Discovery potential for SM Higgs with $H \rightarrow ZZ^{(*)} \rightarrow 4l$ at CMS

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on behalf of CMS collaboration

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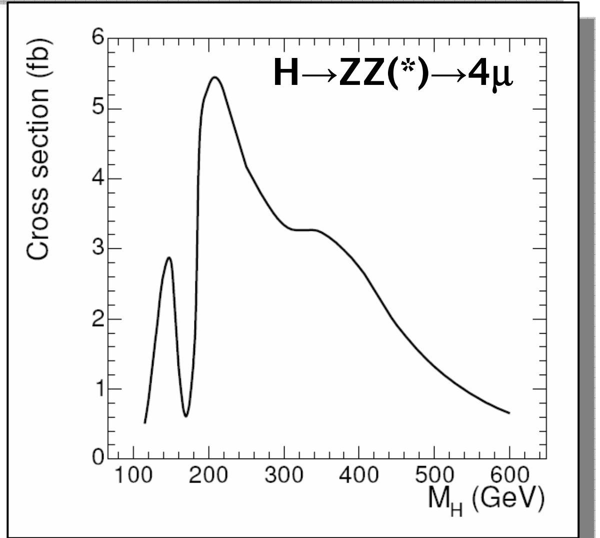
Introduction

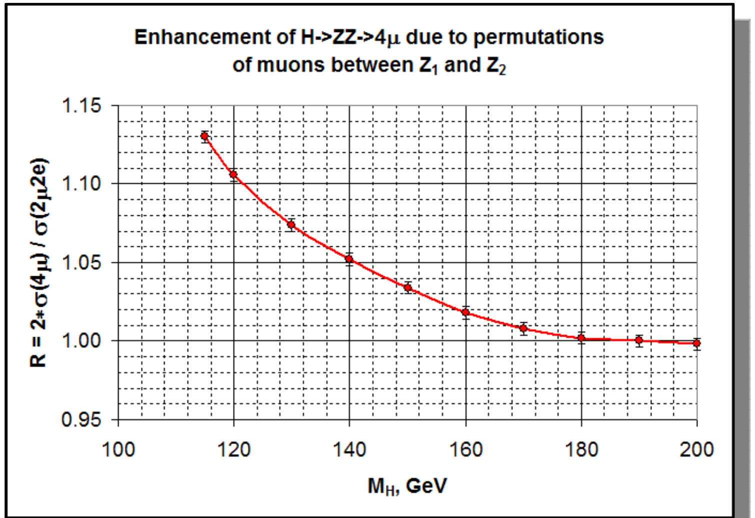
- $H \rightarrow ZZ^{(*)} \rightarrow 4l$ ($4e, 2e2\mu, 4\mu$) is one of the cleanest channels for the discovery of the SM Higgs boson over a wide range of masses. Characteristic topology:
  - 2 pairs of opposite-charged same flavour leptons, isolated, coming from the primary vertex, dileptons mass compatible with m_Z, $m_{4\mu} \sim m_H$
- In the CMS PTDR Vol. II the analysis for all the three final states is performed on fully simulated data
- Full reconstruction is performed using CMS OO reconstruction program including the trigger simulation
- This is also the first attempt to evaluate CMS systematics (theoretical & experimental) in the signal significance

Signal
&
Backgrounds

H→ZZ$^{(*)}$→4l: the signal

- Simulation performed at LO using PYTHIA
  - $p_T(e)>5GeV$, $p_T(\mu)>3GeV$, $|\eta_e|<2.5$, $|\eta_\mu|<2.4$,
  - $5 \text{ GeV} < M_Z < 150 \text{ GeV}$
  - PHOTOS for QED radiation
- NLO cross sections: M. Spira, HIGLU
  - gg->H, VV->H, WH, ZH, ttH initial states included
- H→ZZ$^{(*)}$ BRs: A. Djouadi et al, HDECAY
- Interference enhacement taken into account for $M_H<2M_Z$: $2*\sigma(ZZ\rightarrow 4e,4\mu)/\sigma(ZZ\rightarrow 2e2\mu) > 1$



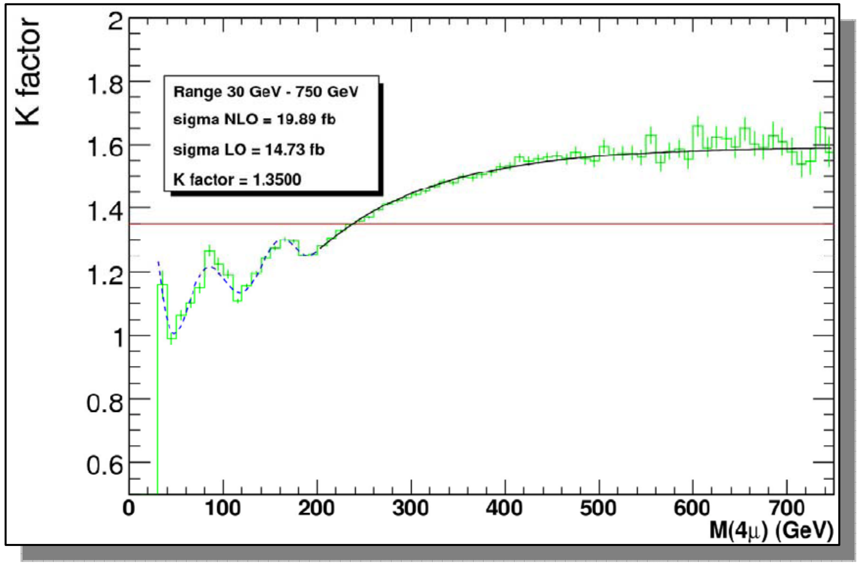


The main background

- Main background is the represented by pp $\rightarrow ZZ^*/\gamma^* \rightarrow 4l$
  - Irreducible background (same final state) with similar kinematical properties
  - Simulated at LO with PYTHIA (s-channel not included) or CompHEP: only initial qq state
    - s-channel max contribution is of 10% at low ZZ masses
  - gg initial state
    - 20% additional LO contribution evaluated using TOPREX
    - ± 8% uncertainties below m_{ZZ} = 200 GeV
- K_{NLO} m_{ZZ} dependant
  - $\langle K_{NLO} \rangle$ =1.35

Total NLO cross-section

$\sigma_{LO}(K(m_{ZZ})+0.2)$ = 29pb



Reducible backgrounds

- **$pp \to Zbb \to 4l$**

Total NLO cross-section
276 pb

  - generated with CompHEP (v4.2) + PYTHIA (v6.227)
  - no b decay forcing
  - $m_{ee} > 5$ GeV & ≥ 2 lepton pairs with mass between 5 and 400 GeV
  - **$K_{NLO} = 2.4 \pm 0.3$** from MCFM

- **$pp \to tt \to 4l$**
  - $W \to l\nu$ and $\tau \to e\nu$, $\mu\nu$ forcing
  - no b decay forcing

Total NLO cross-section
840 pb

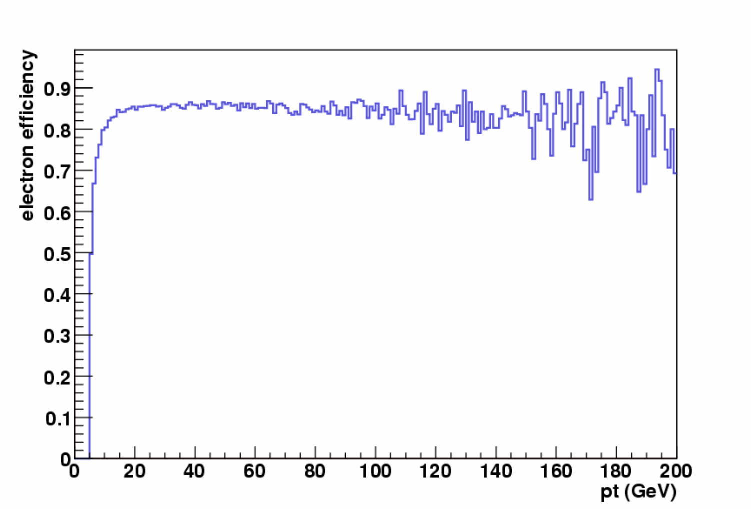
- Other backgrounds (bbbb, bbcc, cccc, single-top, Wbb, Wcc, Zcc) were considered at generator level and found to be negligible

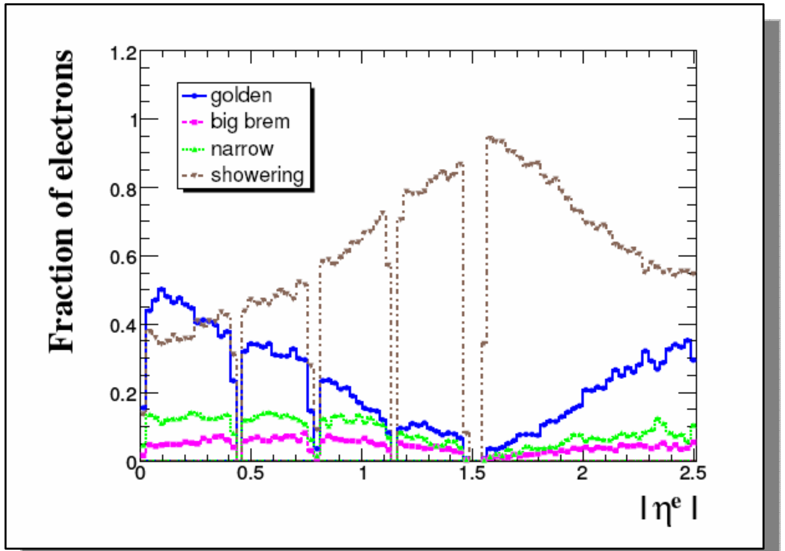
Event reconstruction and selection

Electron reconstruction

- Special care on the electron reconstruction algorithms:
  - Bremsstrahlung in the tracker material
  - Energy lost in the tracker material
- CMS ECAL clustering algorithm optimized for bremsstrahlung collection down to low p_T (>5 GeV)
- Specific e tracking algorithm have been developed (GSF)
  - Possibility to estimate from the track parameters the bremsstrahlung loss
- Classification of electrons for better corrections
- E-p is combined for better momentum estimation
- Many useful variables are available for e identification (to reduce fakes from jets)
- Estimate of the parameters errors per class is available
  - For event-by-event error on 4e reconstructed mass
- More information in:

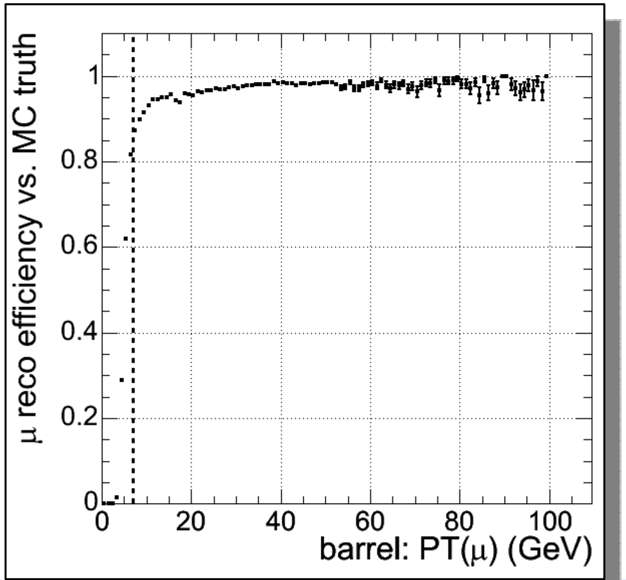
CMS NOTE-2006/040

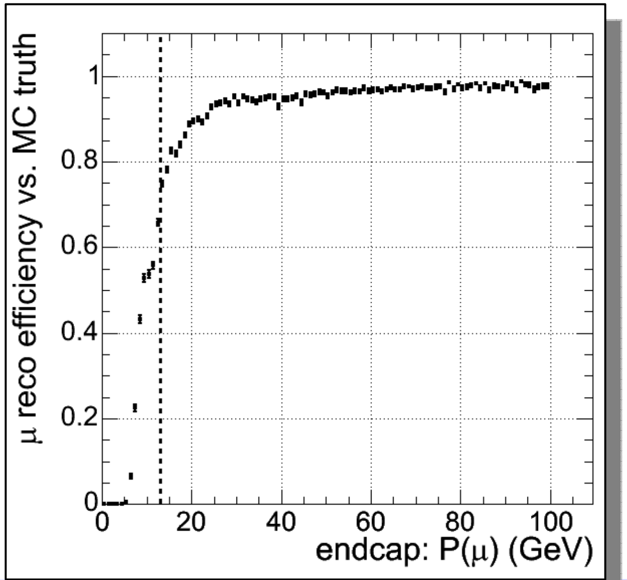


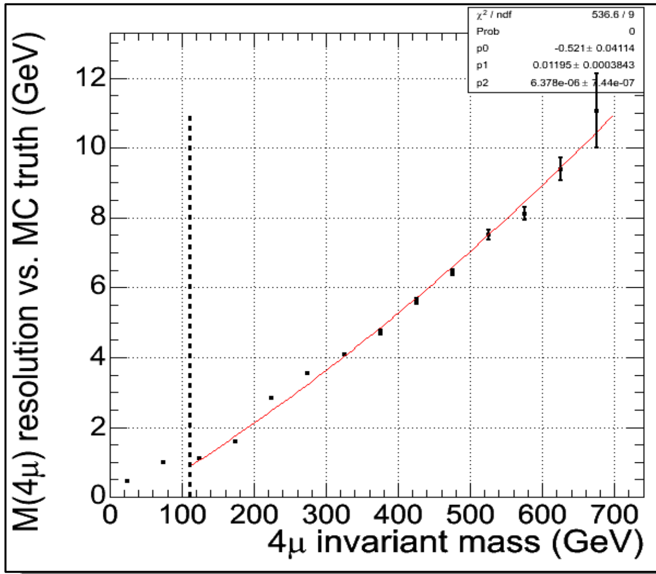


Muon reconstruction

- Offline reconstruction algorithm based on the matching between independent reconstruction in the muon system and in the tracking system
  - Combination of the tracker measurement improves momentum estimation of a factor 10
- Efficient reconstruction for p_T>7 GeV for barrel (|η|<1.1); p>13GeV for endcap (|η|>1.1)

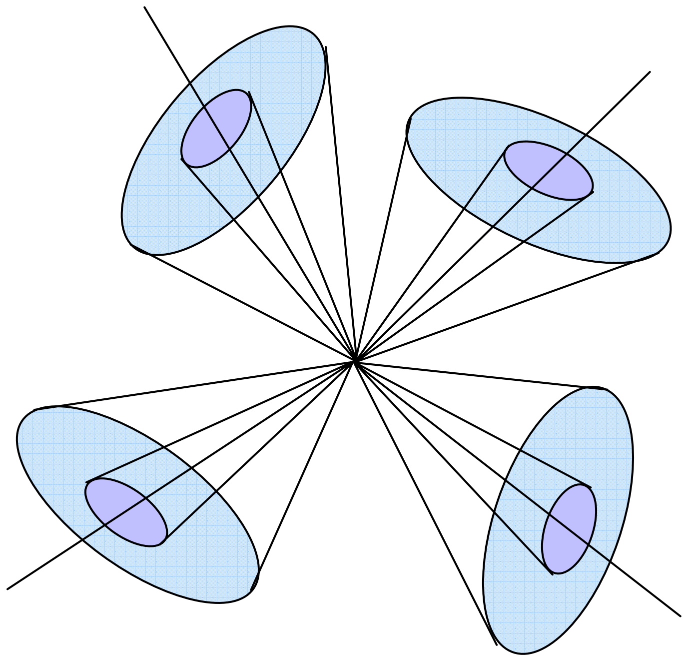






Event selection & data reduction: Isolation & Vertex constraint

- Isolation is the fundamental ingredient to suppress reducible background (Zbb and tt). Require both:
  - Tracker isolation
  - Calorimeter isolation
- Typical isolation cone size used is $\Delta R = 0.2$
- Typical rejection obtained from isolation is between 20-100 for 90% efficiency on signal
- Another tool to suppress tt and Zbb is to impose the lepton vertex constraint
- A rejection factor [2-5] can be achieved for 90-95% signal efficiency



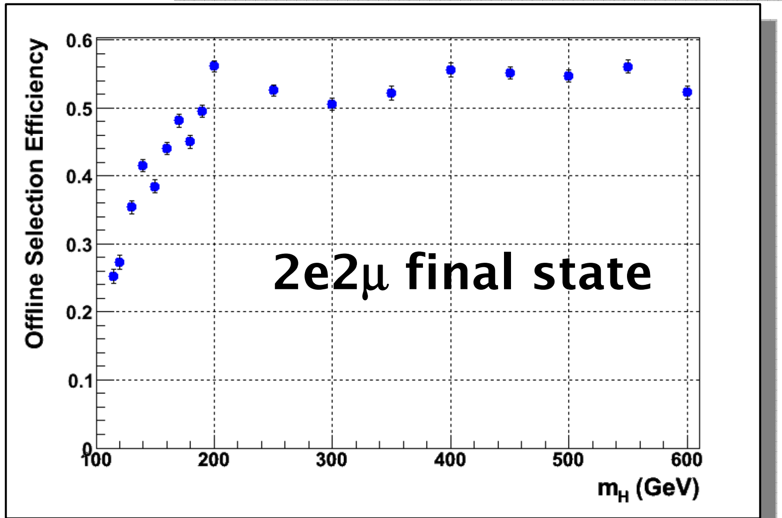
Event selection & data reduction (II): Kinematical cuts

- Electron p_T cuts: Motivation:
  - Backgrounds have important fraction of low pT electrons
  - But low mass Higgs has them too ⇒need balancing
- Typical values for electron p_T optimized cuts for various Higgs mass hypothesis
- Rejection on Zbb and tt from p_T cuts >4-5
- Other useful constraints are the real Z mass constraint (rejection factor around 2 for tt) and in case of mass dependent cuts the constraint on the mass of the remaining lepton pair

m_H (GeV)	p_{T1} (GeV)	p_{T2} (GeV)	p_{T3} (GeV)	p_{T4} (GeV)
120	7	12	15	15
150	7	12	15	15
200	7	15	25	30
300	7	30	40	60

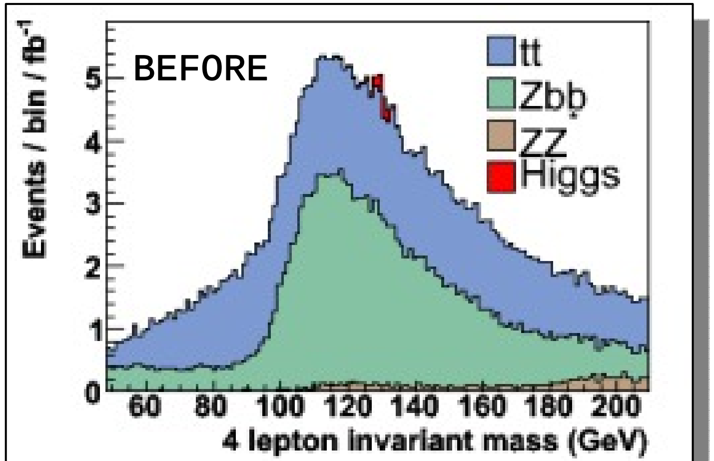
Different strategies for kinematical cuts can be adopted: aim is try to restrict only to the more discriminative cuts or either use only one set of cuts for different mass hypothesis in order to reduce systematics.

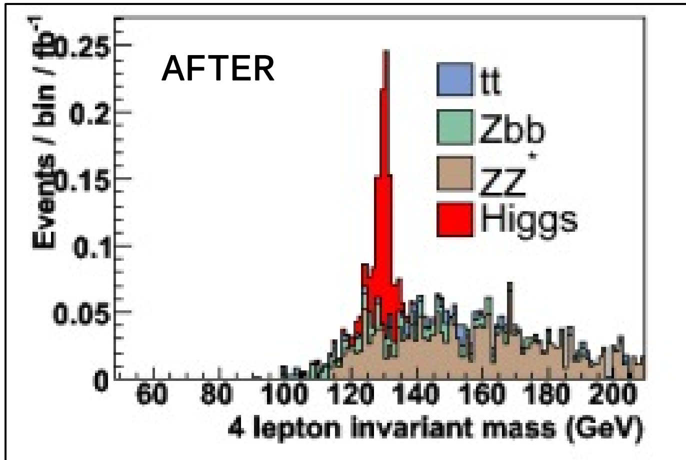
Event selection efficiency



Reconstruction & selection efficiency significantly varies for different Higgs mass hypothesis [25-55%].

After all selections ZZ continuum remains as the dominant or sole background





Systematics

Systematics

- Systematics on the signal significance is related to the knowledge of the level of background in the signal region
- ZZ background can be inferred from control samples (cancellation of luminosity uncertainty and reduction of sensitivity to PDF and QCD)
  - Normalisation to **Z->2l data**

    $$R = (\sigma_{ZZ\rightarrow 4l}{}^{*}\ \varepsilon_{4l}\ {}^{*} \int Ldt\ )\ /\ (\sigma_{Z\rightarrow 2l}{}^{*}\ \varepsilon_{2l}\ {}^{*} \int Ldt\ )$$

    - Theoretical systematics on R from 2% to 8% (varying with m_{4l})
    - Statistical precision very high due to large number of $Z\rightarrow 2l$ events
  - Normalisation to **sidebands**

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

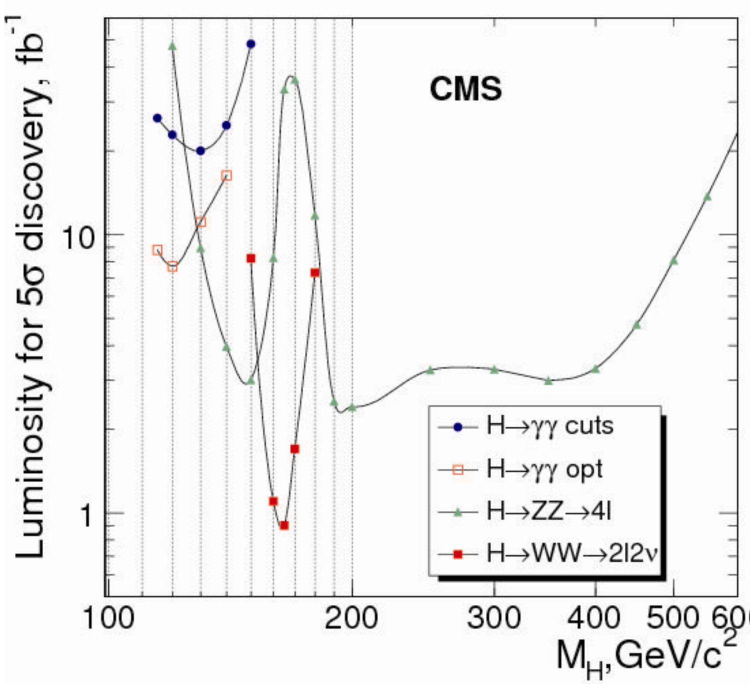
    - Theoretical systematics on α_{MC} from 1% to 4%
    - Limited by available statistics in sidebands

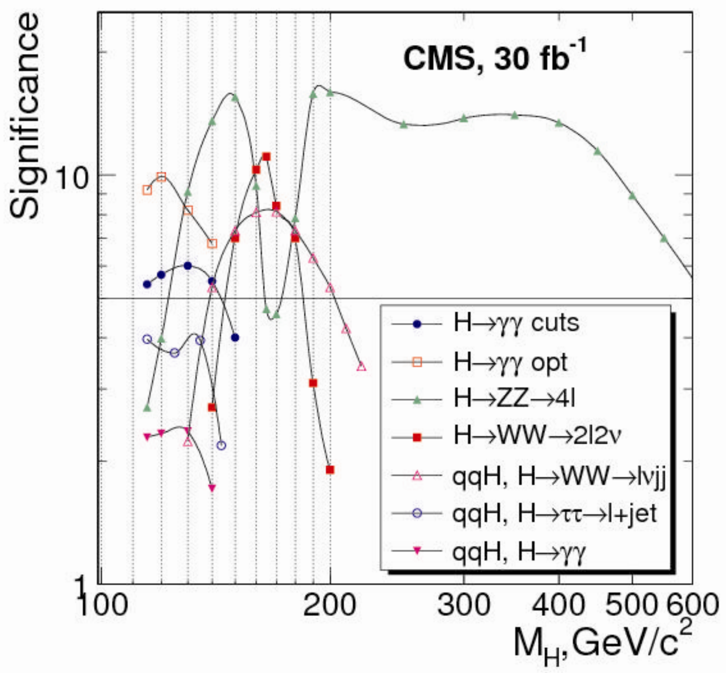
Experimental systematics

- Experimental systematics:
  - L1/HLT Trigger efficiency: ±1%
  - Material budget
  - Energy and momentum scales and resolutions
  - Efficiencies
    - Reconstruction and selection
    - Isolation
    - Identification
- Global strategy for estimating/controlling detector systematics
  - Estimate efficiencies and precision from leptons from W and Z decay
- With 1-2 fb^{-1} of integrated luminosity experimental systematics are estimated to be below 1%

Signal visibility and Higgs measurements

Signal visibility



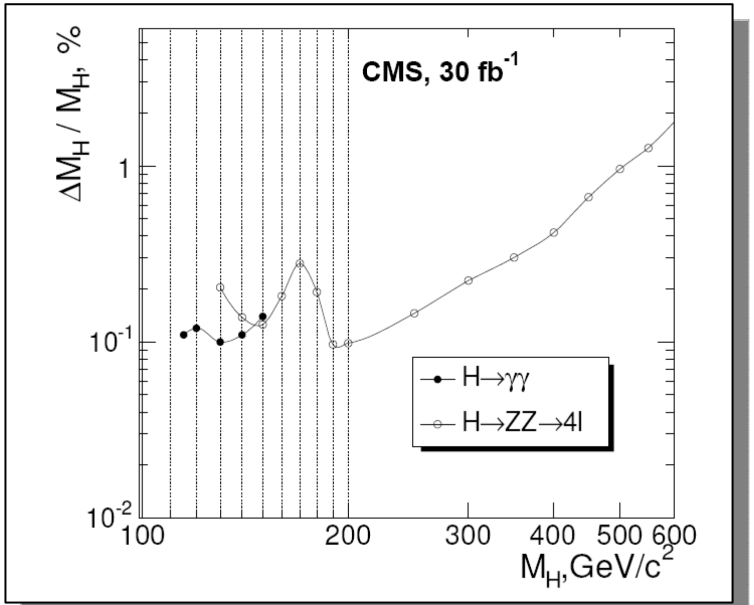


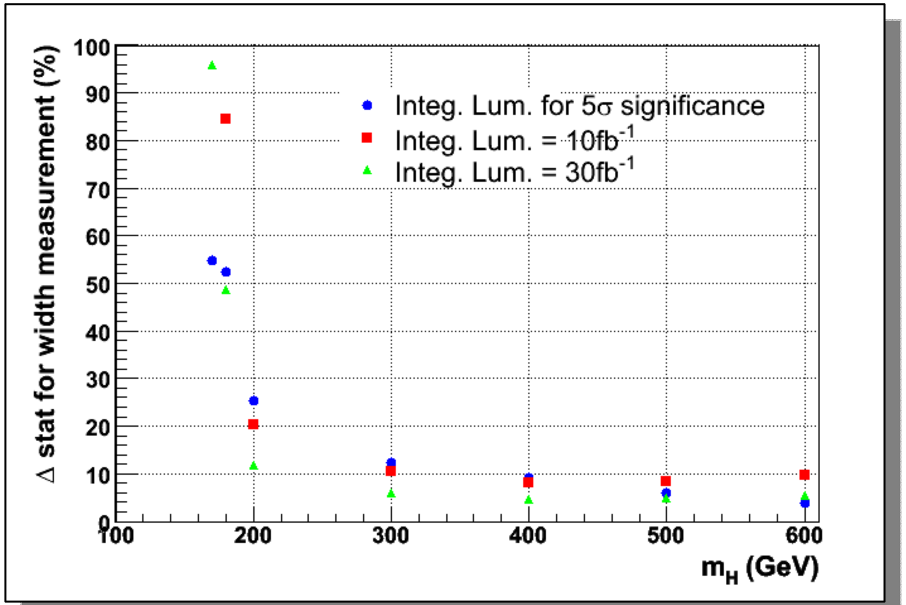
$$\frac{1}{\sqrt{2\pi}}\int_S^\infty e^{-\frac{x^2}{2}}dx = \sum_{i=N_{obs}}^{\infty}\frac{(\mu_B)^i e^{-\mu_B}}{i!}$$

Effect of systematics is included

Less than 10 fb^{-1} required for a 5σ discovery in the channel H→ZZ→4l in the mass range $130<m_H<160$ GeV and $2m_Z<m_H<550$ GeV

Measuring Higgs mass & width

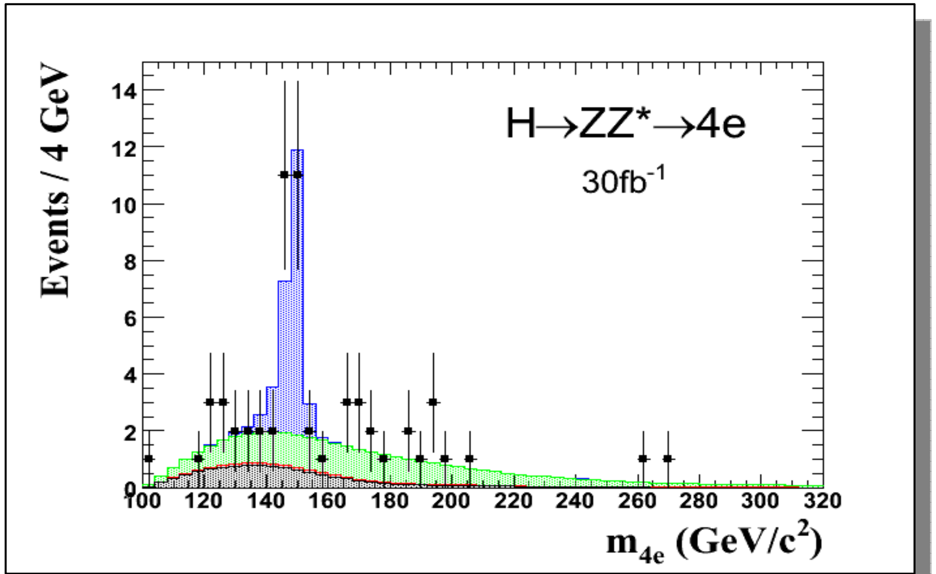




- Higgs mass can be measured in this channel with a precision of better than 1%
- Also the direct measurement of the width is possible with an error <30% for $m_H \geq 200$ GeV

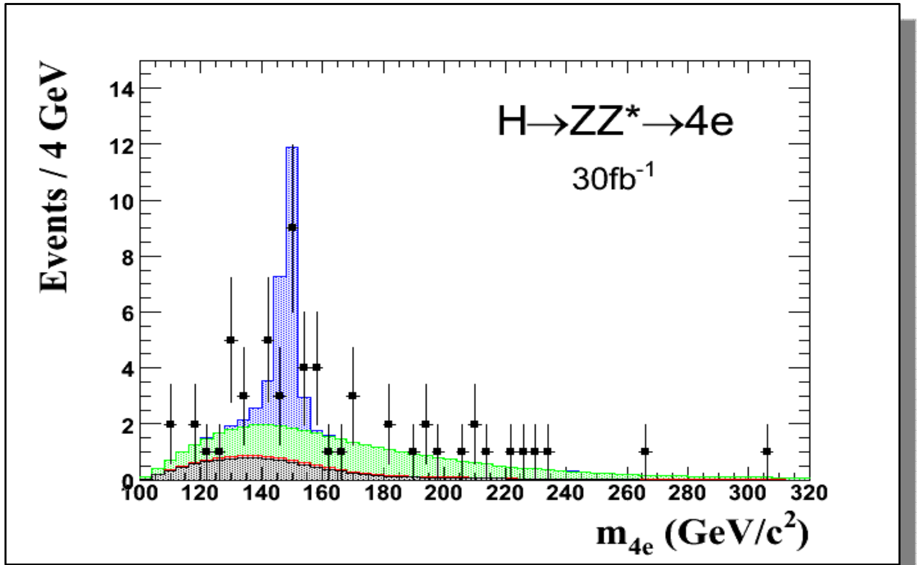
And finally…

- We could be lucky:



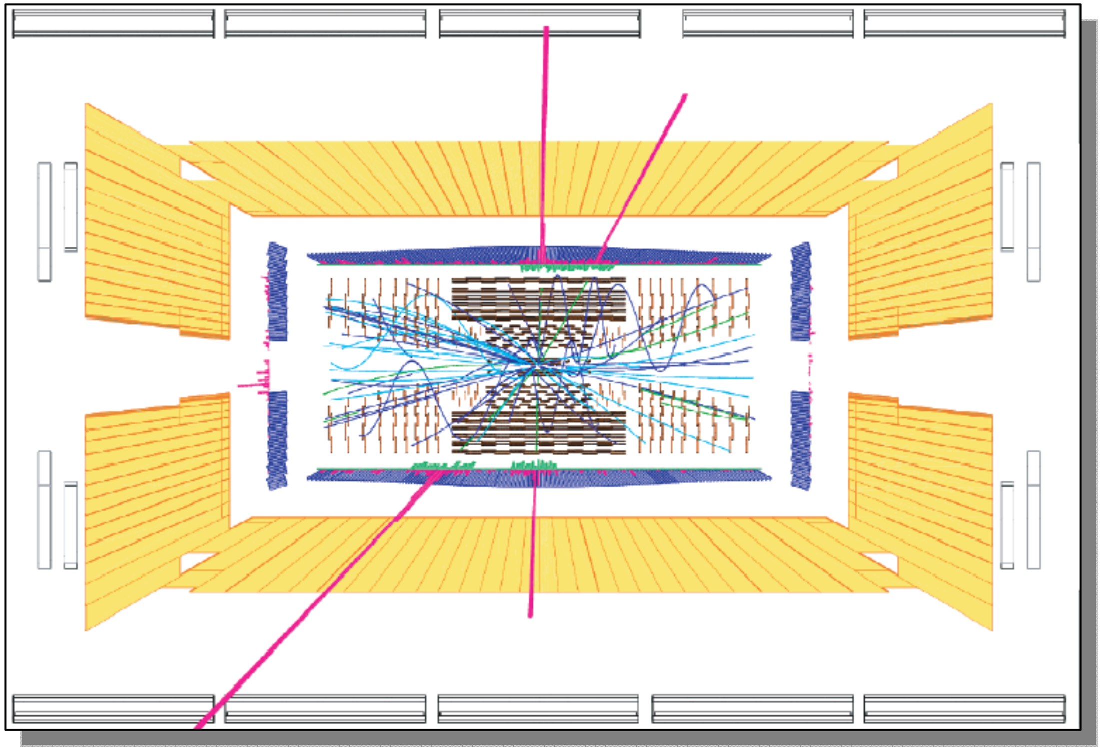
8.5% probability to have equal or more favorable

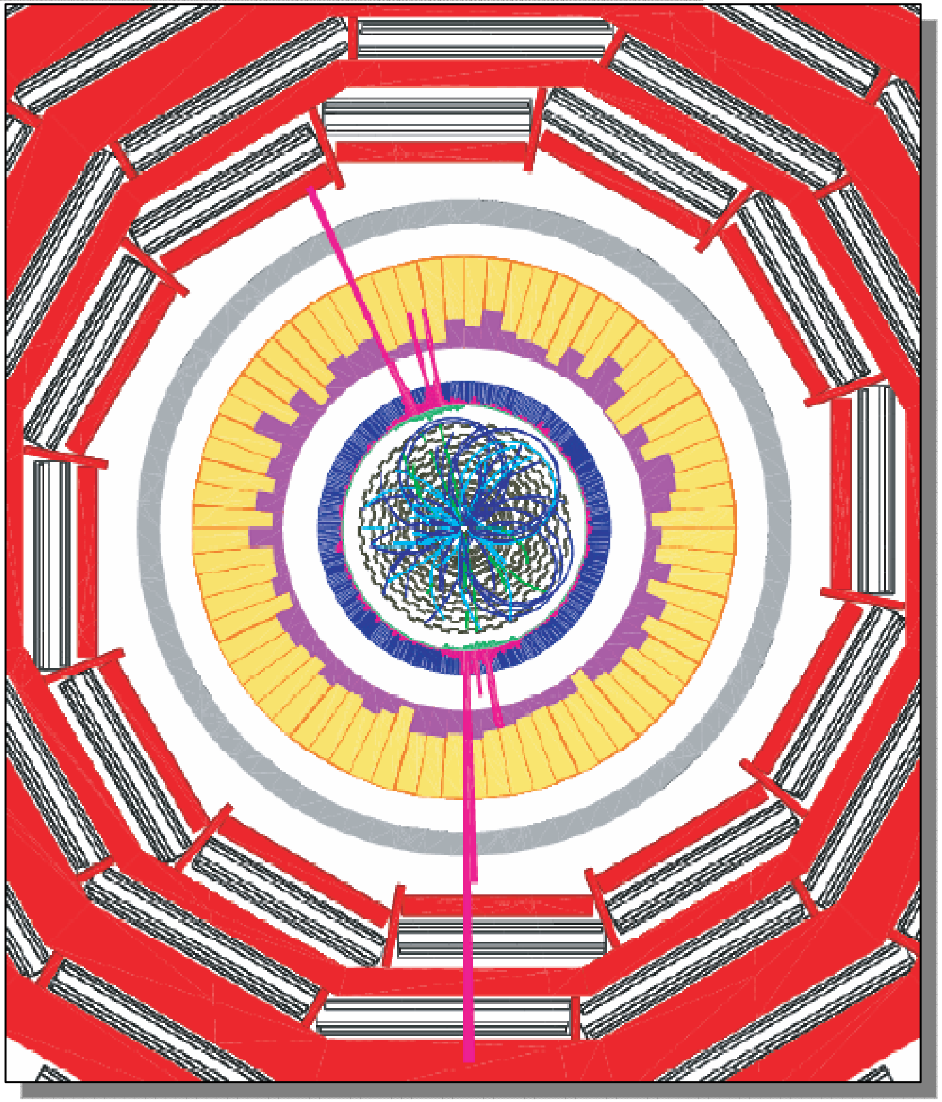
- … or not:



23.5% probability to have equal or less favorable

An event H→4e at CMS...





Summary

- First evaluation performed entirely on CMS full simulation of the CMS SM Higgs discovery potential in the $H \rightarrow ZZ^{(*)} \rightarrow 4l$ channel
- The evalution includes the effect of systematics error, both theoretical and experimental
- 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-2006/122 -- Search Strategy for the Standard Model Higgs Boson in the H->ZZ->4μ Decay Channel using M(4mu)-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-2006/106 -- Discovery potential and search strategy for the Standard Model Higgs boson in the H->ZZ(*)->4μ decay channel using a mass-independent analysis**

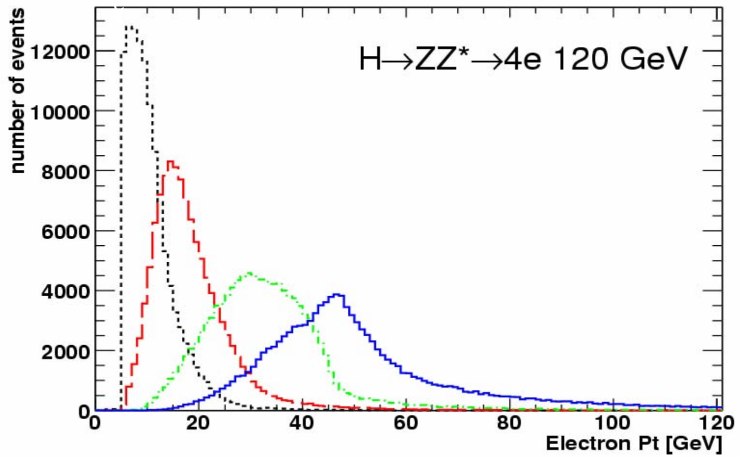
  Authors: M. Aldaya, P. Arce, J. Caballero, B. de la Cruz, P. Garcia-Abia, J.M. Hernandez, M.I. Josa, E. Ruiz
- **CMS NOTE-2006/115 -- Discovery potential for the SM Higgs boson in the H->ZZ(*)->4e decay channel**

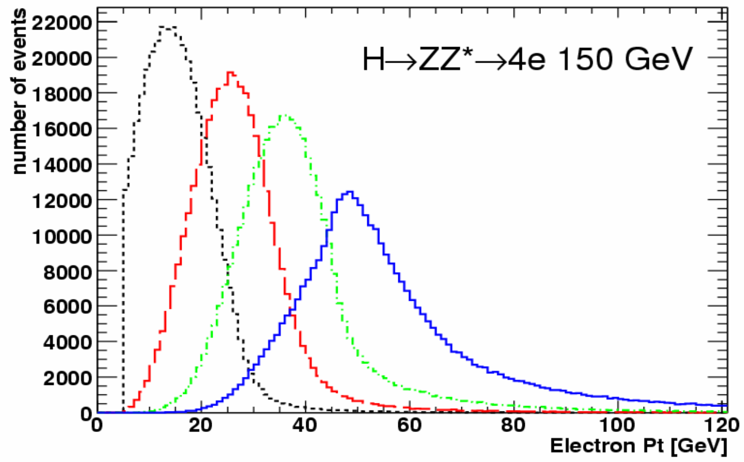
  Authors: S. Baffioni, C. Charlot, F. Ferri, N. Godinovic, P.Meridiani, I. Puljak, R. Salerno, Y. Sirois

Backup

Electrons from Higgs boson decay

- Electrons from Higgs boson decay:
  softest electron typically with $p_T \lesssim$ 10 GeV for mH < 140 GeV

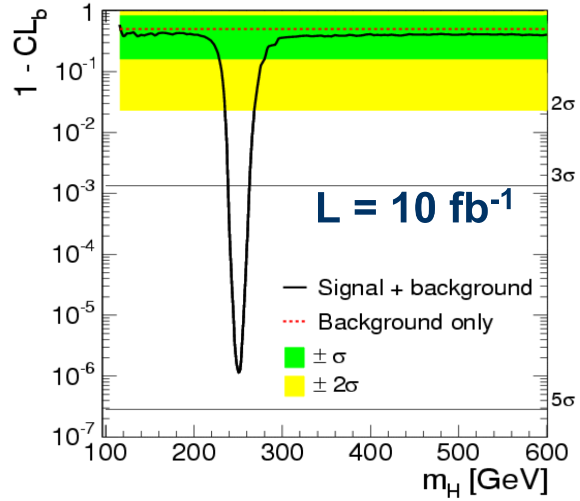


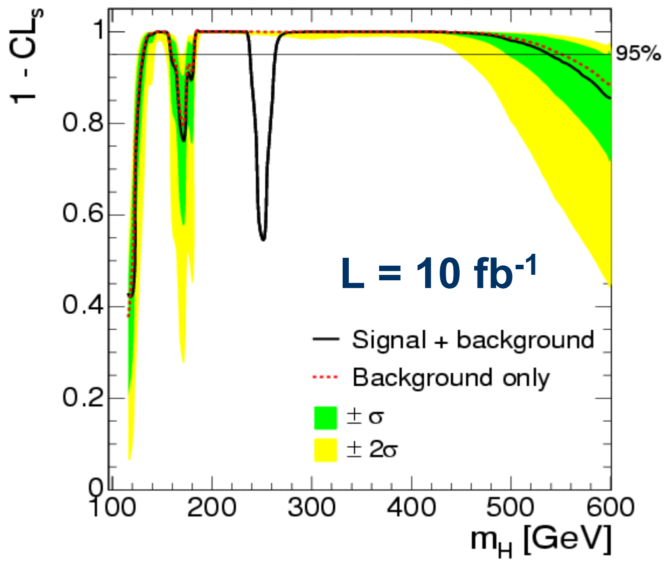


- S. Baffioni et al: “Electron reconstruction in CMS”, CMS Note 2006/040
- Offline reconstruction different from HLT one
- Important effects:
  - **Bremsstrahlung in the tracker material**
  - Incomplete containment in ECAL
  - Energy lost in the tracker material
  - Cracks

Search Strategy

- In a real experiment, a signal-like excess of observed events is considered to be a discovery if the probability for a fluctuation of the background to produce such an excess is < $2.85 \cdot 10^{-7}$ (5σ deviation on the positive tail of a Gaussian distribution)
- This probability is given by the confidence level presented before as $1\text{-}CL_b$
- CL_b measures how compatible with the background is the experiment. CL_s measures if a detected signal looks like the expected signal of a Higgs boson
- In a B-only scenario, a possible signal is excluded at α C.L. if $1\text{-}CL_s > \alpha$ (usually α = 95%)
- Expected $1\text{-}CL_b$ and $1\text{-}CL_s$ distributions for a Higgs boson signal of m_H = 250 GeV and L = 10 fb^{-1}

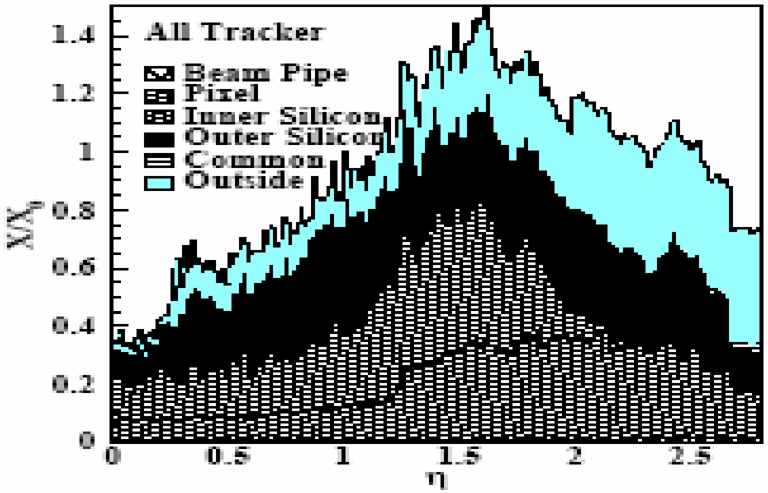


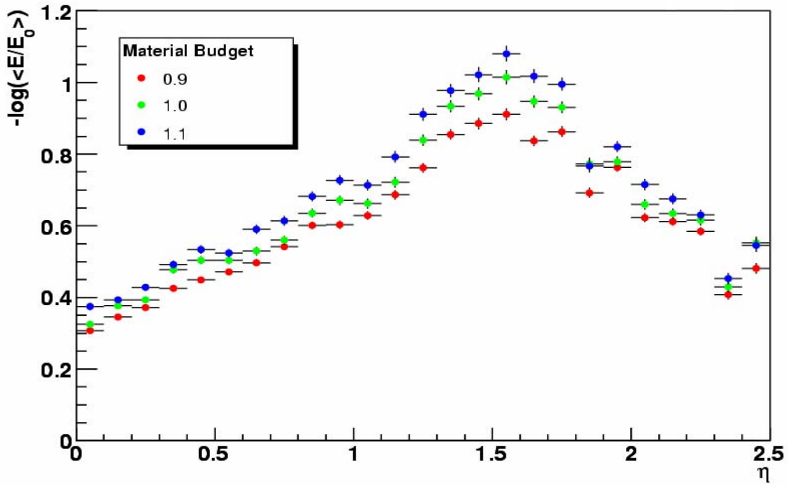


Material budget - method

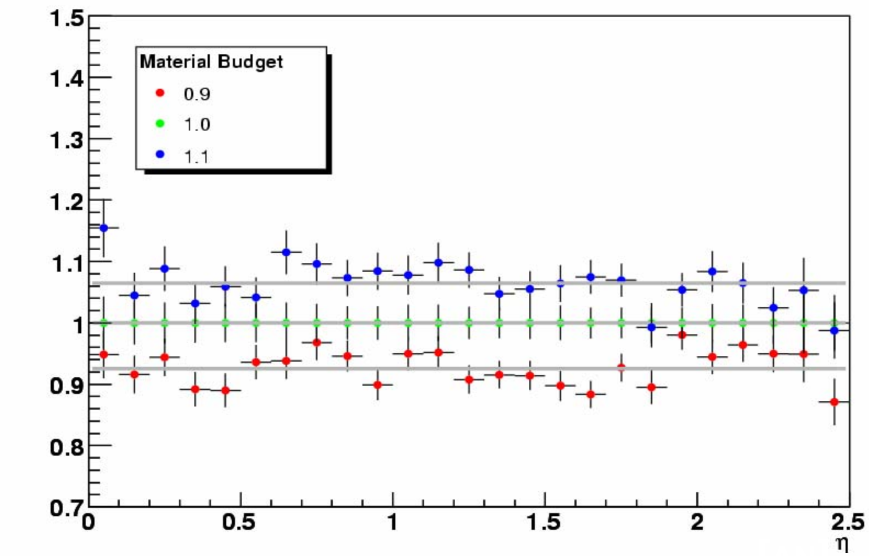
- **A new method to estimate material budget**
  - GSF track finding and fitting algorithm has an usefull track estimate at the outermost point (p_{out})
  - Comparing with initial momentum (p_{in}) we can estimate energy loss and therefore an amout of material traversed

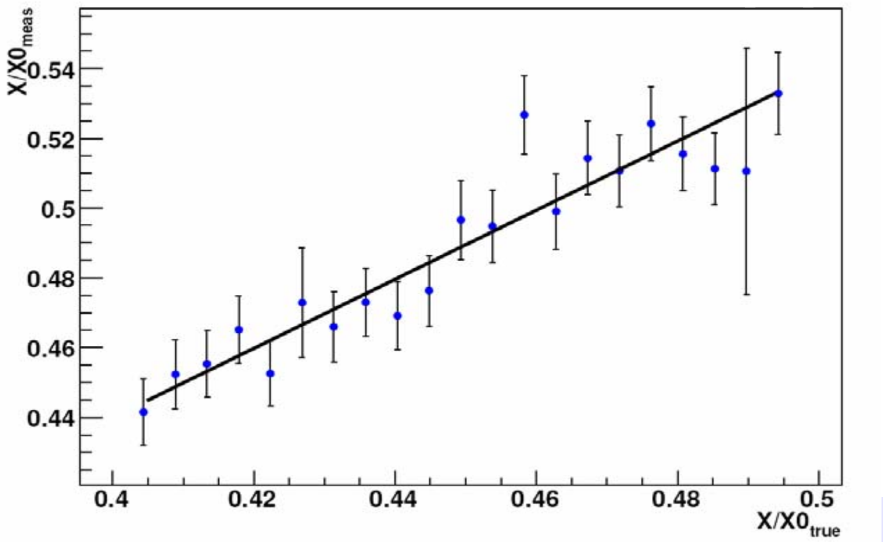
$$\left\langle \frac{E}{E_0} \right\rangle = e^{-\frac{X}{X_0}} \rightarrow \begin{matrix} E \Leftrightarrow p_{out} \\ E_0 \Leftrightarrow p_{in} \end{matrix} \rightarrow \frac{X}{X_0} = -\log \left\langle \frac{E}{E_0} \right\rangle$$





Material budget - results





- Other possible methods for material budget measurements:
  - Conversions in the tracker material
  - Measuring electrons with irradiated photon taking more than 50% of energy
  - Comparing Z→ee resolution: data vs simulation
  - Adjusting tracker material in simulation for the best E/p shape agreement with data
- Expected precision: better than **2%**
- With attained precision no effect on reconstruction efficiency