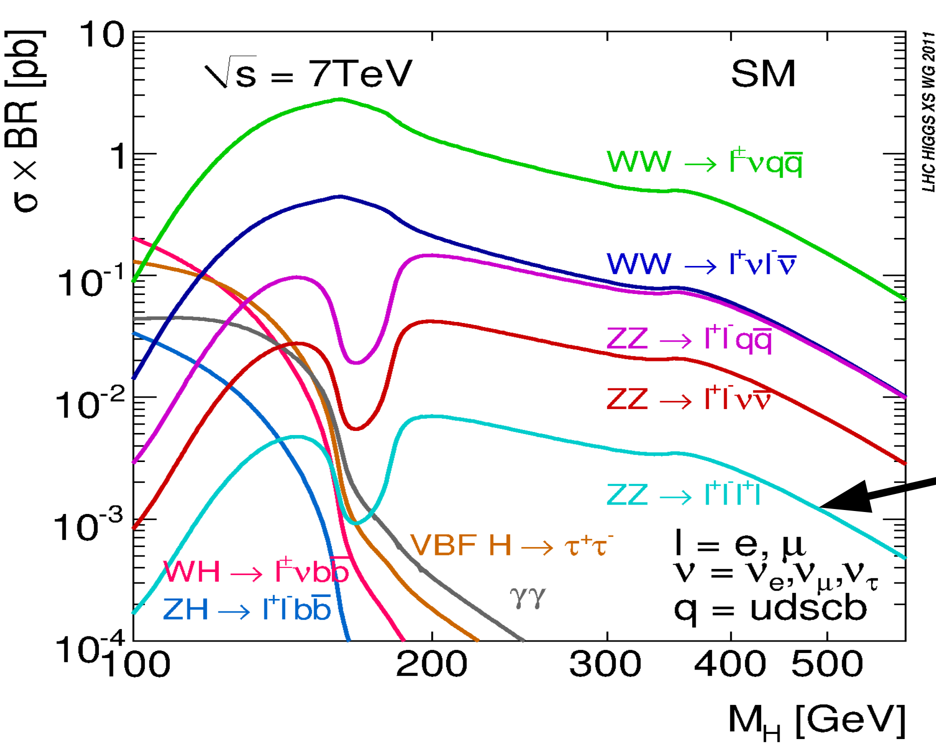
$$\langle Z_W \rangle = \sqrt{\left(2\left((s+b)\ln(1+s/b)-s\right)\right)}$$

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

Expected limits

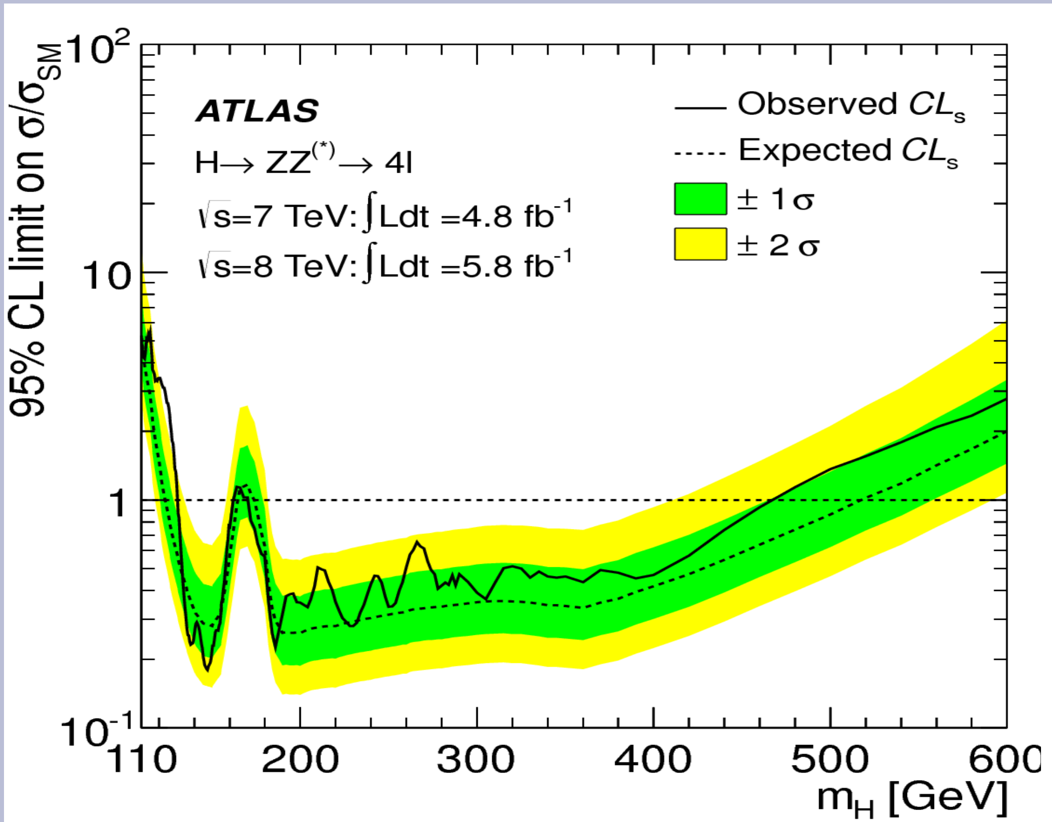
- Expected upper limit
- Observed generally follows
  - Except at 125GeV

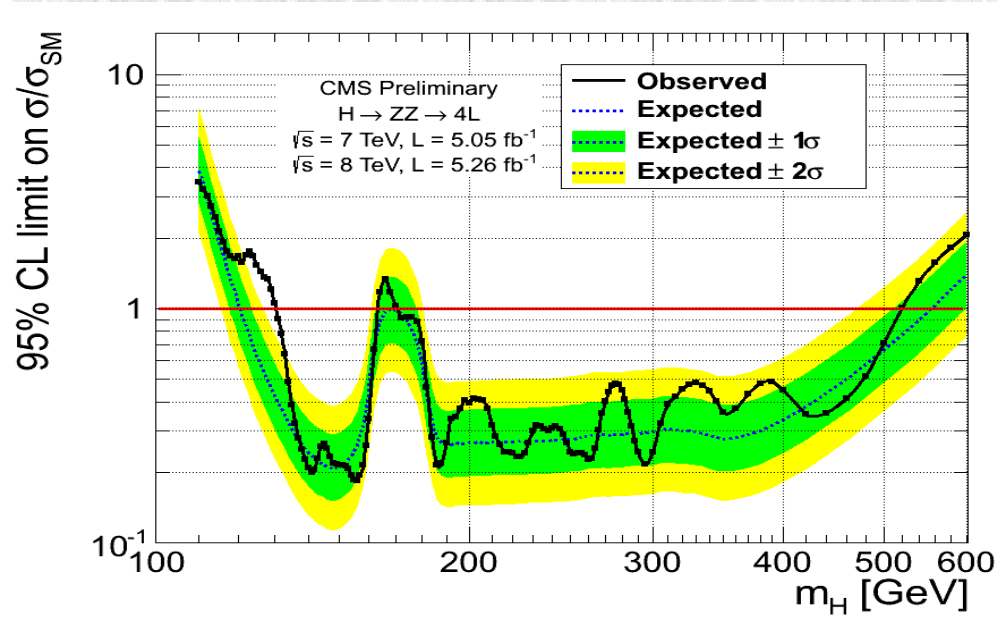




- Shape reflects the H to llll expected event rate

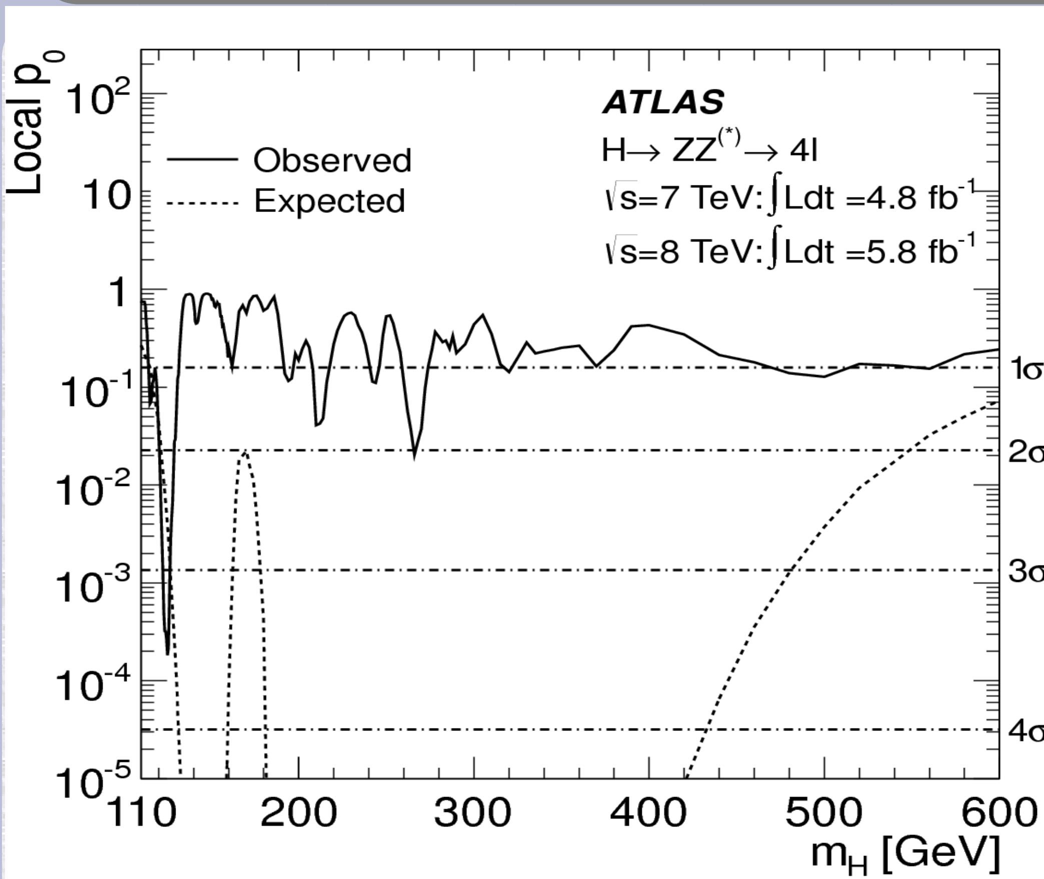
Observed limits

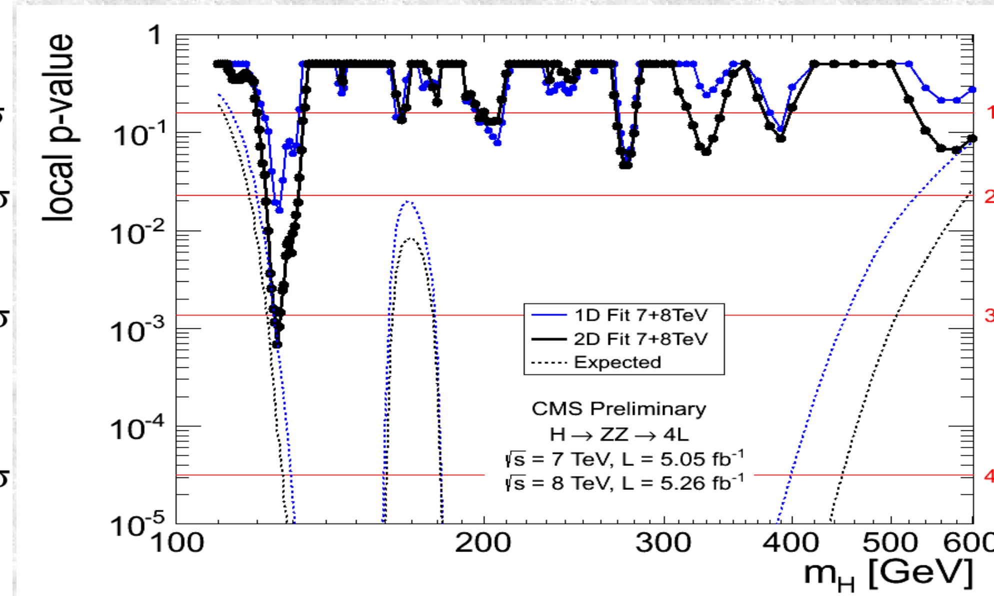




- Both ATLAS and CMS exclude most of 130-500GeV
  - Small expected hole at 170GeV
  - Excess neat 125GeV

Observed limits





- CMS sensitivity improved by 'MELA'
- Each has one p-value below 1 in 1000
- Both peaks at the same place

Conclusion

- Tevatron still interesting
  - Vbb excess of ~3σ for m_H~125
- ZZ to llll discussed in some detail
- Other channels I discuss tomorrow
- Combination and interpretation next week