Search for a SM Higgs boson in the decay channel $H \rightarrow ZZ^{(*)} \rightarrow 4l$ with the CMS experiment

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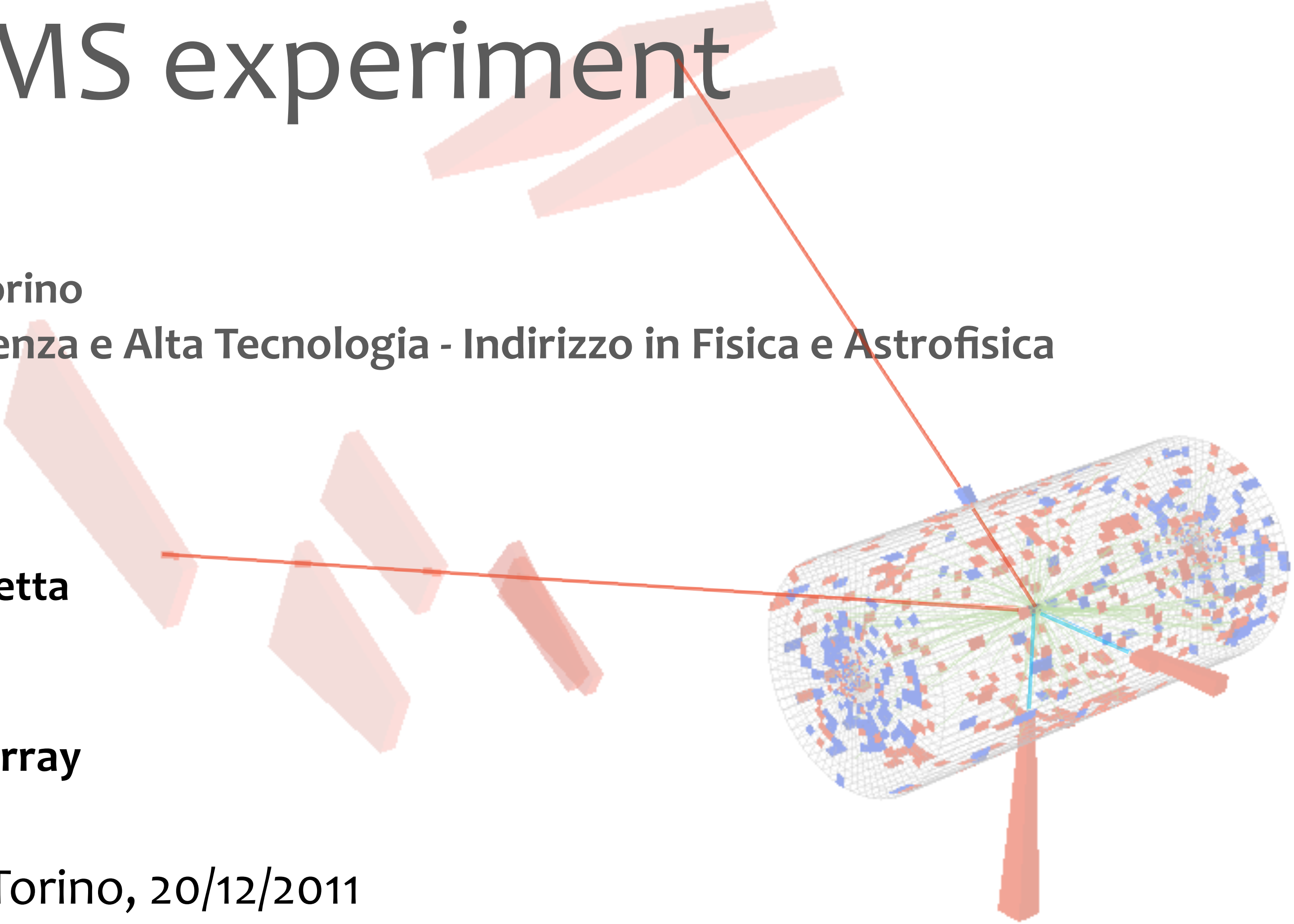
XXIV ciclo



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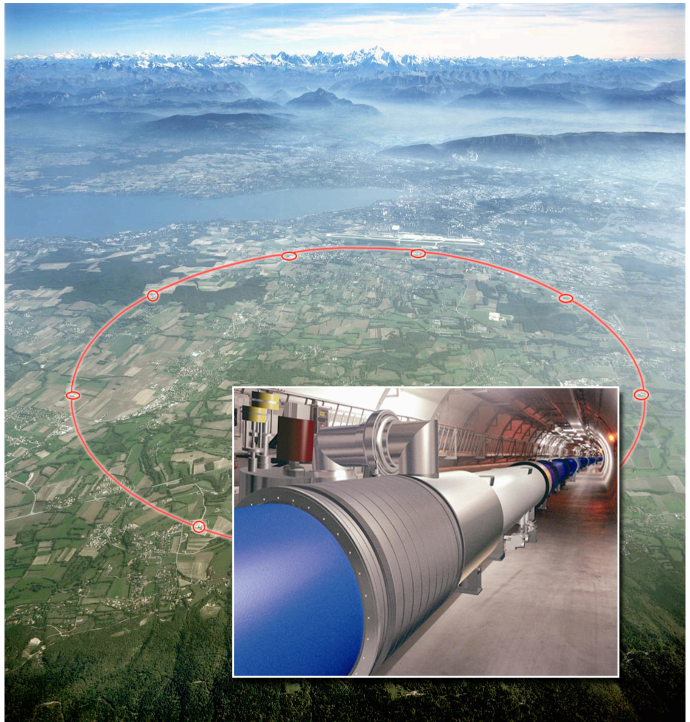
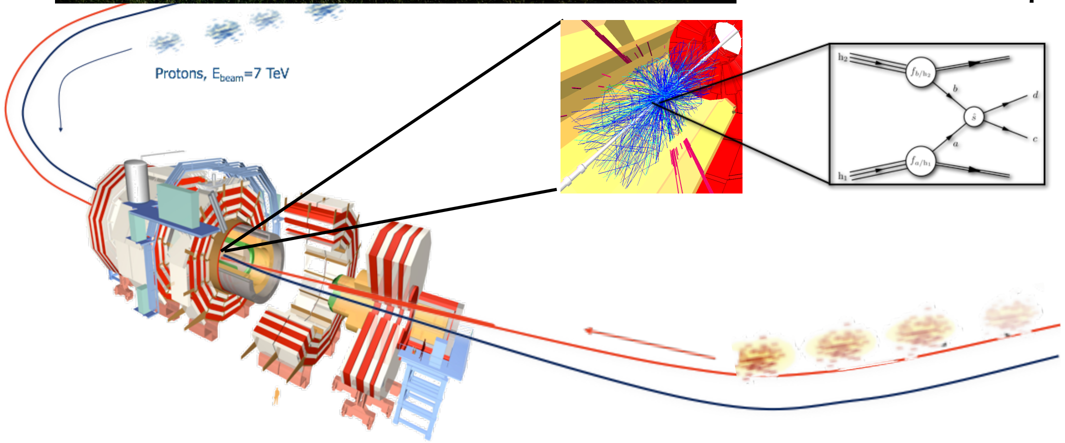
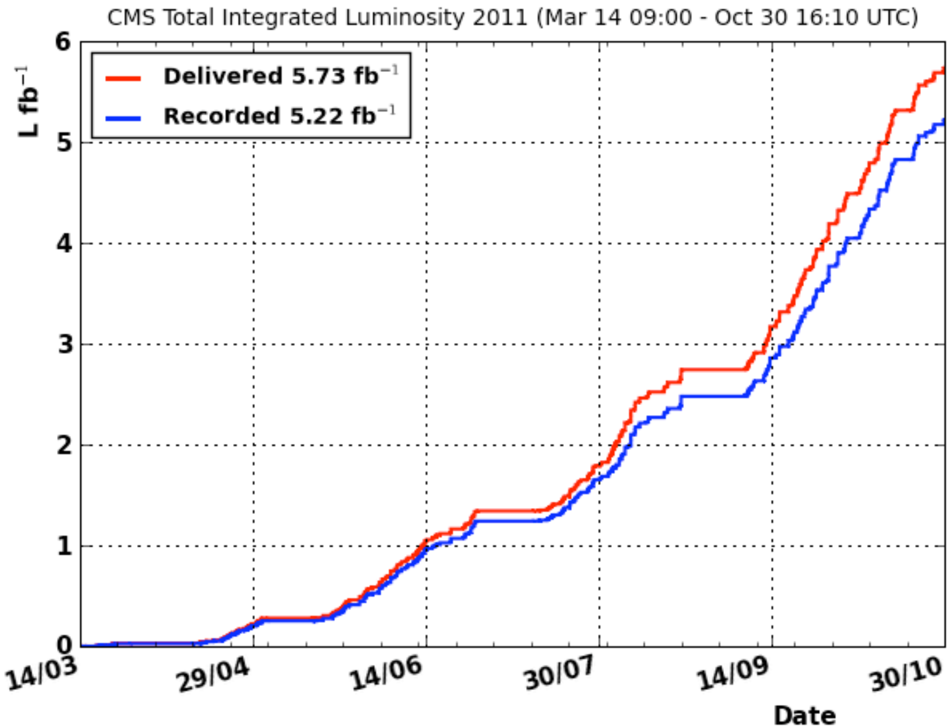
Prelude



- **30 March 2010: first pp collisions at 7 TeV recorded by the LHC experiments.**
- **2010 operations: 47 pb^{-1} delivered**
  - max $\mathcal{L}$= 2 10^{32} $cm^{-2}s^{-1}$
  - max colliding bunches: 368
  - bunch separation: 150 ns
- **2011 operations: from March to October 5.73 fb^{-1}delivered**
  - max $\mathcal{L}$= 3.5 10^{33} $cm^{-2}s^{-1}$
  - max colliding bunches: 1331
  - bunch separation: 50 ns





- **LHC NOMINAL PARAMETERS**
  - $\mathcal{L}$= 10^{34} $cm^{-2}s^{-1}$
  - center of mass energy: 14 TeV
  - bunch separation: 25 ns
  - colliding bunches: 2250

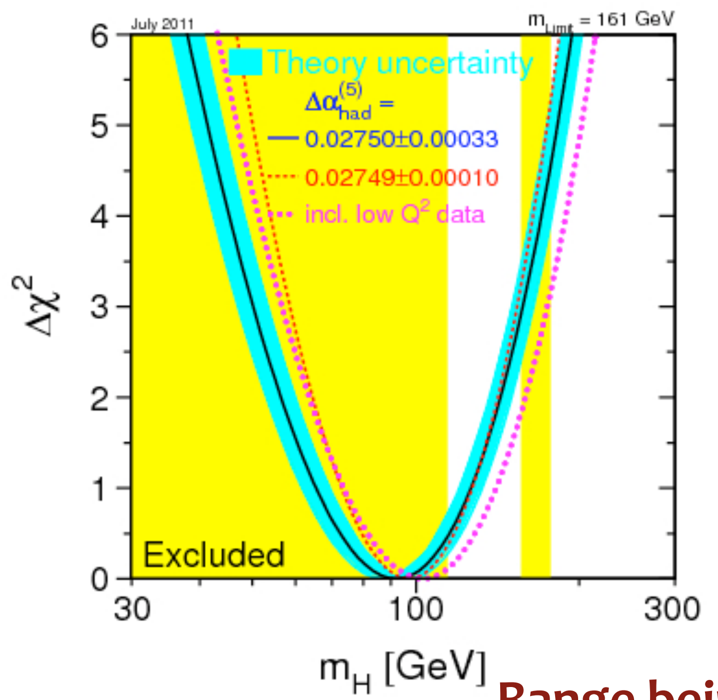
Prelude [2]

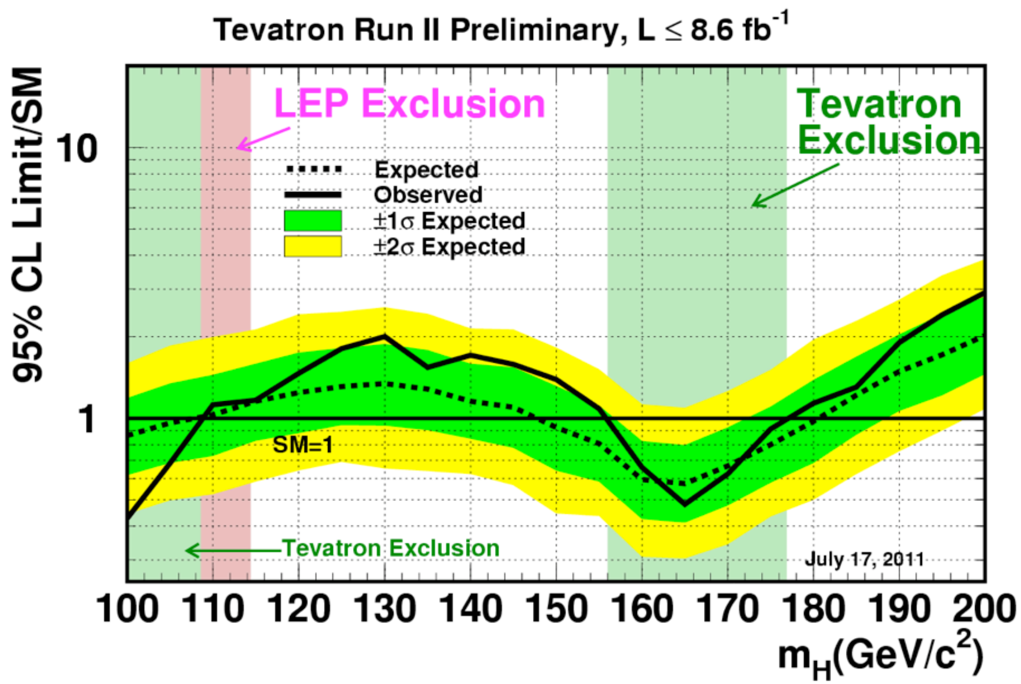
- **The Higgs boson mass:** the only one yet unknown free parameter of the SM

- Prove or exclude the Higgs boson existence:

  a matter of the highest priority in the field of particle physics

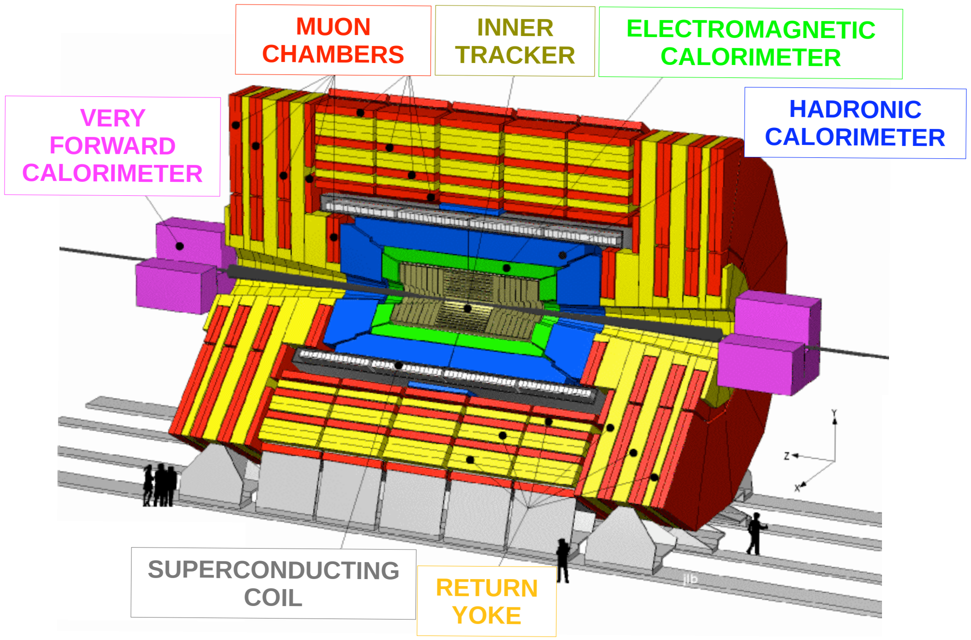
- Theoretical indications and experimental constraints, from direct and indirect searches, narrow the possible range:
  - **Theory: $m_H < \sim 800$ GeV/c^2 to remain in the perturbative regime while considering $V_L V_L$ scattering matrix**
  - **Experiments:**





Range being explored at CMS: 110-600 GeV/c^2

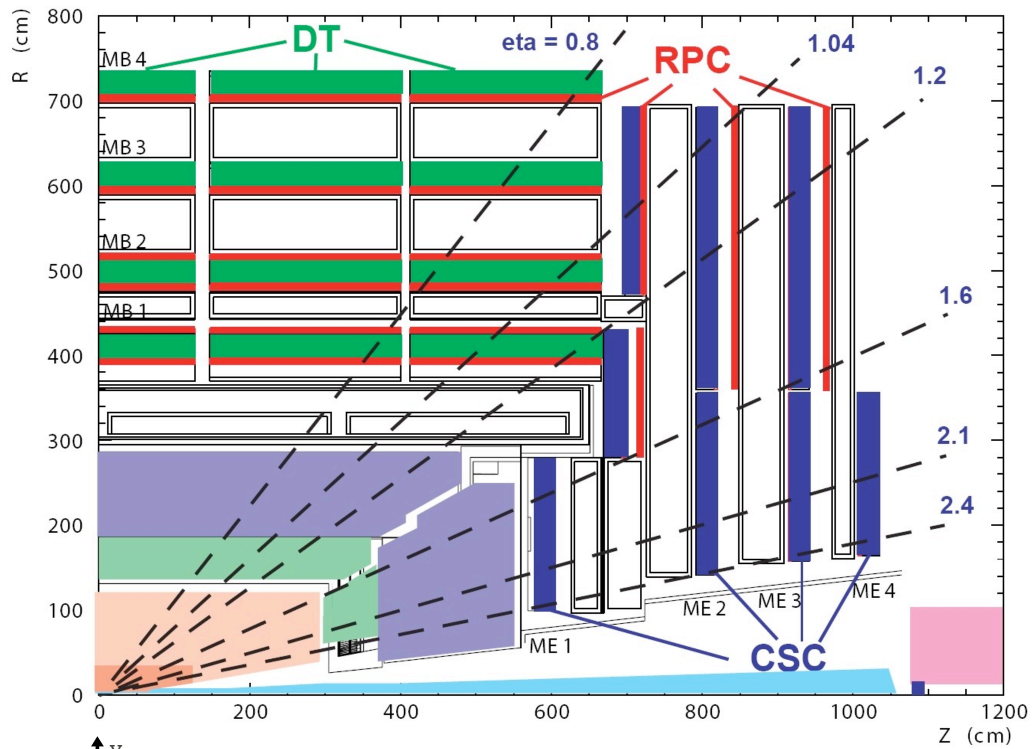
Prelude [3]

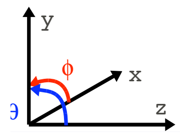


- high lepton reconstruction efficiency
- excellent lepton/photon identification
- excellent lepton/photon energy resolution

CMS LAYOUT:

- 3.8 T superconducting solenoid
- a robust and redundant muon system
- a good electromagnetic calorimeter
- a high-quality tracker system

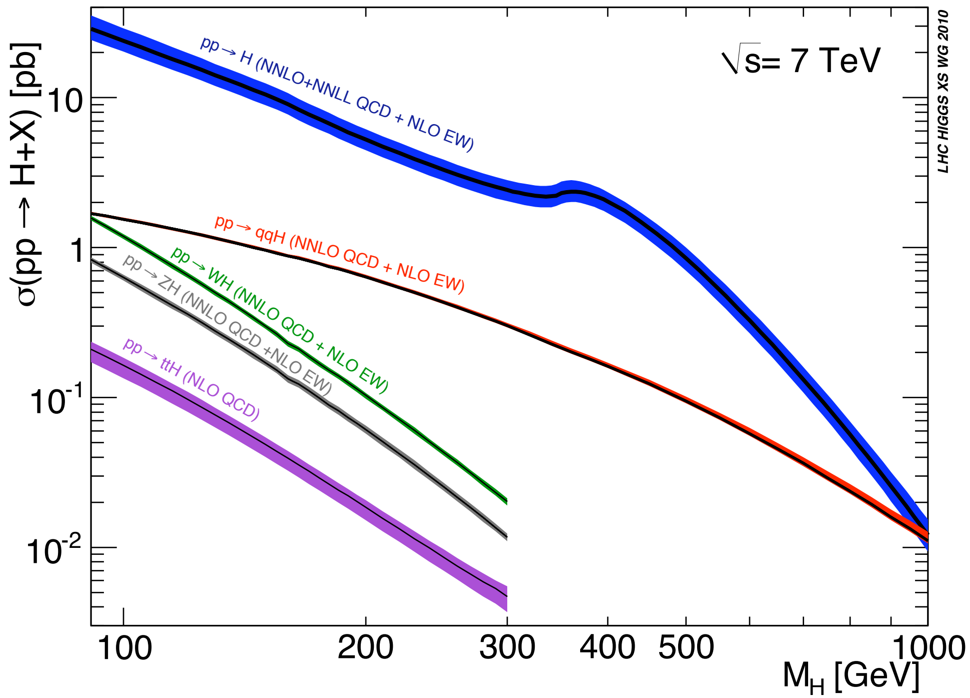


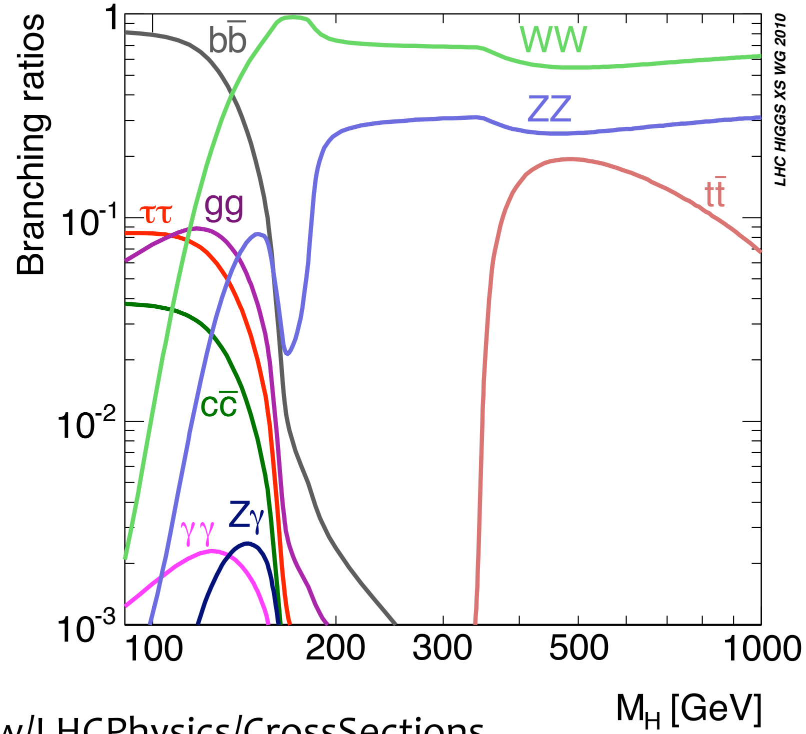


$$\eta = -\ln \tan\frac{\theta}{2}$$

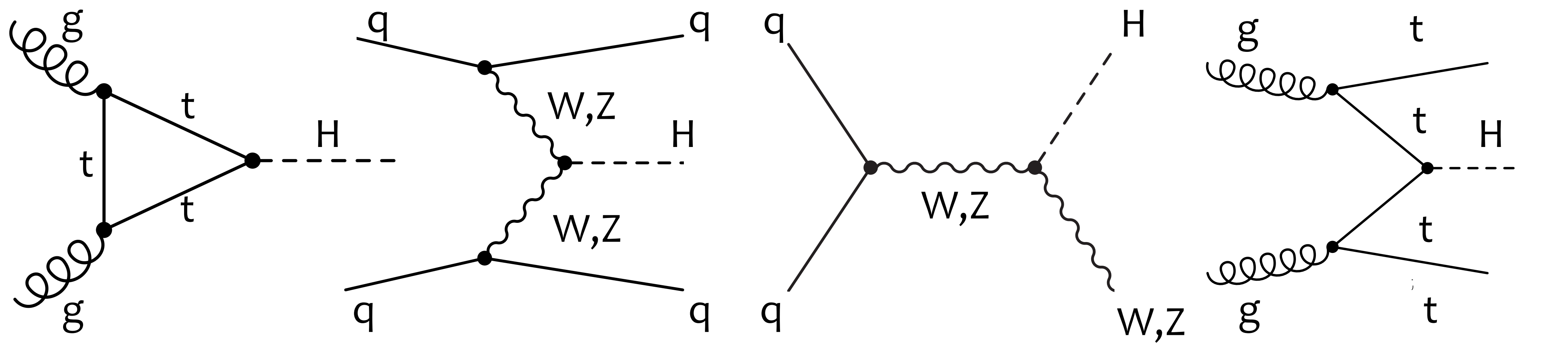
Higgs Physics at LHC

Higgs Production & Decay

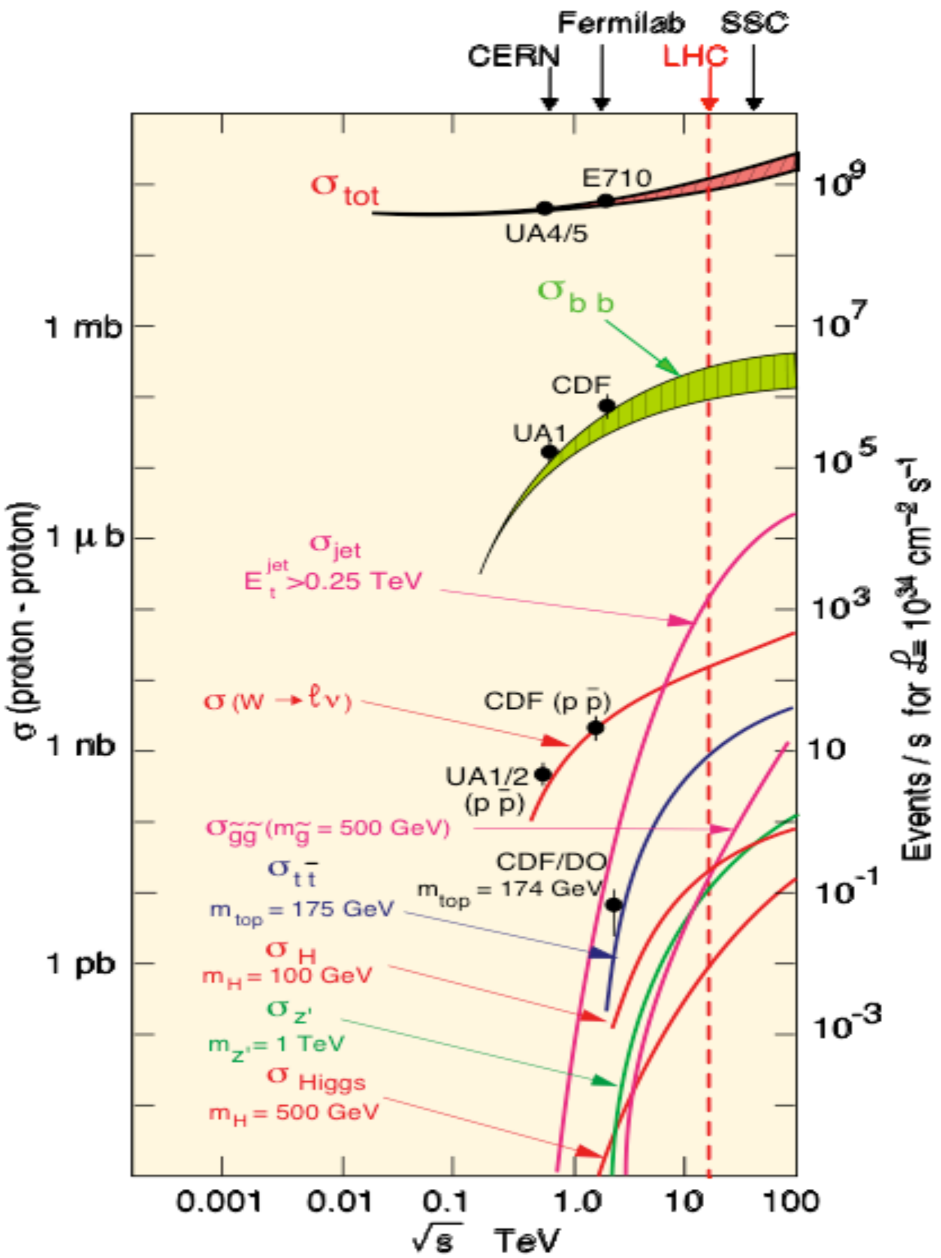




https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections



pp collisions at LHC



- total inelastic non diffractive pp cross section at LHC @ 7 TeV = 60 mb => 6×10^9 times the Higgs production cross section

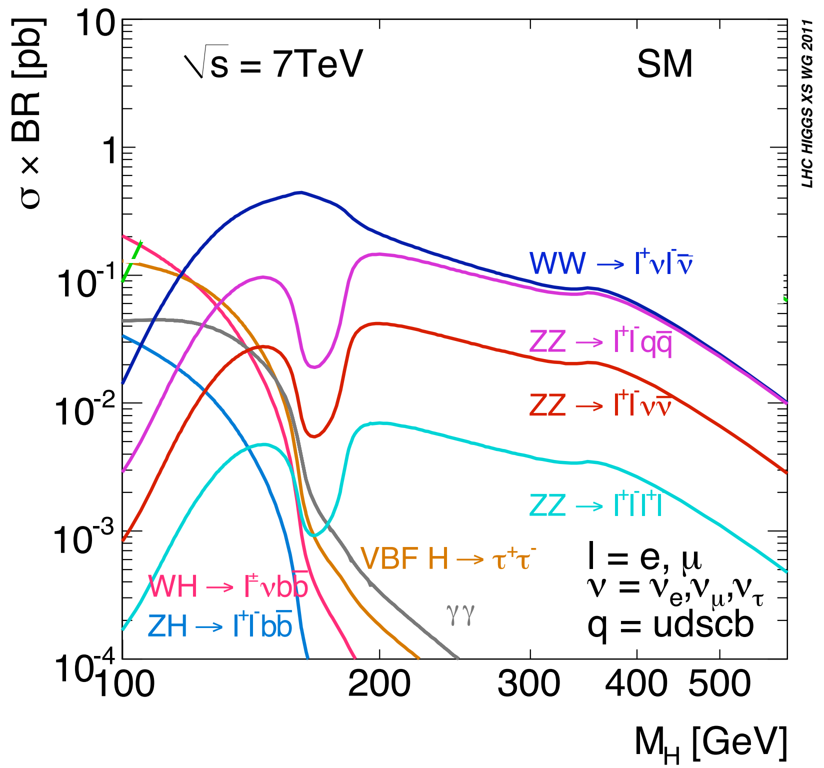
- bb production cross section at LHC @ 7 TeV ~ 50 ub => 5×10^6 times the Higgs production cross section

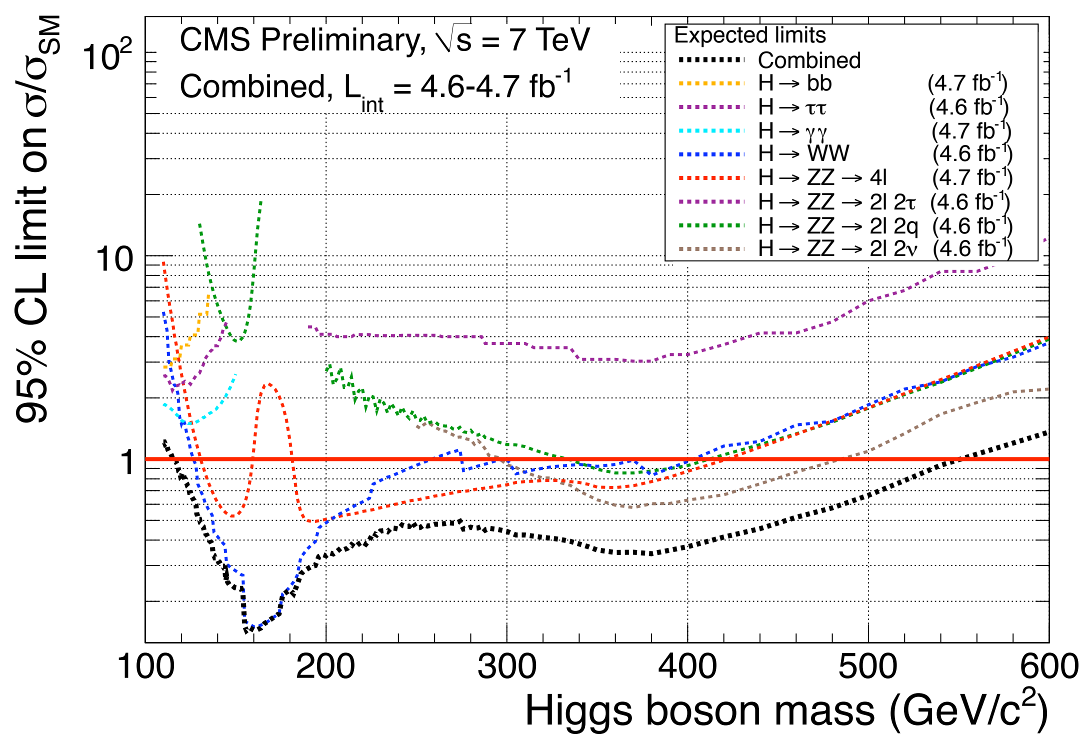
- with 2011 LHC conditions, an average overlap of 10 interactions per bunch crossing [pile-up]

Higgs events: very rare events in an environment overwhelmingly dominated by QCD events:

final states with high p_T isolated leptons or photons are experimentally favored

Higgs search at CMS



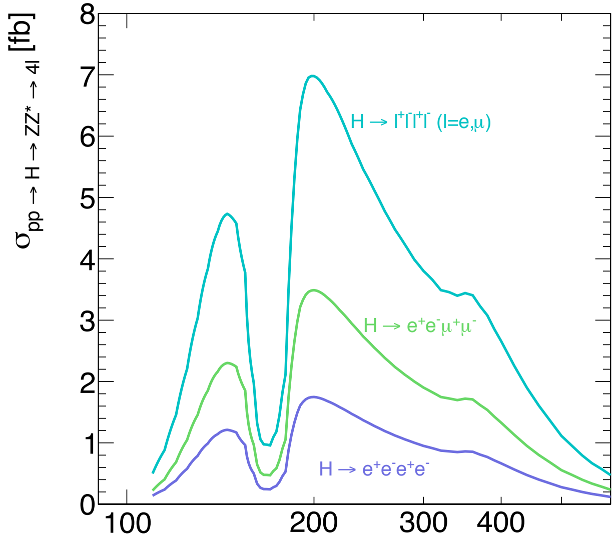


m_H < 135 GeV/c²	**140 < m_H < 180 GeV/c2**	**m_H > 180 GeV/c2**
H->γγ exclusion - discovery	**H->WW->2l2ν**	**H->ZZ channels**
[H->ZZ/WW/ττ/bb ~ sensitivity	ZZ4l also for discovery	ZZ4l also for discovery
ZZ4l also for discovery]		

The search for the SM Higgs in the $ZZ^{(*)} \rightarrow 4l$ decay is the subject of this thesis

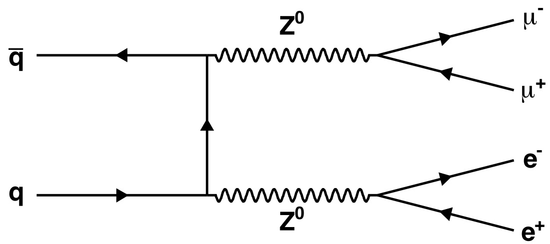
$H \rightarrow ZZ^{(*)} \rightarrow 4l$ (l=e,μ)

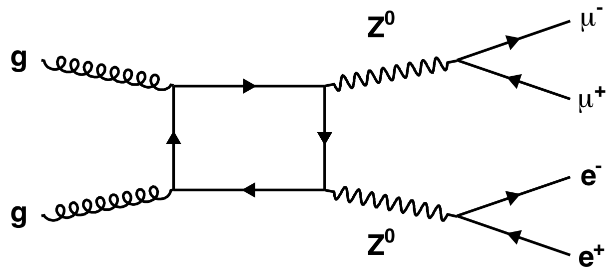
- Final state considered: 4μ, 4e, 2μ2e



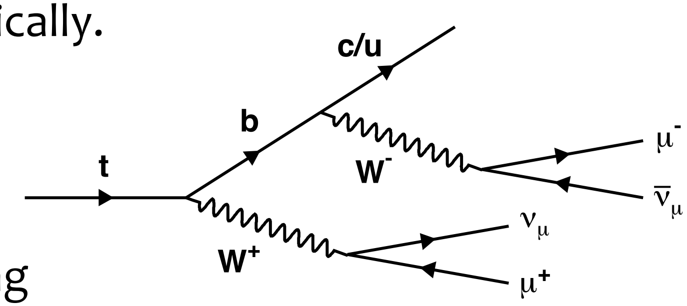
- All Higgs boson production mechanisms are considered as part of the signal **(gg contributions up to NNLO and NNLL; VV fusion up to NNLO corrections - LHC Cross Section WG)**

- **IRREDUCIBLE BACKGROUND:**
$qq \rightarrow ZZ^{(*)} \rightarrow 4l$ / $gg \rightarrow ZZ^{(*)} \rightarrow 4l$





- **REDUCIBLE BACKGROUNDS:**
Zbb/Zcc and **tt pair** production. Events with B mesons decaying semileptonically (~ 20% BR) and W/Z bosons decaying leptonically.



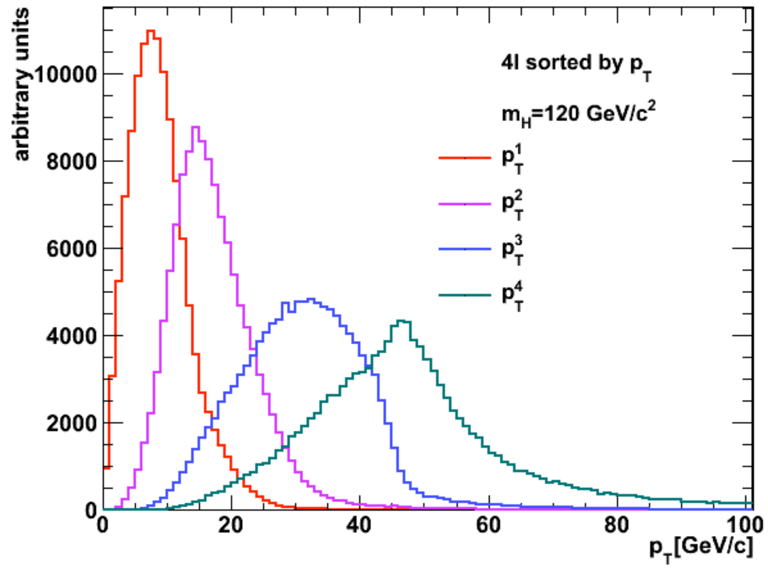
- **INSTRUMENTAL BACKGROUNDS:**
QCD and **Z/W+light jets**. Events with electrons from jets faking leptons, and muons from decay-in-flight of light hadrons.

The Challenge

- **VERY CLEAN SIGNATURE:** 4 isolated leptons arising from a common vertex

The analysis relies solely on the measurement of leptons:

- RECONSTRUCTION
- IDENTIFICATION
- ISOLATION
- PRIMARY VERTEX COMPATIBILITY



- **VERY LOW RATE:**

high signal selection efficiency is MANDATORY

- For $m_H < 2m_Z$ one lepton pair at least couples to a $Z^{(*)}$

=> softest lepton: $p_t < 10$ GeV/c for $m_H < 140$ GeV/c²

High reconstruction efficiency and sufficient discrimination against hadronic jets faking leptons [mainly electrons] and against muons from decay in flight of light hadrons is expecially challenging at low p_T

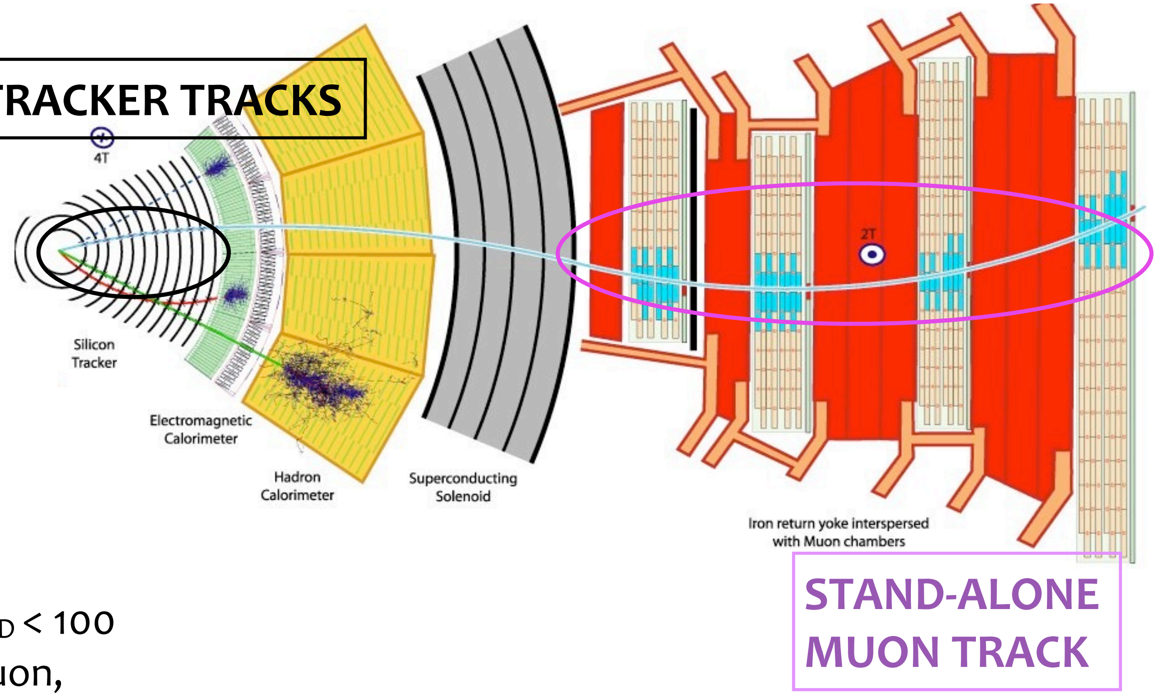
- The event selection is designed to preserve the highest possible signal efficiency while reducing to a negligible level the instrumental and reducible backgrounds.

It is important to **control with data-driven methods the contaminations from Zbb/tt/Z+lightJets.**

Difficulties arise from the rate of 4l backgrounds.

Physics Object : Muons

Muon Reconstruction & Identification



- **Global Muons Reconstruction**

Stand Alone track fit of CSC/DT/RPC segments/hits
Global track fit of stand alone + tracker track
1-2% up to 100 GeV/c > 6% at ~1TeV/c
[better than only tracker if pt > 200 GeV/c]
Efficiency: 98% plateau from 5 GeV/c

- **Loose Muon ID working point**

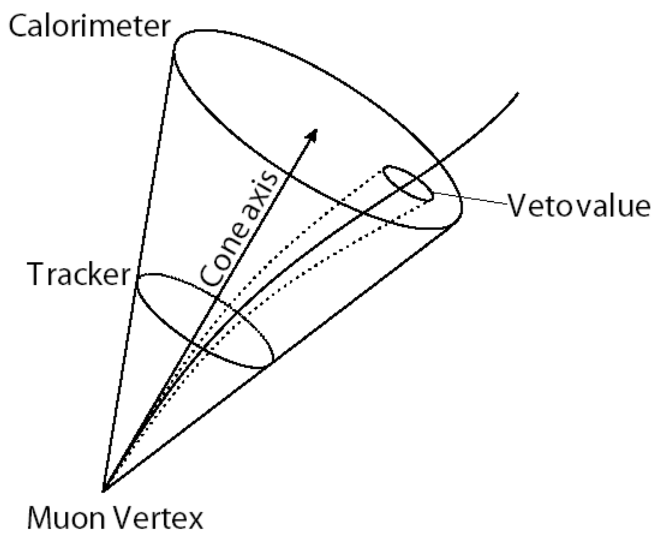
Global Muon Reco + tracker track >=10 hits + $SIP_{3D} < 100$
(<1% prob to reconstruct a proton/kaon/pion as a muon,
no efficiency loss wrt Global Muon reco)

$SIP_{3D} = |IP_{3D}| / \sigma_{IP3D}$ significance of the tridimensional impact parameter
Evaluated wrt the PRIMARY VERTEX

HIGH EFFICIENCY MANDATORY - Min p_t = 5 GeV/c
NEGLIGIBLE QCD BACKGROUND with 4 muons in the final state
Muons from b to be discarded at the end of the selection
(to control with data-driven methods the Zbb/tt backgrounds)

Muon 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

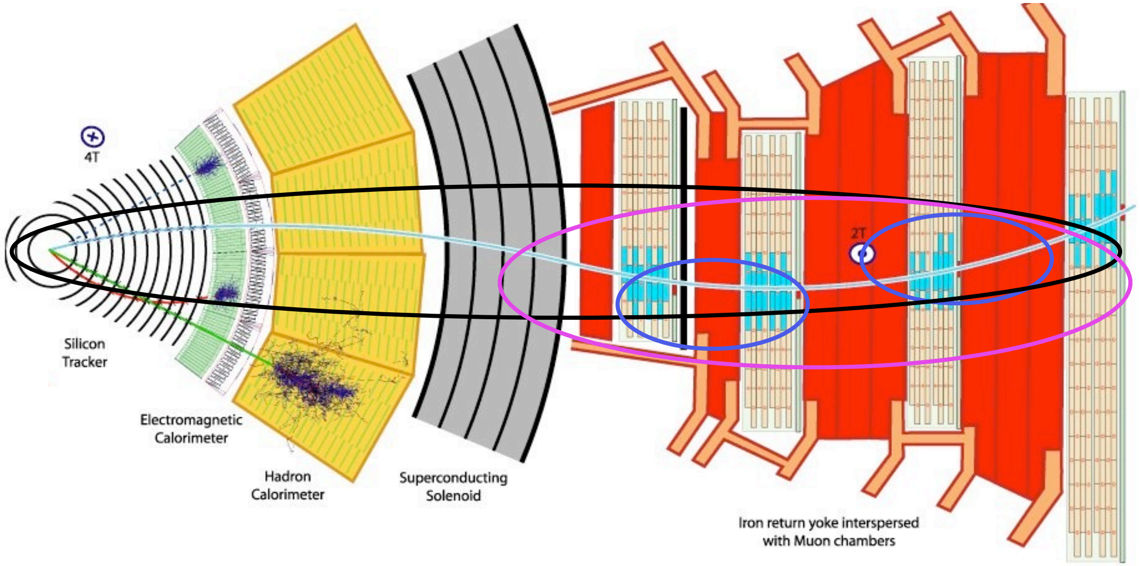
ECAL and HCAL contributions are affected by pile-up conditions
To have a pile-up robust analysis R_{Iso} must be corrected by the average energy flow in the event
[Fast-jet correction]

Muon Trigger

CMS adopts a multi-level trigger design
Each step of the selection uses only part of the available data
Higher trigger levels process fewer events and can use more refined algorithms

L1

Reconstruct the position and provide a raw estimation of muon p_T
Assign the bunch-crossing.
DT/CSC and RPC electronics have their own trigger logic based on segment and hits comparators to find patterns.



HLT: L2

The L1 muon is used to seed the online Stand-Alone reconstruction.
L2 muons are tracks in the spectrometer.

HLT: L3

The L2 muon parameters are used to indicate a ROI in the tracker where the track reconstruction is performed. If a match between a tracker track and the L2 muon is found a global fit is performed.
The L3 muons are global muon tracks.

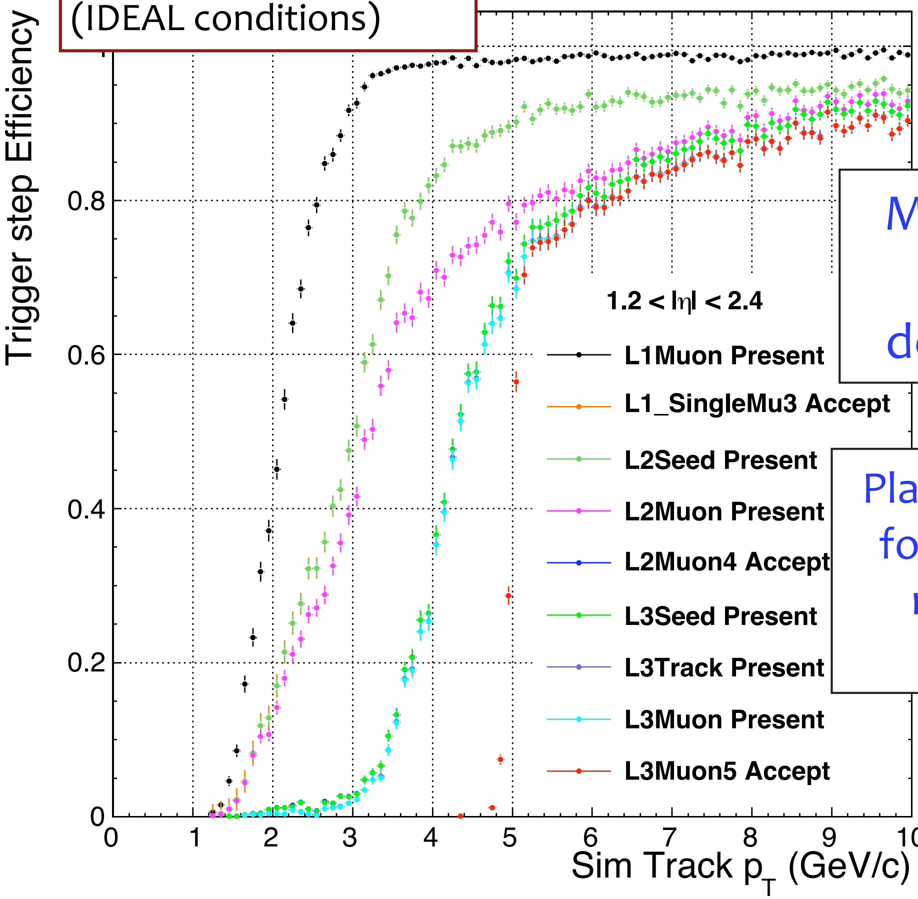
A trigger path is a list of reconstruction and filter modules that results in a final accept/reject

Bit Name	L1	L2	L2 Iso	L3	L3 Iso
HLT_Mu5	$p_T \geq 3$ $q > 3$	$p_T \geq 4$	N/A	$p_T \geq 5$ $\lvert d0 \rvert \leq 2$	N/A
HLT_IsoMu9	$p_T \geq 7$ $q > 3$	$p_T \geq 7$	CaloIso≤ 4	$p_T \geq 9$ $\lvert d0 \rvert \leq 2$	PixelIso≤ 1
HLT_DoubleMu7	$p_T \geq 5$ $q > 3$	$p_T \geq 5$	N/A	$p_T \geq 7$ $\lvert d0 \rvert \leq 2$	N/A

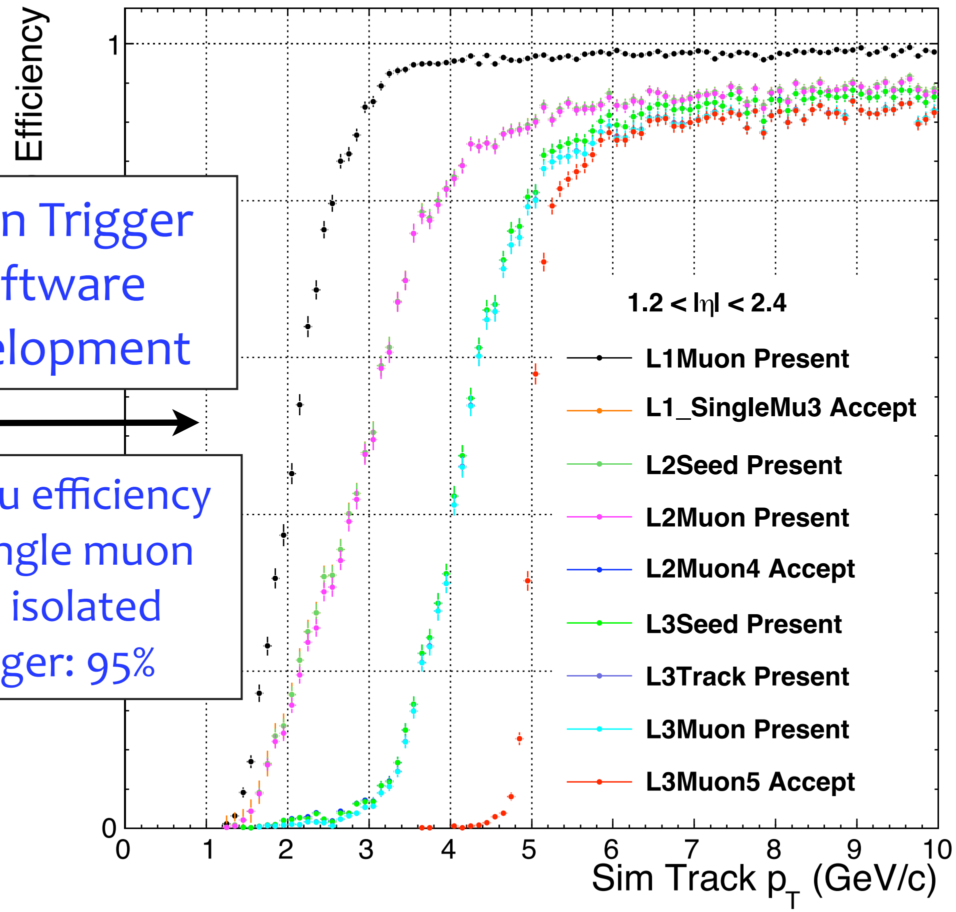
Muon Trigger [2]

- **Trigger efficiency wrt "offline" Global Muon (MC studies)**
- **The HLT_Mu5 Trigger Path example:**

Single-Muon MC events
(IDEAL conditions)



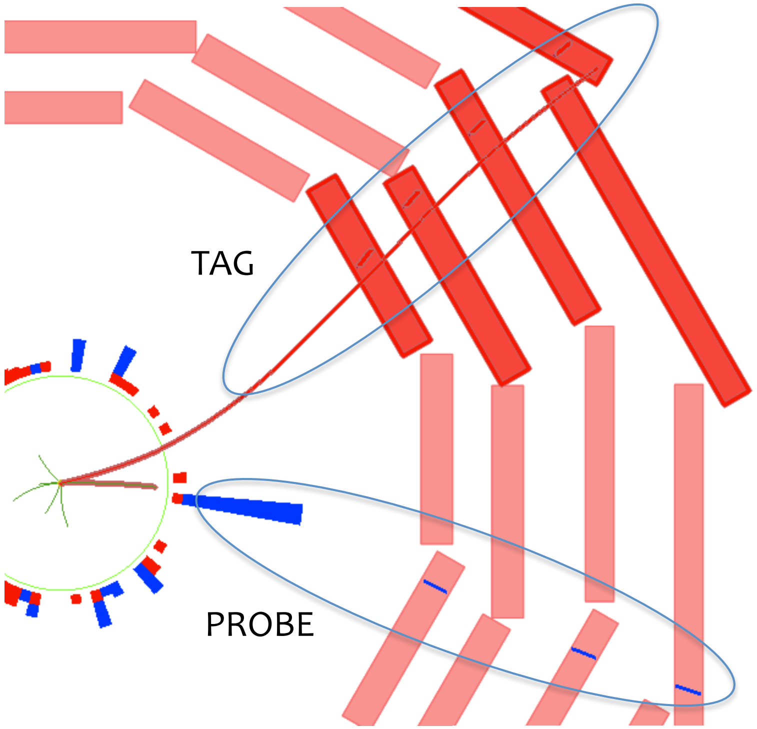
Muon Trigger Software development →



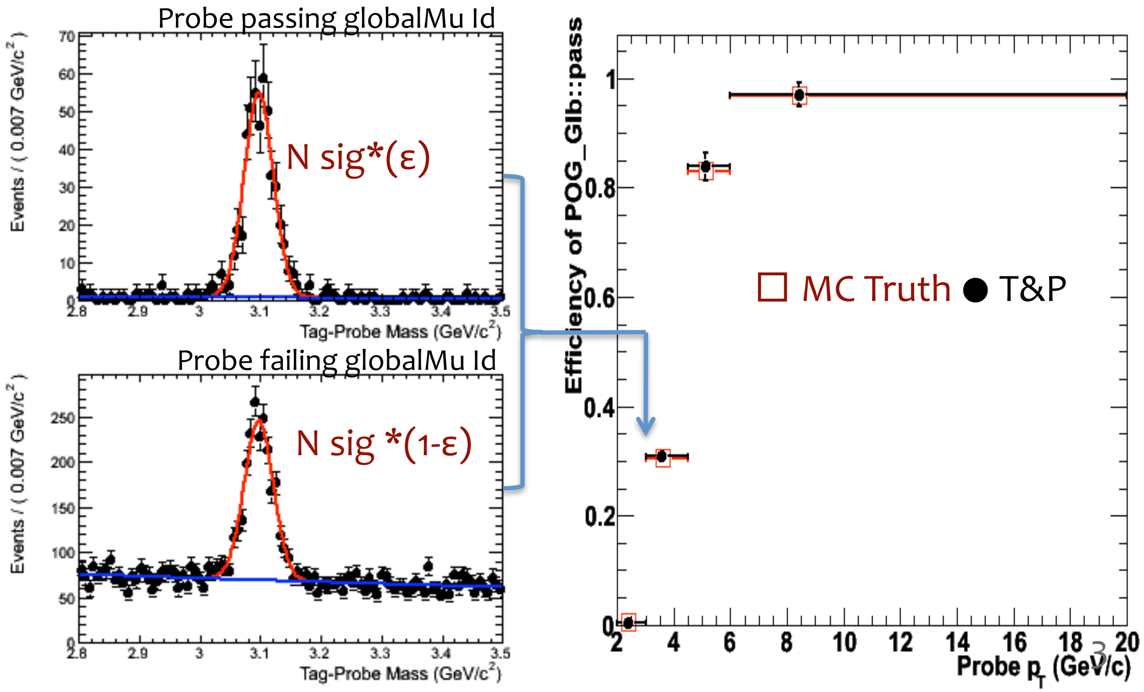
Plateau efficiency for single muon non isolated trigger: 95%

Muon performance studies on data:

Tag And Probe Method



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



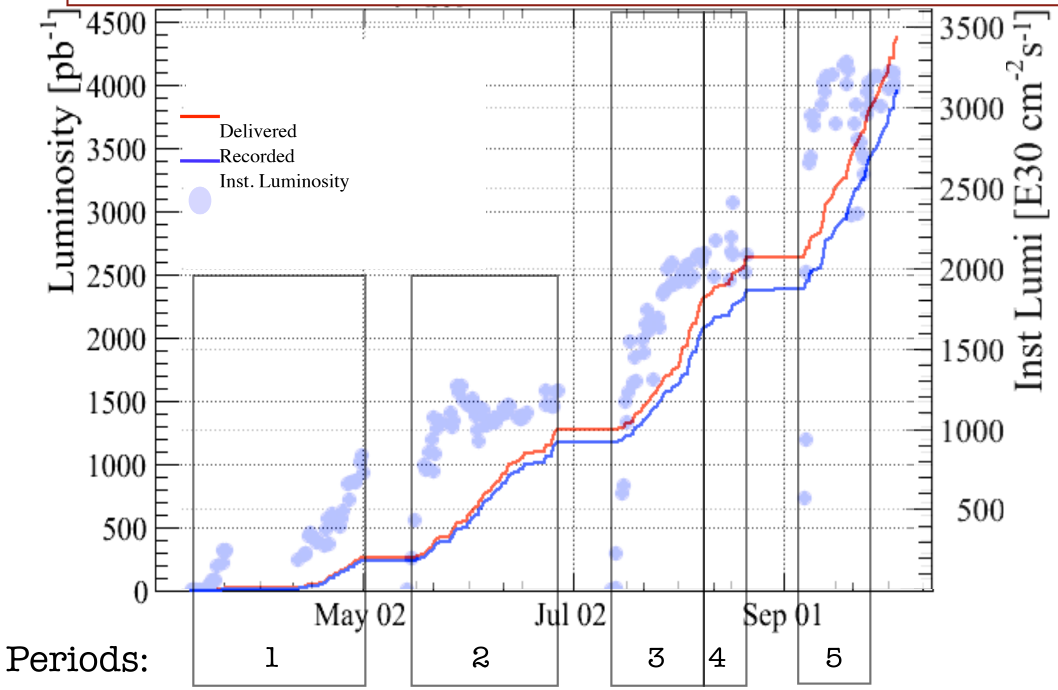
- **Fitting functions** used for the Z (Jpsi) T&P are:
  - Voigtian (Crystal Ball) for the resonance
  - Exponential for the background

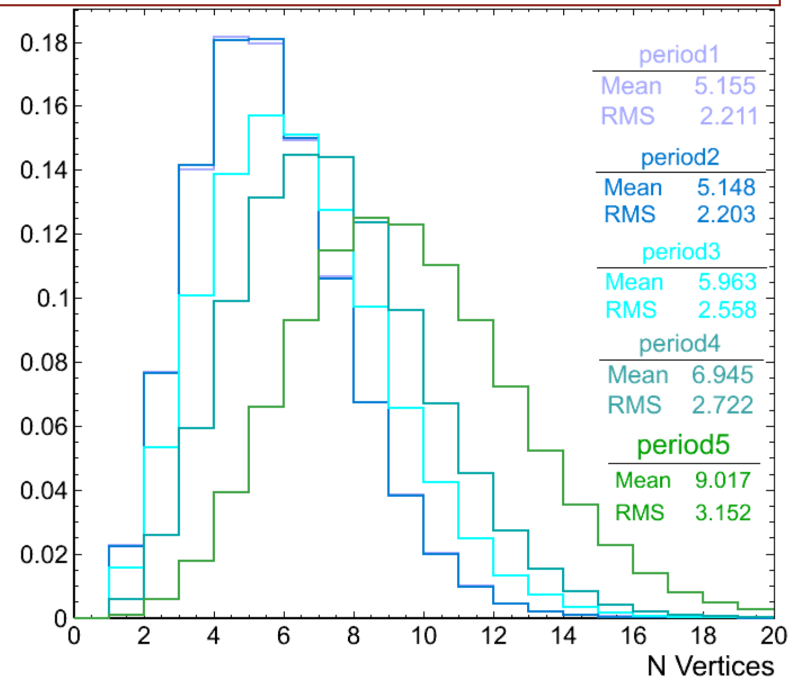
- **Systematic uncertainties** on the measured efficiencies are obtained comparing the results on MC with the MC Truth, and in data varying the functional forms used for the fit

- Efficiencies are measured in **p_T/η/Nvtx bins** for different **data-taking periods [only few examples of the results will be presented]**

2011 data

2011 data divided into 5 periods according to changes of the LHC running conditions => different pile-up conditions / improvements in the trigger configurations at L1 / changes in HLT trigger thresholds to face rate constraints

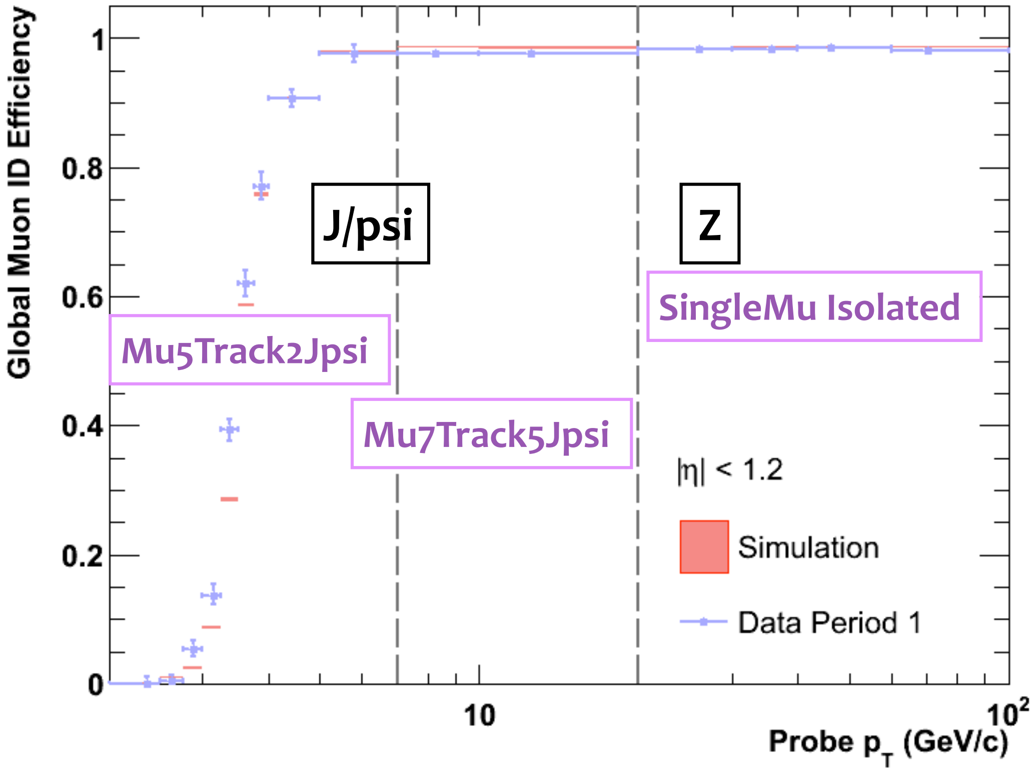


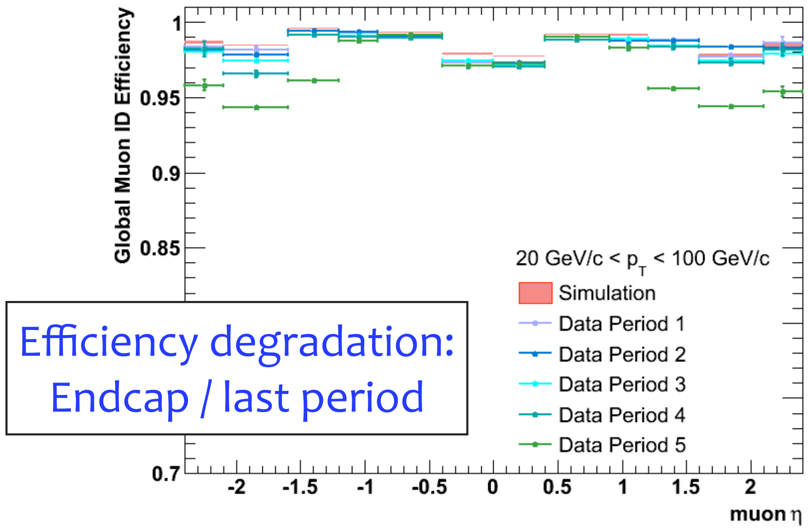


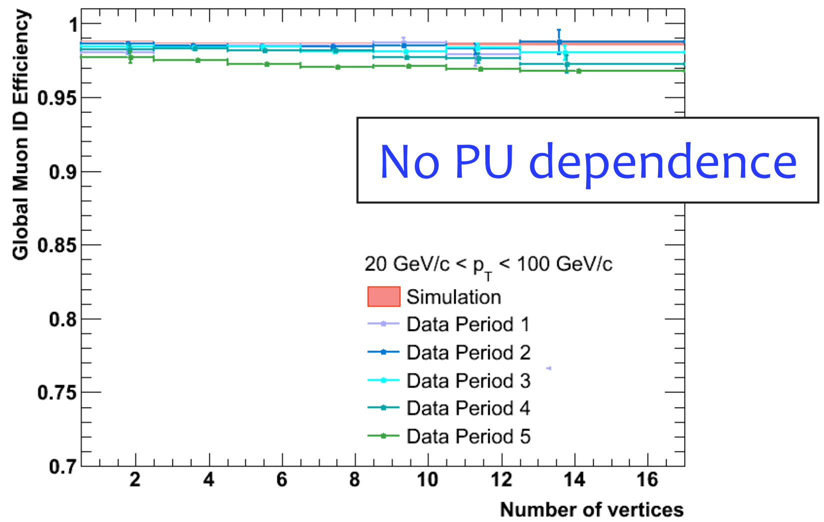
Lowest un-prescaled Single/Double Muon Triggers at the end of each periods

Period 1	HLT_Mu30/ HLT_IsoMu17	HLT_DoubleMu7
Period 2/3/4	HLT_Mu40/ HLT_IsoMu24	HLT_Mu13Mu8
Period 5	HLT_Mu40_eta2p1/HLT_IsoMu24_eta2p1	**HLT_Mu17Mu8**
	Used for T&P	Used for H->4l analysis

Results with 2011 data: Reco & ID



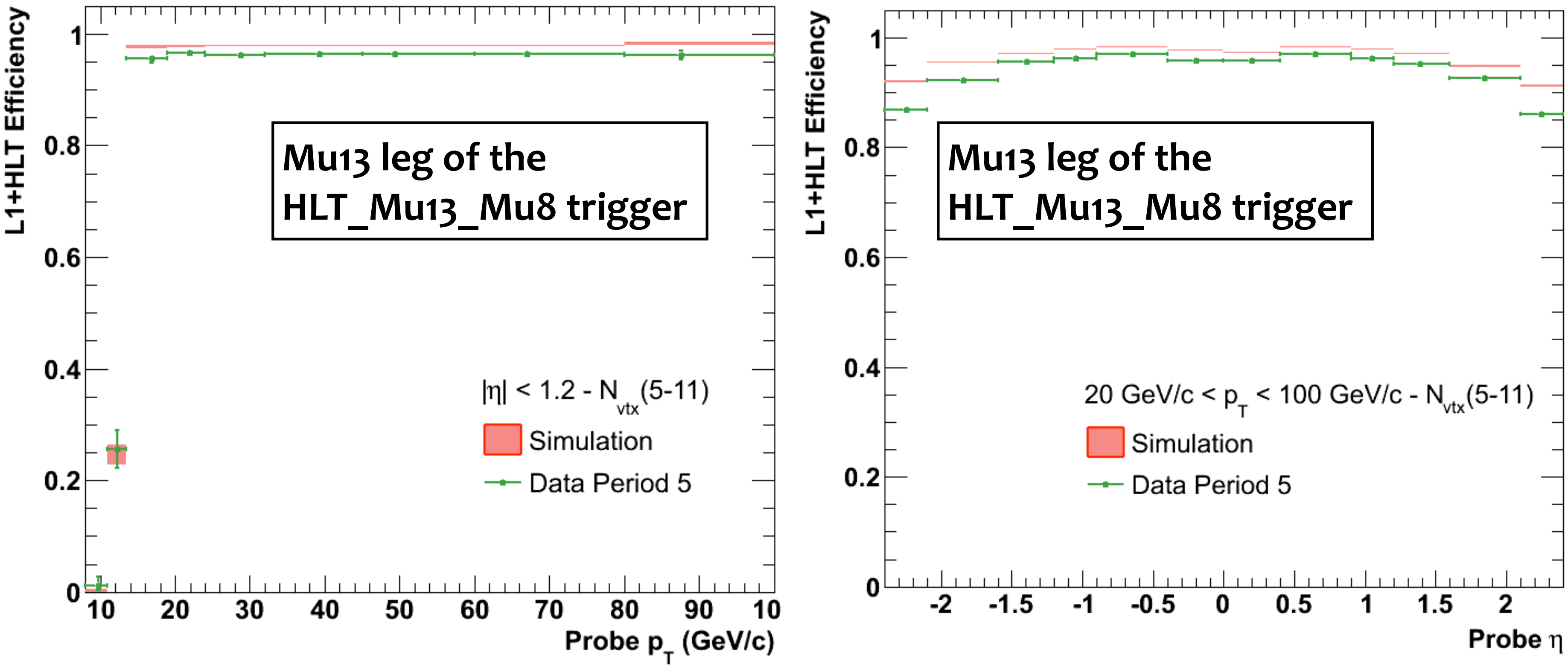




- **Tag: Tight Muon matched with the trigger object**
  Probe: tracker track

- Data/mc efficiency ratios have been measured as a function of p_t/eta/N_{vtx} for each data taking period and have been **used in the H->4l analysis to correct the MC.** Systematic uncertainties on the correction have been determined from the uncertainty on the efficiency measured with the T&P method.

Results with 2011 data: Trigger



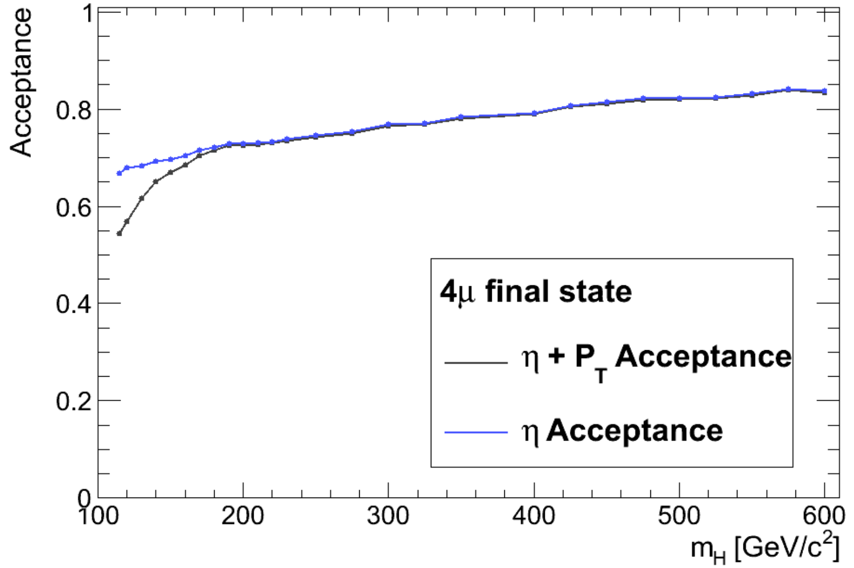
- **Tag: Tight Muon matched with the trigger object / Probe: Global Muon Isolated [RIso< 0.15]**

- 2% data/MC discrepancies at plateau

- In the H->4l analysis the inefficiency and data/MC discrepancies are suppressed since up to 4 leptons are available for the trigger. The remaining effect is covered with a systematic uncertainty

Event Selection

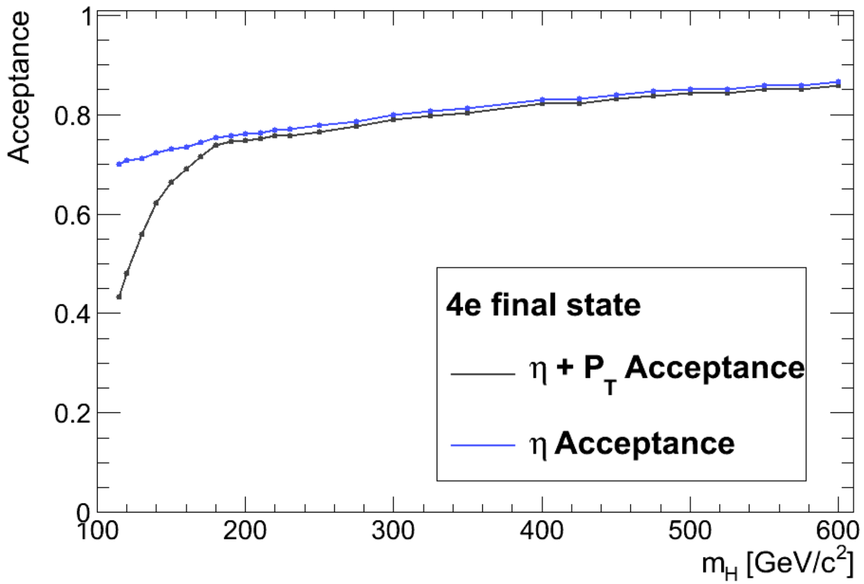
Lepton requirements

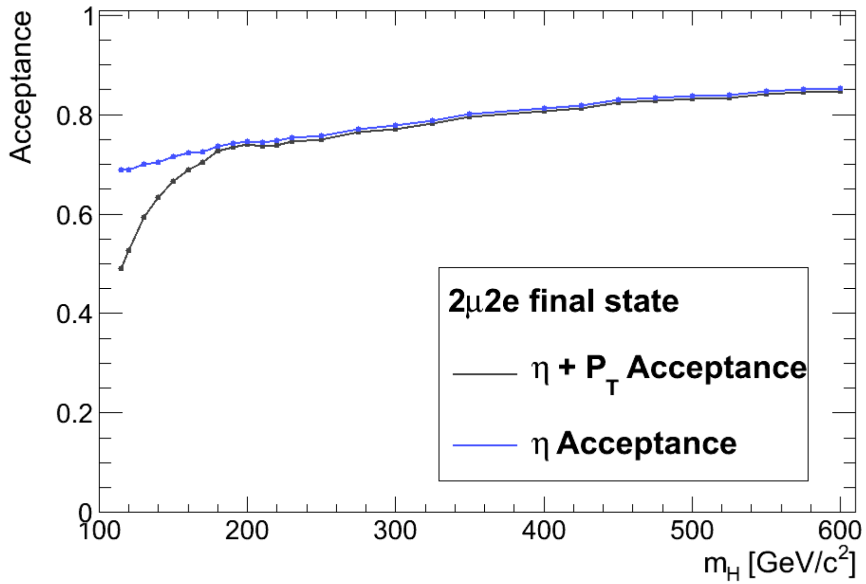


MUONS — $p_t > 5$ - $|\eta| < 2.4$ - Global Muon ID

ELECTRONS — $p_t > 7$ - $|\eta| < 2.5$ - CIC Electron ID

any leptons — Loose Iso Requirement: $R^{Tk}_{Iso} < 0.7$





Preselection

1. *Z₁, a good quality Z candidate* *[the one with mass closest to the Z nominal mass is chosen]*

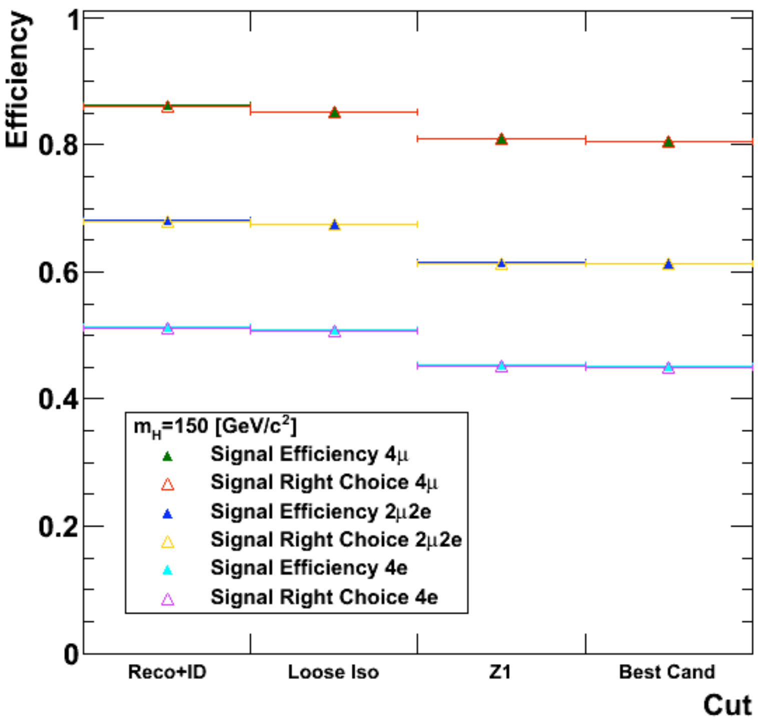
m_{Z1}>50 GeV/c^2 + $p_{T,1}$ > 20 GeV/c + $p_{T,2}$ > 10 GeV/c + ($RelIso_{,1}$ + $RelIso_{,2}$) < 0.35 + $|SIP_{3D}|_{1,2}$ < 4

2. *Z_1 + at least 1lepton*

3. *Z_1 + at least 2leptons of matching flavor and opposite sign*

4. *Best 4l candidate / Z_1, Z_2 assignments*

m_{Z2}>12 GeV/c^2 + m_{Z1Z2}>100 GeV/c^2 + 3/4 l^+l^- combinations have m_{ll} >12 GeV/c^2 (4e/4μ only)



Early choice of the Z1 and Z2

- The signal efficiency is preserved
- Early rejection of backgrounds:
  Z+ converted γ / Low mass resonances

Background reduction cuts

5. *Relative isolation for selected leptons*

for any leptons combination ($Rel_{Iso,i} + Rel_{Iso,j}$) < 0.35

6. *Impact parameter for selected leptons*

$|SIP_{3D}| < 4$

7. *Z and $Z^{(*)}$ kinematics*

$m_{Z1MIN} < m_{Z1} < 120\ GeV/c^2$ + $m_{Z2MIN} < m_{Z2} < 120\ GeV/c^2$

Against reducible backgrounds

To improve the HZZ/ZZ significance according to different H mass hypotheses

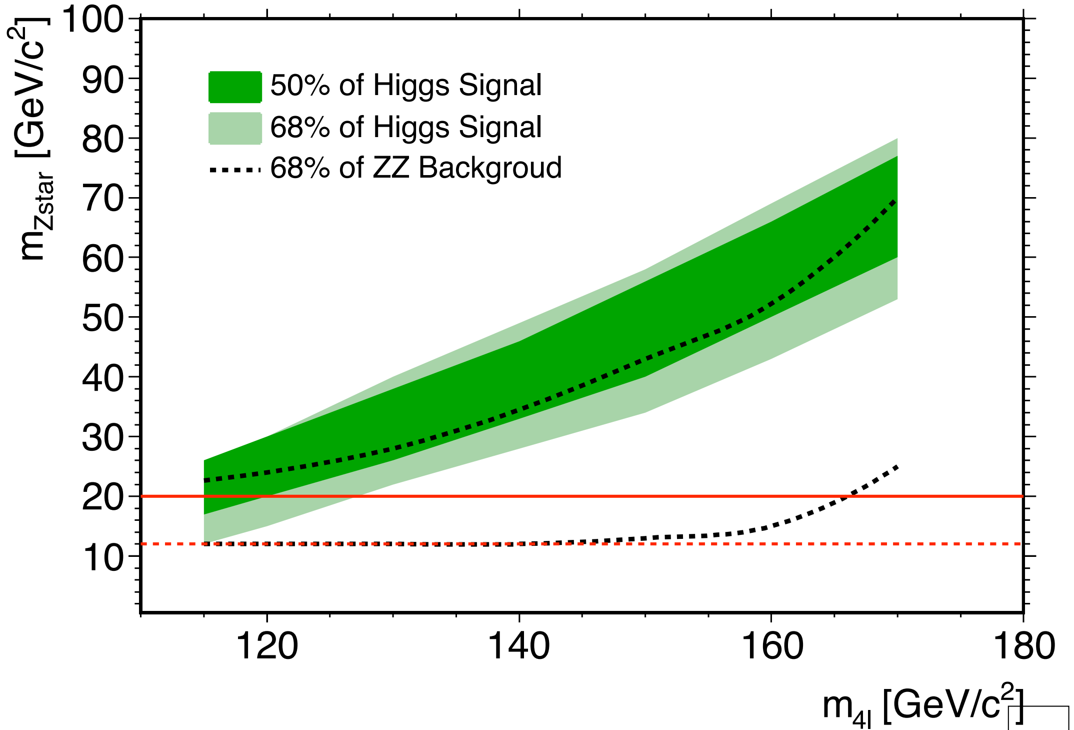
Baseline selection:

$m_{Z1MIN} = 50\ GeV/c^2$ and $m_{Z2MIN} = 120\ GeV/c^2$

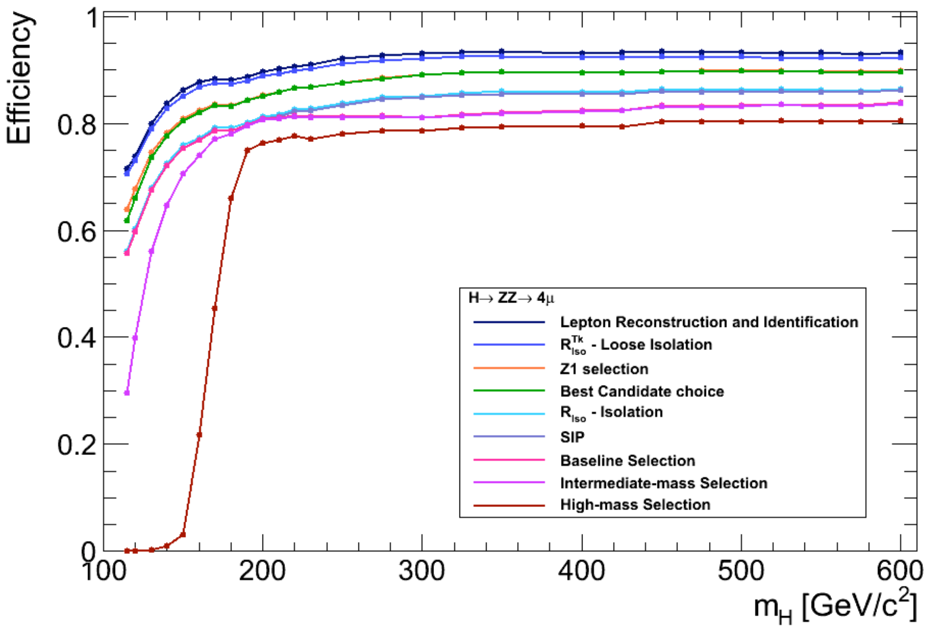
for $m_H < 180\ GeV/c^2$

High-mass (ZZ):

$m_{Z1MIN} = 60\ GeV/c^2$ and $m_{Z2MIN} = 60\ GeV/c^2$
for $m_H > 180\ GeV/c^2$



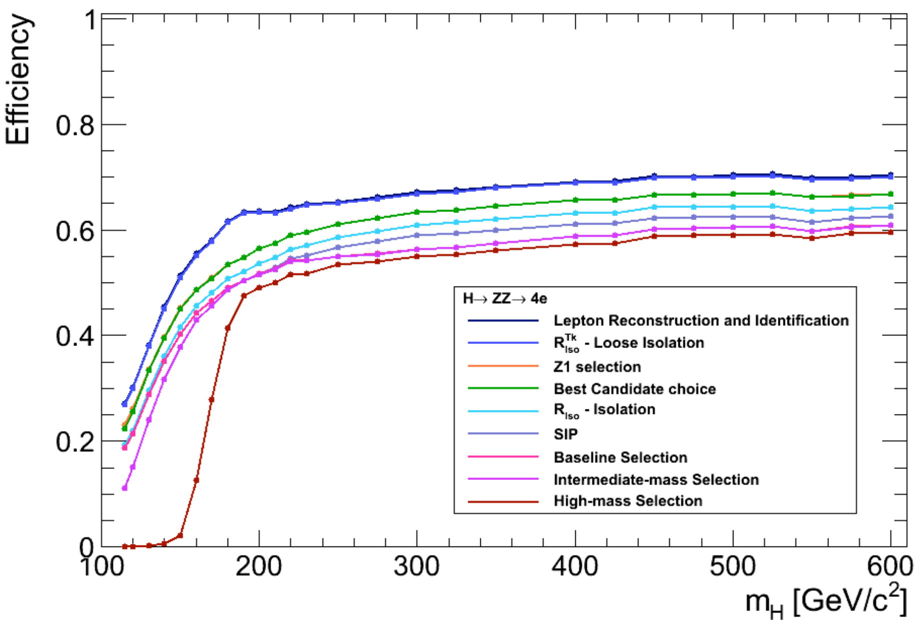
Efficiencies

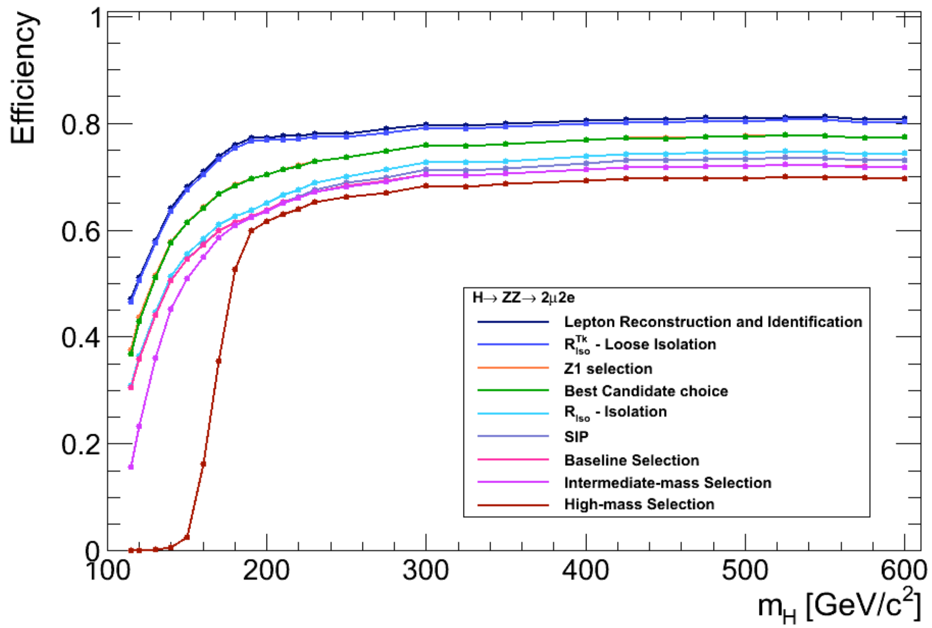


Baseline selection wrt eta acceptance:

- **4μ** 72% [m_H = 190 GeV/c^2] - 82% [m_H = 400 GeV/c^2]
- **4e** 42% [m_H = 190 GeV/c^2] - 59% [m_H = 400 GeV/c^2]
- **2μ2e** 54 % [m_H = 190 GeV/c^2] - 71% [m_H = 400 GeV/c^2]

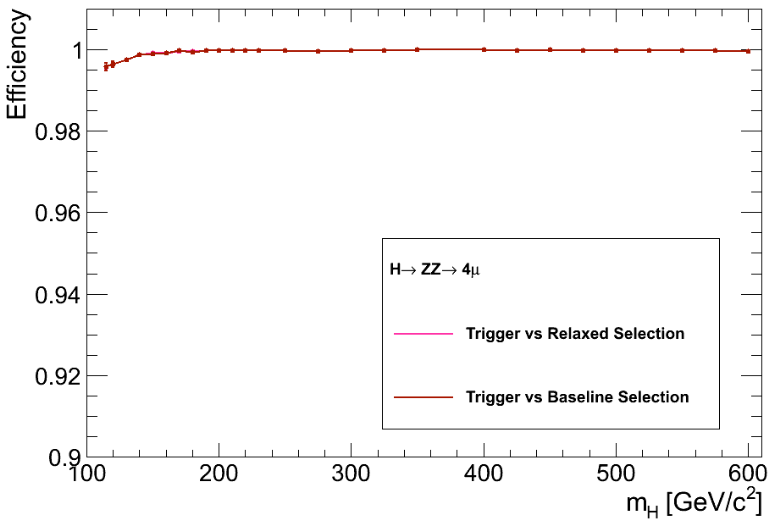
Signal "contamination":
0.5 - 2.5 % (from m_H =120 to m_H=600) from H→ZZ→2τ2μ(e)
< 0.1 % other sources

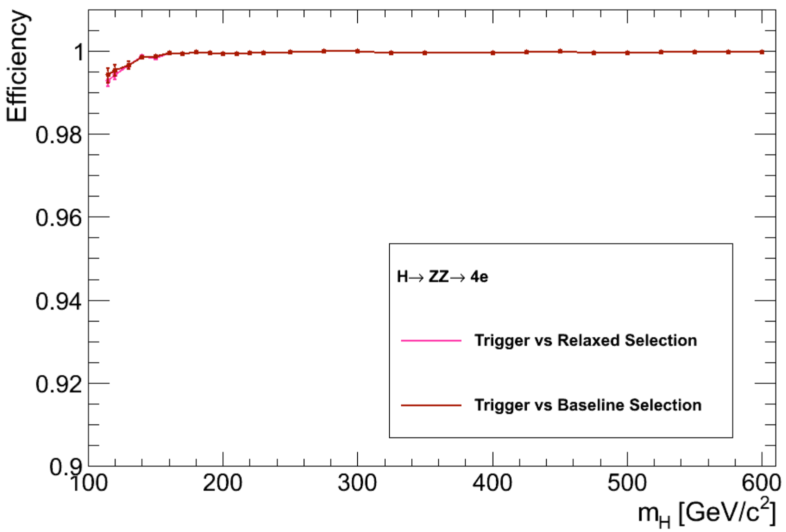




Trigger Requirements

Efficiency of trigger selection on top of the baseline selection

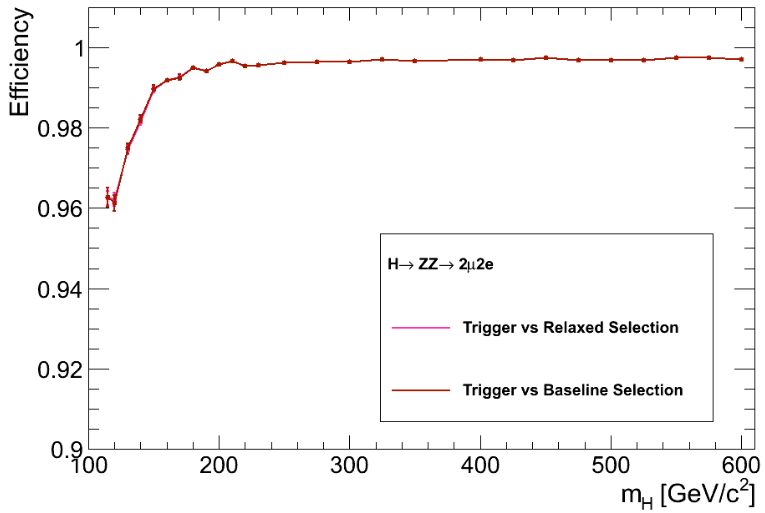




4μ Double Muon Trigger: HLT_Mu17_Mu8

$4e$ Double Electron Trigger: HLT_Ele17_Ele8_CaloIdT_CaloIsoVL_TkIdVL_TrkIsoVL

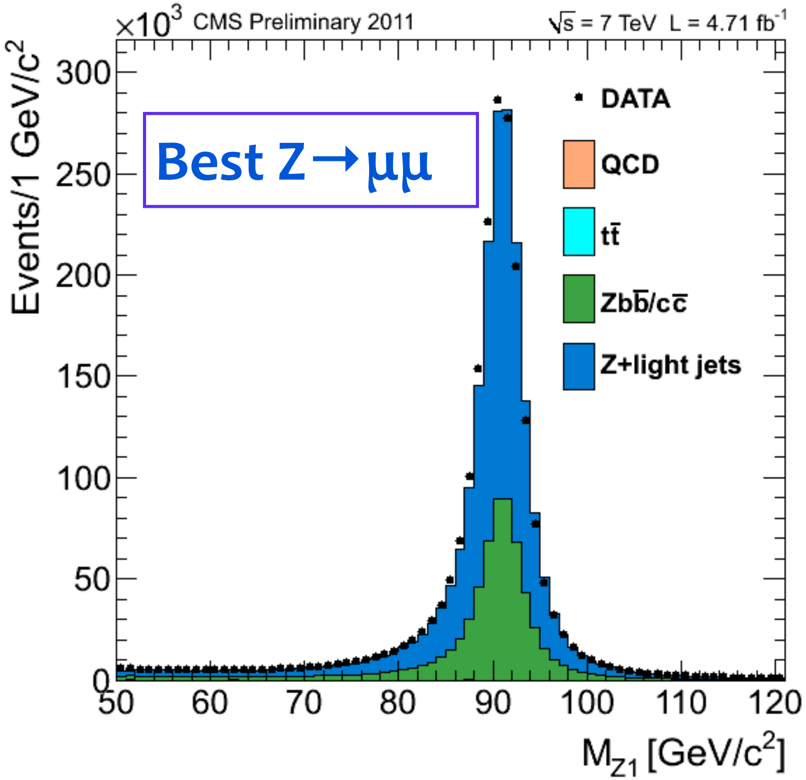
$2\mu 2e$ Or of the above triggers

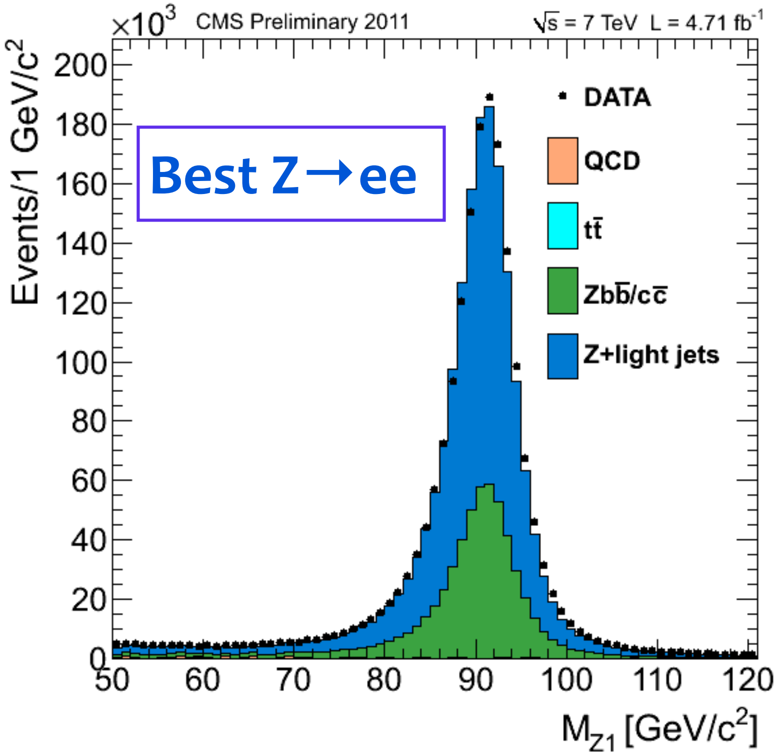


Selection Performance

1. *Z_1, a good quality Z candidate* *[the one with mass closest to the Z nominal mass is chosen]*

$m_{Z1} > 50$ GeV/c^2 + $p_{T,1} > 20$ GeV/c + $p_{T,2} > 10$ GeV/c + $(Rel_{Iso,1} + Rel_{Iso,2}) < 0.35$ + $|SIP_{3D}|_{1,2} < 4$





4.71 fb^{-1}

- At this stage of the selection the **single Z production dominates the event rate**
- Electron energy scale corrections applied on data and mc. Residual uncertainty of 0.3/0.4 % for the electron scale in the barrel/endcap is estimated
- The Z->μμ peak obtained without scale corrections. Dedicated studies estimated a scale uncertainties of 0.5%.

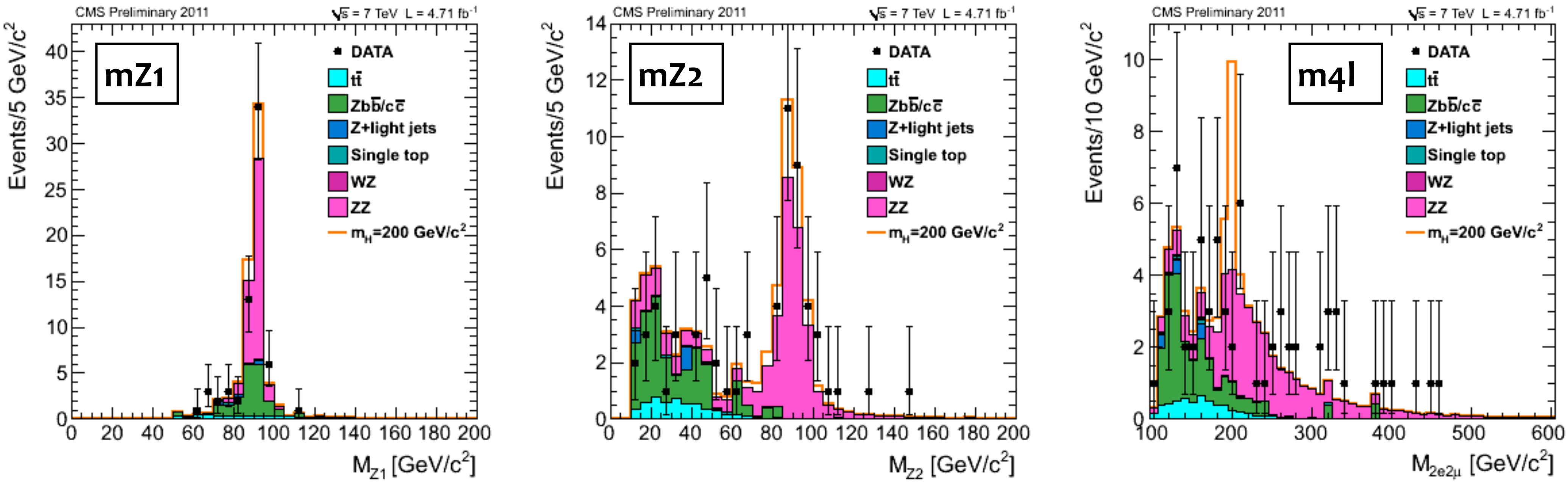
Selection Performance [2]

4. *Best 4l candidate / Z_1, Z_2 assignments*

m_{Z2}>12 GeV/c² + m_{Z1Z2}>100 GeV/c² + 3/4 l^+l^- combinations have m_{ll} >12 GeV/c² (4e/4μ only)

4.71 fb^{-1}

2μ2e

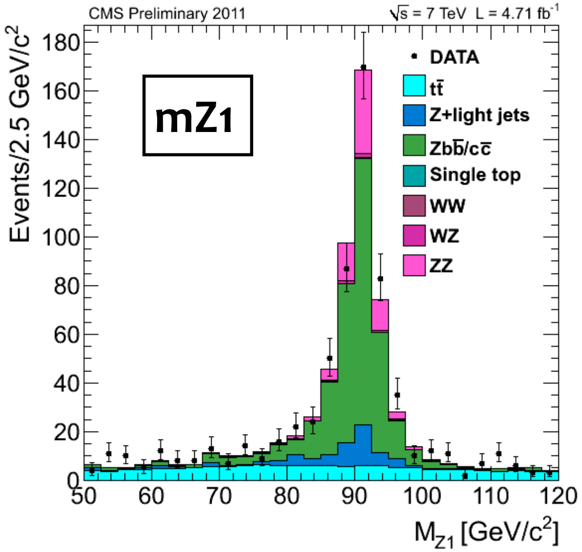


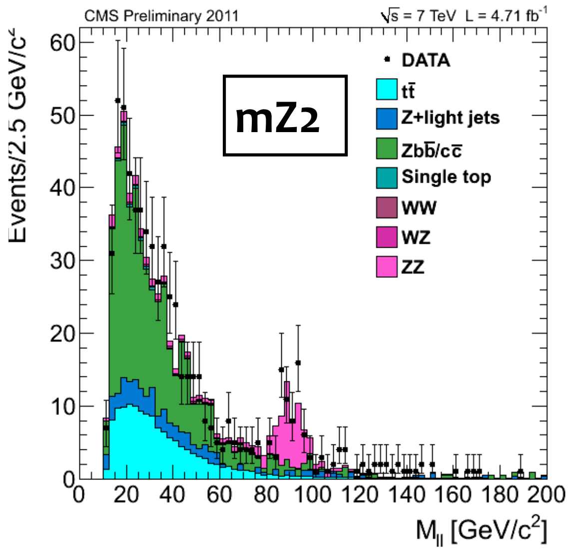
- The sample of 4l events after the preselection contains reducible background from tt and Zbb/cc and a possible contribution from the Z+lightJets instrumental background [in particular in the 4e channel]. A small contribution of WZ events with 1 fake lepton also survives.

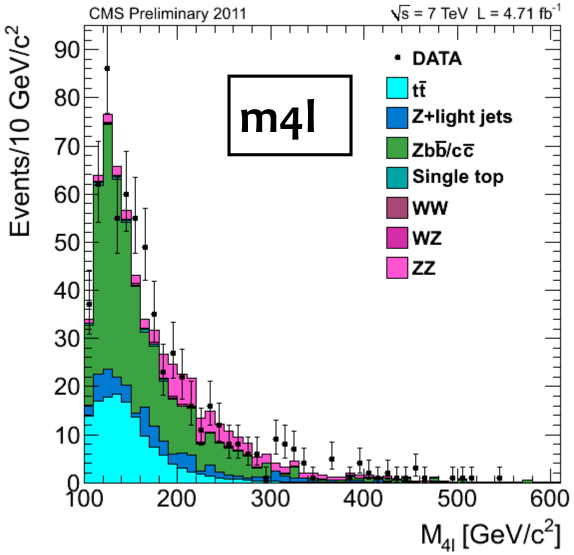
Selection Performance [3]

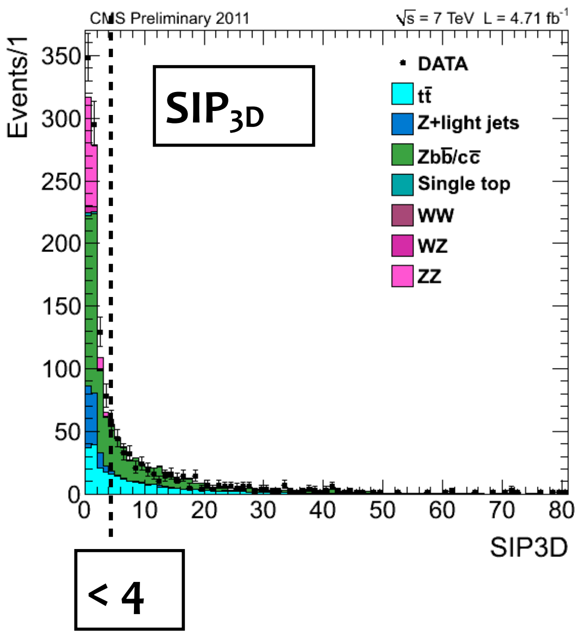
Extended phase space selection

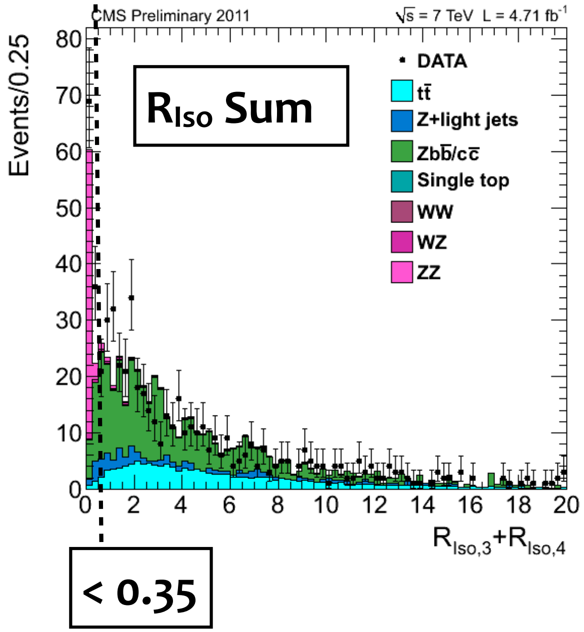
$4.71\ fb^{-1}$





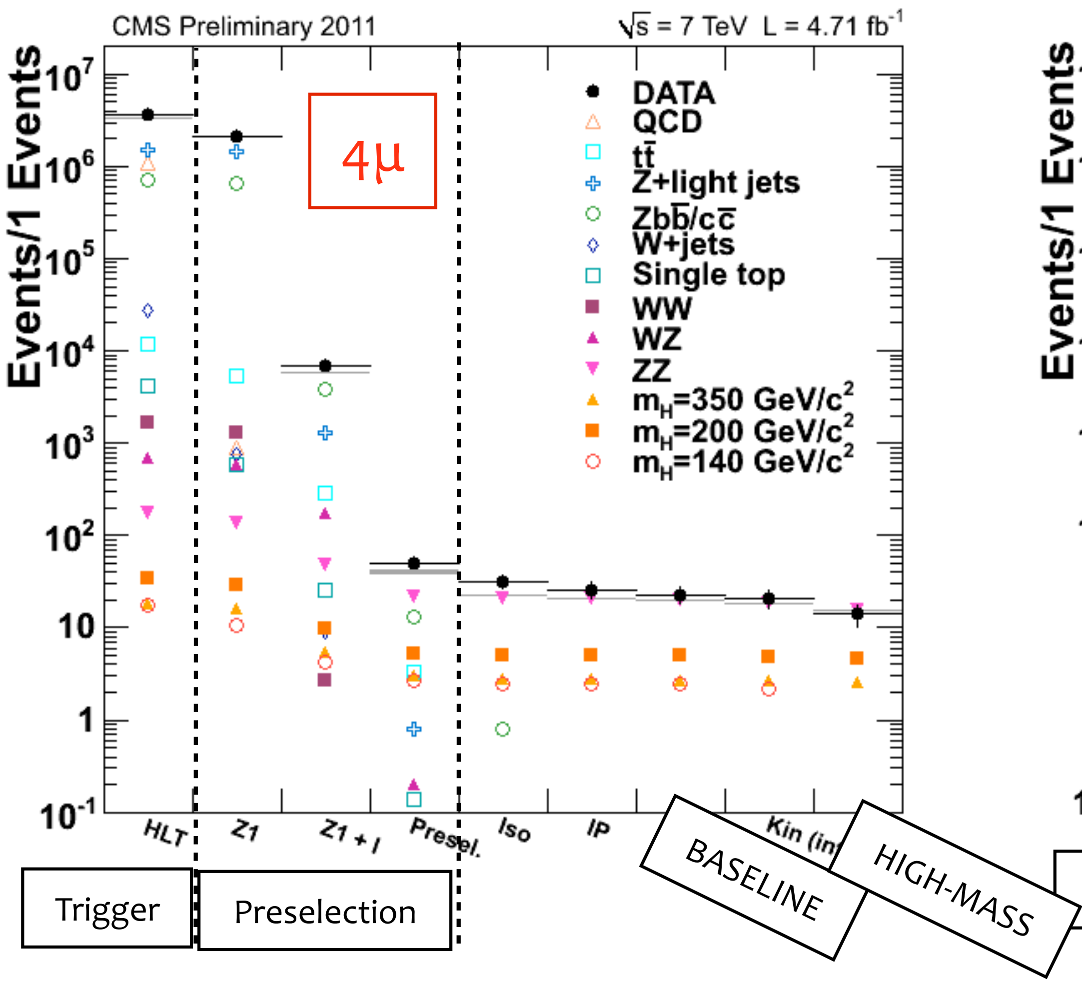


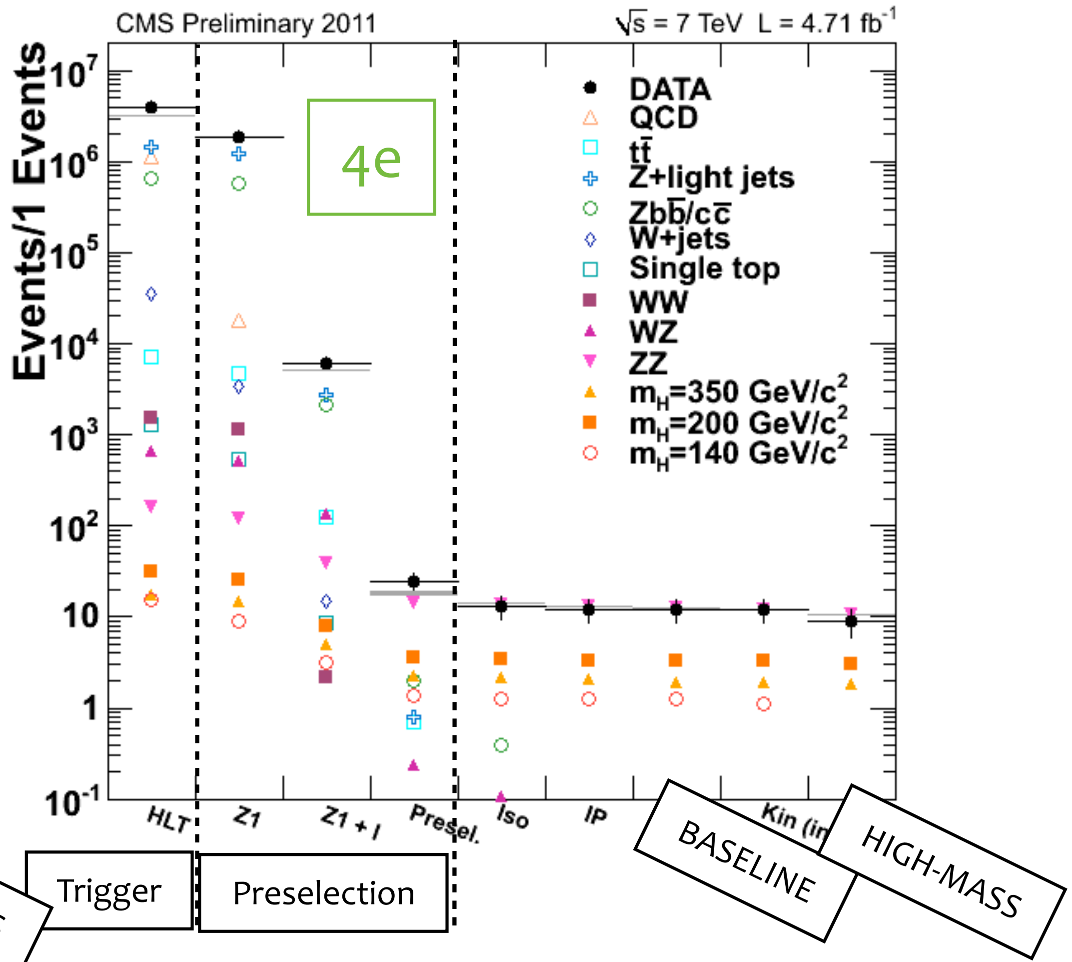




- As a handful of events survives the preselection, the control of the 4l event rate can be performed completely **relaxing the flavour and charge requirements on the additional pair of leptons**: Z1+ 2l events "extended phase space selection"
- Data driven control of background with leptons from b provide **data/mc scale factors: 1.16 +- 0.14 and 1.06 +- 0.22 for Zbb/cc and tt backgrounds**

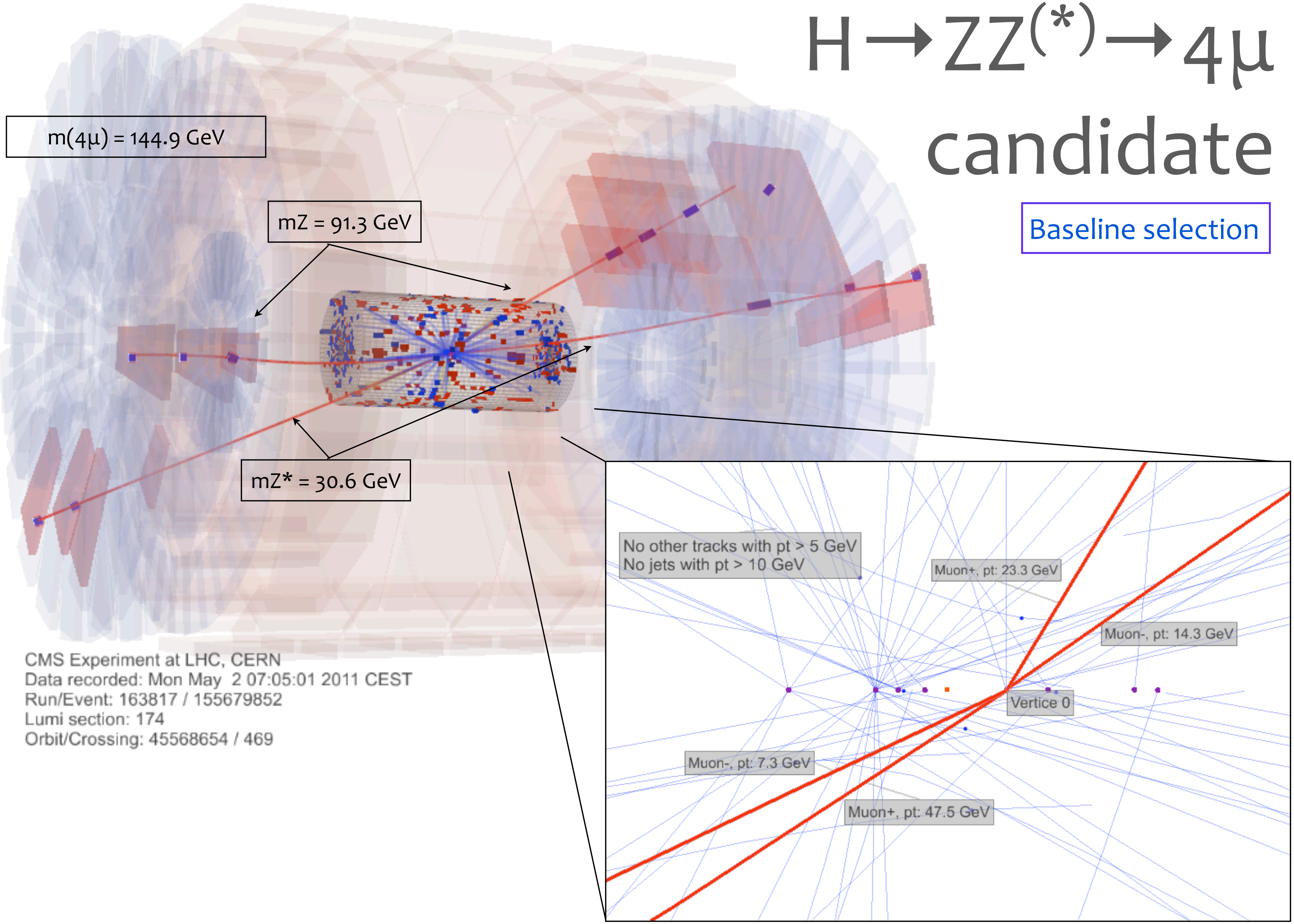
Selection Performance [4]





$H \rightarrow ZZ^{(*)} \rightarrow 4\mu$ candidate

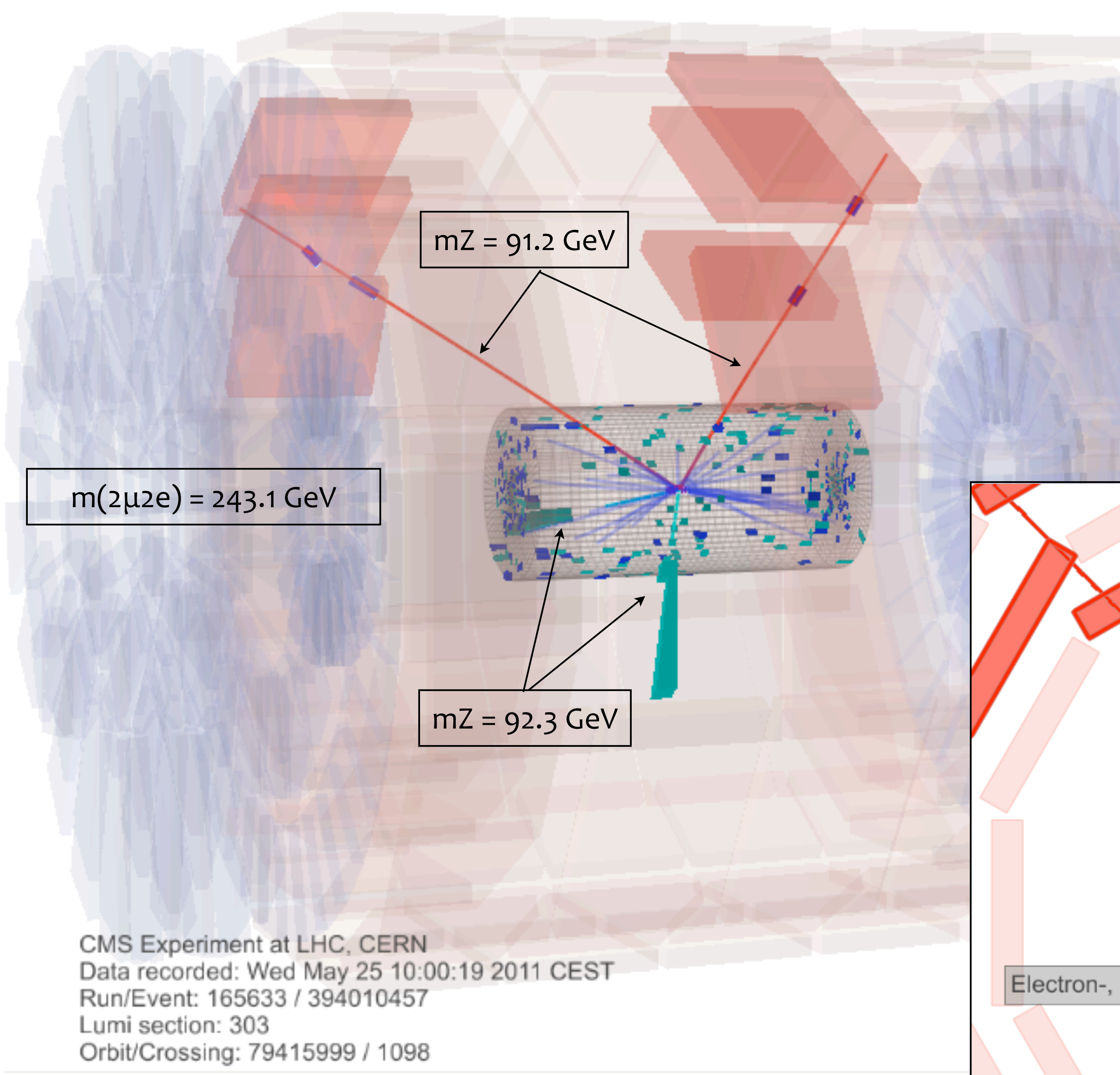
Baseline selection

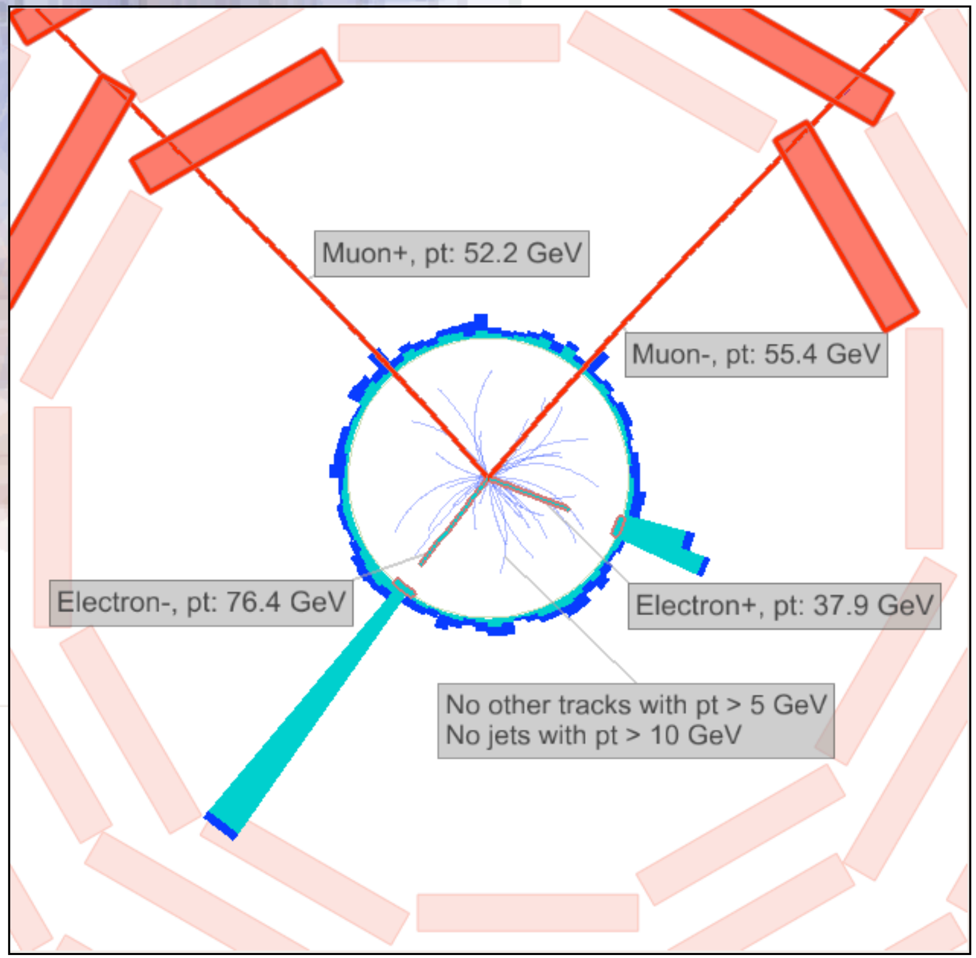


CMS Experiment at LHC, CERN
Data recorded: Mon May 2 07:05:01 2011 CEST
Run/Event: 163817 / 155679852
Lumi section: 174
Orbit/Crossing: 45568654 / 469

H → ZZ → 2μ2e candidate

Baseline and High Mass selection





Reducible Background estimation from data

Strategy

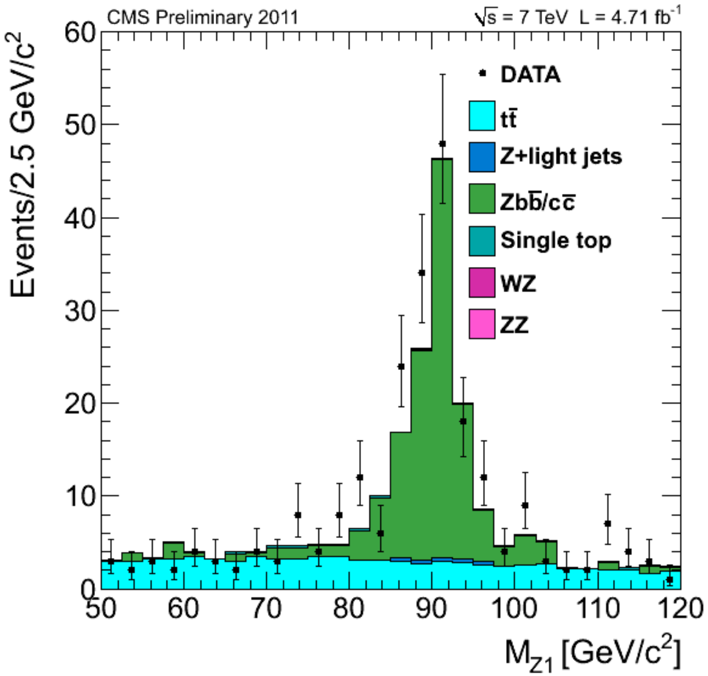
- At the end of the selection, according to the MC, the ZZ background dominates
- Negligible tt/WZ contamination (<< 1%) remains
- It is not possible to conclude on the contamination of Zbb/cc and Z+lightJets - not enough MC events
- In general the small number of events precludes a precise measurement from side-bands
- Alternative typical procedure:

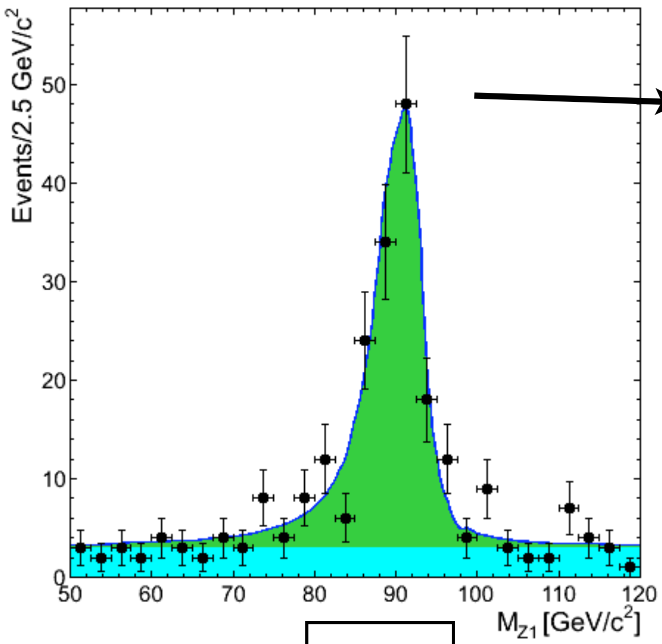
$$N^{\mathrm{B}}_{\mathrm{expect}}\left[m_1, m_2\right] = N^{\mathrm{B}}_{\mathrm{control}} \times \left(\frac{A^{\mathrm{B}}_{\mathrm{signal}}}{A^{\mathrm{B}}_{\mathrm{control}}}\right) \times \int_{m_1}^{m_2} \rho^{\mathrm{B}}(m)\,dm$$

- $N^{\mathrm{B}}_{\mathrm{control}}$: Event in the control region
- $A^{\mathrm{B}}_{\mathrm{signal}}/A^{\mathrm{B}}_{\mathrm{control}}$: Acceptance factors to extrapolate from the Control to the Signal region
- $\int_{m_1}^{m_2} \rho^{\mathrm{B}}(m)\,dm$: Event density model (shape) for the background in the signal region

Zbb/TT Control

Control Region: Z1 + ll [only ID min Pt] with $SIP_{3D}(l) > 5$





Zbb data/ Zbb MC = 1.16+- 0.14
TT data/ TT MC = 1.06 +- 0.22

DATA

MC

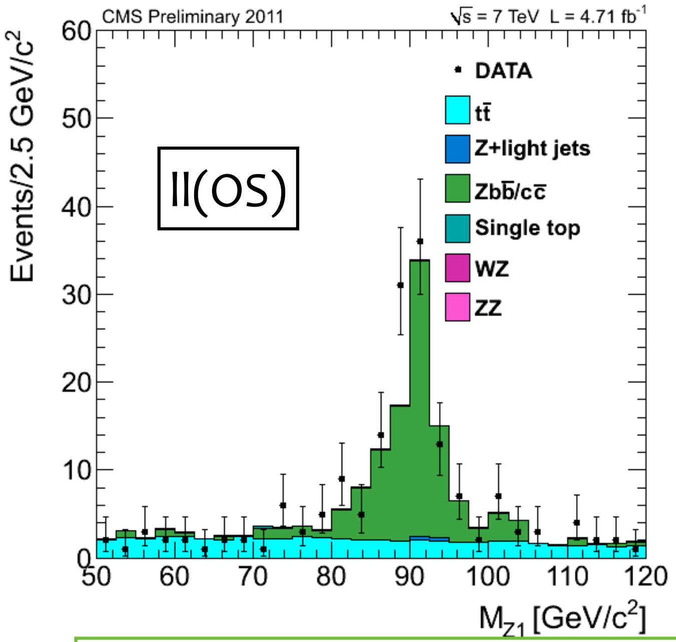
- SIP>5/SIP<4
- Riso<0.35
- 12/60 < mZ2 < 120

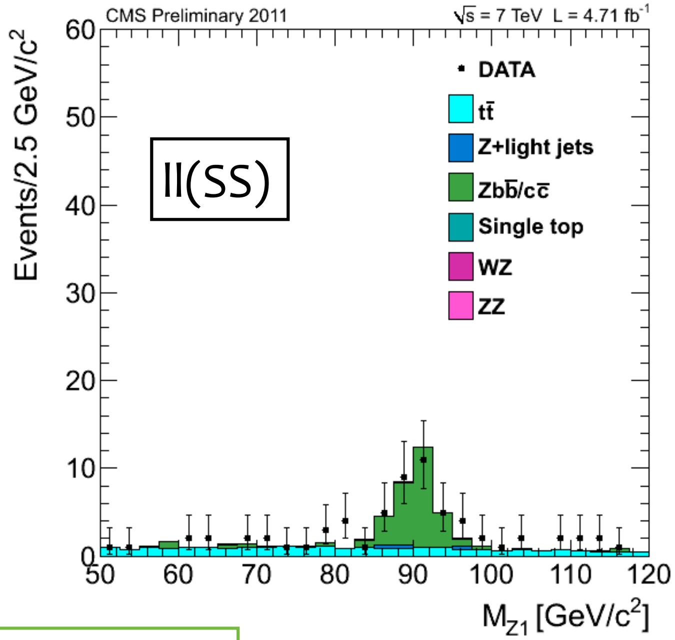
$$N_{expect}^{Zb\bar{b}/c\bar{c}\longrightarrow 4\mu} = N_{control-fit}^{Zb\bar{b}/c\bar{c}\longrightarrow 4\ell} \times \alpha_{4\mu} \times \alpha_{kin1} \times \alpha_{SIP_{3D}} \times \alpha_{R_{Iso}} \times \alpha_{kin2}$$

Extracted from:
Z1+ll(OS)/Z1+ll(SS)
Z1+ll(μμ)/Z1+ll

Extracted from:
(Z1+ll with 3/4 ll combination > 12 && m4l > 100)/(Z1+ll)

Zbb/TT Control [2]

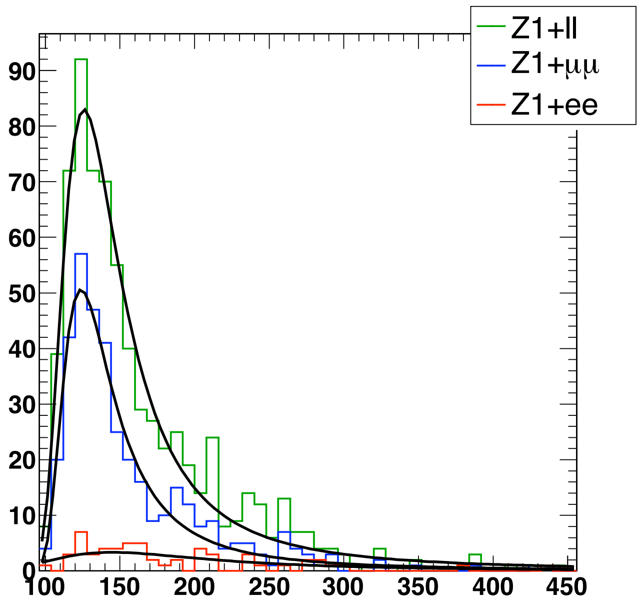




OS/SS = 2.5

ll(mm) = 71%
ll(em) = 25%
ll(ee) = 4%

Results: Shape & Normalization



Background shapes in the signal region: not enough MC events => extracted from the " extended phase space" selection

	baseline	high-mass
$N^{Zb\bar{b}\to 4e}$	0.04 ± 0.03	0.01 ± 0.01
$N^{Zb\bar{b}\to 4\mu}$	0.70 ± 0.30	0.08 ± 0.04
$N^{Zb\bar{b}\to 2e2\mu}$	0.70 ± 0.30	0.09 ± 0.04
$N^{t\bar{t}\to 4e}$	0.03 ± 0.01	-
$N^{t\bar{t}\to 4\mu}$	0.02 ± 0.00	-
$N^{t\bar{t}\to 2e2\mu}$	0.04 ± 0.01	-

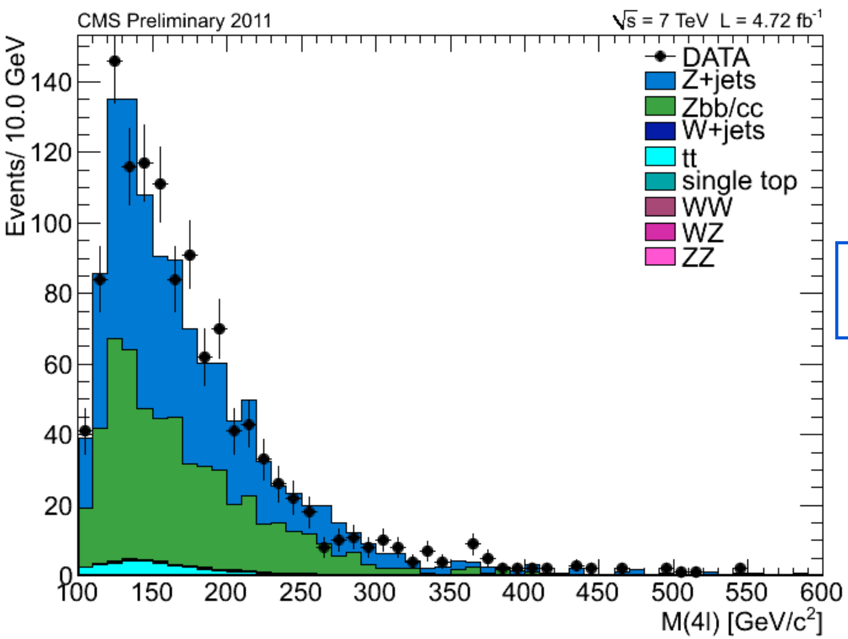
Evaluation of all instrumental and reducible background with a reconstructed Z1 and 2 "fake leptons": Z+X inclusive measurement

All leptons but those from W/Z decay [prompt and isolated]: from decay of heavy quarks/ from decay-in-flight of light hadrons / from jets faking leptons

Control Region:

Z1 + ll SS [ID and ISO relaxed] with $SIP_{3D}(l) < 4$, m4l >100, 3/4 mll > 12

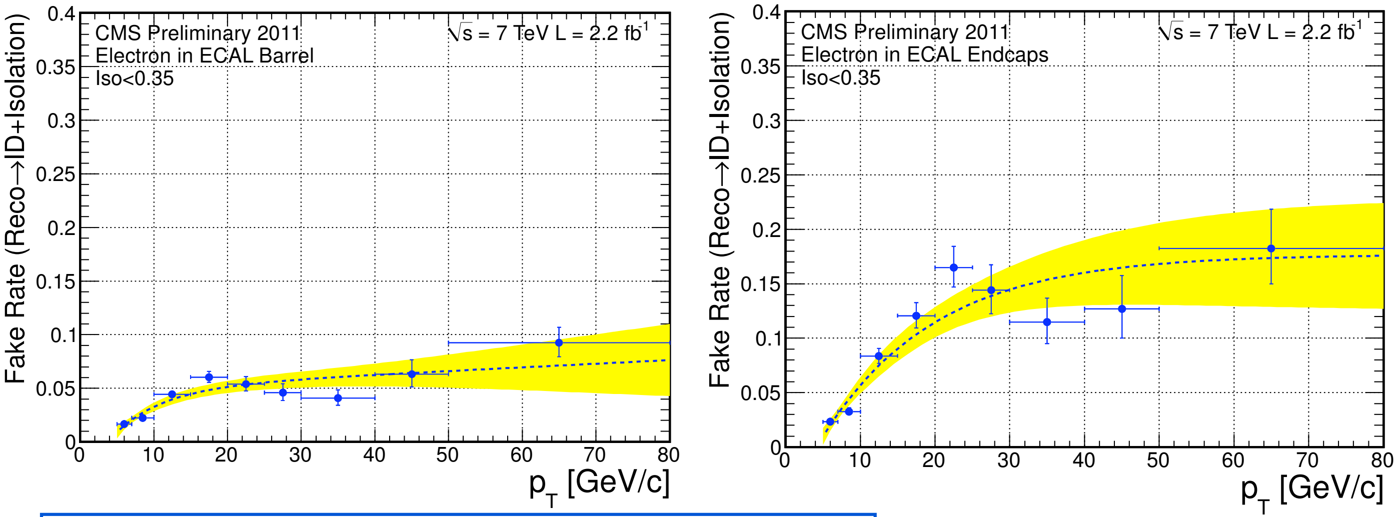
Control regions defined separately for each final state: 4μ/4e/2μ2e



Extrapolation to the signal region with the fake rate method

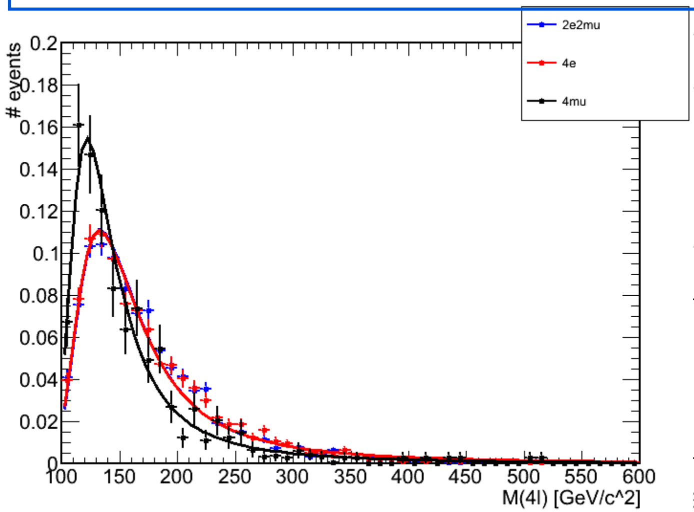
Fake rate measurement

On Z1 + 1 lepton sample (dominated by Z + “fake lepton”) the probability that a muon/electron with relaxed ID and ISO passes the analysis requests is computed



Statistical uncertainties on the number of expected Z+X events from N_{evt} in the CR.
The systematics is obtained varying by +- 1σ the parametrization of the fake rate [yellow band]

Results: Shape & Normalization



	baseline
$N^{Z+X\to 4e}$	1.67 ± 0.05 (3.2%) (stat., 952 events)± 0.50(30.2%)(syst.)
$N^{Z+X\to 4\mu}$	1.13 ± 0.09 (8.3%) (stat., 143 events)± 0.46(40.6%)(syst.)
$N^{Z+X\to 2e2\mu}$	2.71 ± 0.08 (2.9%) (stat., 1215 events)± 0.88(32.6%)(syst.)
	high-mass
$N^{Z+X\to 4e}$	0.47 ± 0.04 (8.4%) (stat., 143 events)± 0.11(22%)(syst.)
$N^{Z+X\to 4\mu}$	0.22 ± 0.03 (20.8%)(stat., 23 events)± 0.06(35.7%)(syst.)
$N^{Z+X\to 2e2\mu}$	0.65 ± 0.05 (7.6%) (stat., 175 events)± 0.16(23.5%)(syst.)

Signal and ZZ background expectations

ZZ background

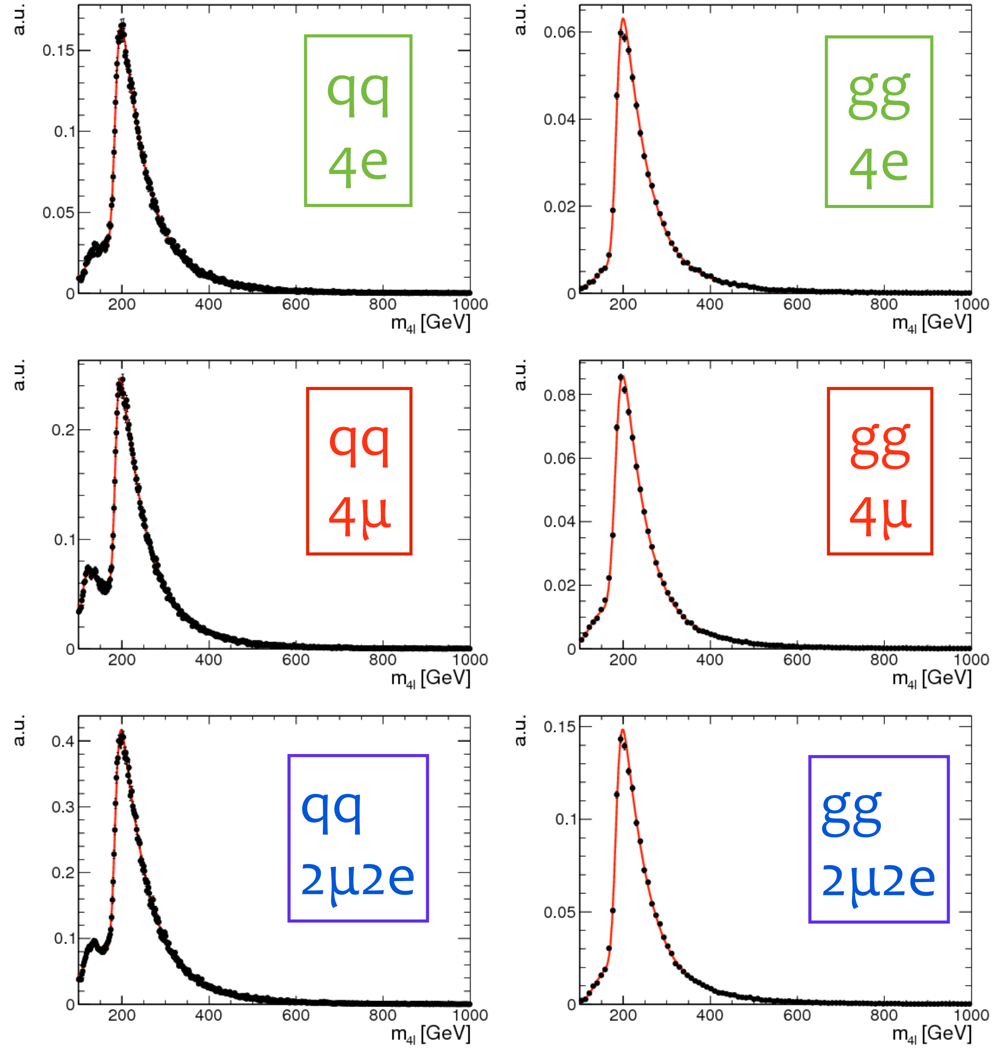
The normalization and shape of the ZZ irreducible background are taken directly from MC.
A fit with an empirical function is performed.

Normalization

baseline	$q\bar{q}$	$N^{ZZ\to4\mu}$	18.0 ± 1.5
		$N^{ZZ\to4e}$	11.5 ± 1.0
		$N^{ZZ\to2\mu2e}$	28.4 ± 2.4
	gg	$N^{ZZ\to4\mu}$	$1.\ 11 \pm 0.34$
		$N^{ZZ\to4e}$	0.77 ± 0.24
		$N^{ZZ\to2\mu2e}$	1.85 ± 0.56
high-mass	$q\bar{q}$	$N^{ZZ\to4\mu}$	13.8 ± 1.2
		$N^{ZZ\to4e}$	9.6 ± 0.8
		$N^{ZZ\to2\mu2e}$	23.2 ± 1.9
	gg	$N^{ZZ\to4\mu}$	0.96 ± 0.29
		$N^{ZZ\to4e}$	0.71 ± 0.22
		$N^{ZZ\to2\mu2e}$	1.68 ± 0.51

MC expectation corrected with data/mc lepton RECO+ID efficiency factors

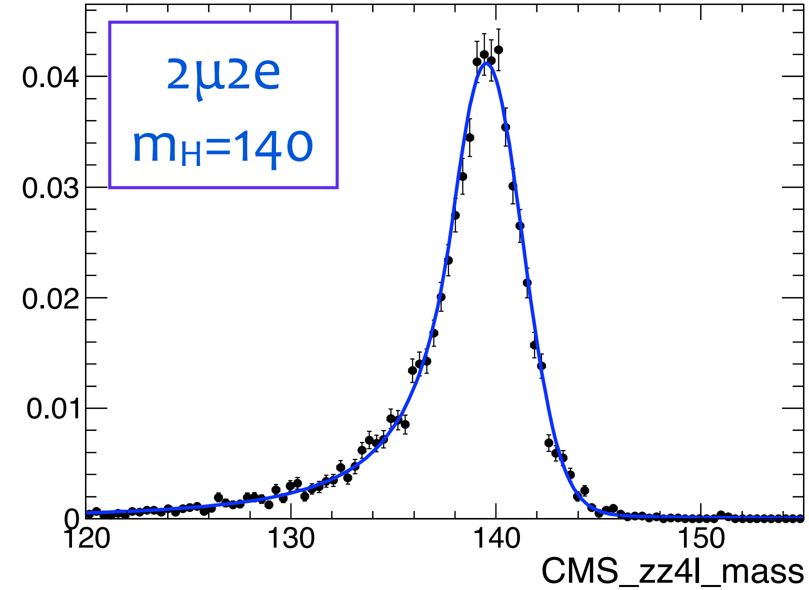
Shapes

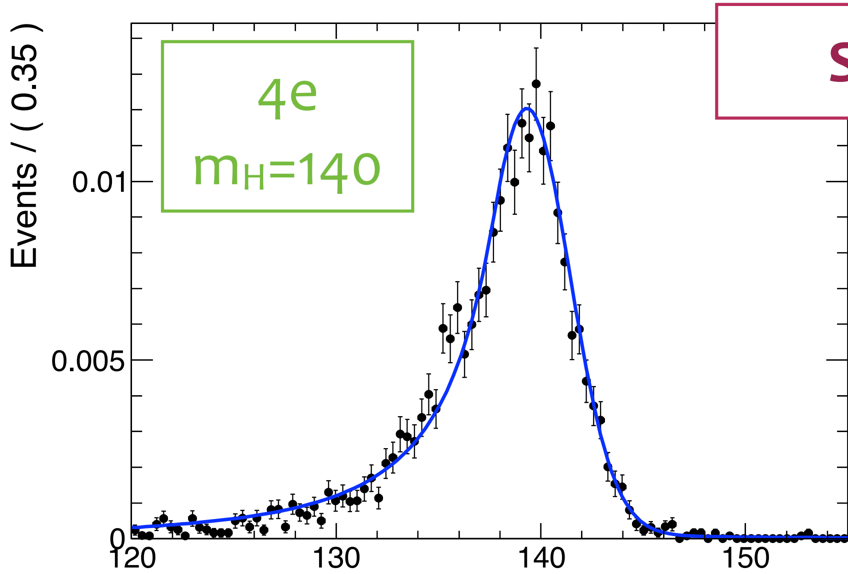


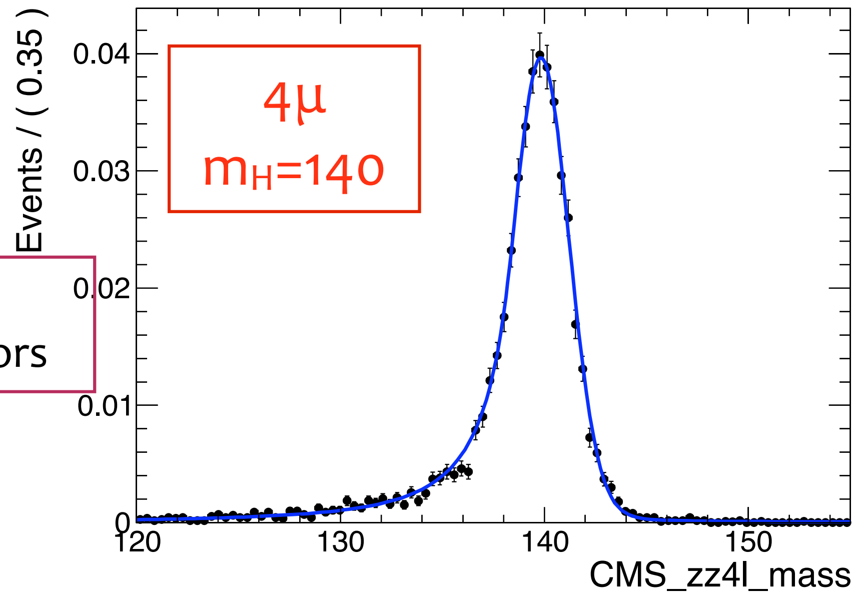
Signal

The signal shape is determined using 17 simulated samples covering the full mass range.
The shape for each simulated sample are fit using a convolution of a Breit-Wigner-like probability density function to describe the theoretical resonance line shape, convoluted with a Crystal-Ball.

Shapes







Normalization

MC expectation corrected with data/mc lepton RECO+ID efficiency factors

Systematics

Theoretical Uncertainties

Source of uncertainties	uncertainties for different processes				
	ggH	VBF	WH	ZH	ttH
gg partonic luminosity	8				8-10
$qq/q\bar{q}$ partonic luminosity		2-7	3-4	3-5	
QCD scale uncert. for $gg \to H$	5-2				
QCD scale uncert. for VBF qqH		0-3			
QCD scale uncert. for VH			0-1	1-2	
QCD scale uncert. for ttH					3-1
4ℓ-acceptance for $gg \to H$	negl.	negl.	negl.	negl.	negl.
Wide Higgs uncertainties	$1+1.5(m_H/1\ \text{TeV}/c^2)$				
Uncertainty on $BR(H \to 4\ell)$	2	2	2	2	2

Signal

Source of uncertainties	uncertainties for different processes	
	$q\bar{q}\to ZZ^{(*)} \to 4\ell$	$gg\to ZZ^{(*)} \to 4\ell$
gg partonic luminosity	-	10
$qq/q\bar{q}$ partonic luminosity	5	-
QCD scale uncert.	2-6	20-45

ZZ bkg

Instrumental Uncertainties

Source of uncertainties	Uncertainties for different channels			$qqZZ/ggZZ \to 4\ell$		
	$4e$	4μ	$2\mu 2e$	$4e$	4μ	$2\mu 2e$
Luminosity	4.5	4.5	4.5	4.5	4.5	4.5
Trigger	1.5	1.5	1.5	1.5	1.5	1.5
electron reco/ID	3.8-1	-	2-0.5	1.8	-	1.1
muon reco/ID	-	2-0.8	1.2-0.4	-	1.0	0.5
electron isolation	2	-	1	2	-	1
muon isolation	-	1	1	-	1	1
electron E_T scale (error on E_T scale)	0.3-0.4	-	0.3-0.4	0.3-0.4	-	0.3-0.4
muon p_T scale (error on p_T scale)	-	0.5	0.5	-	0.5	0.5

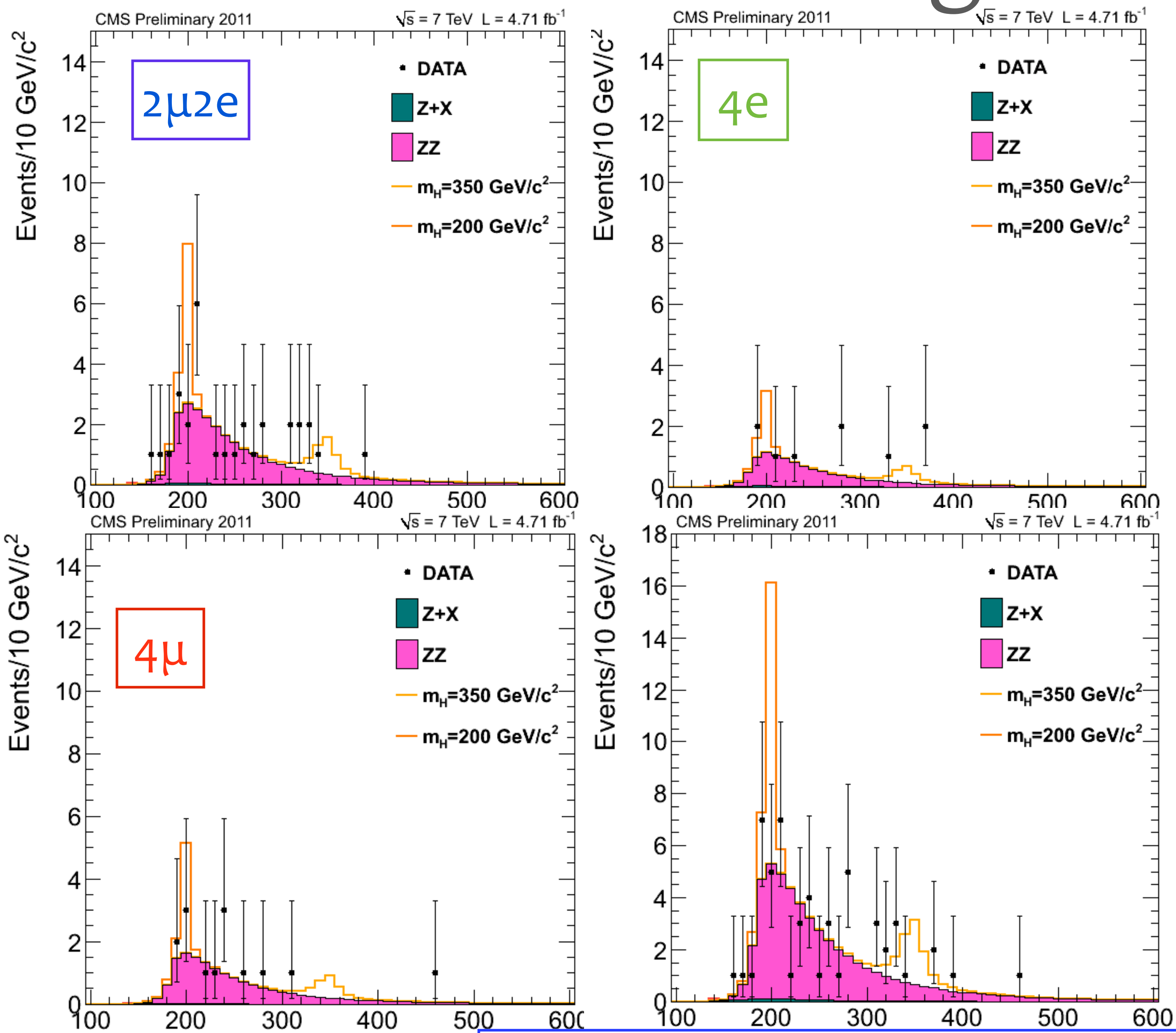
Signal

ZZ bkg

Results

High Mass Selection

for m_H>180 searches



4.71 fb^{-1}

60< mZ1 < 120 GeV/c²
60< mZ2 < 120 GeV/c²

m_{4l} > 100 GeV/c²
Observed events: 52
Expected events: 51.3 ± 4.6

$$\sigma(pp \rightarrow ZZ + X) \times \mathcal{B}(ZZ \rightarrow 4\ell) = 28.1^{+4.5}_{-3.9}(\text{stat.}) \pm 1.0(\text{syst.}) \pm 1.3(\text{lumi.})\ \text{fb}$$

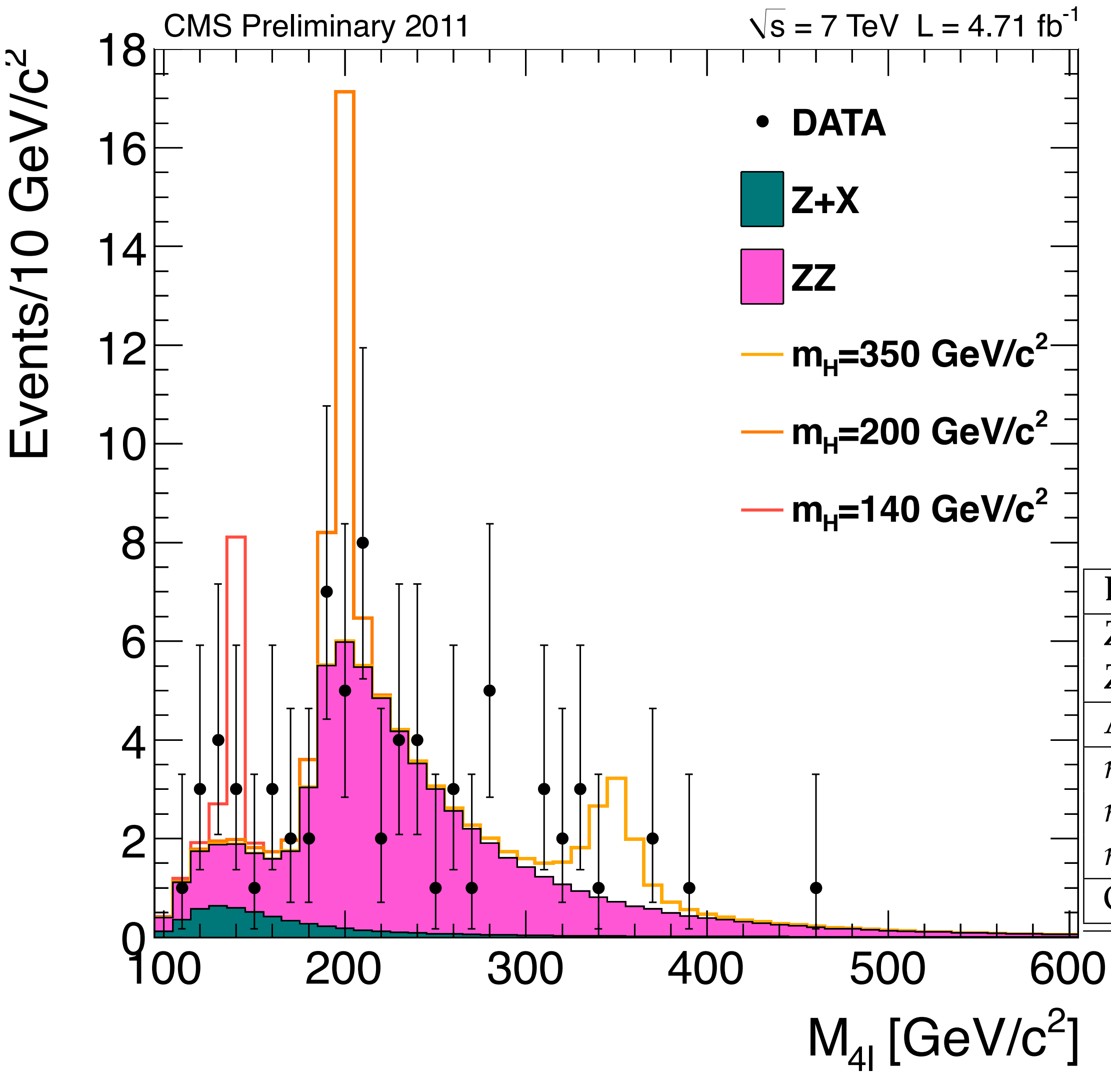
SM expectation [MCFM] = 27.9 +- 1.9

Baseline Selection

for m_H<180 searches

4.71 fb^{-1}

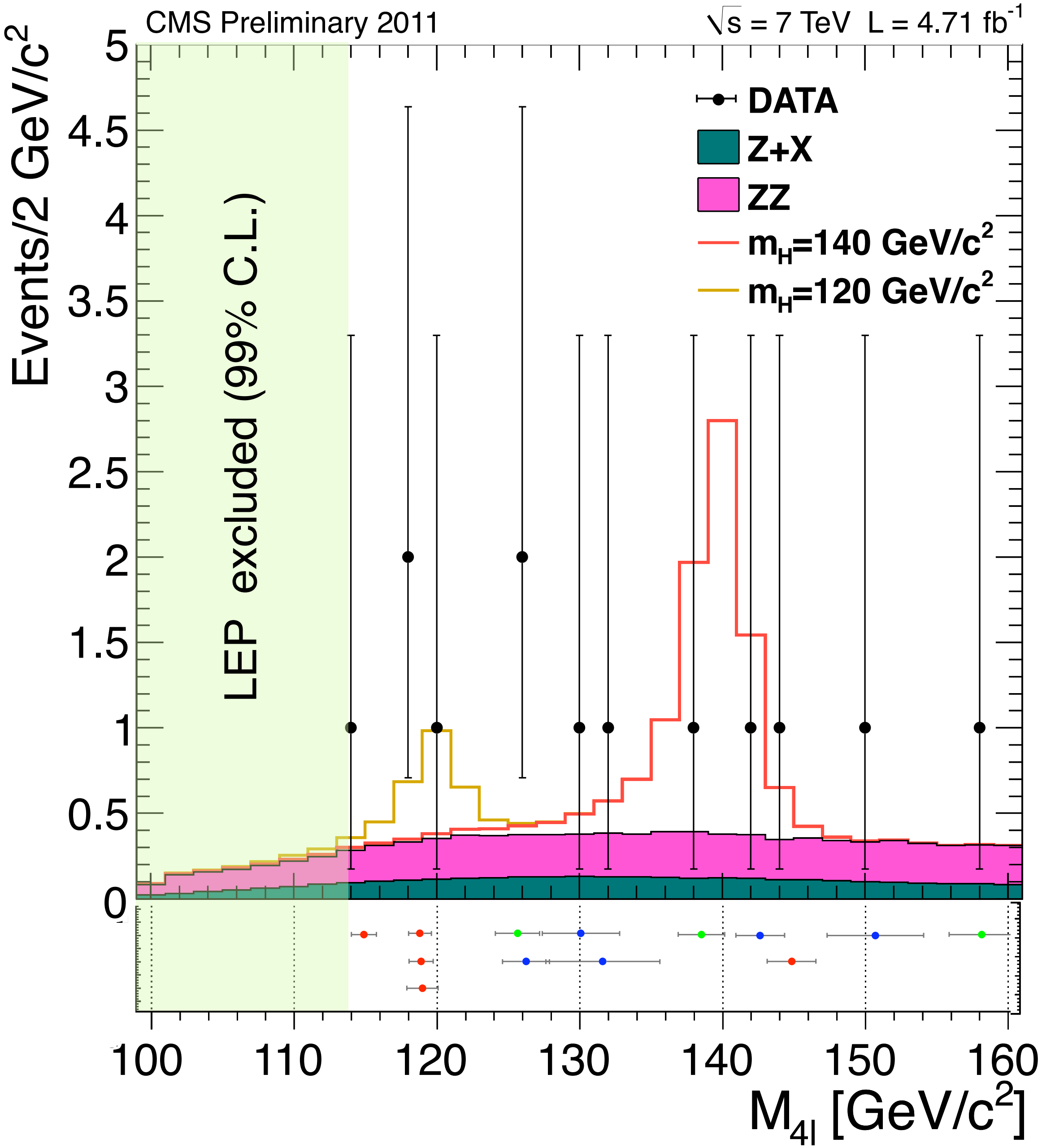
50< mZ1 < 120 GeV/c²
12< mZ2 < 120 GeV/c²



m_{4l} > 100 GeV/c²
Observed events: 72
Expected events: 67.1 ± 6.0

Baseline	$4e$	4μ	$2e2\mu$
ZZ	12.27 ± 1.16	19.11 ± 1.75	30.25 ± 2.78
Z+X	1.67 ± 0.55	1.13 ± 0.55	2.71 ± 0.96
All background	13.94 ± 1.28	20.24 ± 1.83	32.96 ± 2.94
m_H = 120 GeV/c^2	0.25	0.62	0.68
m_H = 140 GeV/c^2	1.32	2.48	3.37
m_H = 350 GeV/c^2	1.95	2.61	4.64
Observed	12	23	37

Low mass region



4.71 fb^{-1}

$50 < mZ1 < 120$ GeV/c^2

$12 < mZ2 < 120$ GeV/c^2

$100 < m_{4l} < 160$ GeV/c^2

Observed events: 13

Expected events: 9.5 ± 1.3

Final state:	4e	4μ	2e2μ
Obs. events:	3	5	5
Exp. events:	1.7	3.3	4.5

Central values

Event-by-event mass uncertainties

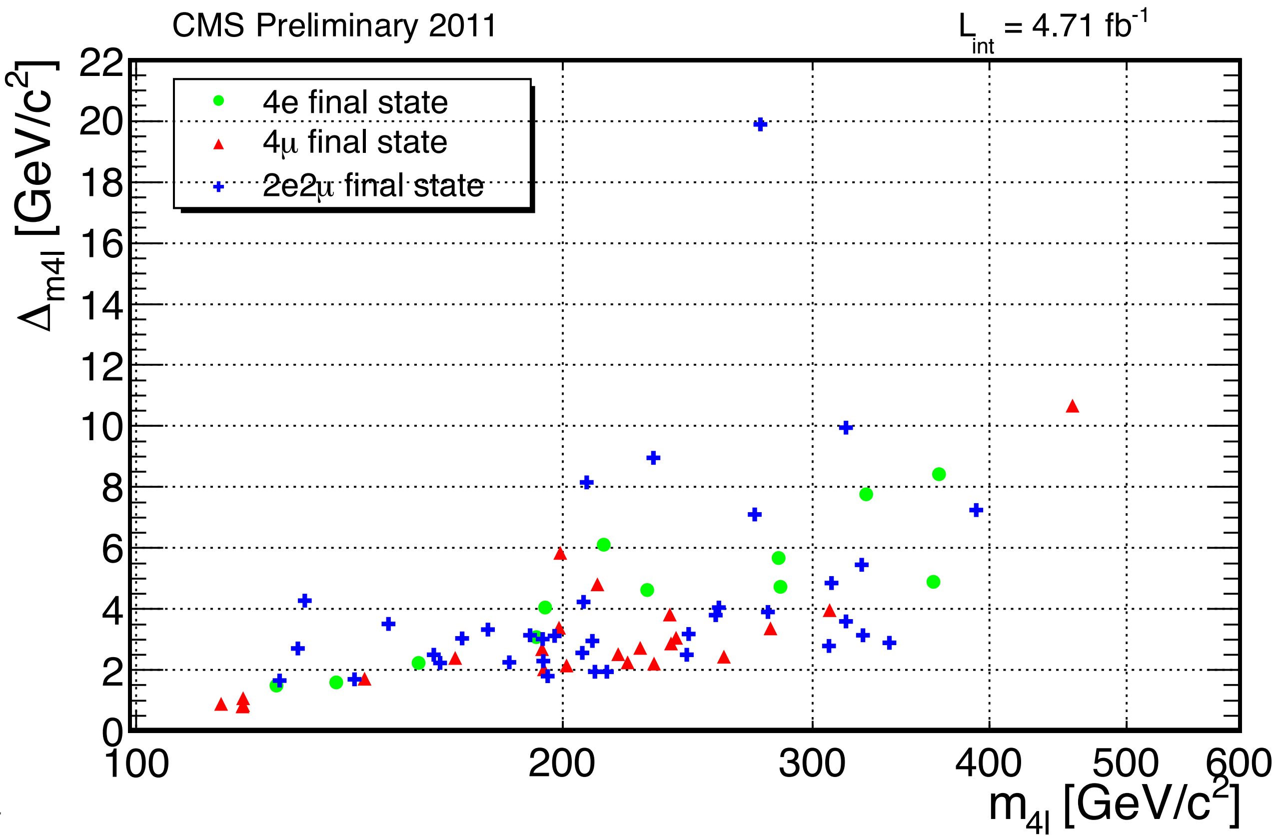
4e / 4μ / 2e2μ

Mass Uncertainties

- The precision on the estimation of the of the m_H can vary significantly on an event-by-event basis [lepton p_T, η]

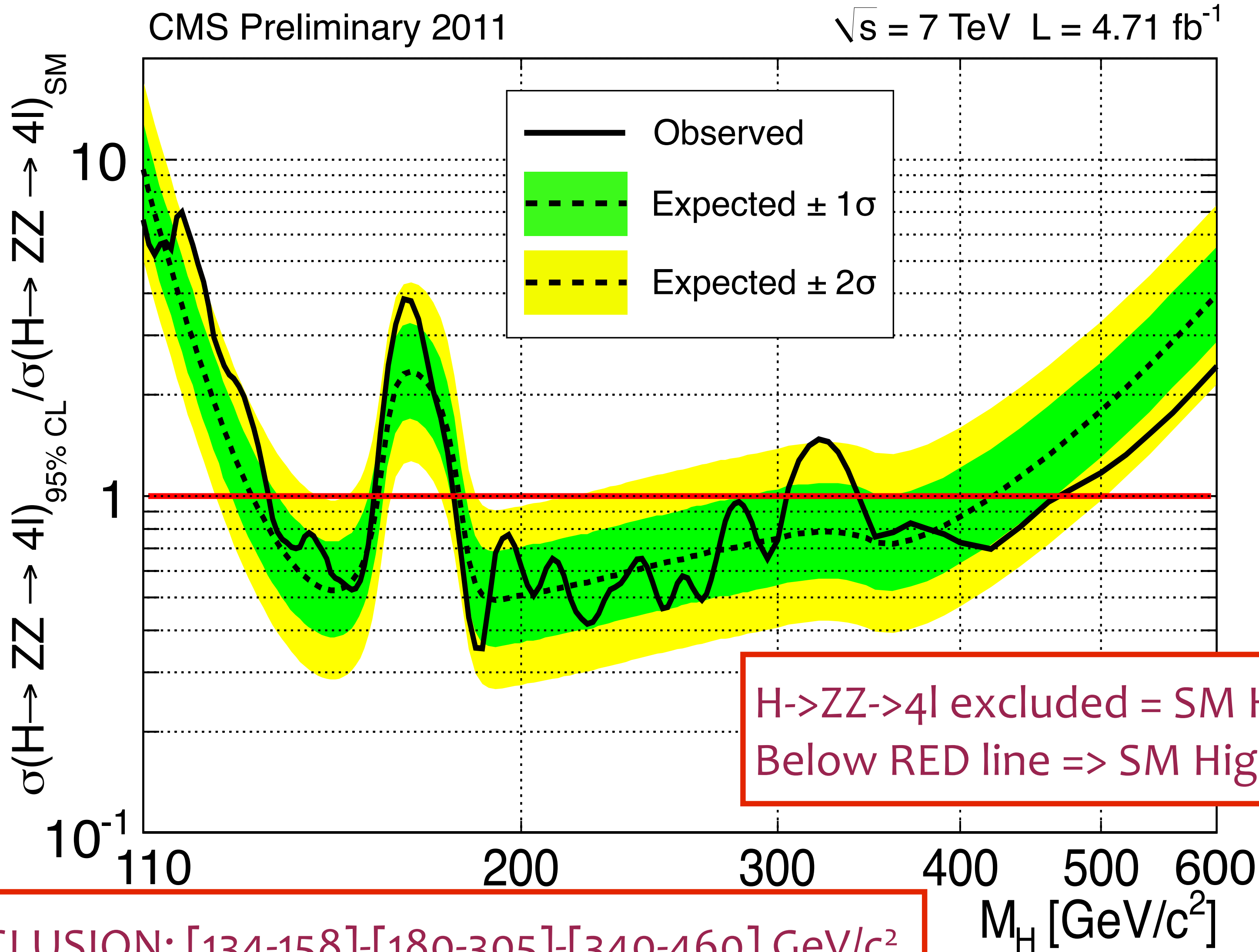
- To take into account this information the uncertainties evaluated on individual lepton legs can be propagated to m_H

- It can allow to improve on the significance on a possible discovery depending on the clustering in mass of a handful of events.



Upper limit

- **INPUTS:** Signal normalization and shape, Bkg normalizations and shapes, systematic uncertainties both on normalizations and shapes.
- Upper limits on the Higgs cross section are computed with the **CL_s method** with the prescriptions of the **LHC Higgs Combination Group**

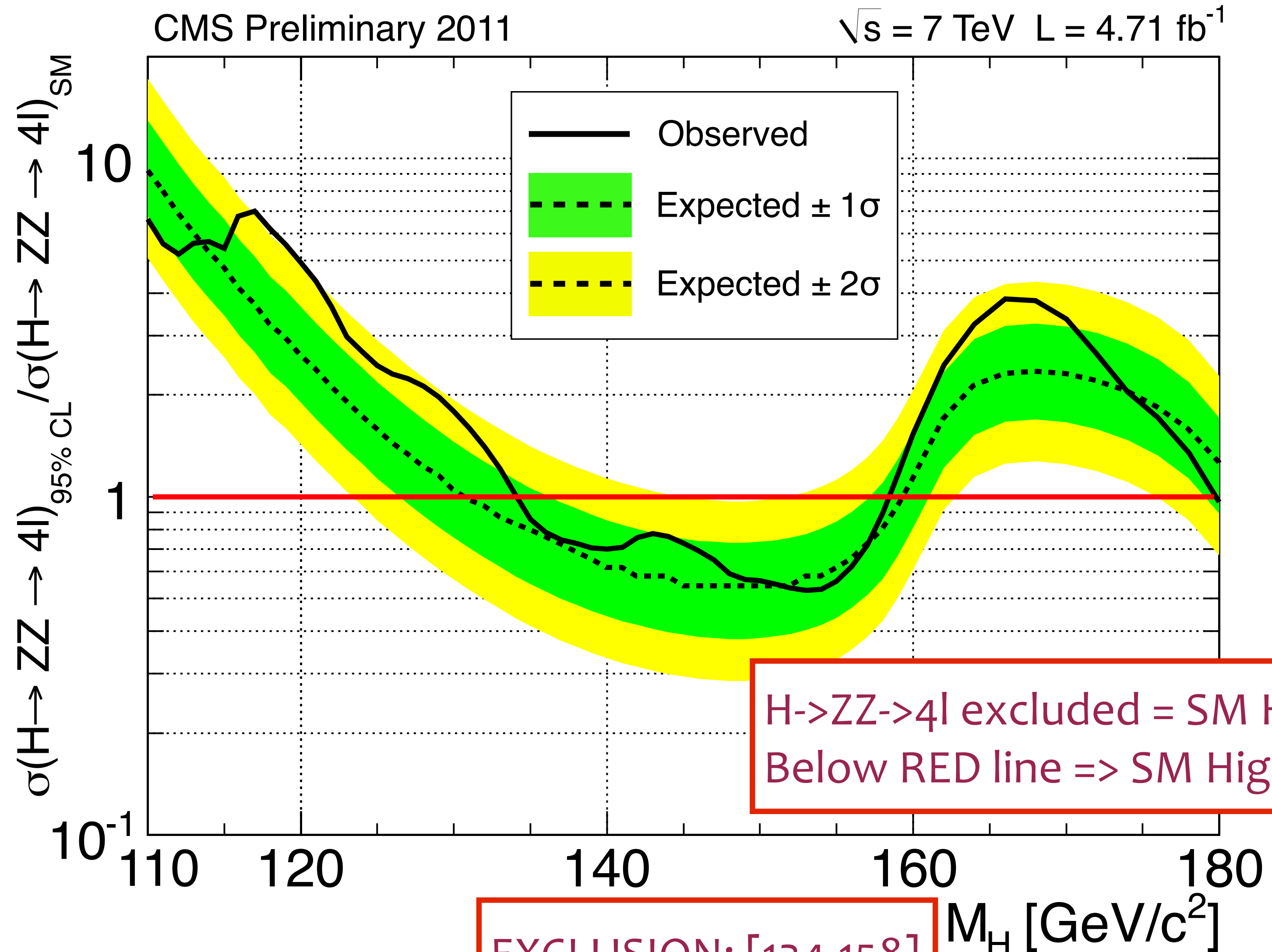


H->ZZ->4l excluded = SM H->ZZ->4l cross section
Below RED line => SM Higgs excluded @ 95 % C.L.

EXCLUSION: [134-158]-[180-305]-[340-460] GeV/c²

Upper limit

- **INPUTS:** Signal normalization and shape, Bkg normalizations and shapes, systematic uncertainties both on normalizations and shapes.
- Upper limits on the Higgs cross section are computed with the **CL_s method** with the prescriptions of the **LHC Higgs Combination Group**



H->ZZ->4l excluded = SM H->ZZ->4l cross section
Below RED line => SM Higgs excluded @ 95 % C.L.

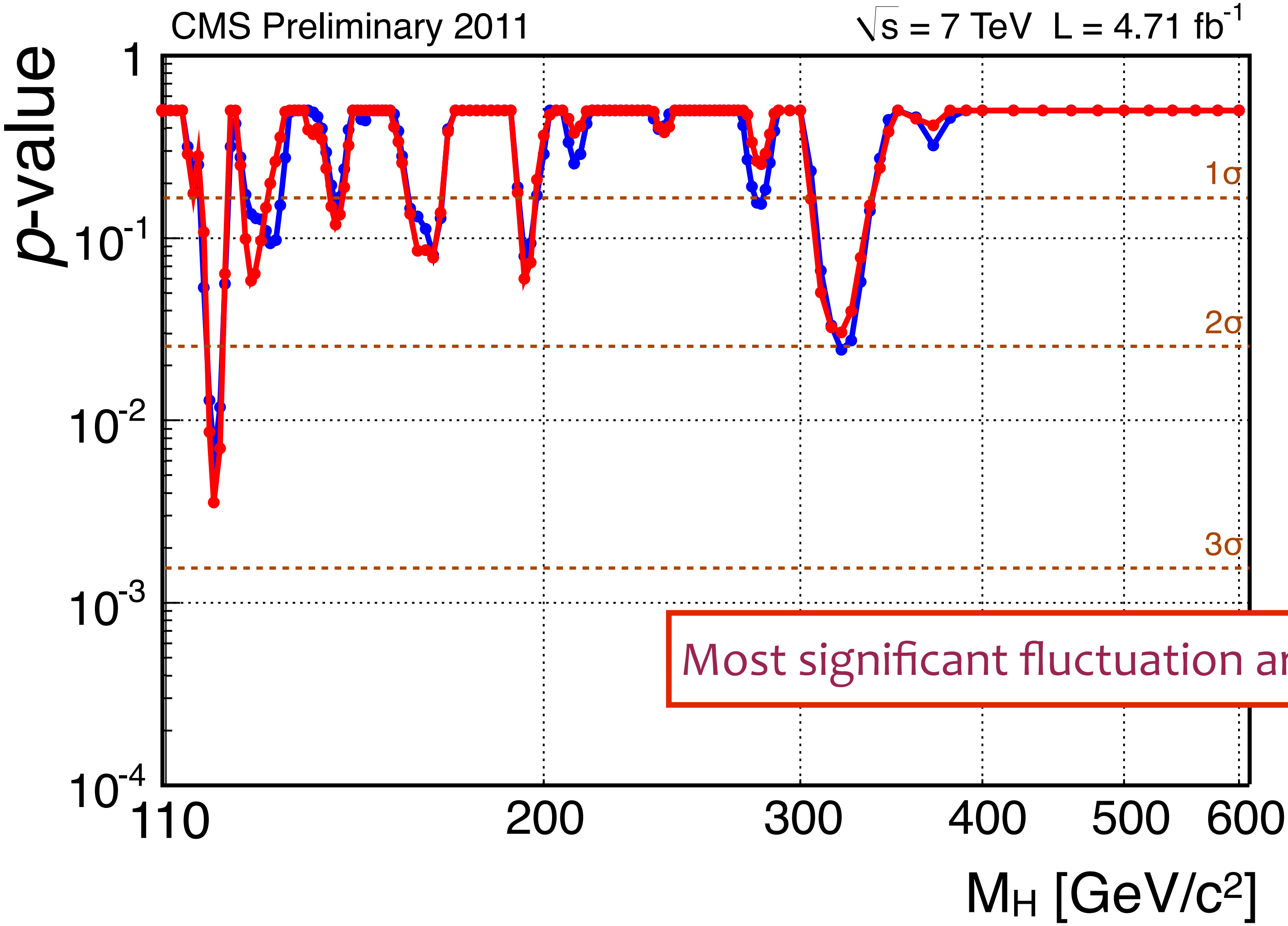
EXCLUSION: [134-158]

p-value

- P-value: probability that the background fluctuate as observed in data

=> Significance of the local fluctuations with respect to the SM expectation as a function of the Higss boson mass

- The results are obtained **with** or **without** taking into account the event-by-event mass error uncertainties



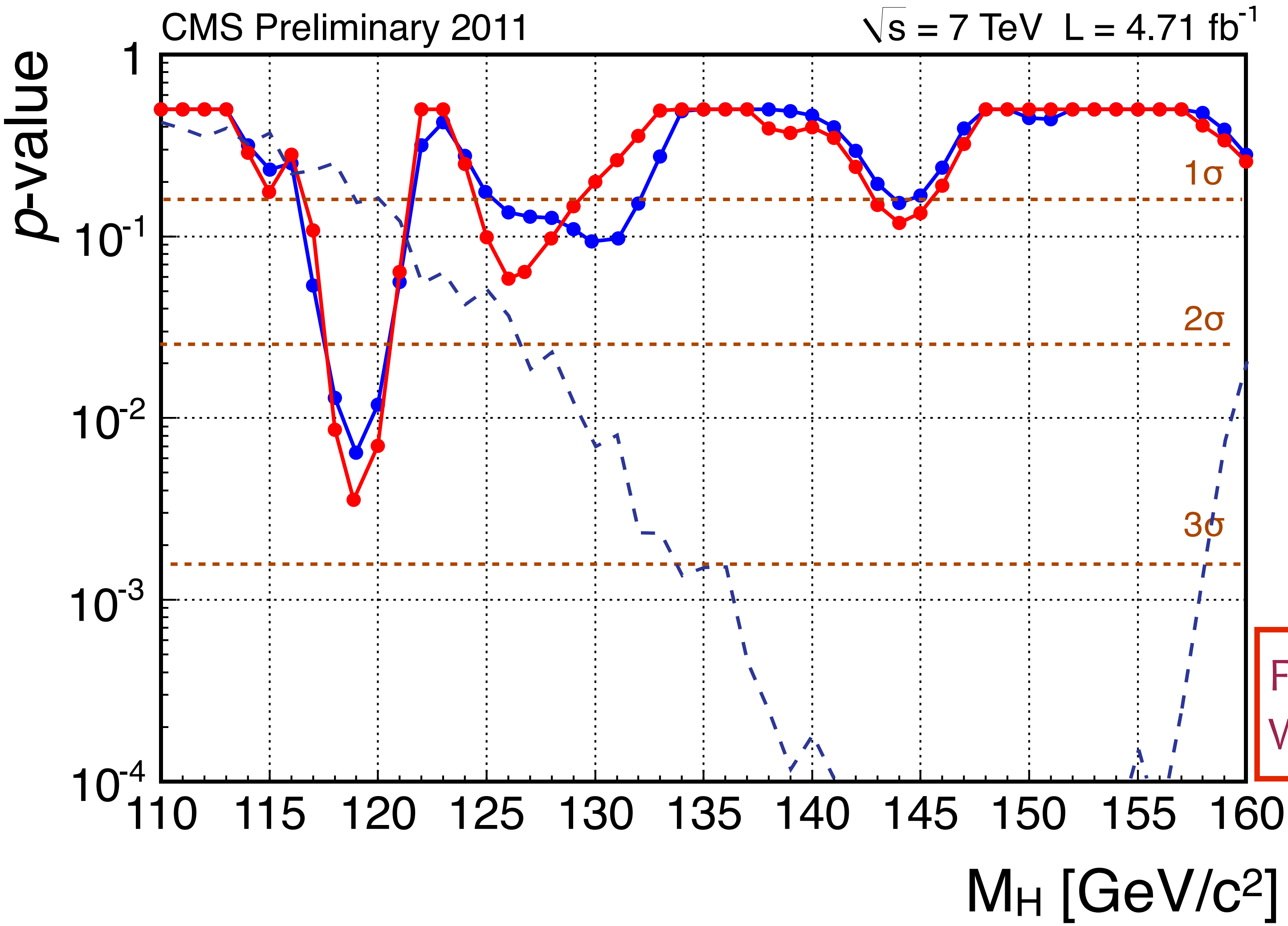
Most significant fluctuation around ~120 and ~320 GeV/c^2

p-value

- P-value: probability that the background fluctuate as observed in data

=> Significance of the local fluctuations with respect to the SM expectation as a function of the Higgs boson mass

- The results are obtained **with** or **without** taking into account the event-by-event mass error uncertainties



Fluctuation ~ 120: **2.5** / **2.9**
With LEE included: **1.0** / **1.6**

Conclusions

- A search for the Standard Model Higgs boson produced in the decay channel **H->ZZ$^{(*)}$->4l** at the CMS experiment has been presented.

- The preparatory work to characterize in detail the **muon trigger, reconstruction and identification performances** has been discussed and its impact on the obtained physics results has been highlighted.

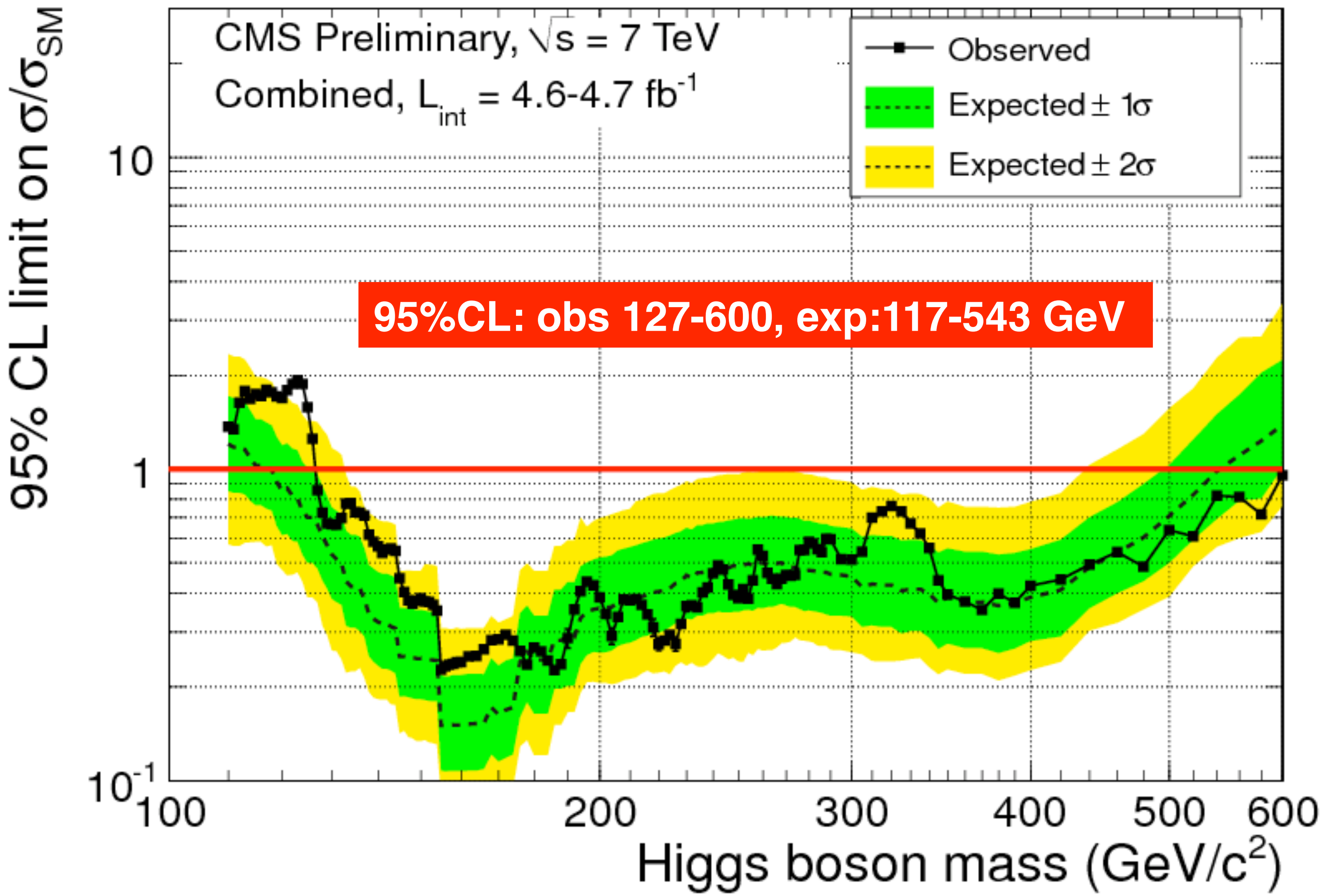
- The choice of the event selection has been motivated in detail.

- The studies to control with data the **instrumental and reducible backgrounds** have been presented. The results prove that their contamination is negligible over most of the mass range, with a **small contamination remaining at low mass.**

- The **ZZ cross section** has been measured and found in agreement with the SM expectations.

- **The Higgs boson existence is excluded at 95% C.L. over a major fraction of the mass range 110< m_H <600 GeV/c^2 and only the region 114.4 < m_H < 133 GeV/c^2 and 173 < m_H < 178 GeV/c^2 remain possibly consistent with the expectations of the SM.**

Backup



CMS Preliminary, √s = 7 TeV
Combined, L_int = 4.6-4.7 fb^-1
Observed
Expected ± 1σ
Expected ± 2σ
95%CL: obs 127-600, exp:117-543 GeV
95% CL limit on σ/σ_SM
10
1
10^-1
100
200
300
400
500
600
Higgs boson mass (GeV/c^2)

Montecarlo Samples

Process	MC generator	$\sigma_{(N)NLO}$	Comments and samples
Higgs boson $H \to ZZ \to 4\ell$			
$gg \to H$	POWHEG	[1-20] fb	$m_H = 110\text{-}600\,GeV/c^2$
$VV \to H$	POWHEG	[0.2-2] fb	$m_H = 110\text{-}600\,GeV/c^2$
WH; ZH; $t\bar{t}H$	PYTHIA	[0.01-0.05] fb	$m_H = 110\text{-}180\,GeV/c^2$
ZZ continuum			
$q\bar{q} \to ZZ \to 4e(4\mu, 4\tau)$	POWHEG	15.34 fb	ZZTo4e(4mu,4tau)_7TeV-powheg-pythia6
$q\bar{q} \to ZZ \to 2e2\mu$	POWHEG	30.68 fb	ZZTo2e2mu_7TeV-powheg-pythia6
$q\bar{q} \to ZZ \to 2e(2\mu)2\tau$	POWHEG	30.68 fb	ZZTo2e(2mu)2tau_7TeV-powheg-pythia6
$gg \to ZZ \to 2\ell 2\ell'$	gg2ZZ	3.48 fb	GluGluToZZTo2L2L_7TeV-gg2zz-pythia6
$gg \to ZZ \to 4\ell$	gg2ZZ	1.74 fb	GluGluToZZTo4L_7TeV-gg2zz-pythia6
Other di-bosons			
$WW \to 2\ell 2\nu$	PYTHIA	4.88 pb	WWTo2L2Nu_TuneZ2_7TeV_pythia6_tauola
$WZ \to 3\ell\nu$	PYTHIA	0.595 pb	WZTo3LNu_TuneZ2_7TeV_pythia6_tauola
$t\bar{t}$ **and single** t			
$t\bar{t} \to \ell^+\ell^-\nu\bar{\nu}b\bar{b}$	POWHEG	17.32 pb	TTTo2L2Nu2B_7TeV-powheg-pythia6
t (s-channel)	POWHEG	3.19 pb	T_TuneZ2_s-channel_7TeV-powheg-tauola
$\bar{t}$ (s-channel)	POWHEG	1.44 pb	Tbar_TuneZ2_s-channel_7TeV-powheg-tauola
t (t-channel)	POWHEG	41.92 pb	T_TuneZ2_t-channel_7TeV-powheg-tauola
$\bar{t}$ (t-channel)	POWHEG	22.65 pb	Tbar_TuneZ2_t-channel_7TeV-powheg-tauola
t (tW-channel)	POWHEG	7.87 pb	T_TuneZ2_tW-channel-DR_7TeV-powheg-tauola
$\bar{t}$ (tW-channel)	POWHEG	7.87 pb	Tbar_TuneZ2_tW-channel-DR_7TeV-powheg-tauola
Z/W + jets ($q = d, u, s, c, b$)			
W + jets	MadGraph	31314 pb	WJetsToLNu_TuneZ2_7TeV-madgraph-tauola
Z + jets	MadGraph	3048 pb	DYJetsToLL_TuneZ2_M-50_7TeV-madgraph-tauola
QCD inclusive multi-jets, binned $\hat{p}_T^{min}$			
$b, c \to e + X$	PYTHIA		QCD_Pt-XXtoYY_BCtoE_TuneZ2_7TeV-pythia6
EM-enriched	PYTHIA		QCD_Pt-XXtoYY_EMEnriched_TuneZ2_7TeV-pythia6
MU-enriched	PYTHIA		QCD_Pt-XXtoYY_MuPt5Enriched_TuneZ2_7TeV-pythia6

Event list

2010/2011A: L = 2.2 fb^{-1}

Event	Run #	Event #	Channel	m_{Z_1}	m_{Z_2} (GeV/c^2)	$m_{4\ell}$	$\Delta m_{4\ell}$	$p_{T,4\ell}$ (GeV/c)	$y_{4\ell}$
A	146511	504867308	4μ	91.365	92.599	201.178	2.1482	2.856	0.183
B	147926	368148849	4μ	101.535	40.041	167.987	2.4012	43.738	1.452
C	163334	286336207	$2e2\mu$	94.513	66.048	163.842	2.2399	10.535	-0.535
D	163659	344708580	$4e$	92.495	28.869	138.576	1.6269	23.976	0.387
E	163795	30998576	$2e2\mu$	92.402	82.345	207.854	8.1536	5.020	1.832
F	163817	155679852	4μ	91.303	34.827	144.912	1.7089	24.125	-0.359
G	165633	394010457	$2e2\mu$	91.219	93.190	244.582	2.5038	11.973	-0.475
R-A	165970	275108397	$2e2\mu$	91.641	14.915	142.622	1.703	11.506	0.902
H	166408	917379387	$2e2\mu$	88.094	105.275	256.486	3.7908	29.329	-1.214
I	166438	78213037	$4e$	87.530	80.658	213.618	6.33505	25.080	0.062
R-B	166438	862270386	4μ	92.106	15.092	211.644	4.8024	9.088	0.080
J	166512	337493970	4μ	90.972	93.179	238.532	2.8681	21.996	0.261
K	166950	1491724484	$2e2\mu$	92.389	92.799	193.510	3.0095	13.949	0.823
L	167281	480301165	4μ	90.420	54.817	222.302	2.2586	42.304	-0.645
R-C	167282	44166176	4μ	90.315	14.724	118.830	0.81305	16.410	0.127
M	167284	1038911933	4μ	77.796	29.675	119.026	1.08445	43.934	0.581
N	167675	876658967	$4e$	92.314	27.221	125.661	1.5515	16.093	0.067
O	167807	966824024	$2e2\mu$	90.192	94.768	325.558	3.1356	40.907	-0.428
P	171106	141954801	$4e$	91.703	92.205	191.587	3.17695	7.497	-0.335
Q	171369	160966858	4μ	90.197	88.933	218.870	2.5162	9.831	0.785
R	172163	191231387	4μ	92.151	87.695	198.821	3.381	8.668	1.231
S	172208	66033190	4μ	87.695	97.017	308.561	3.96865	71.109	0.341
R-D	172620	218903169	$2e2\mu$	93.544	16.963	131.608	4.2458	7.299	1.168
T	172799	10347106	$4e$	91.290	82.978	365.339	5.0692	6.650	0.519
U	172802	107360878	4μ	91.902	85.036	457.923	10.6639	19.019	-0.523
V	172822	2554393033	4μ	90.219	25.359	118.937	0.8533	18.145	-0.340
W	172868	933807102	$2e2\mu$	92.219	89.756	316.705	3.601	22.021	-0.595
X	172949	1188043146	$2e2\mu$	91.821	89.421	195.229	1.7953	39.271	-0.314
Y	172952	559839432	4μ	91.155	37.151	231.938	2.2195	31.741	-0.395
Z	173243	16706390	$4e$	90.767	92.951	284.831	4.89085	29.472	1.496
AA	173657	65557571	$2e2\mu$	91.518	87.826	391.348	7.2423	19.635	1.096
AB	173659	389185367	$4e$	90.968	85.244	229.234	4.7879	12.349	-1.394
AC	173692	2722114329	$2e2\mu$	90.436	93.784	189.628	3.1421	16.184	0.807

2011B: L = 2.5 fb^{-1}

Event	Run #	Event #	Channel	m_{Z_1}	m_{Z_2} (GeV/c^2)	$m_{4\ell}$	$\Delta m_{4\ell}$	$p_{T,4\ell}$ (GeV/c)	$y_{4\ell}$
AD	175906	227517585	$2e2\mu$	92.400	94.236	308.127	2.795	20.414	0.002
AE	175921	297753357	$2e2\mu$	94.963	85.251	231.653	8.9622	10.091	1.272
AF	175921	495614354	$2e2\mu$	92.916	98.722	206.865	4.225	42.325	-1.242
AG	175974	7526662	$2e2\mu$	92.230	98.011	210.752	1.9461	12.519	-0.046
R-E	176201	261184429	$2e2\mu$	91.034	17.000	183.255	2.2529	71.992	-0.487
AH	176207	256888239	$2e2\mu$	89.924	94.223	275.799	19.8991	12.336	-1.645
AI	176304	417897294	$4e$	82.419	39.501	158.218	2.30115	15.049	-0.055
AJ	176304	418052877	$2e2\mu$	91.749	101.763	206.419	2.561	44.274	-0.465
AK	176309	257489763	4μ	89.766	86.302	193.860	2.03205	3.351	-1.145
R-F	176309	1340034258	$2e2\mu$	75.586	12.928	130.079	2.7027	22.434	-1.662
AL	176468	215855118	$2e2\mu$	94.576	102.730	325.094	5.4457	13.280	-0.773
AM	176548	403771114	$4e$	92.887	97.467	327.470	8.04025	81.207	0.266
AN	176799	35688265	4μ	90.583	92.772	193.420	2.68065	27.804	1.614
AO	176886	1057019814	$2e2\mu$	90.133	92.654	257.813	4.0456	12.061	0.021
AP	177074	588602439	4μ	93.013	87.697	240.346	3.059	11.206	-0.064
AQ	177139	290826062	$2e2\mu$	86.489	96.327	193.718	2.301	5.179	-0.655
AR	177222	339499459	$2e2\mu$	90.148	86.388	309.595	4.8542	8.347	1.023
AS	177782	72158025	$2e2\mu$	67.942	48.502	126.245	1.6536	41.762	1.270
AT	177790	222240677	4μ	91.625	93.231	280.363	3.36145	21.879	0.370
AU	177790	657843813	4μ	90.963	91.745	237.879	3.8111	56.688	-0.908
AV	177875	148667118	$4e$	91.721	94.193	368.731	8.7261	21.105	0.900
AW	178100	326364918	$2e2\mu$	92.348	86.556	278.948	3.8948	4.259	-0.051
AX	178116	709511403	$2e2\mu$	94.437	95.421	339.845	2.8886	162.160	-0.929
AY	178421	87514902	4μ	83.352	25.995	114.835	0.88205	58.814	-0.503
AZ	178421	1450980155	$2e2\mu$	89.649	81.374	177.016	3.3319	13.543	1.518
BA	178479	298608854	4μ	89.790	85.759	259.929	2.4334	6.565	-0.955
BB	178479	589085976	$2e2\mu$	89.472	85.948	273.200	7.0993	94.783	-1.094
BC	178703	191352626	$2e2\mu$	87.138	85.023	197.382	3.1096	8.769	0.837
BD	178731	248562036	$2e2\mu$	92.027	89.372	316.958	9.9489	33.715	-1.605
BE	178866	140063742	$2e2\mu$	85.191	47.707	150.691	3.5113	37.484	0.803
BF	178970	57399691	4μ	88.046	74.837	199.211	5.85005	40.907	1.457
BG	178970	122998167	$2e2\mu$	91.742	90.469	245.415	3.1837	9.547	-0.701
BH	179434	86225612	$2e2\mu$	93.705	94.549	209.845	2.9588	59.862	0.084
BI	179452	1459855927	$2e2\mu$	93.427	42.163	162.155	2.4895	13.510	-0.959
BJ	179476	30532070	4μ	92.292	92.304	226.829	2.72435	17.203	-0.752
BK	179563	287281642	$2e2\mu$	95.692	68.620	169.812	3.0342	46.986	-1.321
BL	179563	1409064222	$2e2\mu$	90.274	88.464	214.834	1.9383	16.802	0.537
BM	180076	79350642	$4e$	90.545	89.614	194.296	4.19775	42.111	-1.294
BN	180250	591651181	$4e$	91.568	93.102	284.113	5.8696	43.878	-0.954

Only Baseline (20 evts.)

50 < m_{Z1} < 120

12 < m_{Z2} < 120

Event list

2010/2011A: L = 2.2 fb^{-1}

Event	Run #	Event #	Channel	m_{Z_1}	m_{Z_2} (GeV/c^2)	$m_{4\ell}$	$\Delta m_{4\ell}$	$p_{T,4\ell}$ (GeV/c)	$y_{4\ell}$
A	146511	504867308	4μ	91.365	92.599	201.178	2.1482	2.856	0.183
B	147926	368148849	4μ	101.535	40.041	167.987	2.4012	43.738	1.452
C	163334	286336207	$2e2\mu$	94.513	66.048	163.842	2.2399	10.535	-0.535
D	163659	344708580	$4e$	92.495	28.869	138.576	1.6269	23.976	0.387
E	163795	30998576	$2e2\mu$	92.402	82.345	207.854	8.1536	5.020	1.832
F	163817	155679852	4μ	91.303	34.827	144.912	1.7089	24.125	-0.359
G	165633	394010457	$2e2\mu$	91.219	93.190	244.582	2.5038	11.973	-0.475
R-A	165970	275108397	$2e2\mu$	91.641	14.915	142.622	1.703	11.506	0.902
H	166408	917379387	$2e2\mu$	88.094	105.275	256.486	3.7908	29.329	-1.214
I	166438	78213037	$4e$	87.530	80.658	213.618	6.33505	25.080	0.062
R-B	166438	862270386	4μ	92.106	15.092	211.644	4.8024	9.088	0.080
J	166512	337493970	4μ	90.972	93.179	238.532	2.8681	21.996	0.261
K	166950	1491724484	$2e2\mu$	92.389	92.799	193.510	3.0095	13.949	0.823
L	167281	480301165	4μ	90.420	54.817	222.302	2.2586	42.304	-0.645
R-C	167282	44166176	4μ	90.315	14.724	118.830	0.81305	16.410	0.127
M	167284	1038911933	4μ	77.796	29.675	119.026	1.08445	43.934	0.581
N	167675	876658967	$4e$	92.314	27.221	125.661	1.5515	16.093	0.067
O	167807	966824024	$2e2\mu$	90.192	94.768	325.558	3.1356	40.907	-0.428
P	171106	141954801	$4e$	91.703	92.205	191.587	3.17695	7.497	-0.335
Q	171369	160966858	4μ	90.197	88.933	218.870	2.5162	9.831	0.785
R	172163	191231387	4μ	92.151	87.695	198.821	3.381	8.668	1.231
S	172208	66033190	4μ	87.695	97.017	308.561	3.96865	71.109	0.341
R-D	172620	218903169	$2e2\mu$	93.544	16.963	131.608	4.2458	7.299	1.168
T	172799	10347106	$4e$	91.290	82.978	365.339	5.0692	6.650	0.519
U	172802	107360878	4μ	91.902	85.036	457.923	10.6639	19.019	-0.523
V	172822	2554393033	4μ	90.219	25.359	118.937	0.8533	18.145	-0.340
W	172868	933807102	$2e2\mu$	92.219	89.756	316.705	3.601	22.021	-0.595
X	172949	1188043146	$2e2\mu$	91.821	89.421	195.229	1.7953	39.271	-0.314
Y	172952	559839432	4μ	91.155	37.151	231.938	2.2195	31.741	-0.395
Z	173243	16706390	$4e$	90.767	92.951	284.831	4.89085	29.472	1.496
AA	173657	65557571	$2e2\mu$	91.518	87.826	391.348	7.2423	19.635	1.096
AB	173659	389185367	$4e$	90.968	85.244	229.234	4.7879	12.349	-1.394
AC	173692	2722114329	$2e2\mu$	90.436	93.784	189.628	3.1421	16.184	0.807

2011B: L = 2.5 fb^{-1}

Event	Run #	Event #	Channel	m_{Z_1}	m_{Z_2} (GeV/c^2)	$m_{4\ell}$	$\Delta m_{4\ell}$	$p_{T,4\ell}$ (GeV/c)	$y_{4\ell}$
AD	175906	227517585	$2e2\mu$	92.400	94.236	308.127	2.795	20.414	0.002
AE	175921	297753357	$2e2\mu$	94.963	85.251	231.653	8.9622	10.091	1.272
AF	175921	495614354	$2e2\mu$	92.916	98.722	206.865	4.225	42.325	-1.242
AG	175974	7526662	$2e2\mu$	92.230	98.011	210.752	1.9461	12.519	-0.046
R-E	176201	261184429	$2e2\mu$	91.034	17.000	183.255	2.2529	71.992	-0.487
AH	176207	256888239	$2e2\mu$	89.924	94.223	275.799	19.8991	12.336	-1.645
AI	176304	417897294	$4e$	82.419	39.501	158.218	2.30115	15.049	-0.055
AJ	176304	418052877	$2e2\mu$	91.749	101.763	206.419	2.561	44.274	-0.465
AK	176309	257489763	4μ	89.766	86.302	193.860	2.03205	3.351	-1.145
R-F	176309	1340034258	$2e2\mu$	75.586	12.928	130.079	2.7027	22.434	-1.662
AL	176468	215855118	$2e2\mu$	94.576	102.730	325.094	5.4457	13.280	-0.773
AM	176548	403771114	$4e$	92.887	97.467	327.470	8.04025	81.207	0.266
AN	176799	35688265	4μ	90.583	92.772	193.420	2.68065	27.804	1.614
AO	176886	1057019814	$2e2\mu$	90.133	92.654	257.813	4.0456	12.061	0.021
AP	177074	588602439	4μ	93.013	87.697	240.346	3.059	11.206	-0.064
AQ	177139	290826062	$2e2\mu$	86.489	96.327	193.718	2.301	5.179	-0.655
AR	177222	339499459	$2e2\mu$	90.148	86.388	309.595	4.8542	8.347	1.023
AS	177782	72158025	$2e2\mu$	67.942	48.502	126.245	1.6536	41.762	1.270
AT	177790	222240677	4μ	91.625	93.231	280.363	3.36145	21.879	0.370
AU	177790	657843813	4μ	90.963	91.745	237.879	3.8111	56.688	-0.908
AV	177875	148667118	$4e$	91.721	94.193	368.731	8.7261	21.105	0.900
AW	178100	326364918	$2e2\mu$	92.348	86.556	278.948	3.8948	4.259	-0.051
AX	178116	709511403	$2e2\mu$	94.437	95.421	339.845	2.8886	162.160	-0.929
AY	178421	87514902	4μ	83.352	25.995	114.835	0.88205	58.814	-0.503
AZ	178421	1450980155	$2e2\mu$	89.649	81.374	177.016	3.3319	13.543	1.518
BA	178479	298608854	4μ	89.790	85.759	259.929	2.4334	6.565	-0.955
BB	178479	589085976	$2e2\mu$	89.472	85.948	273.200	7.0993	94.783	-1.094
BC	178703	191352626	$2e2\mu$	87.138	85.023	197.382	3.1096	8.769	0.837
BD	178731	248562036	$2e2\mu$	92.027	89.372	316.958	9.9489	33.715	-1.605
BE	178866	140063742	$2e2\mu$	85.191	47.707	150.691	3.5113	37.484	0.803
BF	178970	57399691	4μ	88.046	74.837	199.211	5.85005	40.907	1.457
BG	178970	122998167	$2e2\mu$	91.742	90.469	245.415	3.1837	9.547	-0.701
BH	179434	86225612	$2e2\mu$	93.705	94.549	209.845	2.9588	59.862	0.084
BI	179452	1459855927	$2e2\mu$	93.427	42.163	162.155	2.4895	13.510	-0.959
BJ	179476	30532070	4μ	92.292	92.304	226.829	2.72435	17.203	-0.752
BK	179563	287281642	$2e2\mu$	95.692	68.620	169.812	3.0342	46.986	-1.321
BL	179563	1409064222	$2e2\mu$	90.274	88.464	214.834	1.9383	16.802	0.537
BM	180076	79350642	$4e$	90.545	89.614	194.296	4.19775	42.111	-1.294
BN	180250	591651181	$4e$	91.568	93.102	284.113	5.8696	43.878	-0.954

4e (12)

4μ (23)

2e2μ (37)

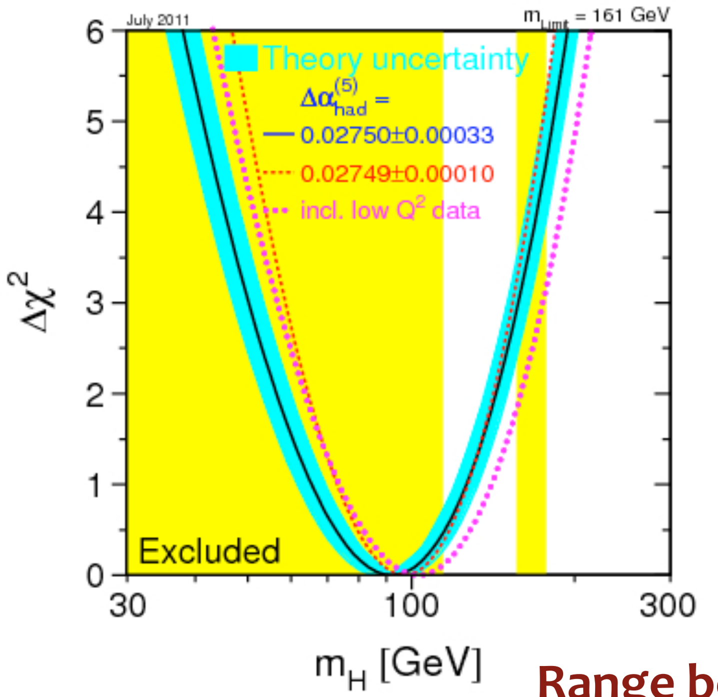
Prelude [2]

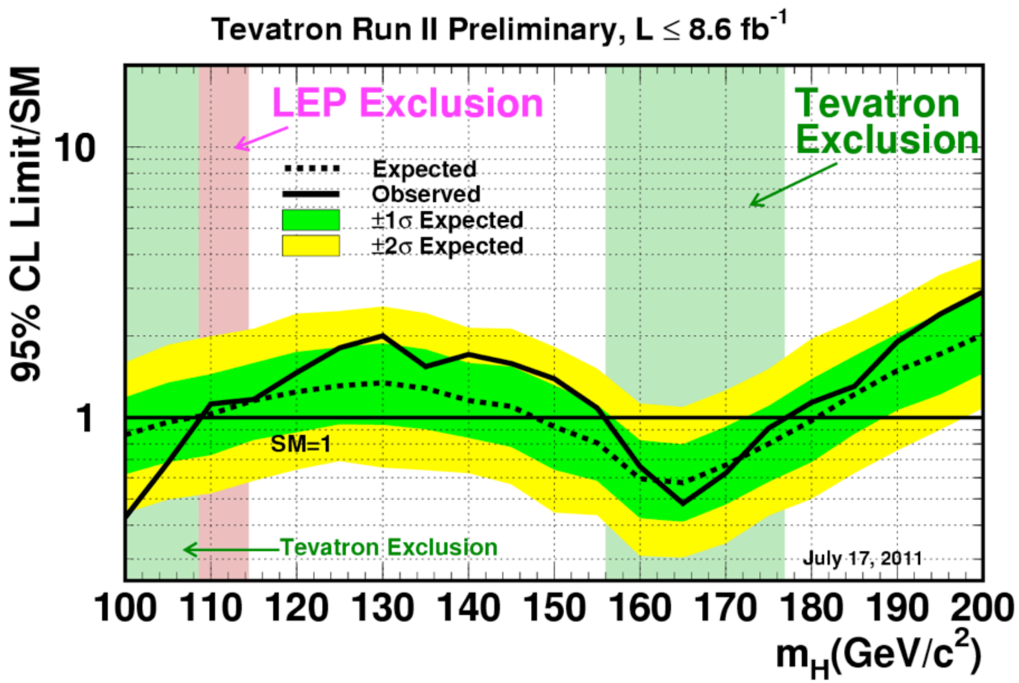
- **The Higgs boson mass:** the only one yet unknown free parameter of the SM

- Prove or exclude, the Higgs boson existence:

  a matter of highest priority in the field of particle physics

- Theoretical indication exists and experimental constraints, from direct and indirect searches, narrow the possible range:
  - **Theory: m_H< ~ 800 GeV/c² to remain in the perturbative regime while considering V_L scattering matrix**
  - **Direct searches at LEP: m_H > 114.4 GeV/c² at 95% C.L.**
  - **Direct searches at Tevatron [July 2011]: 156-177 GeV/c² range excluded at 95% C.L.**
  - **Indirect experimental indication [EWK fit - July 2011]: favorable value 92 GeV/c², 161 GeV/c² upper limit at 95% C.L.**





Range being explored at CMS: 110-600 GeV/c²

The Signal: $H \rightarrow ZZ^{(*)} \rightarrow 4l$ ($l=e,\mu$)

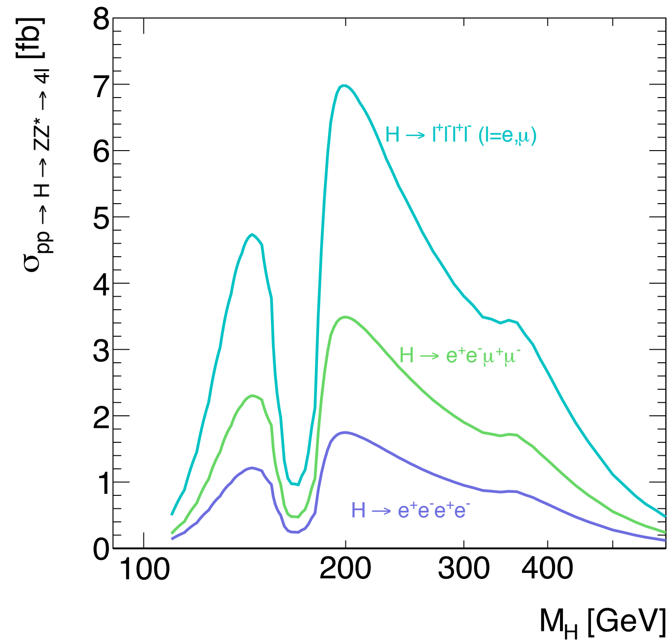
- Final state considered: 4μ, 4e, 2μ2e

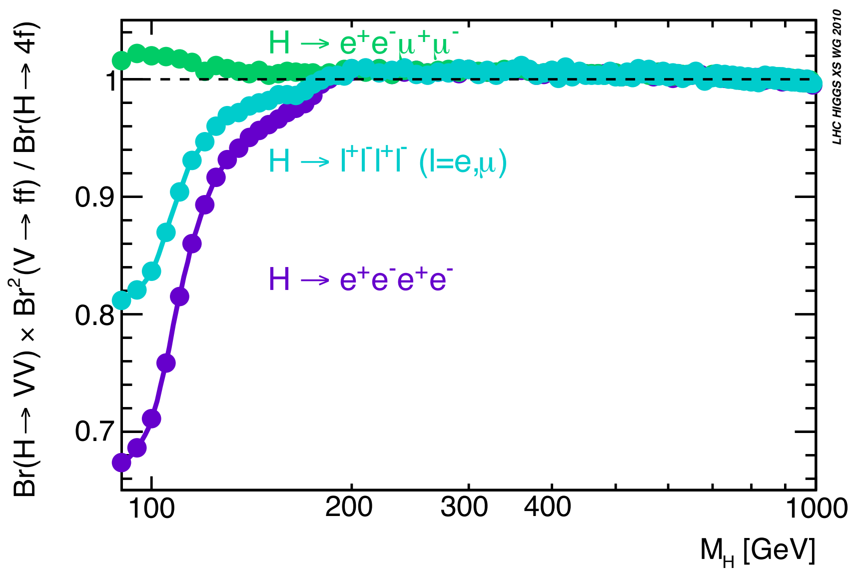
- All Higgs boson production mechanisms are considered as part of the signal

- MC Generated events were processed through the full detector simulation and event reconstruction and have been reweighted according to the total cross section **(gg contributions up to NNLO and NNLL and the VV fusion up to NNLO corrections - LHC Cross Section WG)**

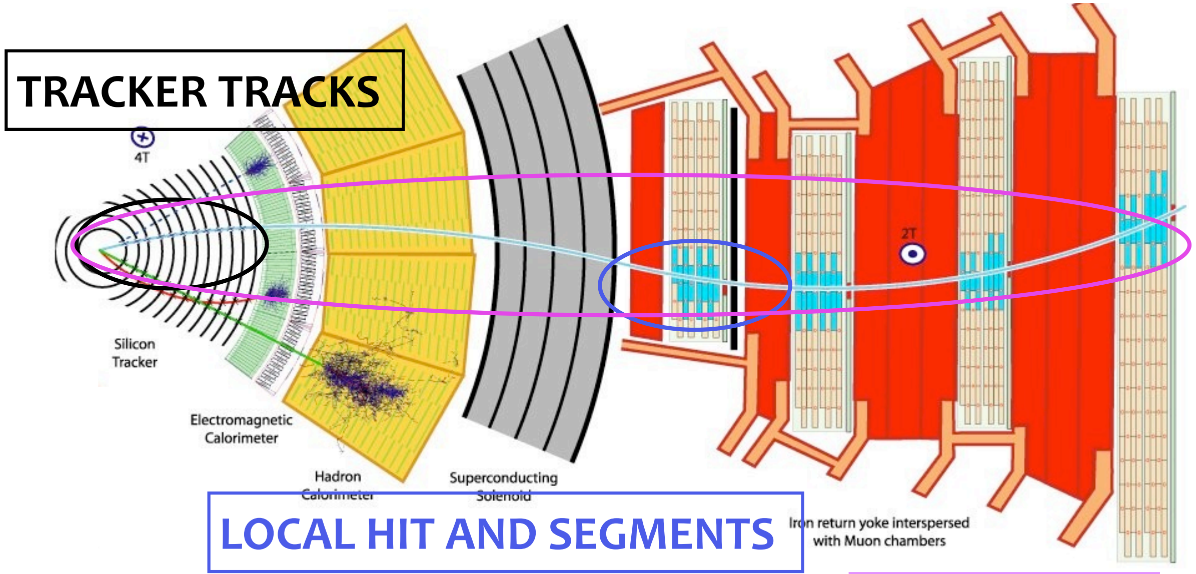
- The 4μ and 4e channel cross section are enhanced in the case of off-shell Z due to an interference of amplitudes with permutation of identical leptons from different Z [Profecy4f]

Process	**MC generator**	$\sigma_{(N)NLO}$
Higgs boson $H \rightarrow ZZ \rightarrow 4\ell$		
$gg \rightarrow H$	POWHEG	[1-20] fb
$VV \rightarrow H$	POWHEG	[0.2-2] fb
WH; ZH; $t\bar{t}H$	PYTHIA	[0.01-0.05] fb





Muon Reconstruction



- **Stand-Alone Muons Reconstruction**

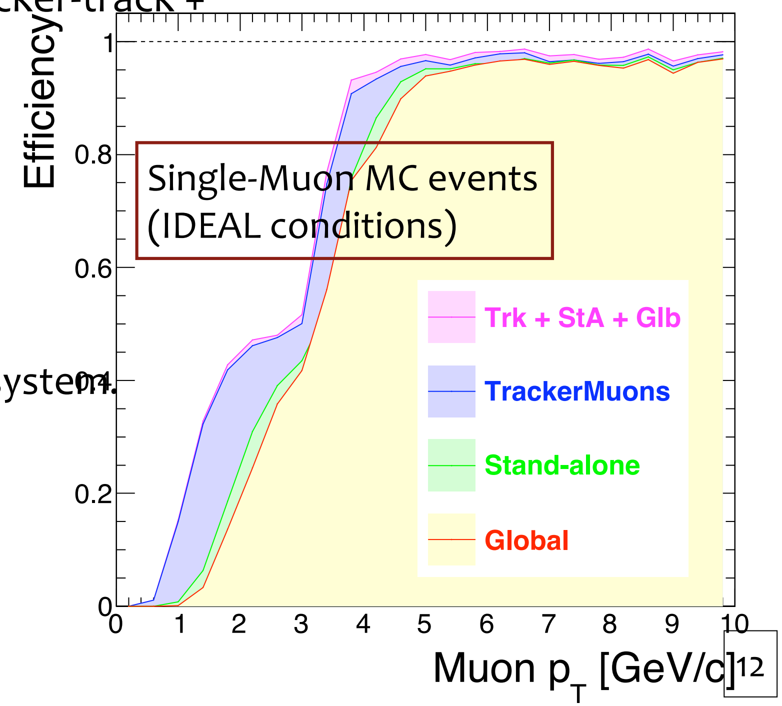
track in the muon spectrometer:
DT/CSC/RPC segments and individual hits are matched to generate seed.
From the seeds a fitting procedure
[kalman filter (KF) technique] is performed.
Resolution: 10-15% up to 100 GeV/c
- 30% at ~1TeV/c

- **Global Muons Reconstruction**

Global track obtained matching each stand-alone with a compatible tracker-track +
Global fit of the measurements with a KF technique.
Resolution: 10-15% up to 100 GeV/c
- 30% at ~1TeV/c [better then only tracker if pt > 200 GeV/c]

- **Tracker Muons Reconstruction**

Tracker driven approach: each track with pt >0.5 propagated to the muon system.
Compatibility with DT/CSC segments defined with position and angular matching criteria. A tracker muon require at least one match.
Gain in efficiency at low p_t.



Muon Identification

QUALITY SELECTION:

- **Tight Muons: prompt muons from W/Z decay**

Global Muon + norm $\chi^2 < 10$ + at least matching with 2 muon segments (tracker muon with 2 matches) + tracker track >=10 hits + $|d_{xy}| <= 0.2$cm + $|d_z| <= 0.1$ cm
(0.1% prob to reconstruct a proton/kaon/pion as a muon / - 2% efficiency wrt Global Muon reco)

- **Soft Muons: low pt muons for B physics**

Tracker Muon + tight requirement on the pulls in local x and y position between the segment and the track
(1% prob to reconstruct a proton/kaon/pion as a muon)

- **Global Muons: H->4l analysis muon object**

Global Muon + tracker track >=10 hits + $SIP_{3D} < 100$
(<1% prob to reconstruct a proton/kaon/pion as a muon, no efficiency loss wrt Global Muon reco)

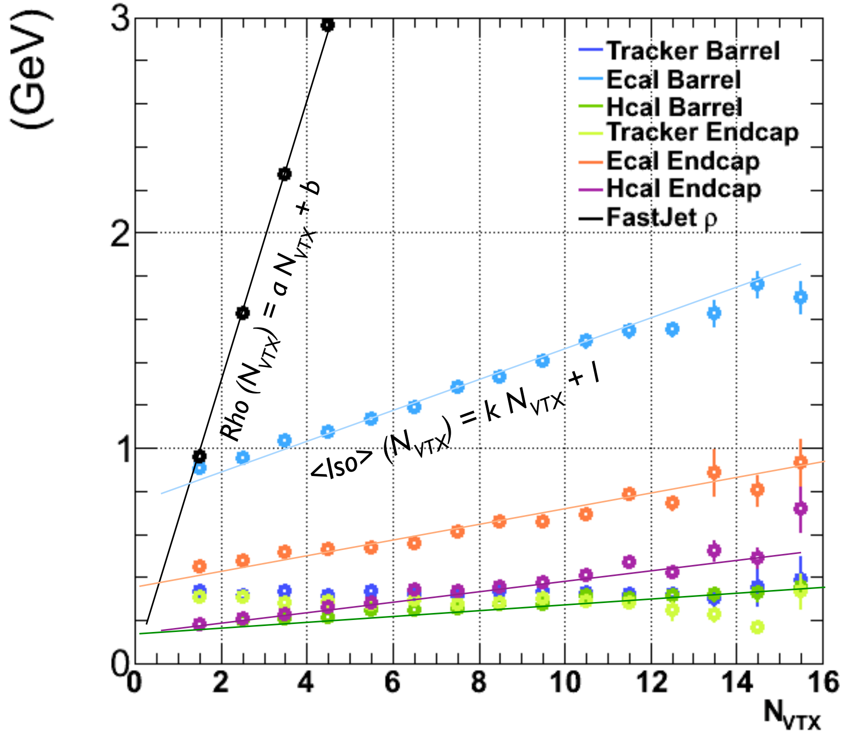
HIGH EFFICIENCY MANDATORY - Min p_t = 5 GeV/c OK for low Higgs masses
NEGLIGIBLE QCD BACKGROUND REQUIRING 4 muon in the final state
Muons from b to be discarded just at the end of the selection
(to control with data-driven methods the Zbb/tt backgrounds)

$|d_{xy}|$ transverse impact parameter
$|d_z|$ longitudinal impact parameter
$SIP_{3D} = |IP_{3D}| / \sigma_{IP3D}$ significance of the tridimensional impact parameter
Evaluated wrt the PRIMARY VERTEX

Lepton Isolation

PileUp corrections

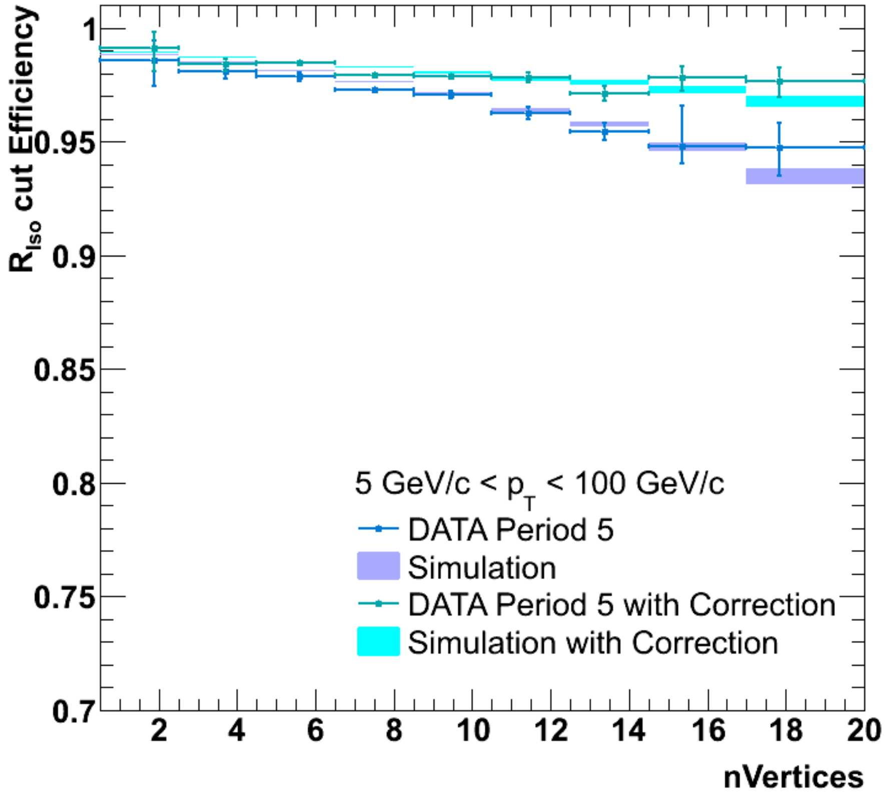
Correction using event-by-event measurement of PU energy density (rho), instead of using geometrical areas the effective area is used



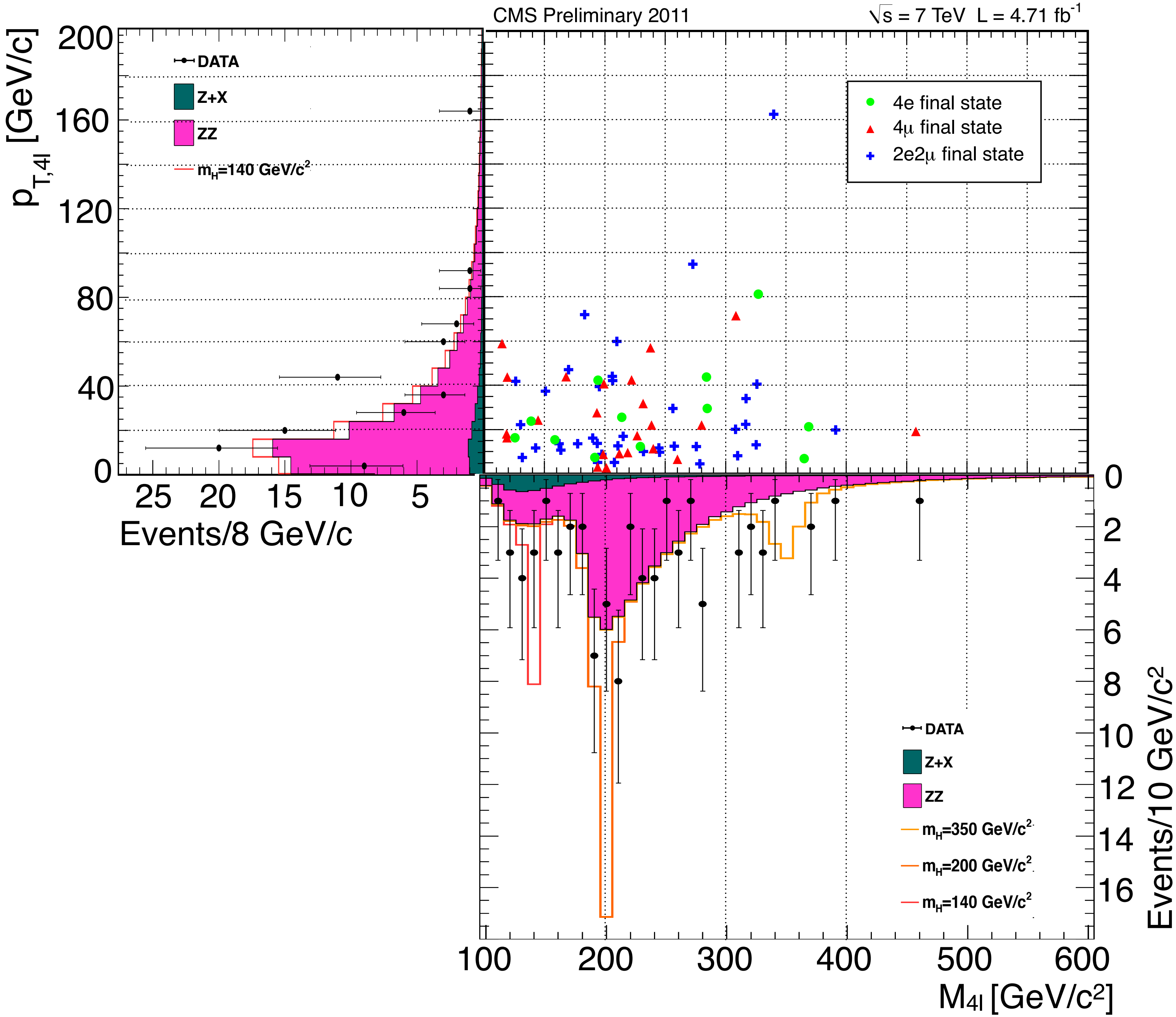
Effective area (A_{eff}) is defined for each isolation variable as the ratio of the slopes from linearly fitting the mean isolation vs. #PV and
the energy density vs #PV

Effect of the correction

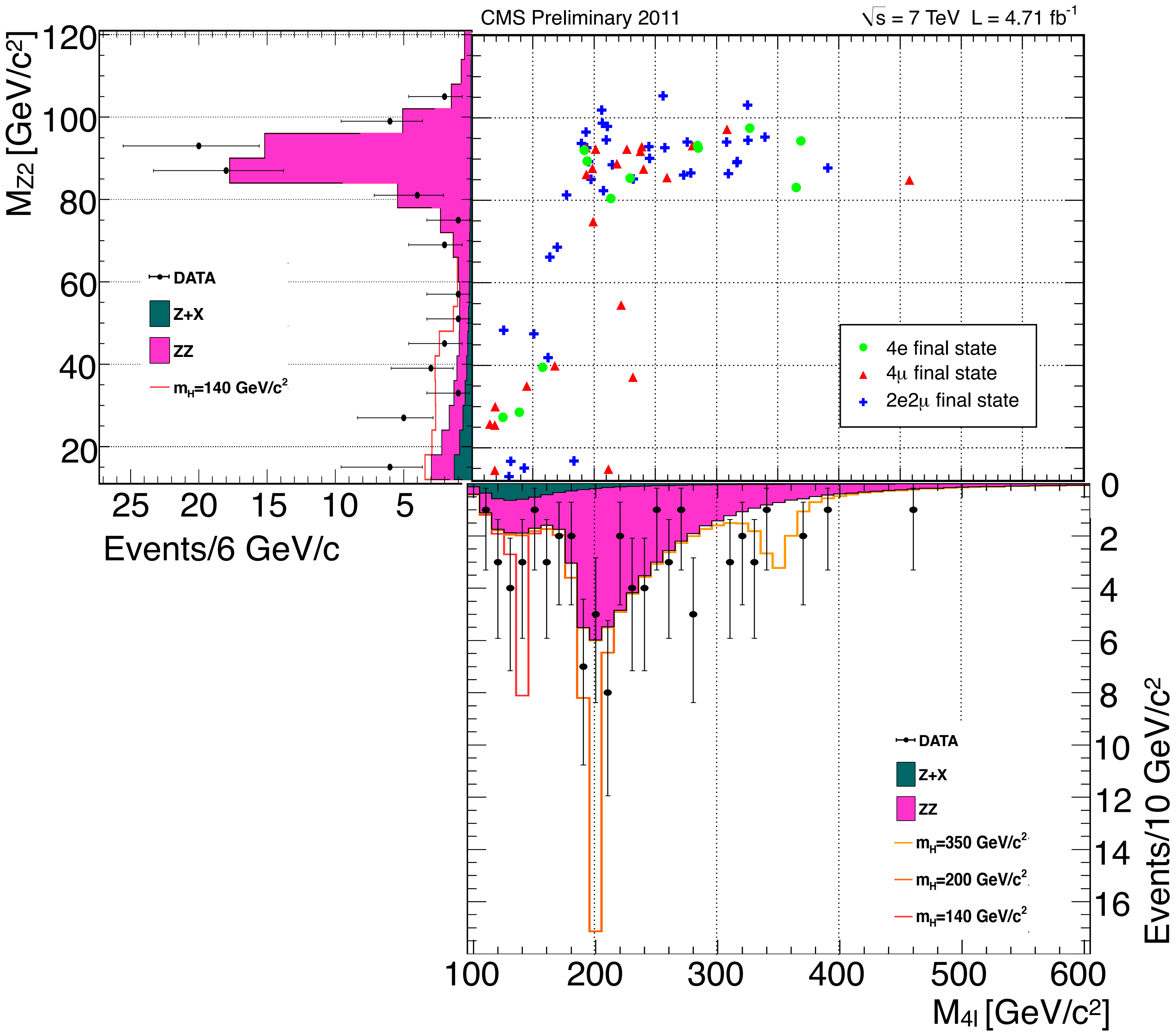
$R_{Iso} < 0.15$



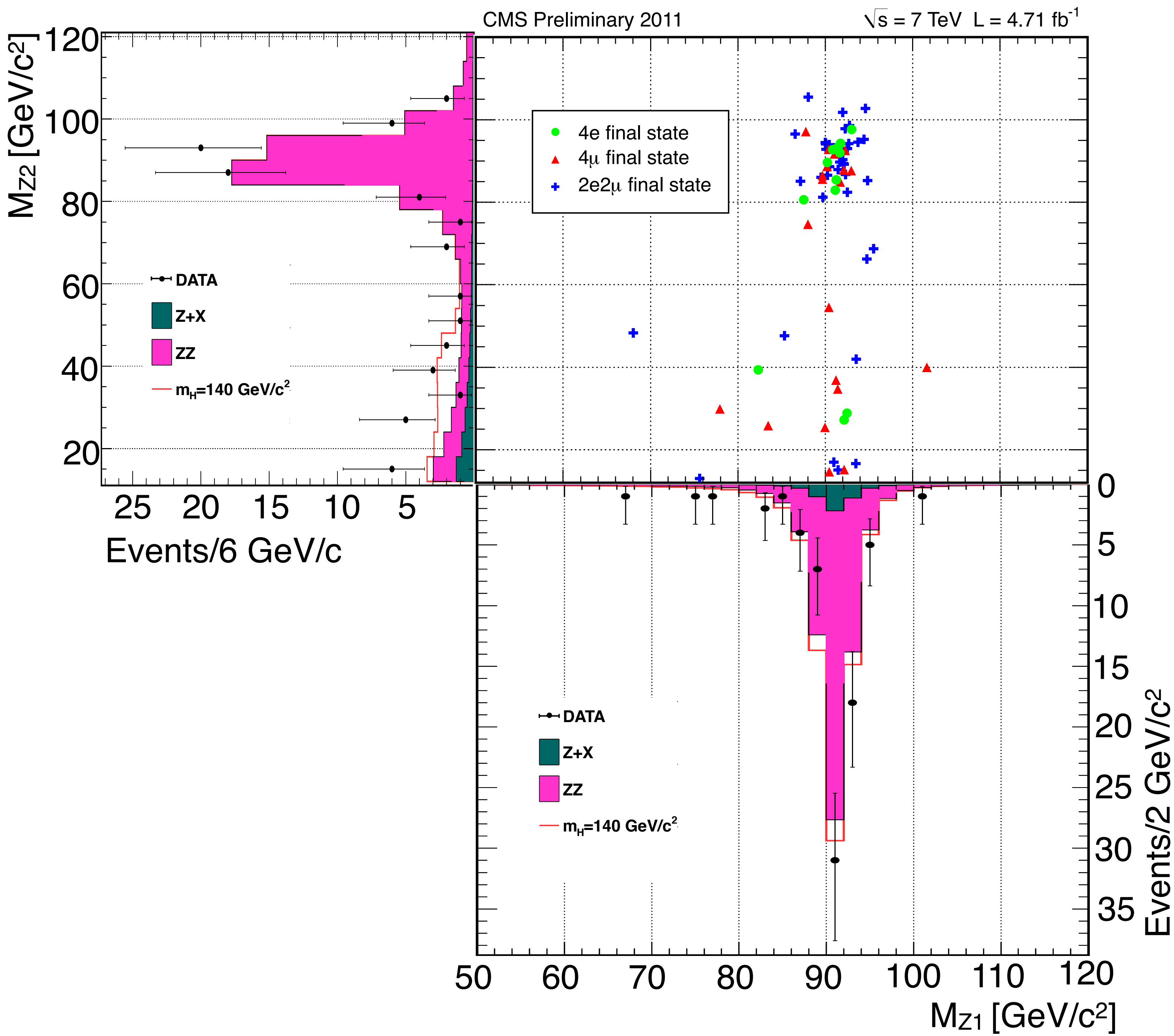
Baseline Selection



Baseline Selection



Baseline Selection



[Muon] Trigger

- **TRIGGER : real time selection of events to be recorded**

- With the current (nominal) luminosity: bunch crossing rate of 20 MHz (40 MHz)
Data size per event ~ 1 MB.

- Technical difficulties in handling, storing, processing this amount of data: in 25 ns it is impossible to read out all raw data from the detector

- Interesting events have cross section << of the total one: a selection must be performed on line on the basis of the physics content of the event

CMS adopts a multi-level trigger design
Each step of the selection uses only part of the available data
Higher trigger levels process fewer events and can use more refined algorithms

L1 Trigger:
based on custom-made hardware and uses only coarsely segmented data from calorimeters and muon system, while the high-resolution data is held in pipeline memories in the front-end electronics.
It has to reduce the event rate to ~ 100 KHz.

High Level Trigger: HLT
software implemented in a single-processor farm, organized in several logical levels of increasing complexity. It has to reduce the rate to ~ 100 Hz
- **1/4 of the bandwidth is allocated for muon triggers**

Preselection

1. *Z₁, a good quality Z candidate* *[the one with mass closest to the Z nominal mass is chosen]*

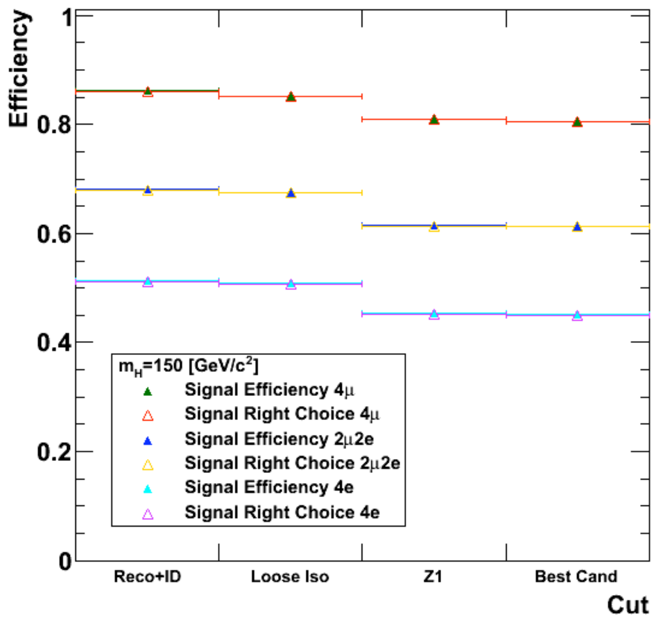
m_{Z1}>50 GeV/c² + $p_{T,1}$ > 20 GeV/c + $p_{T,2}$ > 10 GeV/c + ($Rel_{Iso,1}$ + $Rel_{Iso,2}$) < 0.35 + $|SIP_{3D}|_{1,2}$ < 4

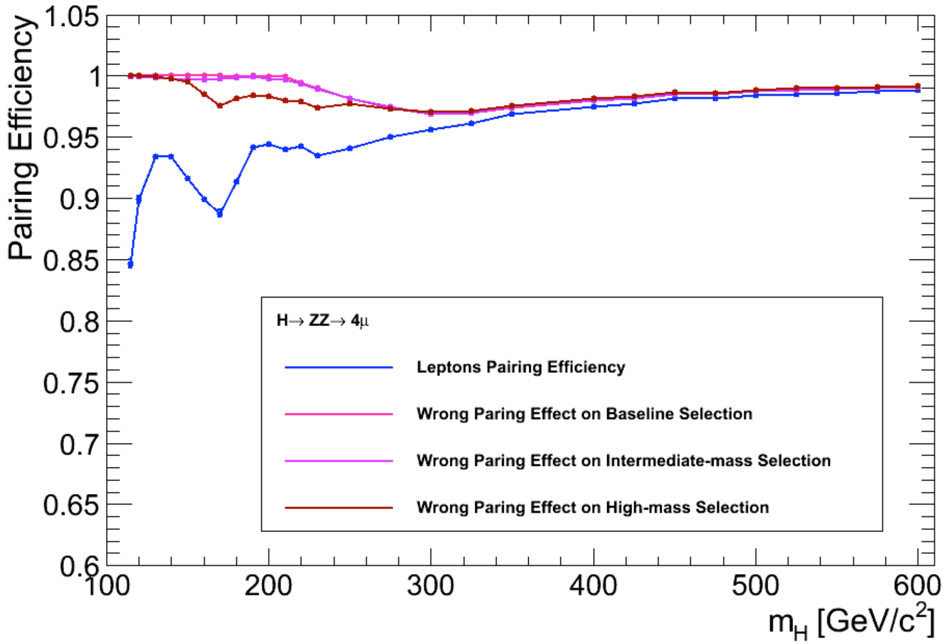
2. *Z_1 + at least 1lepton*

3. *Z_1 + at least 2leptons of matching flavor and opposite sign*

4. *Best 4l candidate / Z_1, Z_2 assignments*

m_{Z2}>12 GeV/c² + m_{Z1Z2}>100 GeV/c² + 3/4 l^+l^- combinations have m_{ll} >12 GeV/c² (4e/4μ only)





Early choice of the Z1 and Z2

- The signal efficiency is preserved
- Early rejection of backgrounds: Z+ converted γ / Low mass resonances
- up to 3% efficiency loss at the end of the selection due to wrong leptons pairing

Strategy

- At the end of the selection, according to the MC event yields, the ZZ background dominates
- Negligible tt/WZ contamination (<< 1%) remains
- It is not possible to conclude on the contamination of Zbb/cc and Z+lightJets - not enough MC events
- In general the small number of events precludes a precise measurement from side-bands
- Alternative typical procedure:
  - select a wide background control region relaxing/inverting the event selection
  - verify that the event rate change according to the expectation from simulation
  - extrapolate back to the signal phase space with ratio of acceptance factors extracted from MC

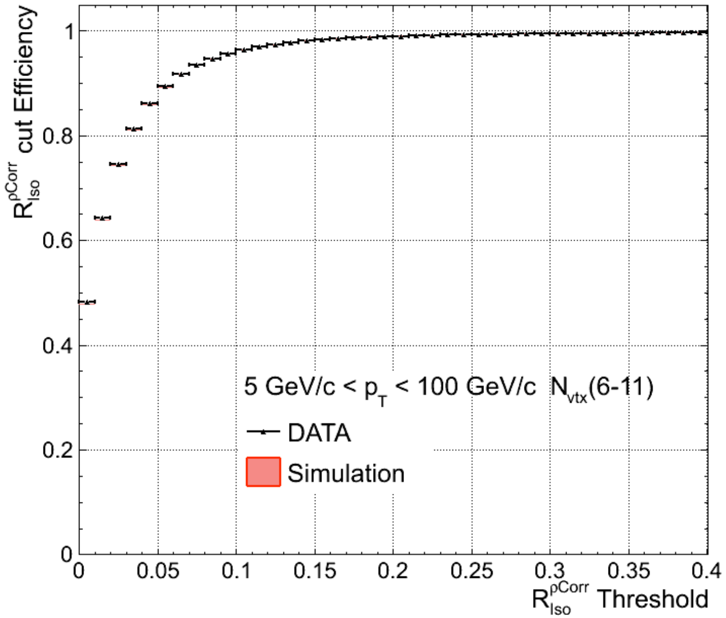
$$N^{\mathrm{B}}_{\mathrm{expect}}\left[m_1, m_2\right] = N^{\mathrm{B}}_{\mathrm{control}} \times \left(\frac{A^{\mathrm{B}}_{\mathrm{signal}}}{A^{\mathrm{B}}_{\mathrm{control}}}\right) \times \int_{m_1}^{m_2} \rho^{\mathrm{B}}(m)dm$$

Event in the control region

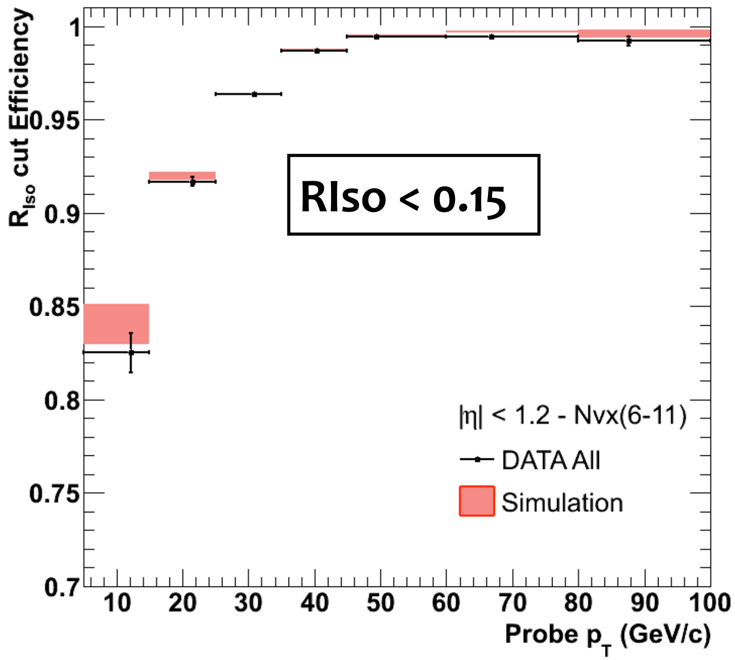
Acceptance factors to extrapolate from the Control to the Signal region

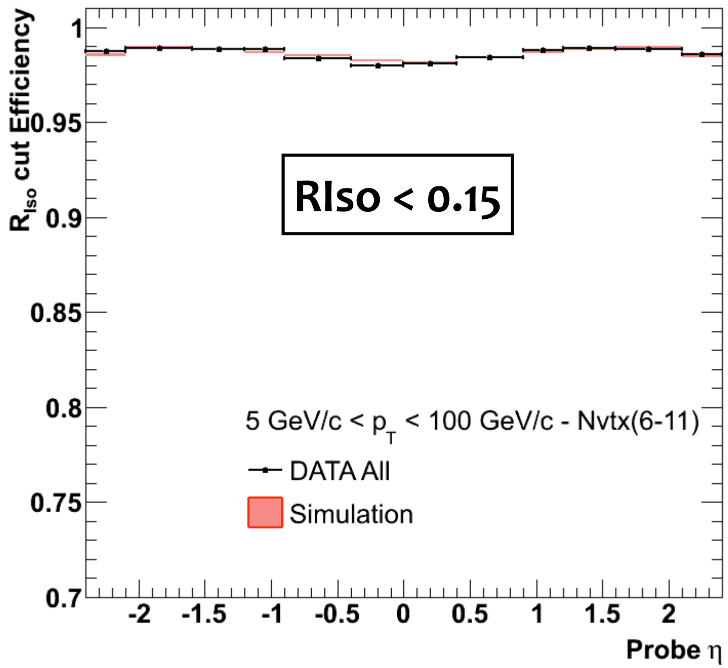
Event density model (shape) for the background in the signal region

Results with 2011 data: ISO

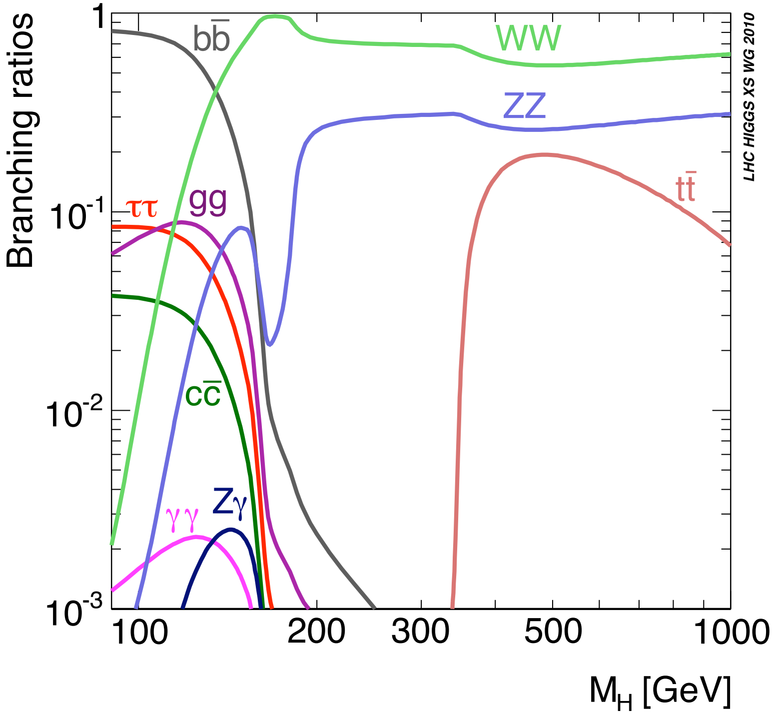


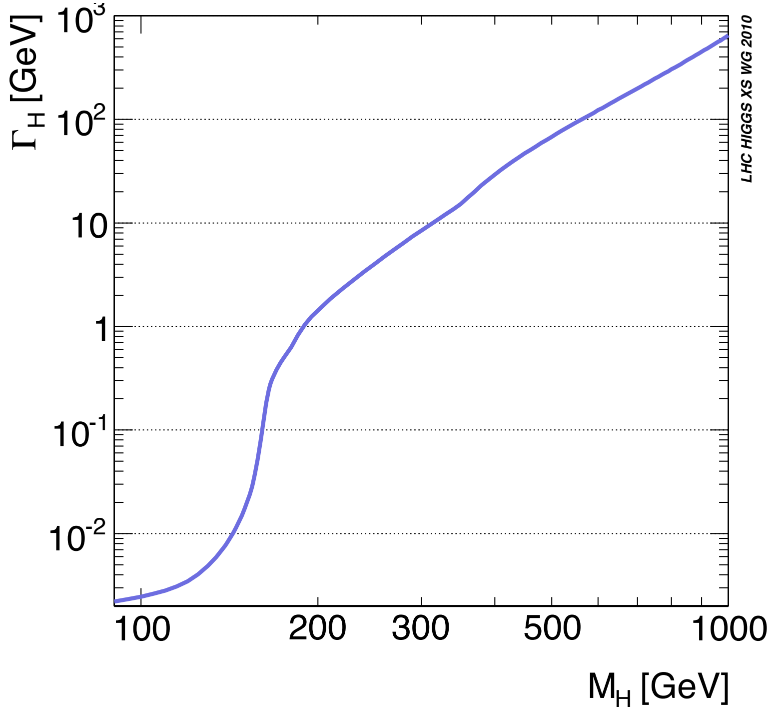
- **Tag: Tight Muon matched with the trigger object / Probe: Global Muon**
- **Good data/mc agreement:** no correction factors are propagated to the MC expected yields but only a systematic is computed





Higgs Decay





- Fermion decay modes dominate the BR in the low mass region ($m_H < 150$ GeV/c²) with the bb decay

- When the decay channels into vector bosons open up, they quickly dominate

- Peak in the WW decay at ~160 GeV/c²

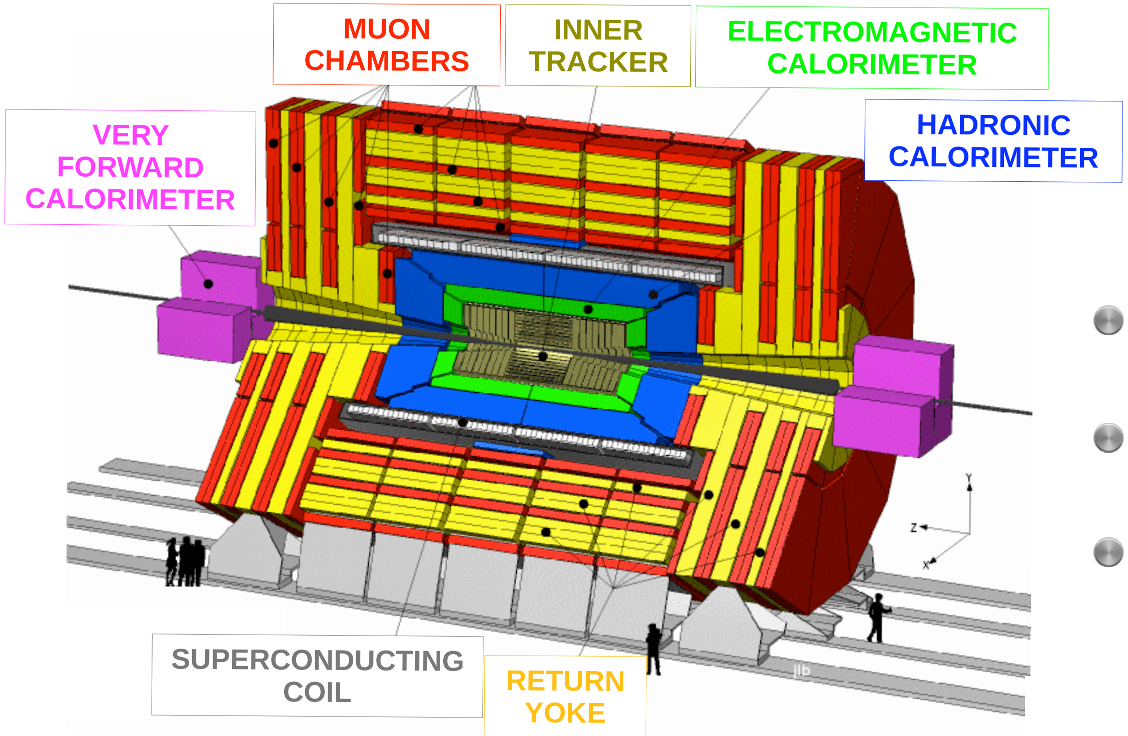
- From masses ~ 200 GeV/c² the ZZ/WW BR ~ 1/3

- Γ_H rapidly increase with m_H, but remains < 1 GeV/c² up to m_H ~ 200 GeV/c²
  - the experimental resolution is ~ 1-4 GeV/c²

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

The **C**ompact **M**uon **S**olenoid detector

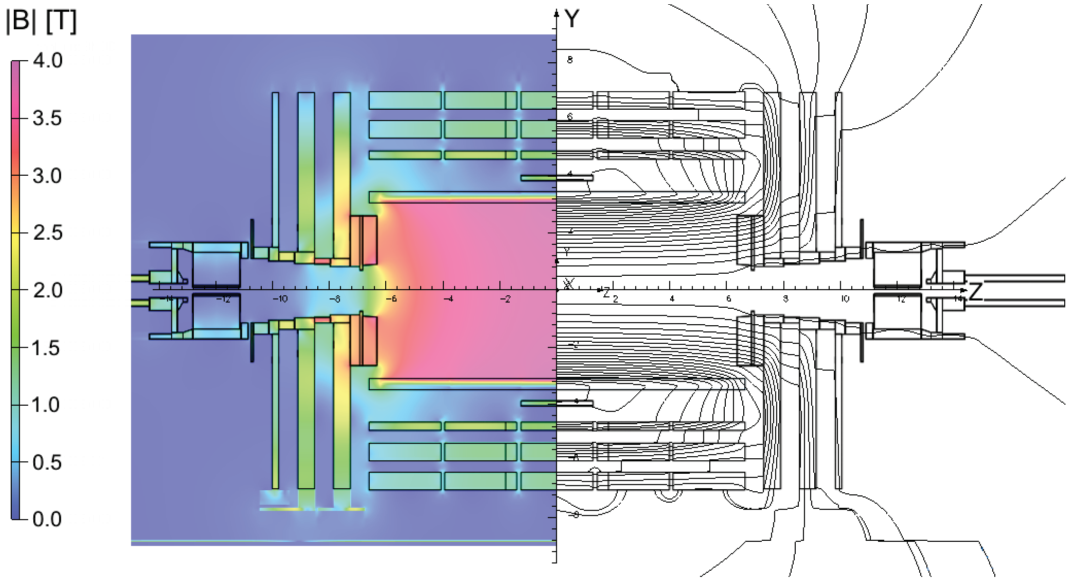
Layout



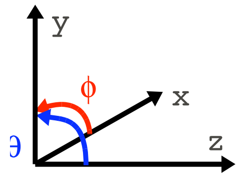
- high lepton reconstruction efficiency
- excellent lepton/photon identification
- excellent lepton/photon energy resolution

Main Features:

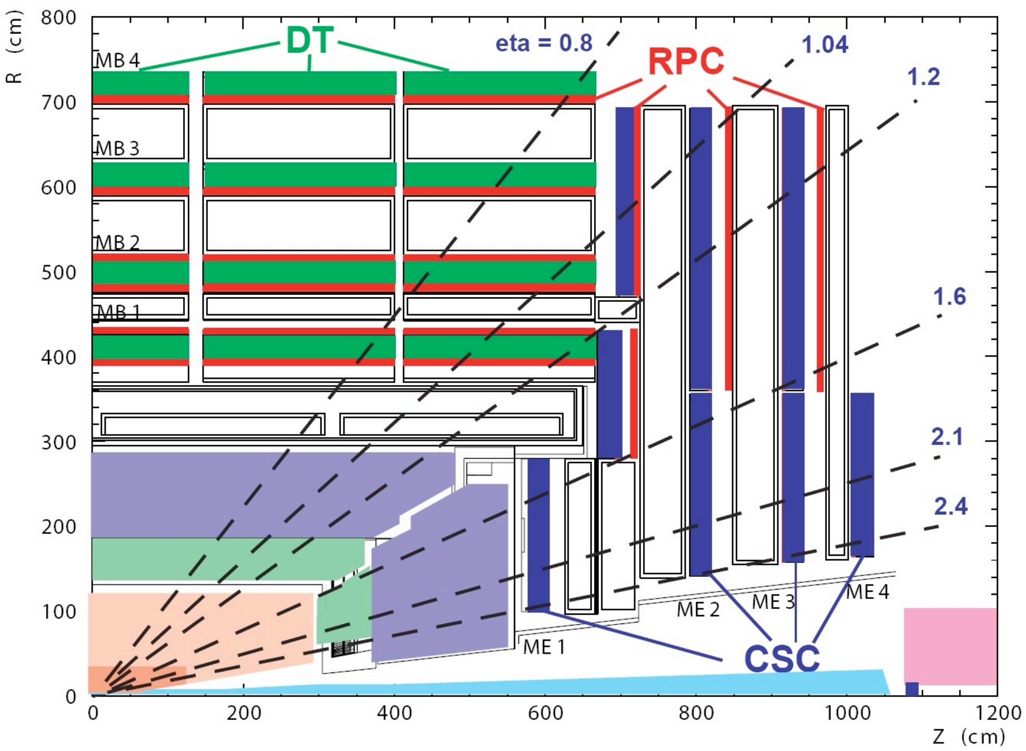
- 3.8 T superconducting solenoid
- a robust and redundant muon system
- a good electromagnetic calorimeter
- a high-quality tracker system



The Muon System



$$\eta = -\ln \tan\frac{\theta}{2}$$



Barrel: η < 0.9

Overlap: 0.9 < η < 1.2

Endcap: 1.2 < η < 2.4

- Outside the magnet coil, the iron return yoke hosts the MUON SPECTROMETER [|η| < 2.4]
  - **triggering on muons**
  - **identifying muons**
  - **assisting the tracker in measuring momentum and charge of high-p_T muons.**
- 3 types of gaseous particle detectors
  - **Drift Tube (DT) chambers** [|η| < 2.1]
  - **Cathode Strip Chambers (CSC)** [0.9 < |η| < 2.4]
  - **Resistive Plate Chambers (RPC)** [|η| < 1.6]

High Mass Selection
for ZZ cross section measurement

$$\sigma(pp \to ZZ + X) \times \mathcal{B}(ZZ \to 4\ell) = \frac{\sum_{i_{ch}} (N_{\rm obs}(i_{\rm ch}) - N_{\rm back}(i_{\rm ch}))}{A \times \epsilon_{(ZZ \to 4\ell)} \times \mathcal{L}}$$

$$A = \frac{N_{MC}(60 < M_{Z_1} < 120, 60 < M_{Z_2} < 120, |\eta| < 2.4(2.5), p_T > 5(7))}{N_{MC}(60 < M_{Z_1} < 120, 60 < M_{Z_2} < 120)} \qquad \varepsilon = \frac{N_{MC} - high - mass - selection}{N_{MC}(60 < M_{Z_1} < 120, 60 < M_{Z_2} < 120, |\eta| < 2.4(2.5), p_T > 5(7)}$$

Final state	$N_{\rm obs}$	$N_{\rm back}(Z+X)$	$N_{\rm back}(ZZ_\tau)$	$N_{exp} ZZ \to 4\ell$
4μ	14	0.47 ± 0.26	0.031 ± 0.003	14.7 ± 1.3
4e	8	0.22 ± 0.07	0.026 ± 0.002	10.3 ± 1.0
$2e2\mu$	30	0.65 ± 0.20	0.057 ± 0.005	24.8 ± 2.3
Total	52	1.34 ± 0.53	0.115 ± 0.010	49.78 ± 4.6

$$\sigma(pp \to ZZ + X) \times \mathcal{B}(ZZ \to 4\ell) = 28.1^{+4.5}_{-3.9}(\text{stat.}) \pm 1.0(\text{syst.}) \pm 1.3(\text{lumi.})\ \text{fb}$$

SM expectation [MCFM] = 27.9 +- 1.9

SYSTEMATIC UNCERTAINTIES:

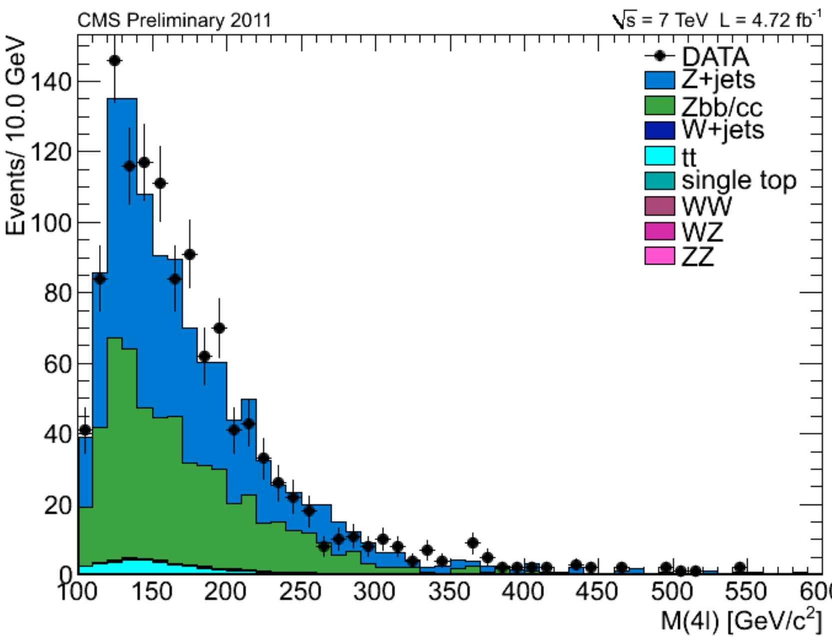
- Instrumental systematics on lepton measurements affecting the efficiencies
- Syst uncertainties on N_{back} from data-driven estimation
- Theoretical uncertainties [PDF and QCD scale] affecting the acceptance

Evaluation of all instrumental and reducible background with a reconstructed Z1 and 2 "fake leptons": Z+X inclusive measurement

All leptons but those from W/Z decay [prompt and isolated]: from decay of heavy quarks/ from decay-in-flight of light hadrons / from jets faking leptons

Control Region:

Z1 + ll SS [ID and ISO relaxed] with $SIP_{3D}(l) < 4$, m4l >100, 3/4 mll > 12



Control regions defined separately for each final state: 4μ/4e/2μ2e

Extrapolation to the signal region with the fake rate method

$$N^{Z+X}_{expect} = N^{DATA} \times \left(\frac{OS}{SS}\right)^{MC} \times$$
$$\Big[\epsilon_1(p_T,\eta)_{|R_{iso}<0.175} \times \epsilon_2(p_T,\eta)_{|R_{iso}<0.175} +$$
$$\frac{1}{2} \times \epsilon_1(p_T,\eta)_{|R_{iso}<0.175} \times \epsilon_2(p_T,\eta)_{|0.175<R_{iso}<0.35} +$$
$$\frac{1}{2} \times \epsilon_1(p_T,\eta)_{|0.175<R_{iso}<0.35} \times \epsilon_2(p_T,\eta)_{|R_{iso}<0.175}\Big]$$