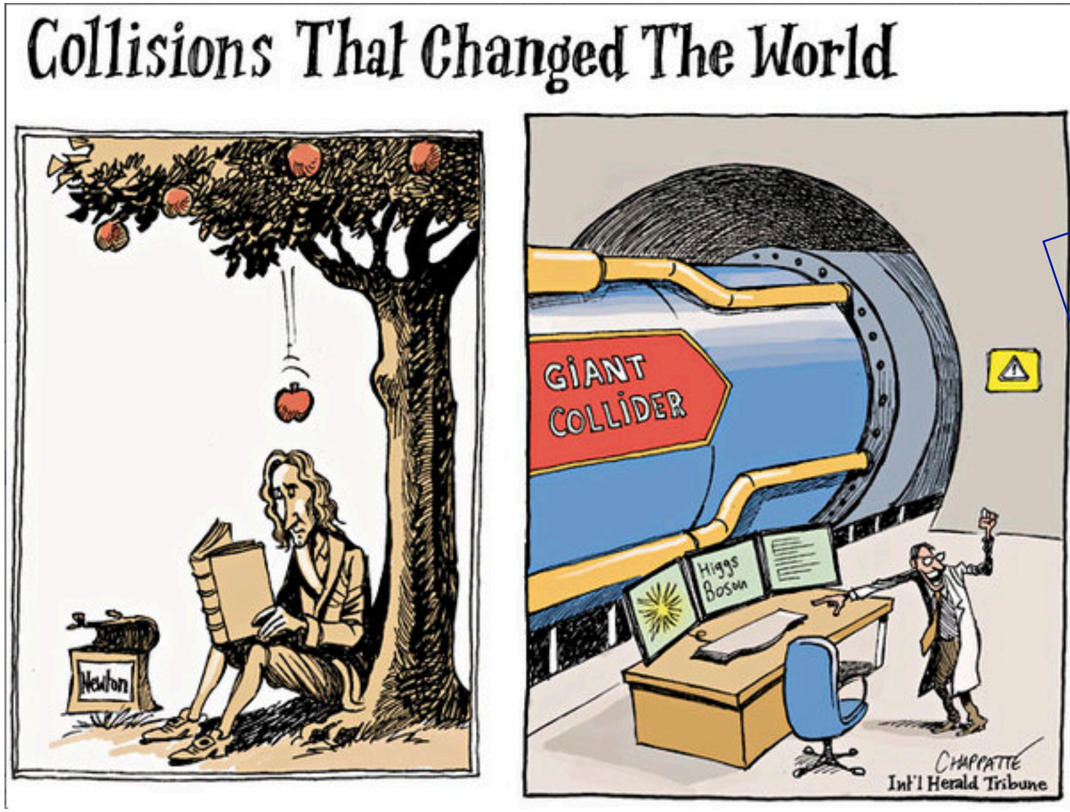
SM Higgs Boson searches at LHC



WELL ....
NOT YET !!!

Chiara Mariotti

Outline

- The LHC
- The experiments
- Trigger and performances
- Lepton ID and measurement from data
- Rediscovery of SM
- Higgs Boson Cross Sections
- The results with the 2011 data.

Introduction

- The LHC started 9 years after the end of LEP.

- The detectors were ready and soon we realized that we were indeed understanding them.

- The start-up from the physics point of view was very successful and we got immediately tons of results!

- The statistical precision is enough already now to distinguish the relevance of Higher Order (NLO vs LO and more)

  W.r.t. LEP, theoretical predictions are ready in advance and can match the experimental precision…

- There is still a long way to go (at 8 TeV, 14 TeV and …) and we all hope to discover the Higgs (!) but also something new, maybe totally unexpected.

The LHC

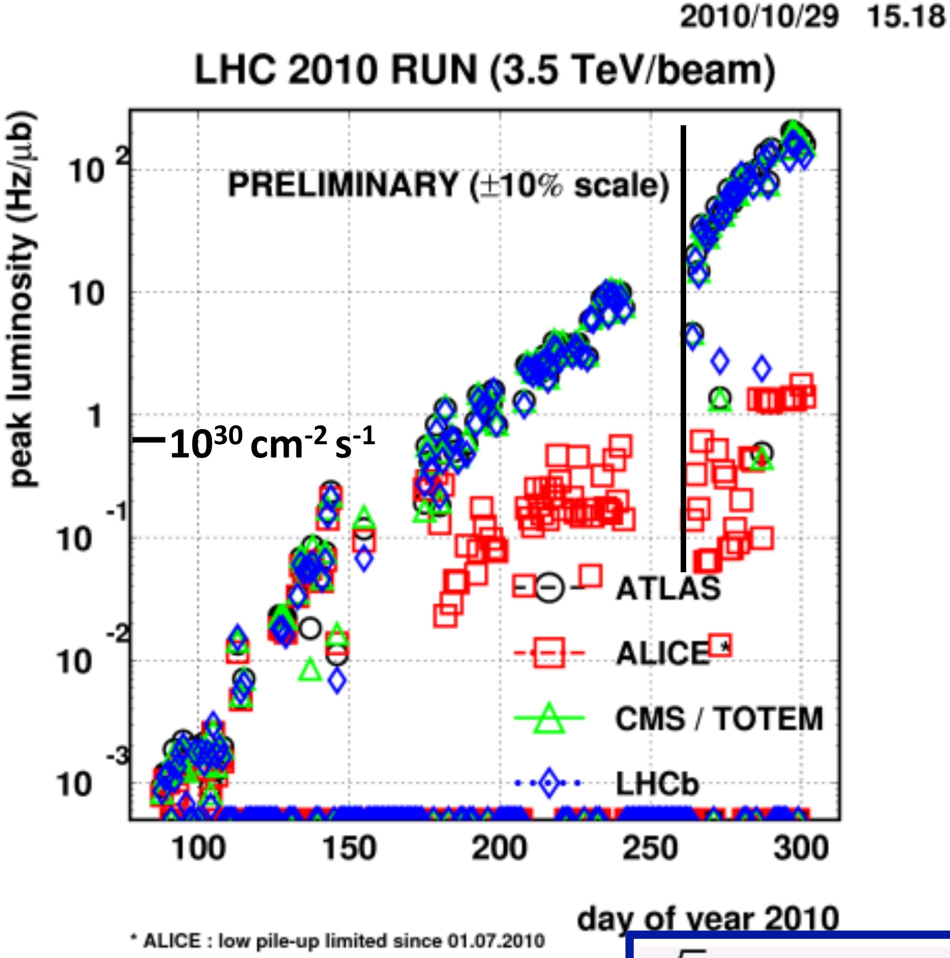
7 TeV
proton-proton
accelerator-collider
built in the LEP
tunnel

1982 : First studies for the LHC project
1994 : Approval of the LHC by the CERN Council
1996 : Final decision to start the LHC construction
2004 : Start of the LHC installation
2006 : Start of hardware commissioning
2008 : End of hardware commissioning and start of commissioning with beam
2009-2030: Physics operation

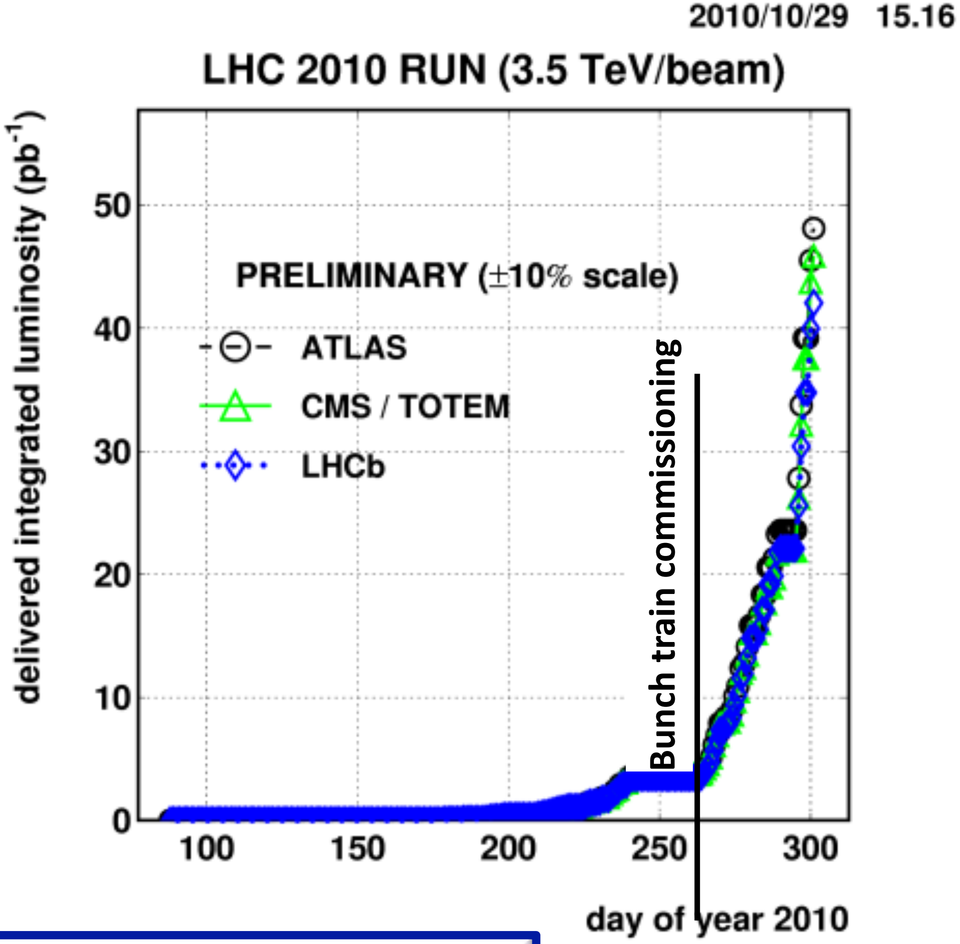
Beams of LEAD nuclei will be also accelerated, smashing together with a collision energy of 1150 TeV

Luminosity evolution 2010

5 orders of magnitude in ~200 days



~50 pb^{-1} delivered, half of it in the last week!



$$\sqrt{s} = 0.9 \text{ TeV} \Rightarrow \text{ Luminosity} \sim 10\ \mu b^{-1}$$

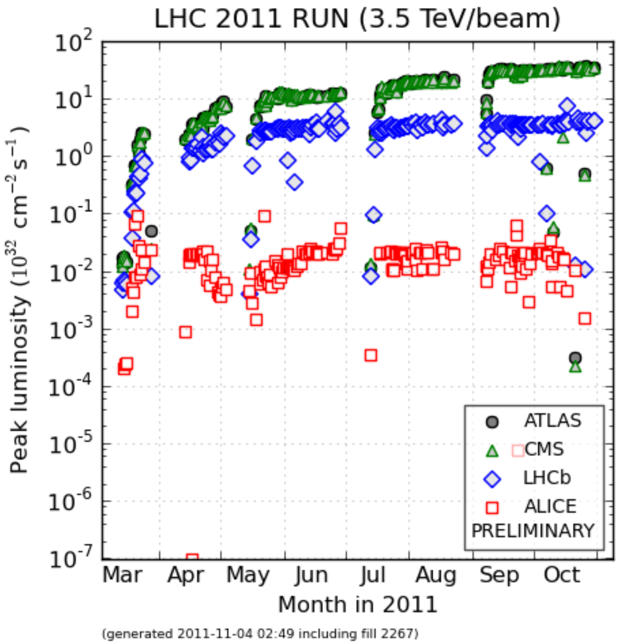
$$\sqrt{s} = 2.36 \text{ TeV} \Rightarrow \text{ Luminosity} < 1\ \mu b^{-1}$$

$$\sqrt{s} = 7 \text{ TeV (2010)} \Rightarrow \text{ Luminosity} \sim 46 \text{ pb}^{-1}$$

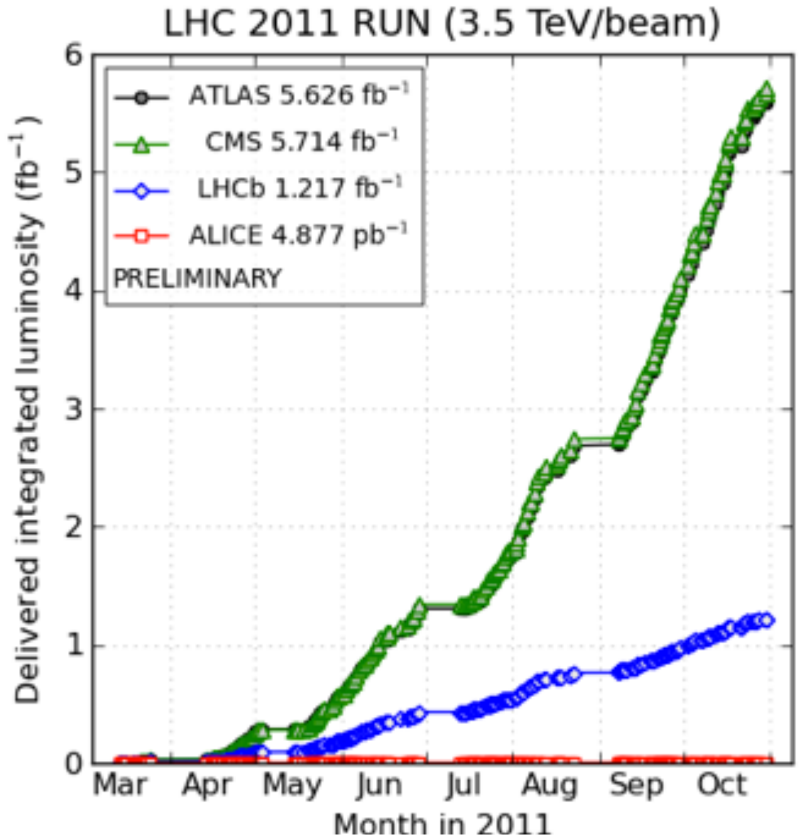
LHC in 2011

Simply magnificent !!!

Peak Lumi
3.3×10^{33}

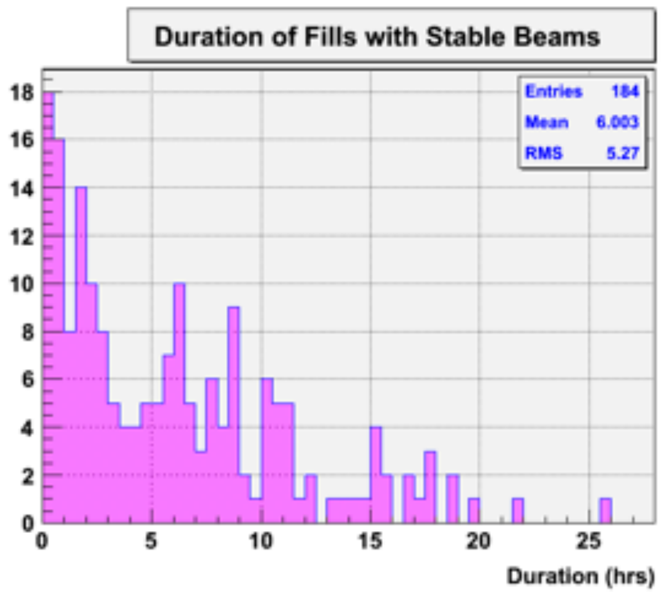


Total Lumi



~90% recorded by the ATLAS and CMS

Best Fill

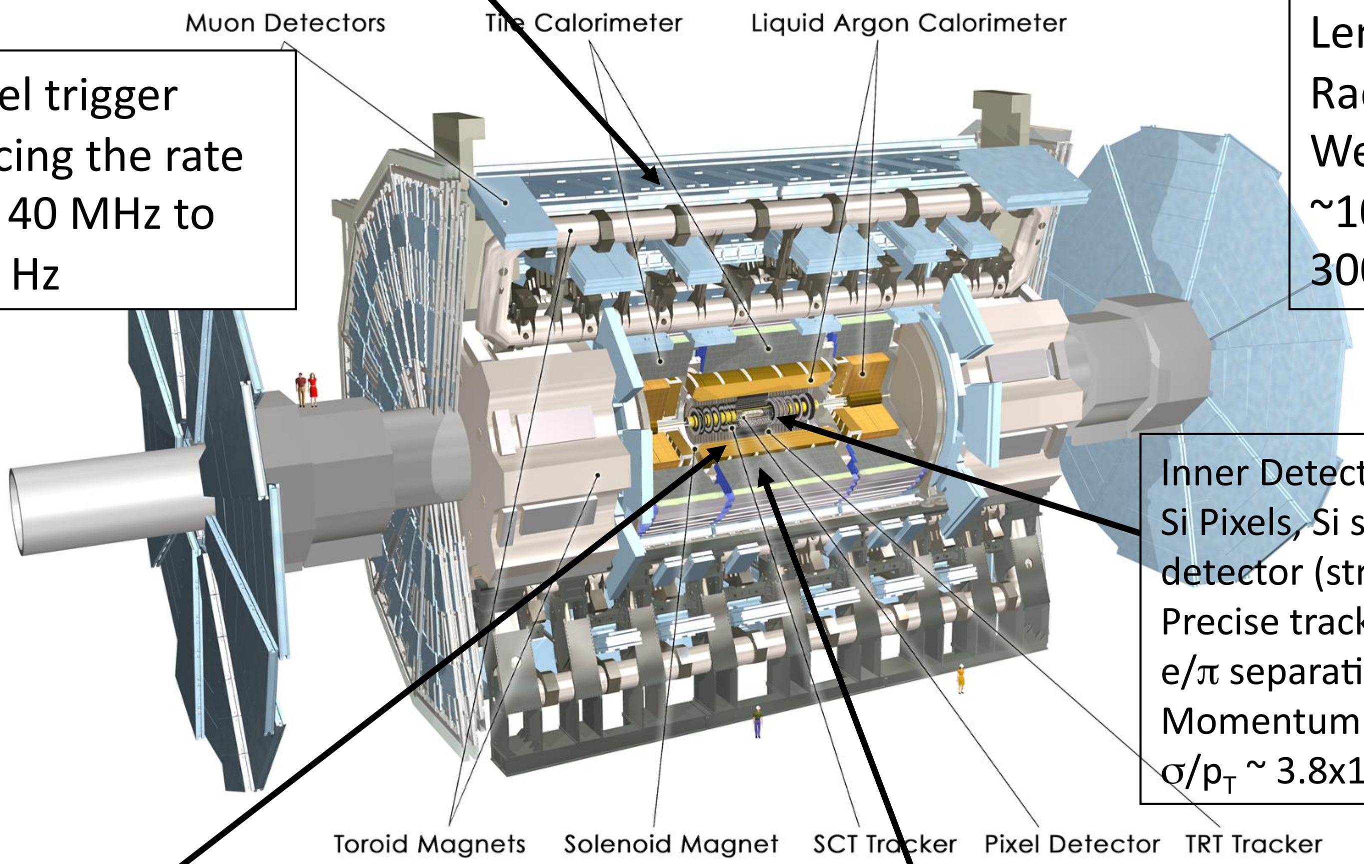


Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ 1 TeV

The experiments: ATLAS

3-level trigger reducing the rate from 40 MHz to ~200 Hz

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

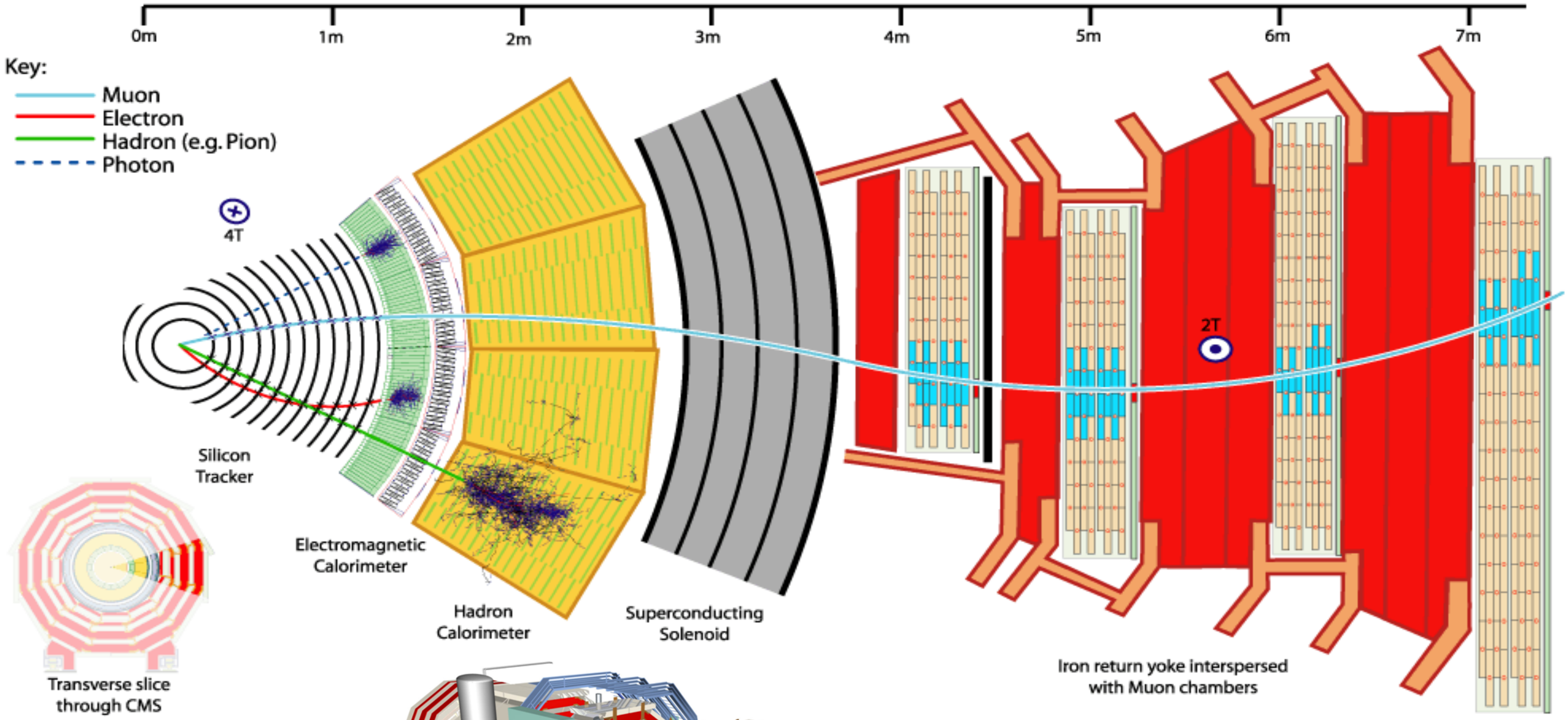


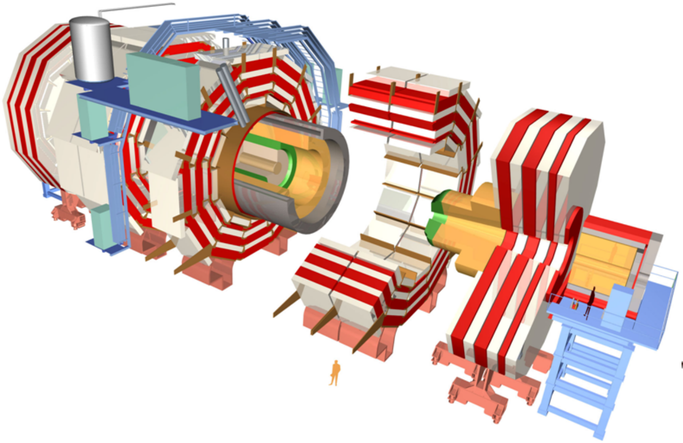
Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing,
e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\text{x}10^{-4}\, p_T\,(\text{GeV}) \oplus 0.015$

EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

The Experiments: CMS





No particle should go undetected

Production rates at LHC

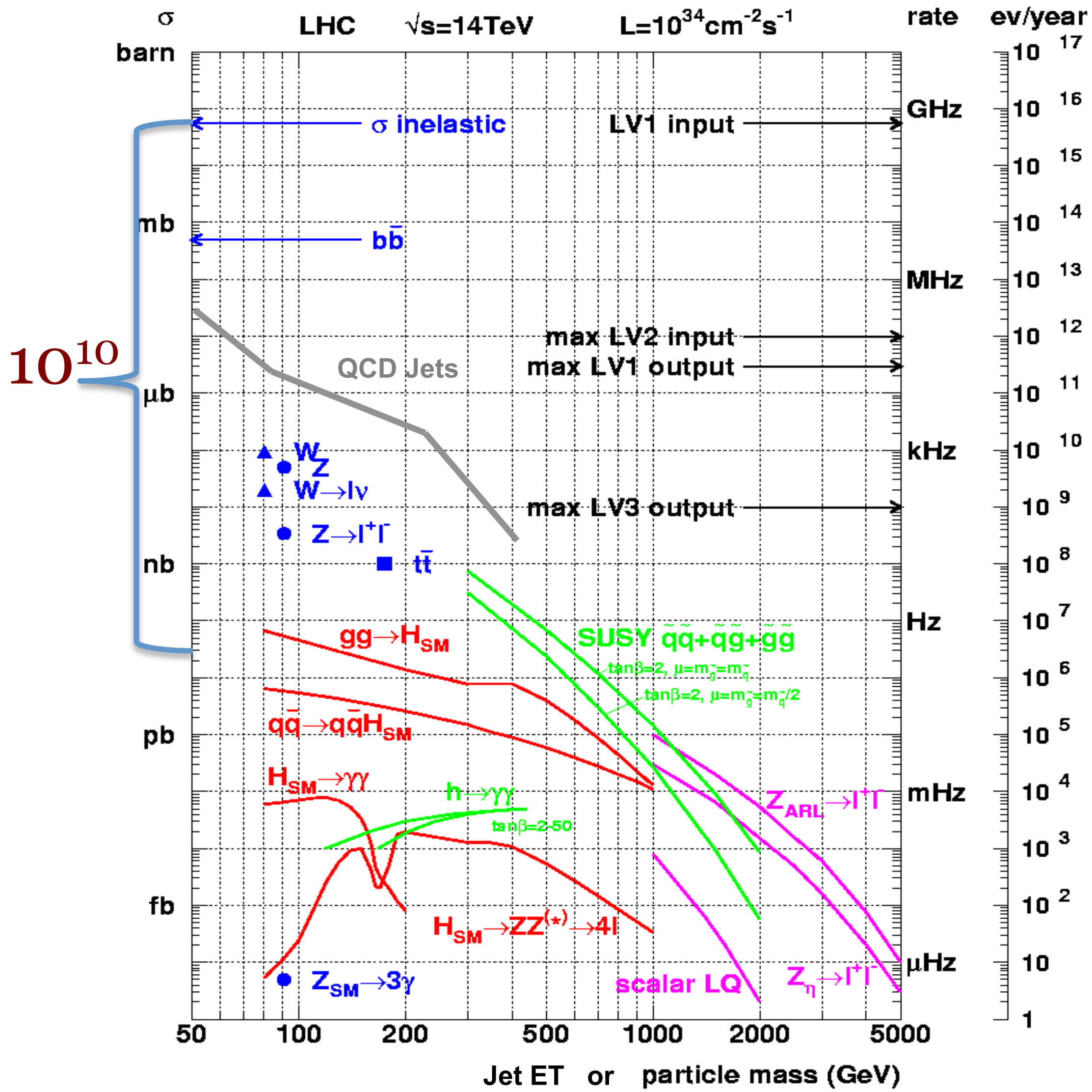
At sqrt(s)=14 TeV

σ_{tot} ~ 105 mb
$\sigma_{elastic}$ ~ 28 mb
σ_{inel} ~ 65 mb

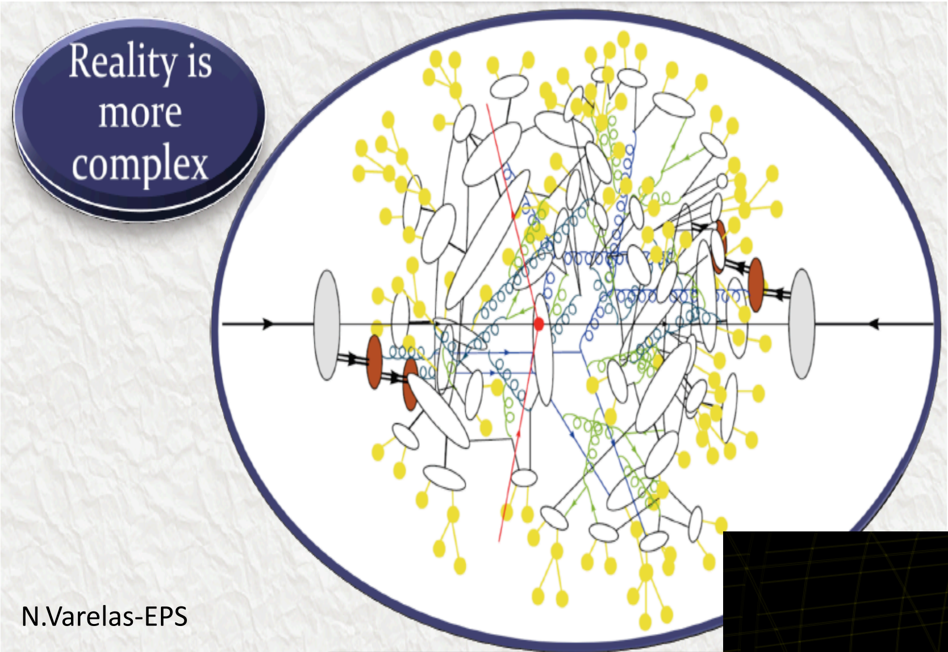
Evt rate $= L.\sigma = 10^{34} \times 65\ 10^{-27}$ /s
$= 6.5 \times 10^{8}$ /s

W→eν	15 events/second
Z→ee	1.5
tt	0.8
bb	10^5
H(200 GeV)	0.001

- **General event properties**
- **Heavy flavour physics**
- **Standard Model physics**
- **including QCD jets**
- **Higgs searches**
- **Searches for SUSY**
- **Examples of searches**
- **for 'exotic' new physics**



The trigger



At LHC the collision rate will be 40 MHz

The Event size ~1 Mbyte

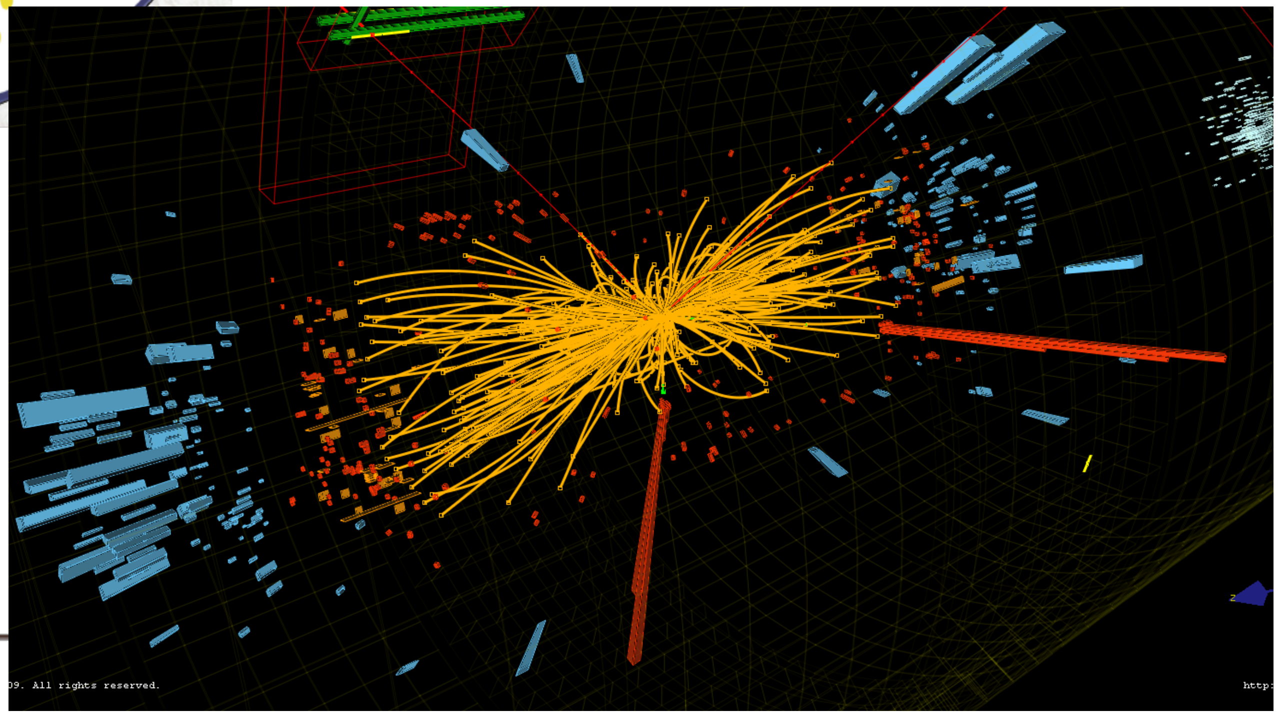
Band width limit ~ 100 Gbyte

→

Mass storage rate ~100 Hz

Thus we should select the events with the "TRIGGER"

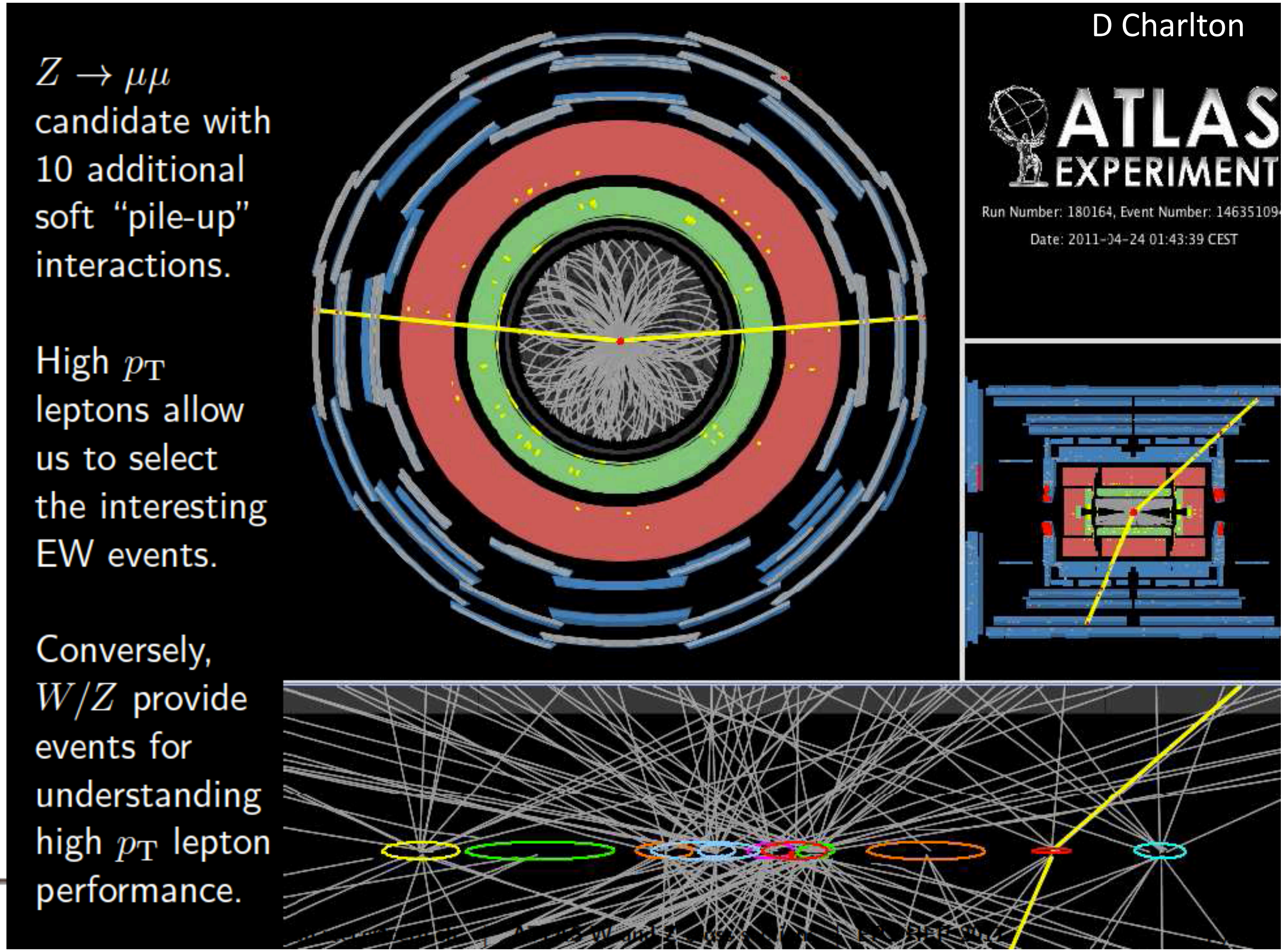
Typical event at LHC



Leptons

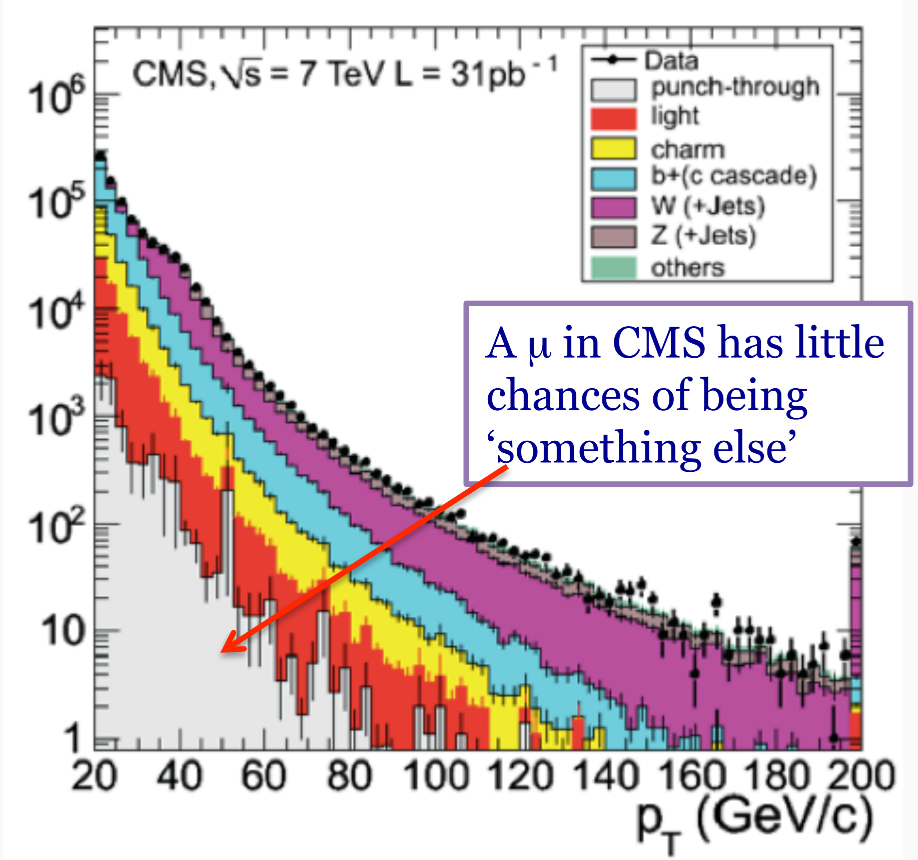
In an hadronic environment, leptons are clean physics objects.
They can be used to trigger the event.
They give access to precision EW physics and searches.

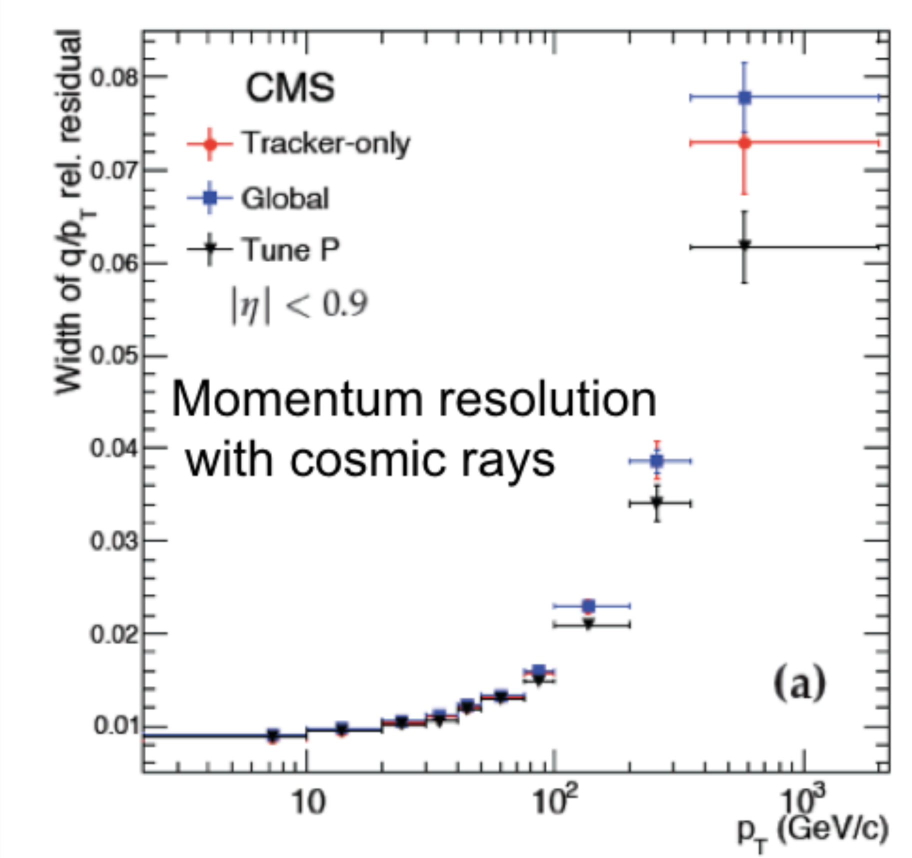
Both the experiments have very high trigger, reconstruction and identification efficiency for the leptons.



Muons

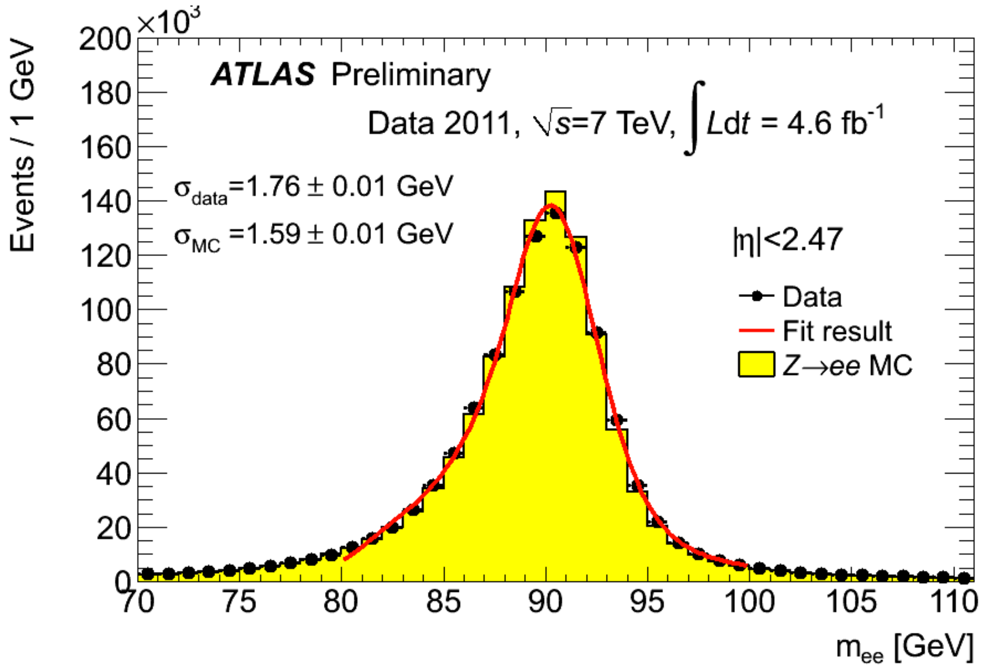
Muons: achieved nominal (or better than) performance

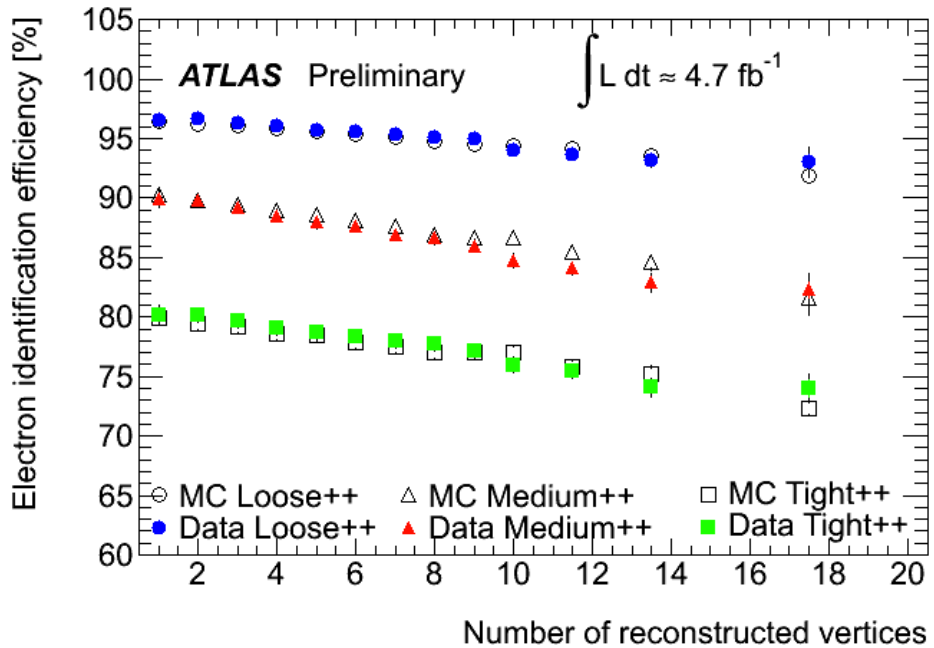




Electrons

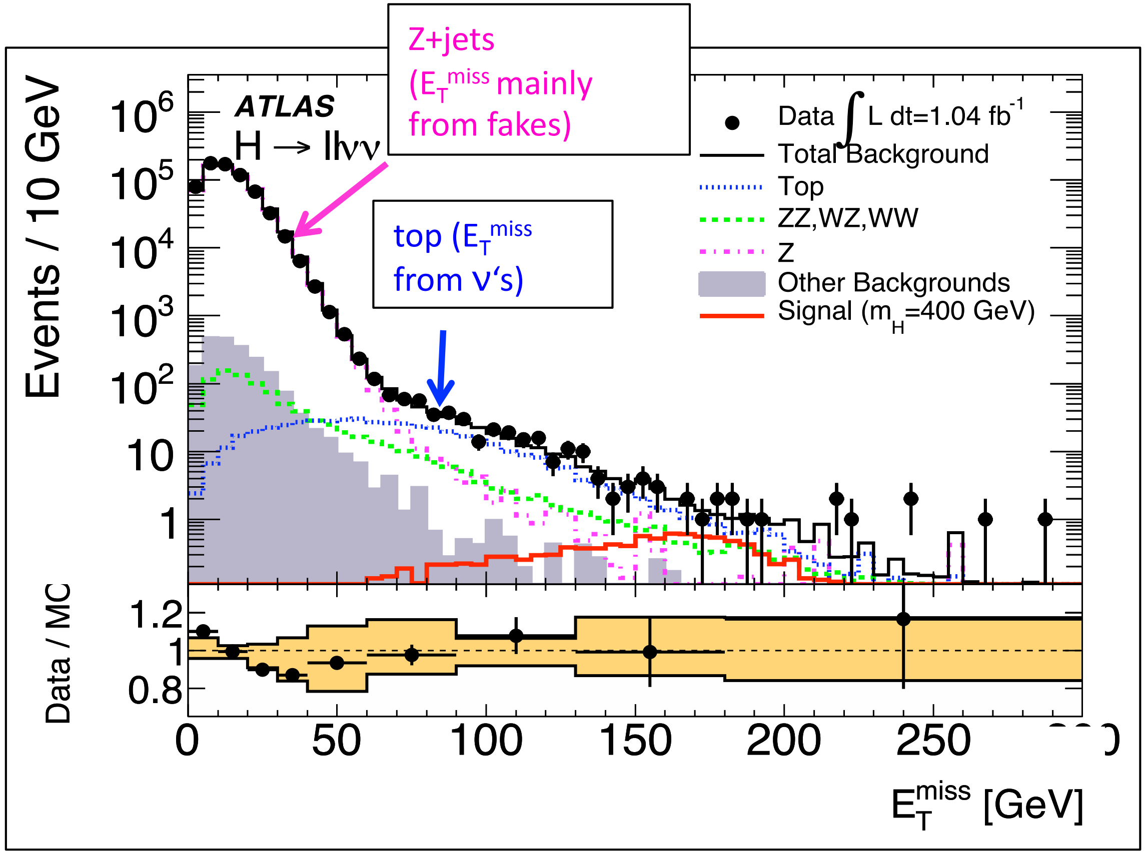
- Electrons: more difficult, but still very clean





E_T missing

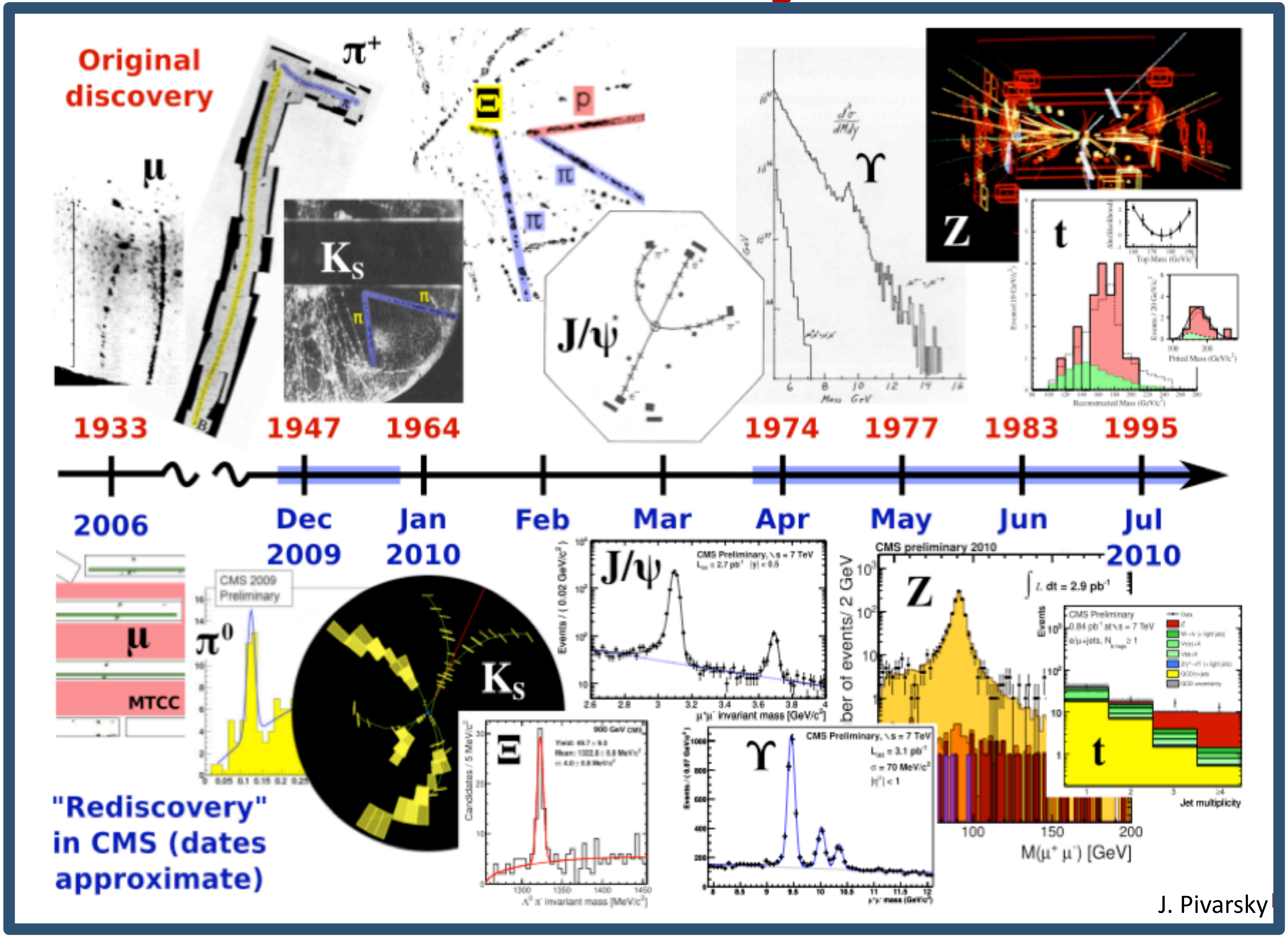
- Excellent performance of E_t^{miss} measurement even with high pile-up.



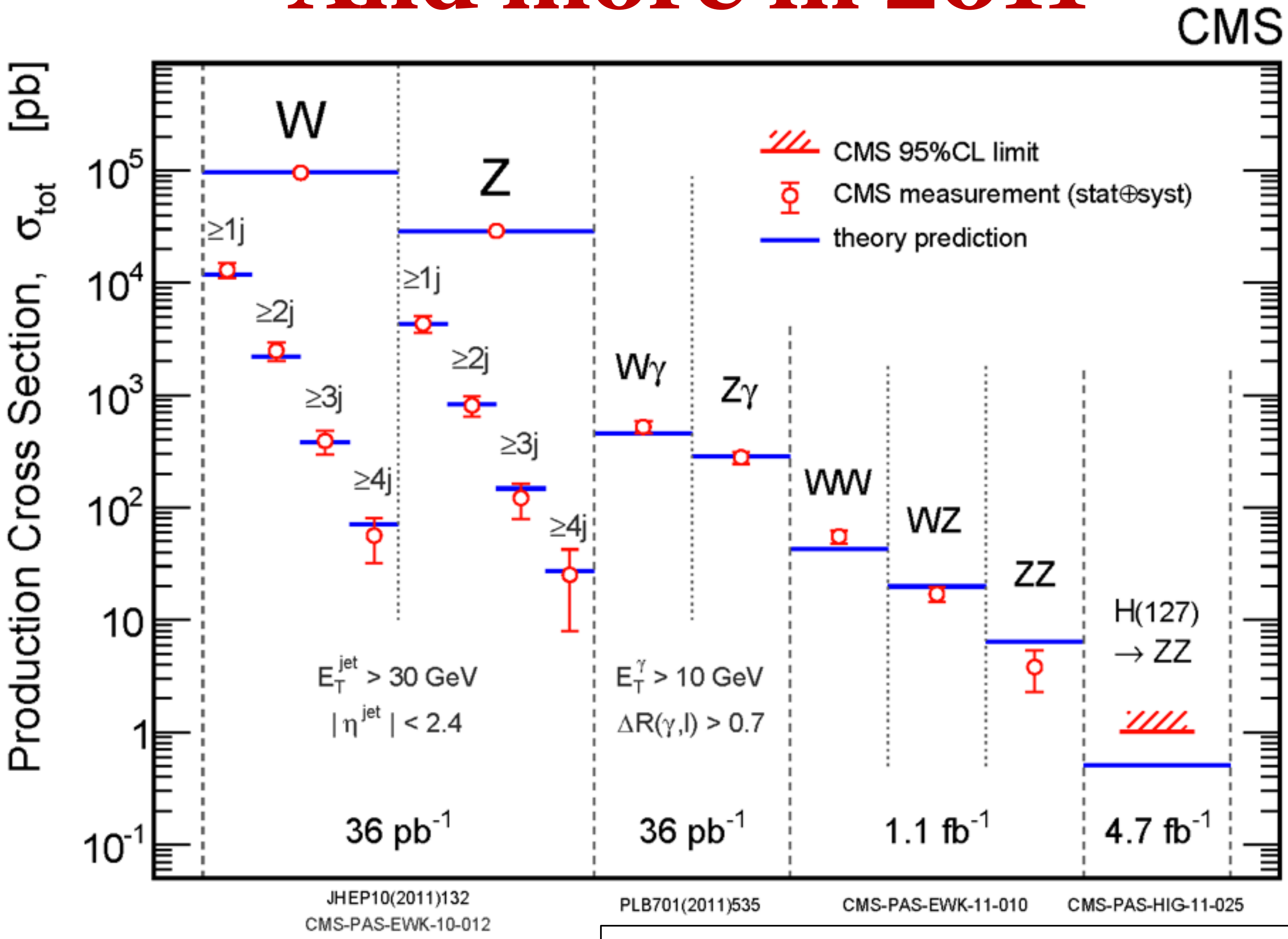
E_T^{miss} spectrum in data for events with a lepton pair with $m_{ll} \sim m_Z$ well described
(over 5 orders of magnitude !)
by various background components.

Note: dominated by real E_T^{miss} from ν's already for $E_T^{miss} \sim 50$ GeV
→ little tails from detector effects !

S.M. rediscovery in 2010

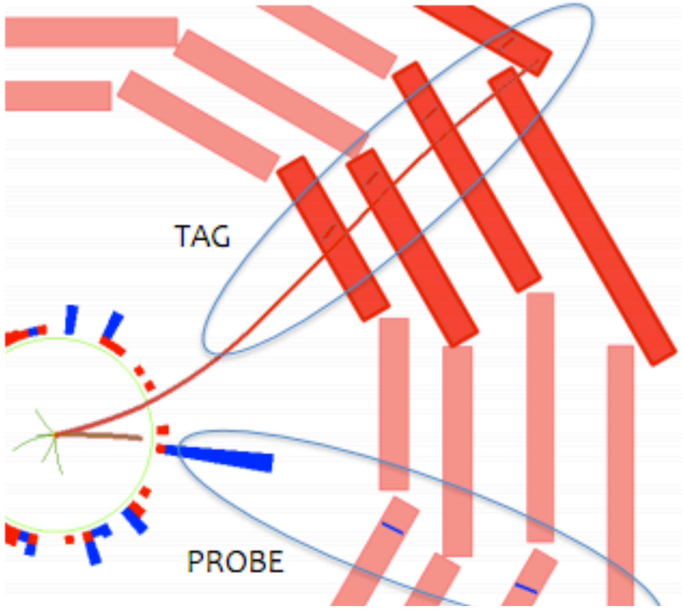


And more in 2011



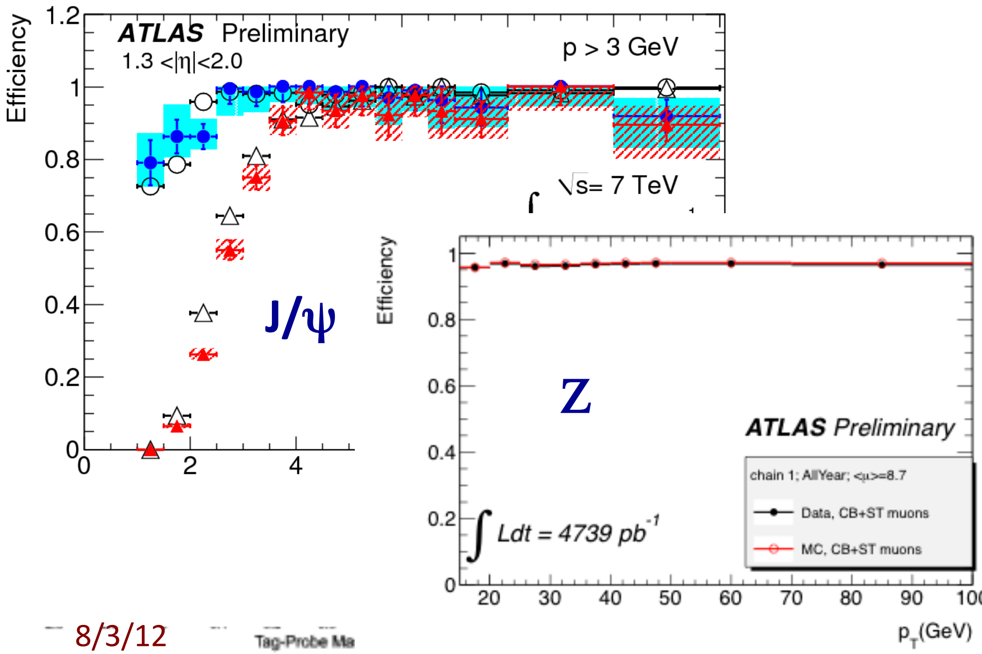
In our present dataset (~ 5 fb^{-1}) we have (after selection cuts):
~ 30 M W→ μν, eν events
~ 3 M Z → μμ, ee events
~ 60000 top-pair events

Performance studies on data



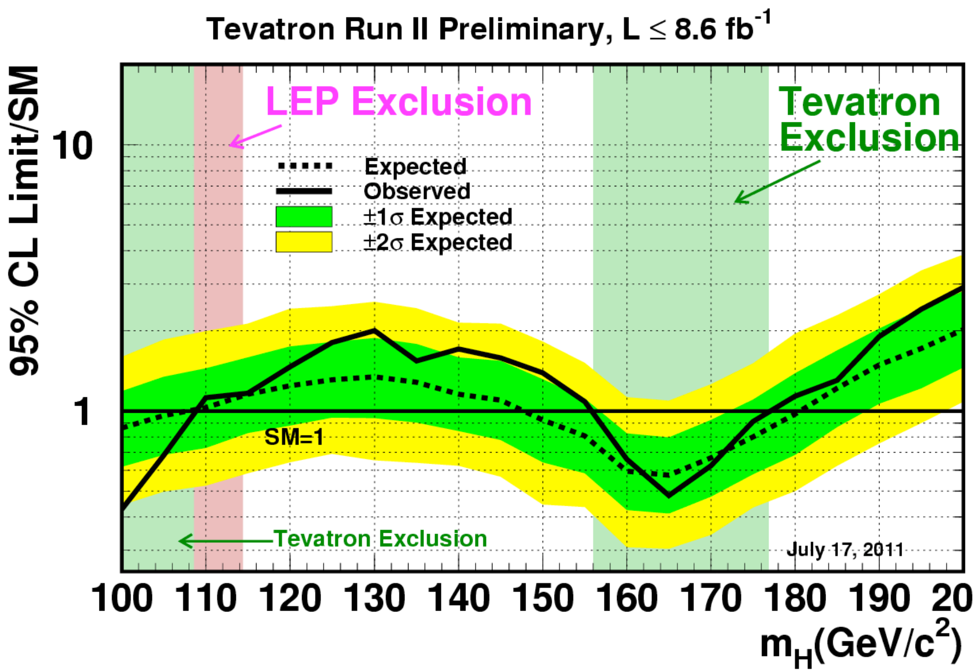
Tag And Probe Method

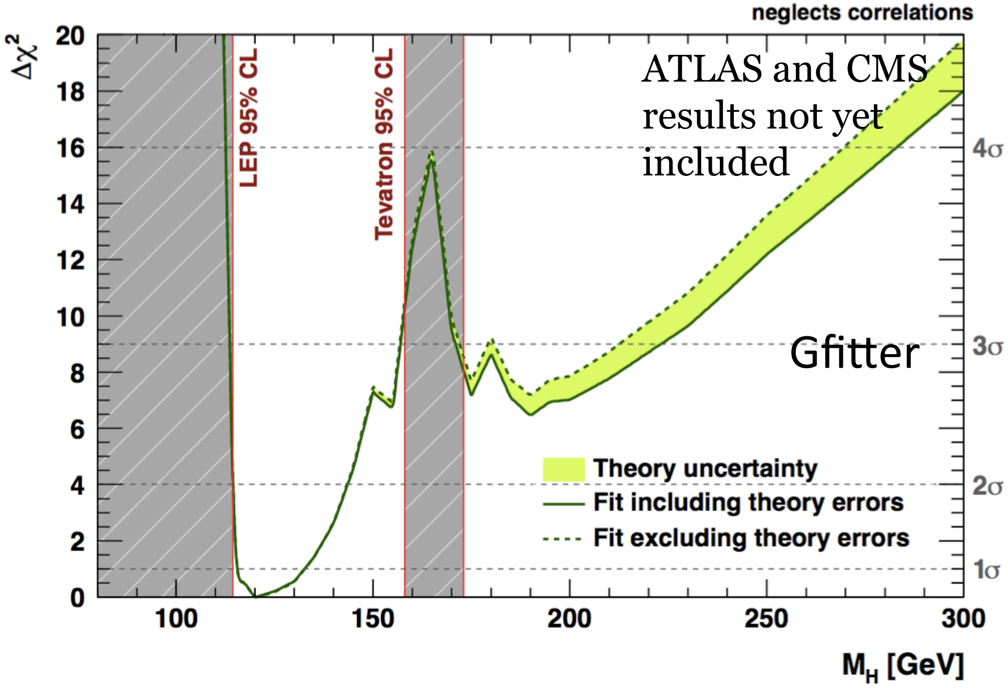
$$\varepsilon_{\mu} = \varepsilon_{reco/(track)} * \varepsilon_{ID/reco} * \varepsilon_{ISO/ID} * \varepsilon_{trigger1leg/ISO}$$



- **Fitting functions** used for the Z (Jpsi) T&P are:
  - Voigtian (Crystal Ball) for the resonance
  - Exponential for the background
- **Systematic uncertainties** on the measured efficiencies are obtained comparing the results on MC with the MC Truth, and in data varying the functional forms used for the fit
- Efficiencies are measured in **p_T/η/Nvtx bins** for different **data-taking periods [only few examples of the results will be presented]**

The Higgs before LHC





- Direct searches
  - LEP: M_H>114.4 GeV at 95% CL
  - Tevatron: $|M_H$-166$|$>10 GeV at 95% CL
- Indirect constraints from precision EW measurements
  - $M_H = 96^{+31}_{-24}$ GeV, M_H<169 GeV at 95% CL (standard fit)
  - $M_H = 120^{+12}_{-5}$ GeV ,M_H<143 GeV at 95% CL (including direct searches)
- SUSY prefers a light Higgs

The LHC Higgs Cross Section WG

- About 2 years ago, exactly the day LHC was delivering the first collision to the experiments, a group formed by TH and EXP (the LHC Higgs Cross Section WG) was founded in order to provide precision Higgs predictions.

- The goal was to access the most advanced theory predictions for the Higgs Cross Section and Branching Ratio: central value and uncertainties

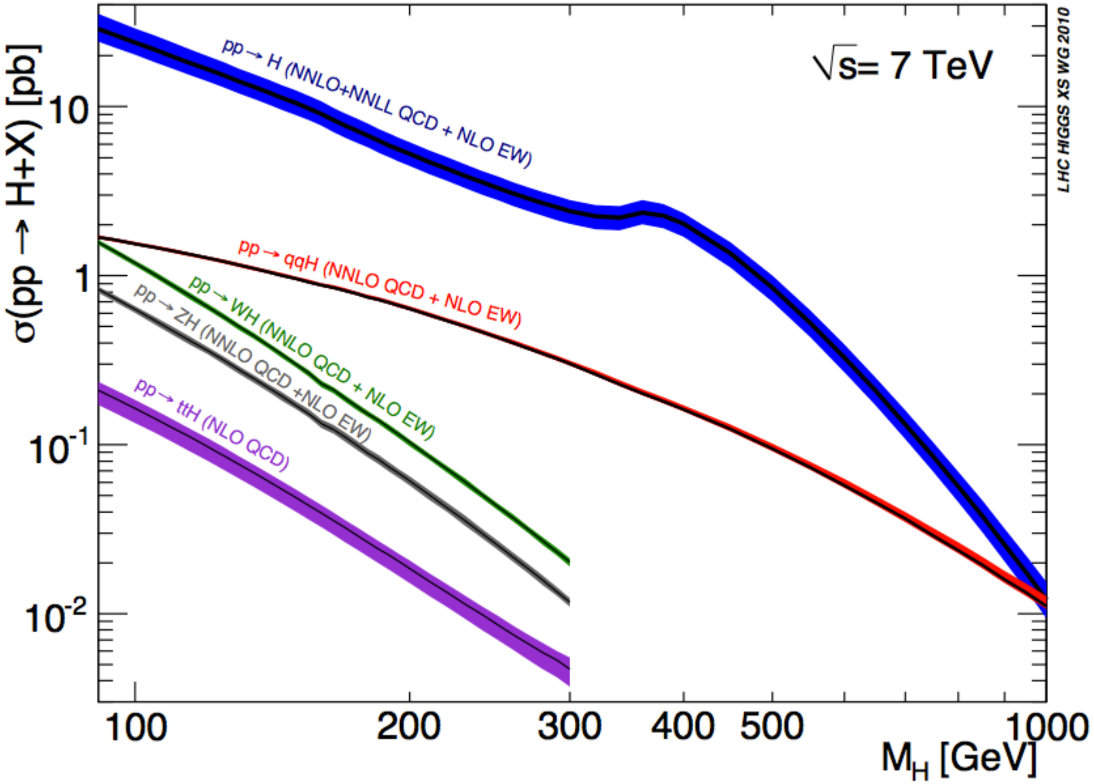
⬇

- Experiments are thus from day "1" coherently using the **COMMON INPUTS** provided by the LHC H XS WG (CERN-2011-002, "YR1", and CERN-2012-002, "YR2").

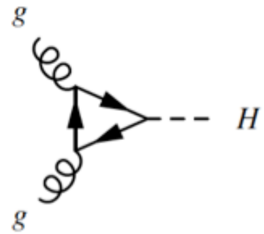
  This facilitates the comparison and the combination* of the individual results

*LHC Higgs Combination group. Only experimentalists

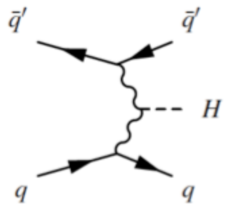
Inclusive Cross Sections



ggF: NNLO+NNLL QCD + NLO EW

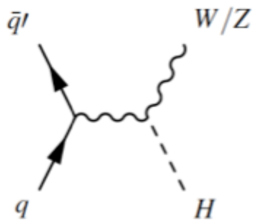


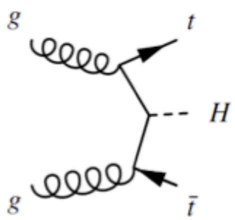
qqH: NNLO QCD + NLO EW



WH: NNLO QCD + NLO EW

ZH: NNLO QCD + NLO EW





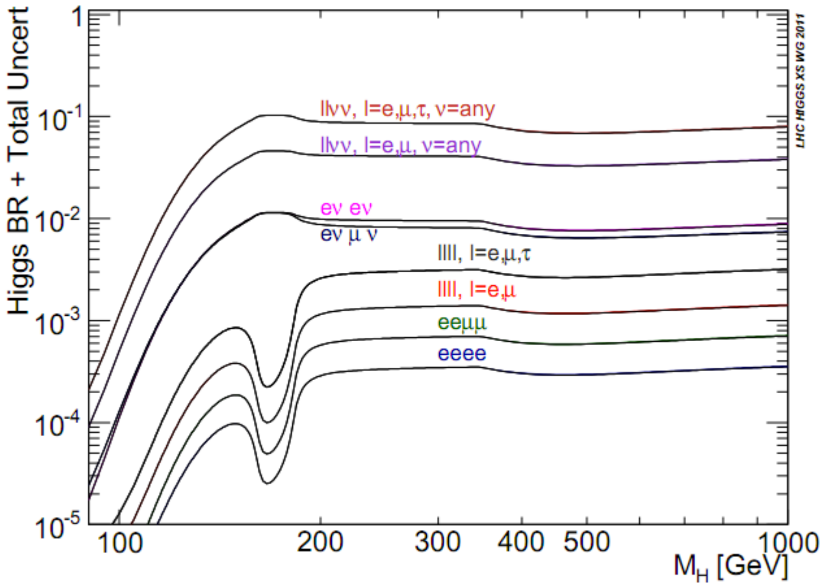
ttH: NLO QCD

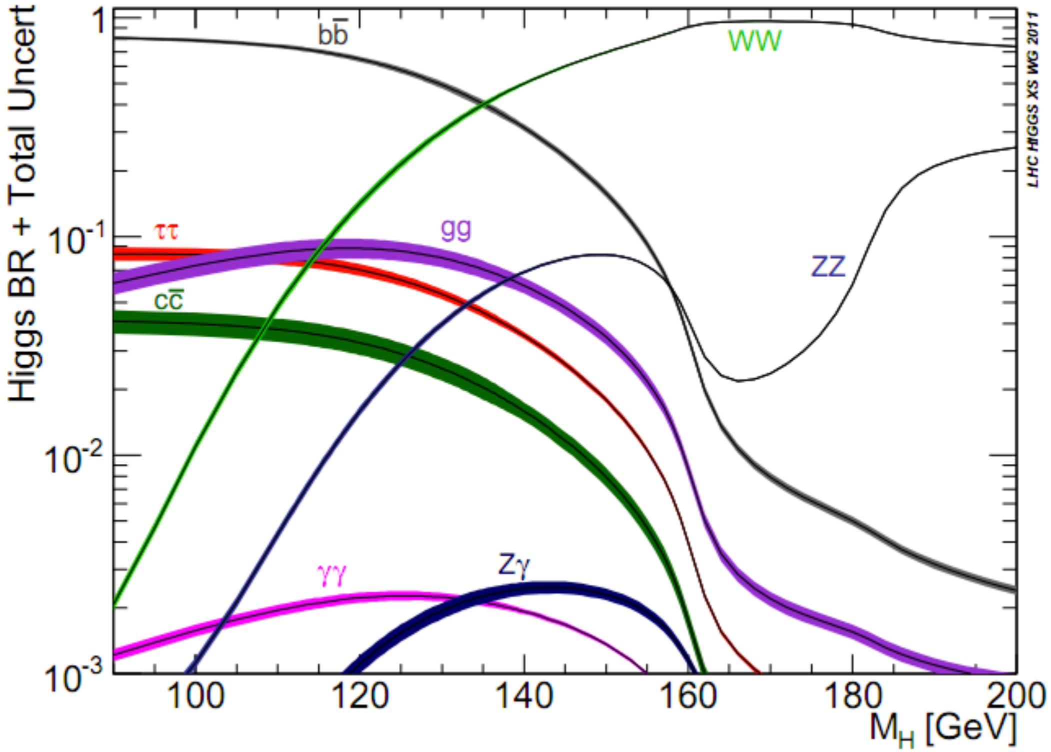
	$K_{NNLO/NLO}$ ($K_{NLO/LO}$)	Scale	PDF+a_S	Total error
ggF	+25% (+100%)	+12% -7%	±8%	+20 -15%
VBF	<1% (+5-10%)	±1%	±4%	±5%
WH/ ZH	+2-6% (+30%)	±1%	±4%	±5%
ttH	- (+5-20%)	+4% -10%	±8%	+12 -18%

Branching Ratios

$$\Gamma_H = \Gamma^{HD} - \Gamma^{HD}_{ZZ} - \Gamma^{HD}_{WW} + \Gamma^{Proph.}_{4f} + \Gamma^{HD}_{\gamma\gamma}\delta^{QED}_{\gamma ff}$$

MH	Decay	THU	PU	Total
120 GeV	H→γγ	±2.9%	±2.5%	±5.4%
	H→bb	±1.3%	±1.5%	±2.8%
	H→ττ	±3.6%	±2.5%	±6.1%
150 GeV	H→WW	±0.3%	±0.6%	±0.9%
	H→ZZ	±0.3%	±0.6%	±0.9%

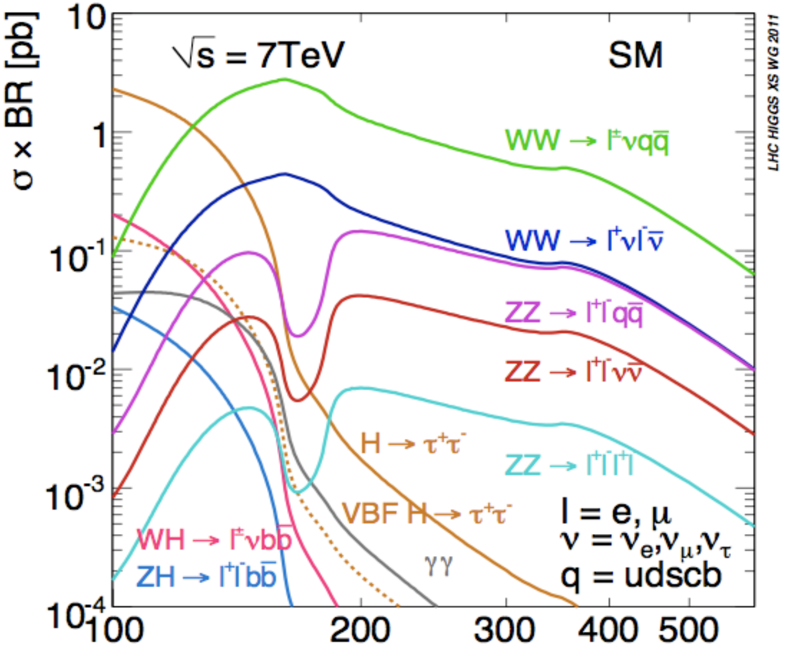




HD=HDecay

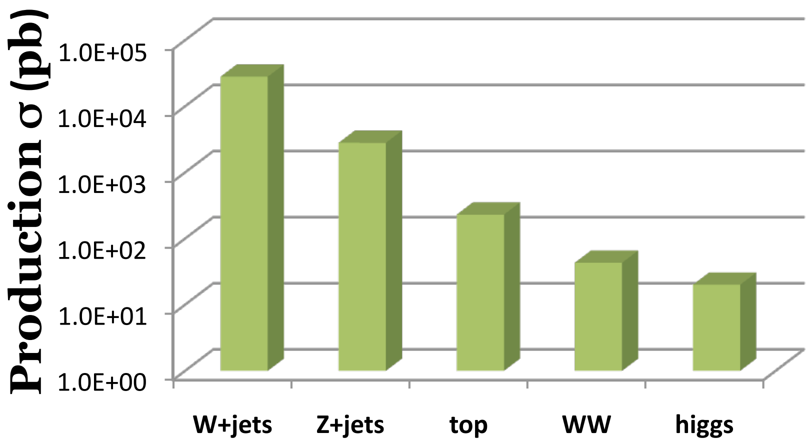
Proph = Prophecy4f NLO QCD+NLO EW

Higgs search strategy

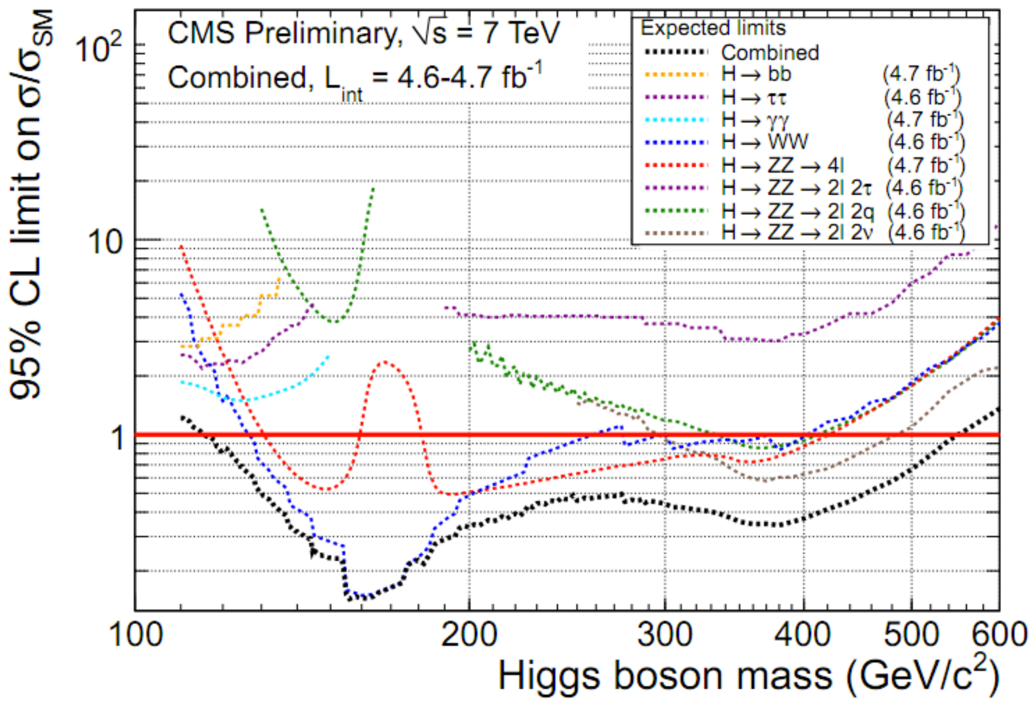


Events expected to be produced with L=1 fb^{-1}

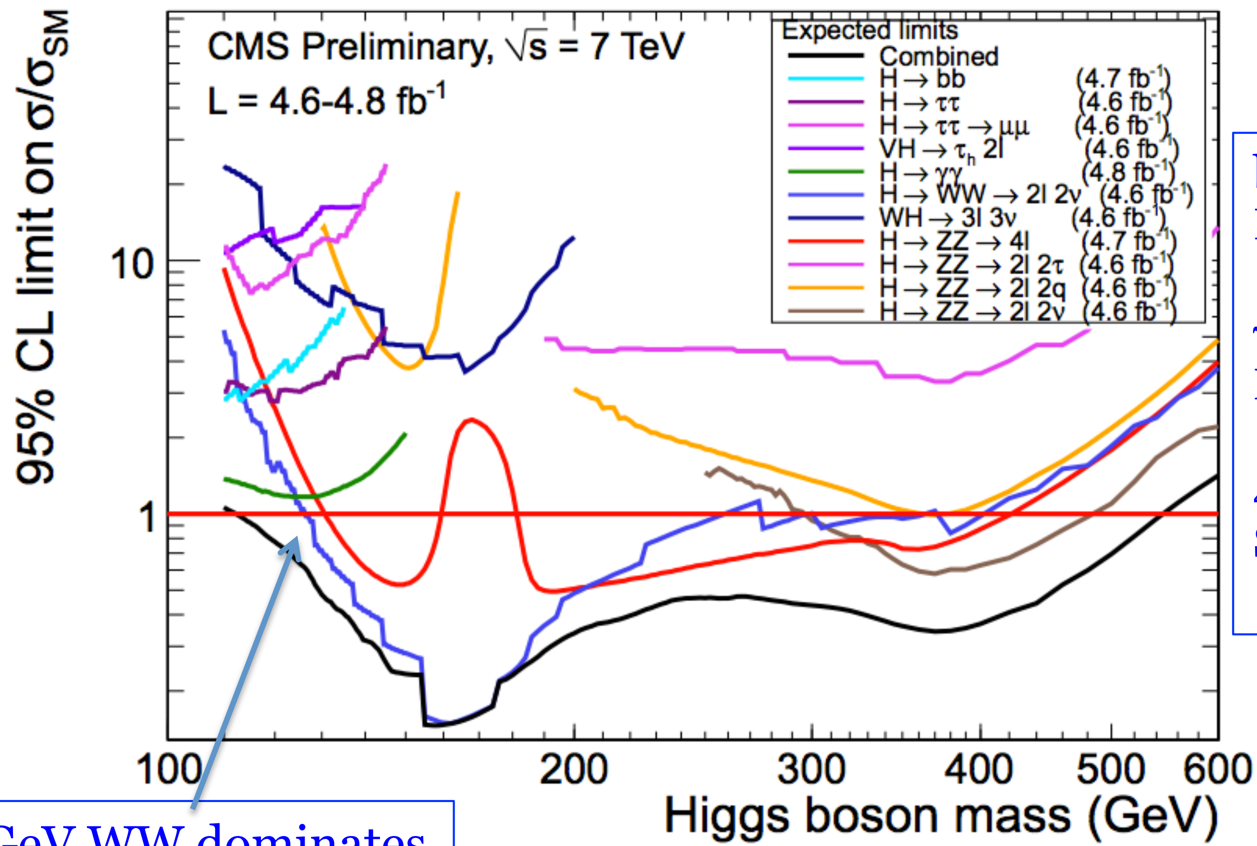
m_H, GeV	WW→lvlv	ZZ→4l	γγ
120	127	1.5	43
150	390	4.6	16
300	89	3.8	0.04



Higgs production cross section tiny compared to other QCD and EWK processes



Higgs search strategy



bb/ττ/WW
Poor mass resol

γγ and 4l
Excellent mass resol

4l is ~backg free
Single event has
an impact

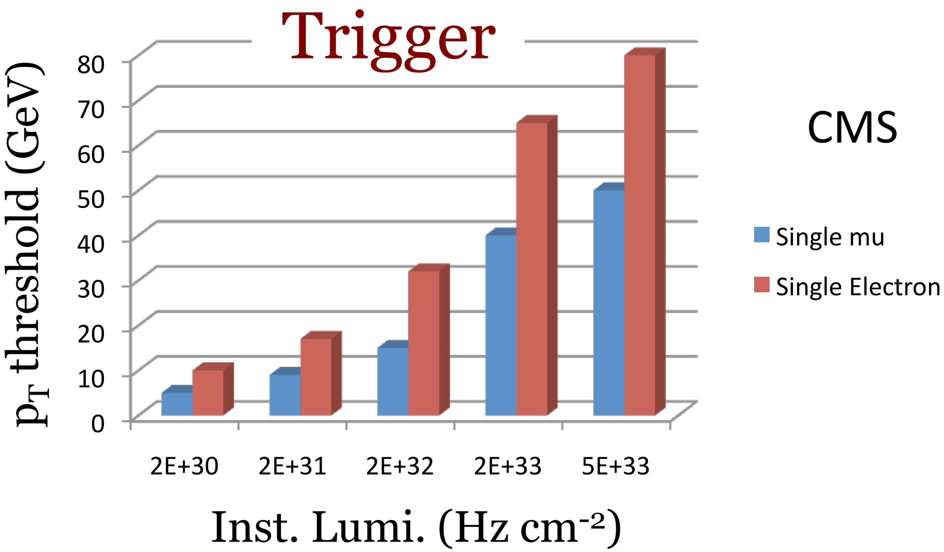
Above ~123 GeV WW dominates
At lower masses γγ takes over

m_H < 135 GeV
H -> γγ exclusion and discovery
H -> 4l exclusion and discovery
H -> WW/ττ/bb

140 < m_H < 180 GeV
H -> WW->2l2ν
ZZ->4l also

m_H>180 GeV
H ->ZZ channels for discovery
H->WW->lνjj

The challenge of the high Lumi

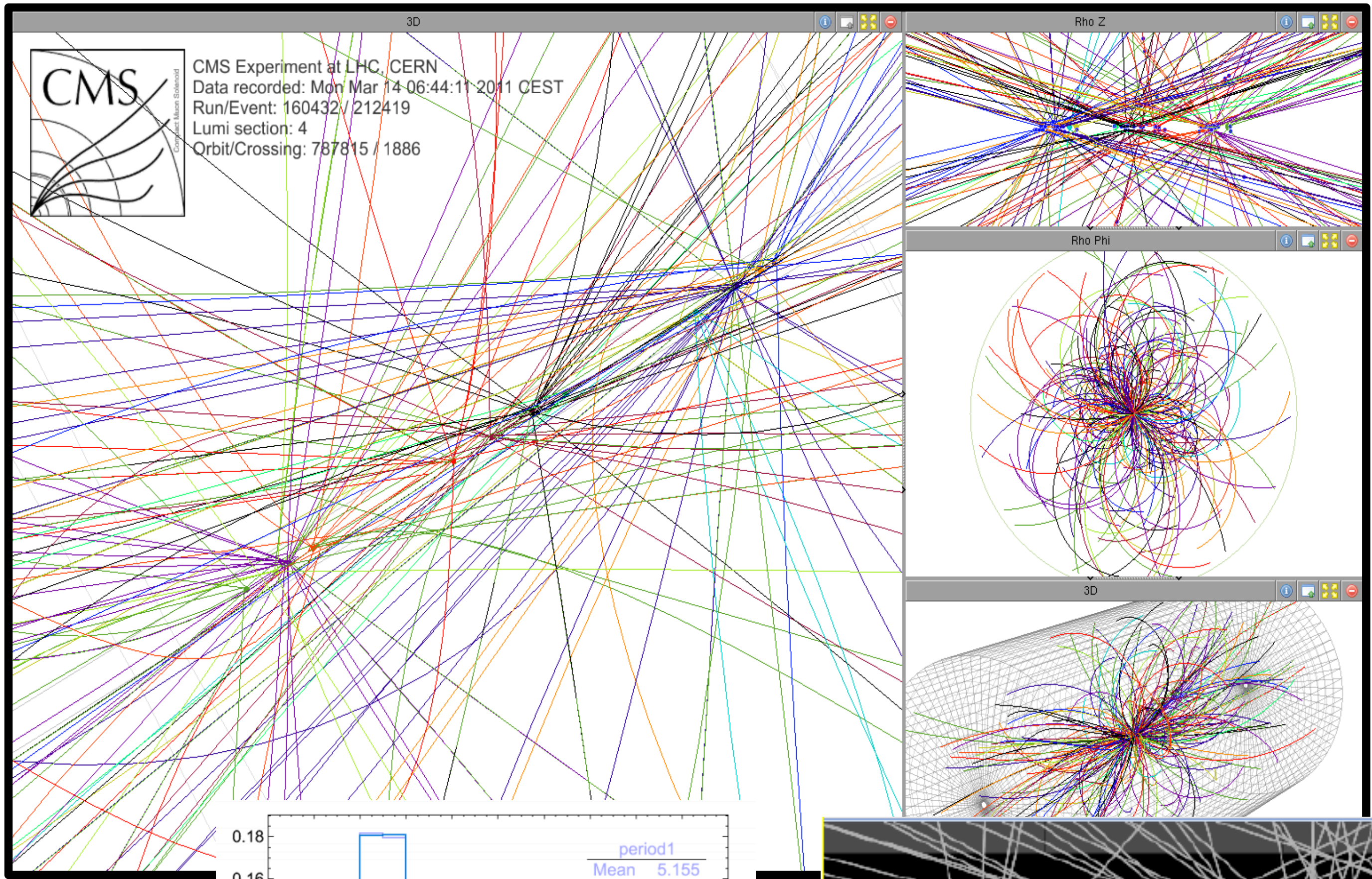


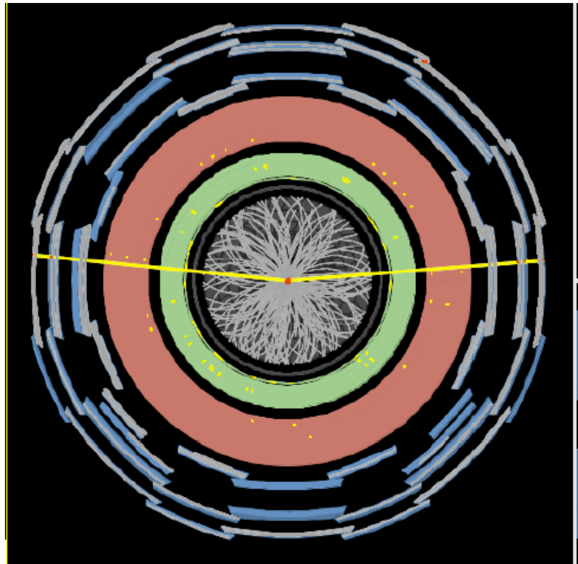
Evolution of trigger threshold for single non isolated leptons vs inst. lumi

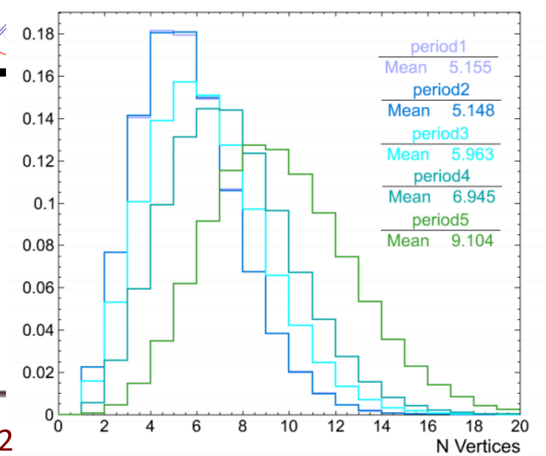
- Inclusive triggers have reached such high thresholds that can not be used anymore for many analyses
- In the context of each analysis dedicated triggers suitable for the specific final state have to be devised:
  - H->WW->lνlν, H->ZZ-> 4l: Double mu and double electron thresholds at (17,8) GeV
  - H->γγ: Double photon (36,18) GeV
- Challenging for the low mass Higgs searches

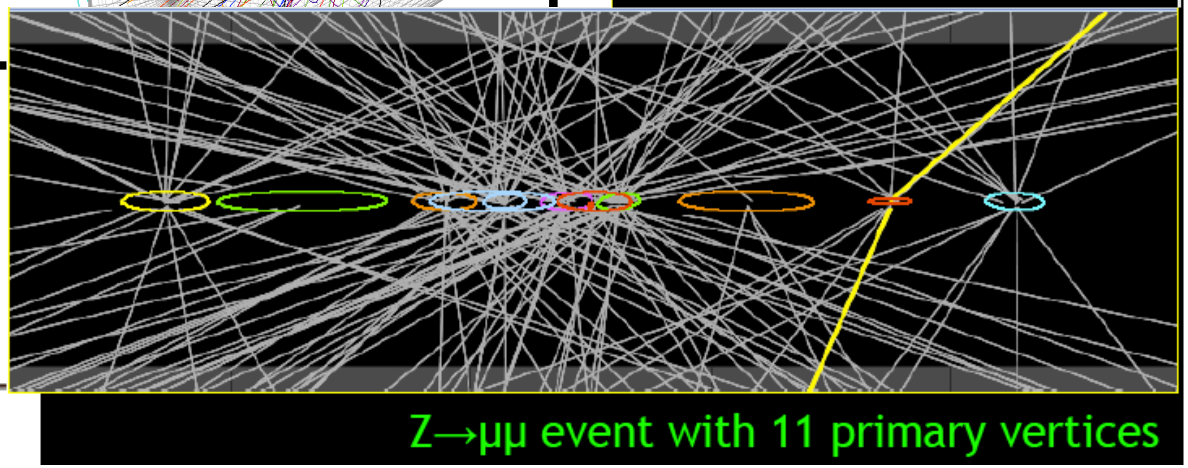
Pile-up: a “manageable nuisance”

V.Sharma



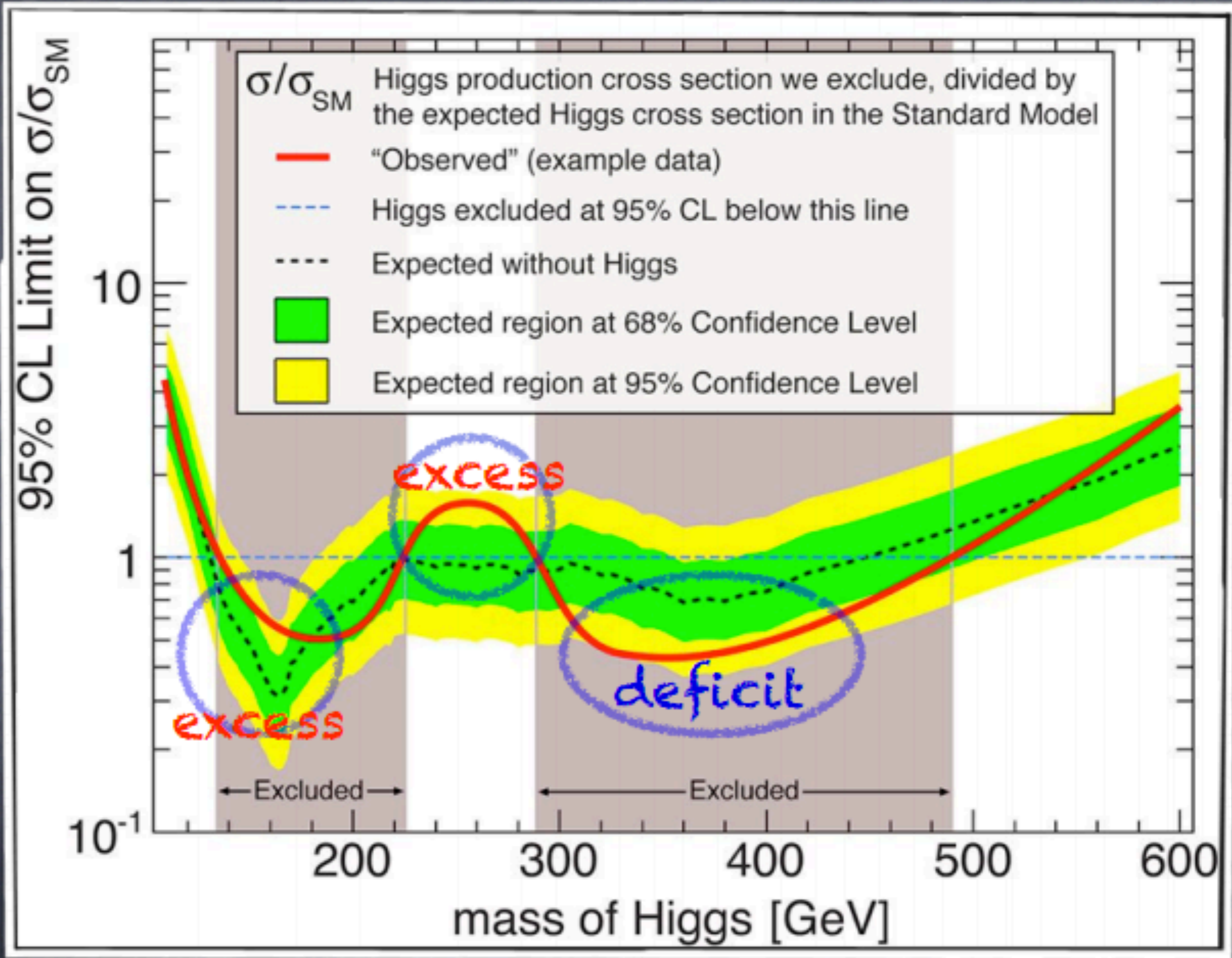






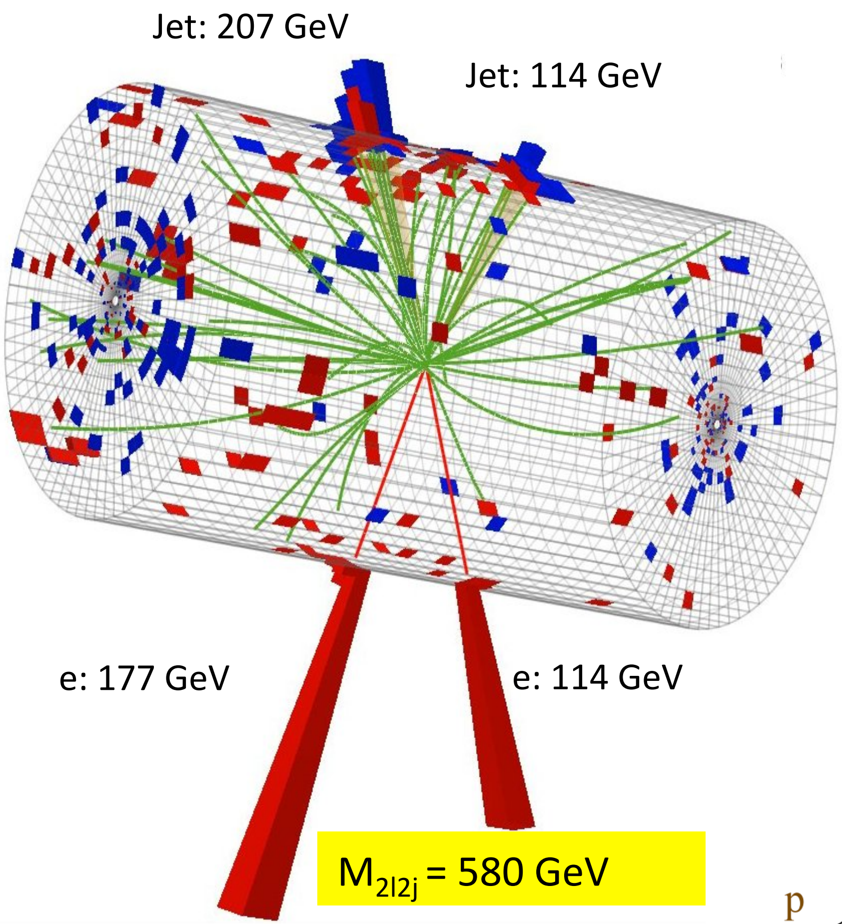
Understanding The Yellow and Green Bands

$$\mu = \frac{\sigma}{\sigma_{SM}}$$

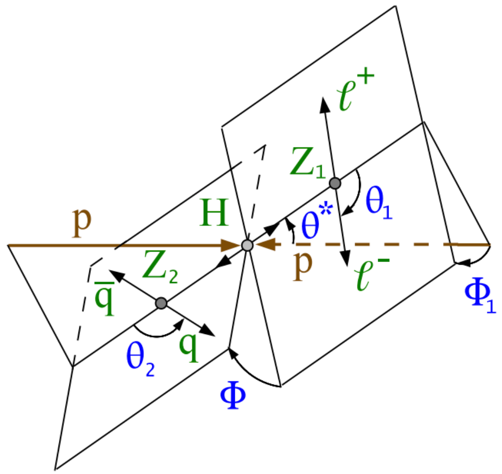


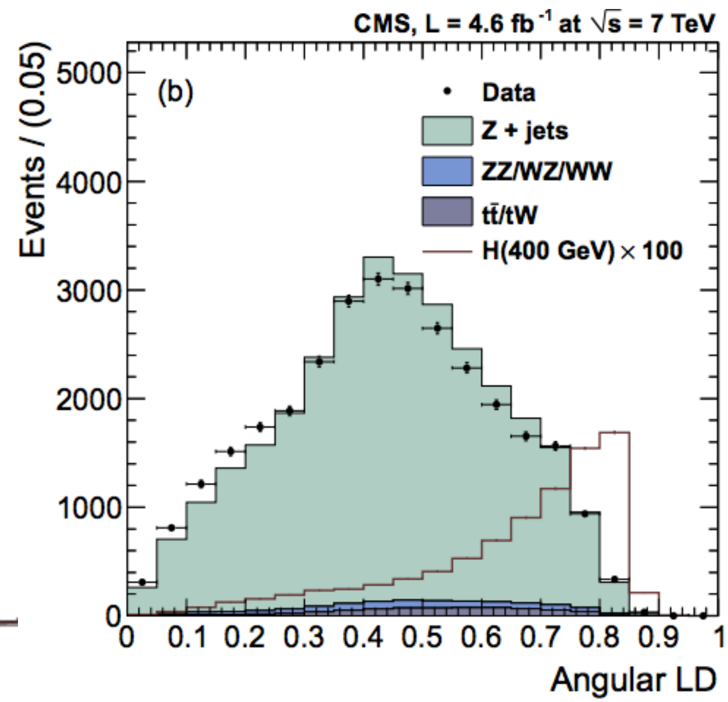
The High Mass

H→ZZ→llqq

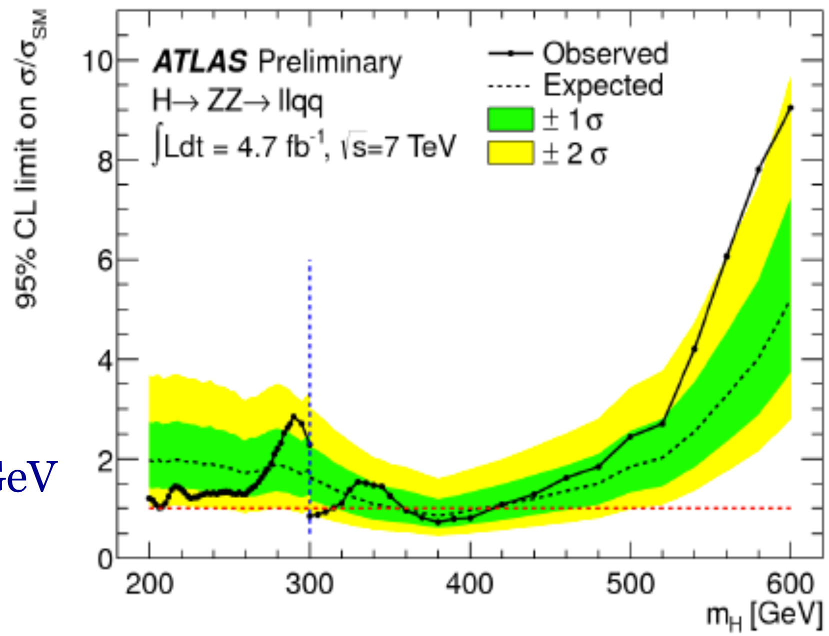


- Highest rate amongst all H → ZZ final states
- Search for a peak (σ~10 GeV) in M_{2l2j} distribution
- Events categorized by presence of 0, 1, 2 b-jets
- Major background: Z+jets ; ttbar suppressed by ME_T requirement
- CMS: Use 5 angles of scalar H → ZZ → 2l2q in a likelihood discriminant
- Background shape, normalization ← data sideband

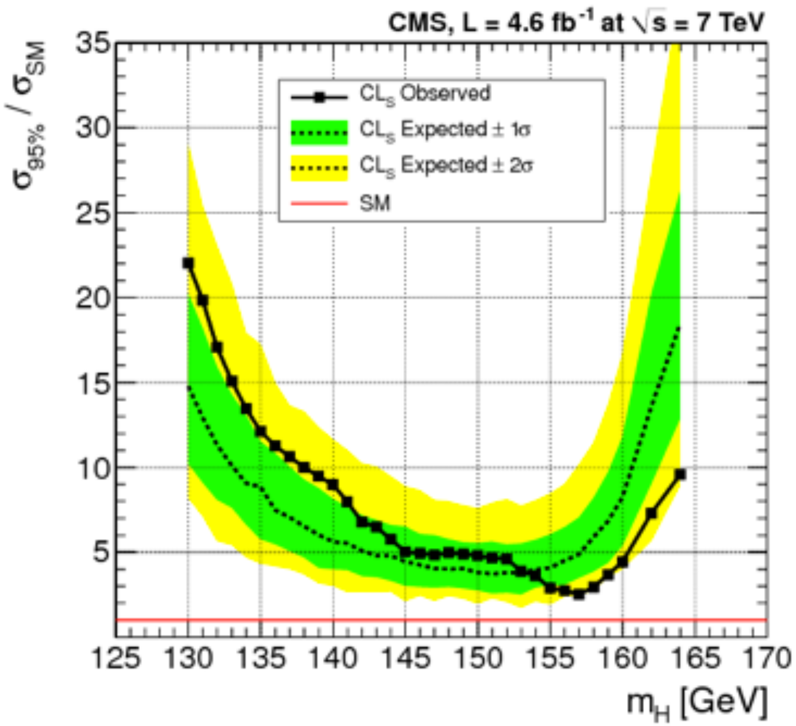


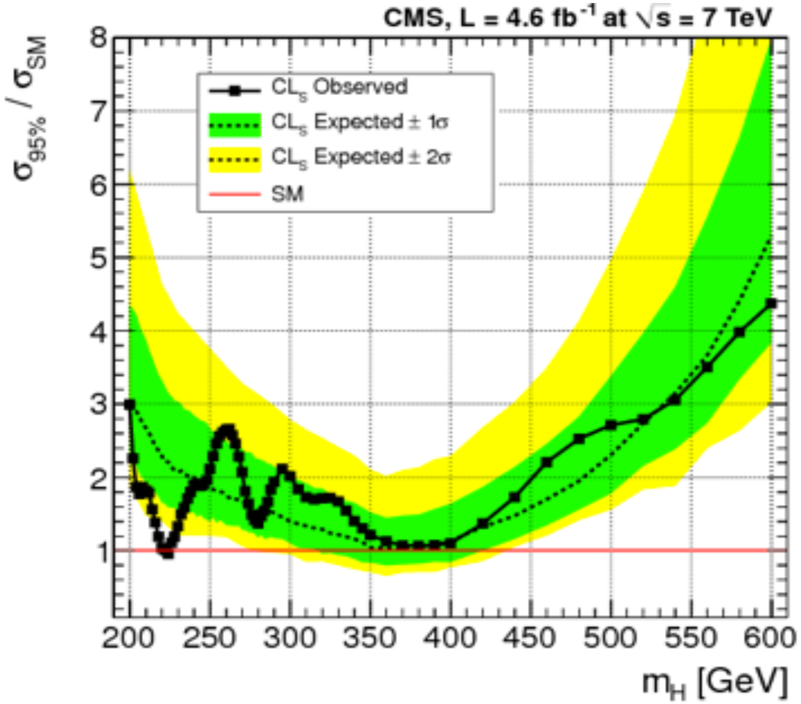


H → ZZ → llqq

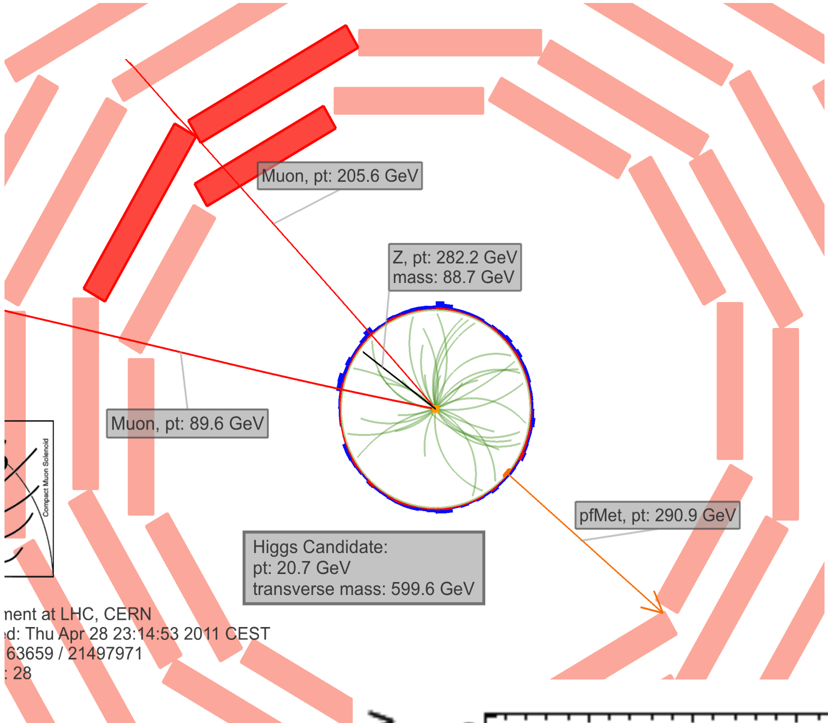


Atlas: Expected Exclusion: 360 – 400 GeV
Observed Exclusion: 300-310, 360-400 GeV

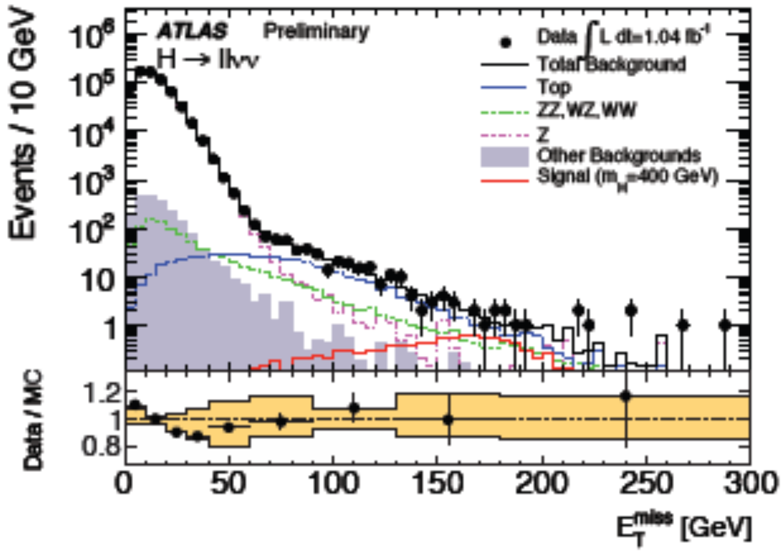


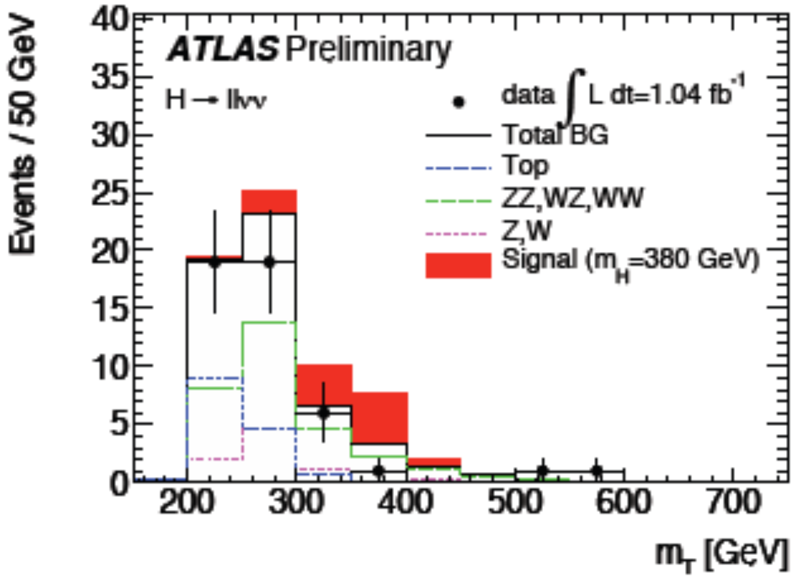


H→ZZ→llνν

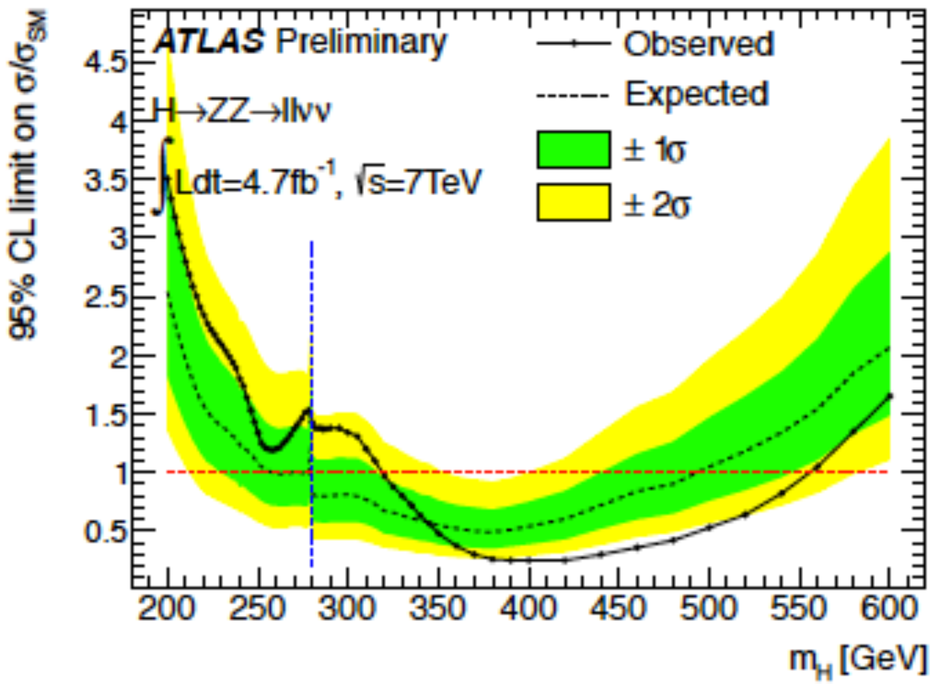


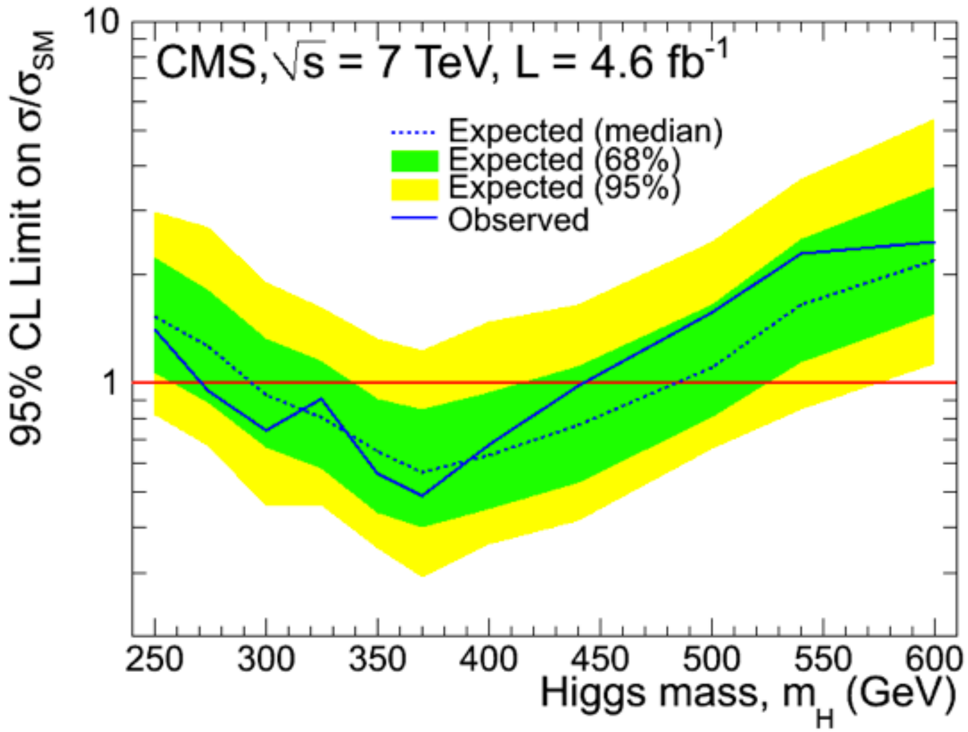
- Z→ ll candidate : M_Z ± 15 GeV; P_T (ll) > 25 GeV
- Use $M_T{}^2 = (\sqrt{P_{TZ}{}^2 + M_Z{}^2} + \sqrt{MET^2 + M_Z{}^2})^2 - (\vec{P_{TZ}} + M\vec{E}T)^2$
- Major backgrounds: Z+Jets, ttbar & WZ
  - ME_T requirement to suppress Z + jets by x10^5
  - Anti b-tag to suppress ttbar
- Residual ZZ, WZ background estimate from MC
- Residual backgrounds estimated from data
  - γ + jets (for Z+Jets) ; eμ sample (for ttbar +WW)





Results for llνν

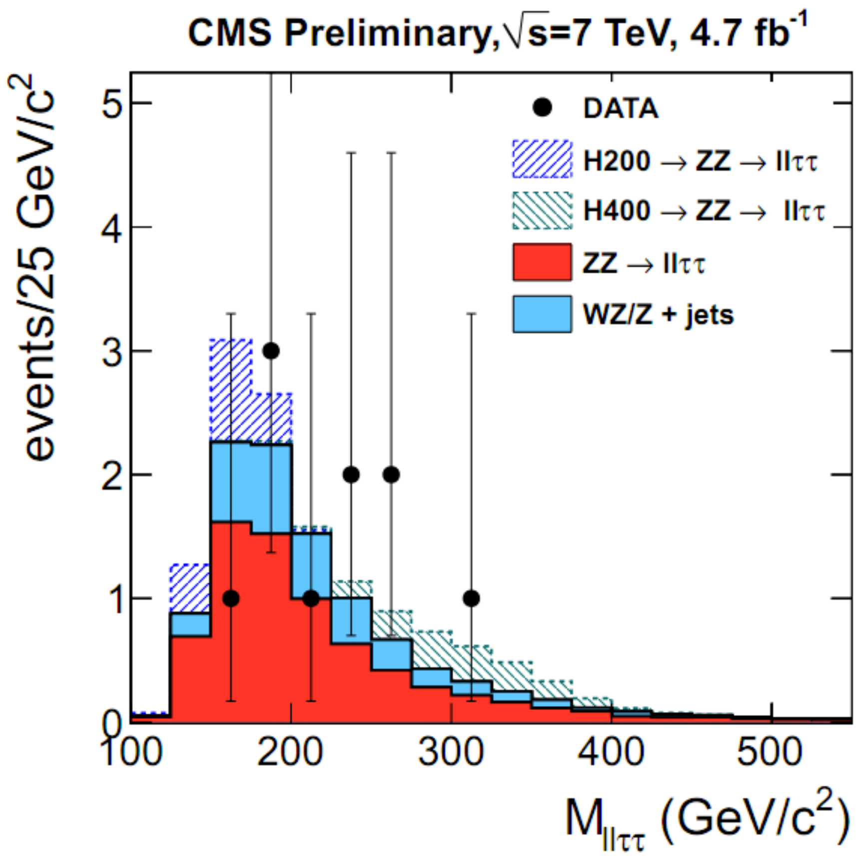


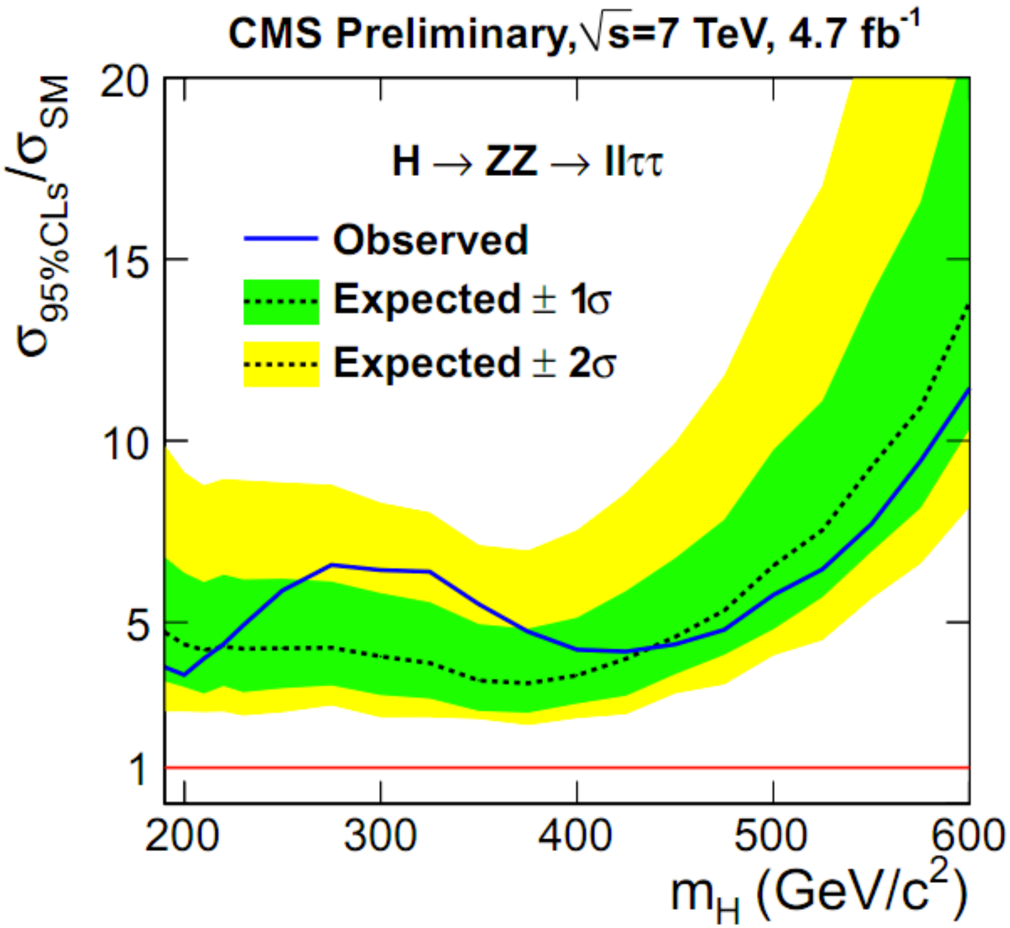


ATLAS: Exp excl: 260-490 GeV
Obs excl: 320-560 GeV

CMS: Exp excl: 290- 490 GeV
Obs excl: 270 – 440 GeV

CMS: H → ZZ → 2l 2τ

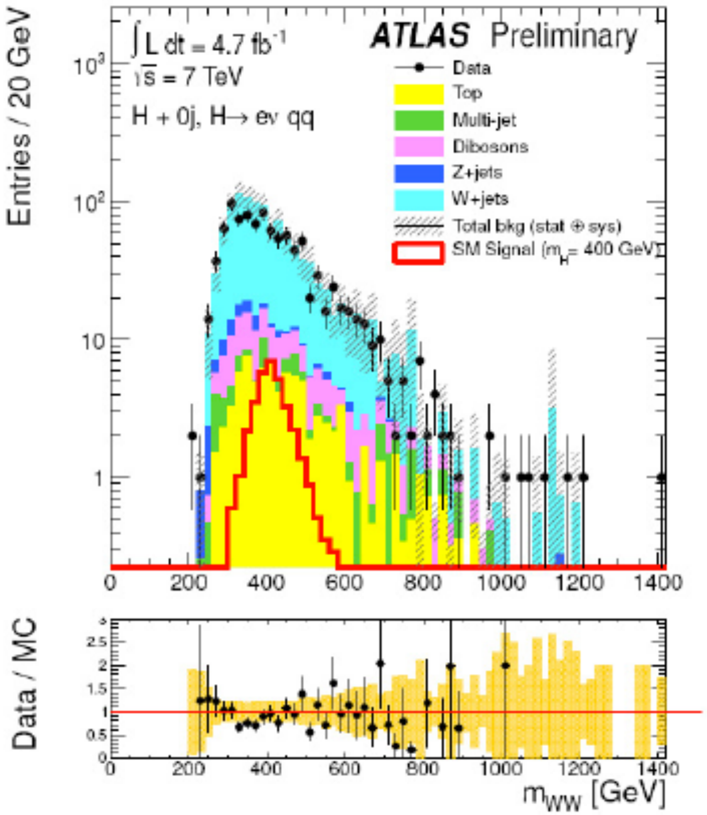


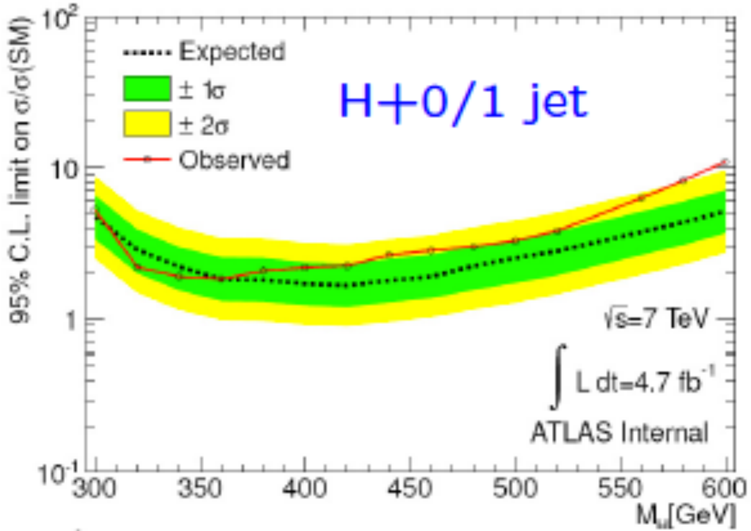


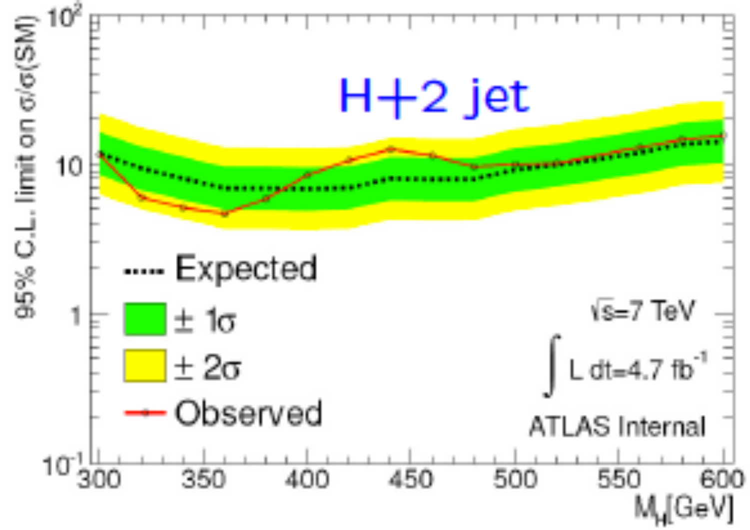
- Using both $\tau_{had}\tau_{had}$ and $\tau_{had}\tau_{l}$ final states
- Requires $30<M_{\tau}<80$ GeV

ATLAS: H → WW →lljj

- Invariant mass reconstruction imposing m(lv)= M(W)
- Analysis divided into jet categories: 0.1,2 (VBF) jets.
- Background from the fit to the lvjj mass spectrum
- Major systematic uncert:
  jet energy scale and resolution (10-20 %)
  pile-up (10-15%)

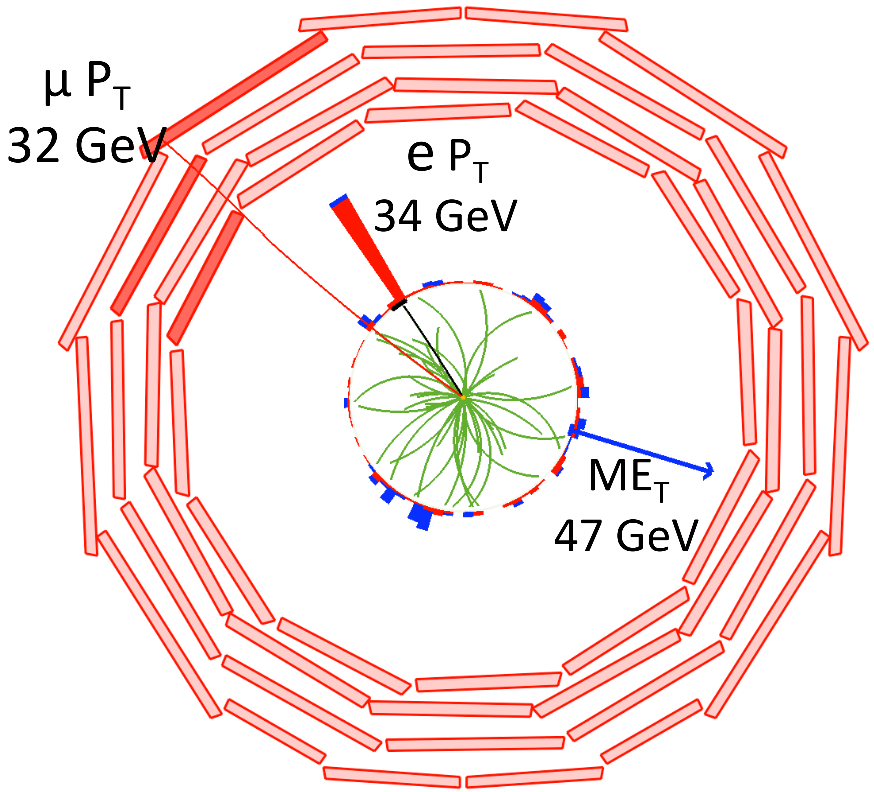






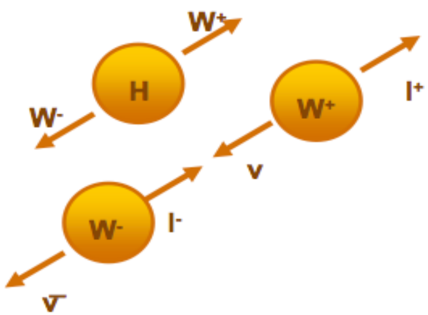
The Low Mass

$H \rightarrow WW \rightarrow l\nu l\nu$

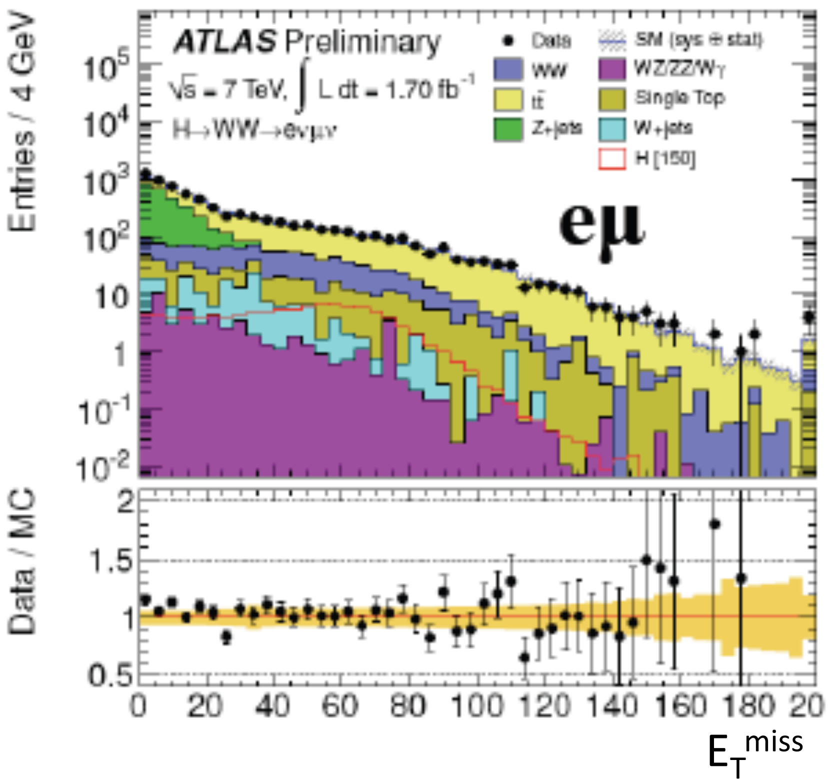


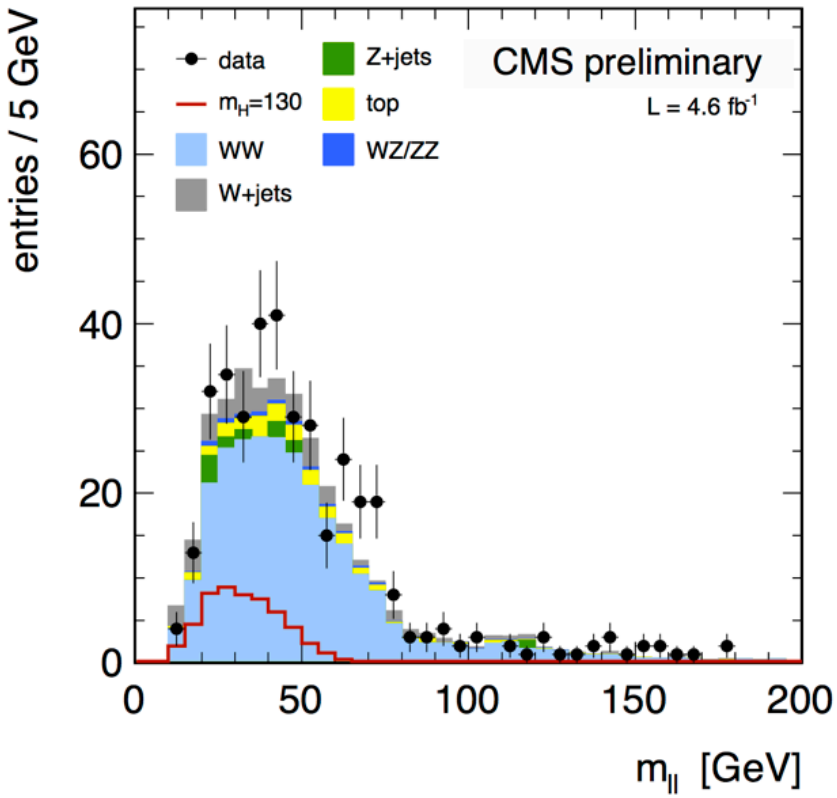
- Channel with highest sensitivity
- No mass reconstruction, signal extraction from event counting
- Clean signature:
  - 2 isolated, high p_T leptons with small opening angle
  - High ME_T
  - Analysis performed on exclusive jet multiplicities (0, 1, 2-jet bins)
- Analysis optimized depending on the Higgs mass hypothesis
  - p_T^l, M_{ll}, M_T, Df as discriminating variables
  - VBF selections for the 2-jet case

Vectors from the decay of a scalar and V-A structure of W decay lead to small leptons opening angle (especially true for on-shell Ws)



H →WW



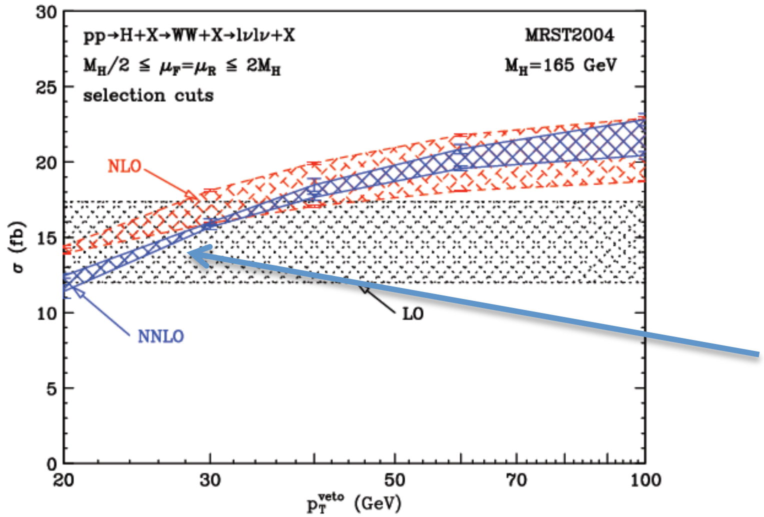


- Drell –Yan: Suppressed by M_{ll} and ME_T cuts (pileup affect MET)
- W+jets (with one jet faking a lepton): lepton ID is important
- Top (tt and single top): b-tag veto (or additional soft muon)
- WW: M(ll), MT and Δϕ

All the background are estimated from DATA in “control regions”

WW+ 0, 1, 2 jets

The NNLO band overlaps with the NLO one for $p_T^{veto} \geq 30$ GeV



WW + 0 jet: Veto jet of p_T>30 GeV
WW + 1 jet: 1 jet of p_T>30 GeV
WW + 2 jet: 2 jet of p_T>30 GeV - VBF like

Asking jet veto, means "eliminate" diagrams with real gluon emission

The HWW analysis is divided in 3 regions: +0, +1 and +2 jets.

To get the correct TH uncertainty on the XS in the three regions:

Theoretically we can compute: σ_{total}, $\sigma_{\geq 1}$, $\sigma_{\geq 2}$, thus

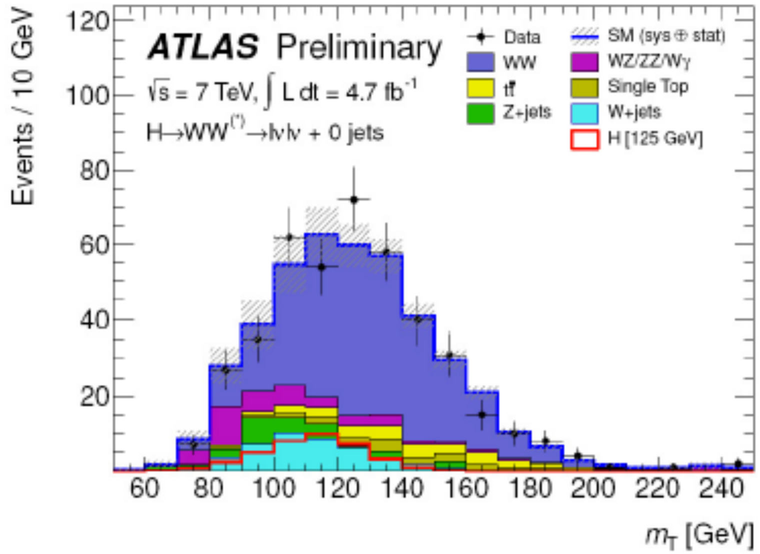
$$\sigma_0=\sigma_{total}-\sigma_{\geq 1}\ ,\ \sigma_1=\sigma_{\geq 1}-\sigma_{\geq 2},\ \sigma_{\geq 2}$$

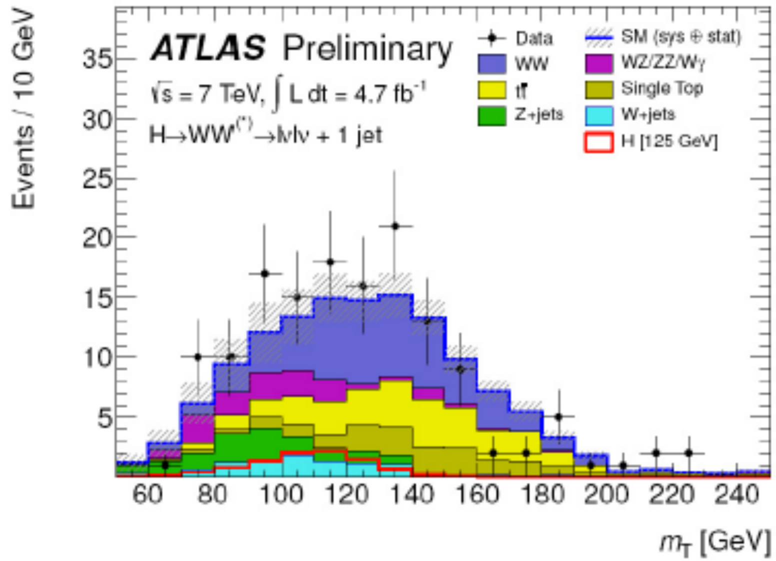
TH uncert:

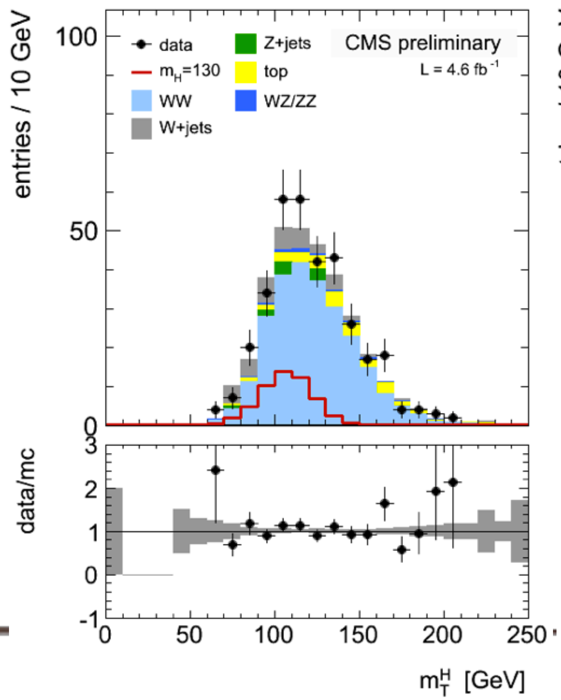
- $\delta\sigma_{\geq 0}=\delta\sigma_{total}$ From Yellow Report (i.e. HNNLO/FEHIP)
- $\delta\sigma_{\geq 1}$ HNNLO/FEHIP or MCFM (identical)
- $\delta\sigma_{\geq}$ HNNLO/FEHIP gives LO, MCFM NLO

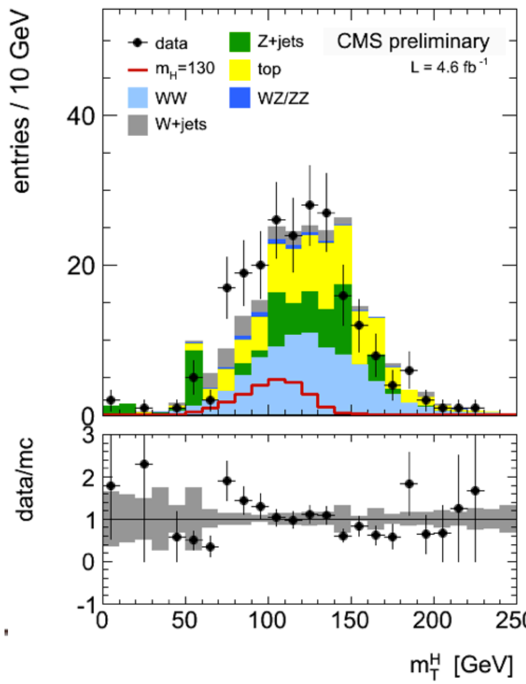
$\delta\sigma_{\geq 0}$	+12-7%
$\delta\sigma_{\geq 1}$	±20%
$\delta\sigma_{\geq 2}$	±30% (NLO) ±70% (LO)

H→WW+ 0,1,2 jets

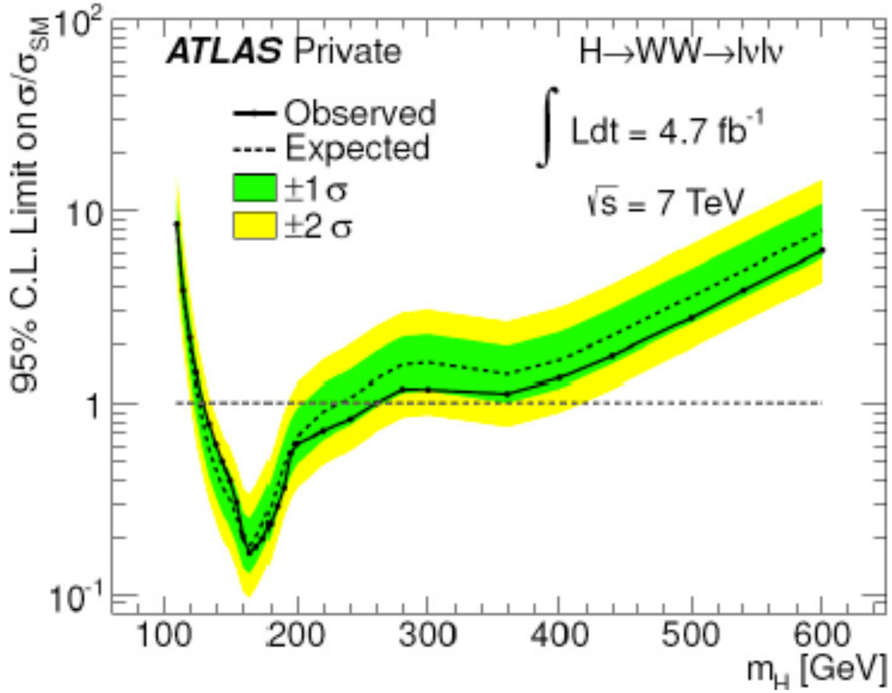

ATLAS Preliminary
$\sqrt{s}$ = 7 TeV, $\int$ L dt = 4.7 fb^{-1}
H→WW$^{(*)}$→lνlν + 0 jets
Data
WW
tt̄
Z+jets
SM (sys ⊕ stat)
WZ/ZZ/Wγ
Single Top
W+jets
H [125 GeV]
Events / 10 GeV
m_T [GeV]

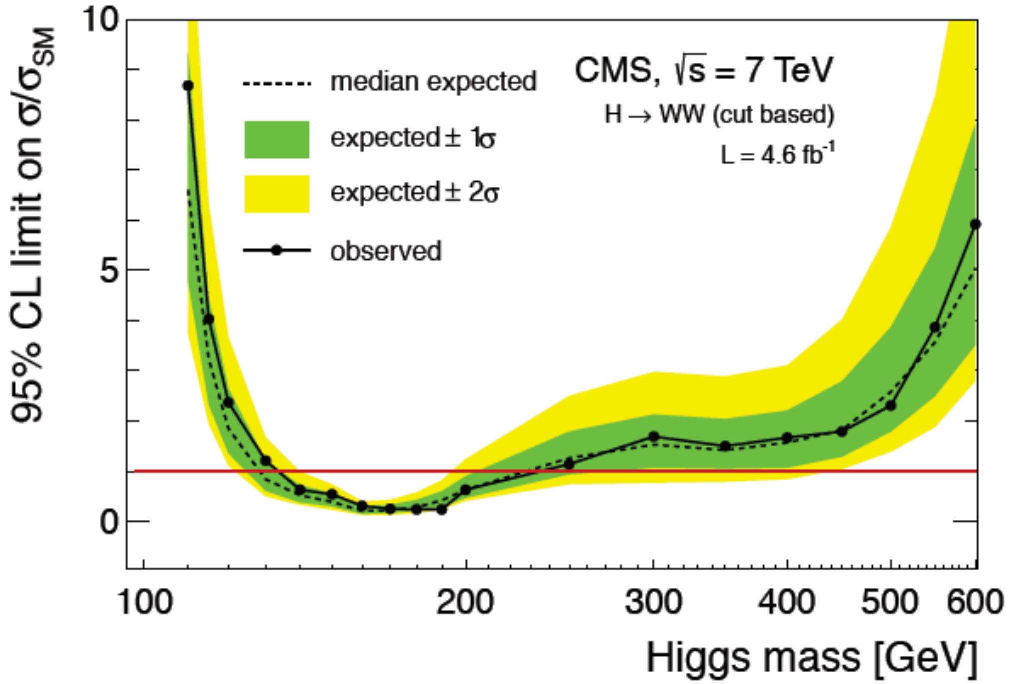

ATLAS Preliminary
$\sqrt{s}$ = 7 TeV, $\int$ L dt = 4.7 fb^{-1}
H→WW$^{(*)}$→lνlν + 1 jet
Data
WW
tt̄
Z+jets
SM (sys ⊕ stat)
WZ/ZZ/Wγ
Single Top
W+jets
H [125 GeV]
Events / 10 GeV
m_T [GeV]


data
m_H=130
WW
W+jets
Z+jets
top
WZ/ZZ
CMS preliminary
L = 4.6 fb^{-1}
entries / 10 GeV
data/mc
m_T^H [GeV]


data
m_H=130
WW
W+jets
Z+jets
top
WZ/ZZ
CMS preliminary
L = 4.6 fb^{-1}
entries / 10 GeV
data/mc
m_T^H [GeV]

H → WW→lνlν





m_H=125 GeV	0-jet ee	0-jet $\mu\mu$	0-jet $e\mu$
Total bkg.	58±5	114±10	257±13
Signal	3.8±0.1	9.0±0.1	25±0.2
Observed	52	138	237
m_H=125 GeV	1-jet ee	1-jet $\mu\mu$	1-jet $e\mu$
Total bkg.	21±3	37±5	76±6
Signal	1.1±0.1	2.3±0.1	6.0±0.1
Observed	19	36	90

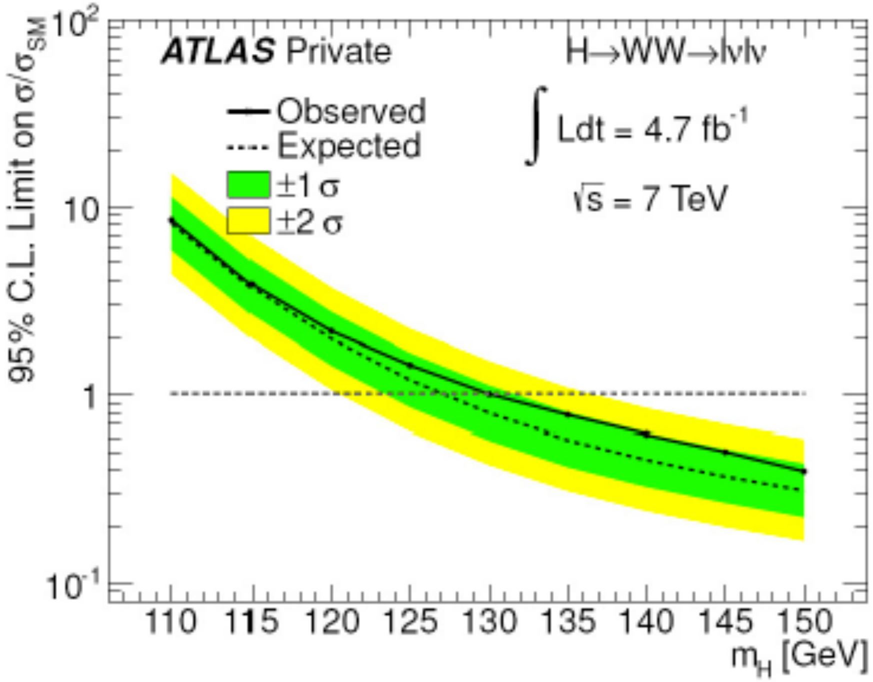
(Statistical uncertainties only.)

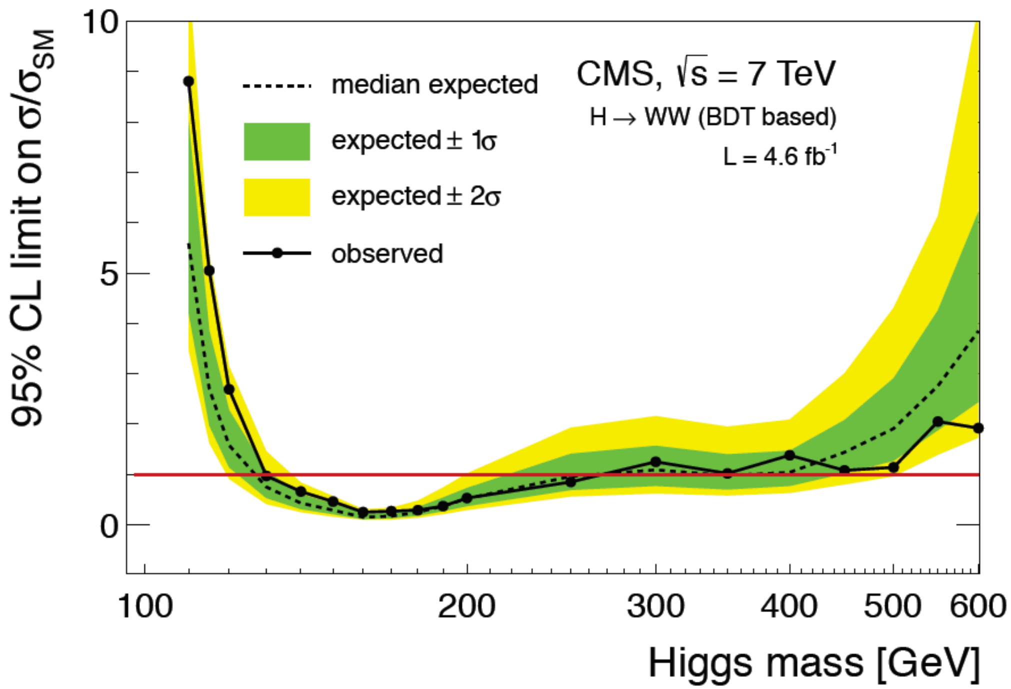
Category	H mass	Data	All MC	H →WW
0 jets	130	193	191.5±14	45.2±2.1
1 jets	130	105	79.9±7.7	17.6±0.8
2 jets	130	10	13.3±4	2.7±0.2

ATLAS: Exp excl : 127 – 234 GeV
Obs Excl: 130 - 260 GeV

CMS: Exp excl: 127 – 270 GeV
Obs Excl: 129 – 270 GeV

Zoom

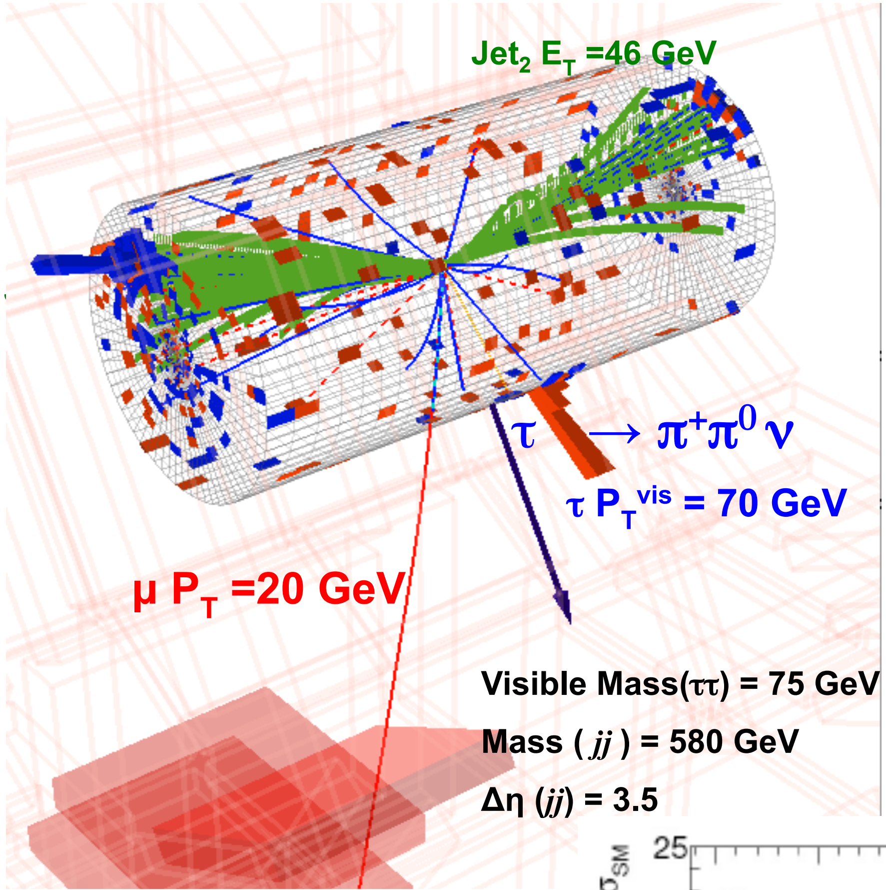




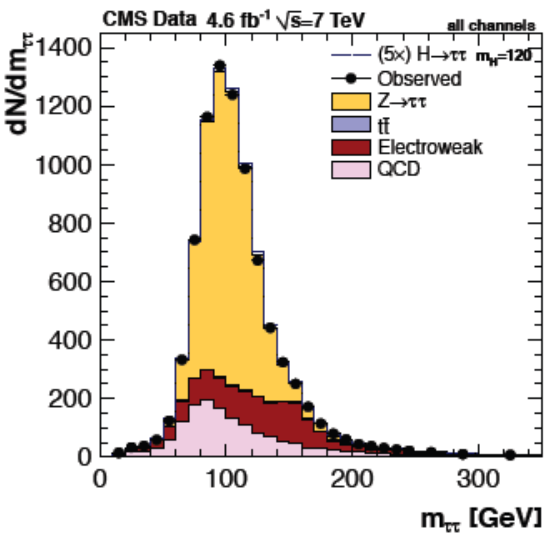
ATLAS: Exp excl : 127 – 234 GeV
Obs Excl: 130 - 260 GeV

CMS: Exp excl: 127 – 270 GeV
Obs Excl: 129 – 270 GeV

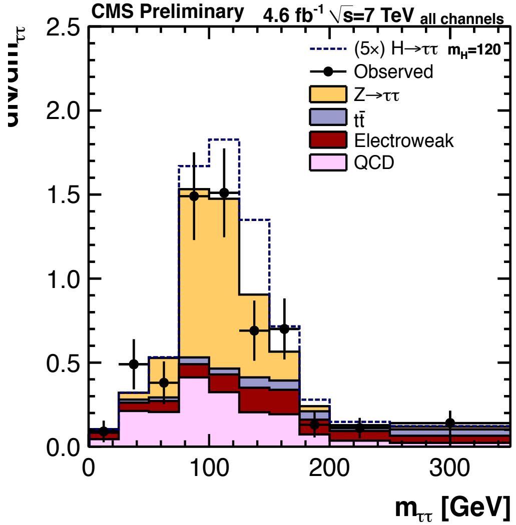
H → ττ



Inclusive /1 boosted jet



VBF modes are cleanest



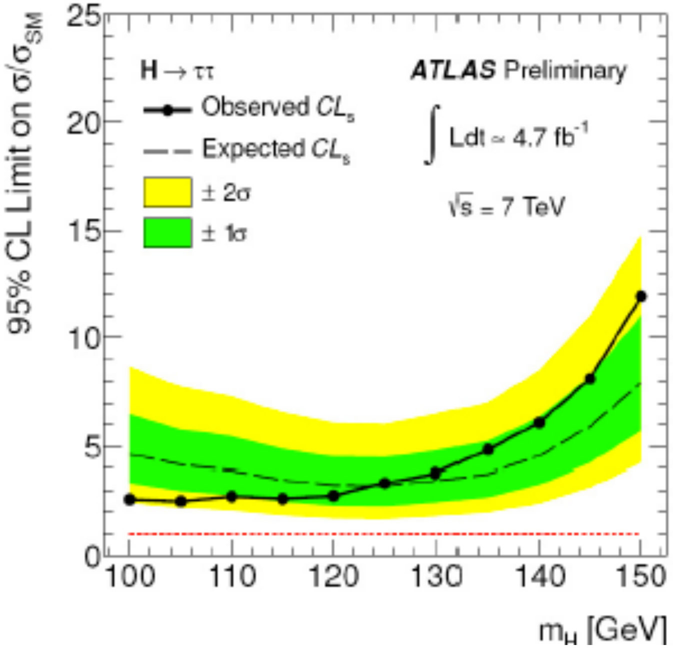
Search in

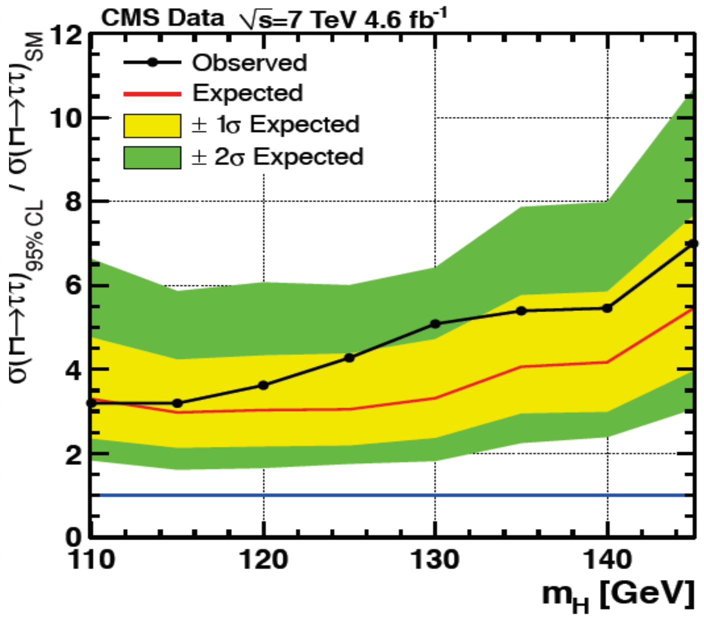
$\tau_e + \tau_h$, $\tau_\mu + \tau_h$, $\tau_e + \tau_\mu$

Background:

QCD,

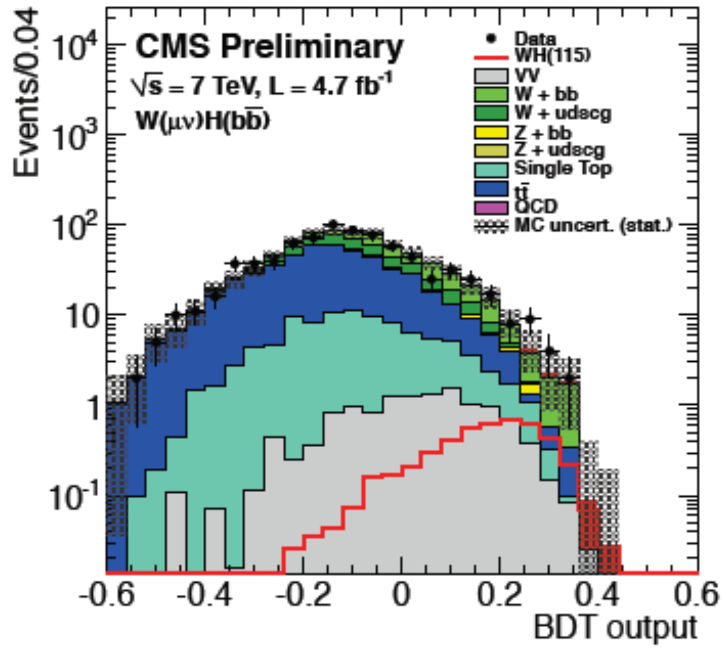
EWK Z → ττ (irreducible)

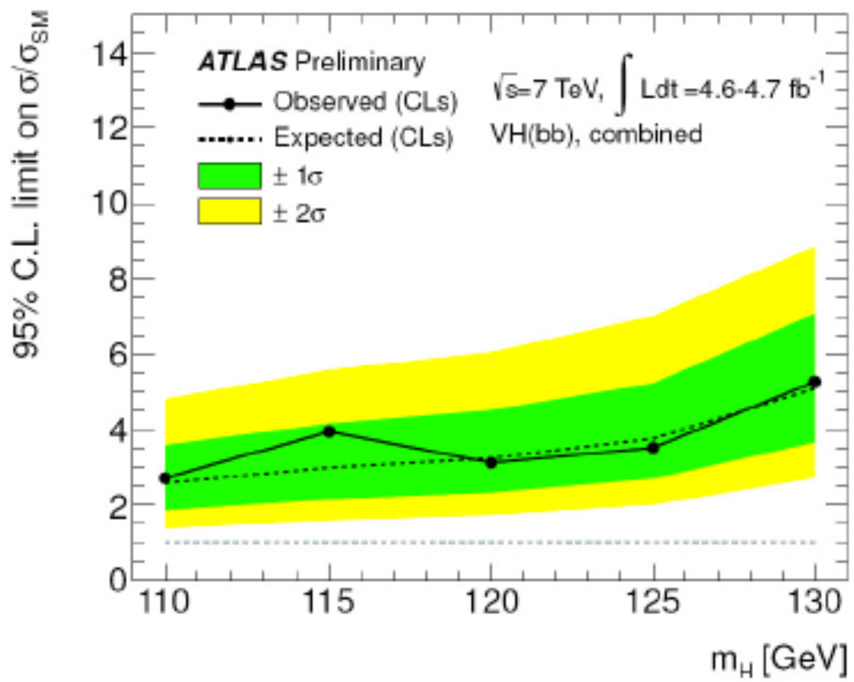


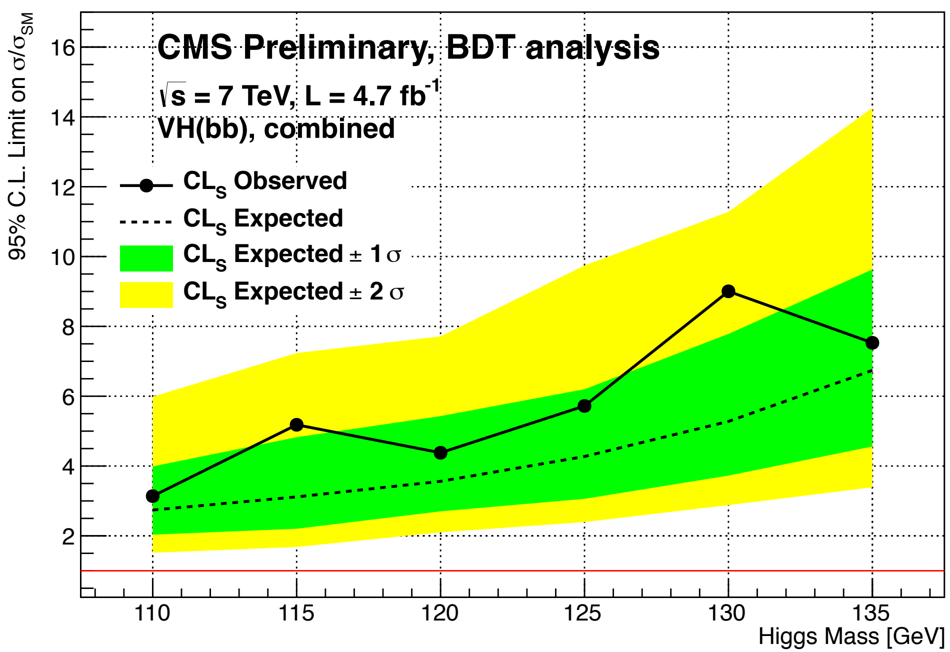


H → bb

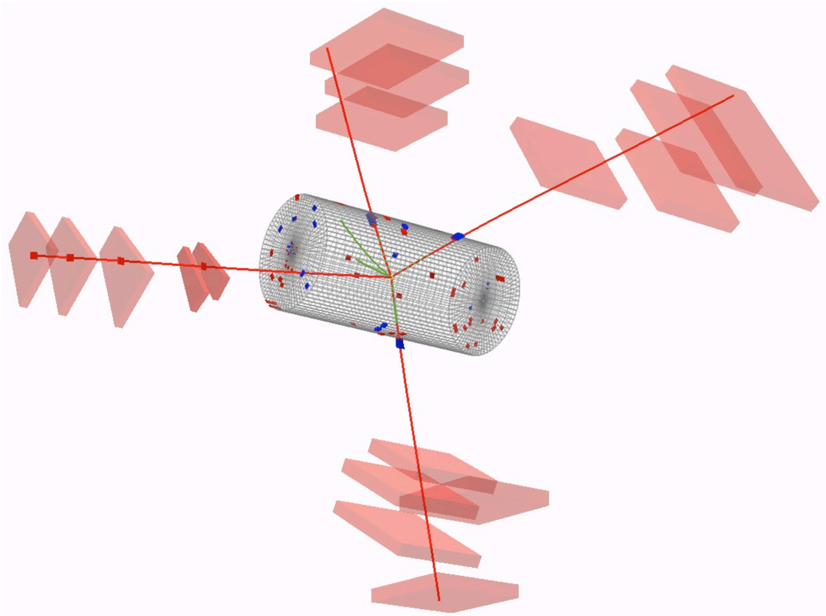
- ATLAS and CMS exploits the W/Z+H associate production with the Higgs heavily boosted
  - Require p_T^{bb}>100 (150) GeV for ZH (WH)
- Topology is very clear, several final states considered:
  - *lνbb, llbb, ννbb*
  - Δφ(V,H), tight b-tagging







H → ZZ → 4l

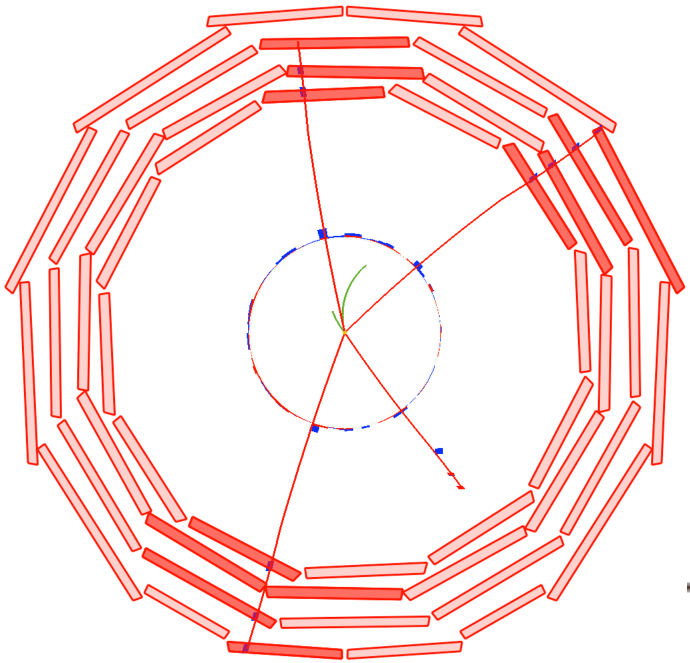


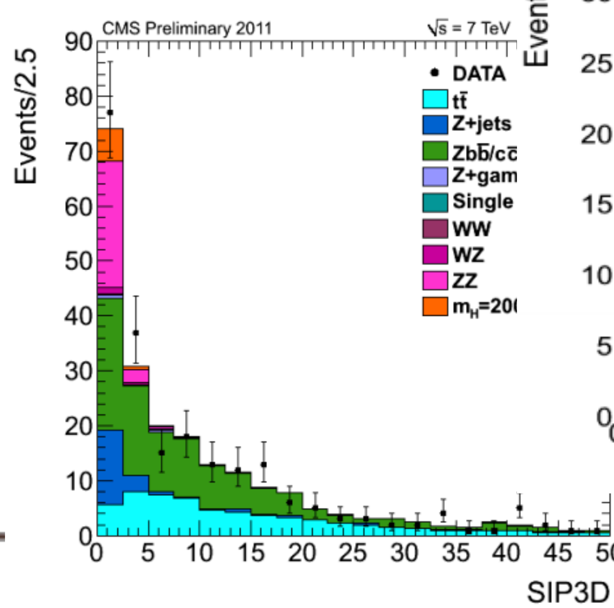
The final states considered are 4μ, 4e, 2e2μ

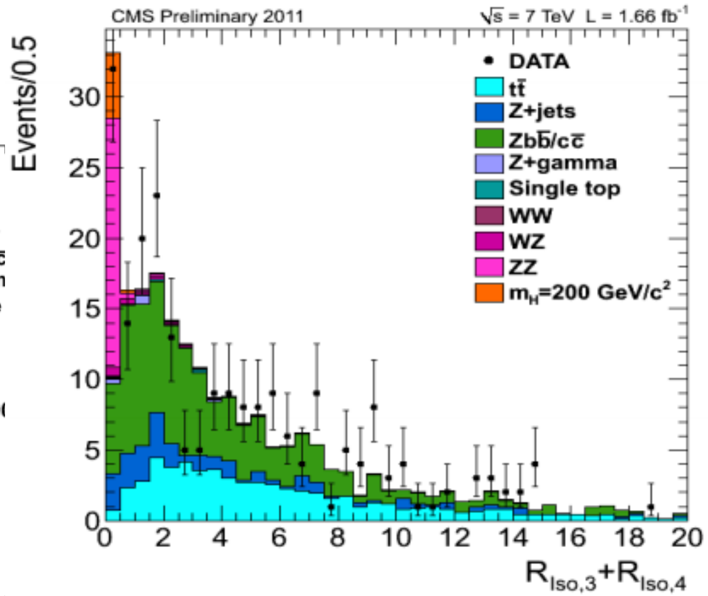
Very tiny cross section ->
thus highest efficiency must be conserved

Very clean final state:

- 4 leptons of high pt,
- isolated
- coming from the primary vertex



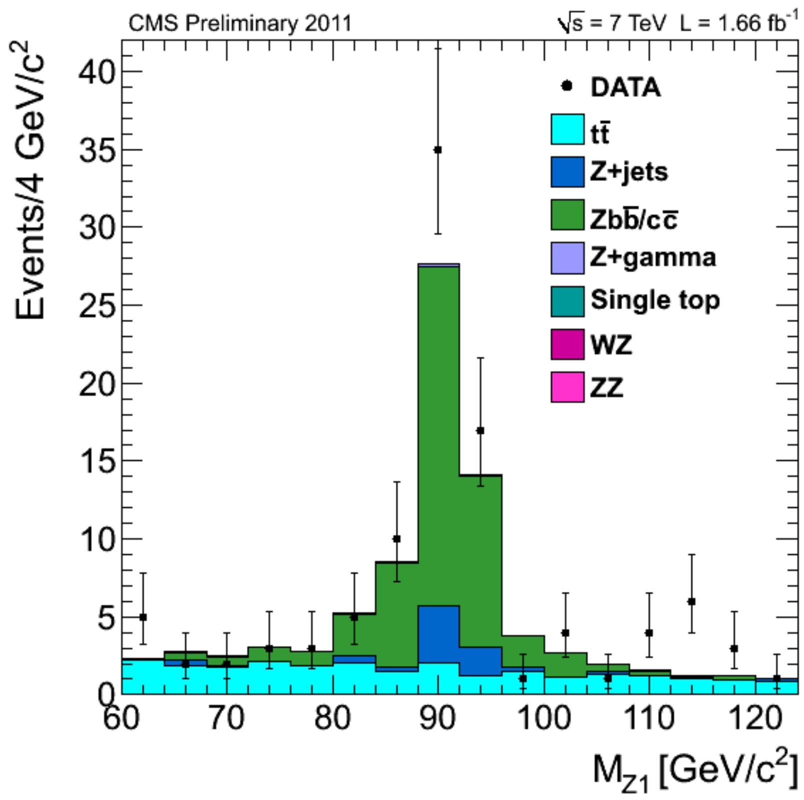




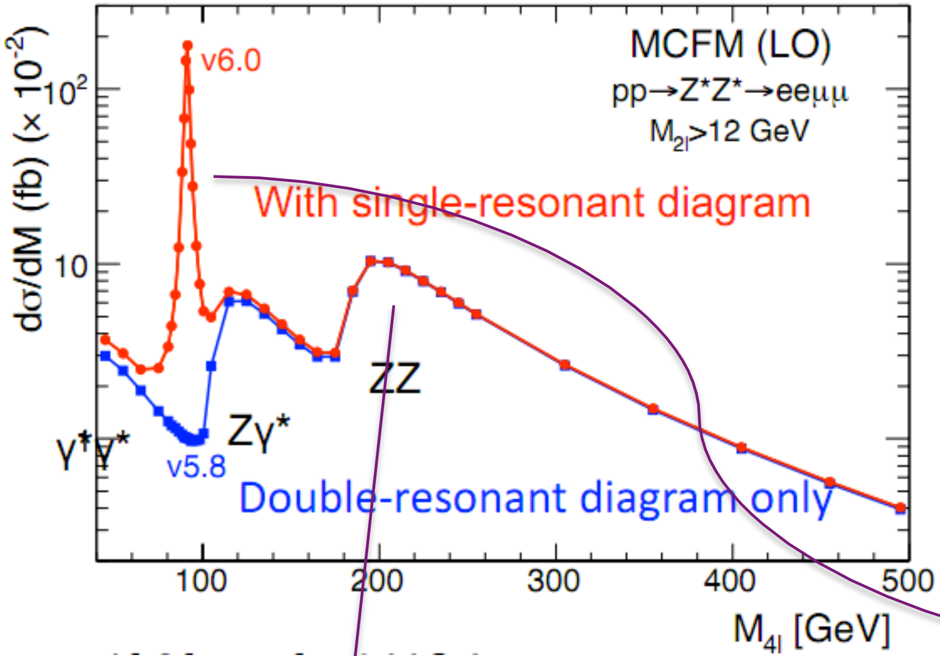
Chiara Mariotti, Torino & CERN

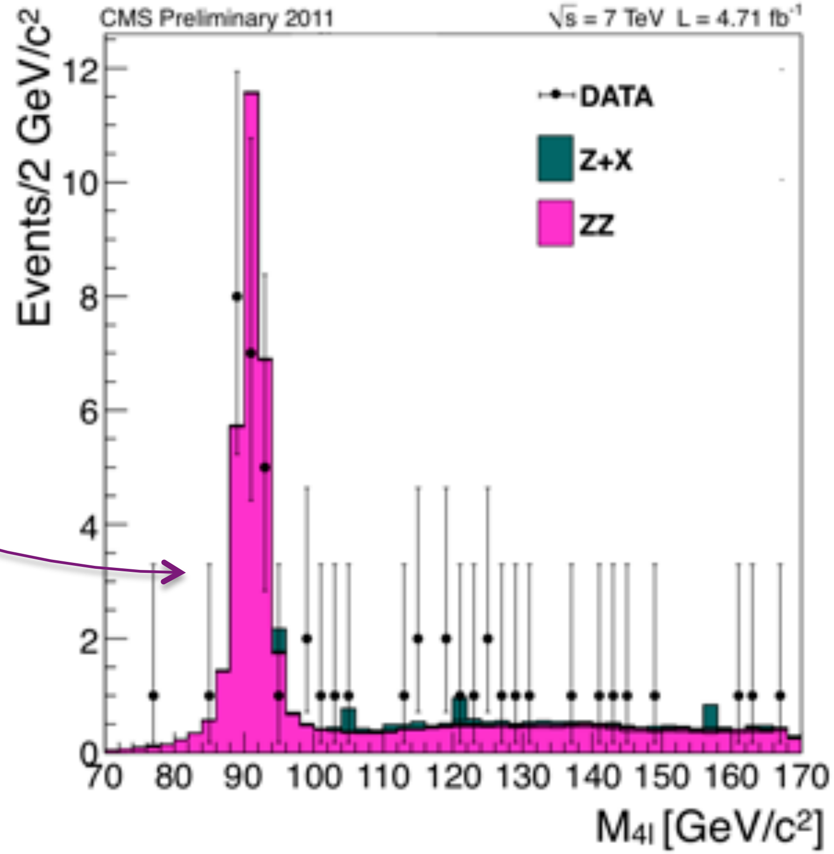
Zbb + tt → 4l

- Reducible backgrounds (Zbb/tt) is measured in a dedicated control region:
  - Same requirements for the on-shell Z candidate as for the signal
  - Relaxed selections on charge, flavor and isolation and inverted IP cut for the other lepton pair
  - From this plot we can disentangle Zbb from tt, by fitting the "Z peak" and a polinomial for tt.
  - Comparing data/MC, we can get the k-factor (MC are at LO or NLO)



pp → 4l



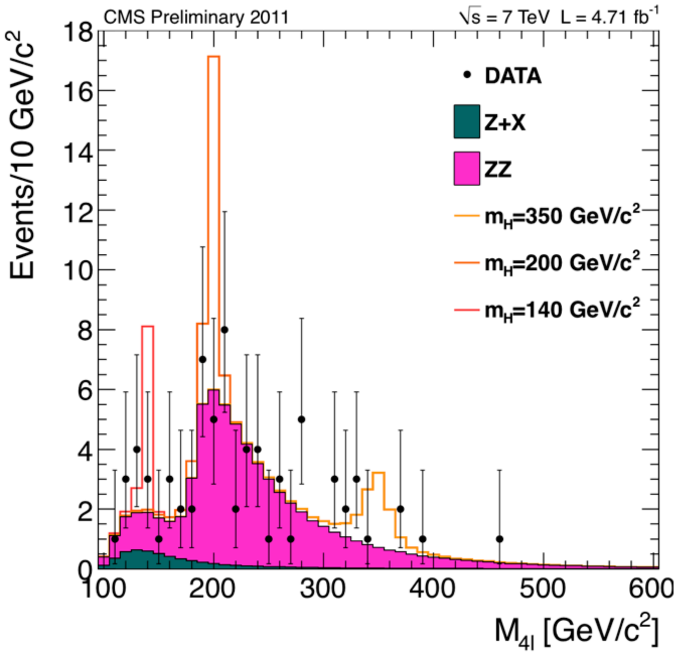


Measurement of the ZZ cross section with both Z on shell (60<MZ<120):

$$\sigma(pp \to ZZ + X) \times \mathcal{B}(ZZ \to 4\ell) = 28.1^{+4.6}_{-4.0}(\text{stat.}) \pm 1.2(\text{syst.}) \pm 1.3(\text{lumi.})\ \text{fb}$$

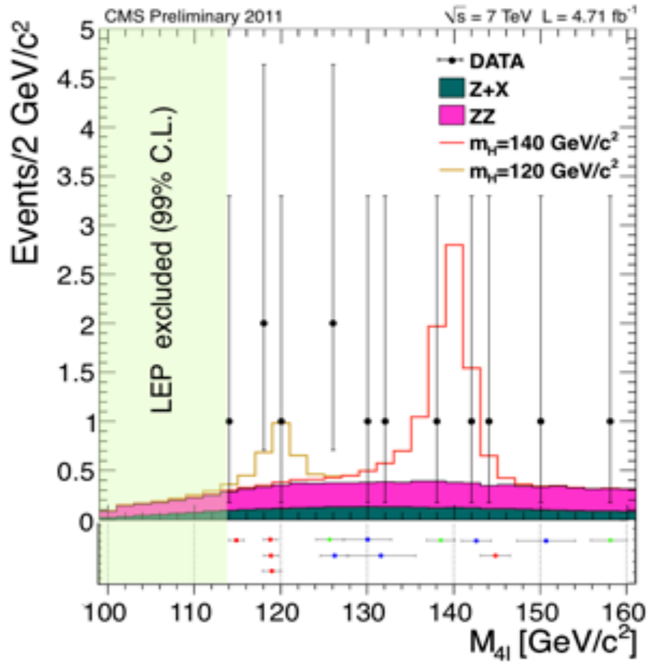
To be compared with the SM XS = 27.9 +- 1.9 fb

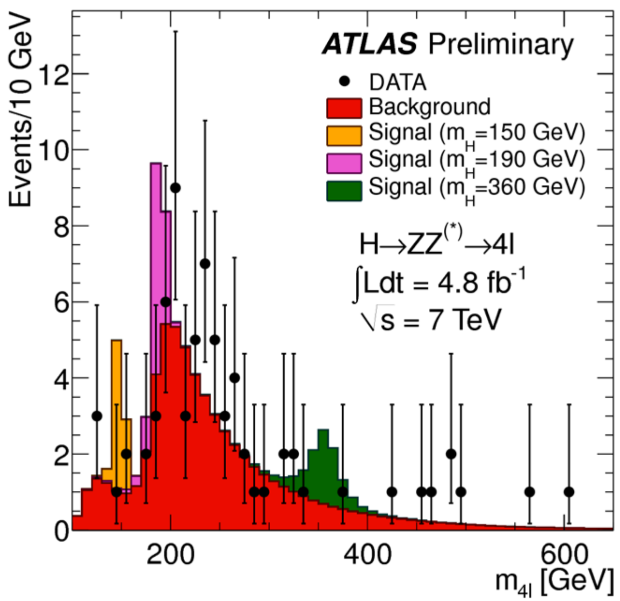
Results: H→ZZ→4l



For M_{4l}>100 GeV
Data: 72 Observed
MC: 67.1 ± 6.0

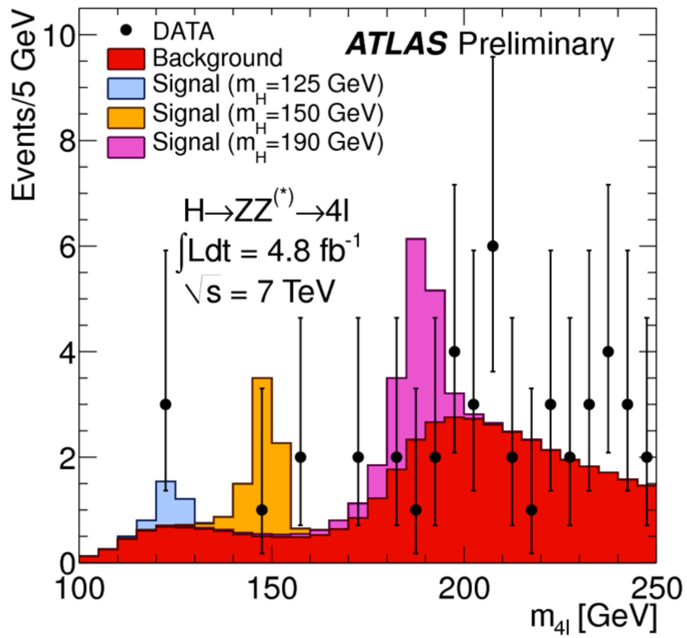
For 100<M_{4l}<160 GeV
Data: 13 observed
MC: 9.5 ± 1.3



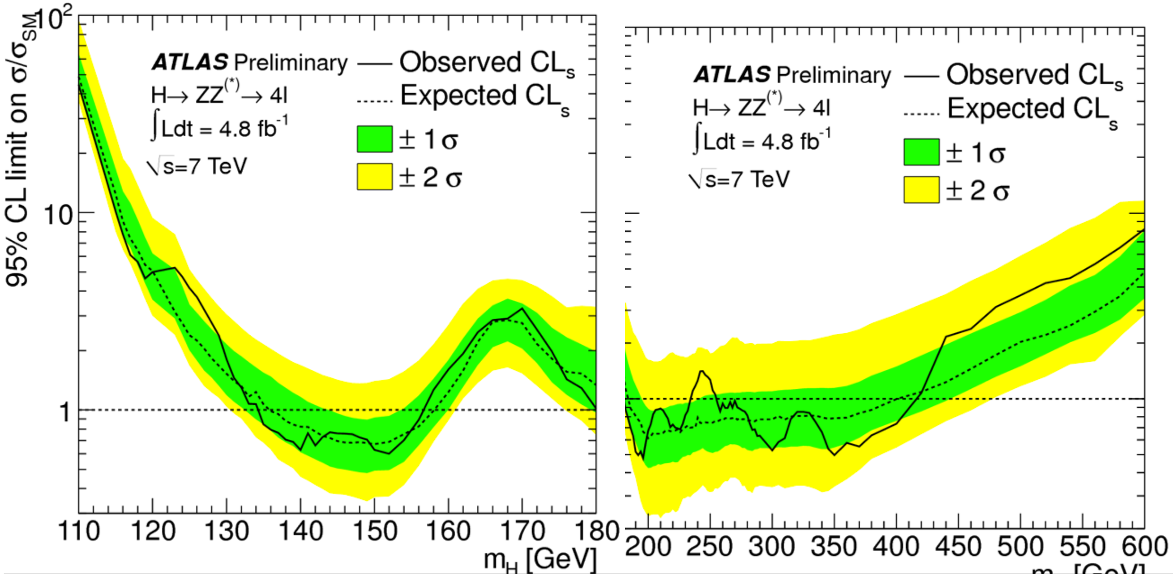


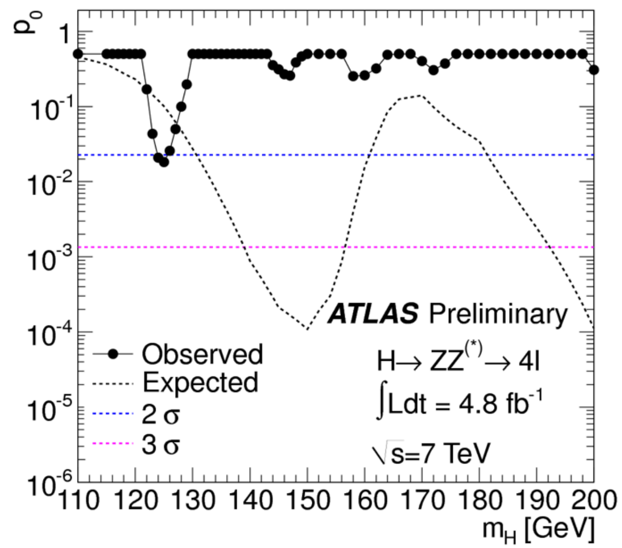
For M_{4l}>100 GeV
Data: 71 Observed
MC: 62 ± 9

For 100<M_{4l}<180 GeV
Data: 8 observed
MC: 9.3 ± 1.5



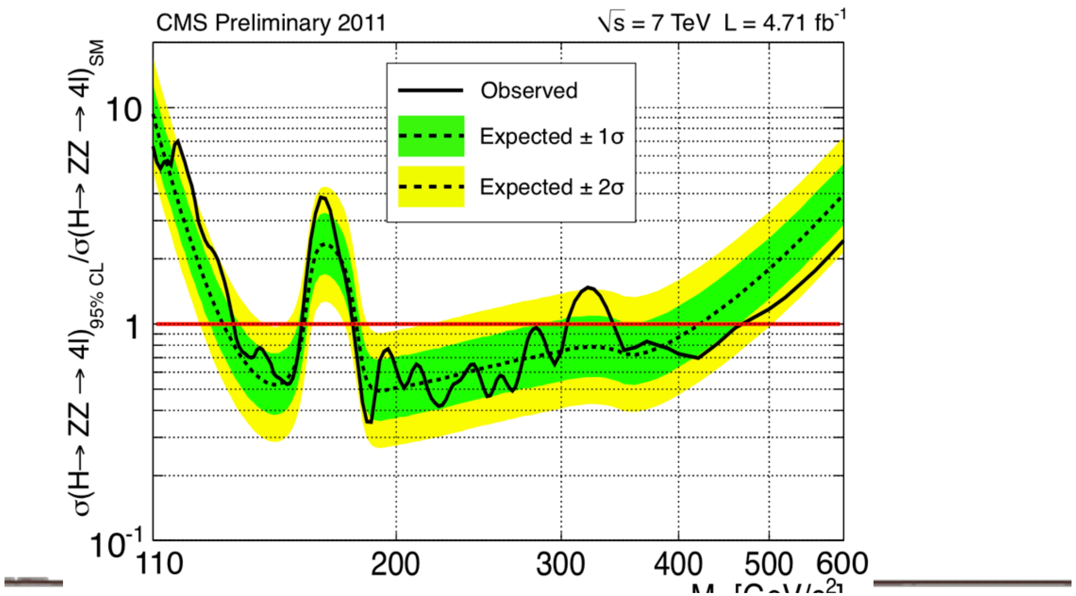
Results

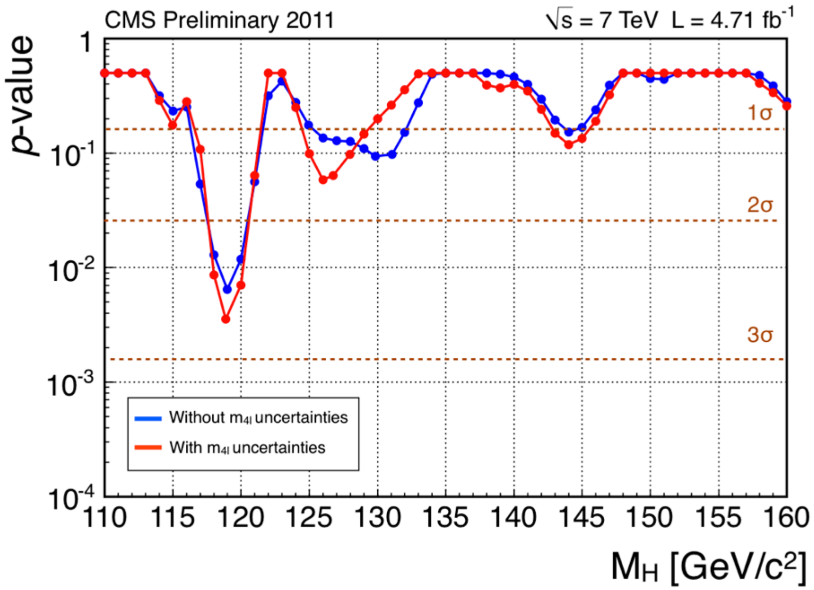




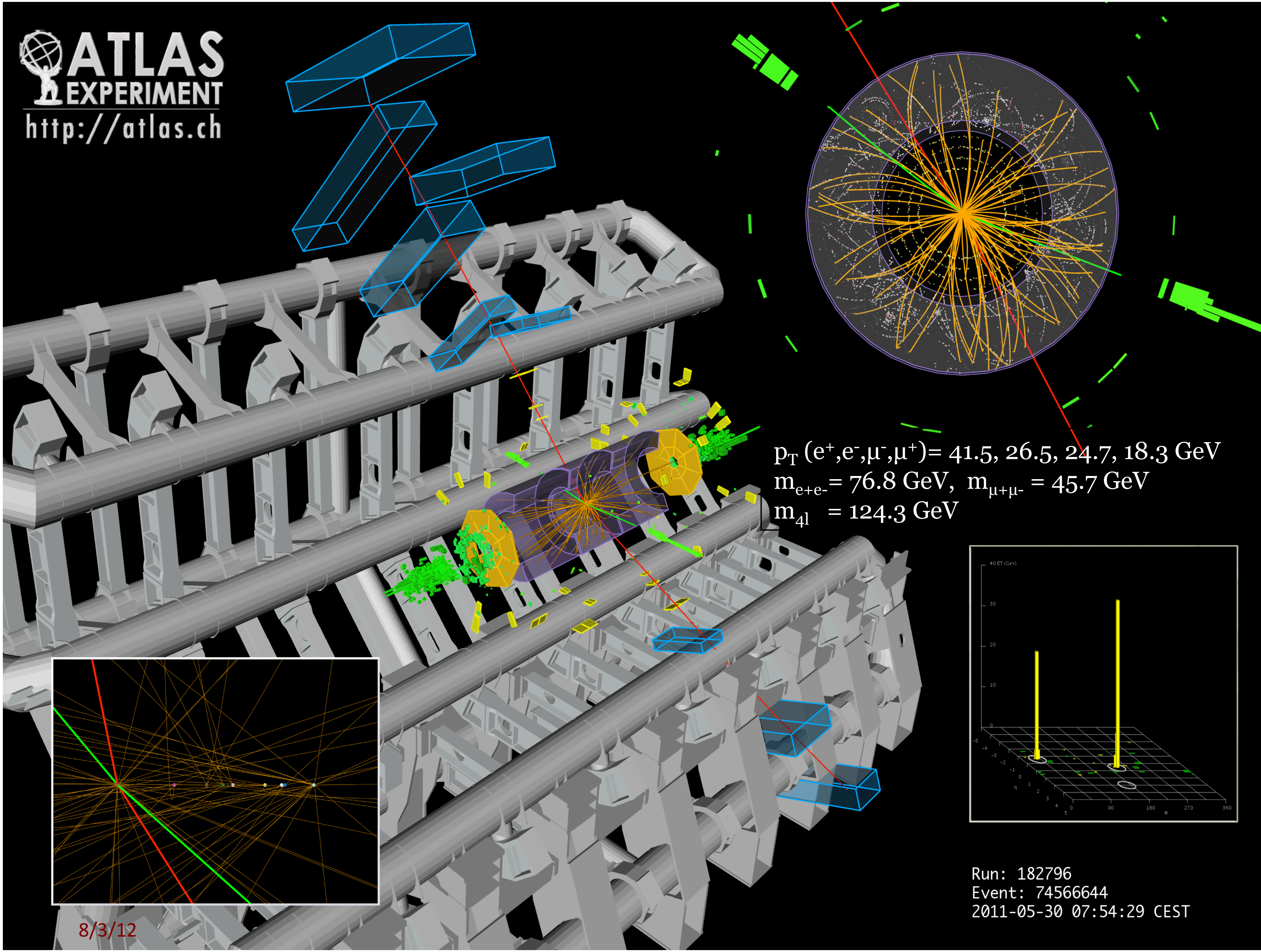
Excluded (95% CL): $135 < m_H < 156$ GeV and $181 < m_H < 415$ GeV (except 234-255 GeV)
Expected (95% CL): $137 < m_H < 158$ GeV and $185 < m_H < 400$ GeV

P-value: The significance of the local fluctuations with respect to the standard model expectation. To reject a background only hypotesis.

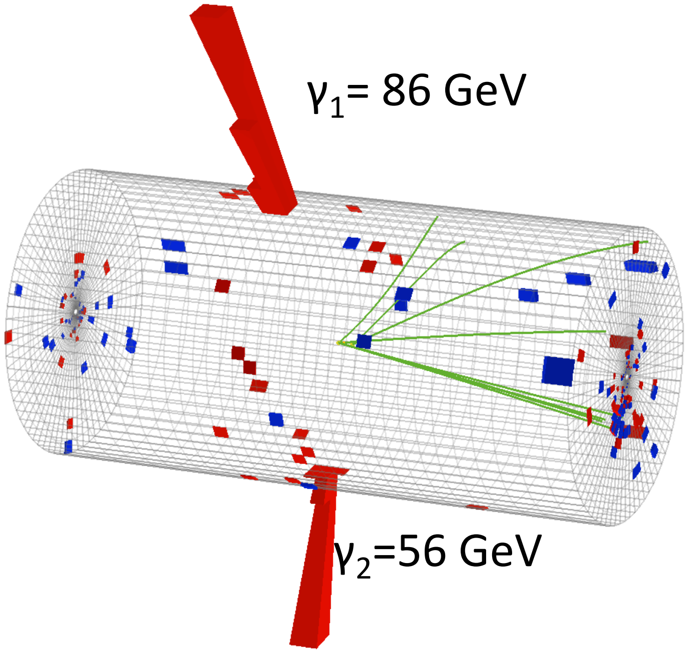


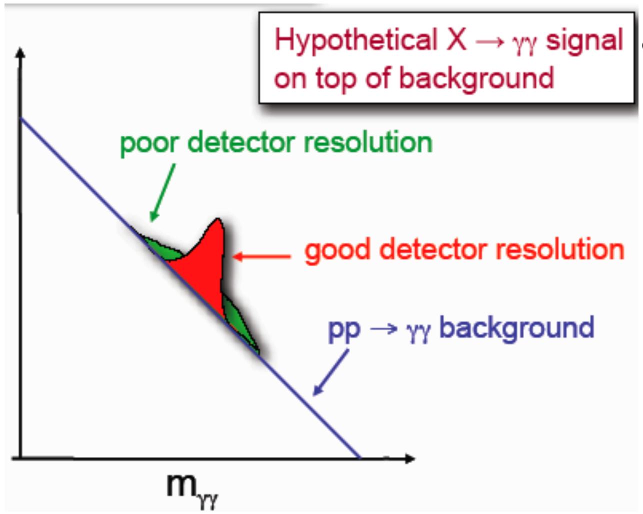


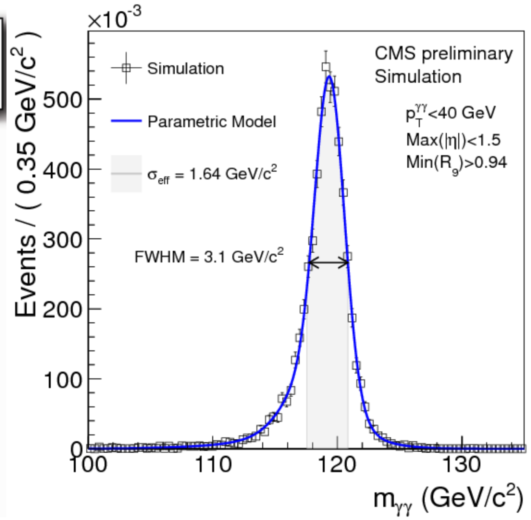
134 < mH < 158 GeV, 180 < mH < 305 GeV and 340 < mH < 460 GeV.


ATLAS
EXPERIMENT
http://atlas.ch
p_T (e^+,e^-,μ^-,μ^+)= 41.5, 26.5, 24.7, 18.3 GeV
m_{e+e-}= 76.8 GeV, $m_{\mu+\mu-}$ = 45.7 GeV
m_{4l} = 124.3 GeV
Run: 182796
Event: 74566644
2011-05-30 07:54:29 CEST
8/3/12

H → γγ

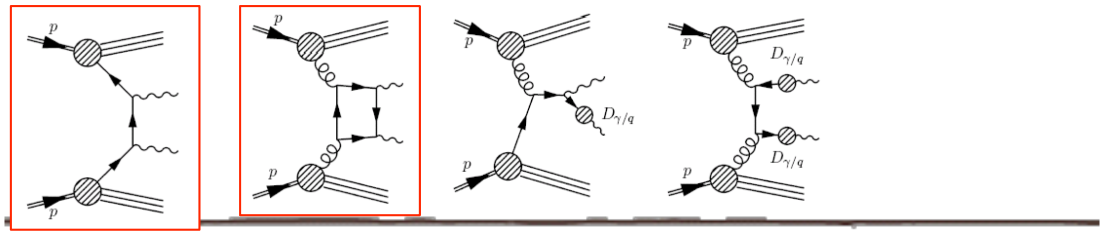


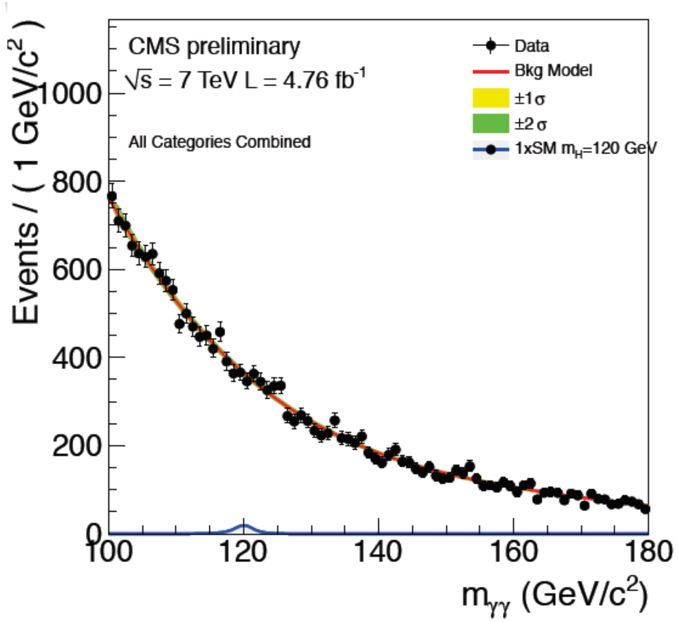




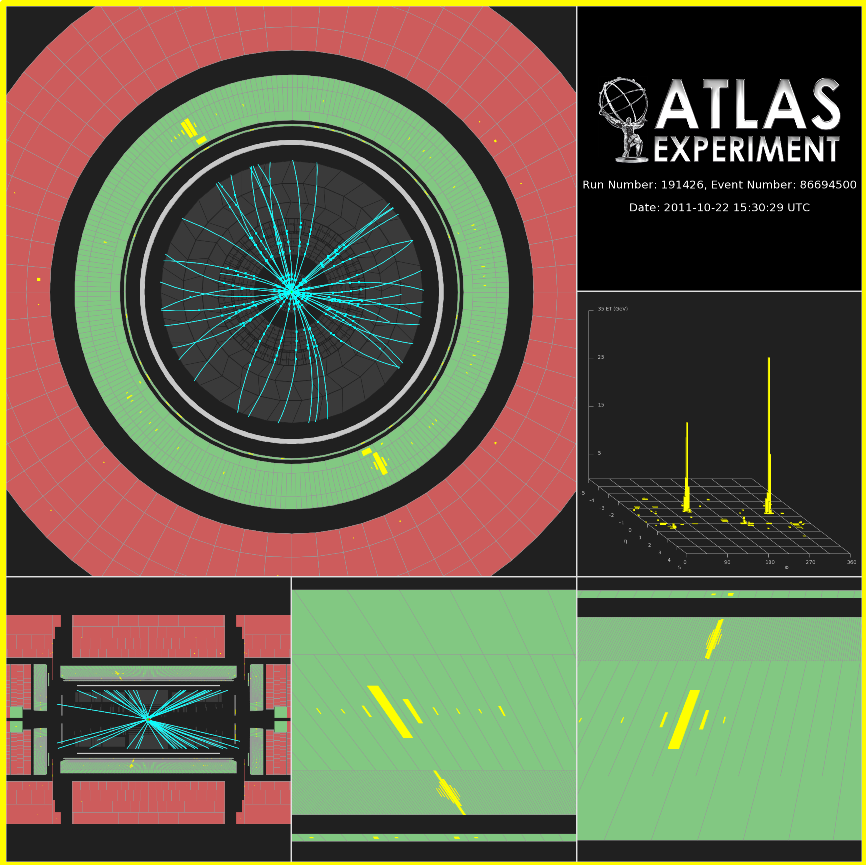
Signature: 2 energetic, isolated γ, narrow mass peak

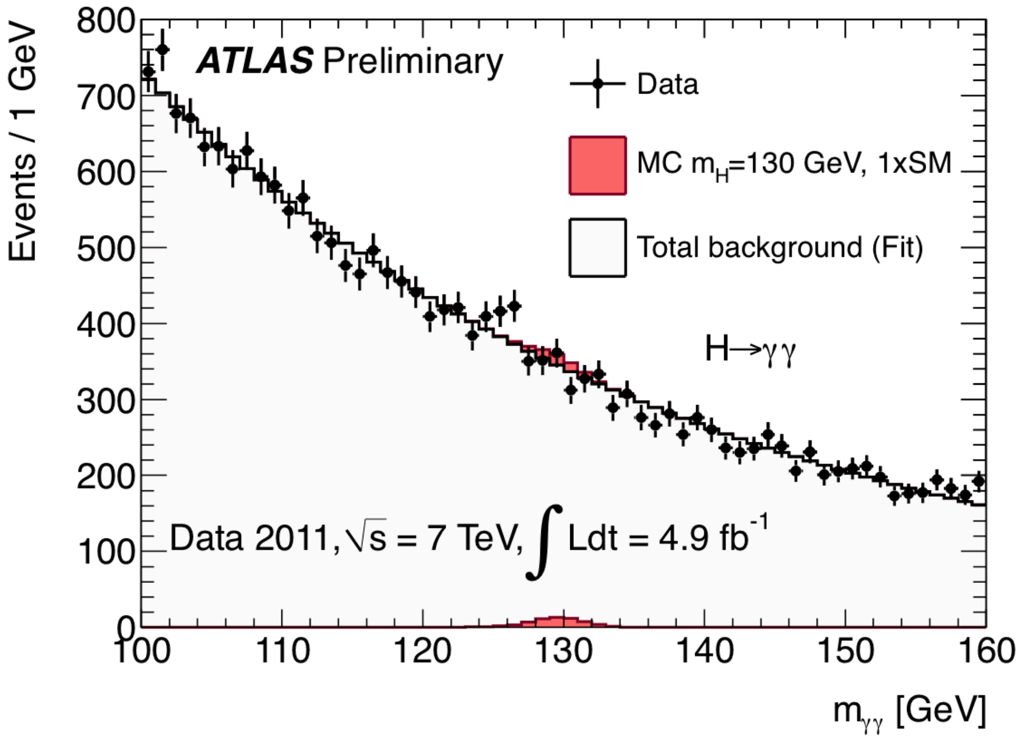
Background: Large & partly irreducible QCD. Measured from $M_{\gamma\gamma}$ sidebands in data





Atlas: H→γγ





Small cross-section: σ ~ 40 fb

→ 70 signal events expected after selection / 3000 background (S/~0.02)

Simple final state: two high-p_T isolated photons

- E_T (γ_1, γ_2) > 40, 25 GeV

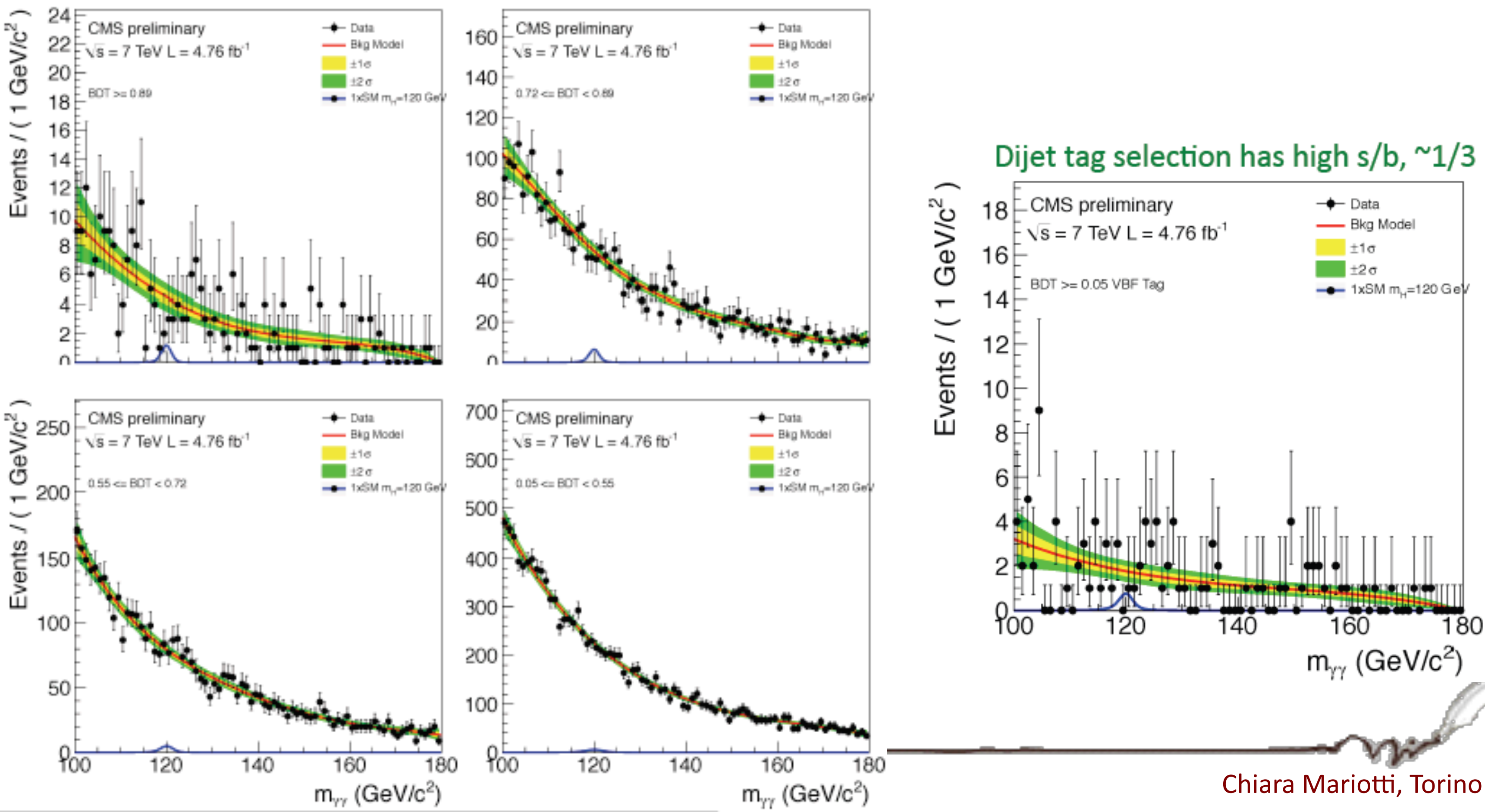
Events divided into 9 categories based on η-photon (e.g. central, rest, …),

CMS: H→γγ

- A new analysis: variables combined in a BTD
- Sensitivity improved by about 40% in integrated luminosity
- 4 classes of events (by varying S/B) plus the VBF category.

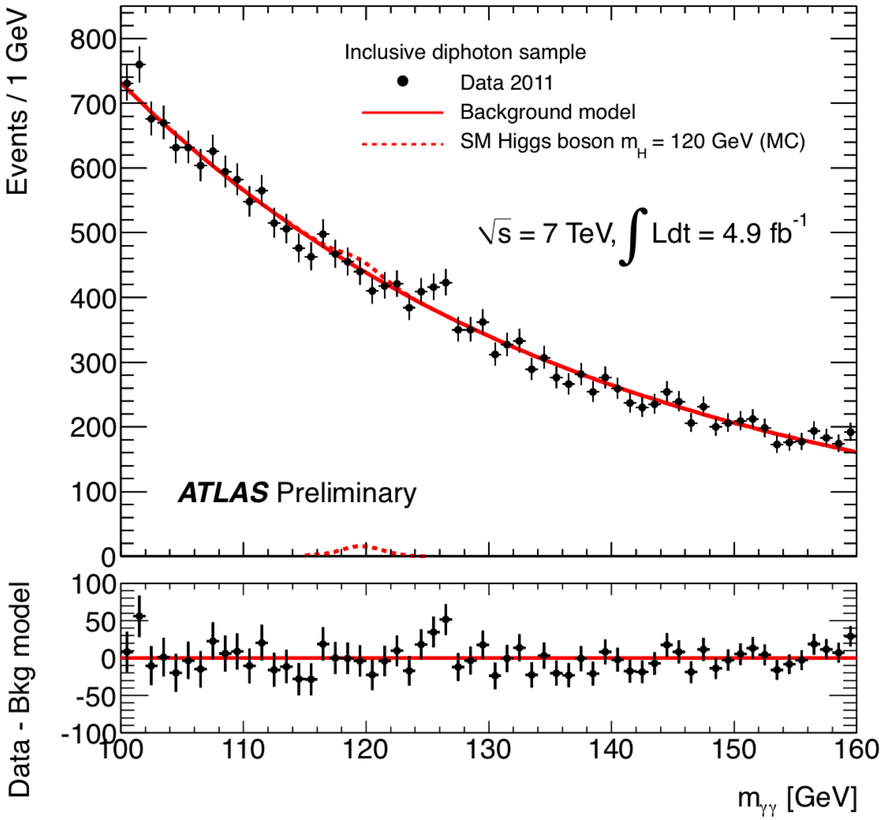
Events passing VBF selection removed

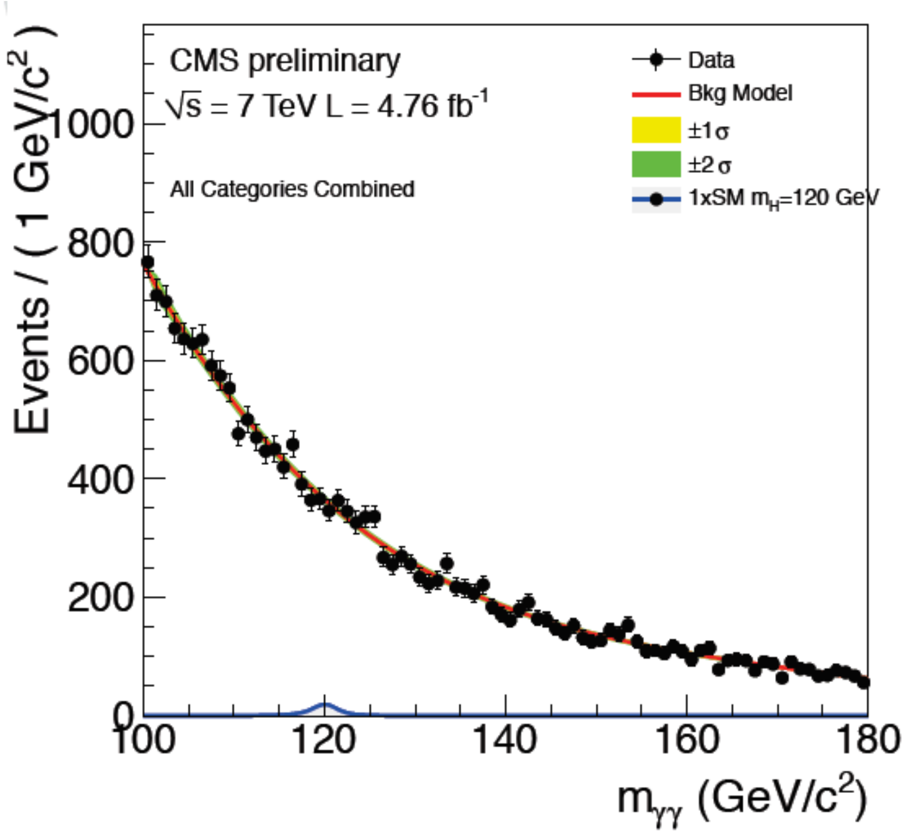
Dijet tag selection has high s/b, ~1/3



Chiara Mariotti, Torino & CERN

Results H → γγ

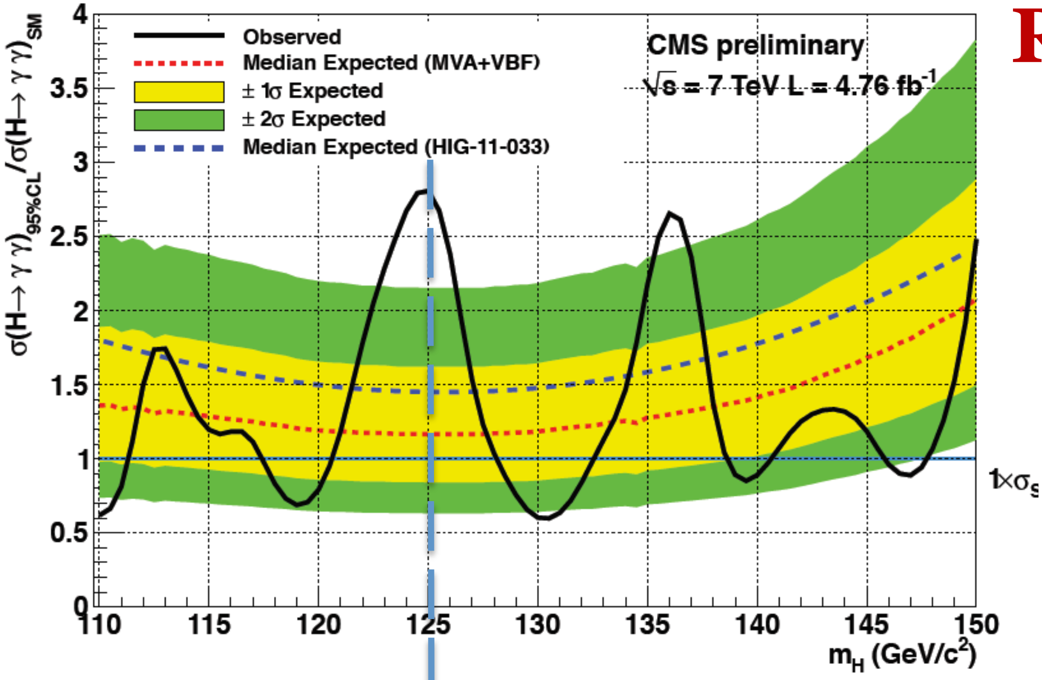


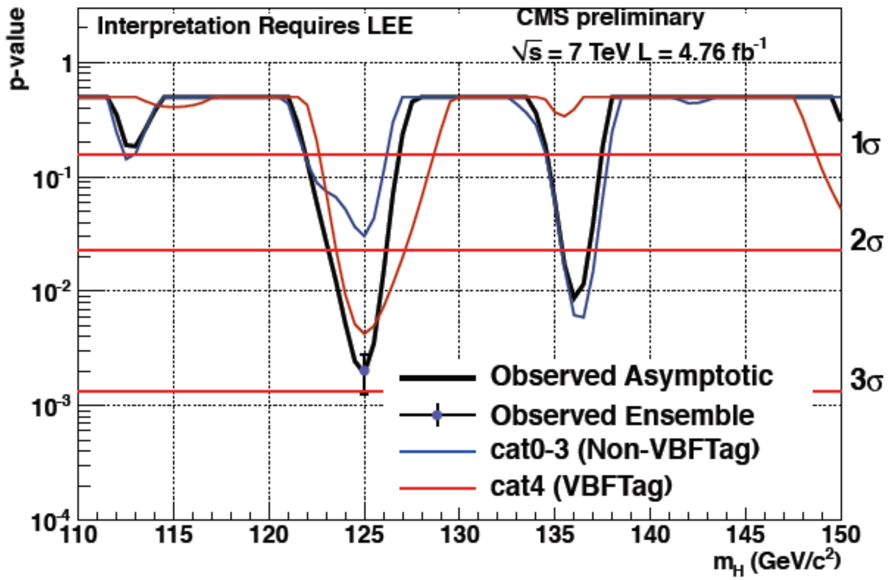


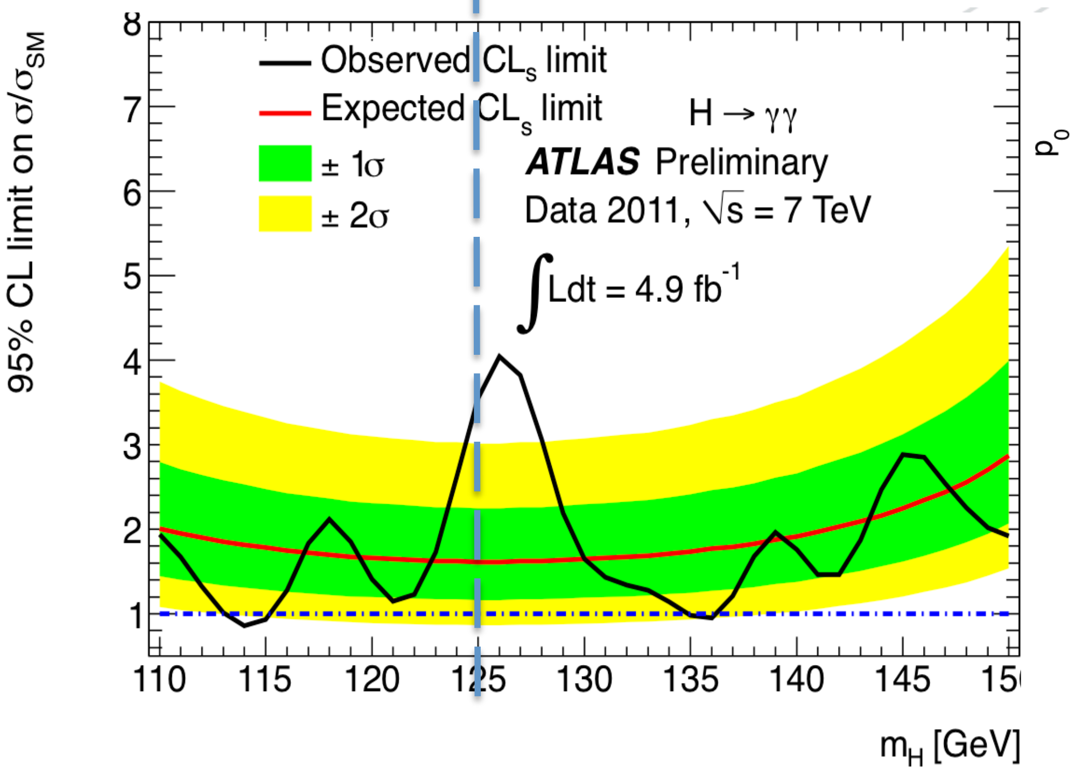
Fit to the background:
exponential

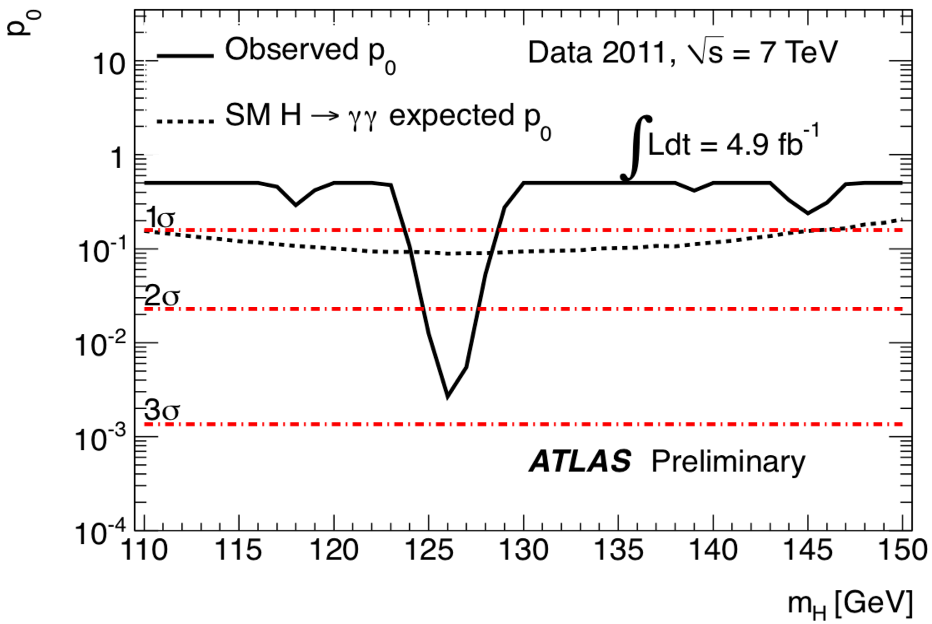
Fit to the background:
5 order polinomial

Results : R and p-value

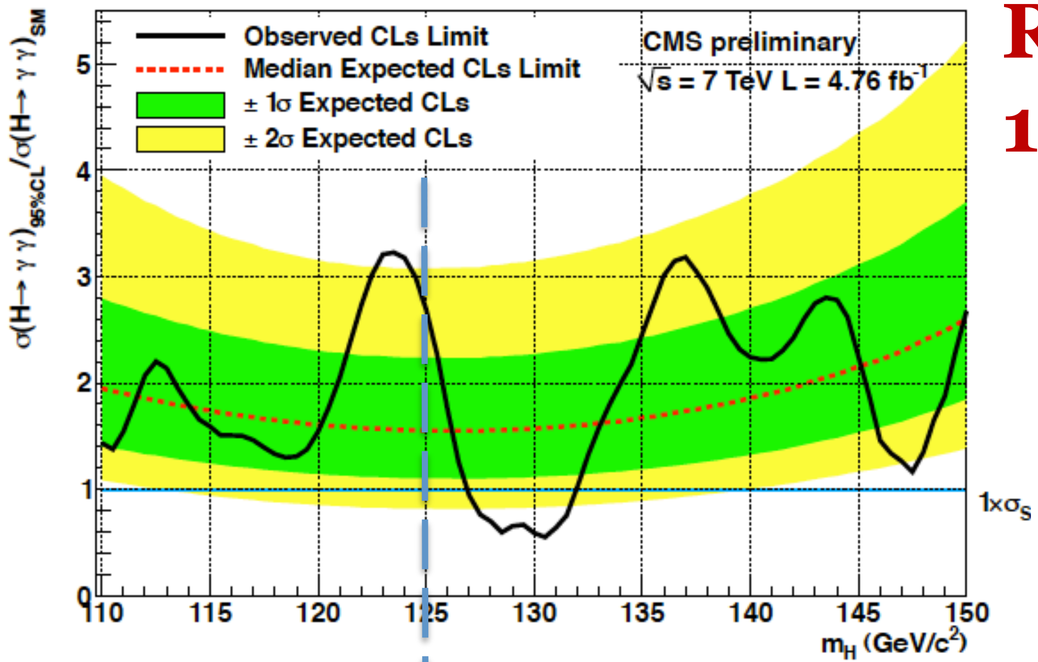


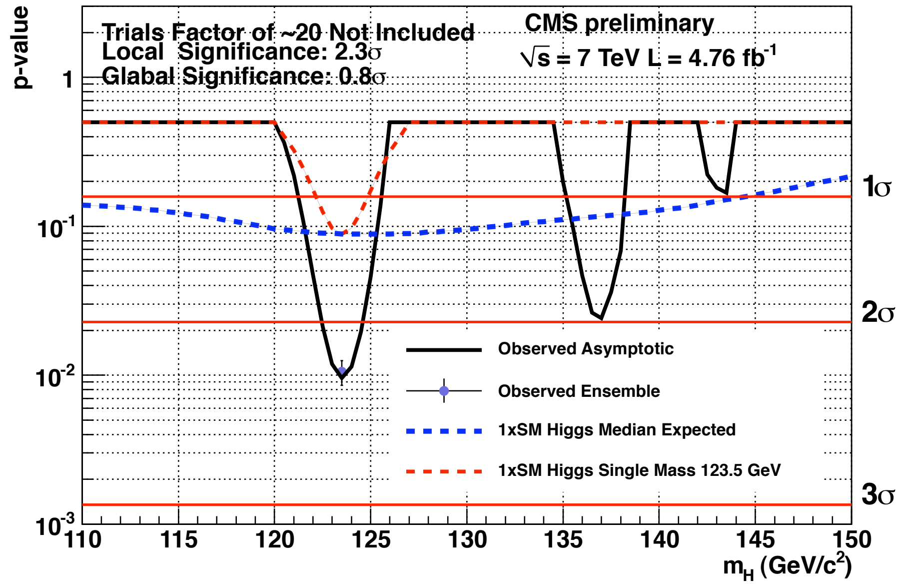


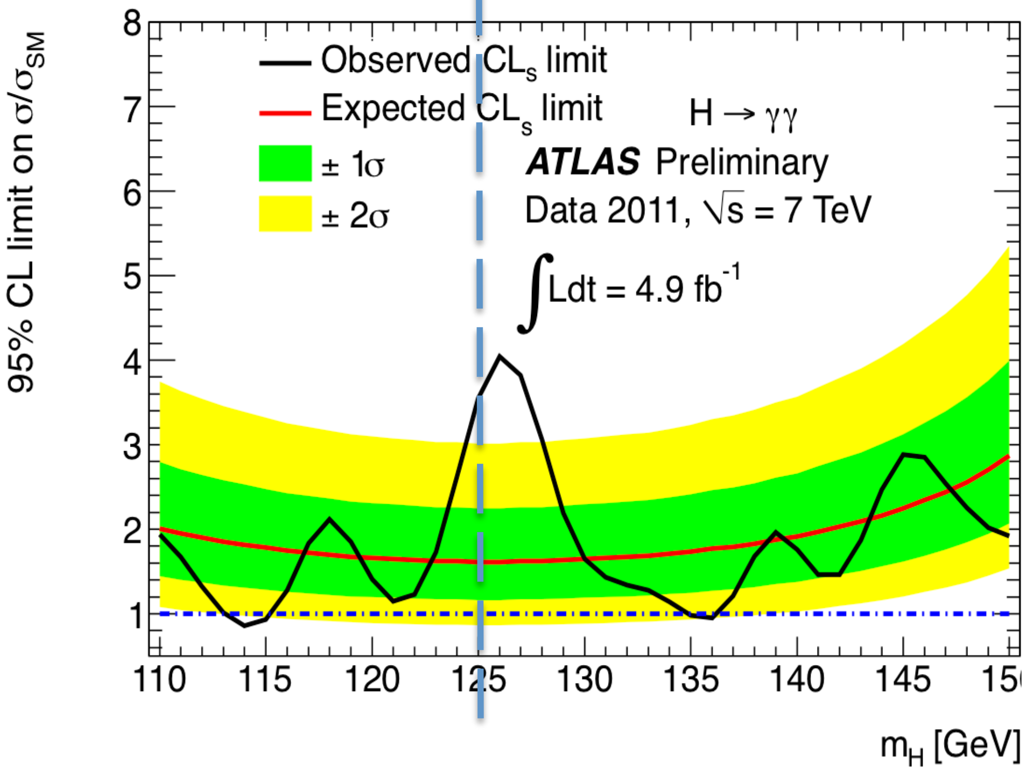


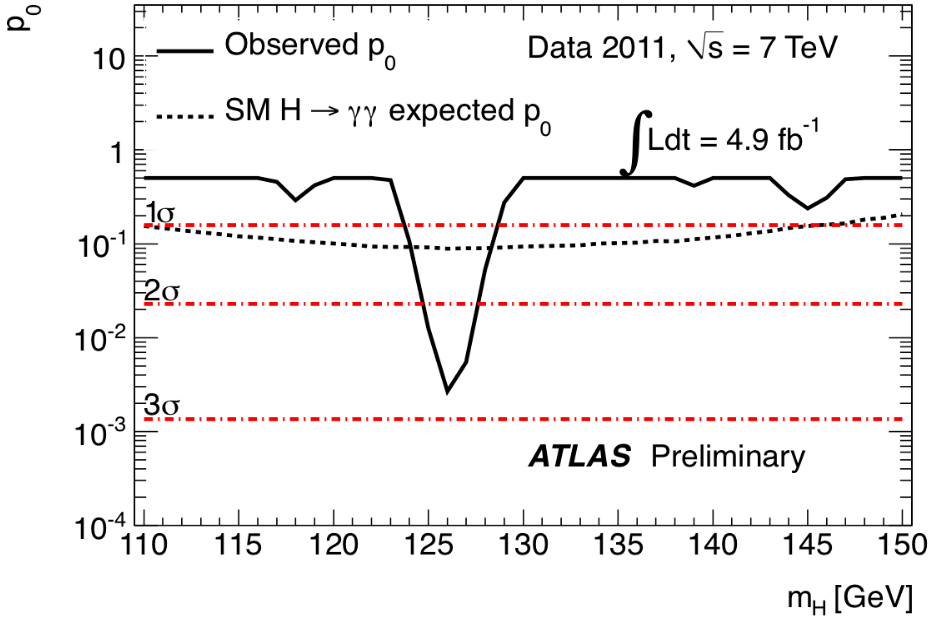


Results : R and p-value 13 -Dec - 2012

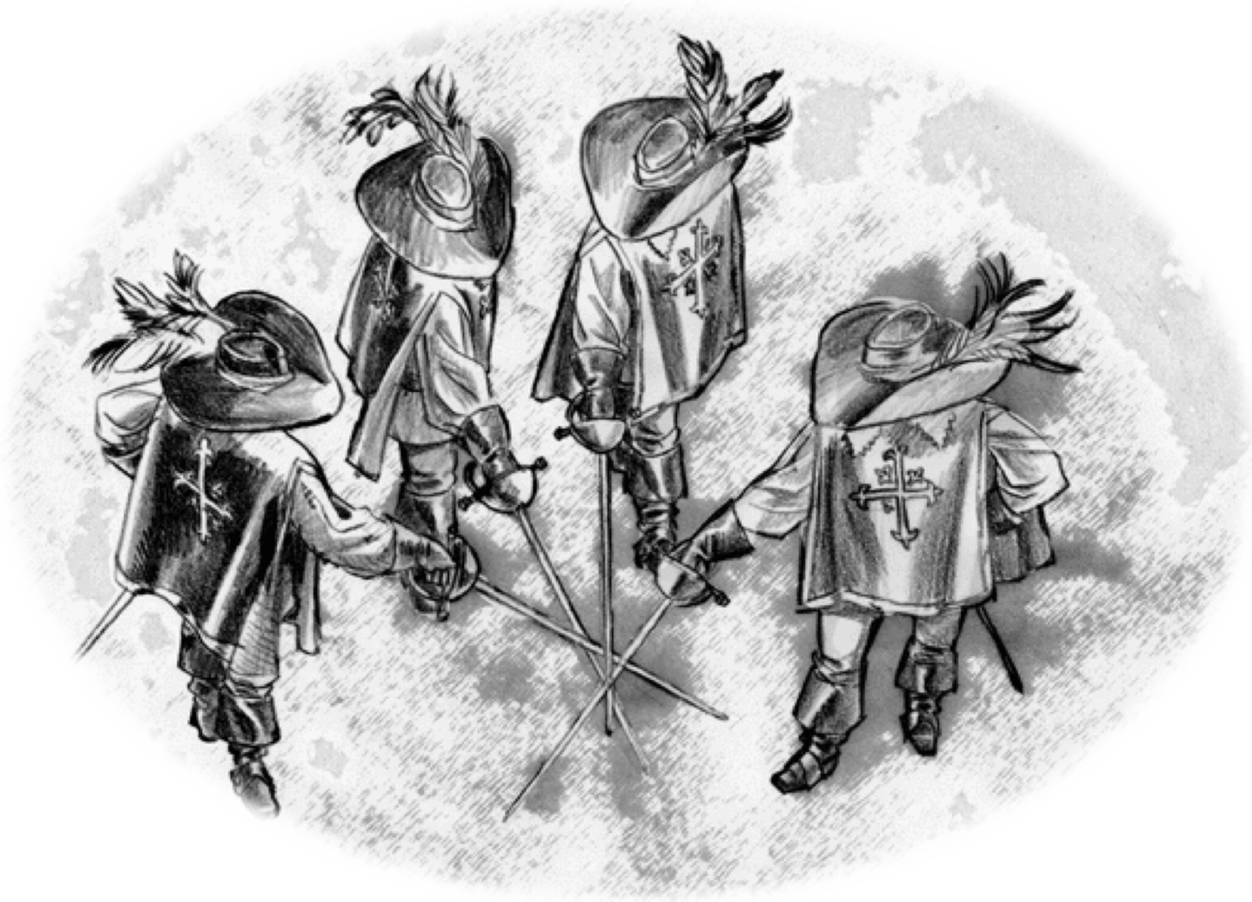






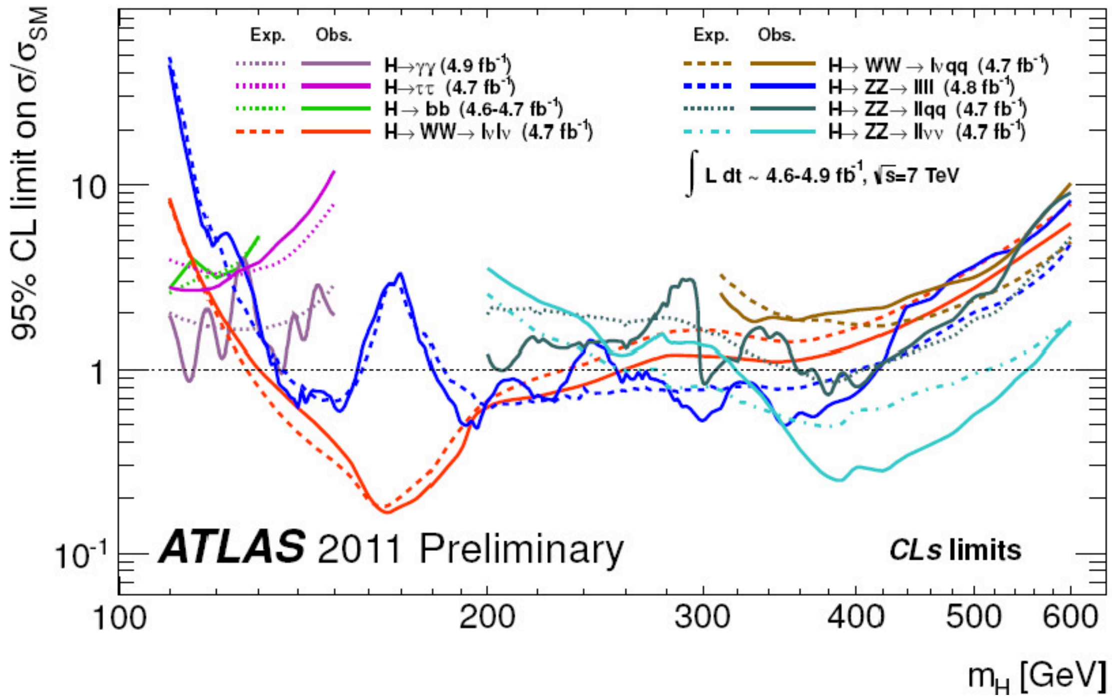


Combination !



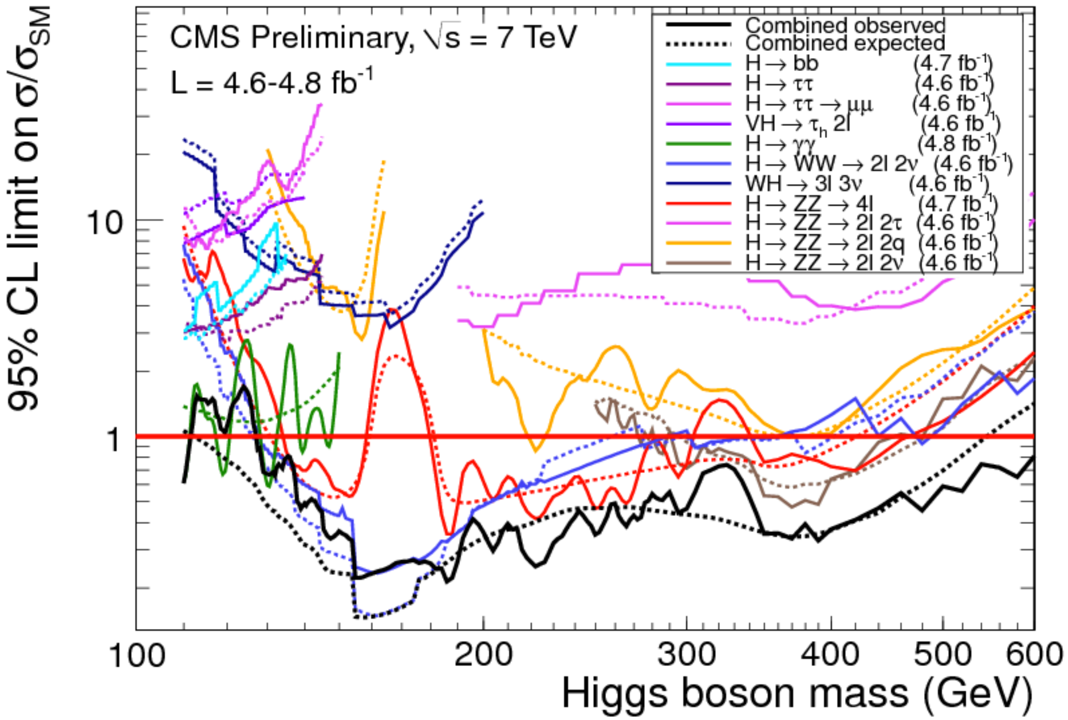
G. Petrucciani

Channel by channel



ATLAS:

8 channels, all (but γγ and 4l) new



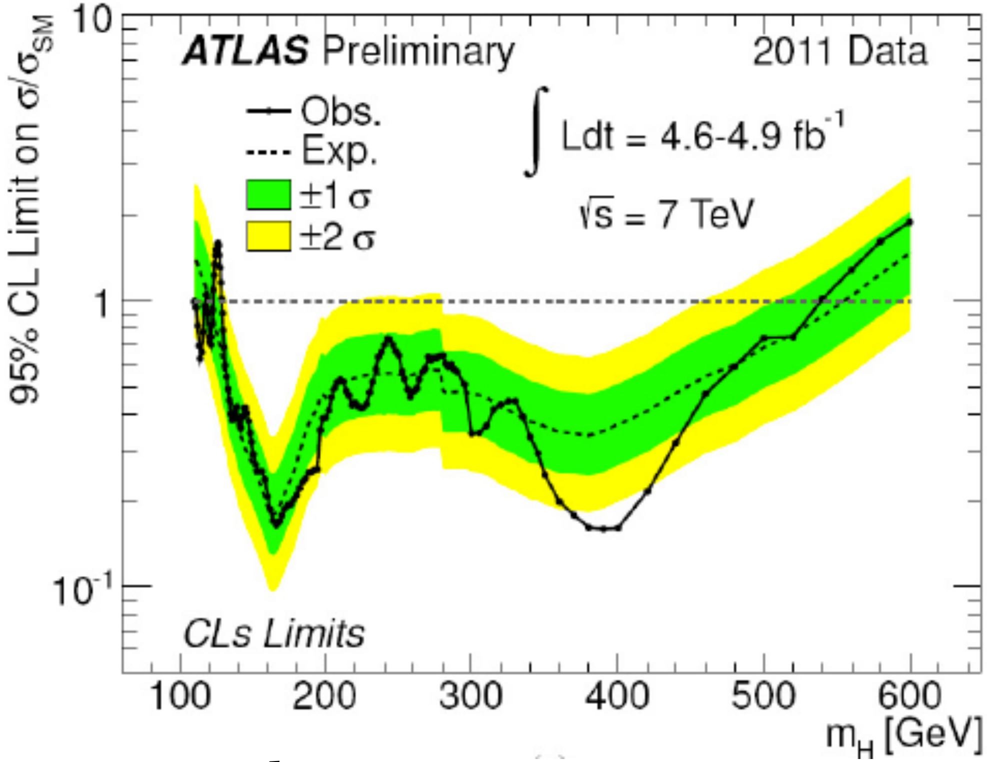
CMS:

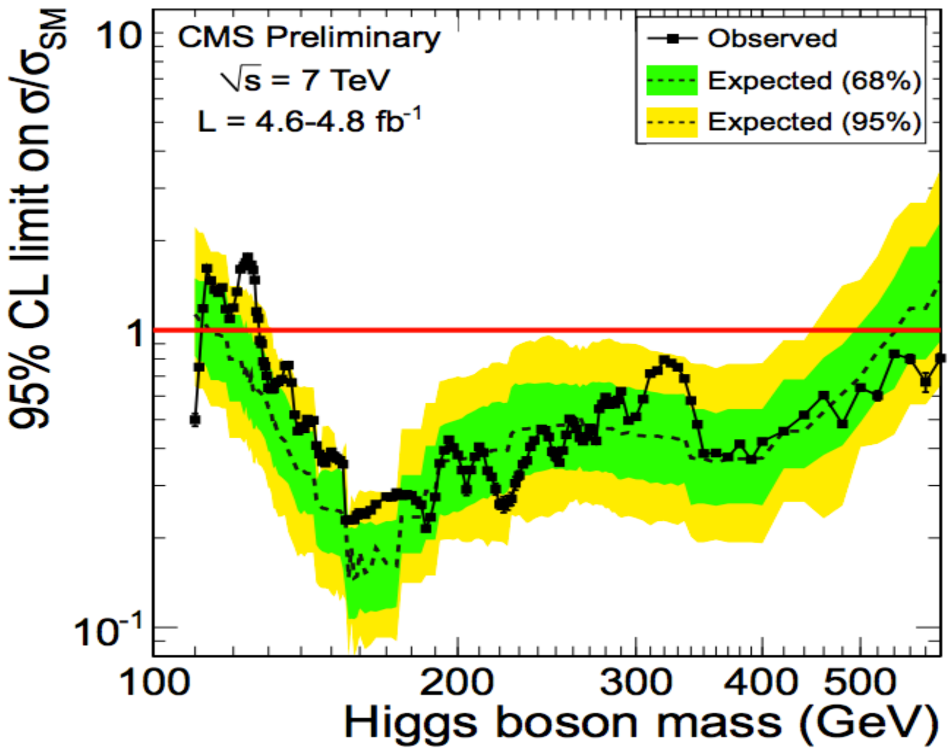
11 channels:

New γγ

New HW→3l2ν, H→ττ→μμ

The SM Higgs as of today





Expected at 95% CL:

$119.8 < M_H < 567$ GeV

New γγ $114.5 < m_H < 543$ GeV

Observed at 95% CL:

$110 < m_H < 117.5$ GeV

$118.4 < m_H < 122.7$ GeV,

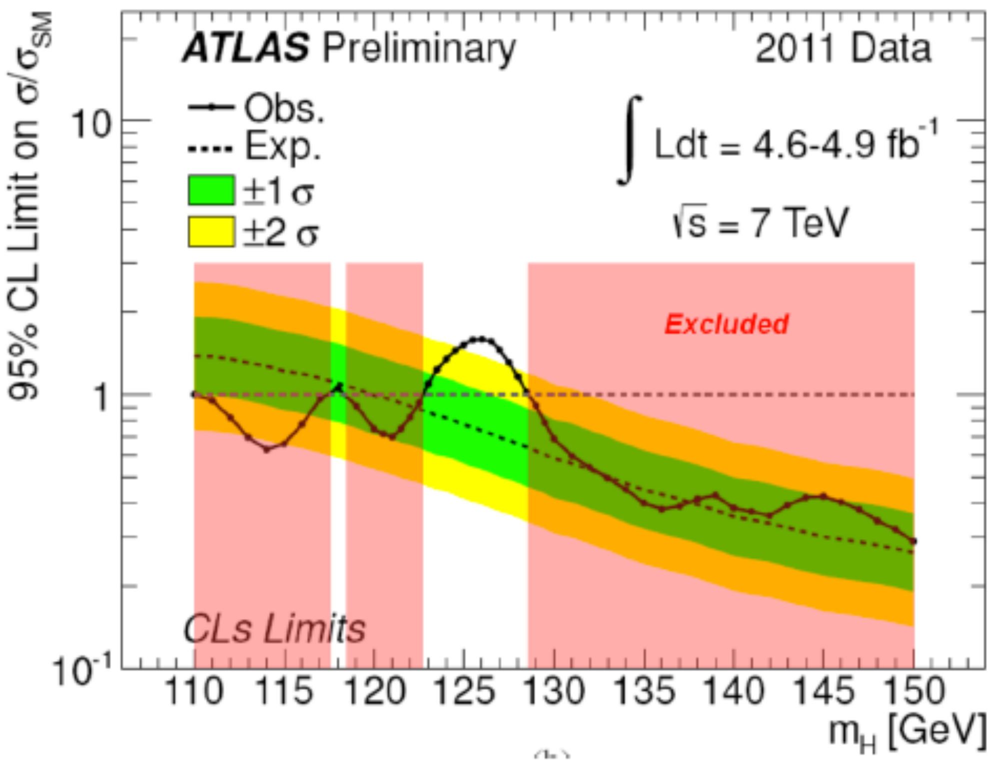
$128.6 < m_H < 529.3$ GeV

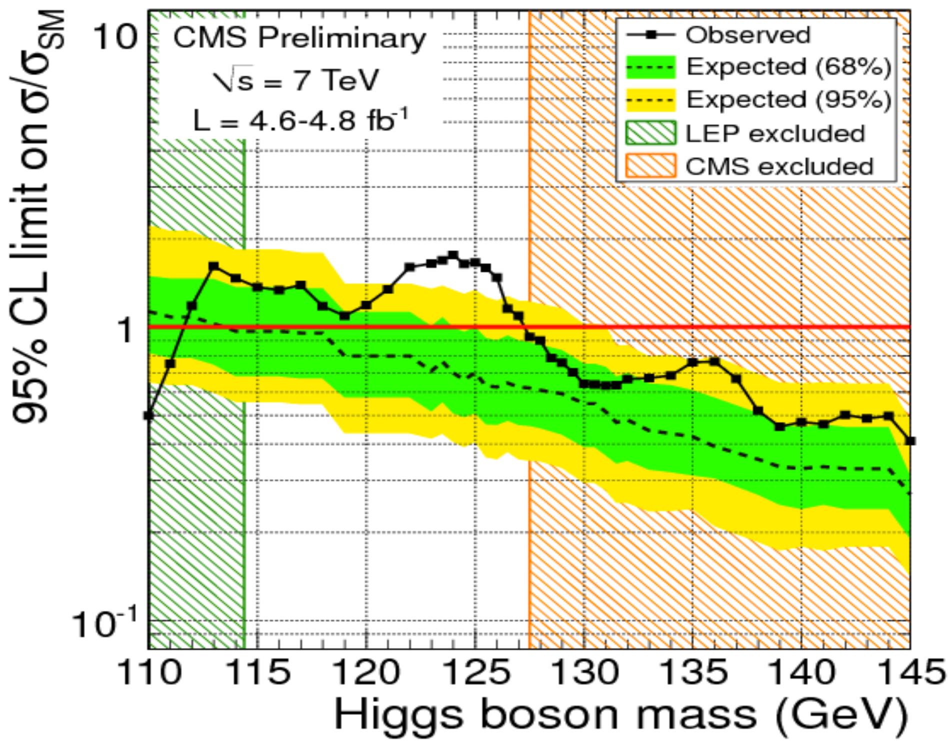
$127.5 < m_H < 600$GeV

Observed at 99% CL: $129.8 < m_H < 486$ GeV

$129 < m_H < 525$ GeV

Low Mass Range





Observed at 95% CL:

$110 < m_H < 117.5$ GeV

$118.4 < m_H < 122.7$ GeV,

$128.6 < m_H < 529.3$ GeV

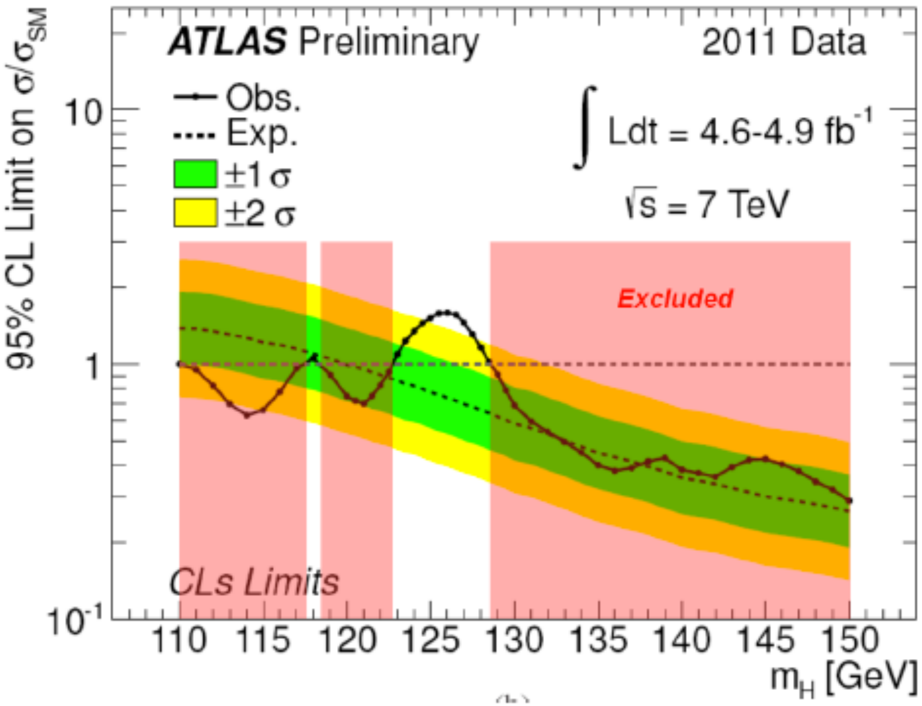
$127.5 < m_H < 600$GeV

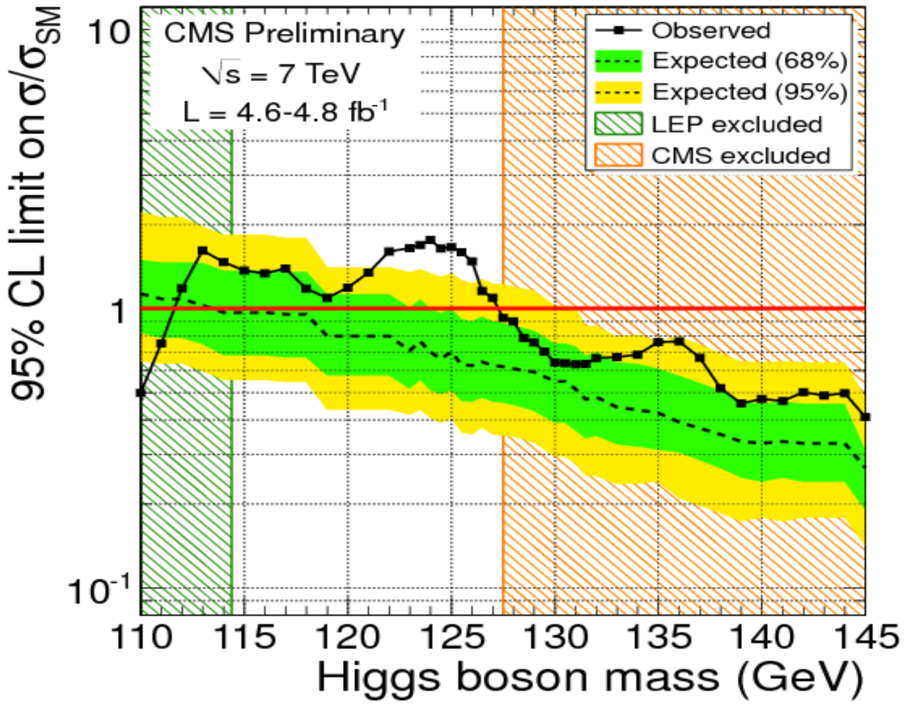
Expected at 95% CL:

$119.8 < M_H < 567$ GeV

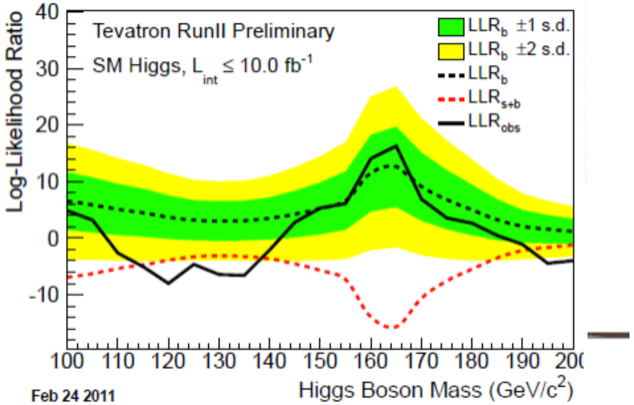
$114.5 < m_H < 543$ GeV

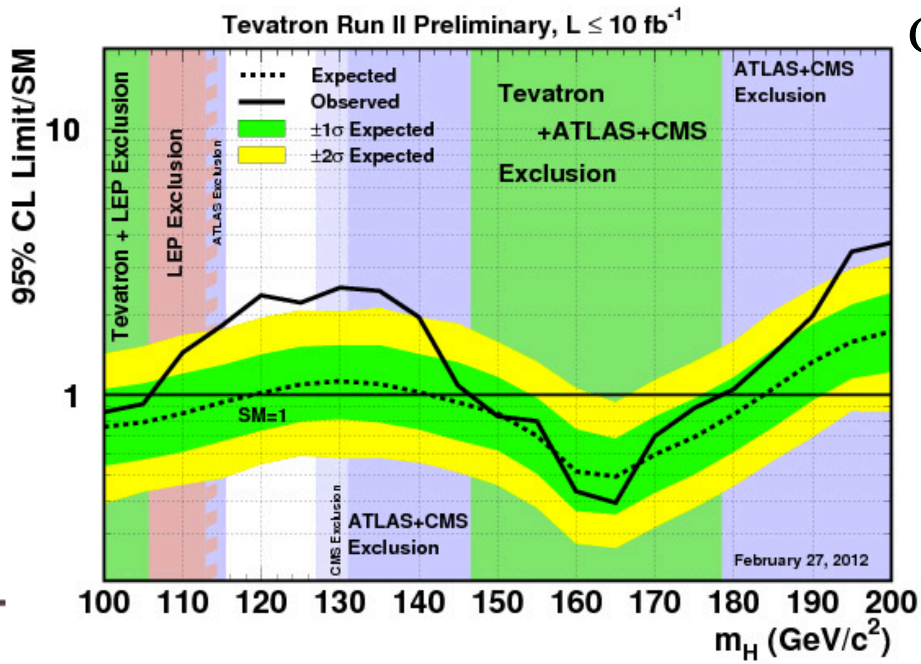
in both experiments the observed exclusion is weaker than expected





...and TEVATRON





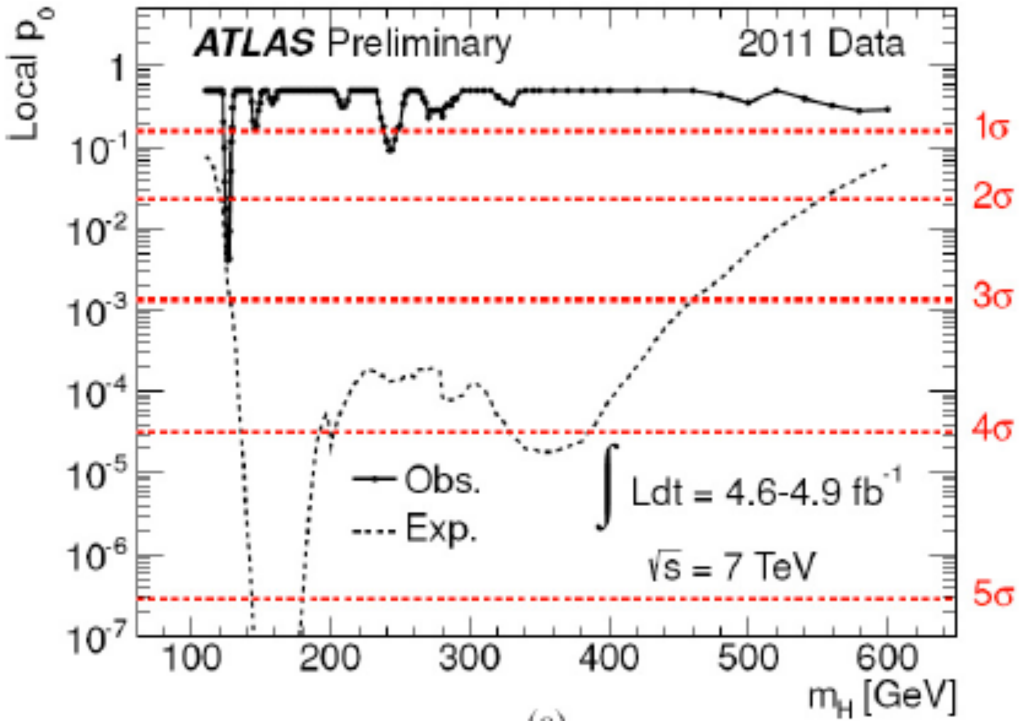
Global significance

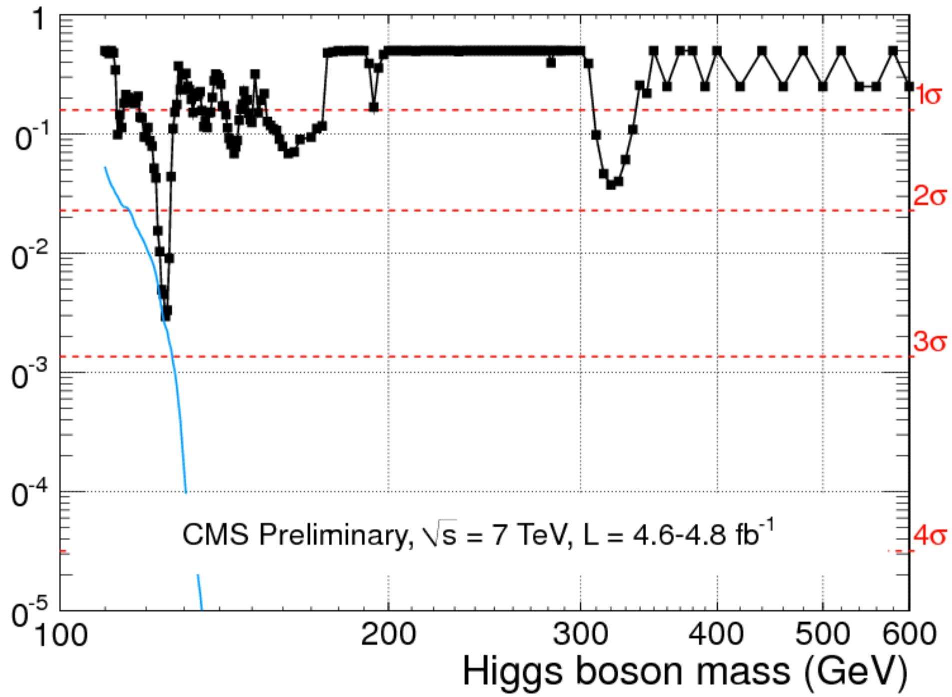
~2.2 σ

a Mariotti, Torino & CERN

Consistency with B only Hypothesis

- Excesses are quantified using p-values: use to reject a background only hypotesis





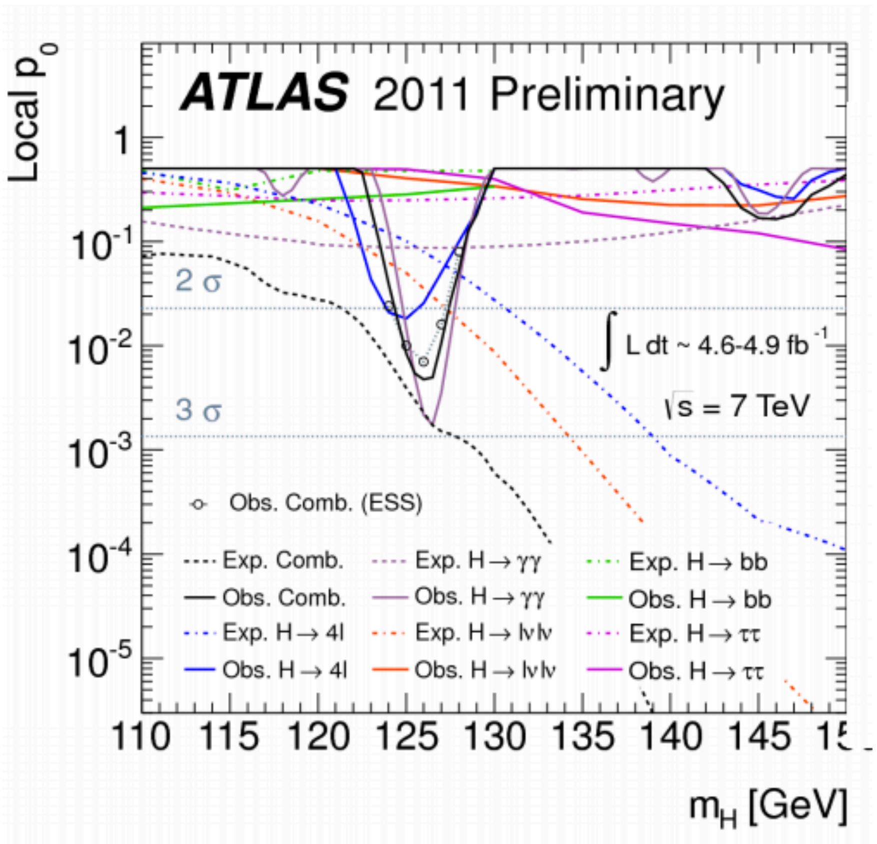
Maximum deviation from background-only expectation observed for m_H~126 GeV

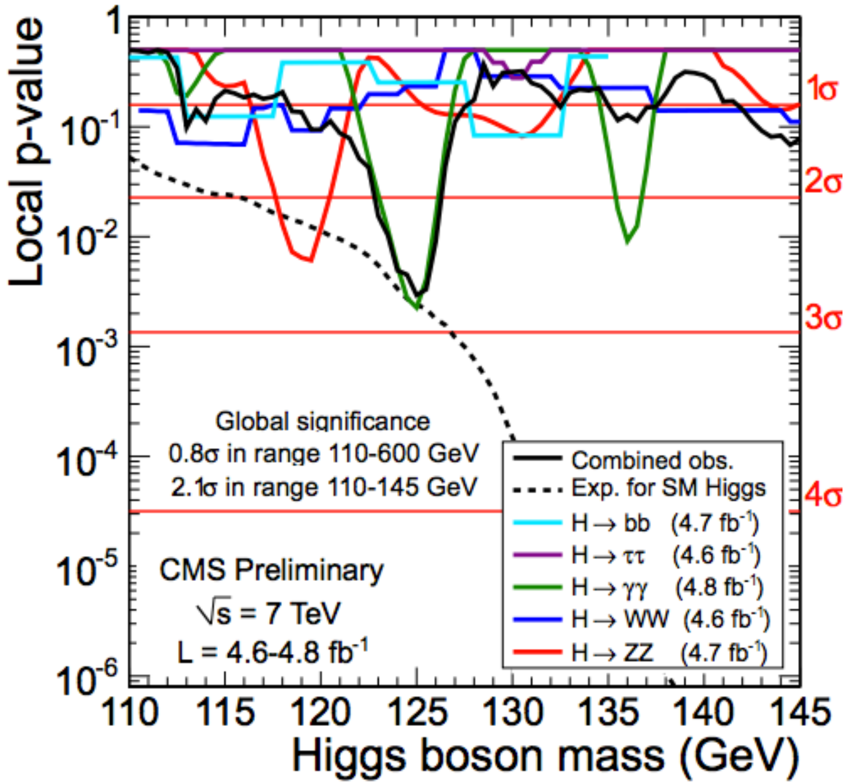
126 GeV: H → γγ and H→ZZ →4l
>460 GeV: mostly H→WW→lνqq

Max. deviation from background-only observed for m_H~125 GeV

119 GeV: 3 H→4l events
124 GeV: H→2γ events
325 GeV: 9 H→4l events

Consistency with BG-Only: Low Mass





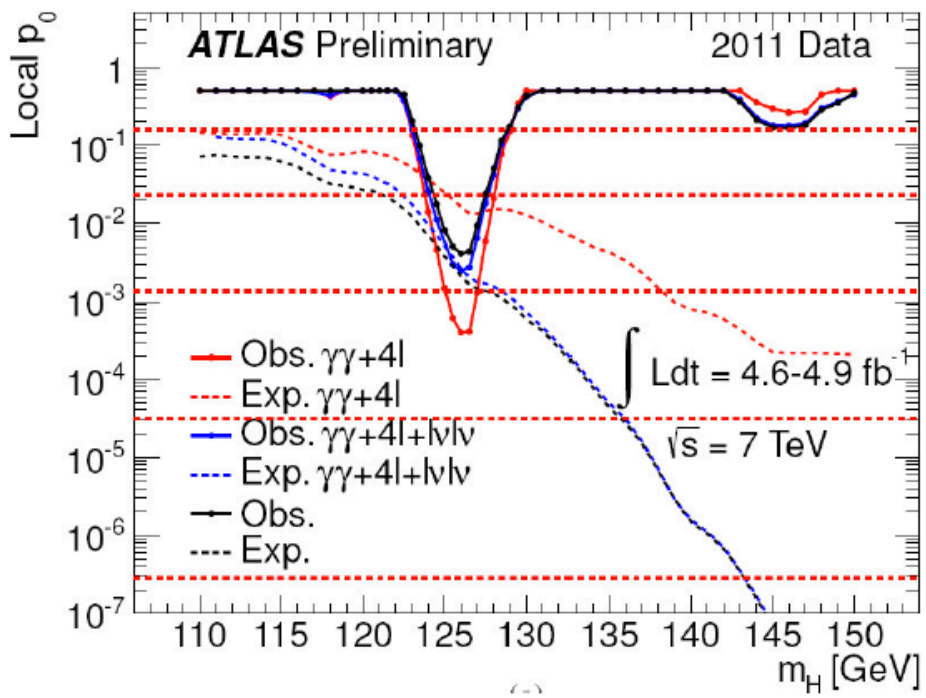
γγ: 2.8σ at 126 GeV
4l: 2.1σ at 125 GeV

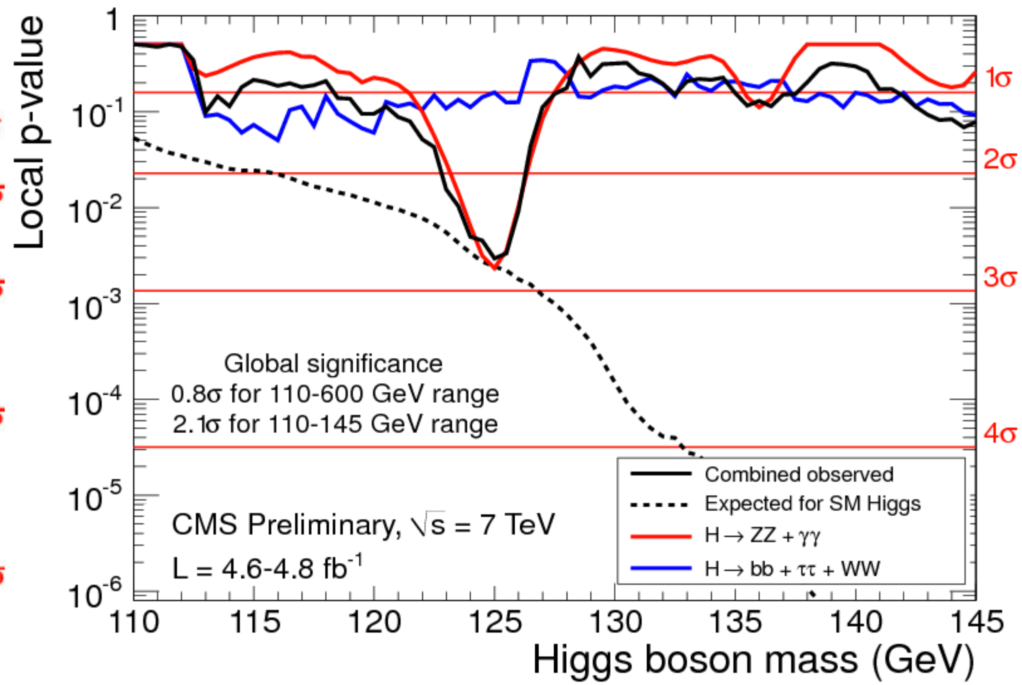
Observed local significance 2.5 σ at 126 GeV
(expected 2.8 σ)
Global 2.1 σ

γγ: 2.9σ at 125 GeV
4l: 2.5σ at 119.5 GeV

Observed local significance 2.8 σ at 156 GeV
(expected 2.9 σ)
Global 2.1 σ

Consistency with BG-Only: Low Mass





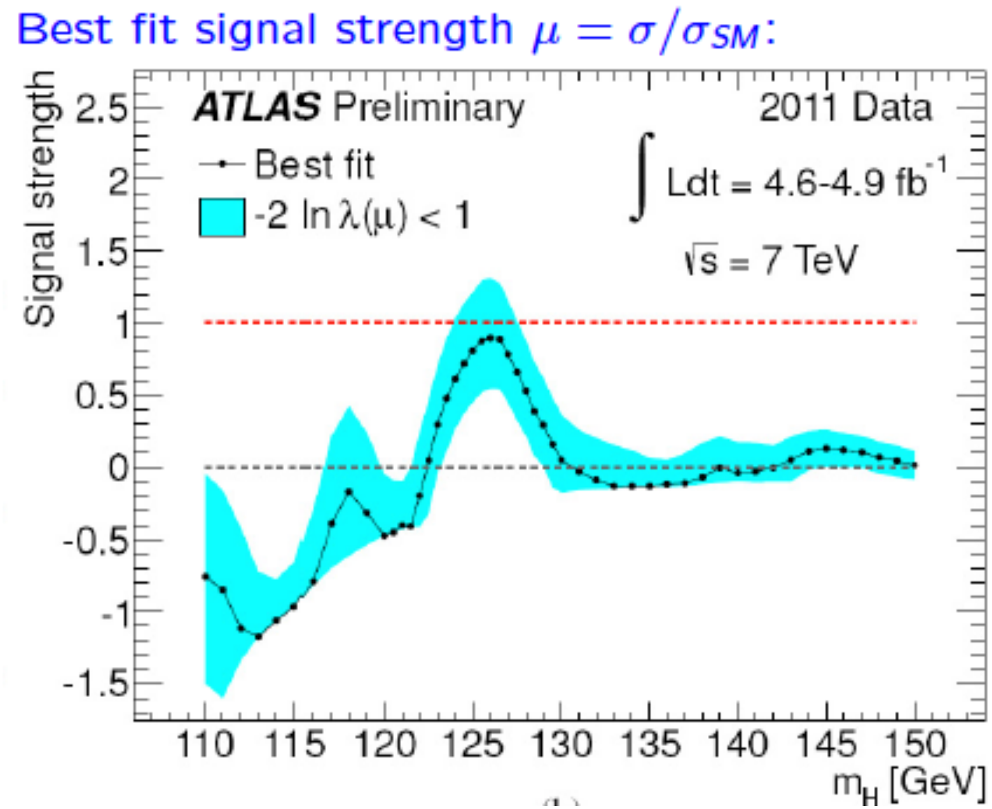
Excess observed at 126 GeV

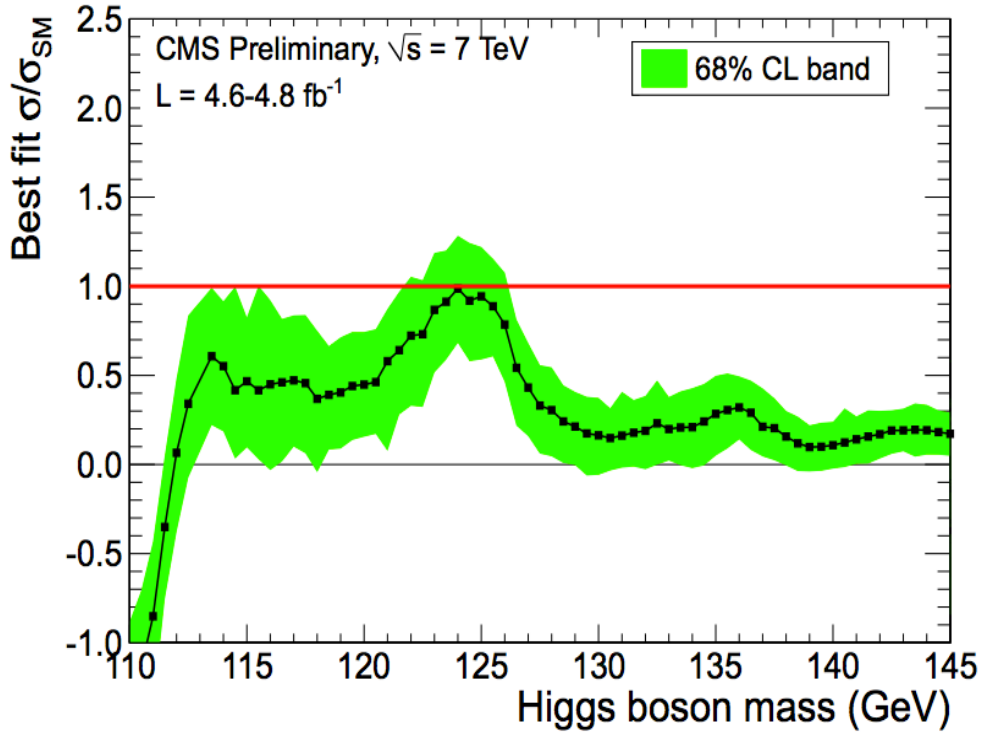
Observed local significance 2.5 σ
(expected 2.8 σ)

Excess observed at 125 GeV
(γγ deficit compensate HZZ excess at 119)

Observed local significance 2.8 σ
(expected 2.9 σ)

Best Fit for Signal Strength w.r.t. SM Rate

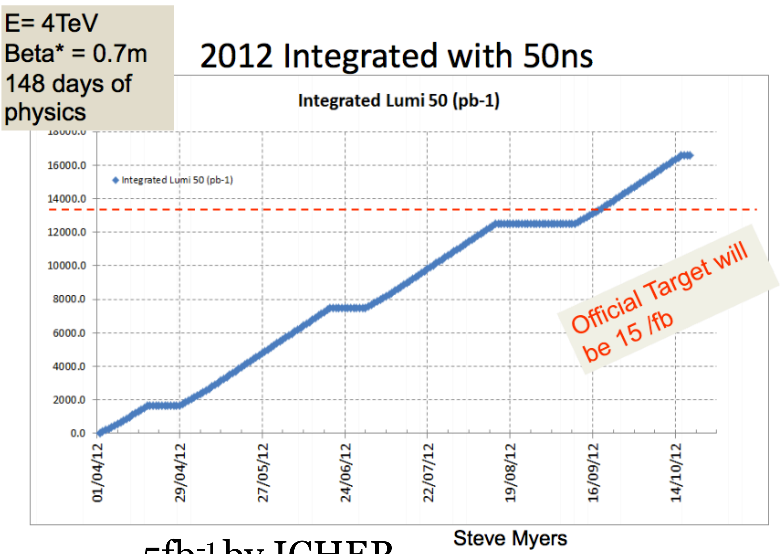




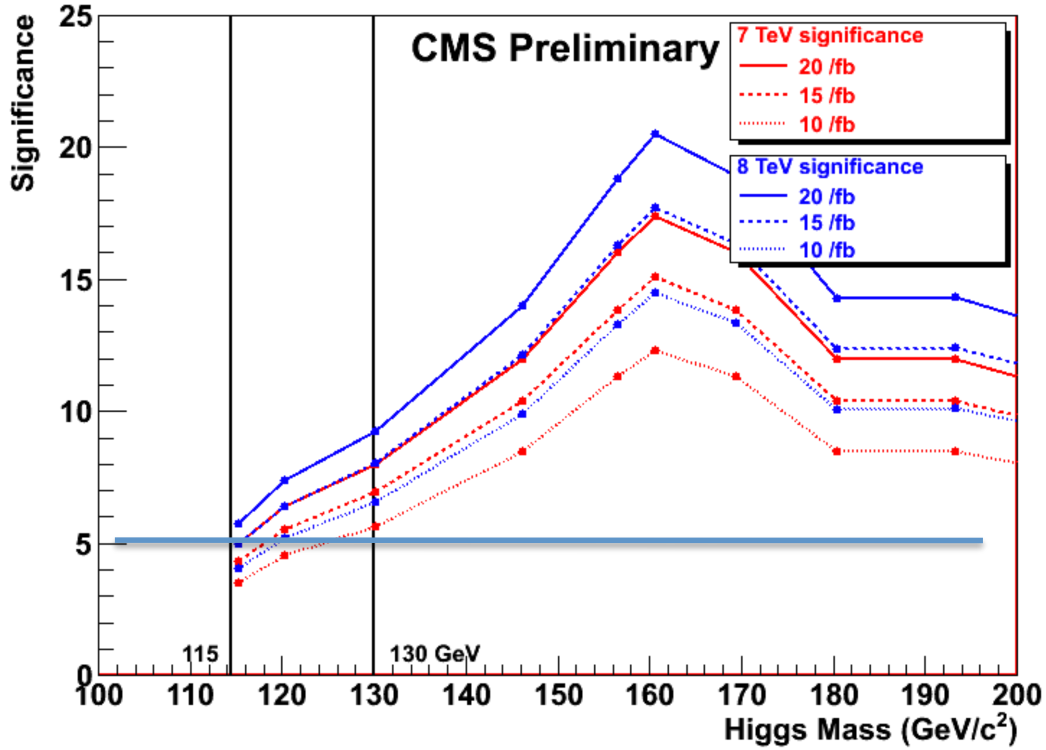
Mass values with highest signal strength parameter
slightly different
But not an inconsistent picture

Near future

By the end of the 8 TeV run in 2012, the luminosity collected will hopefully allow us to have 5 sigma everywhere.
Maybe difficult at 115 Gev
The very high mass will be investigated as well.

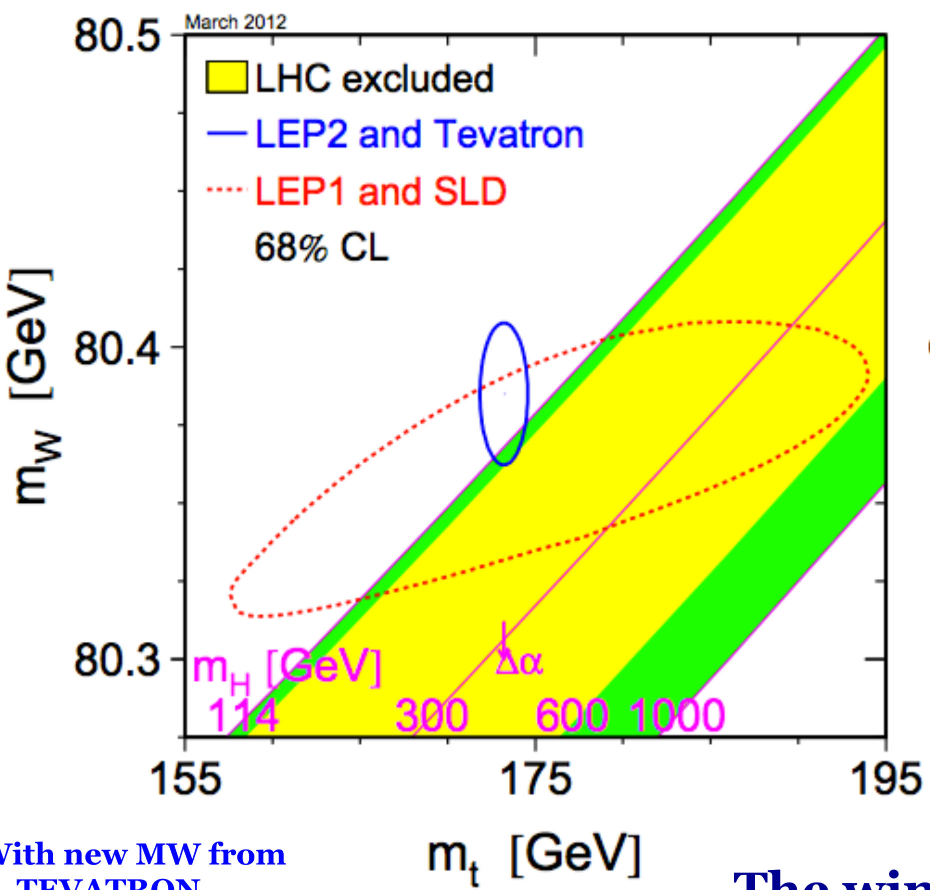


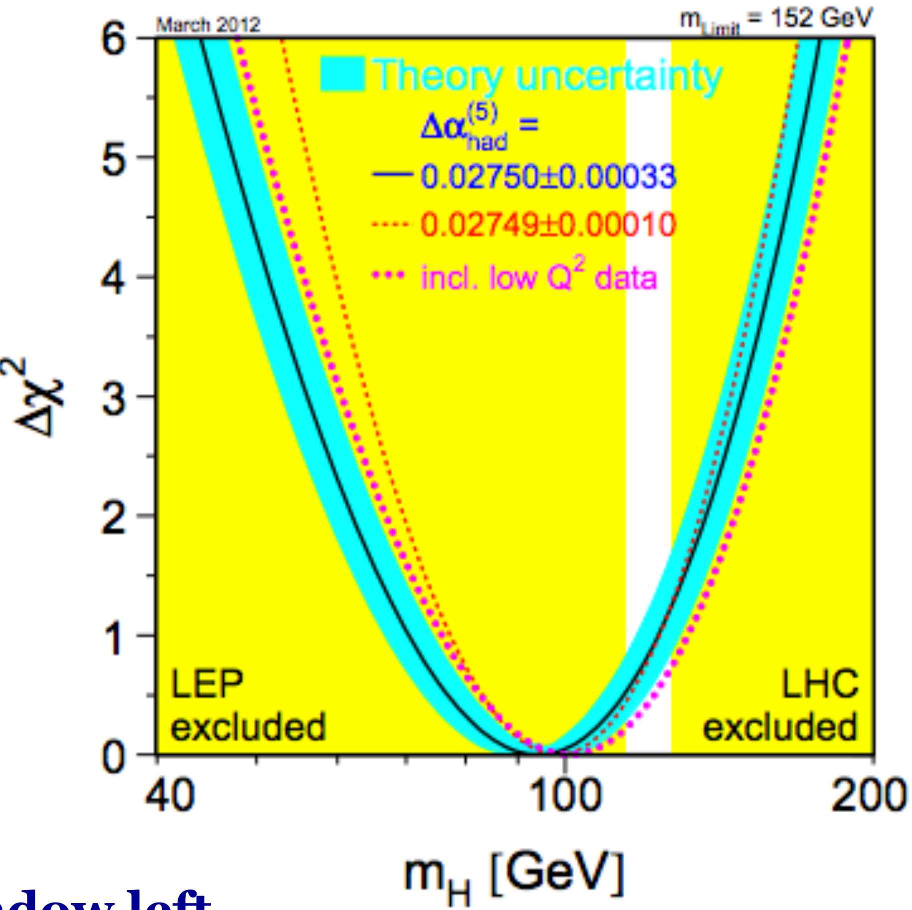
~ 5fb^{-1} by ICHEP
~ 15 fb^{-1} by Nov



By the end of 2012 five sigma everywhere, maybe difficult at 115 GeV

The SM Higgs as of today





With new MW from TEVATRON MW= 80.375±0.15

The window left is between ~117 – 127 GeV in agreement with EW precision physics

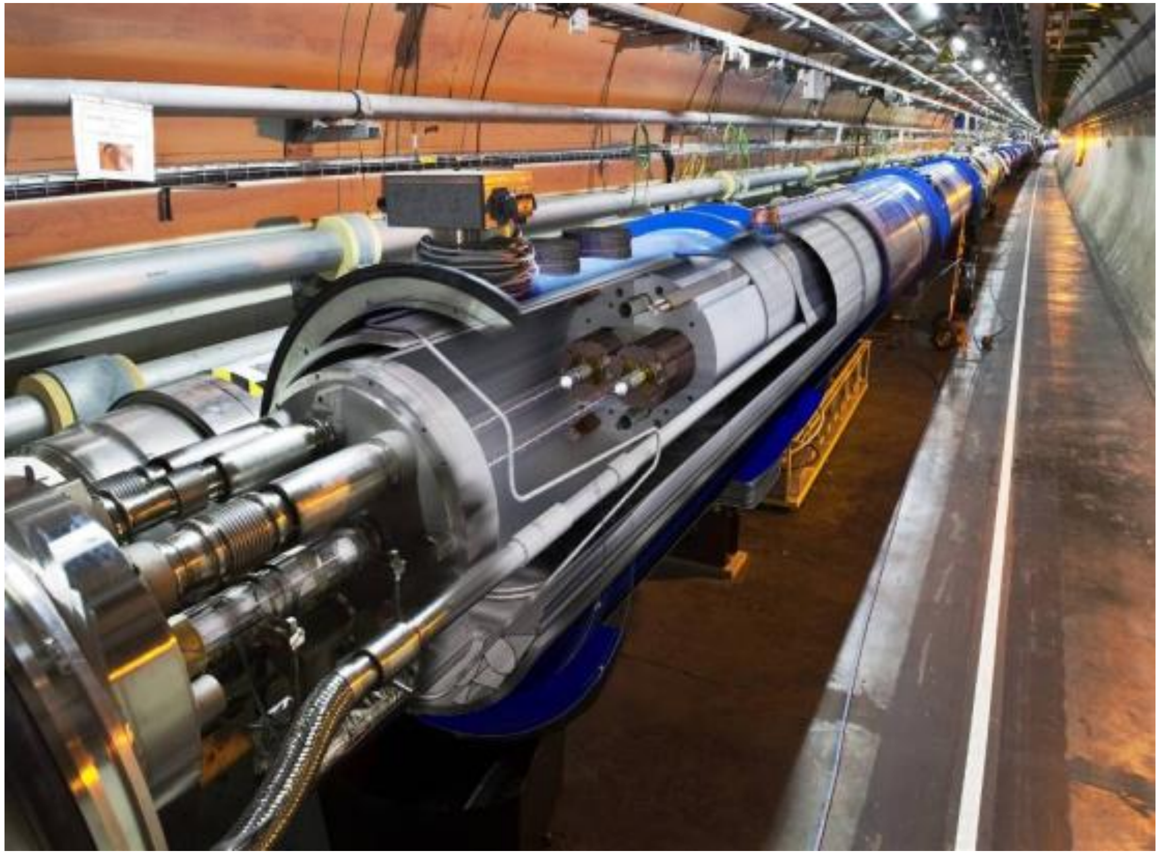
Summary

- Fantastic years at LHC: lots of data and analyses, measurements and searches…
- We did things we never imagined would be possible 2 years ago.
- Unfortunately we did not discover anything up to now/ Fortunately we did not exclude everything up to now!
- But more luminosity and higher energy will come.
- We do not yet know what is in front of us: maybe another unexpected interpretation of our world!

backup

LHC

What is special with LHC machine ?



- The highest field accelerator magnets: 8.3 T (ultimate: 9 T)
- Proton-Proton machine : Twin-aperture main magnets
- The largest superconducting magnet system (~8000 magnets)
- The largest 1.9 K cryogenics installation (superfluid helium)
- The highest currents controlled with high precision (up to 13 kA)
- The highest precision ever demanded from the power converters, a few ppm
- A sophisticated and ultra-reliable magnet quench protection system

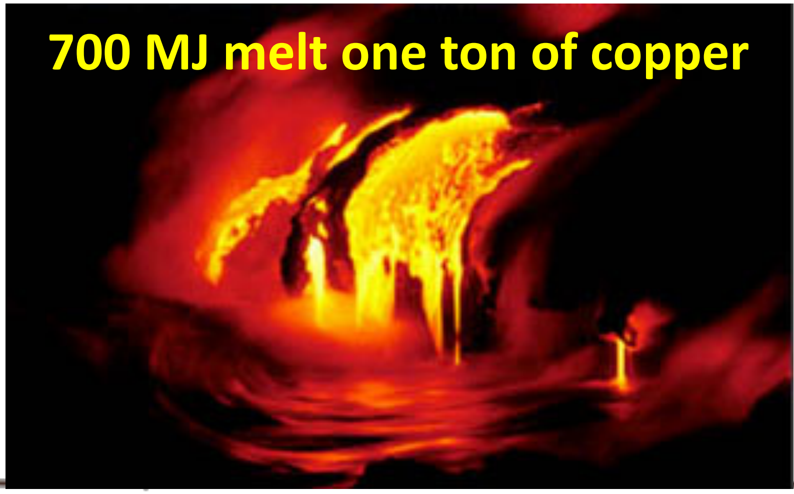
Energy management challenges

Energy stored in the magnet system: ~10 GJoule

CMS Magnet 2GJ

Energy stored in the two beams:
720 MJ ***[6 10^{14} protons (1 ng of H+) at 7 TeV]***

Machine protection system: about 7000 channels, each redundant, corresponds to 350 tons of material. In case any failure is detected, the beams are dumped



154 magnets in series per sector (x8)

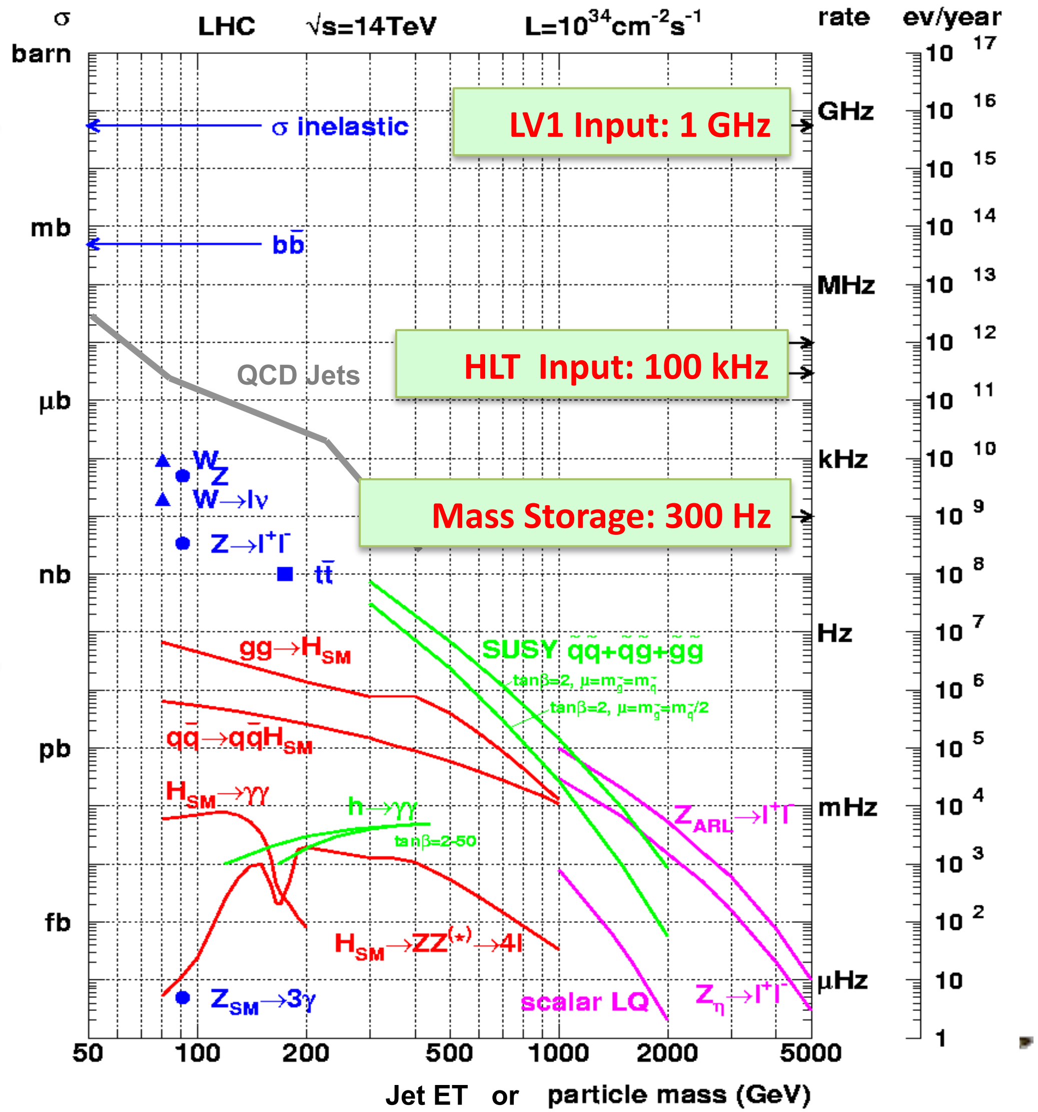
700 MJoule dissipated in 88 μs

700.106 / 88.106 ≅ 8 TW

90 kg of TNT per beam

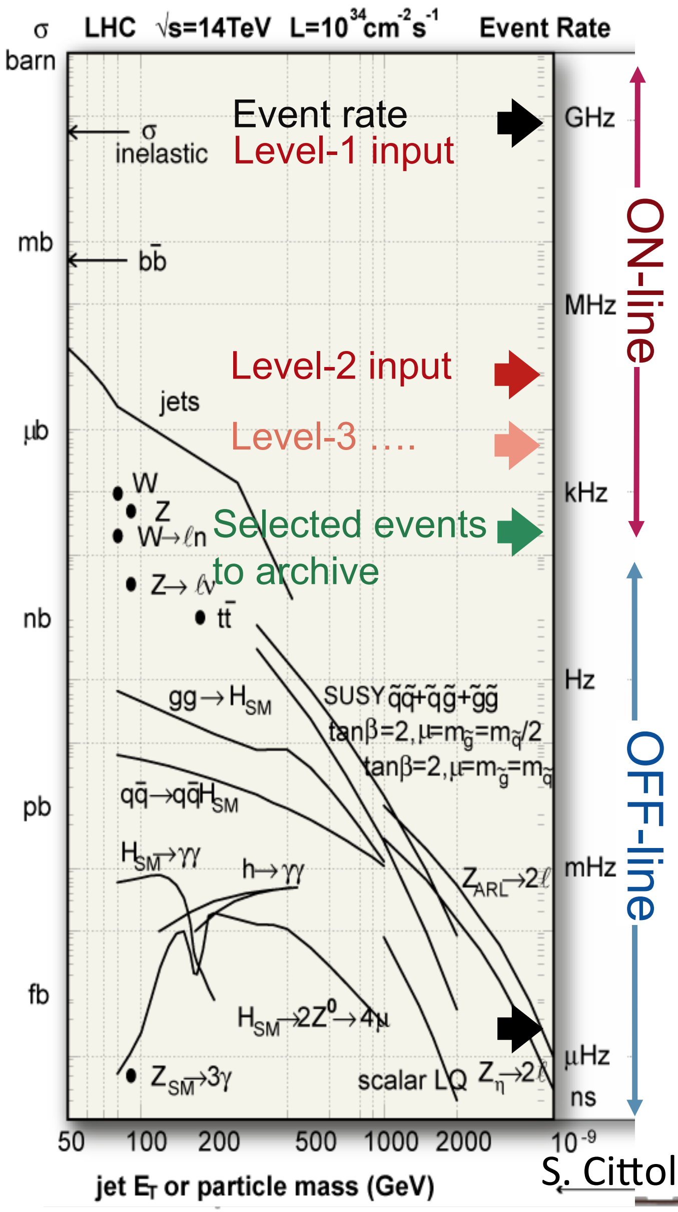
Production rates at LHC

10^{10}



"At LEP every event is signal.
At LHC every event is background."
Sam Ting, LEPC, Sept-2000

Trigger



S. Cittolin

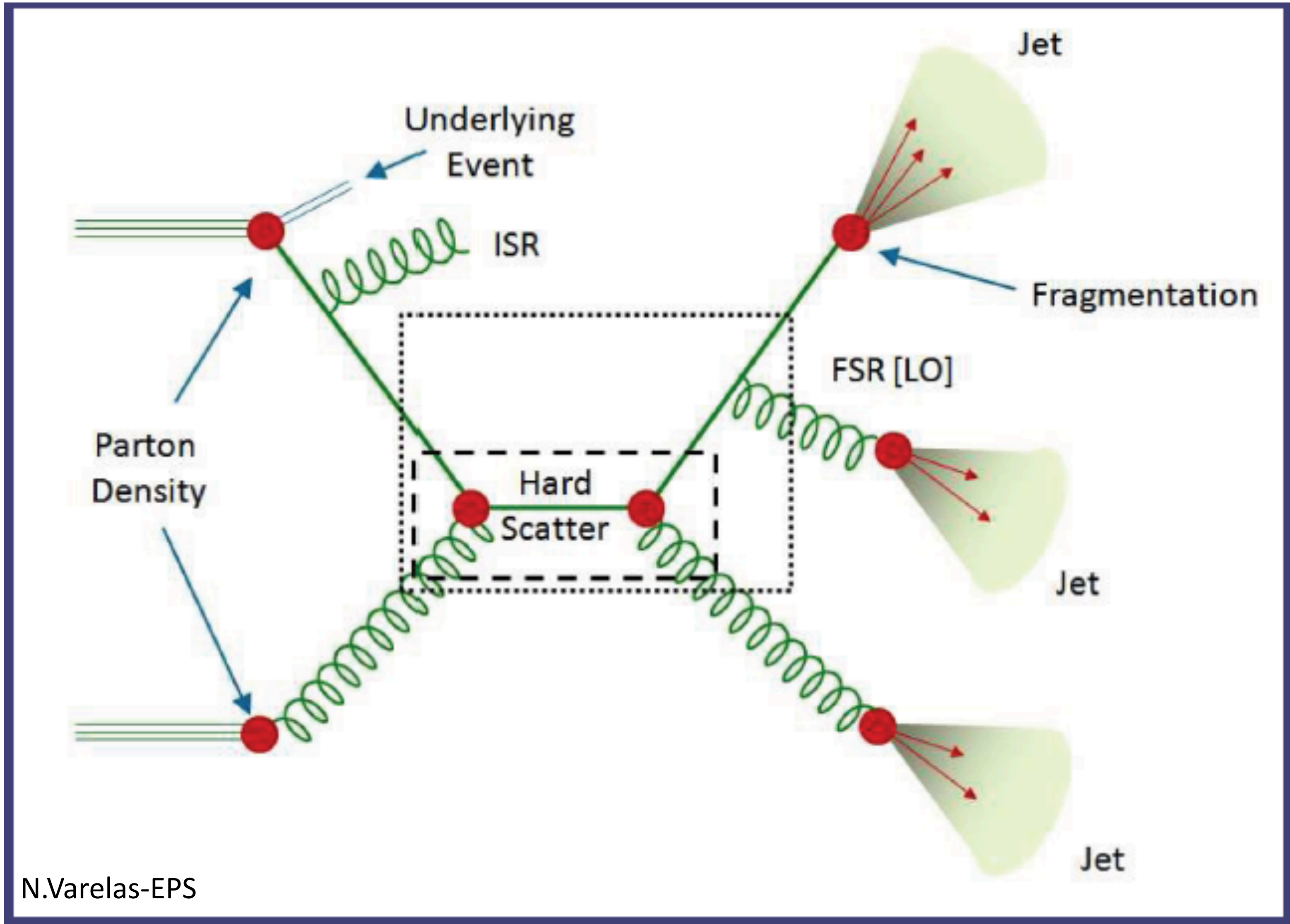
- At LHC the collision rate will be 40 MHz
  The Event size ~1 Mbyte

  Band width limit ~ 100 Gbyte →
  Mass storage rate ~100 Hz

Thus we should select the events with "the Trigger"

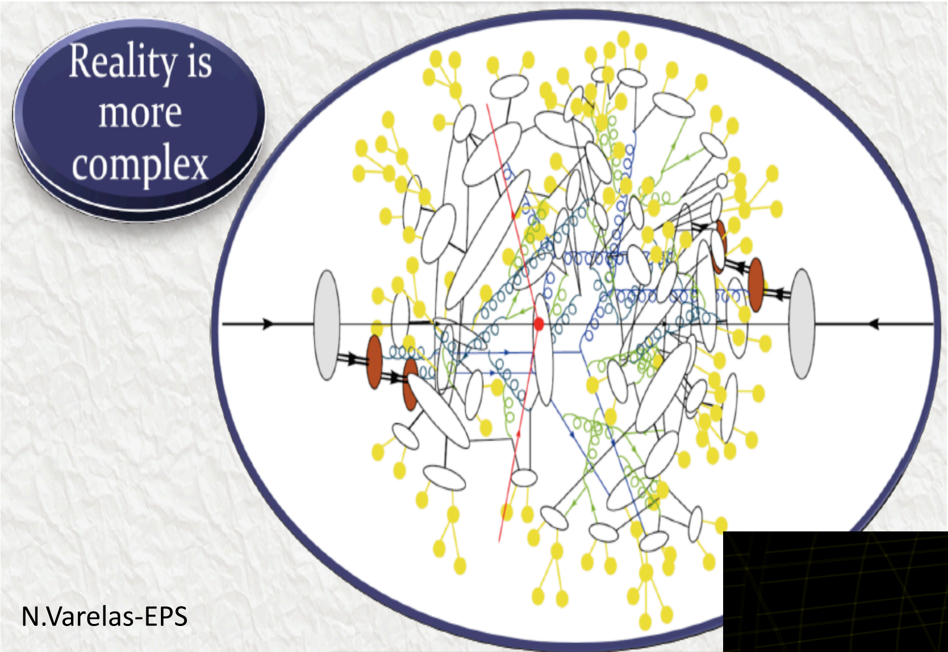
- Level-1 Trigger input 40 MHz
- Level-2 Trigger input 100 kHz (HLT for CMS)
- Level-3 Trigger input xx kHz (HLT for Atlas)

QCD at LHC

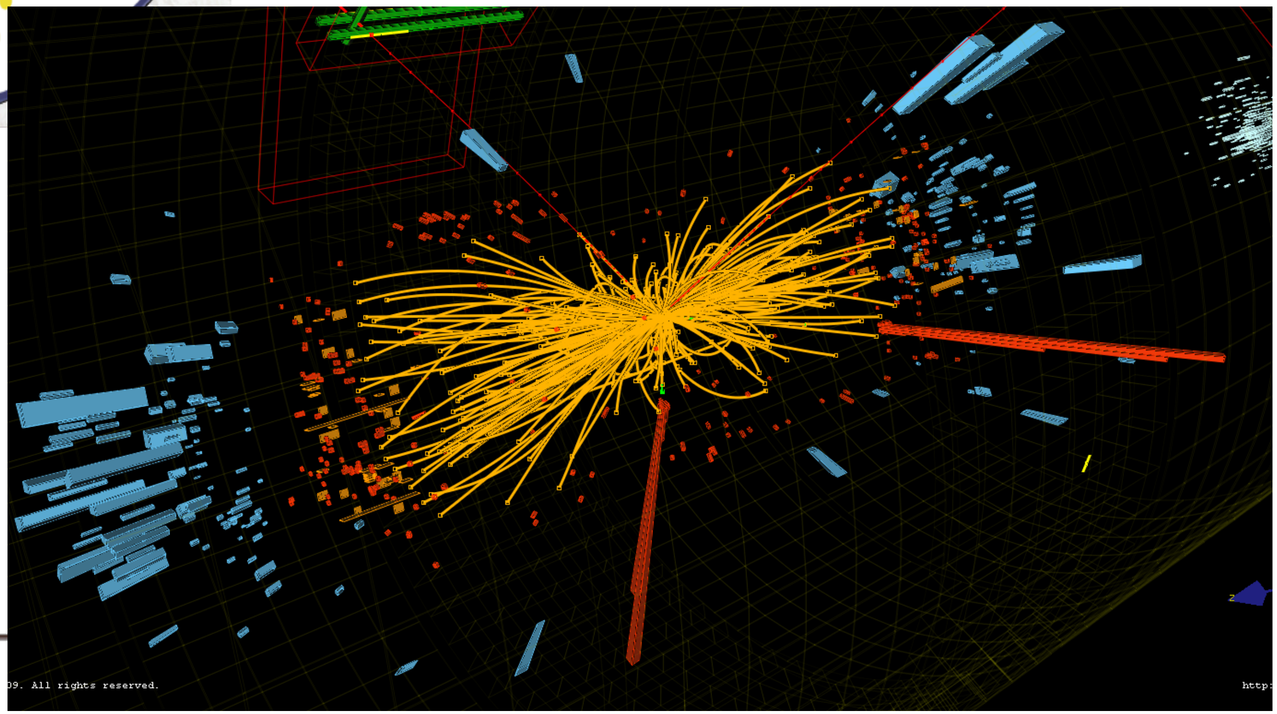


Jet
Underlying
Event
ISR
Fragmentation
FSR [LO]
Parton
Density
Hard
Scatter
Jet
Jet
N.Varelas-EPS

Reality is more complex!



Understanding of QCD is important for
-Interpretation of data
-Precision studies
-Searches of new physics



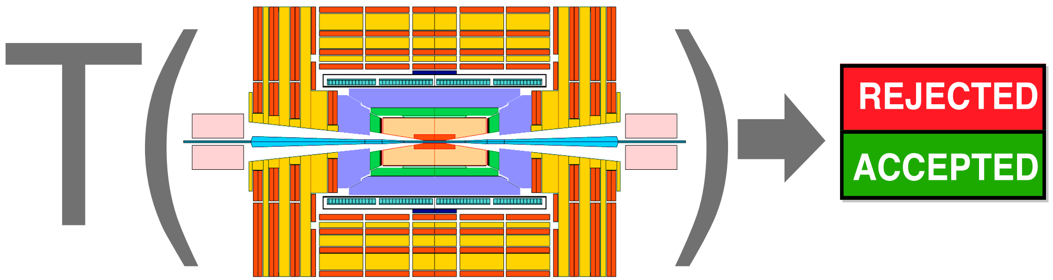
Event selection: The trigger system

Mandate:

"Look at (almost) all bunch crossings, select most interesting ones, collect all detector information and store it for off-line analysis"

P.S. For a reasonable amount of CHF

The trigger is a function of :



Event data & Apparatus
Physics channels & Parameters

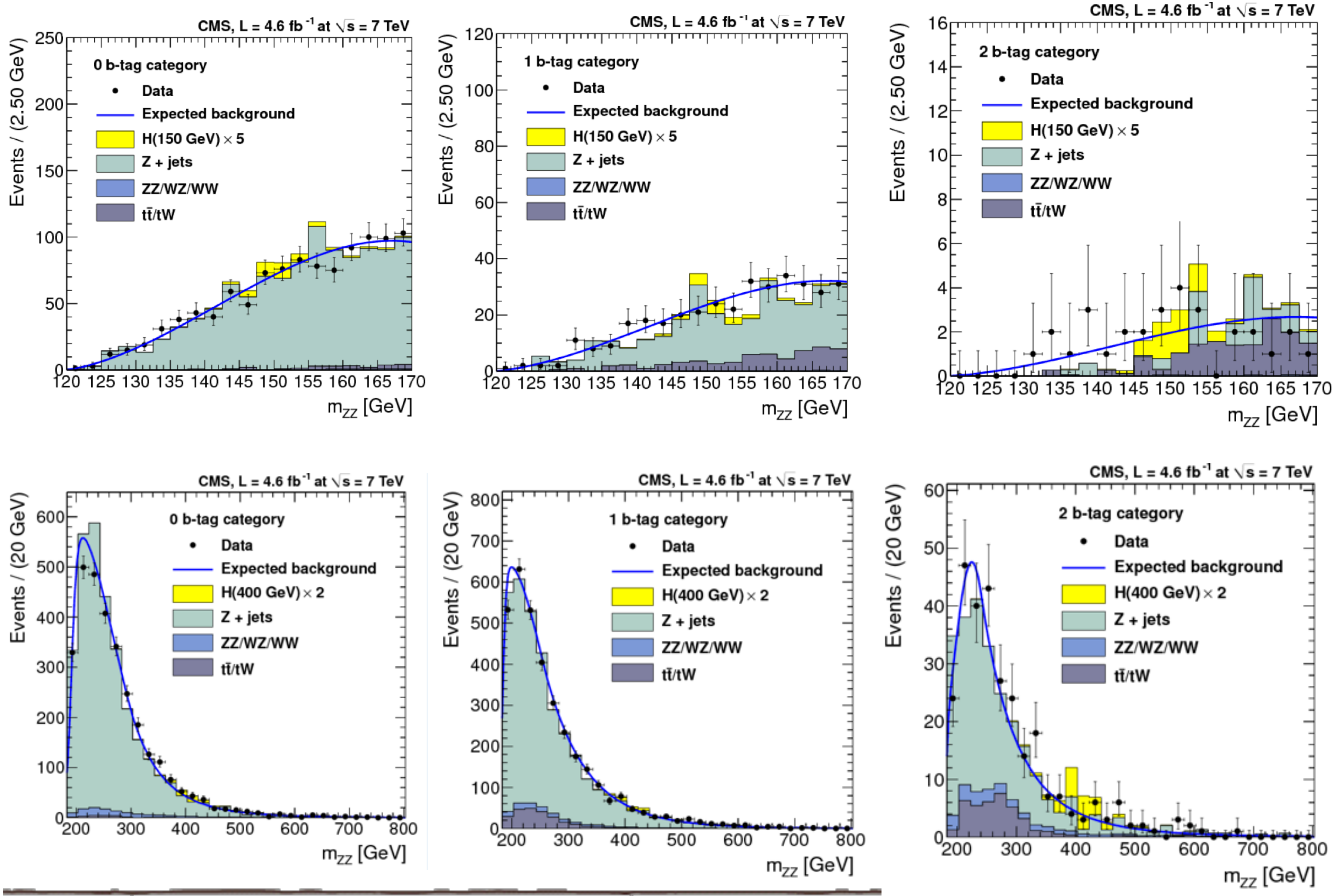
Since the detector data are not all promptly available and the function is highly complex, T(...) is evaluated by successive approximations called :

TRIGGER LEVELS

(possibly with zero dead time)

S. Cittolin

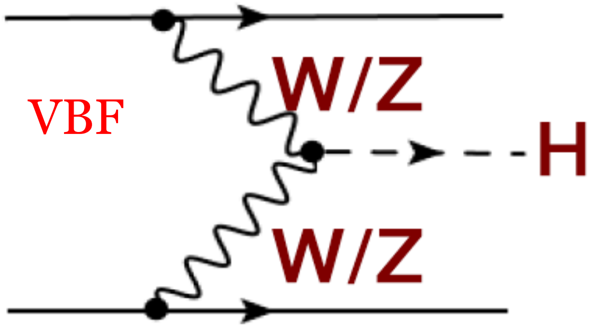
M_{ZZ}


CMS, L = 4.6 fb^{-1} at $\sqrt{s}$ = 7 TeV
0 b-tag category
Data
Expected background
H(150 GeV) × 5
Z + jets
ZZ/WZ/WW
$t\bar{t}$/tW
Events / (2.50 GeV)
m_{ZZ} [GeV]
CMS, L = 4.6 fb^{-1} at $\sqrt{s}$ = 7 TeV
1 b-tag category
Data
Expected background
H(150 GeV) × 5
Z + jets
ZZ/WZ/WW
$t\bar{t}$/tW
Events / (2.50 GeV)
m_{ZZ} [GeV]
CMS, L = 4.6 fb^{-1} at $\sqrt{s}$ = 7 TeV
2 b-tag category
Data
Expected background
H(150 GeV) × 5
Z + jets
ZZ/WZ/WW
$t\bar{t}$/tW
Events / (2.50 GeV)
m_{ZZ} [GeV]
CMS, L = 4.6 fb^{-1} at $\sqrt{s}$ = 7 TeV
0 b-tag category
Data
Expected background
H(400 GeV) × 2
Z + jets
ZZ/WZ/WW
$t\bar{t}$/tW
Events / (20 GeV)
m_{ZZ} [GeV]
CMS, L = 4.6 fb^{-1} at $\sqrt{s}$ = 7 TeV
1 b-tag category
Data
Expected background
H(400 GeV) × 2
Z + jets
ZZ/WZ/WW
$t\bar{t}$/tW
Events / (20 GeV)
m_{ZZ} [GeV]
CMS, L = 4.6 fb^{-1} at $\sqrt{s}$ = 7 TeV
2 b-tag category
Data
Expected background
H(400 GeV) × 2
Z + jets
ZZ/WZ/WW
$t\bar{t}$/tW
Events / (20 GeV)
m_{ZZ} [GeV]

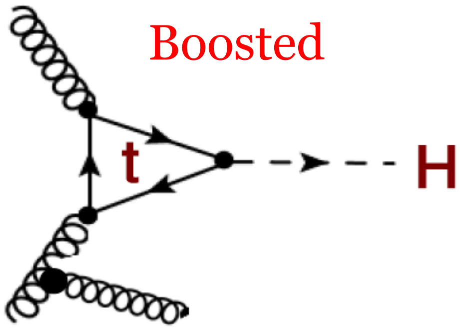
CMS: H → ττ

optimize sensitivity by splitting in jet/topology categories: VBF highest sensitivity
but all production modes considered: gg→H, VBF, W(Z)H, ttH

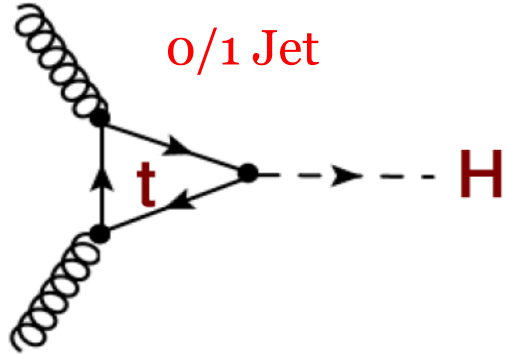
VBF

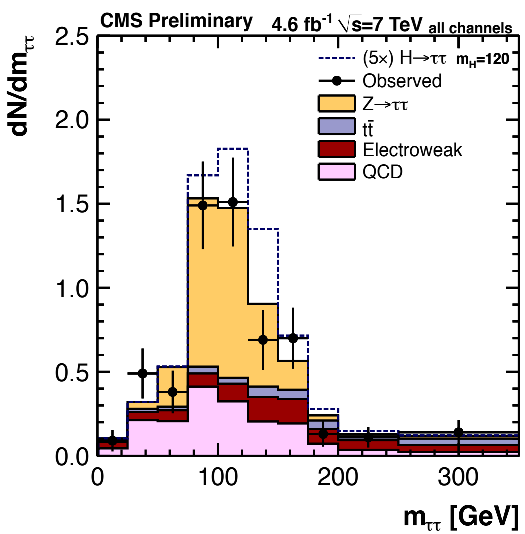


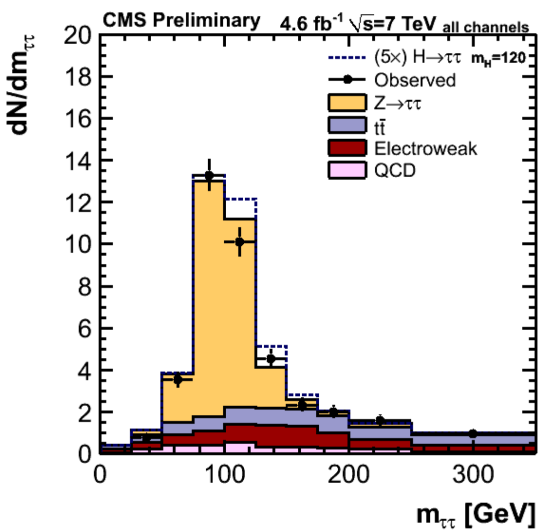
Boosted

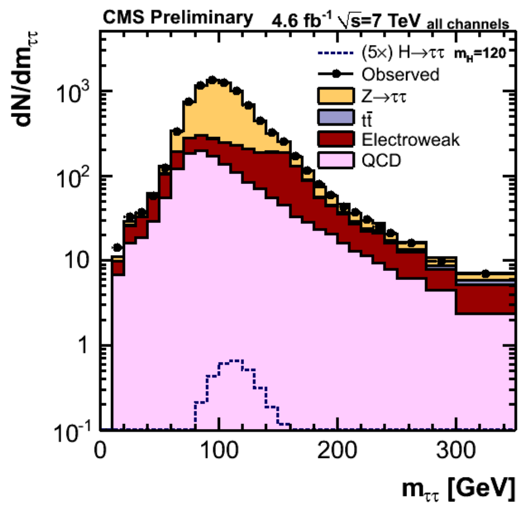


0/1 Jet



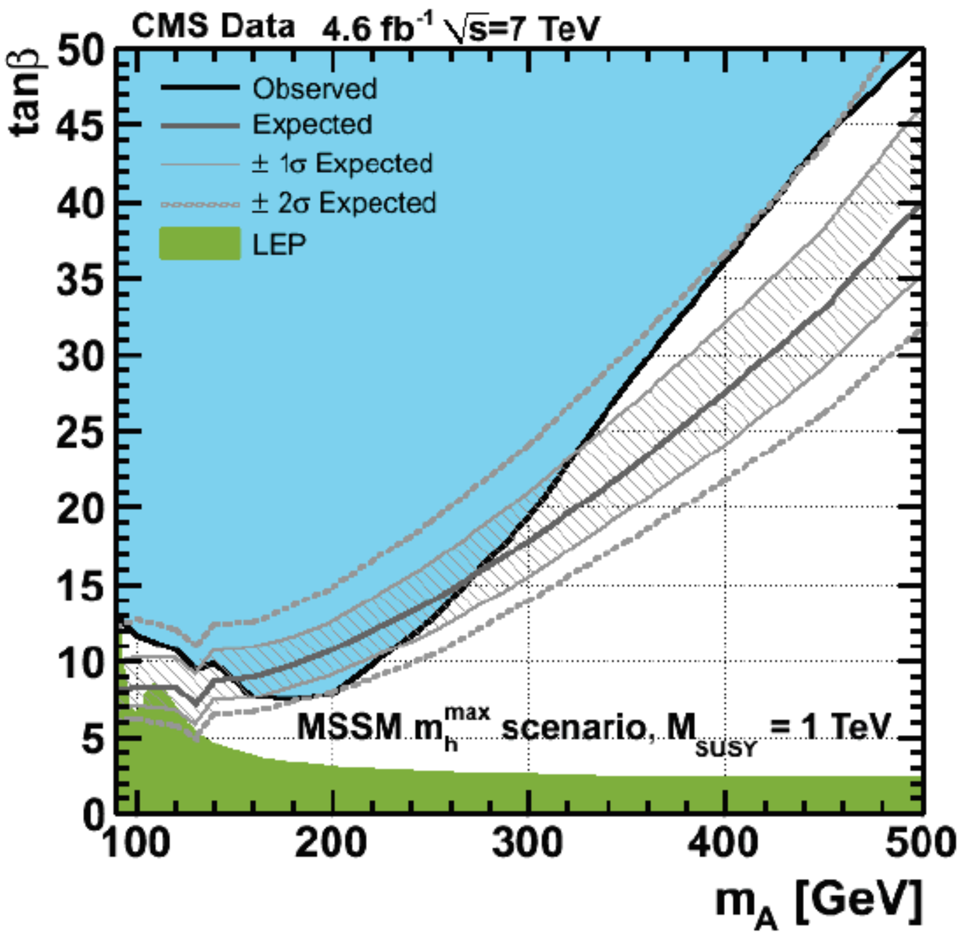


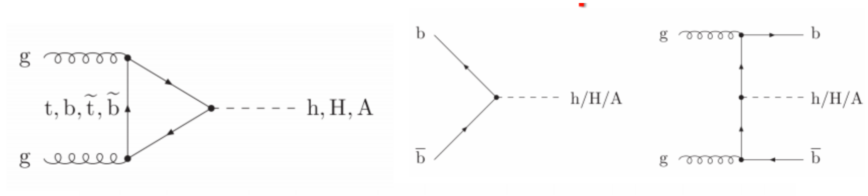




Sig/BG	1/24	1/75	1/460
Signal	6±1	14±2	180±20
Background	140±10	1050±170	83000±4000

MSSM ϕ

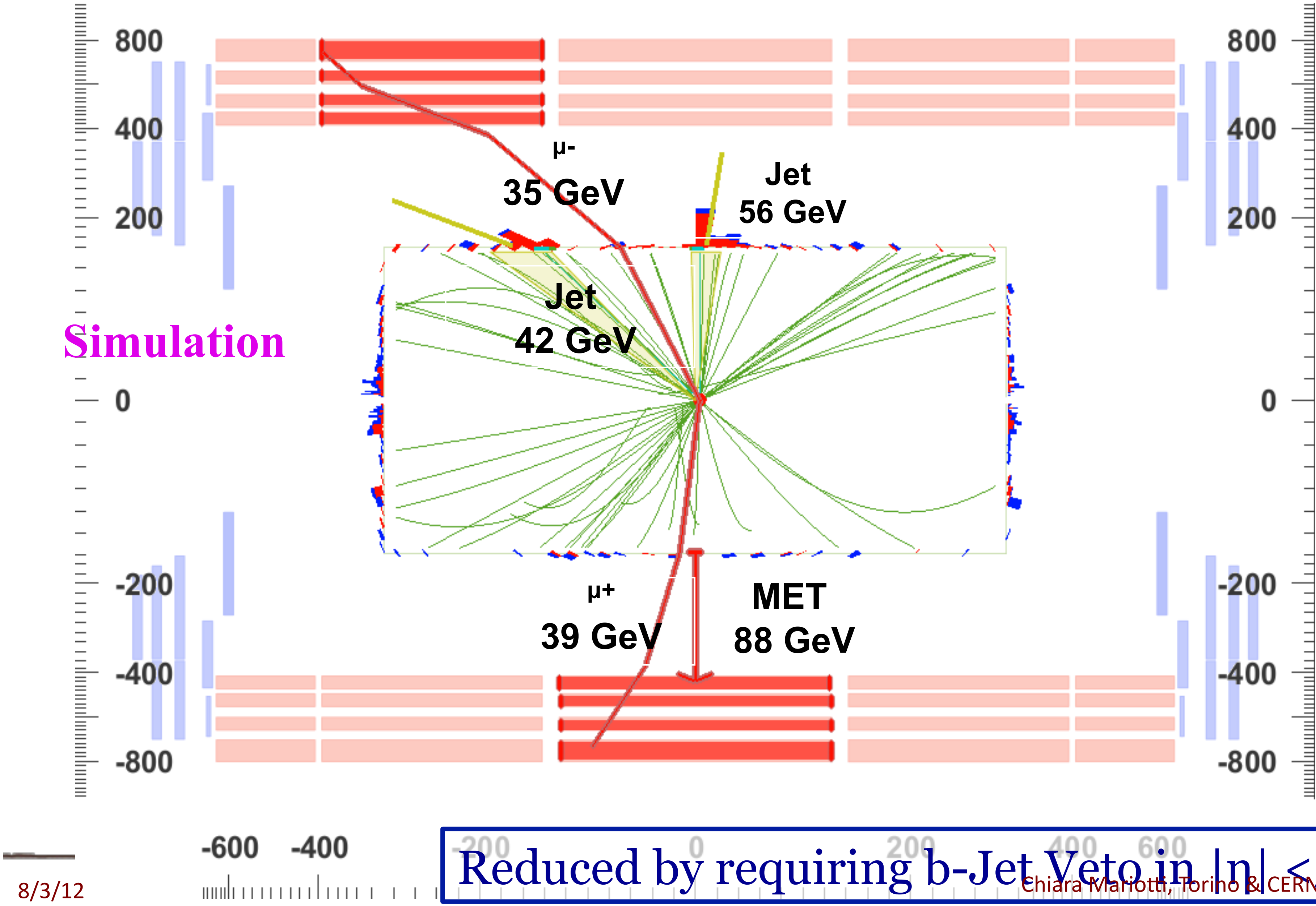




$\phi \rightarrow \tau\tau$
Combining btag
and non btag events

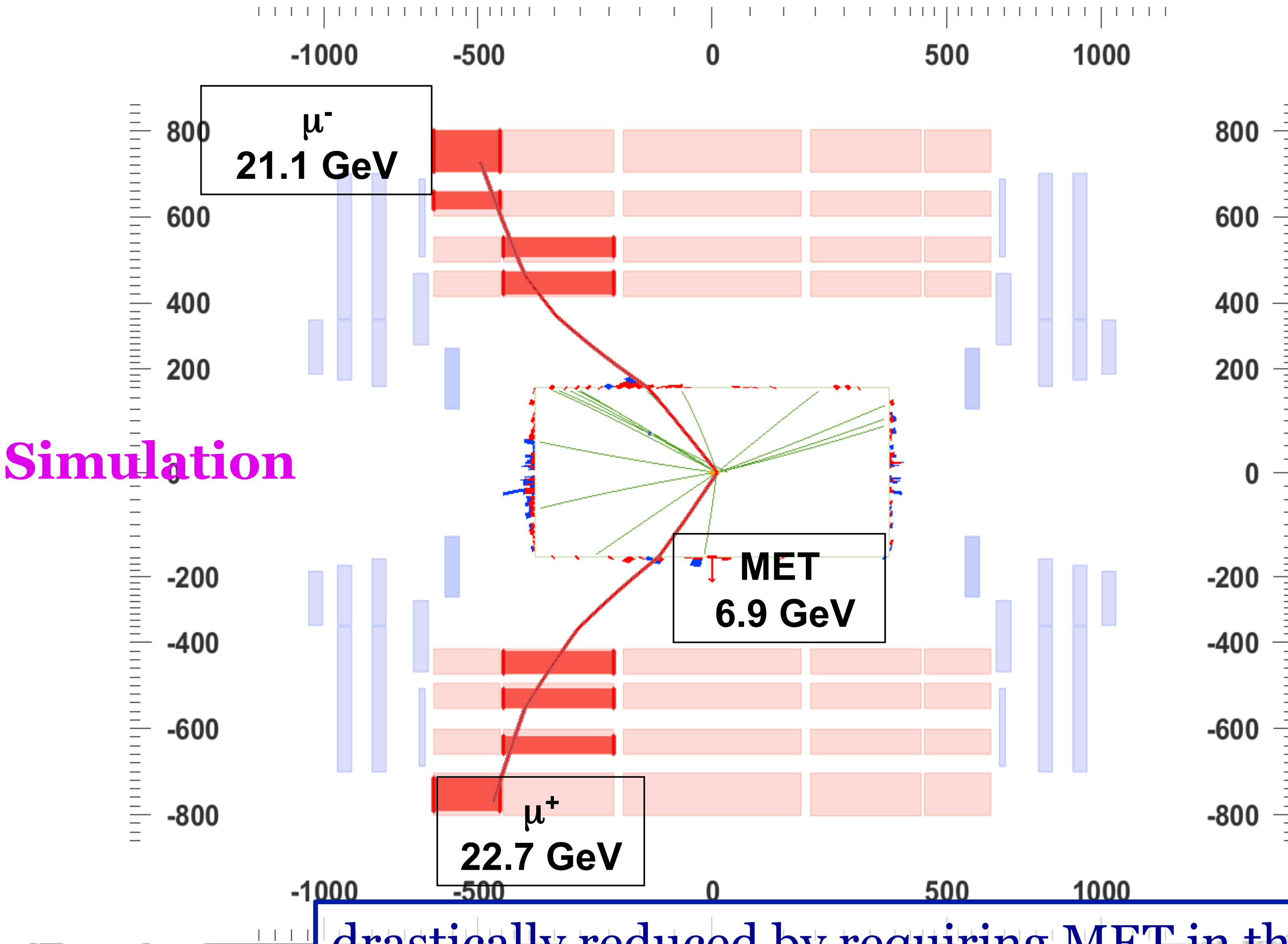
- Most sensitive channel for neutral Higgs searches in the context of SUSY models
  - Large portion of tanβ-M_A plane excluded

Major background mode: ttbar



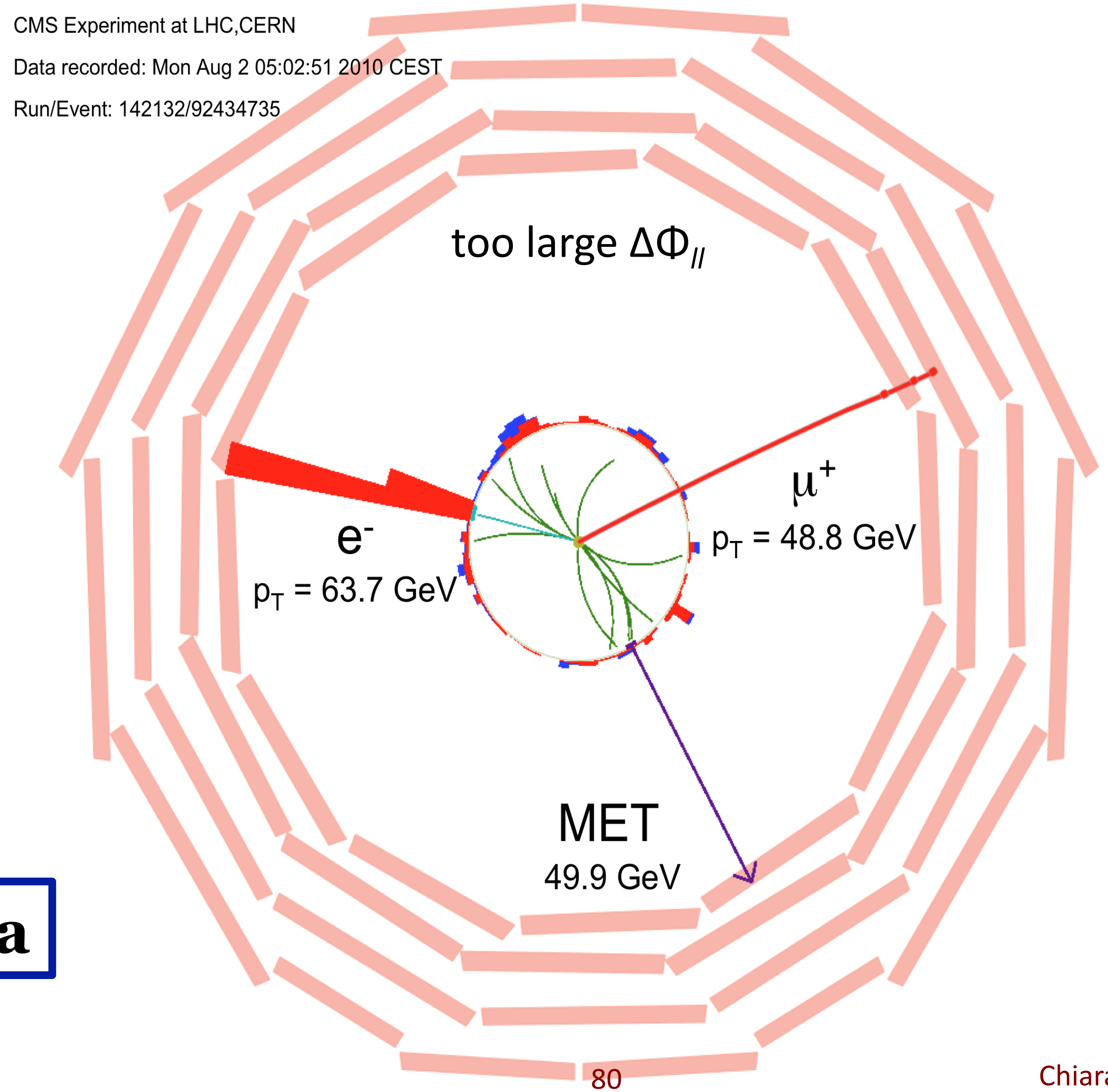
Reduced by requiring b-Jet Veto in |η| <5

Major background: Drell-Yan



drastically reduced by requiring MET in the event

pp → WW is major irreducible background

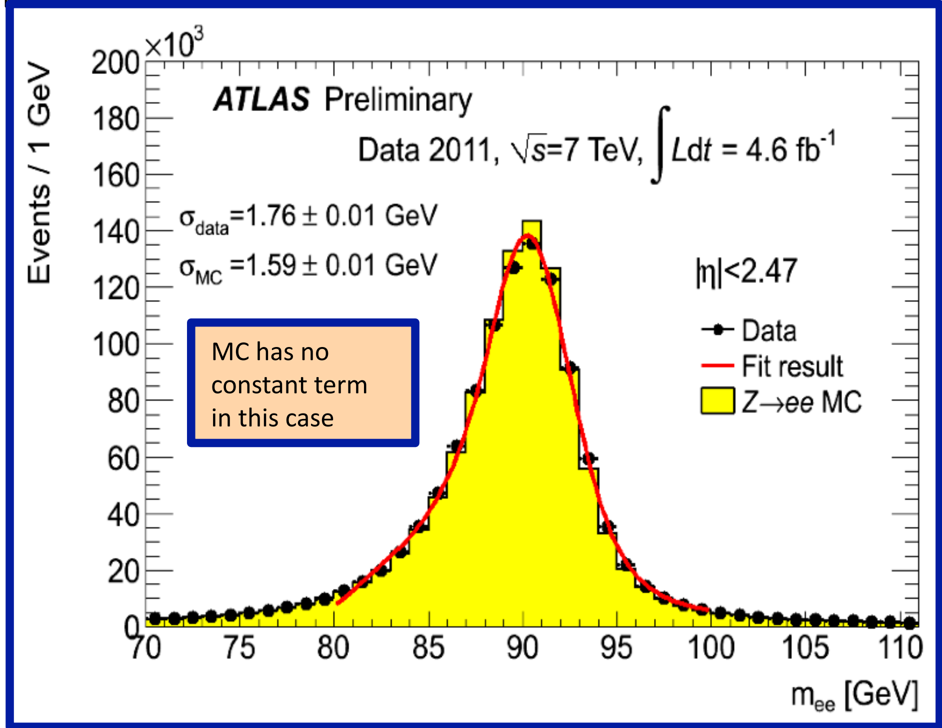


2010 Data

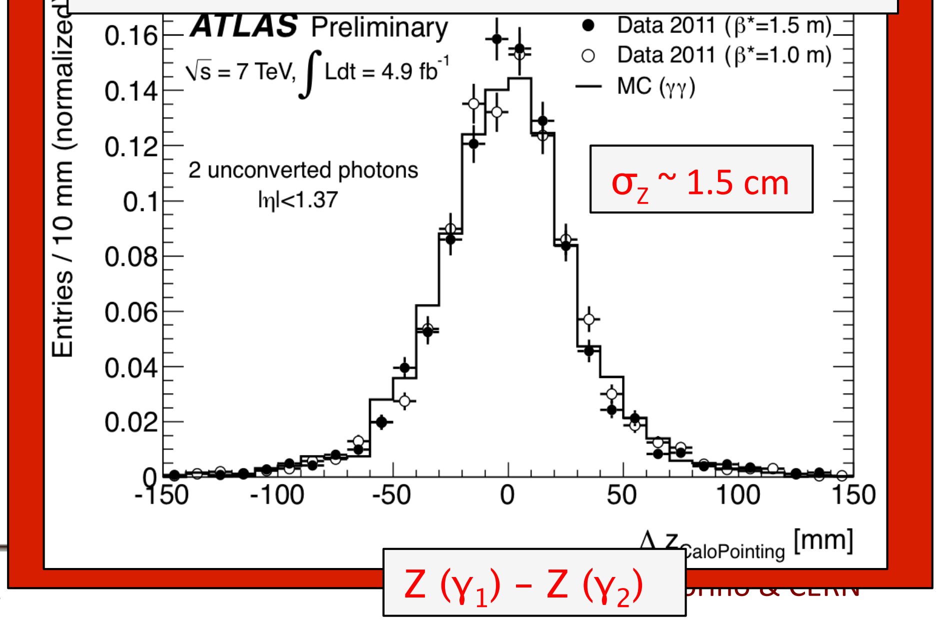
Atlas: $m^2_{\gamma\gamma} = 2E_1E_2(1-\cos\alpha)$

m_H=120 GeV	σ ($m_{\gamma\gamma}$) GeV	Event fraction in ± 1.4 σ ($m_{\gamma\gamma}$)
All	1.7	80 %
Best category (unconverted central)	1.4	84%
Worst category (~10%) (≥ 1 γ converted, ≥ 1 γ near barrel/end-cap transition)	2.3	70%

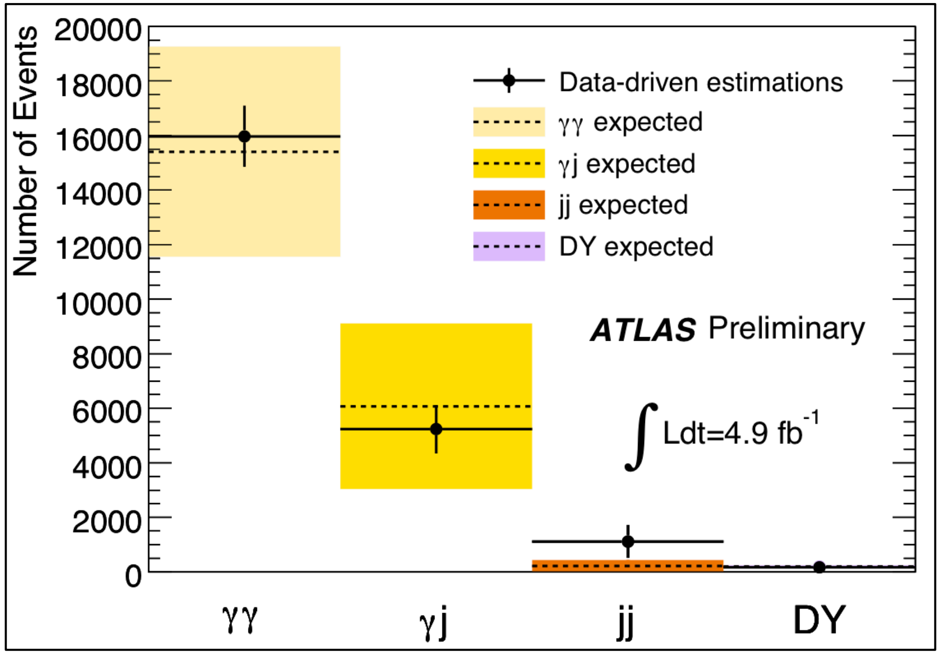
Use longitudinal (and lateral) segmentation of EM cal to measure photon polar angle ϑ.
Crucial at high pile-up: many vertices distributed over σ_Z (LHC beam spot) ~ 5.6 cm → difficult to know which one produced the γγ pair.
The EM pointing capability reduce σ_Z to ~1.5 cm
Negligible for Mγγ resolution,
but robust for Pile-Up



Z-vertex as measured in γγ events after
selection from calorimeter "pointing"



Atlas: H → γγ results



Sample composition estimated from data using control samples

	Number of events	Fraction
γγ	16000 ± 1120	71 ±5 %
γj	5230 ± 890	23 ±4 %
jj	1130 ± 600	5 ±3 %
DY/Z	165 ± 8	0.7 ±0.1 %

Photon identification efficiency: ~ 85±5% from MC, cross-checked with data (Z→ ee, Z→ eeγ, μμγ)

After all cuts: 22489 events with 100 < $m_{\gamma\gamma}$ < 160 GeV observed in the data
Expected signal efficiency: ~ 35% for m_H=125 GeV

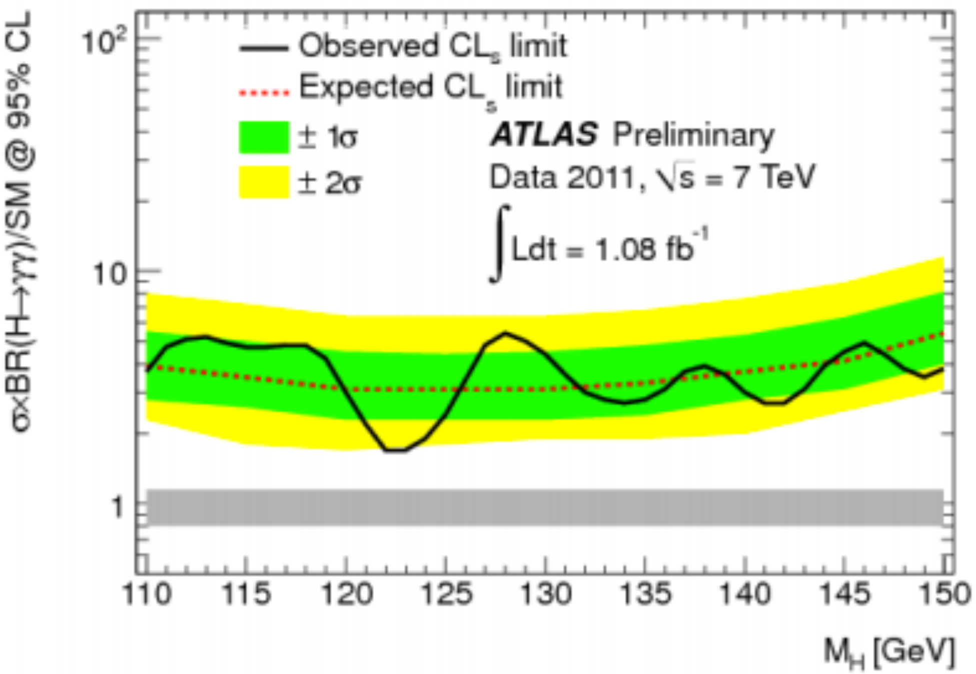
Main systematic uncertainties

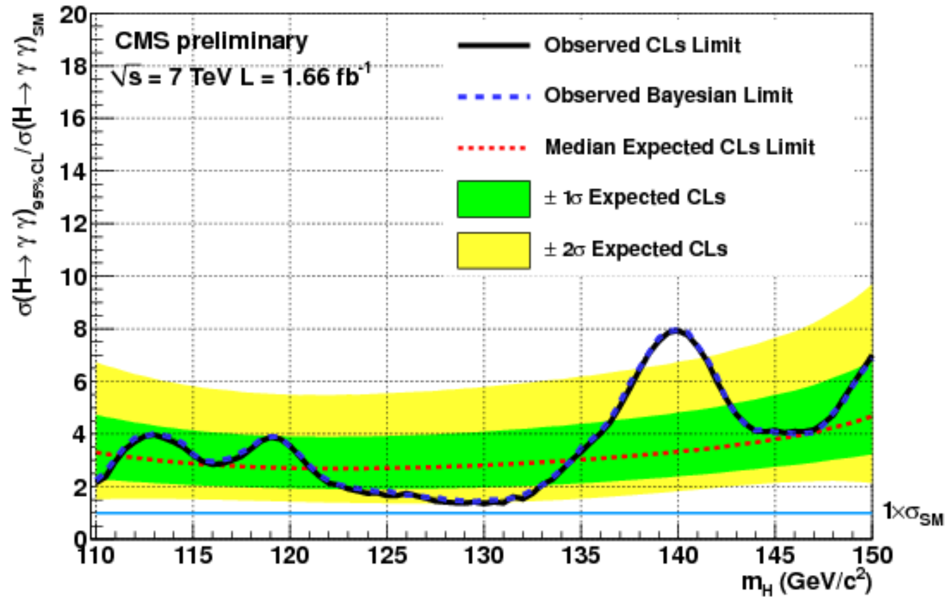
Expected signal yield : ~ 20%
H→ γγ mass resolution : ~ 14%
H→ γγ p_T modeling : ~ 8%
Background modeling : ±0.1-5.6 events

Type and source	Uncertainty
Event yield	
Photon reconstruction and identification	±11%
Effect of pileup on photon identification	±4%
Isolation cut efficiency	±5%
Trigger efficiency	±1%
Higgs boson cross section	+15%/−11%
Higgs boson p_T modeling	±1%
Luminosity	±3.9%
Mass resolution	
Calorimeter energy resolution	±12%
Photon energy calibration	±6%
Effect of pileup on energy resolution	±3%
Photon angular resolution	±1%
Migration	
Higgs boson p_T modeling	±8%
Conversion reconstruction	±4.5%

H → γγ, in the summer

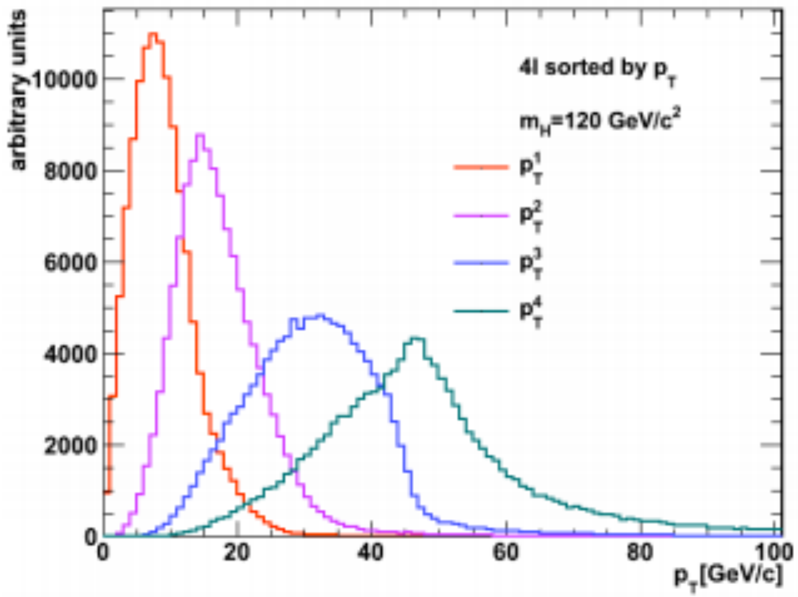
Dominated by gg-fusion



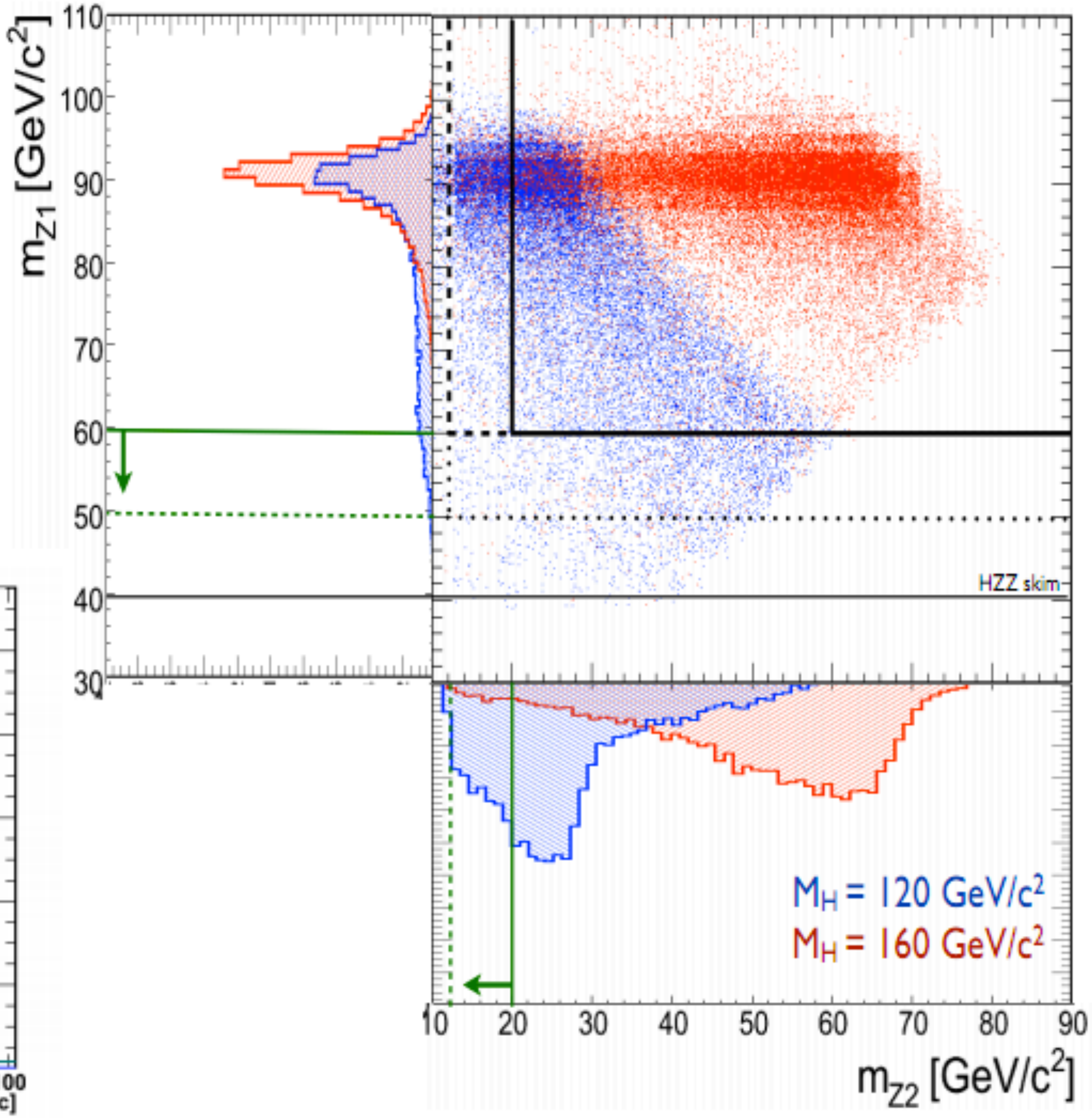


- Two high pt, isolated photons, pointing to a PV
- Different photon categories treated differently.
- M(γγ) resolution very similar.
- Results very similar
- Fluctuations: excess and deficit…. We will see!

M_{Z1} vs M_{Z2}



arbitrary units
4l sorted by p_T
m_H=120 GeV/c^2
p_T^1
p_T^2
p_T^3
p_T^4
p_T [GeV/c]



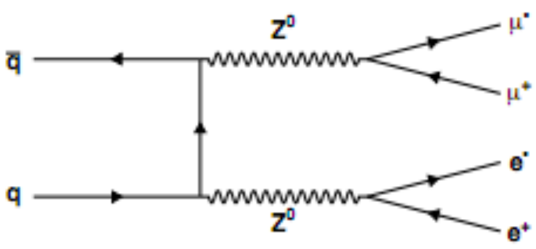
m_Z1 [GeV/c^2]
HZZ skim
M_H = 120 GeV/c^2
M_H = 160 GeV/c^2
m_Z2 [GeV/c^2]

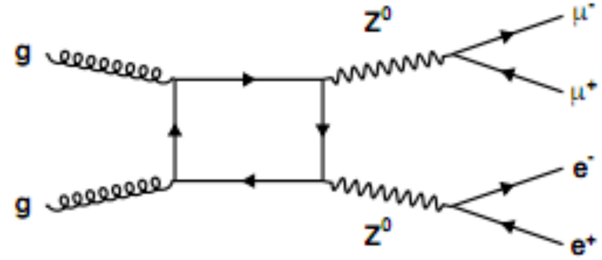
The background

Irreducible background:

$qq \rightarrow ZZ^{(*)} \rightarrow 4l$

$gg \rightarrow ZZ^{(*)} \rightarrow 4l$



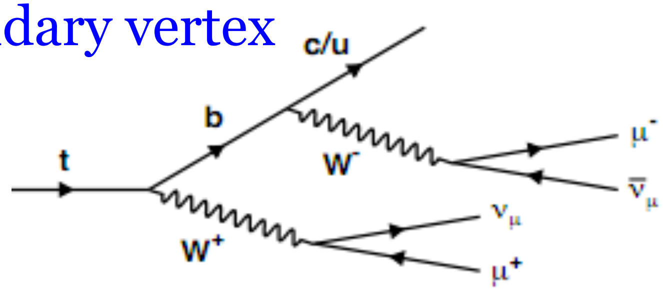


Reducible background:

Zbb/Zcc and **tt pair** production.

I.e. events with B hadrons decaying semileptonically

Leptons are inside jets and originating from secondary vertex

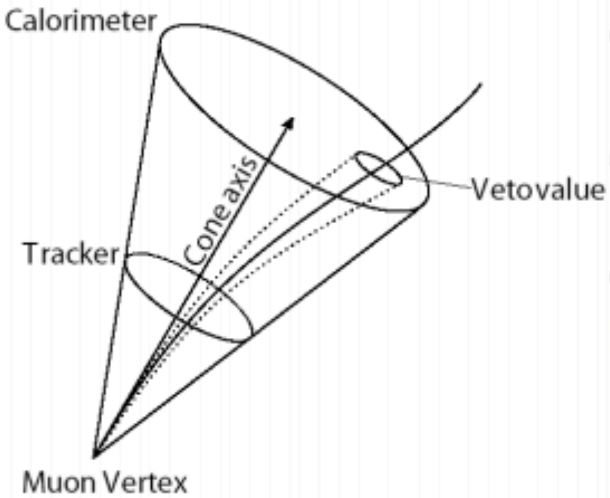


Instrumental background:

QCD and **Z/W+light jets**. Events with jets faking leptons (mostly electrons)

Isolation

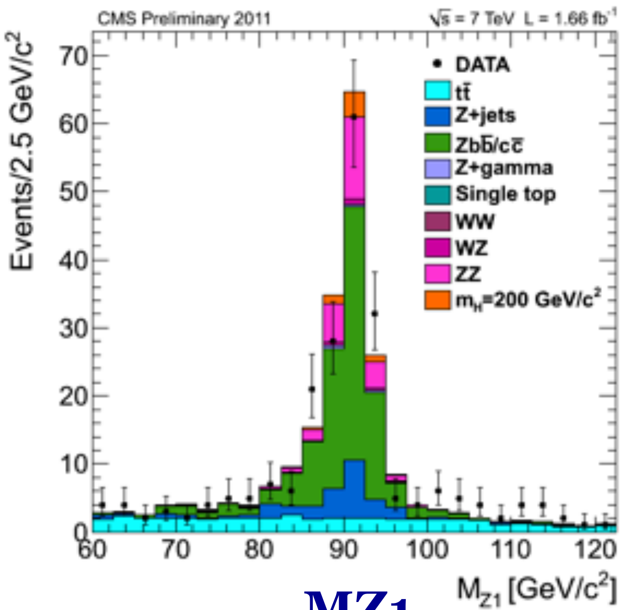
The requirement that the energy flow in the vicinity of a muon is below a certain threshold helps discriminating muons from W/Z from muons produced as a result of QCD processes.



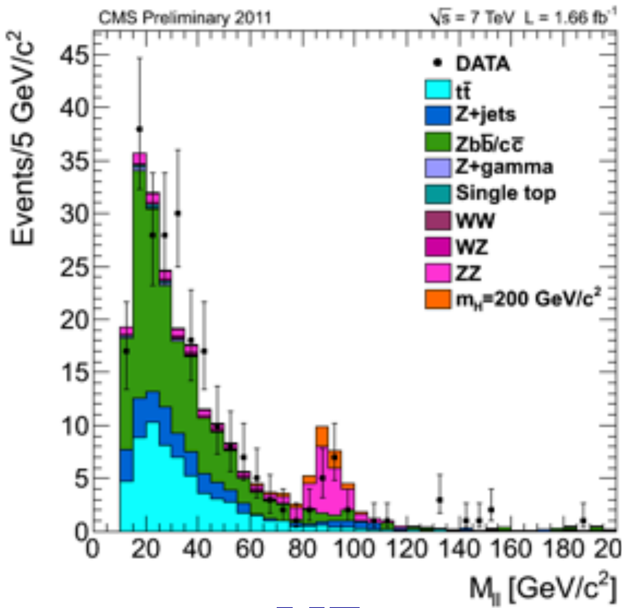
- $R^{Tk}_{Iso} = [TK_{iso03} / p_T]$
- $R_{Iso} = [(TK_{iso03} + ECAL_{iso03} + HCAL_{iso03})/p_T]$
- H->4l analysis: a cut on the sum of R_{Iso} of the two least isolated leptons < 0.35 is chosen
  - $R_{Iso} < 0.15$ usual working point for W/Z lepton selection

ECAL and HCAL contributions are affected by pile-up conditions
To have a pile-up robust analysis R_{Iso} must be corrected by the average energy flow in the event
[Fast-jet correction]

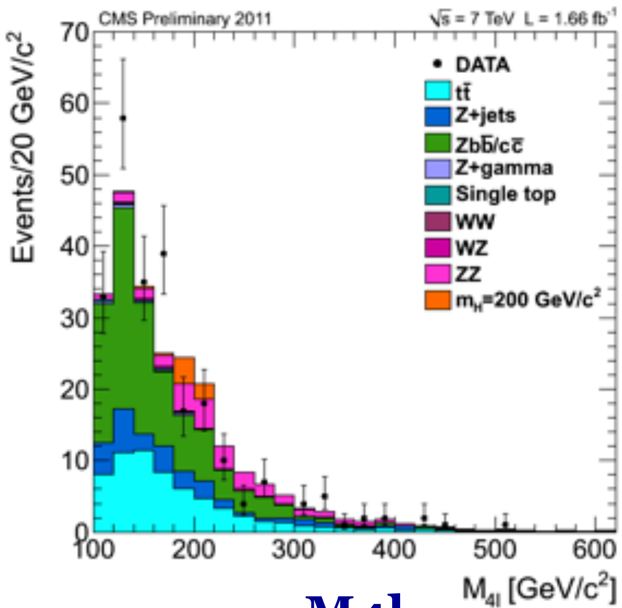
H → ZZ → 4l



MZ1



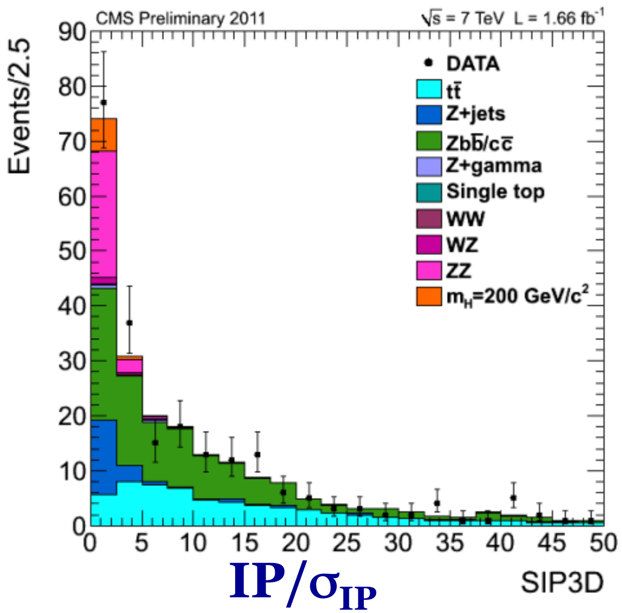
MZ2



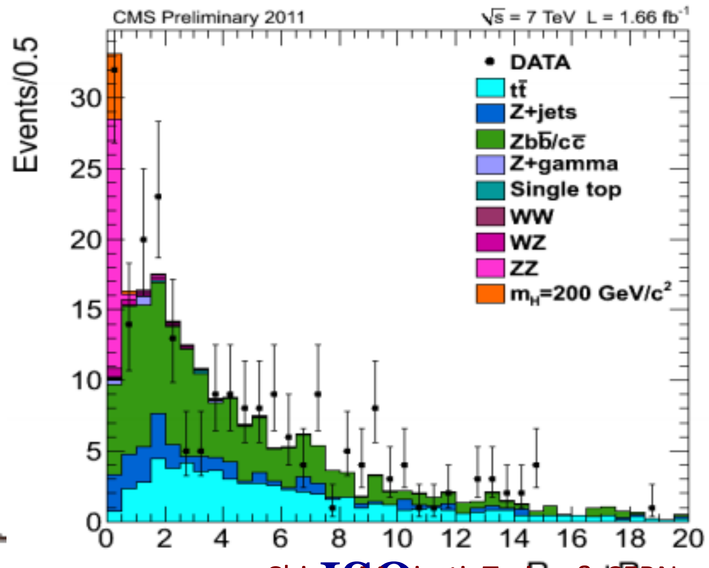
M4l

2 leptons of pT>20, 10 GeV
Isolated and from PV ->
the couple closest to MZ

PLUS
2 leptons of pT>5 (7) GeV
with M>20 GeV
Isolated and from PV



IP/σ_{IP}



ISO

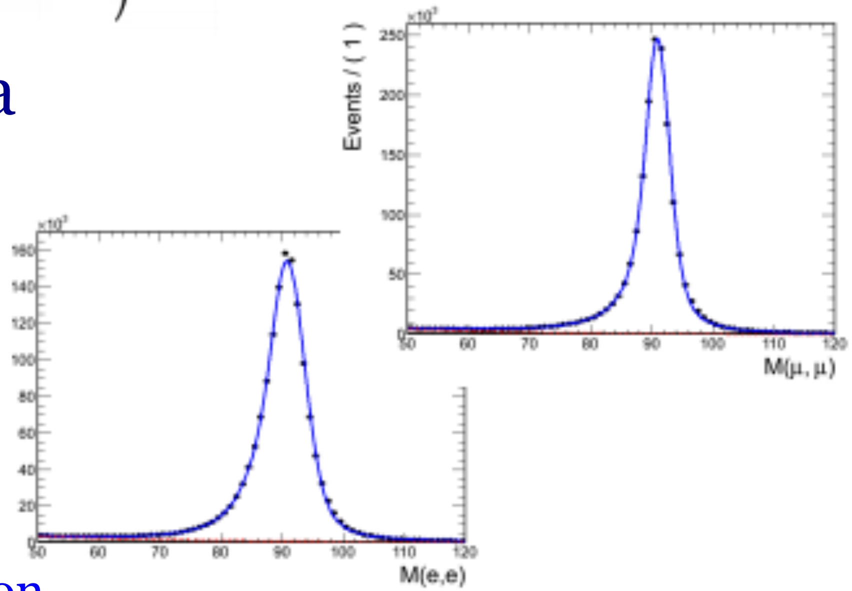
ZZ continuum

- Directly from MC:

$$\left(\sigma_{NLO}^{q\bar{q}\to ZZ\to 4l} \times \varepsilon_{MC}^{q\bar{q}\to ZZ\to 4l} + \sigma_{LO}^{gg\to ZZ\to 4l} \times \varepsilon_{MC}^{gg\to ZZ\to 4l}\right) \times L$$

- Normalization to Z rate in data

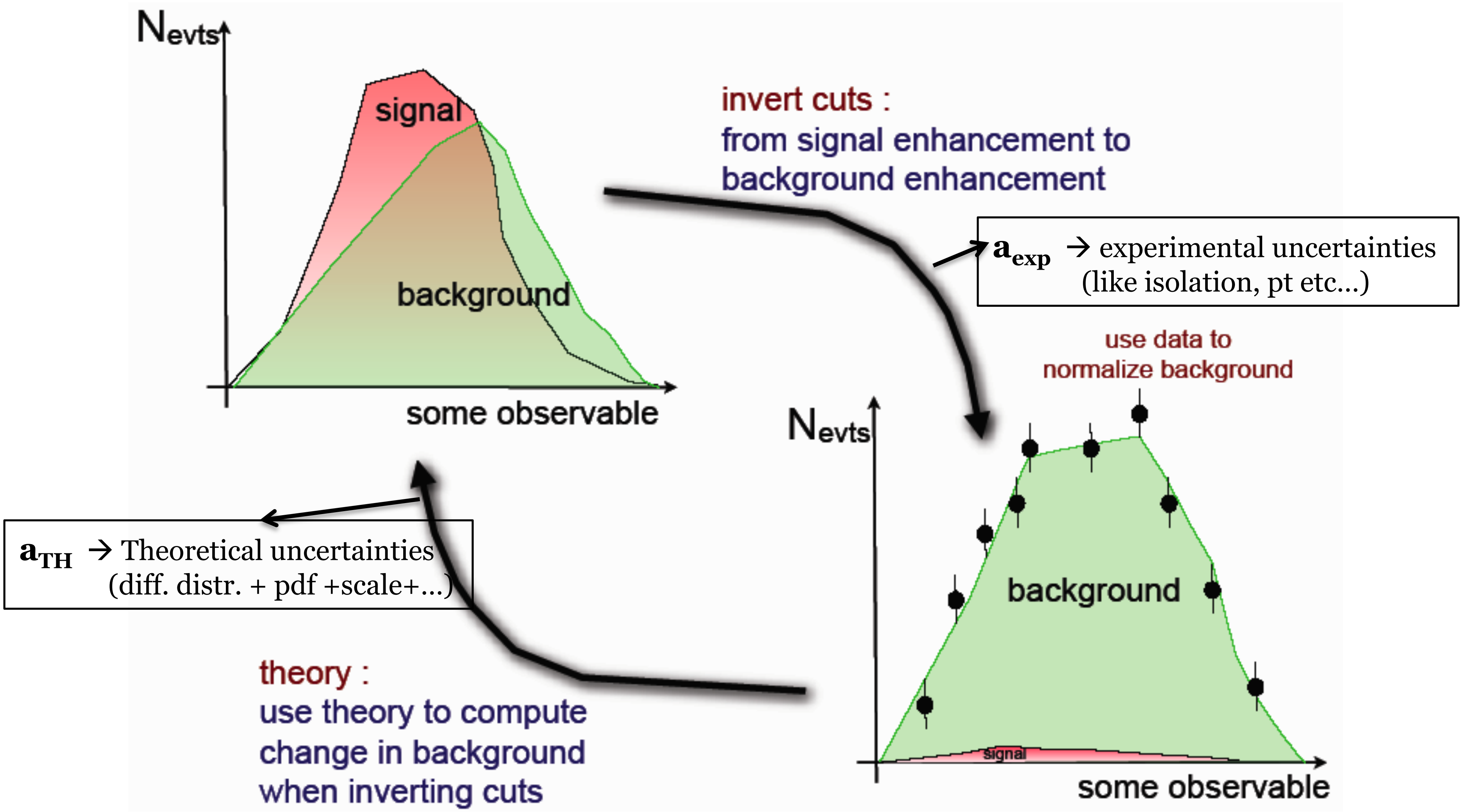
$$\frac{\sigma_{NLO}^{q\bar{q}\to ZZ\to 4l} + \sigma_{LO}^{gg\to ZZ\to 4l}}{\sigma_{NNLO}^{q\bar{q}\to Z\to 2l}} \times \frac{\varepsilon_{MC}^{ZZ\to 4l}}{\varepsilon_{MC}^{Z\to 2l}} \times N_{data}^{Z\to ll}$$



  - The luminosity uncert. cancel in the ratio
  - The TH uncertainties as YR prescription ~ 10% (PDF4LHC prescription + QCD scale)

- Results: the two agree within %

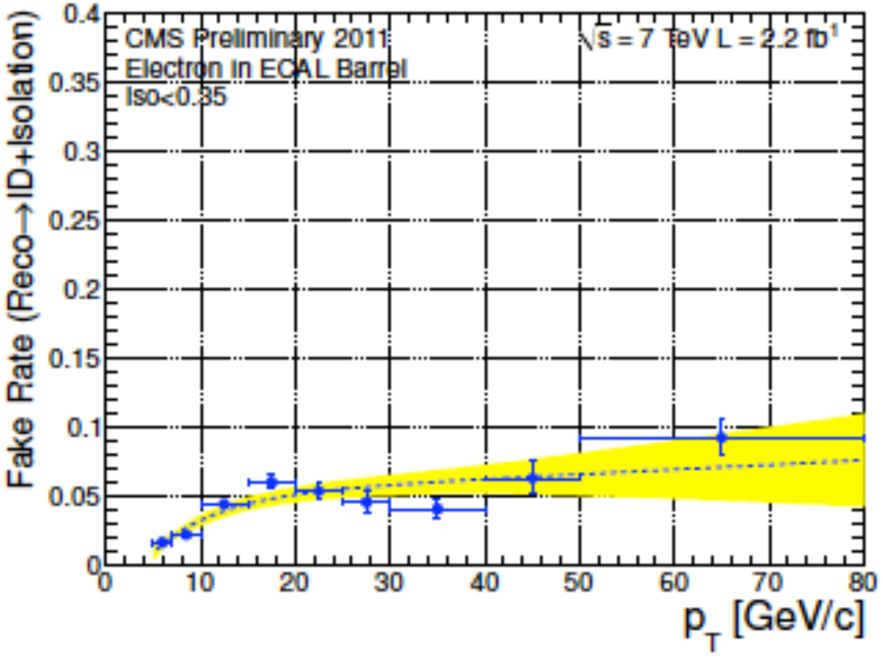
The control of the background

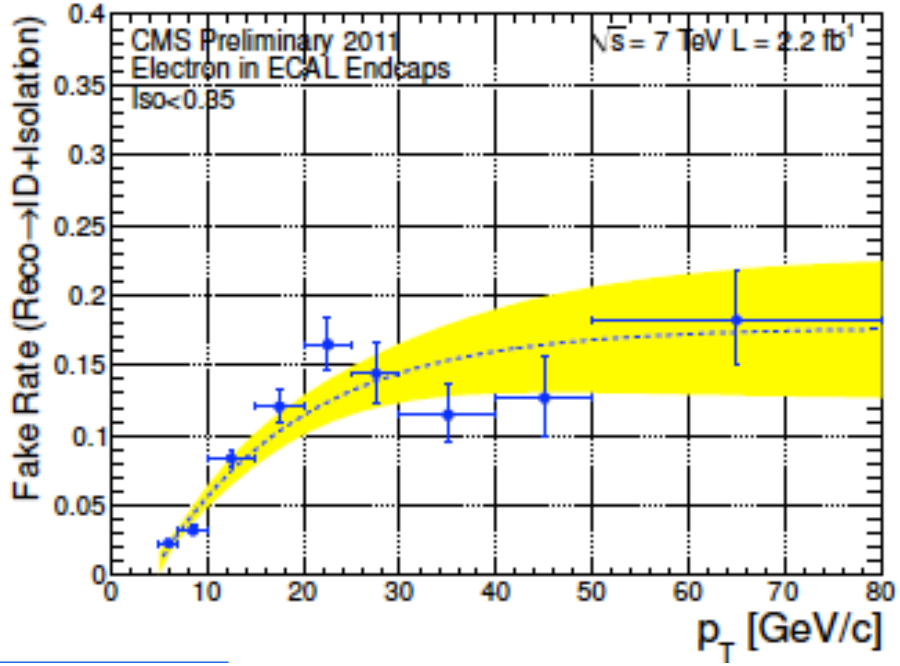


- $N^B_{(\text{signal region})} = a_{exp} * a_{TH} * N^B_{\text{control region}}$

a_{exp} - uncorr between exp
a_{TH} - 100% correlated

Z+jets

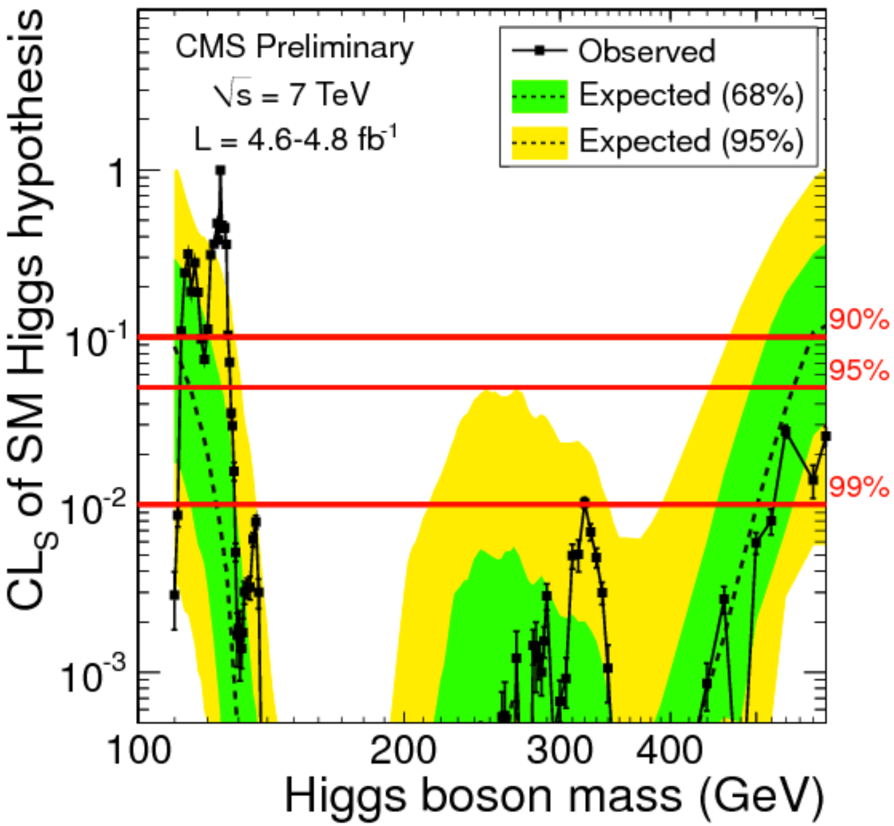


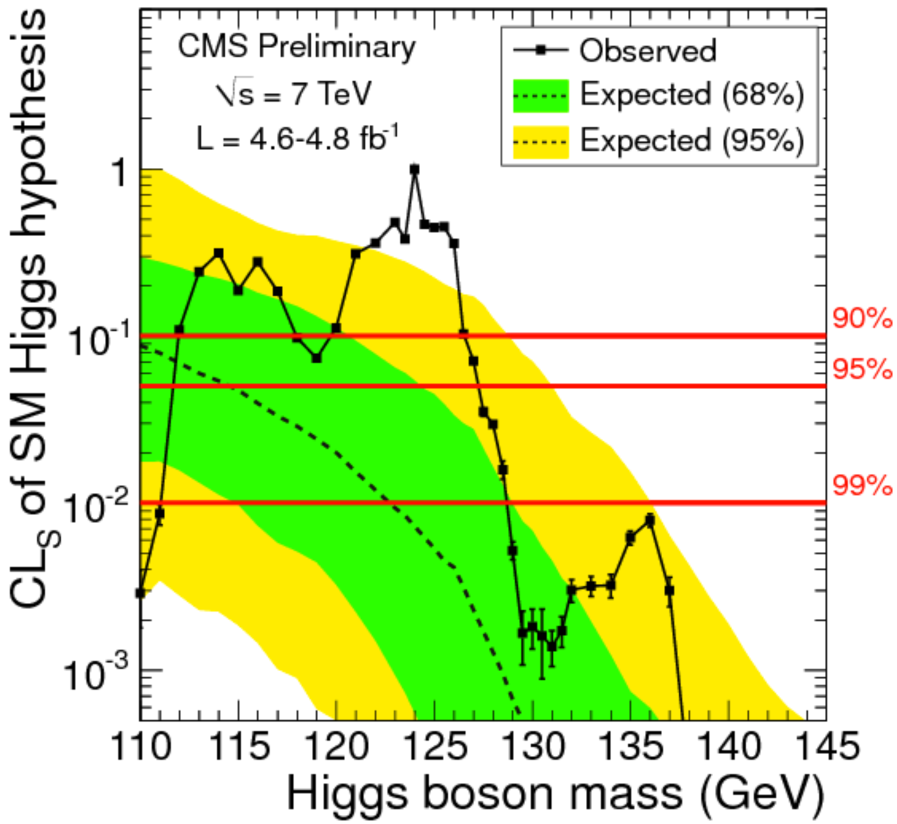


In the Z1+1 leptons sample:
the probabiity that a muon/electron with relaxed ID and ISO passes the analysis requests

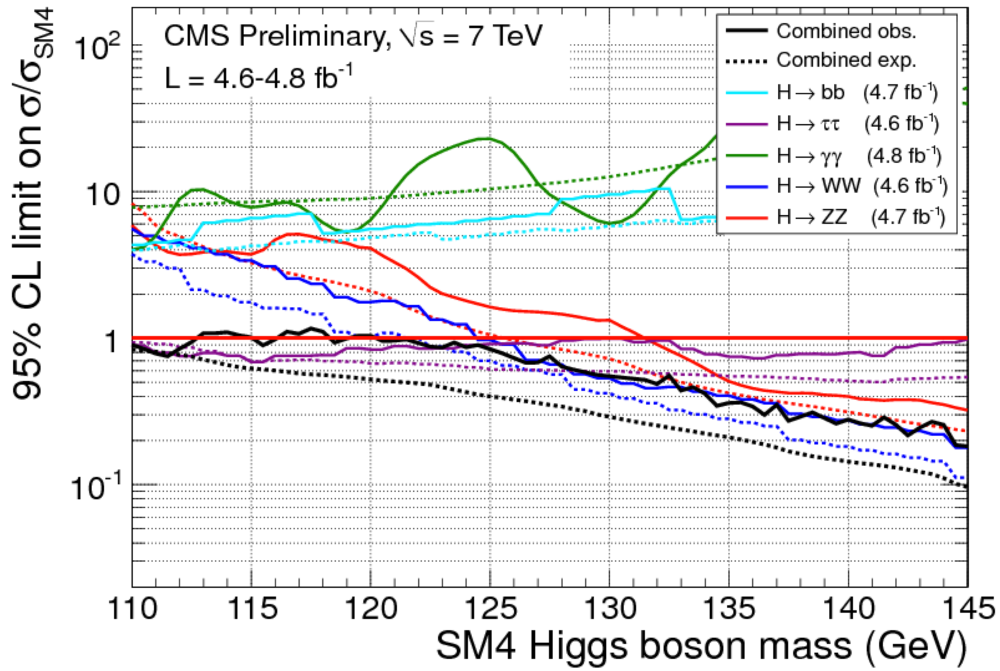
More checks done on the Z1+SS vs Z1+OS samples.

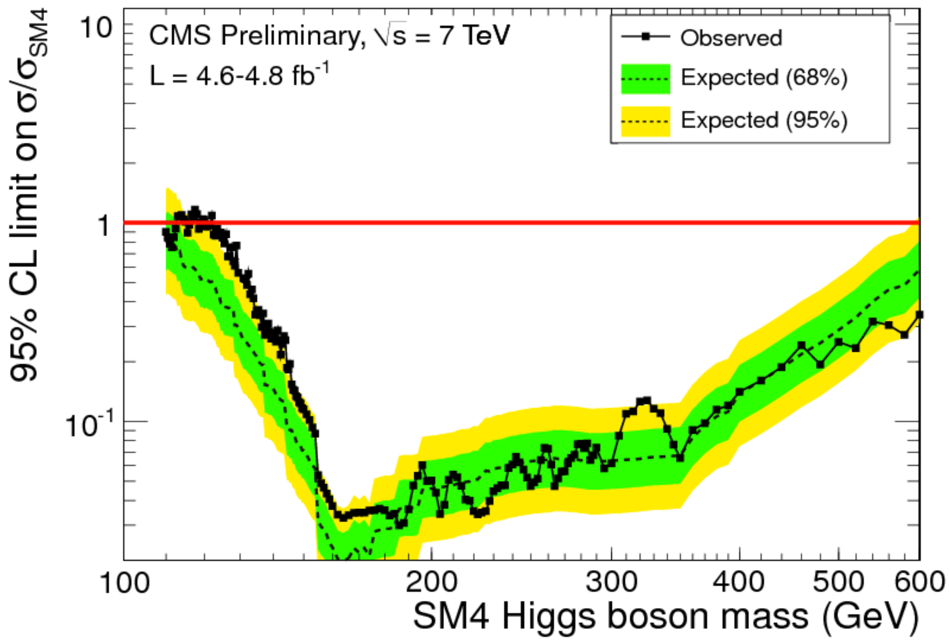
CLs


CMS Preliminary
√s = 7 TeV
L = 4.6-4.8 fb-1
Observed
Expected (68%)
Expected (95%)
90%
95%
99%
CLS of SM Higgs hypothesis
1
10-1
10-2
10-3
100
200
300
400
Higgs boson mass (GeV)


CMS Preliminary
√s = 7 TeV
L = 4.6-4.8 fb-1
Observed
Expected (68%)
Expected (95%)
90%
95%
99%
CLS of SM Higgs hypothesis
1
10-1
10-2
10-3
110
115
120
125
130
135
140
145
Higgs boson mass (GeV)

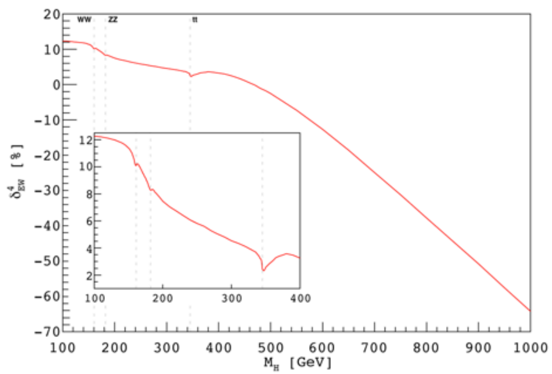
Higgs in the SM4

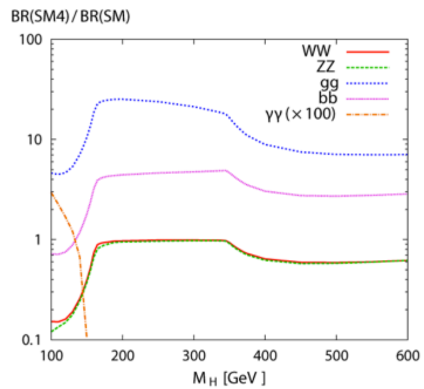




Excluded in the range: 120 - 600 GeV

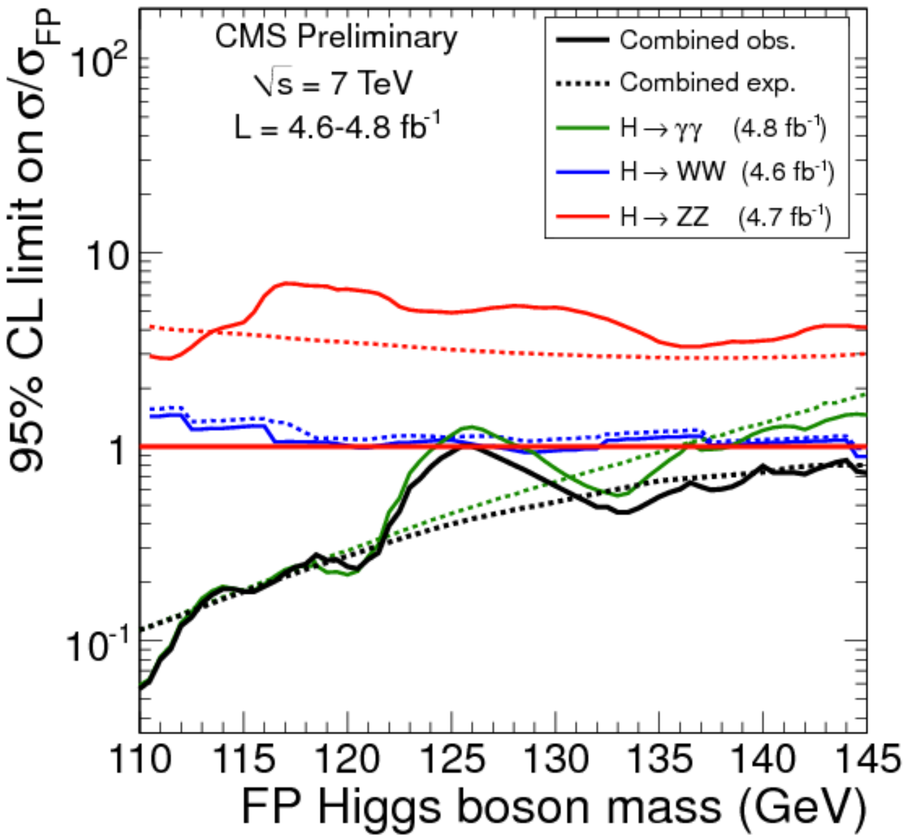
New values from CERN 2012-002 including EW correction to production and decay

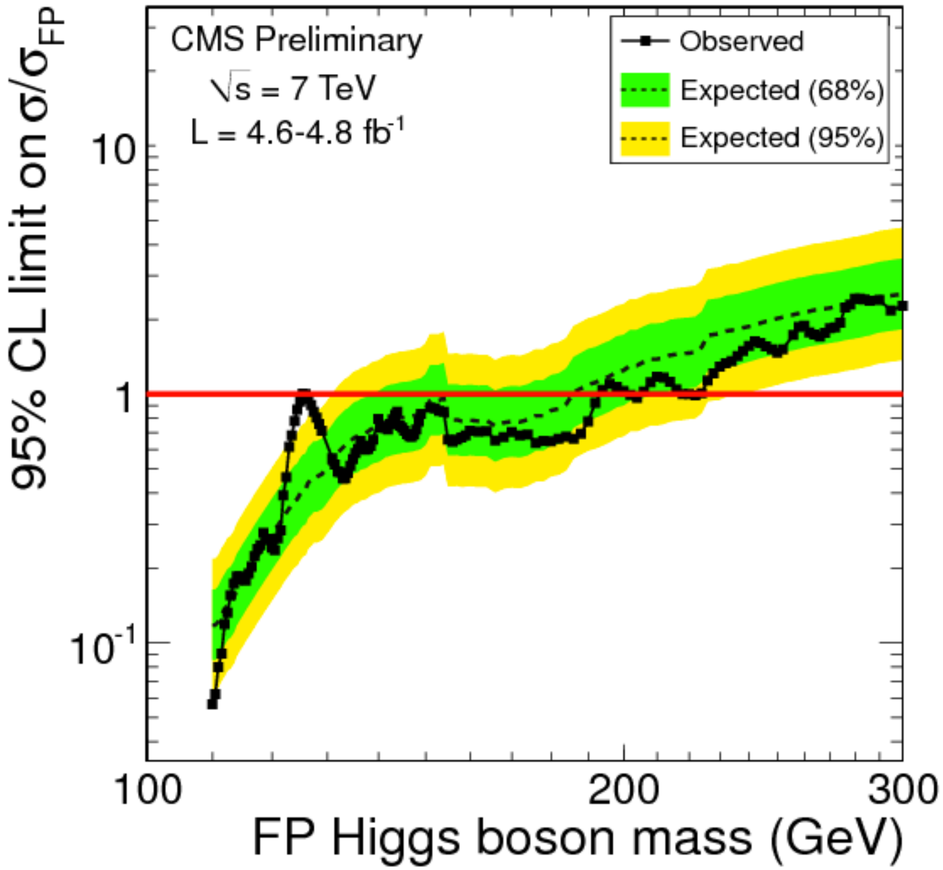




Chiara Mariotti, Torino & CERN

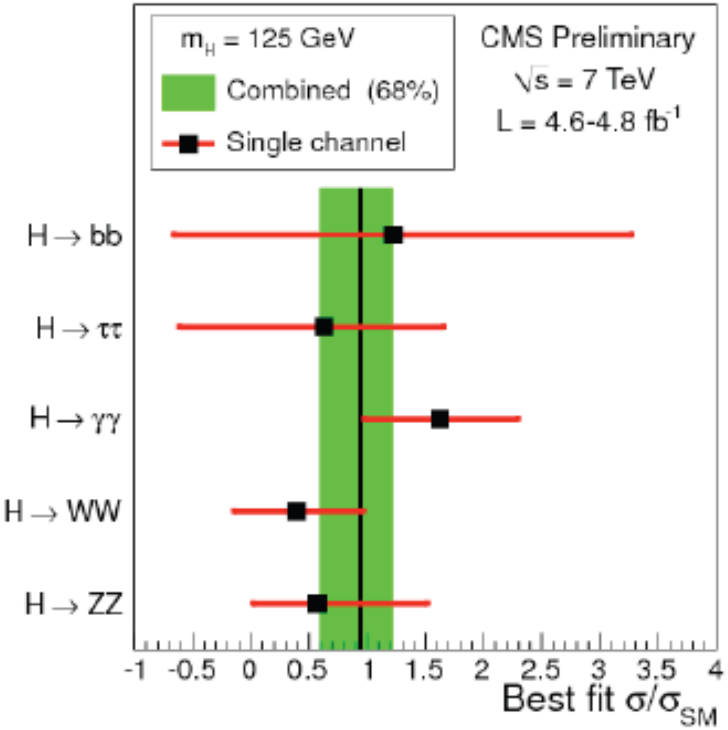
Limits in the Fermiophobic scenario

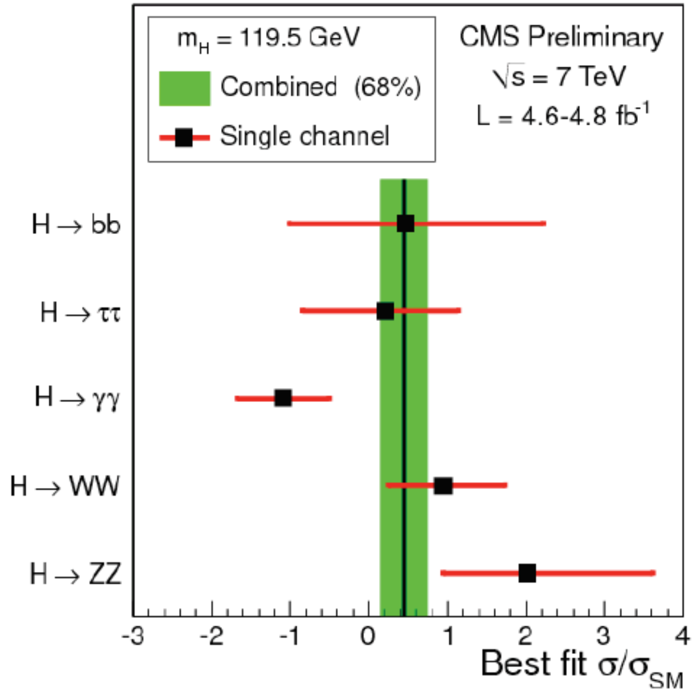




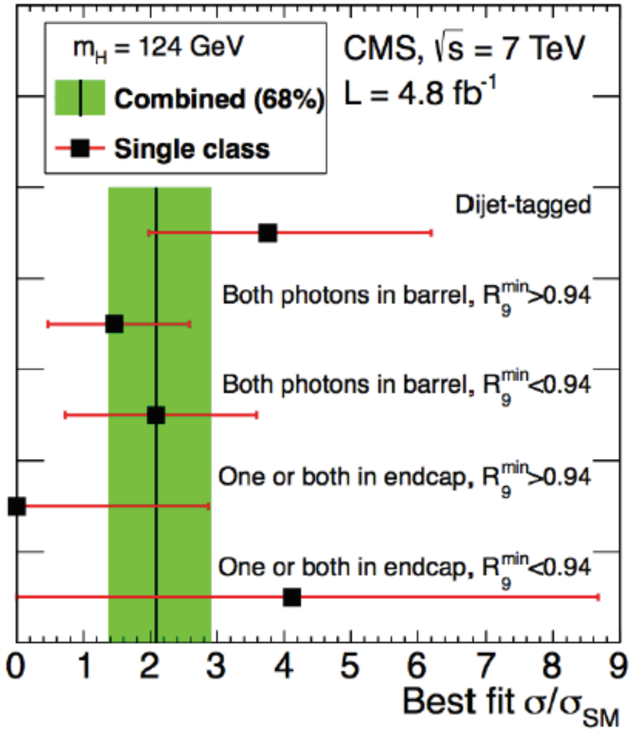
Excluded in the range: 110 – 192 GeV

Comparison of channels for M_H=125 GeV





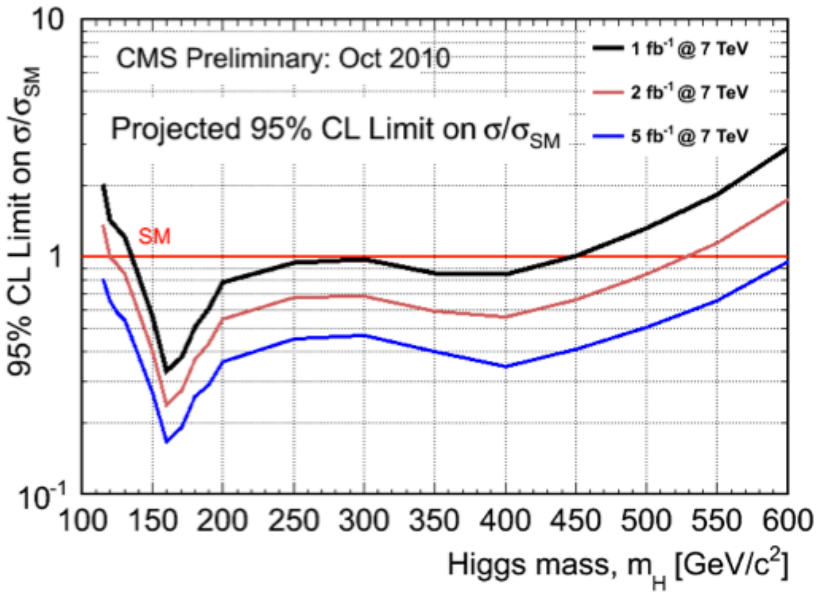
Fit of the signal strength
$\mu=\sigma/\sigma_{SM}$

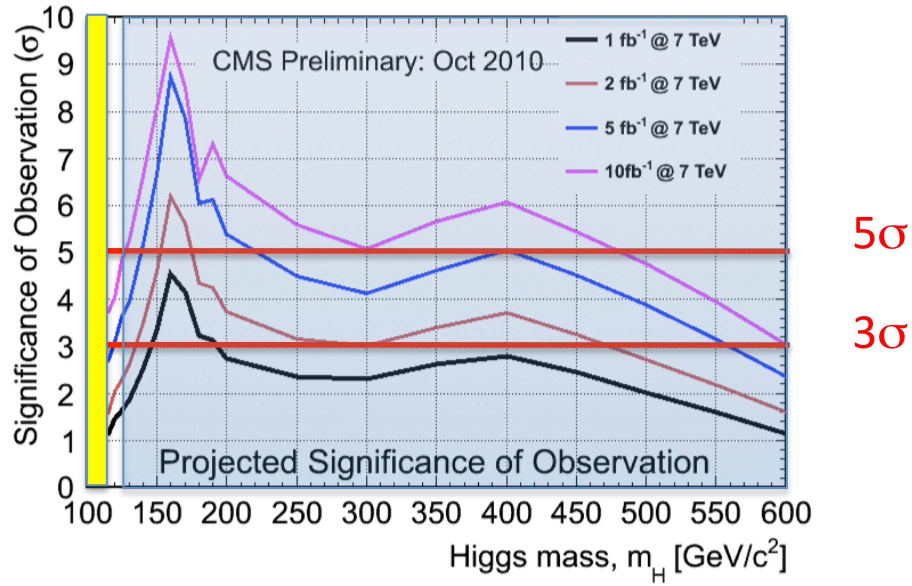


Near future

- By the end of the 8 TeV run in 2012, the luminosity collected will hopefully allow us to have 5 sigma everywhere.

Maybe difficult at 115 Gev





Excluded at 95%CL

Interlude: Methodology of Hypothesis Testing at LHC

only basic ideas, for details and technical issues see:

profile likelihood

Glen Cowan, Kyle Cranmer, Eilam Gross, and Ofer Vitells. Asymptotic formulae for likelihood-based tests of new physics. *Eur.Phys.J.*, C71:1554, 2011.

look elsewhere effect

Eilam Gross and Ofer Vitells. Trial factors for the look elsewhere effect in high energy physics. *The European Physical Journal C - Particles and Fields*, 70:525–530, 2010. 10.1140/epjc/s10052-010-1470-8.

CL_S method

A. L. Read. Presentation of search results: the CLs technique. *J. Phys. G: Nucl. Part. Phys.*, 28, 2002.

A. L. Read. Modified frequentist analysis of search results (the CLs method). *in Proceedings of the First Workshop on Confidence Limits, CERN, Geneva, Switzerland*, 2000.

Thomas Junk. Confidence level computation for combining searches with small statistics. *Nucl.Instrum.Meth.*, A434:435–443, 1999.

LHC combination procedure

CMS NOTE-2011/005

Basics of Hypothesis Testing

Specify what are you looking for: obervation or exclusion of signal

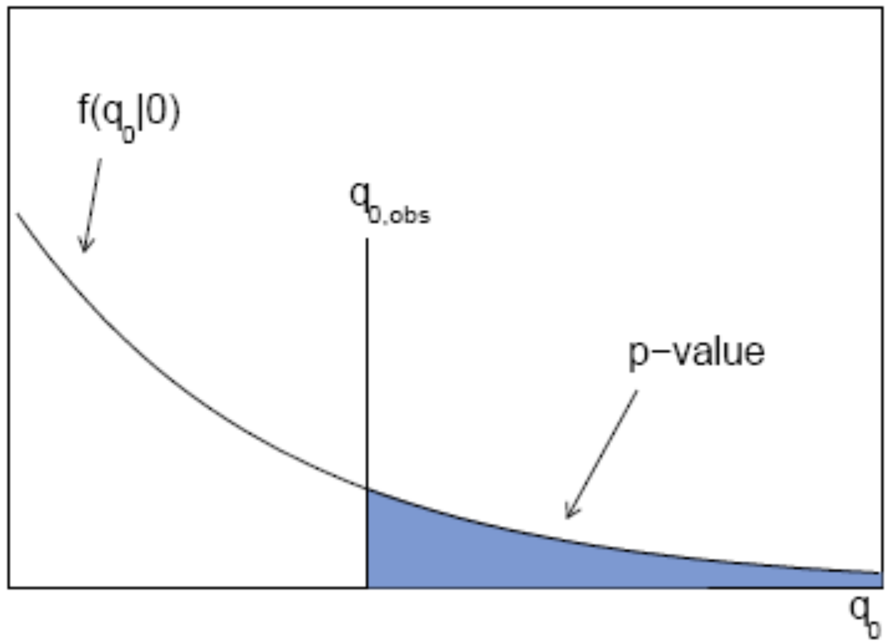
Phrase null hypothesis H_0 as opposite to what you are interested in
as you can only falsify/reject hypothesis but not approve them

Observation of Higgs → H_0: no Higgs, only SM background processes
Exclusion of Higgs → H_0: Higgs and SM background processes

Quantify agreement with H_0
by choosing a test statistic t
(any function of your data)
at LHC: perfect agreement t=0
deviation t>0

Get probability densitiy function for
$t=q_0$ and calculate p-value

$$p_0 = \int_{q_{0,\mathrm{obs}}}^{\infty} f(q_0|0)\, dq_0$$

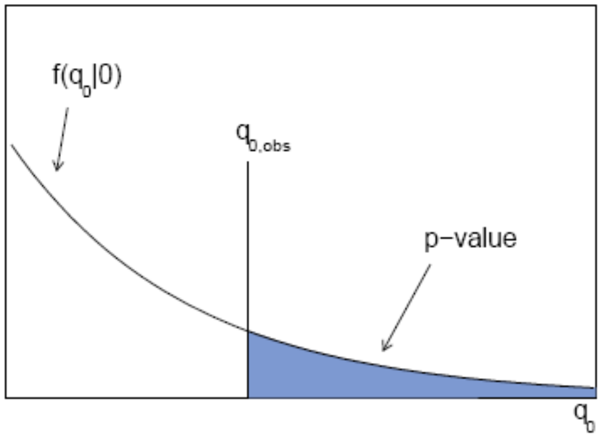


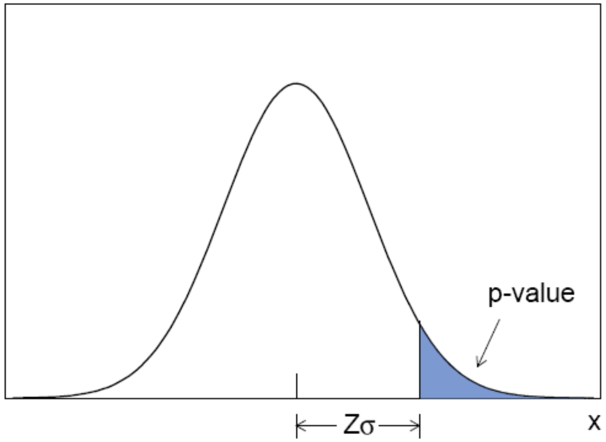
P-Value, Significance and Confidence Level

if p-Value < predefined value (signifcance level, error of first kind) then reject null hypothesis

convention: for discovery require P-value (BG only) $< 2.87\times10^{-7}$

for exclusion require P-value (Higgs+BG) < 0.05





$$p = \int_Z^{\infty} \frac{1}{\sqrt{2\pi}} e^{-x^2/2}\,dx = 1 - \Phi(Z)$$

$$Z = \Phi^{-1}(1-p)$$

p-value can be translated in significance via Standard Gauss pdf.

a significance of 5 (1.64) corresponds to P= 2.87×10^{-7} (0.05)

if p-Value is x then one says „this hypothesis is excluded with a confidence level of CL=1-x“

the frequency of false exclusion (error of 1st kind) is x.

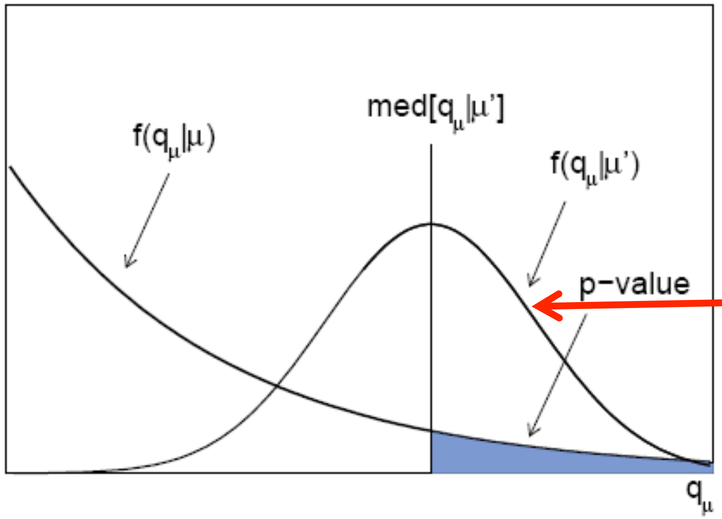
Decisions to Take

Decisions to take:

i) test statistics t → profile likelihood

ii) how to deal with syst. uncertainties → nuisance parameters + profiling

iii) derivation of pdfs for t under hypotheses → often asymptotics usable



fixing the significance level α for H_0
i.e. for p-value < α reject H_0

best test maximizes power of H_0 w.rt. alternative hypothesis H_1

Let b be the expected number of background events, $f_b(x)$ their mass shape
s be the expected number of signal events $f_s(x)$ their mass shape

The observation be n mass values of candidate events x_i

Likelihood Ratio from Neyman-Pearson Lemma

The likelihood to observe this sample under the background and signal + background hypotheses are:

$$L_b = \frac{b^n}{n!} e^{-b} \prod_{i=1}^{n} f(\mathbf{x}_i|\mathrm{b}) \qquad L_{s+b} = \frac{(s+b)^n}{n!} e^{-(s+b)} \prod_{i=1}^{n} (\pi_\mathrm{s} f(\mathbf{x}_i|\mathrm{s}) + \pi_\mathrm{b} f(\mathbf{x}_i|\mathrm{b}))$$

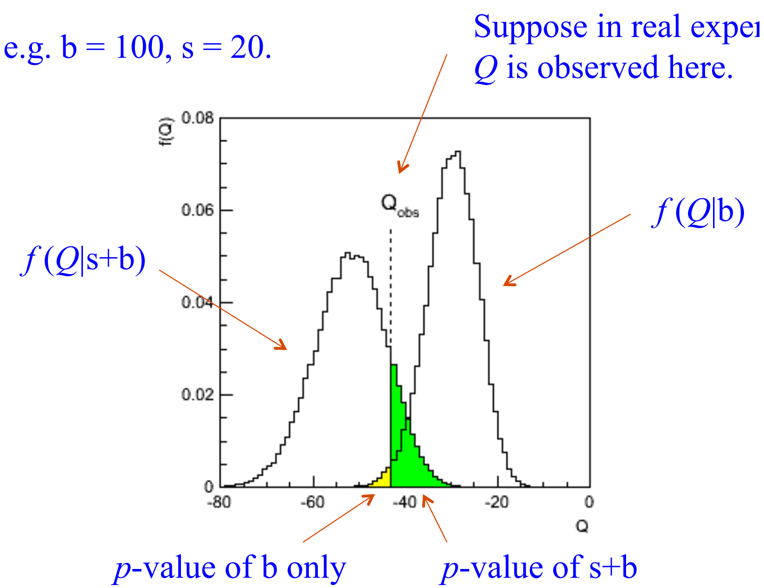
The Neyman-Pearson lemma tells us that the best test statistic is given by the likelihood ratio or any monotonic function of it, e.g.

$$\frac{L_{s+b}}{L_b}$$

$$Q = -2\ln\frac{L_{s+b}}{L_b} = -s + \sum_{i=1}^{n} \ln\left(1 + \frac{s}{b}\frac{f(\mathrm{x}_i|\mathrm{s})}{f(\mathrm{x}_i|\mathrm{b})}\right)$$

used at LEP

Take e.g. b = 100, s = 20.



Test Statistic at LHC: Profile Likelihood

Signal and background yields and shapes are affected by syst. uncertainties
→ parametrize by (not interesting) nuisance parameters θ.

e.g. uncertaintes of reco ID efficiencies, theoretical cross sections, acceptances of selection cuts, extrapolating from control to signal region

$$\mathcal{L}(\mathrm{data}\,|\,\mu,\theta) = \mathrm{Poisson}\,(\,\mathrm{data}\,|\,\mu\cdot s(\theta)+b(\theta)\,)\cdot p(\tilde{\theta}|\theta)$$

in Neyman-Pearson's L_{s+b}/L_b test statistic the signal strength μ is fixed under H_0 and H_1 hypotheses

Now only fix μ under null hypothesis H_0 and let it be estimated from data via maximum likelihood method under alternative hypothesis H_1
→ profile likelihood test statistic

$$\lambda(\mu) = \frac{L(\mu,\hat{\hat{\theta}})}{L(\hat{\mu},\hat{\theta})}$$

fixed under H_0

maximum likelihood estimate under H_0

$\hat{\mu}, \hat{\theta}$ maximum likelihood estimates under H_1

Profile Likelihood Test Statistic for Discovery

H_0: only background → $\mu=0$ H_1: signal and background,
μ parametrises strength w.r.t. SM Higgs predicton

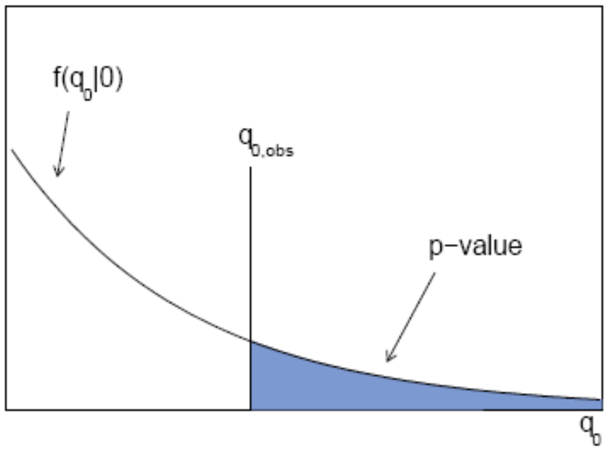
test statistic q_0:

$$q_0 = \begin{cases} -2\ln\lambda(0) & \hat{\mu} \geq 0 \\ 0 & \hat{\mu} < 0 \end{cases}$$

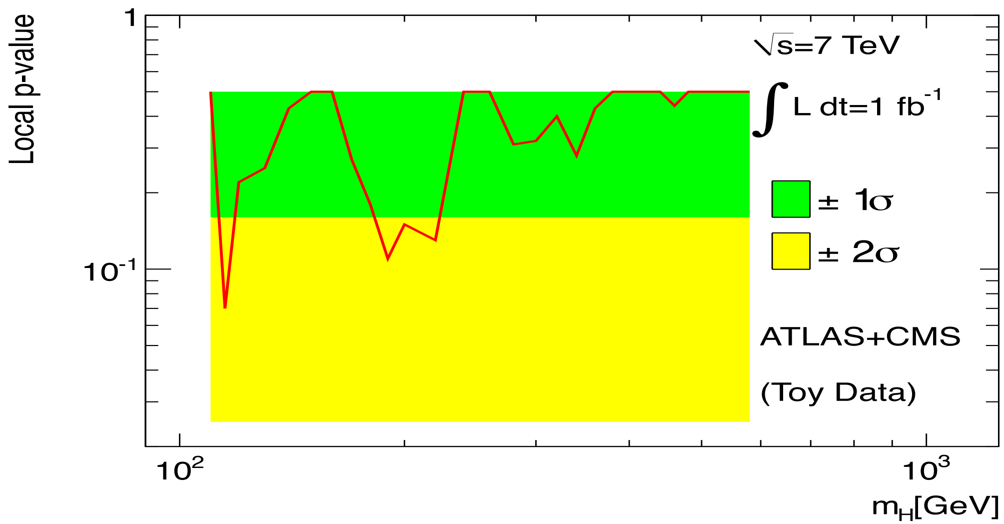
$\lambda(0)$ btw. 0: H_1 like and 1:H_0 like

→q_0 between 0 and infinifity
0: H_0 like >> 0 H_1-like

one sided test, only positive signal strength considered as deviation from H_0



$$p_0 = \int_{q_{0,\mathrm{obs}}}^{\infty} f(q_0|0)\, dq_0$$



The „Look Elsewhere Effect“ (LLE)

So far: local p-value/ significance = prob. to see such an excess at fixed M_H
as we specified M_H in the alternative hypothesis H_1

$$t_{\text{fix}} = -2\ln\frac{L(0,m_0)}{L(\hat{\mu},m_0)} \qquad p_{\text{fix}} = \int_{t_{\text{fix,obs}}}^{\infty} f(t_{\text{fix}}|0)\,dt_{\text{fix}} \qquad Z_{\text{fix}} = \Phi^{-1}(1-p_{\text{fix}})$$

now ask: prob. to see such an excess anywhere in given mass range
→ let mass be a nuisance parameter in fit of new test statistic

$$t_{\text{float}} = -2\ln\frac{L(0)}{L(\hat{\mu},\hat{m})} \qquad p_{\text{float}} = \int_{t_{\text{float,obs}}}^{\infty} f(t_{\text{float}}|0)\,dt_{\text{float}}$$

p_{float} also called global p-value. calculation very cumbersome. lot of MC experiments

$$F_{\text{trials}} \equiv \frac{p_{\text{float}}}{p_{\text{fix}}}$$

trial factor ~ number of independent search regions in considered mass range.
can be calculated approximately with little MC simulation

Profile Likelihood Test Statistic for Exclusion

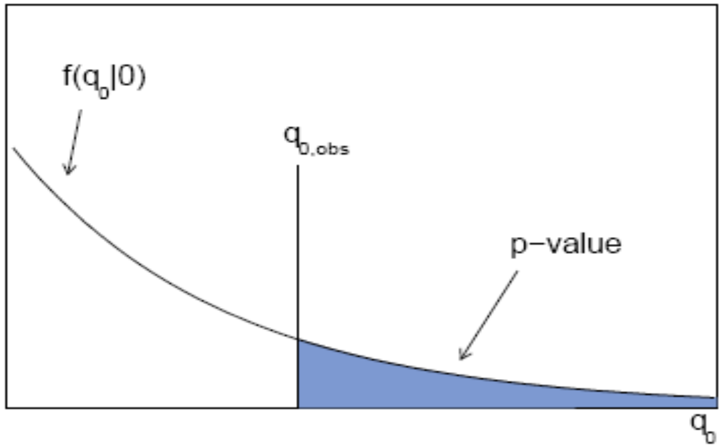
H_0: signal+background → μ=1 H1: background only
μ parametrises strength w.r.t. SM Higgs predicton

test statistic q_μ:

$$\tilde{\lambda}(\mu) = \begin{cases} \dfrac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(\hat{\mu},\hat{\theta})} & \hat{\mu} \geq 0, \\ \dfrac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(0,\hat{\hat{\theta}}(0))} & \hat{\mu} < 0\,. \end{cases}$$

$$\tilde{q}_\mu = \begin{cases} -2\ln\tilde{\lambda}(\mu) & \hat{\mu} \leq \mu \\ 0 & \hat{\mu} > \mu \end{cases}$$

for negative signal strength set it to 0 and determine then nuisance pars.
one sided test, only signal strength< μ considered as inconsistent with H_0



different test statistic then for discovery

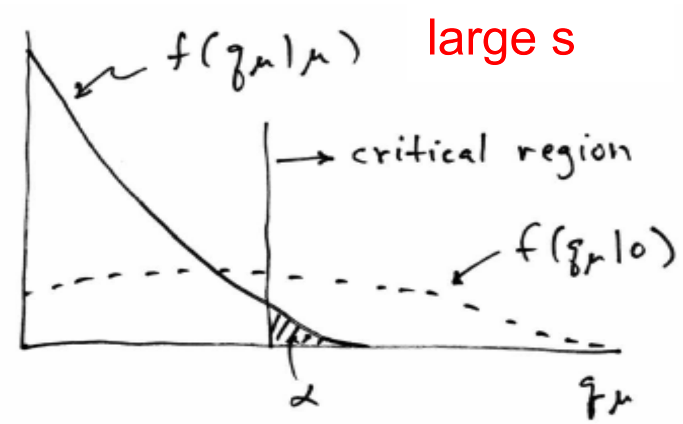
here values ~0 are signal+background like observations

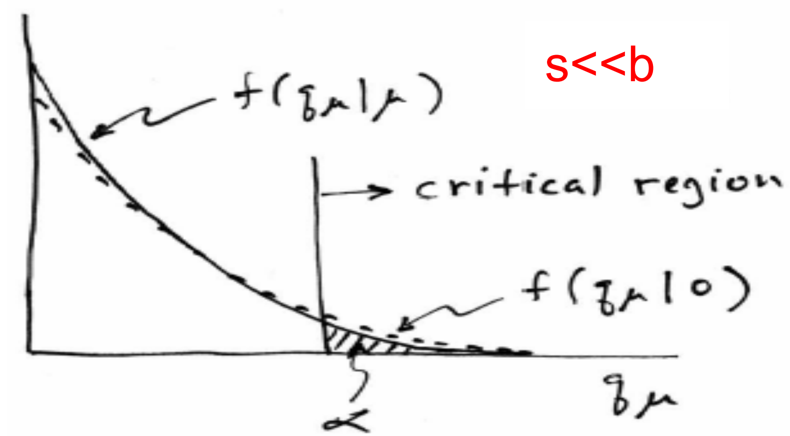
The „Problem“ with the Pure Frequentist Method

$$p_\mu = P(\tilde{q}_\mu \geq \tilde{q}_\mu^{obs} \,|\, \text{signal+background}) = \int_{\tilde{q}_\mu^{\text{obs}}}^{\infty} f(\tilde{q}_\mu|\mu, \hat{\theta}_\mu^{\text{obs}})\, d\tilde{q}_\mu$$

Pure frequentist would stop and say: „signal+background“ hypothesis is exlcuded with a confidence level CL_{S+B} of 1- p_μ

„Problem“: Spurious exclusion of signals with no sensitivity (s<<b)





signal+BG-like ← → BG only like

by construction: probabilty to reject μ if μ is true is α
probability to reject μ if μ=0 is only slighty greater than α φορ σ<<β.
→ probability to exlcude hypotheses with zero signal ~α „spurios exclusion“

A Solution: the CL_S Method

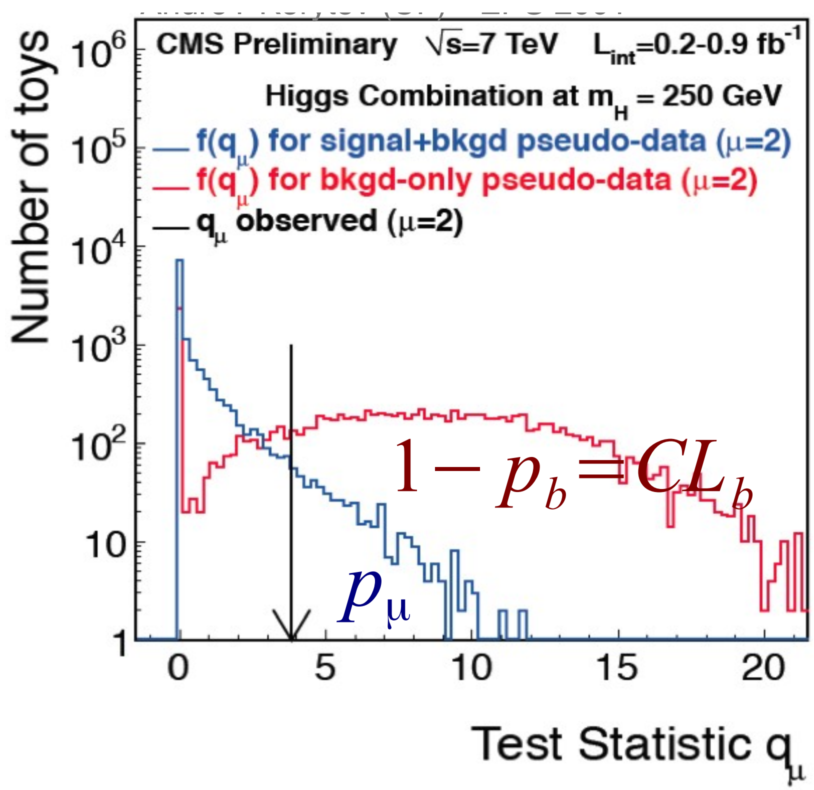
Spurious exclusion caused by downwards fluctuation of background
→ penalize such outcomes in an „ad hoc“ way

$$1 - p_b = P(\tilde{q}_\mu \geq \tilde{q}_\mu^{obs} \,|\, \text{background-only}) = \int_{q_0^{obs}}^{\infty} f(\tilde{q}_\mu | 0, \hat{\theta}_0^{obs})\, d\tilde{q}_\mu$$

$$p_\mu = P(\tilde{q}_\mu \geq \tilde{q}_\mu^{obs} \,|\, \text{signal+background}) = \int_{\tilde{q}_\mu^{obs}}^{\infty} f(\tilde{q}_\mu | \mu, \hat{\theta}_\mu^{obs})\, d\tilde{q}_\mu$$

$$CL_s = p_\mu / (1 - p_b)$$

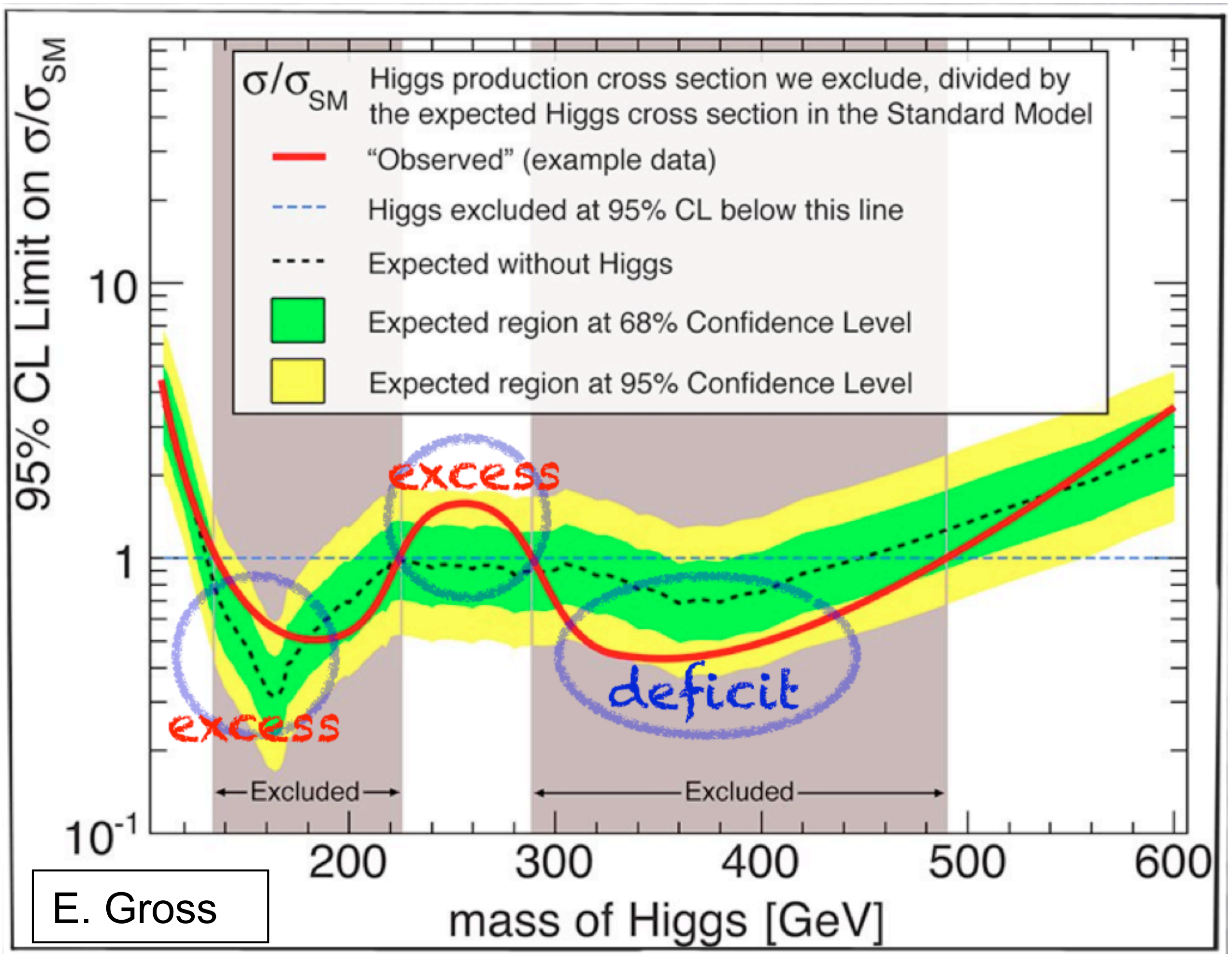
Caveat: p_b ist not equal p_0
different test statistic



if CL_S<5% we call a μ hypothesis excluded at 95% CL (but true coverage larger)

upper limit on μ: adjust μ to value for which CL_S= 5%

Typical Exclusion Plot Looks Like This ...



expected limit: median value of μ which will be excluded under H_1 BG-only
green and yellow bands are 68% (95%) confidence ntervals around this