$H \rightarrow ZZ^{(*)} \rightarrow 4$ leptons in CMS

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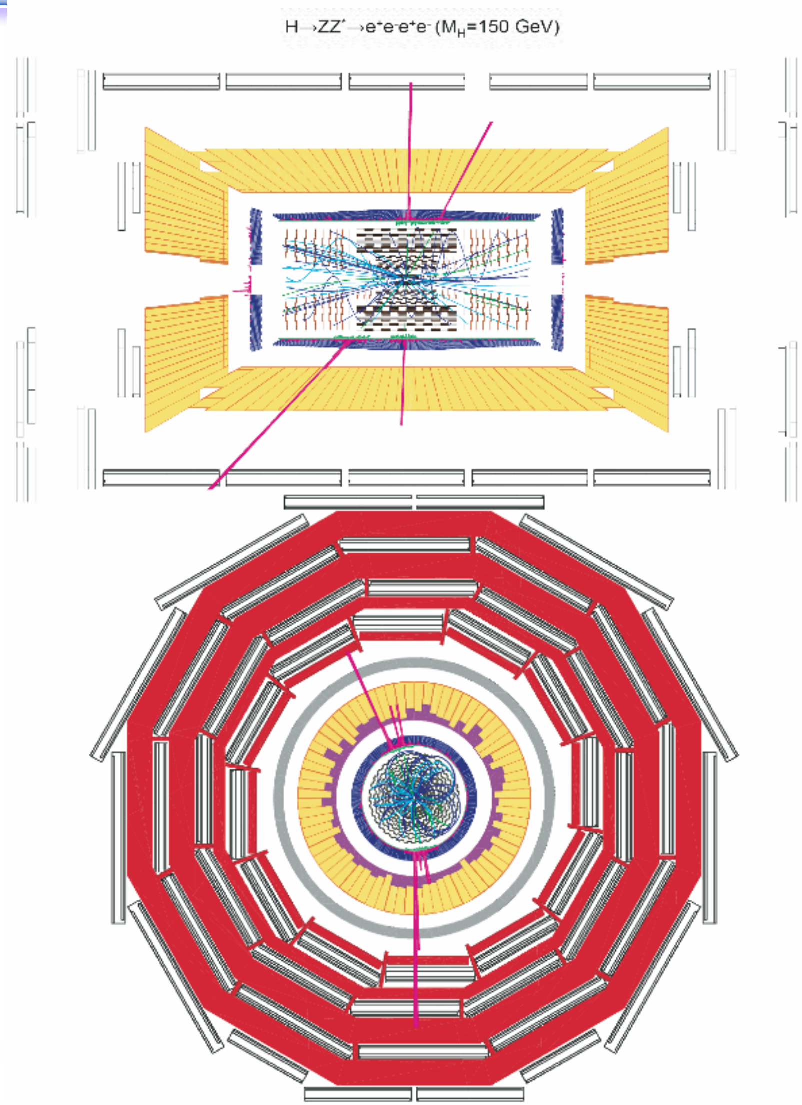
LHC DAYS IN SPLIT

2 - 7 October 2006

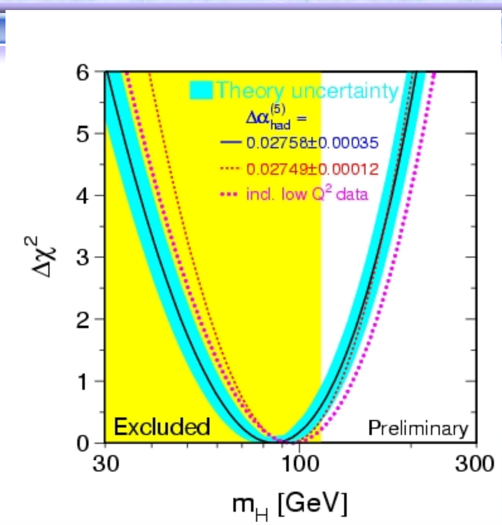
Outline

- Introduction
- CMS
- Signal and backgrounds
- Electron and muon reconstruction
- Online selection
- Offline selection
- $ZZ^{(*)}$ background estimation
- Systematics
- Results
  - Discovery potential
  - Measurements

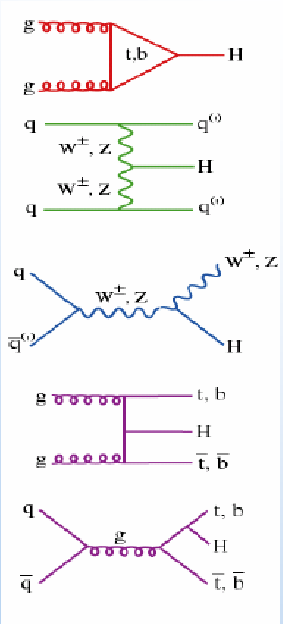


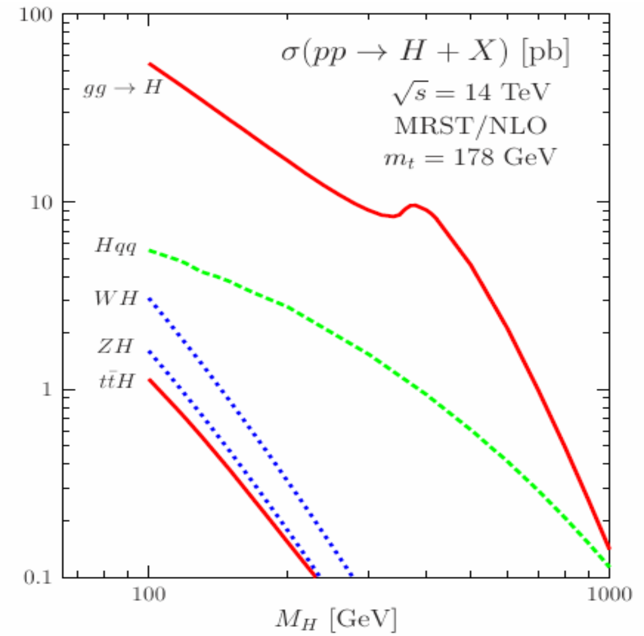
Introduction

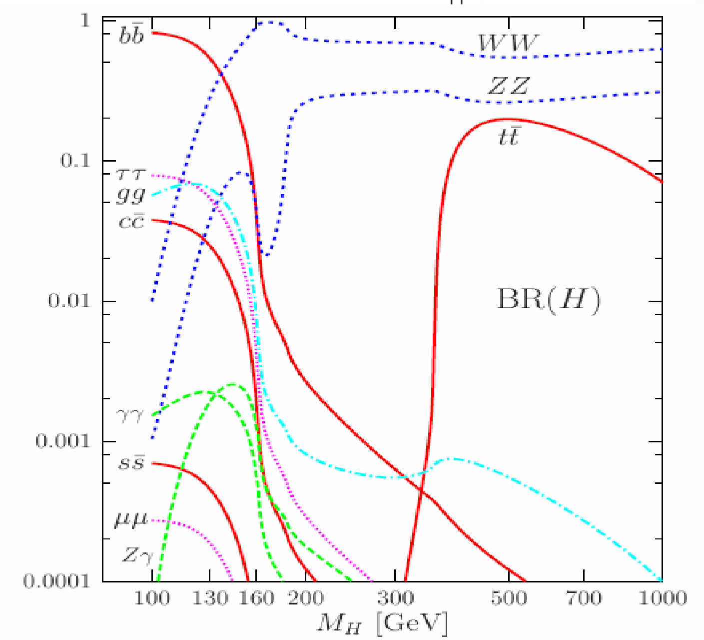
- Constraints on Higgs boson mass:
  - Indirect constraints from EW fit: m_H < 166 GeV @95% CL
  - Direct limit from LEP: M_H > 114.4 GeV



- Production and decay:







Introduction (2)

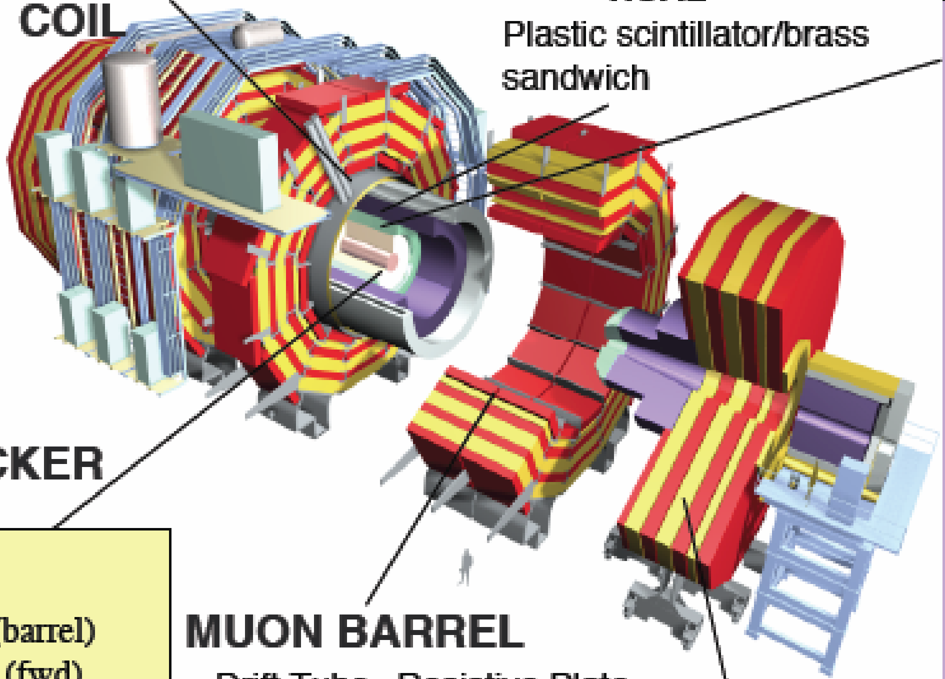
- $H \rightarrow ZZ^{(*)} \rightarrow 4l$:
  - $\mu^+ \mu^- \mu^+ \mu^-$
  - $e^+ e^- e^+ e^-$
  - $e^+ e^- \mu^+ \mu^-$
- One of the most sensitive channels for the discovery of the SM Higgs boson over a wide range of masses
  - High branching ratio $H \rightarrow ZZ^*$
  - Very clean signature: 2 pairs of leptons
    - opposite-charged
    - same flavor
    - isolated
    - coming from the primary vertex
  - Relatively small backgrounds

CMS

SUPERCONDUCTING COIL

HCAL
Plastic scintillator/brass sandwich

CALORIMETERS



TRACKER

PIXEL
3 layers (barrel)
2x2disks (fwd)

SST
>8 hits, depending on η

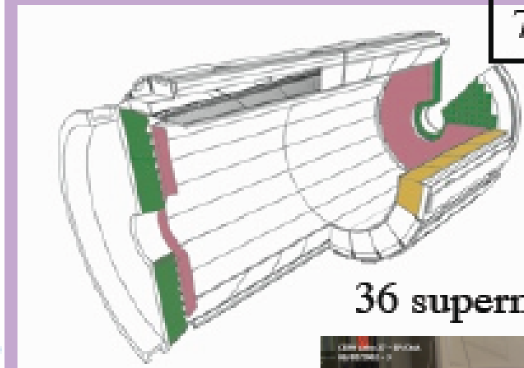
$|\eta|<2.5$

MUON BARREL
Drift Tube   Resistive Plate
Cathode Strip Chambers

Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

ECAL Scintillating PbWO4 crystals

75848 Xtals



36 supermodules

4 dees

$|\eta|<2.6$

2x5 Xtal modules

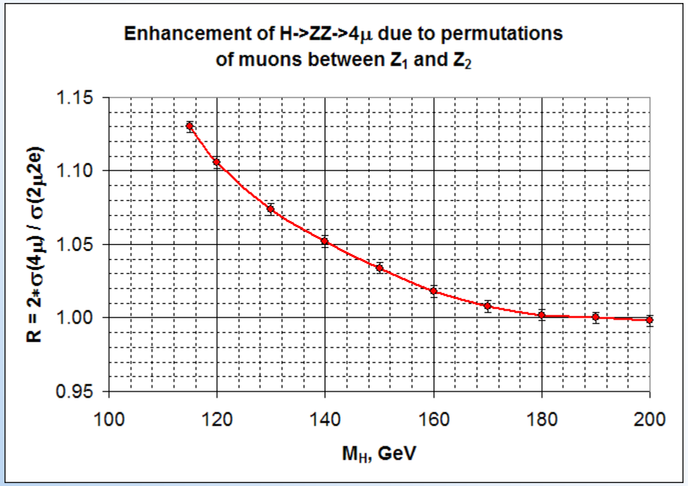
General strategy

- 3 independent analysis but common tools:
  - Generation, simulation
  - Signal and background production and cross-sections
  - Counting experiment approach

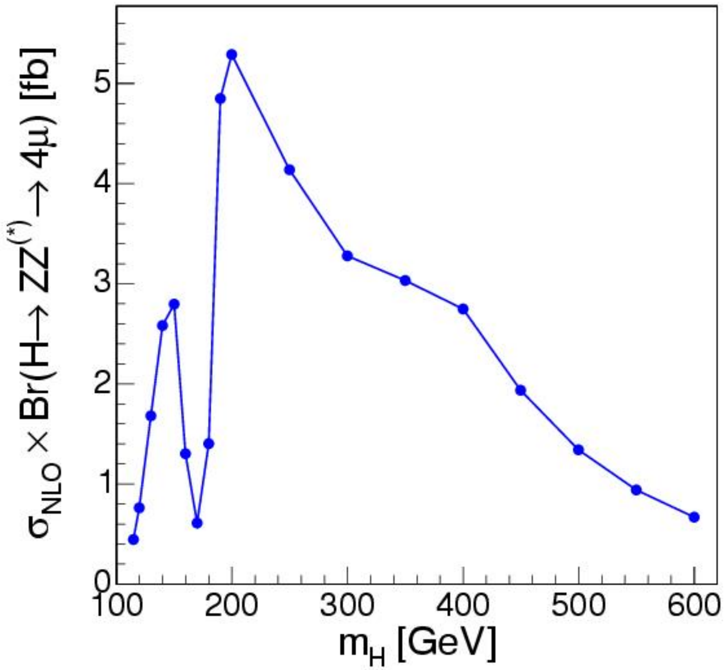
- Realistic conditions:
  - Full simulation of the detector is used
  - LHC low luminosity conditions $L = 2.10^{33}\ cm^{-2}\ s^{-1}$
  - Energy center of mass = 14 TeV
  - Cut analysis, mass dependent or independent
  - Evaluation of systematics
  - Measurement of background using data

Signal

- Generation ($115 < m_H < 600$ GeV):
  - Pythia
    - LO *gg* fusion and *vbf* production
    - PHOTOS for QED radiations
  - Normalized to NLO cross sections + all other production modes
  - Decay $H \to ZZ^{(*)} \to$ leptons
  - Interference enhancement for 4e and 4μ



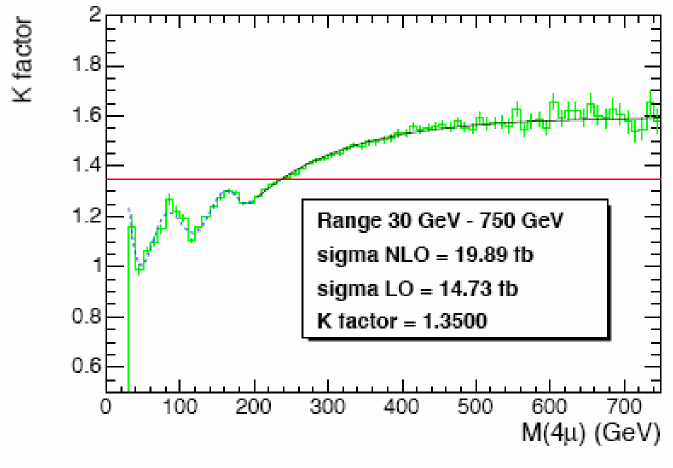
- Generator preselection:
  - 4μ: $2\mu^+$ & $2\mu^-$ $p_T^\mu>3$ GeV $|\eta^\mu|<2.4$
  - 4e: $2e^+$ & $2e^-$ $p_T^e>5$ GeV $|\eta^e|<2.7$
  - $2e2\mu$: e^+e^- & $\mu^+\mu^-$ same cuts



Backgrounds

- Main backgrounds (same presel):
  - ZZ* → 4l:
    - Irreducible background
    - 2e2μ & 4e: Pythia LO, *qq* and *t*-channel only
    - 4μ: Comphep+Pythia LO, +*s*-channel (10%)
    - NLO MCFM m_{4l} dependent factor + 20% *gg*

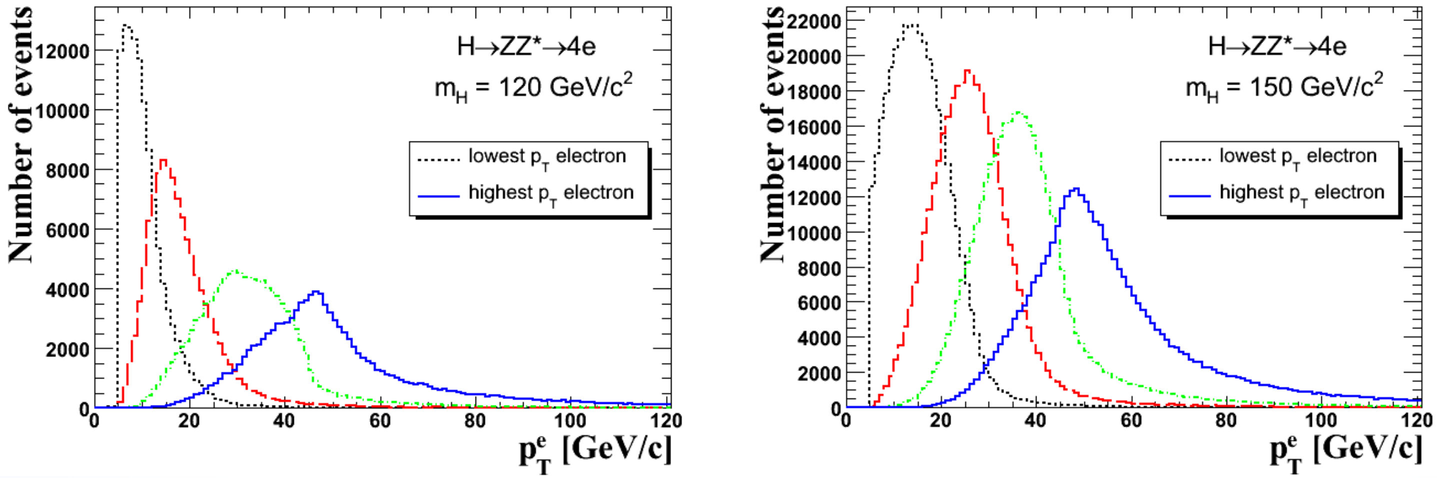
$$\sigma_{NLO} = \left[K_{NLO}(m_{ZZ}) + 0.2\right] \cdot \sigma_{LO}$$



- Zbb → 4l (llbb → 4l)
  - Comphep+Pythia LO
  - NLO MCFM K_{NLO} = 2.4 ± 0.3
  - No b decay forcing
  - ≥2 l^+l^- with $5 < m_{l^+l^-} < 400$ GeV
- tt → 4l
  - PYTHIA LO *gg/qq*
  - No b decay forcing
  - NLO

	Initial σ (pb)	σ*BR*ε (fb) 4μ	σ*BR*ε (fb) 4e	σ*BR*ε (fb) 2e2μ
ZZ*→4l	29	89	20	37
Zbb→4l	276 555 2e2μ	290	120	390
tt→4l	840	233	194	743

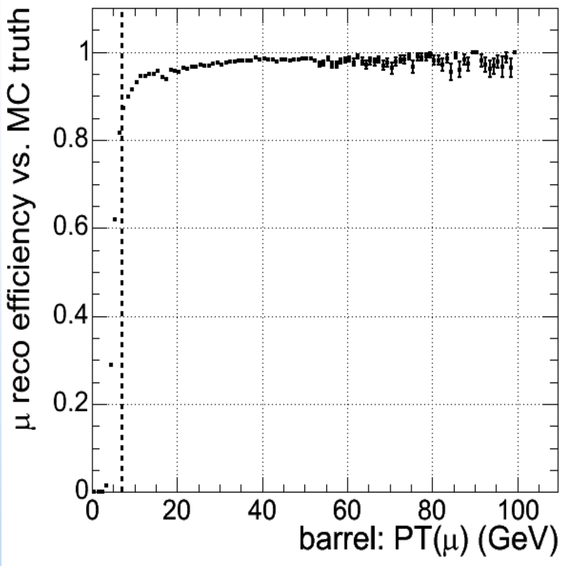
Electron reconstruction

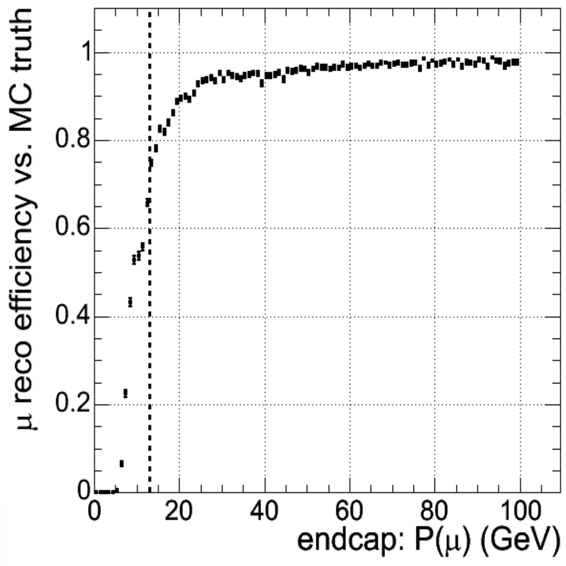


- ⇒ requires good electron reconstruction until low p_T
  - Tracker material (~1 X_0) + strong magnetic field (4 T) ⇒ large effects: brem, energy lost
  - New reconstruction algorithms developed :
    - Use of Gaussian Sum Filter tracking - electron track reconstructed right out to ECAL surface.
    - Extend clusters in ϕ and p_T for better brem collection
  - Classification of electrons → correction by class
    Combination E & p → better momentum estimation
  - Error estimation of the parameters for each electron

Muon reconstruction

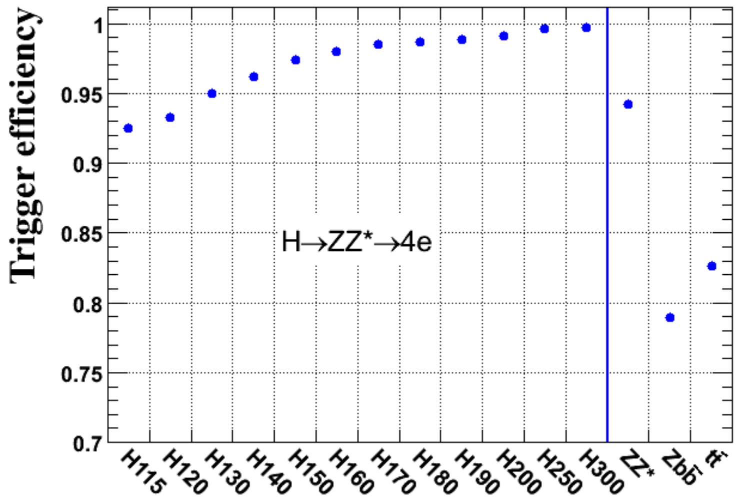
- Reconstruction algorithm: matching between independent reconstruction
  - in the muon system
  - and in the tracking system
- Efficient reconstruction:
  - $p_T > 7$ GeV for barrel ($|\eta_\mu|<1.1$)
  - $p > 13$ GeV for endcap ($|\eta_\mu|>1.1$)

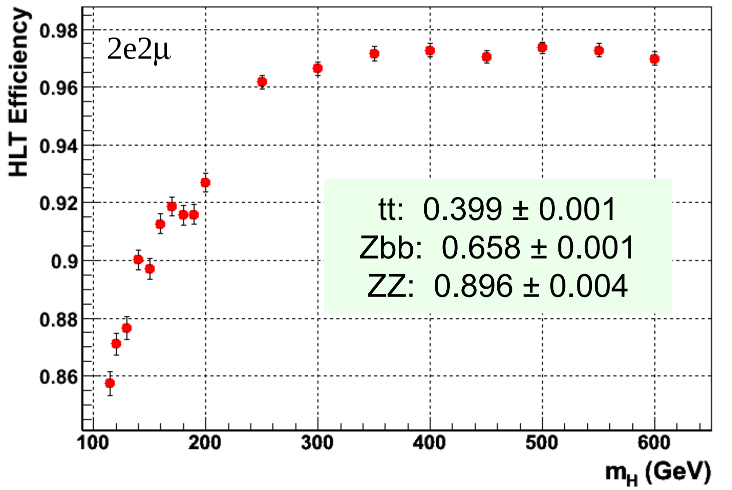




Trigger

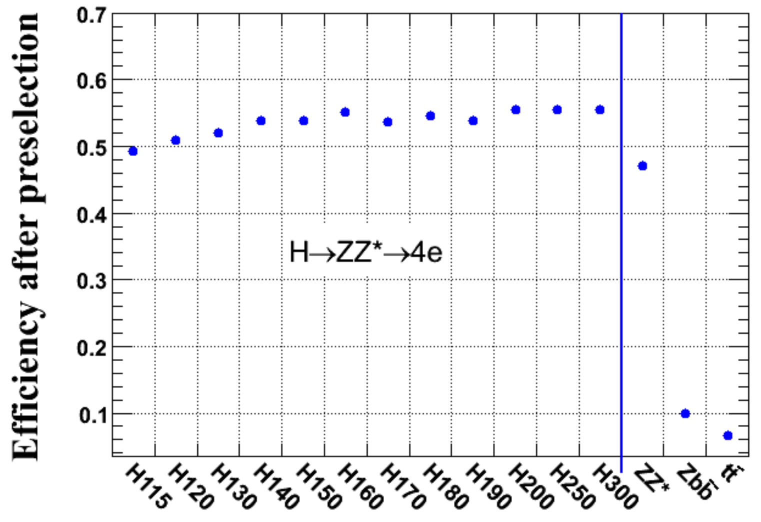
- LHC bunch crossing rate = 40 MHz
- CMS trigger:
  - Level 1 (hardware)
  - High Level Trigger (software)
- Chosen triggers:
  - 4μ:
    - single muon (E_T > 19 GeV)
    - or double muon (E_T > 7 GeV)
    - efficiency ~100% for all masses
  - 4e:
    - single electron (E_T > 26 GeV)
    - or double electron (E_T > 14.5 GeV)
  - 2e2μ:
    - double electron
    - or double muon

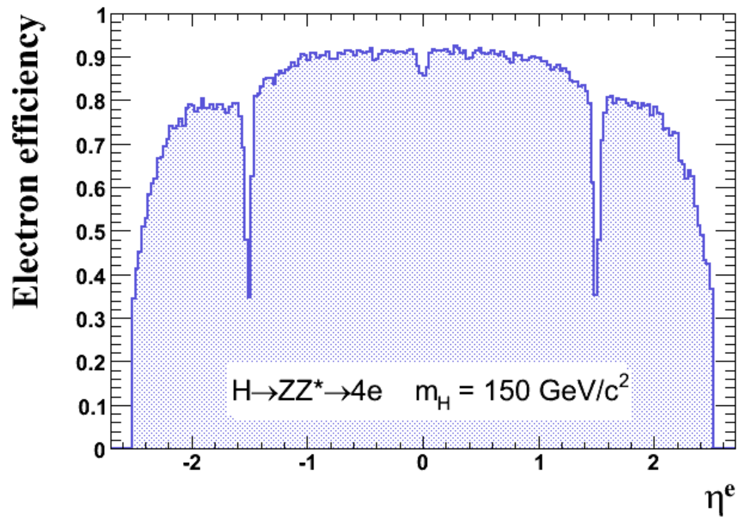


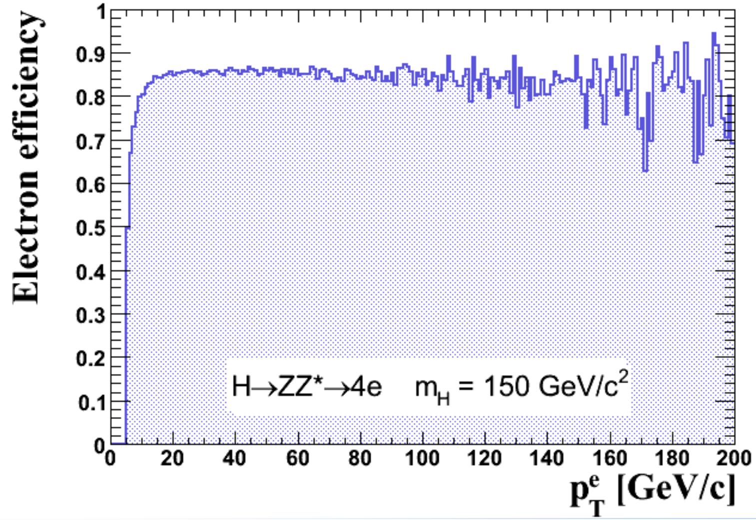


Preselection

- $4e: \geq 2e^+ 2e^-$ verifying
  - $E_{ecal} / p_{track} < 3$
  - $|\Delta\eta| < 0.02; \ |\Delta\phi| < 0.1$
  - $H/E < 0.2$
  - Loose iso: $\Sigma p_T^{tracks}{}_{,R=0.2}/p_T^e < 0.5$
  - $p_T > 5$ GeV $|\eta|<2.5$

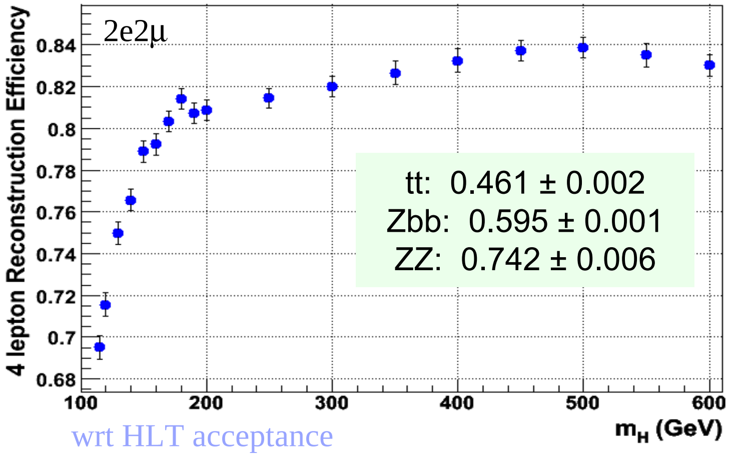




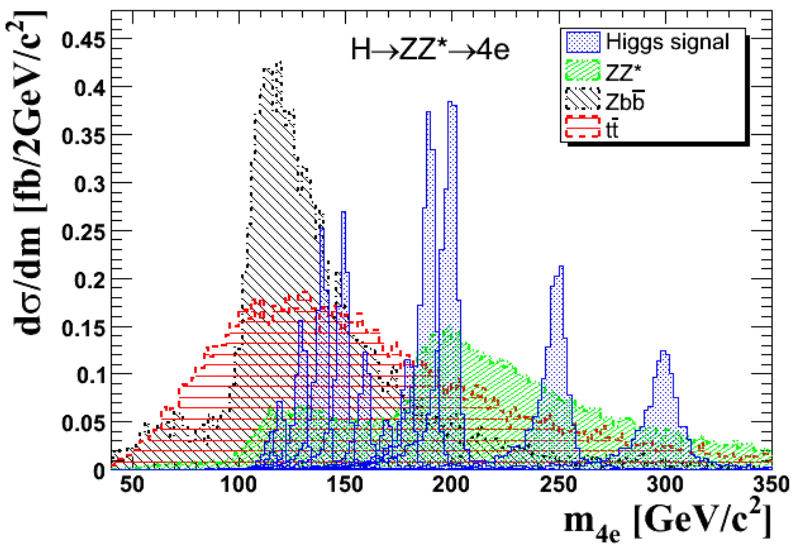


Preselection

- $2e2\mu$: $e^+e^-\mu^+\mu^-$
  - Likelihood on electrons based on track-cluster matching ($\Delta\eta$ and E_{ecal}/p_{track}), cluster shape and H/E



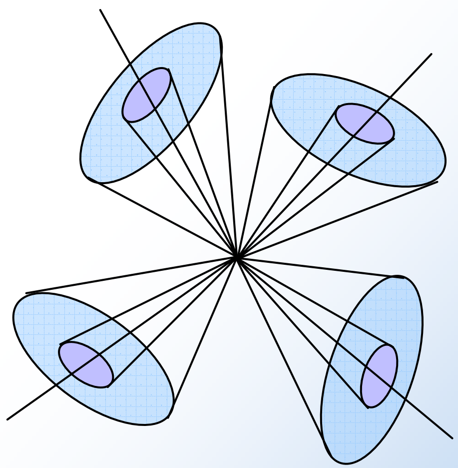
- After preselection



- 4μ: $\geq 2\mu^+ 2\mu^-$
  - $p_T > 7$ GeV for barrel ($|\eta|<1.1$); $p > 13$ GeV for endcaps ($|\eta|>1.1$)
  - $m_{\mu+\mu-} > 12$ GeV for all permutations

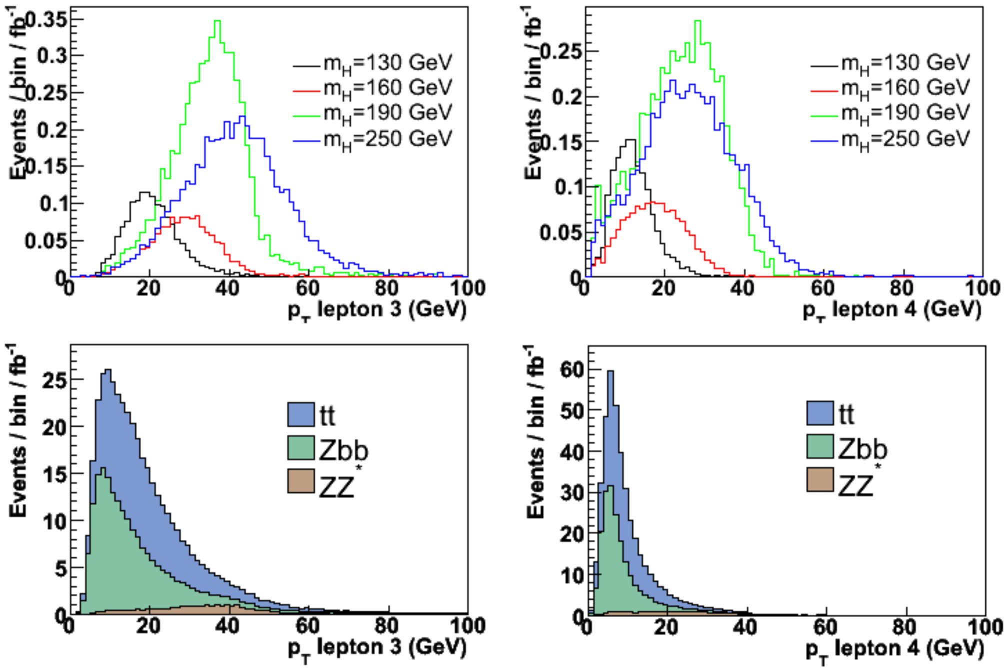
Isolated primary leptons

- 4 leptons:
  - Signal and ZZ* background: from the primary vertex and isolated
  - Zbb and tt: leptons from b are from displaced vertices and not isolated
- Vertexing and impact parameter tools
  - Cut on longitudinal and transverse impact parameter for the 4 leptons
  - Refit of vertex with the 4 leptons (2e2μ)
- Isolation:
  - Track isolation $\Sigma p_T^{tracks}{}_{,R=0.2}/p_T^l$
  - Ecal isolation (4μ)
  - Hadronic isolation $\Sigma E_T^{HCAL}{}_{,R=0.2}/p_T^l$
- Performances:
  - Signal efficiencies 81 - 85 %
  - Rejection tt ~ 20 Zbb ~ 5 - 10

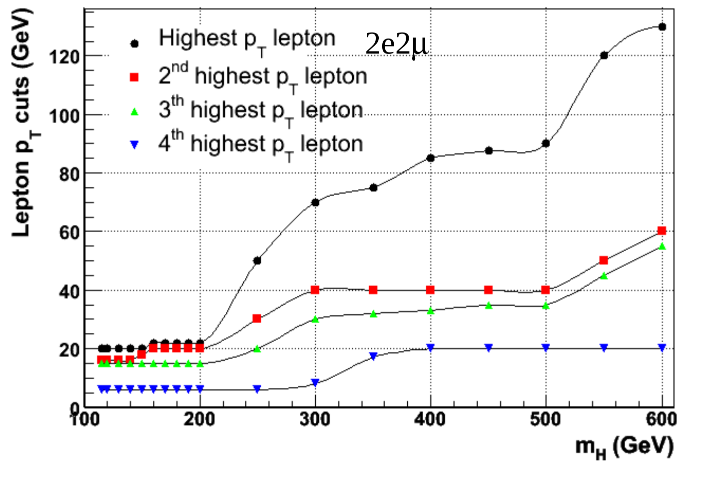


Kinematical event selection

- Lepton p_T: 2e2μ



- Typical cuts



- Performances:
  - signal efficiencies 75 - 98 %
  - Zbb rejection 4 -1000
  - tt rejection 3 - 50

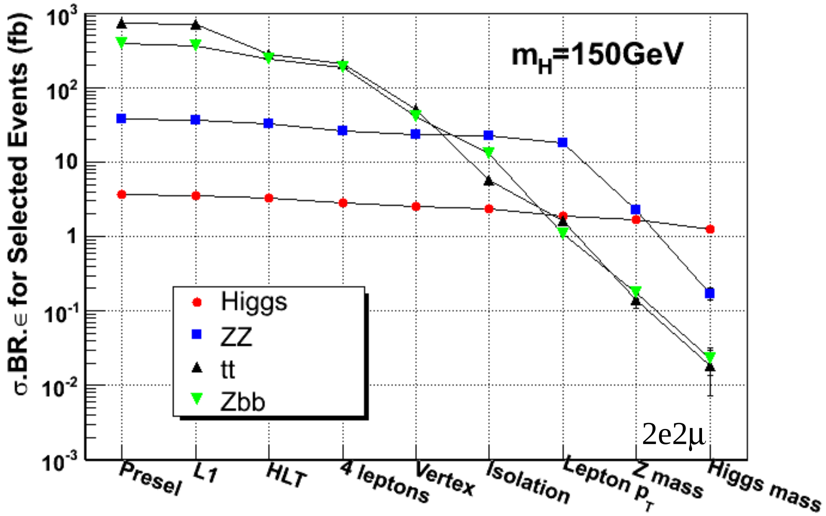
- Invariant masses :

$$M_{Z^{(*)}}^{\min} < M_{Z^{(*)}} < M_{Z^{(*)}}^{\max}$$

  - Mass dependent cuts
  - Help rejecting more reducible backgrounds and ZZ* in 4e and 2e2μ, not in 4μ

Selection: summary

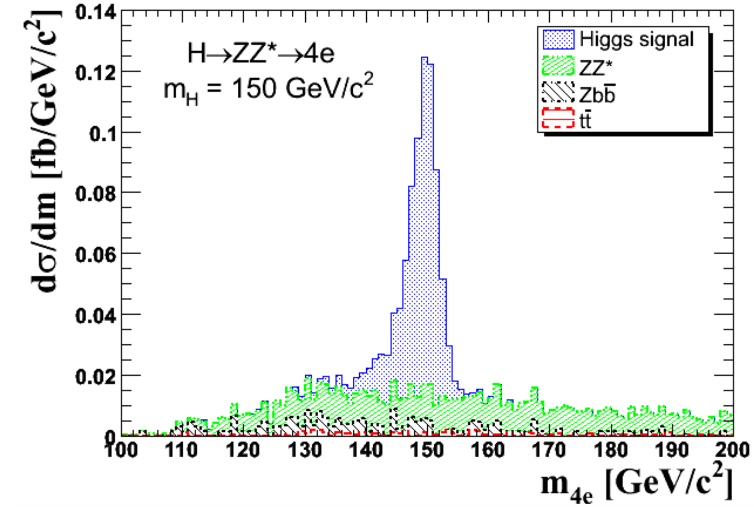
- Typical performances (depending on masses):
  - Signal efficiencies 25 - 50 %
  - ZZ* rejection 20 - 4
  - Zbb rejection 500 -100000
  - tt rejection 2000 - 20000

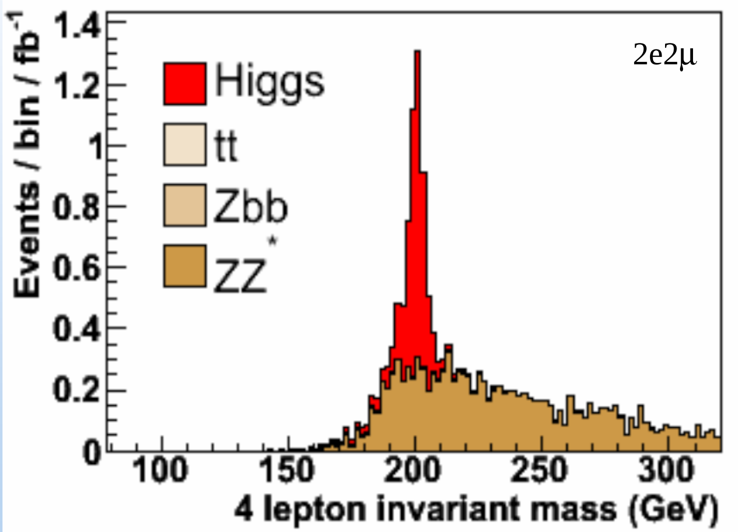


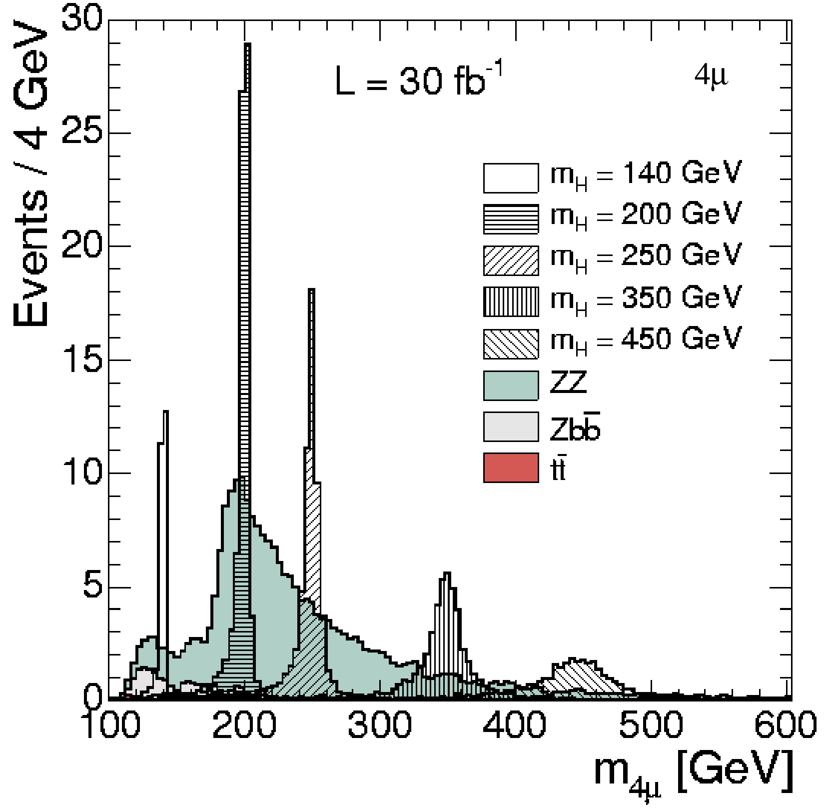
- For all masses:

ZZ* dominant or sole:	>75%		>97%	for $m_H > 2m_Z$
Zbb:	20 - 15%	low masses	<2%	for $m_H > 2m_Z$
tt:	5 - 7%	low masses	<0.6 %	for $m_H > 2m_Z$

After event selection





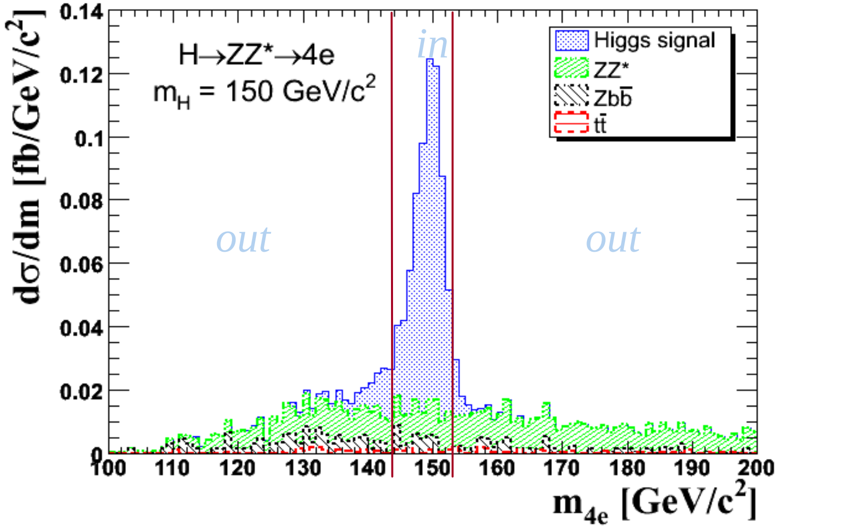


ZZ* background estimation

- ZZ* dominant or sole ⇒ estimation:
  - Direct simulation ⇒ large theoretical uncertainties
  - Normalization to Z → l^+l^- data ⇒ partial systematics cancellation
  - From sidebands

$$N^{in}_{bckgd}\Big|_{Measured} = \alpha_{MC} N^{out}_{bckgd}\Big|_{Data}$$

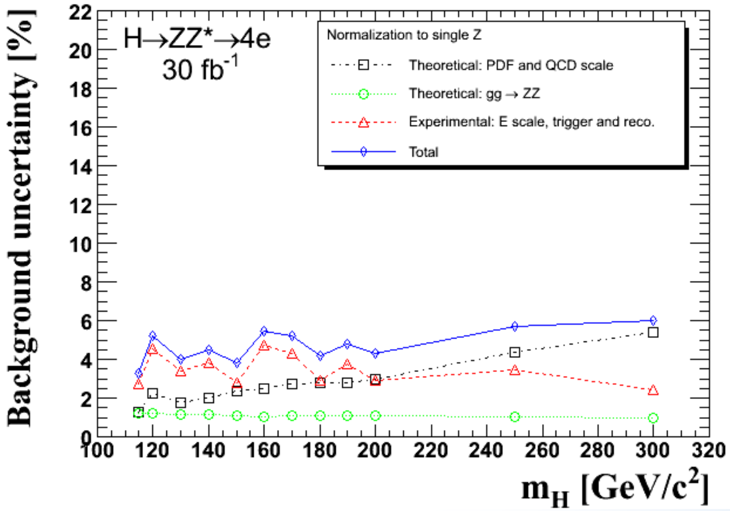
$$\alpha_{MC} = \frac{N^{in}_{bckgd}}{N^{out}_{bckgd}}\Bigg|_{MC}$$



⇒ very low theoretical uncertainties but large statistical uncertainties

Systematics

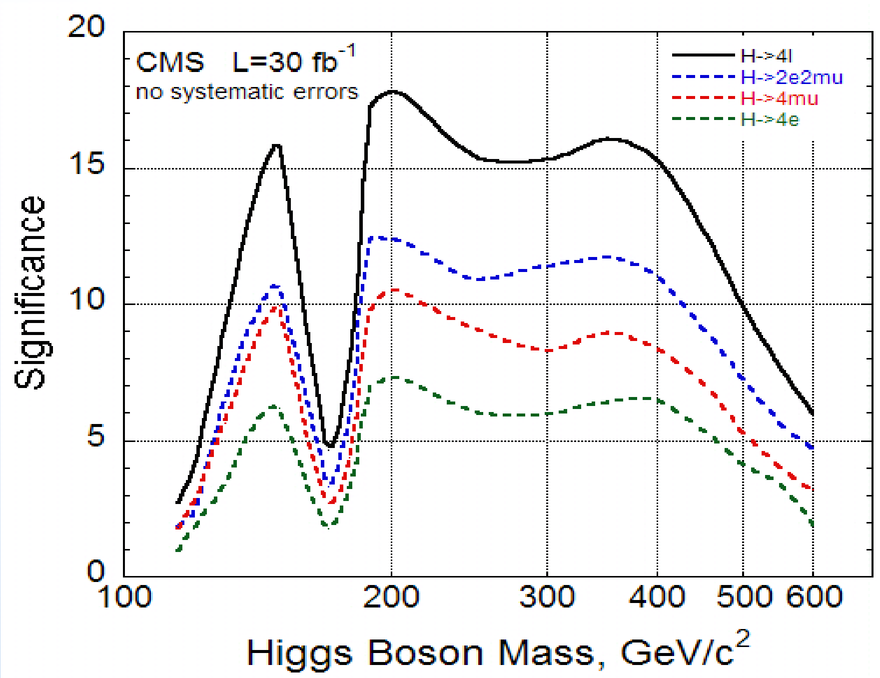
- Theoretical uncertainties
  - PDF
  - QCD scale
- Experimental uncertainties
  - Luminosity : ±3% for ∫Ldt > 10 fb^{-1}
  - Trigger efficiency: ±1%
  - Material budget
  - Reconstruction, isolation, and identification efficiencies
  - Energy scales

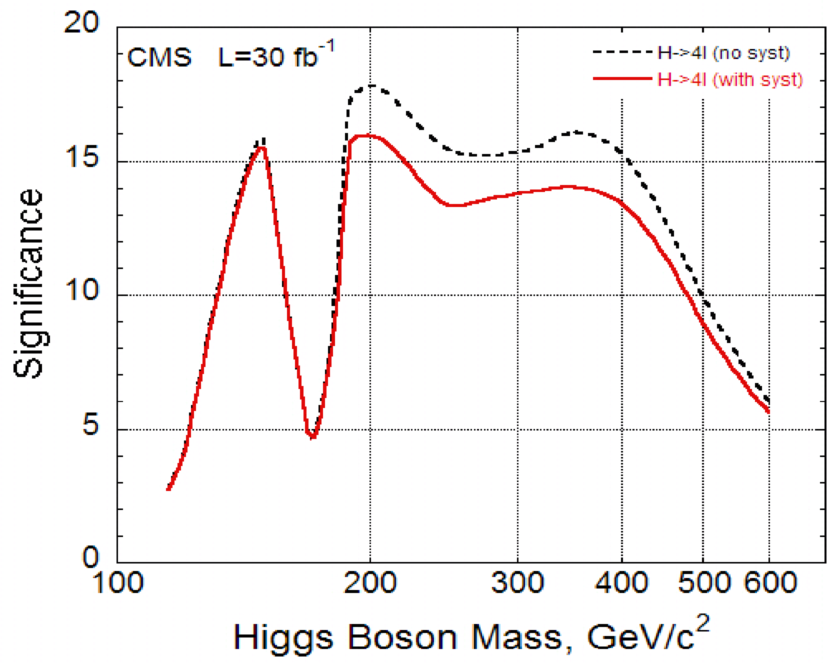


- Experimental uncertainties estimation
  - Use leptons from W → lν and Z → ll data
  - Extrapolate to other regions with MC simulations
  - ⇒ 0% material budget, 1% efficiency, 0.5 % - 1% energy scale

Discovery potential

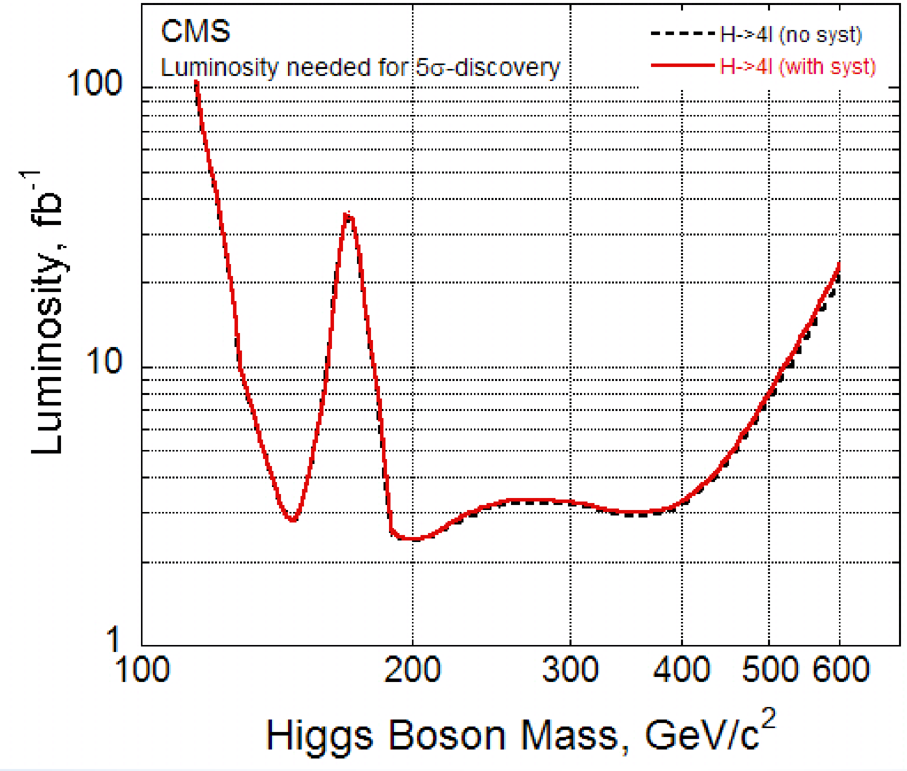
- Significance versus m_H
  - No systematics :
  - Effect of systematics :





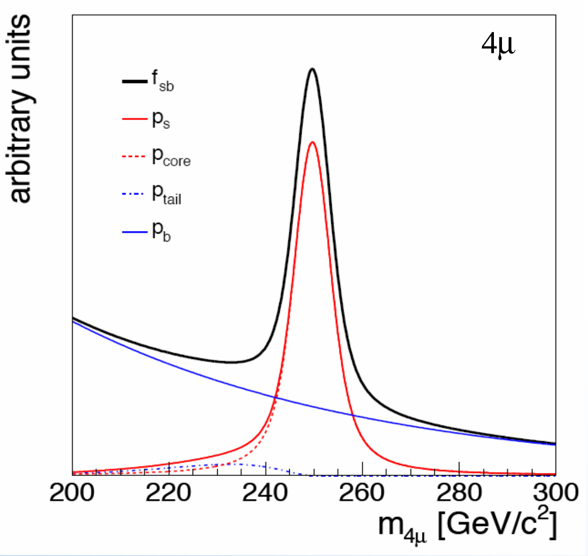
Discovery potential

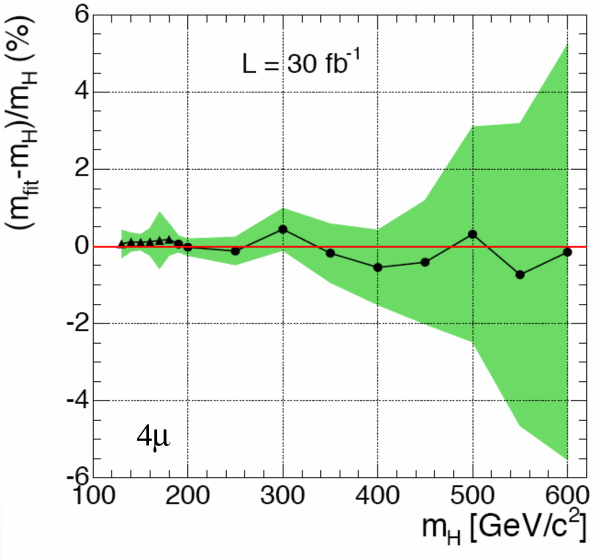
- Needed luminosity for 5σ discovery versus m_H

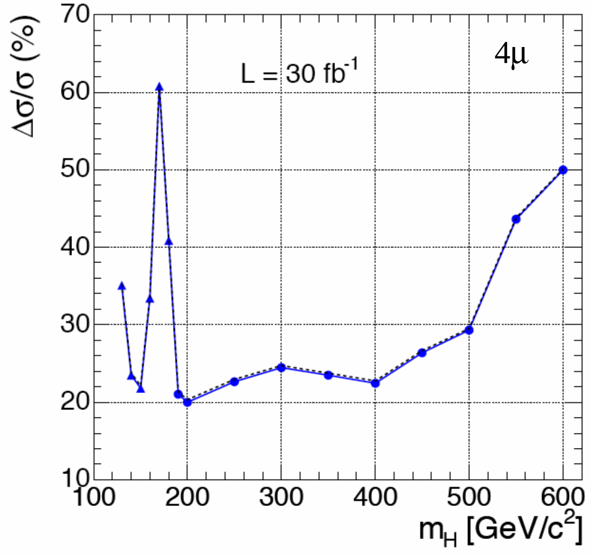


Measurements

- Components of fit:
- Mass:
- Cross section:







Summary

- CMS SM Higgs discovery potential in the $H \rightarrow ZZ^{(*)} \rightarrow 4l$ channel :
  - First evaluation performed entirely on CMS full simulation
  - Includes the evaluation of systematics error, both theoretical and experimental
  - Background estimation strategy on data
- Discovery is possible with less than 10 fb^{-1} in a wide range of mass:
  $130 < m_H < 160$ GeV and $2m_Z < m_H < 550$ GeV

References

- CMS Collaboration, Physics TDR Vol. I, CERN/LHCC 2006-001
- CMS Collaboration, Physics TDR Vol. II, CERN/LHCC 2006-021
- CMS NOTE-2006/106 -- *Discovery potential and search strategy for the Standard Model Higgs boson in the $H \to ZZ^{(*)} \to 4\mu$ decay channel using a mass-independent analysis*

  Authors: M. Aldaya, P. Arce, J. Caballero, B. de la Cruz, P. Garcia-Abia, J.M. Hernández, M.I. Josa
- CMS NOTE-2006/107 -- *A method for determining the mass, cross section, and width of the Standard Model Higgs boson using the $H \to ZZ^{(*)} \to 4\mu$ decay channel*

  Authors: M. Aldaya, P. Arce, B. de la Cruz, P. Garcia-Abia, J.M. Hernández, M.I. Josa
- CMS NOTE-2006/115 -- *Discovery potential for the SM Higgs boson in the $H \to ZZ^{(*)} \to 4e$ decay channel*

  Authors: S. Baffioni, C. Charlot, F. Ferri, N. Godinovic, P.Meridiani, I. Puljak, R. Salerno, Y. Sirois
- CMS NOTE-2006/122 -- *Search Strategy for the Standard Model Higgs Boson in the $H \to ZZ^{(*)} \to 4\mu$ Decay Channel using $M(4\mu)$-Dependent Cuts*

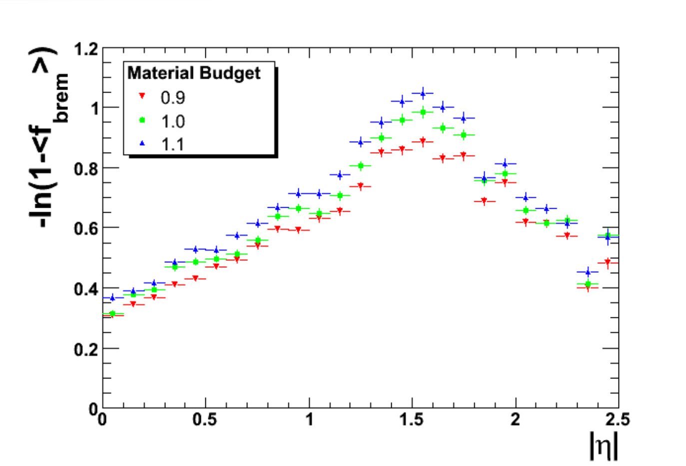
  Authors: S. Abdullin, D. Acosta, P. Bartalini, R. Cavanaugh, A. Drozdetskiy, A. Korytov, G. Mitselmakher, Yu. Pakhotin, B. Scurlock, A. Sherstnev
- CMS NOTE-2006/136 -- *Search for the Standard Model Higgs Boson in the Two-Electron and Two-Muon Final State with CMS*

  Authors: D.Futyan, D. Fortin, D. Giordano

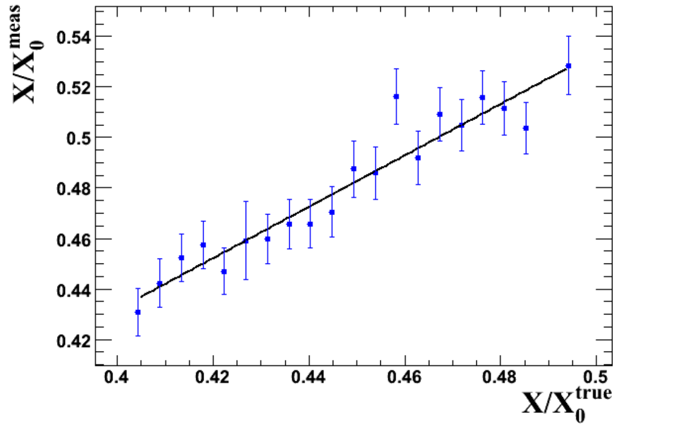
Backup slides

Systematics: material budget

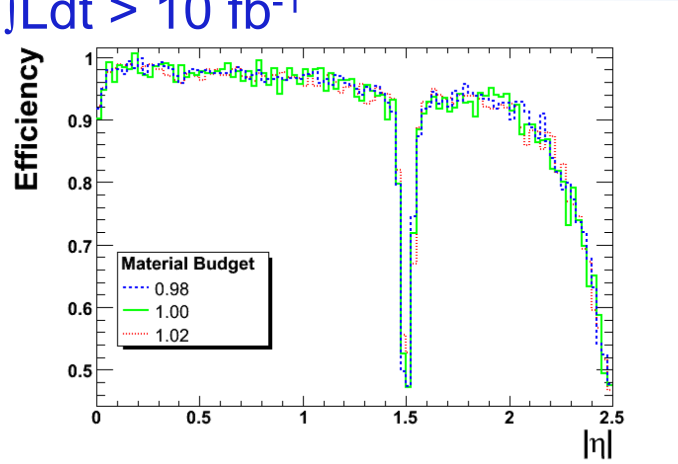
- Material budget
  - Bad knowledge
    ⇒ source of systematics
  - Electron reconstruction
    ⇒ measurement with
    $f_{brem} = (P_{in} - P_{out}) / P_{in}$



- Correlation measurement/real



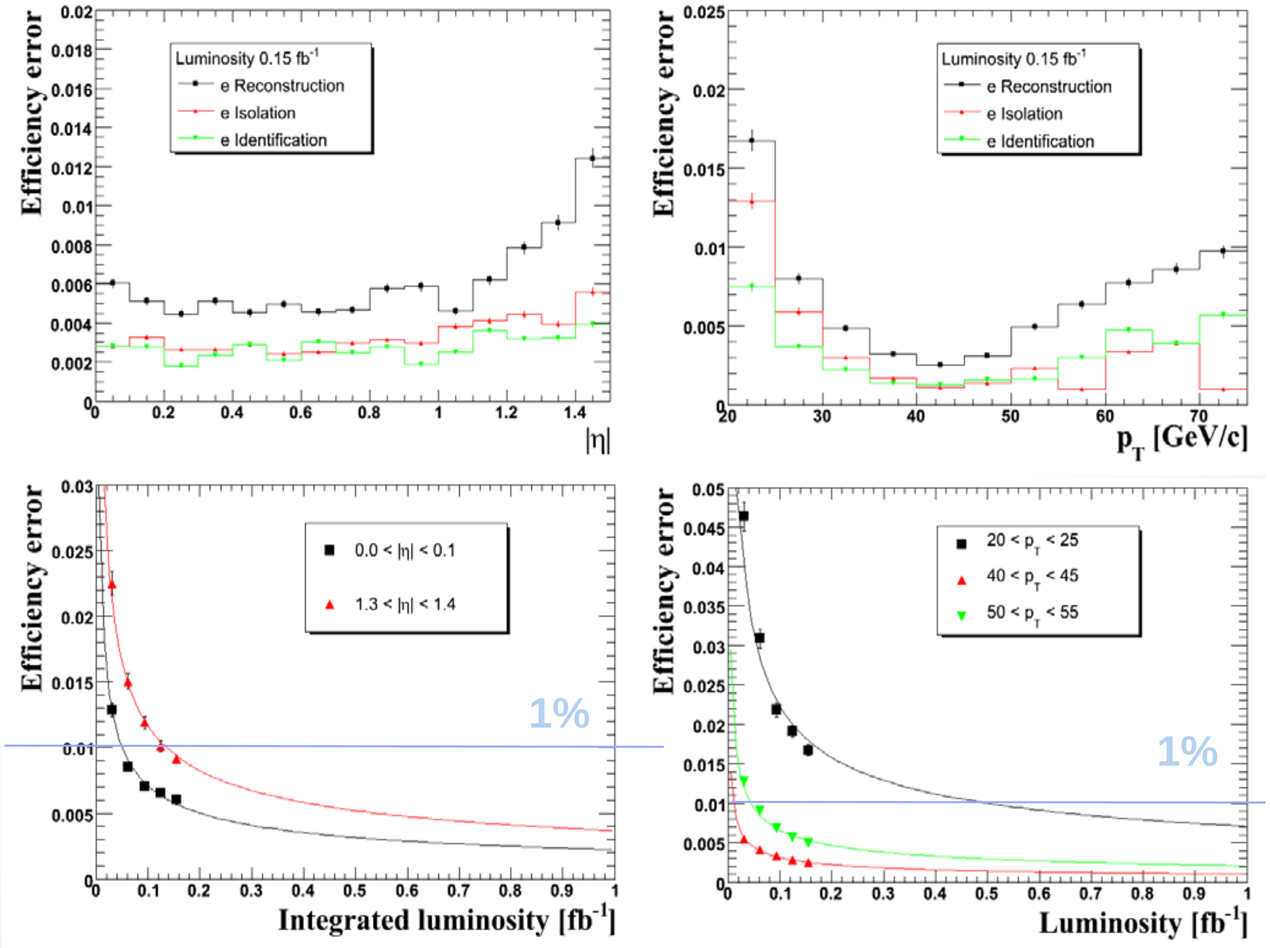
- Precision better than 2 % with $\int Ldt > 10\ fb^{-1}$



- ⇒ no effect on reco efficiency

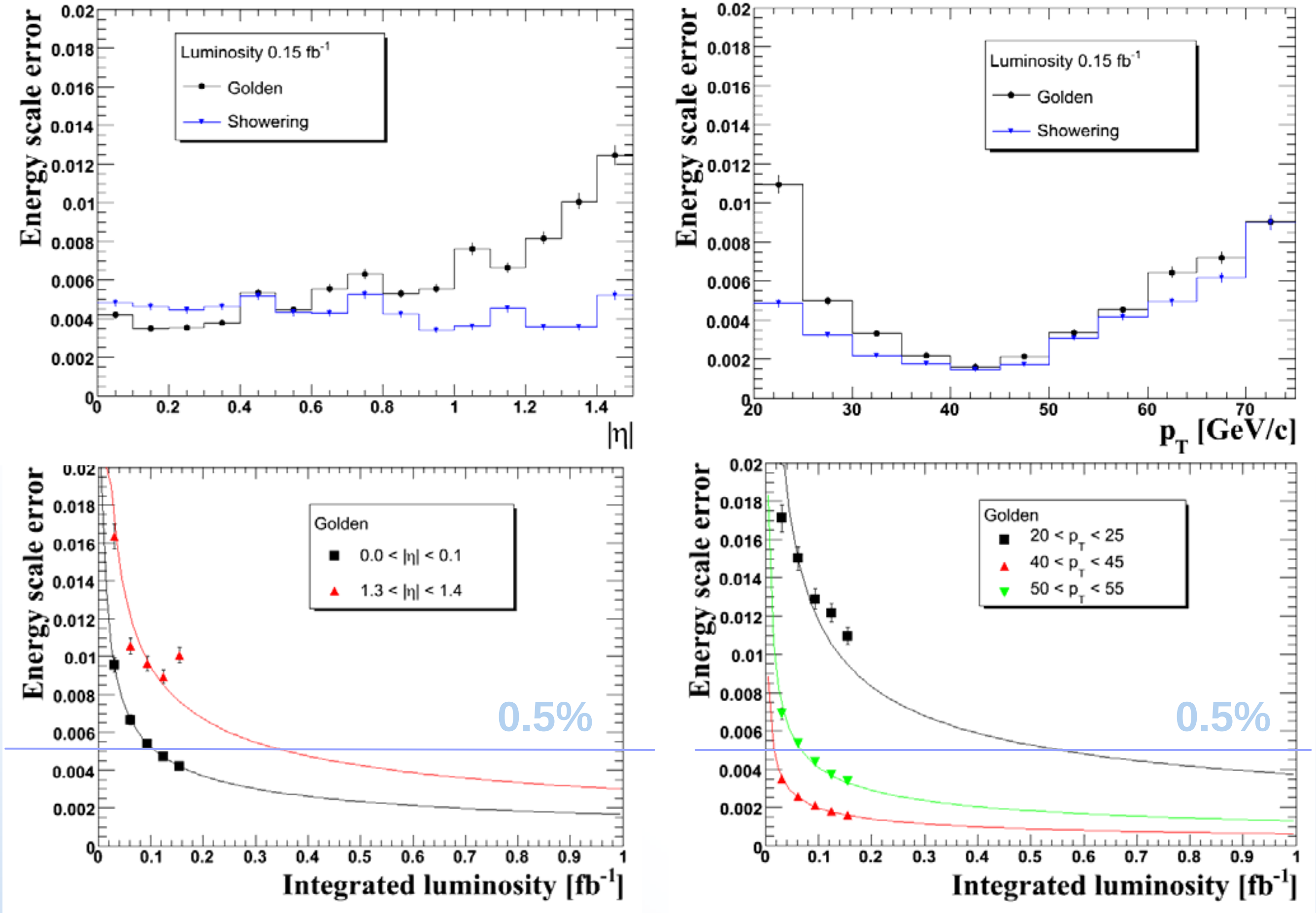
Systematics: efficiencies

- Electrons from Z
  - Large statistics
  - Z selection with one golden electron ⇒ efficiencies mesurements on the other leg



⇒ reconstruction uncertainties <1% per electron

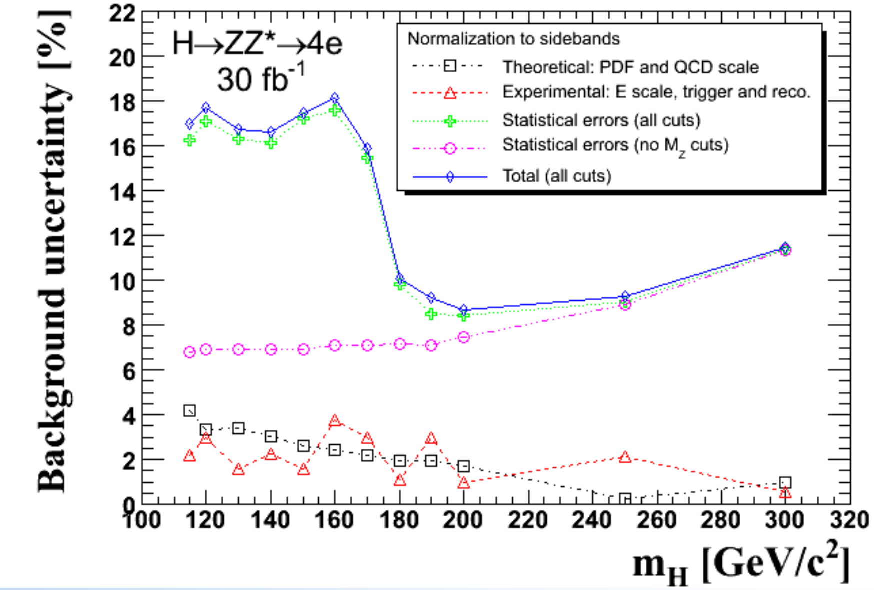
Systematics: energy scale



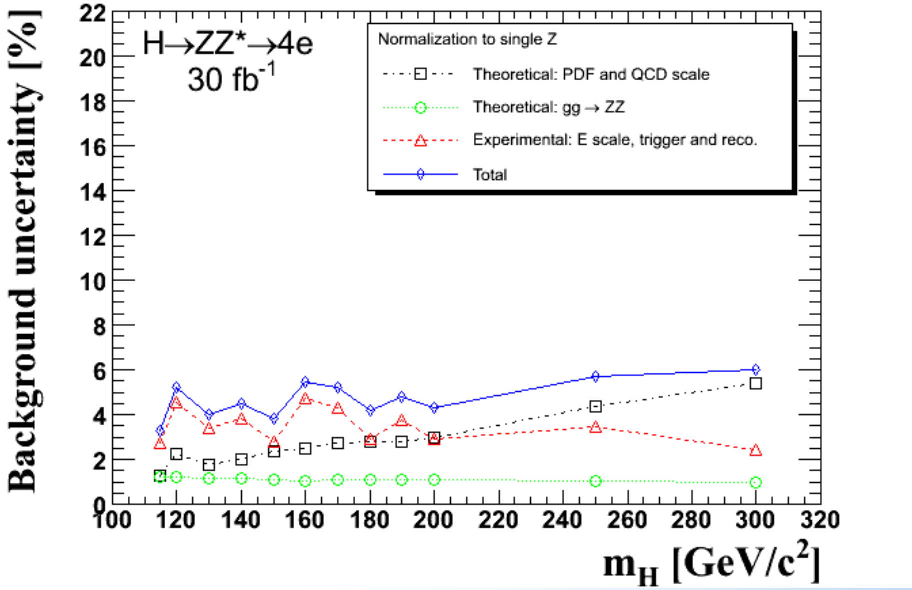
same method ⇒ incertainties 0.5 % barrel 1% endcap

Systematics

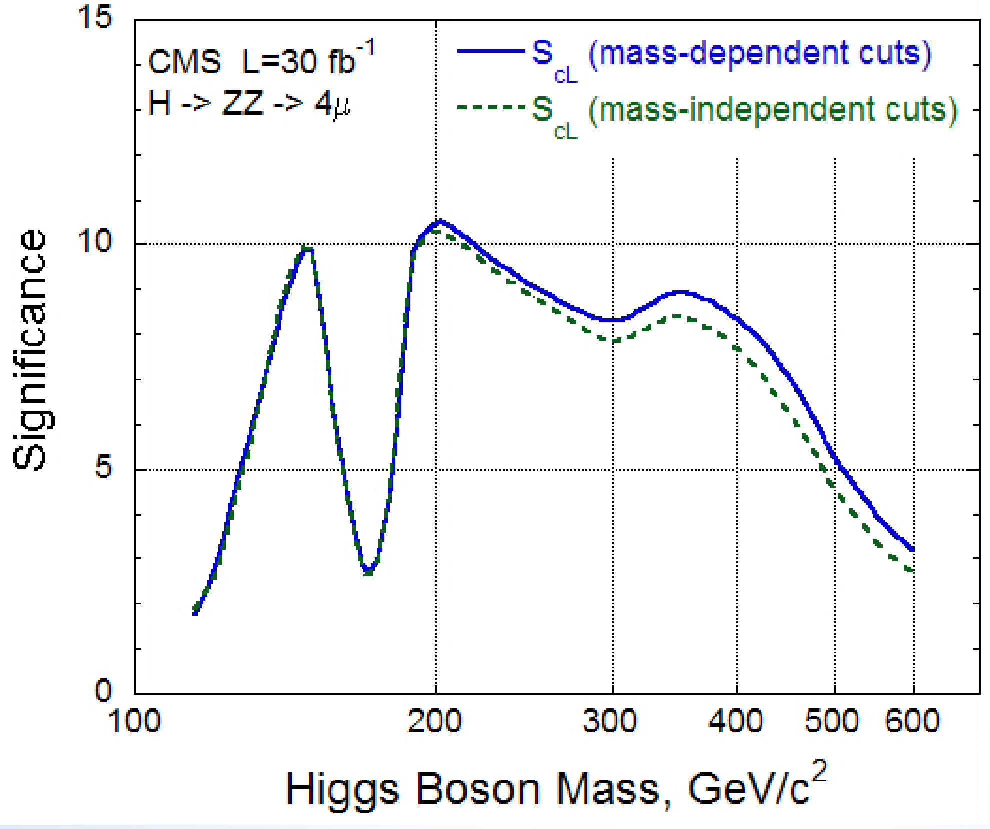
- Sidebands



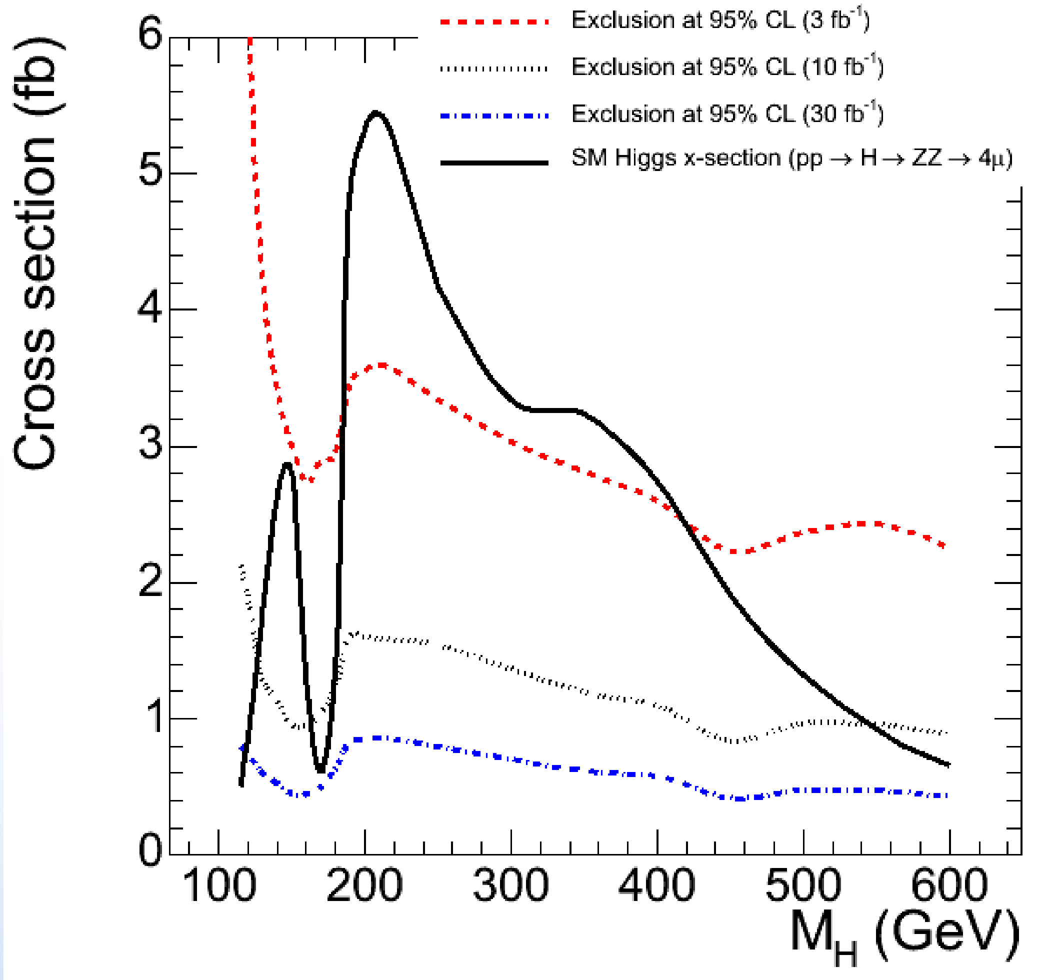
- Normalization to $Z \rightarrow e^+e^-$



Mass dependent-non dependent cuts



95% CL exclusion



Single MC experiments