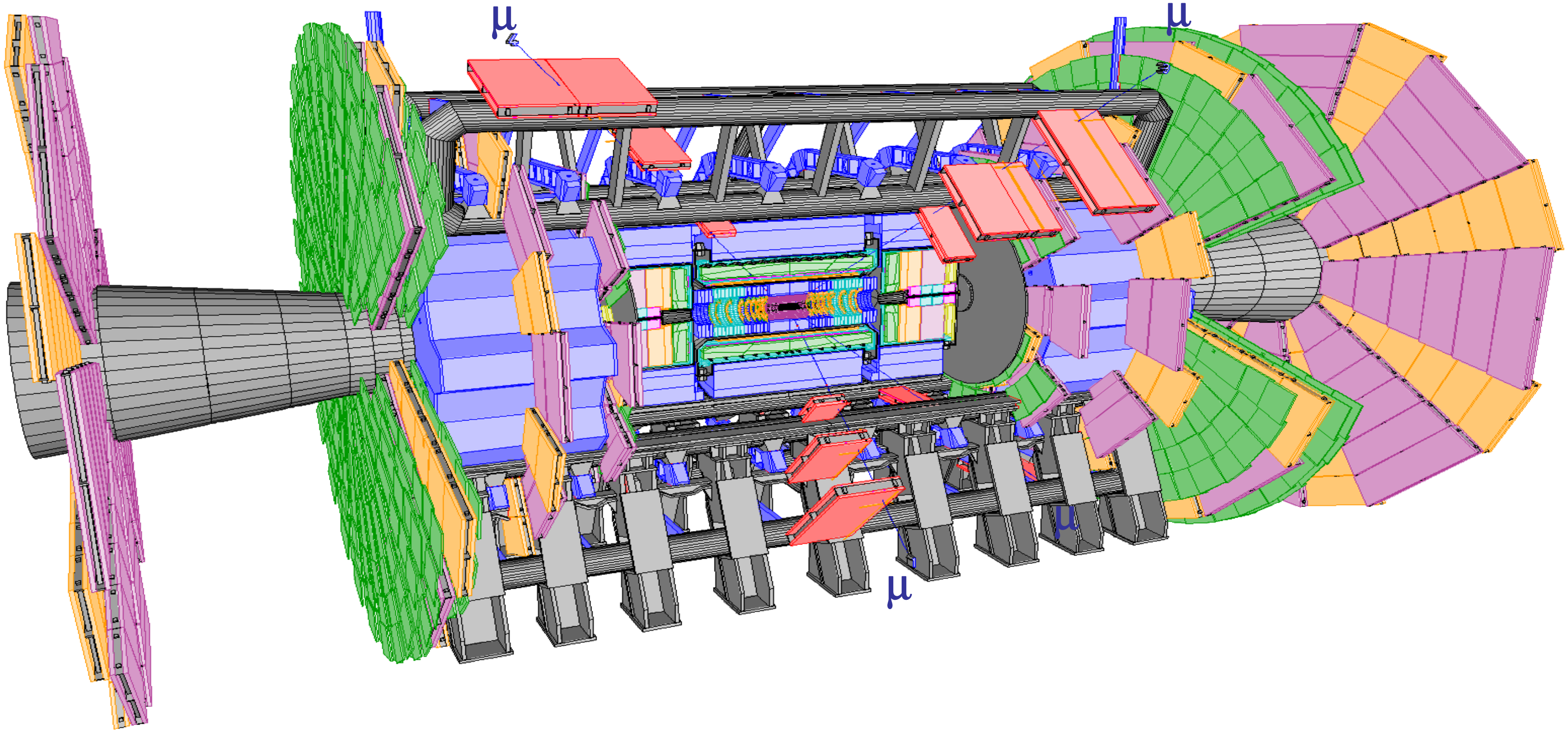
# Study of $H \rightarrow ZZ^{*} \rightarrow 4\mu$ channel with full ATLAS detector simulation

**Samira Hassani**

**DAPNIA/SPP-Saclay France**



# $H \rightarrow ZZ^* \rightarrow 4\mu$

1) Introduction

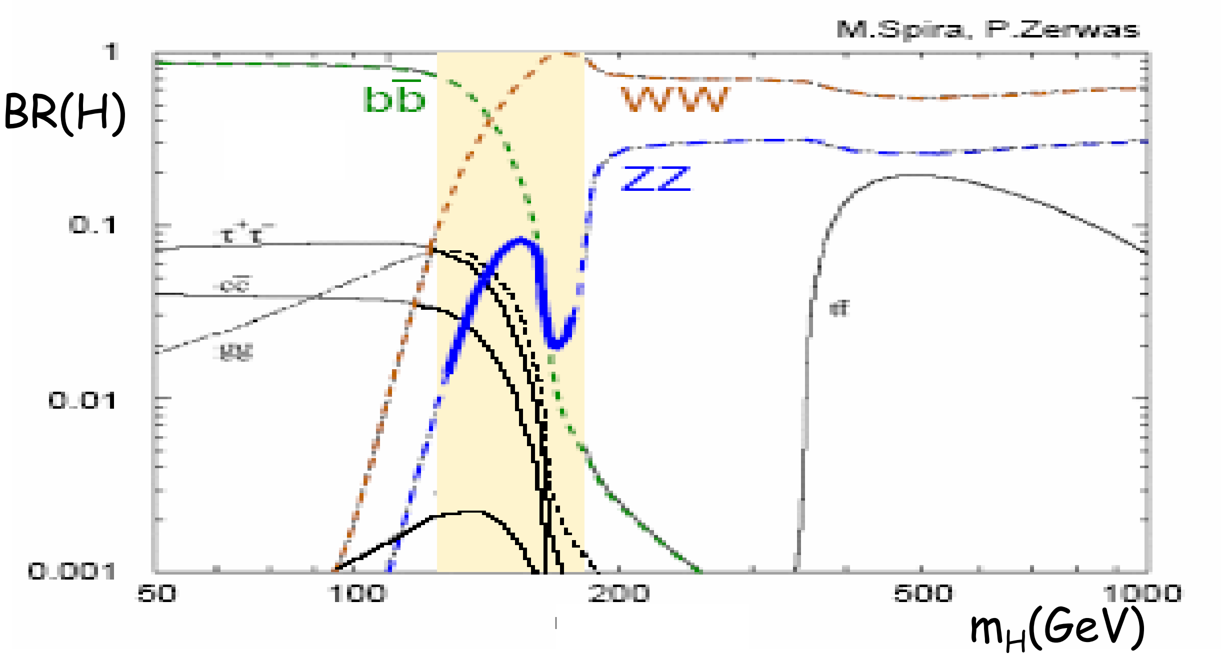
- ✓ Signal and backgrounds
- ✓ Performance of $\mu$ detection

2) Analysis steps optimized for low luminosity

- ✓ Higgs mass resolution
- ✓ Background rejection
- ✓ Expected significance

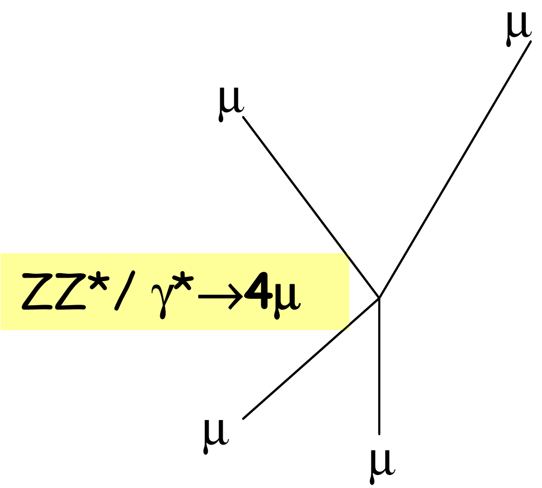
3) Summary

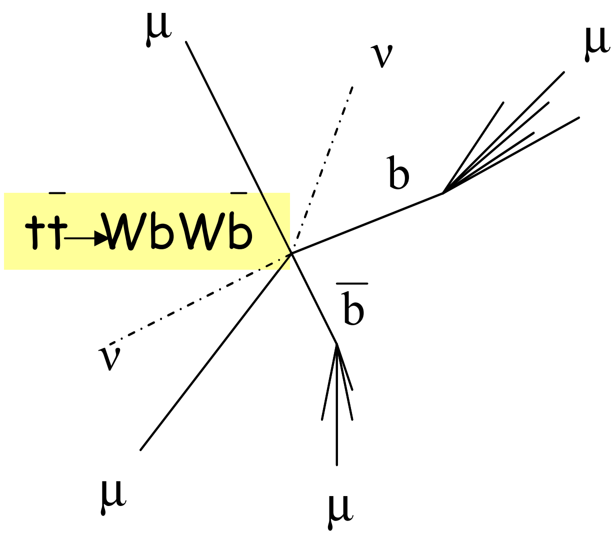
# 1) Introduction: Signal $H \to ZZ^* \to 4\mu$

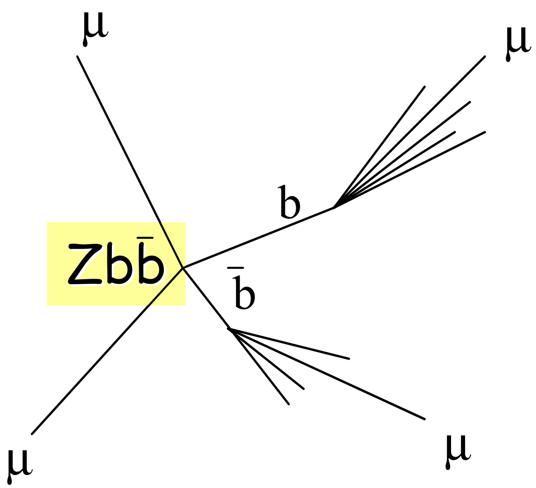



- For the mass range $130 < m_H < 180$GeV, the Higgs decays to:
  - $H \to W\,W^* \to ll\,\nu\,\nu$ ( $E_T$miss)
  - $H \to bb$ (QCD background)
  - $H \to ZZ^* \to 4l$ (clean signature and rather low background)
- For $m_H < 2m_Z$, Higgs is narrow $\Rightarrow$ good detector resolution in $\mu$ is essential

# 1) Introduction: Background to H → ZZ*→ 4μ



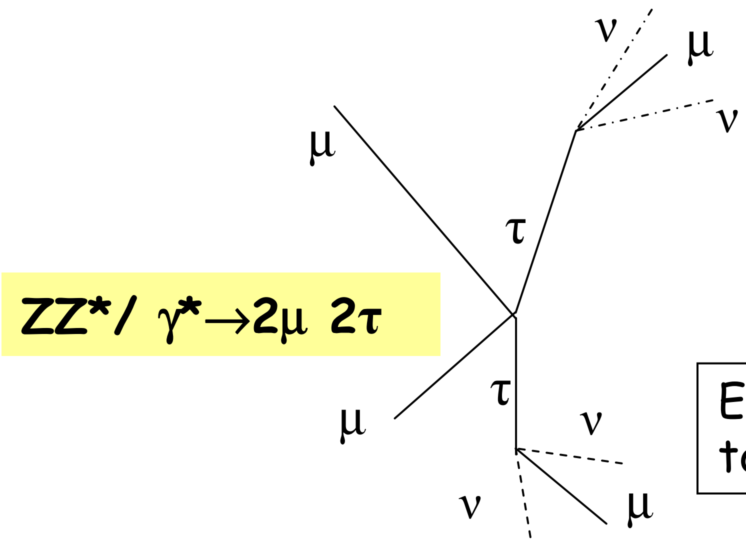




Continuum Irreducible

Non-Resonant reducible

Resonant reducible




Expected to contribute on the level of 10% to the total background

# 1) Introduction: Background to $H \rightarrow ZZ^* \rightarrow 4\mu$

| Process | $\sigma$XBR(fb) | $\sigma$XBR(fb) used for analysis | Events Stored |
|---|---|---|---|
| $gg \rightarrow H \rightarrow 4\mu$ (m=130 GeV) | 0.535 | 0.682 (gg fusion+VBF ) | 50 K |
| $gg \rightarrow H \rightarrow 4\mu$ (m=150 GeV) | 1.02 | 1.325 (gg fusion+VBF) | 50 K |
| $gg \rightarrow H \rightarrow 4\mu$ (m=180 GeV) | 0.573 | 0.759 (gg fusion+VBF) | 50 K |
| $qq \rightarrow (Z/\gamma^*)(Z^*/\gamma^*) \rightarrow 4\mu$ | 17.6 | 22.88 (1.3 factor account for missing $gg \rightarrow ZZ$) | 115 K |
| $qq \rightarrow (Z/\gamma^*)(Z^*/\gamma^*) \rightarrow 2\mu 2\tau$ | 35.2 | 45.76 (1.3 factor account for missing $gg \rightarrow ZZ$) | 28 K |
| $gg \rightarrow (Z/\gamma^*)bb$, with $(Z/\gamma^*) \rightarrow 2\mu$ | 22.4 x$10^3$ | 22.4 x$10^3$ | 94 K |
| $gg, qq \rightarrow tt \rightarrow WbWb$, with $W \rightarrow \mu\nu$ | 5.73 x$10^3$ | 5.73 x$10^3$ | 700 K |

- All processes generated with PYTHIA except for Zbb generated with AcerMC (for production and simulation details see ATL-COM-PHY-2003-018)
- Zbb events dominate at production level (tt events a factor 4 smaller) and contain a genuine Z, which makes their rejection more difficult
- ~ 1 M events (Data Challenge 1) simulated and reconstructed within the ATHENA framework

# 1) Introduction: First stage of event selection

***kinematic cuts :***

✓ Two muons $P_T > 20$ GeV , $|\eta| < 2.5$ — for Trigger

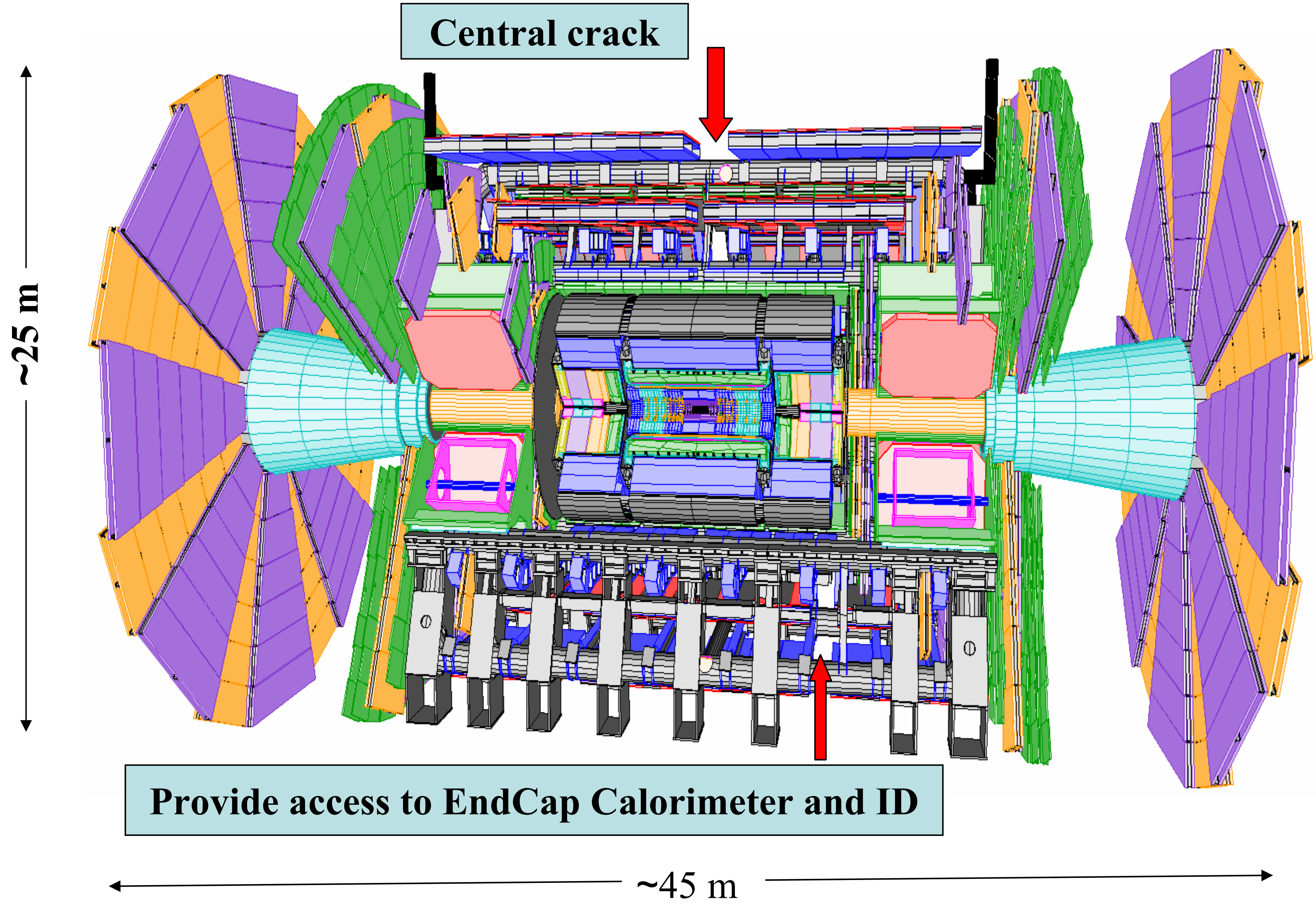
✓ Two additional muons $P_T > 7$ GeV , $|\eta| < 2.5$

✓ $m12 = M(\mu+ \mu-) = M_Z \pm M_{Window}$ GeV — against tt background

✓ $m34 = M(\mu+ \mu-) > M_{Threshold}$ GeV — against tt and Zbb cascade decays and $Z\gamma^*$ background

| Higgs mass (GeV) | 130 | 150 | 180 |
|---|---|---|---|
| $M_{Window}$ | ± 15 | ± 10 | ± 6 |
| $M_{Threshold}$ | > 20 | > 30 | > 60 |
| Acceptance of kinematic cuts (%) | 35.6 | 44.4 | 55.6 |

# What's new for Muon System since PhysicsTDR (1999)?



# 1) Introduction : Muon measurement

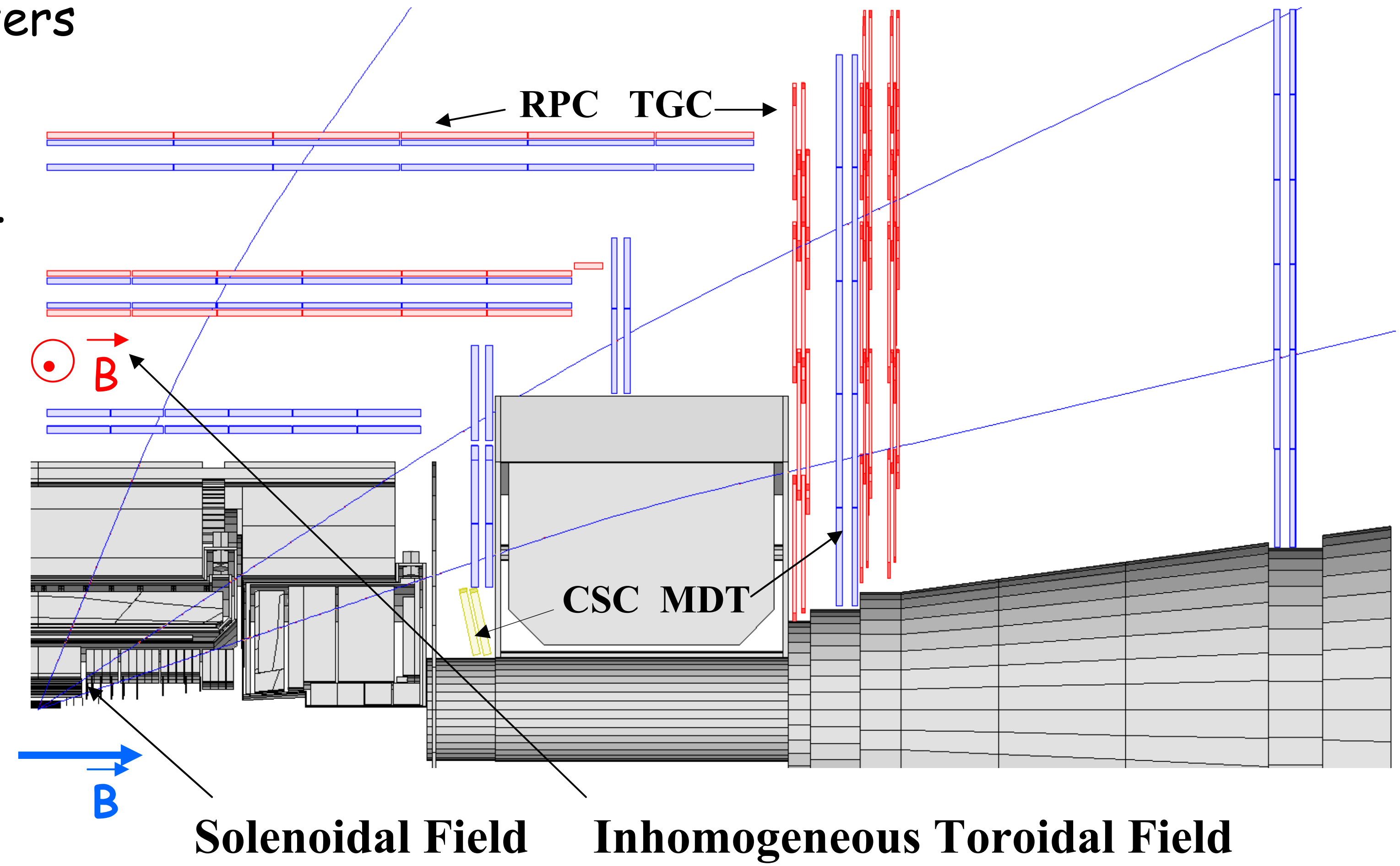
Traversing Atlas a μ is detected in

- 2 high precision tracking systems: Inner Detector and μ System
- Calorimeters

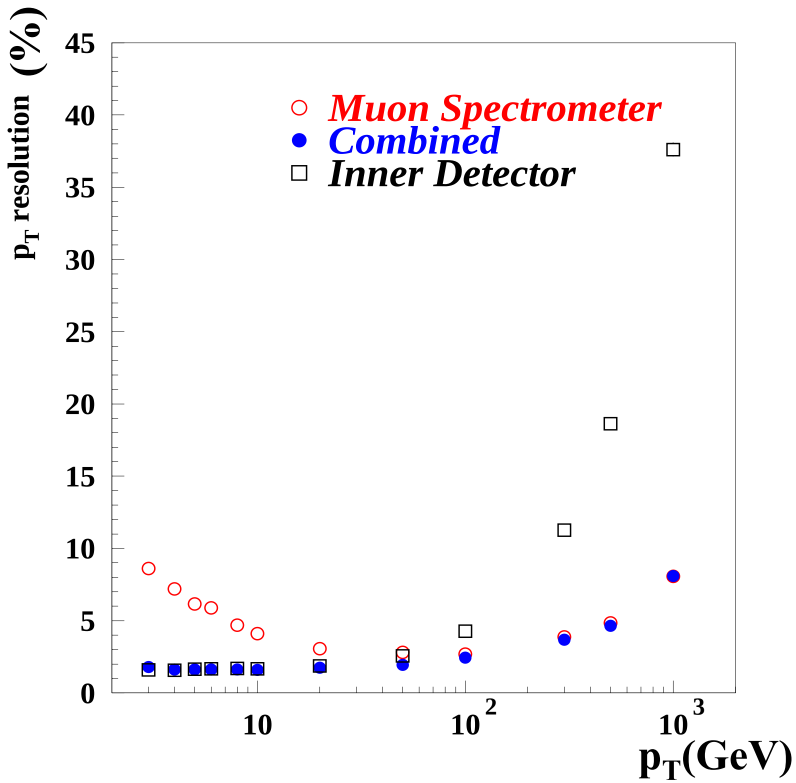
μ Syst Best at higher $p_T$

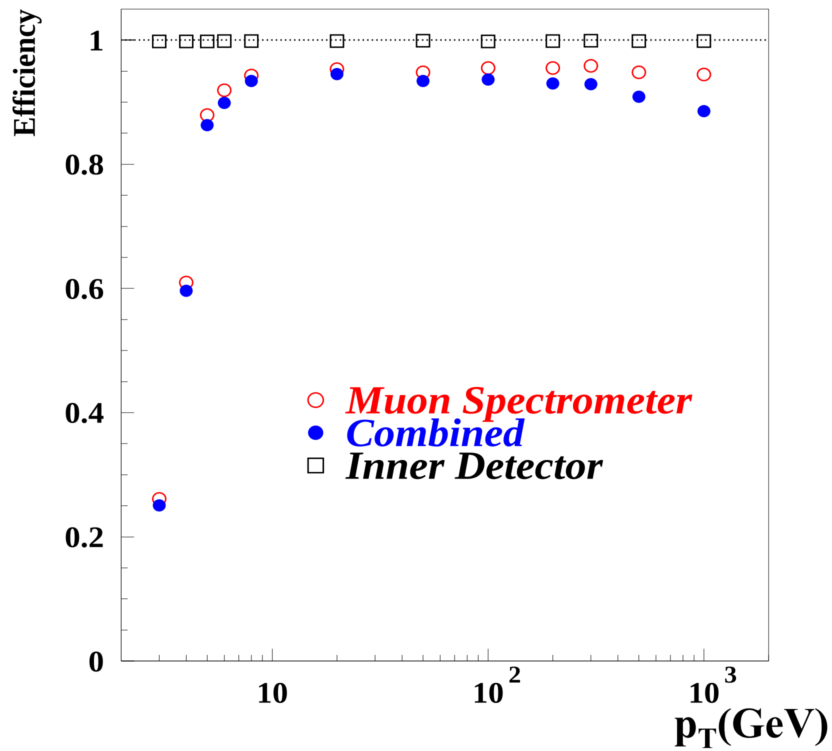
E loss >3GeV

ID Best at lower $p_T$



# 1) Introduction: Single μ performance




- ✓ The Inner Detector ( Muon System ) measurements dominate the combined transverse momentum below (above) 50 GeV
- ✓ Muon System efficiency decreased by **~ 2 %** at all pT w.r.t TDR
- ✓ New layout of μ-spectrometer causes a ~9% efficiency loss in the H→4 μ signal

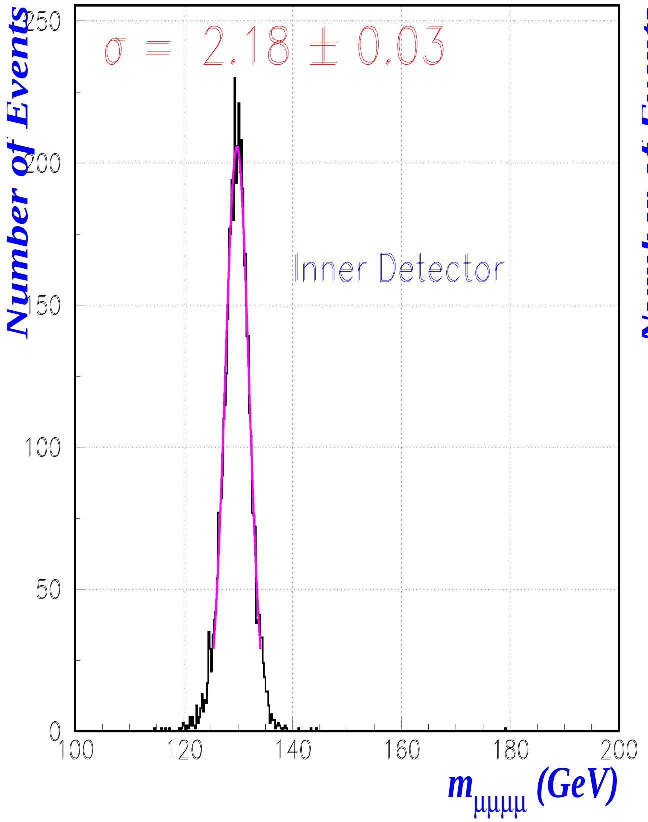
# 2) Analysis: Higgs mass resolution

- The Higgs mass resolution is perfomed by using:
  - standalone Muon System
  - Inner Detector only
- To improve the mass measurement:
  - Combination of tracks in the inner detector and the Muon system, two strategies can be used:
    - STACO : Statistical combination of two independent measurements by means of their covariance matrices
    - MUID : fitting the global muon track using the hits from the two subdtectors which were found and used separately by the standalone reconstruction
  - Kinematic constraint of the Z mass : Minimization of a $\chi^2$ (track parameters, covariance matrices Z mass and width).

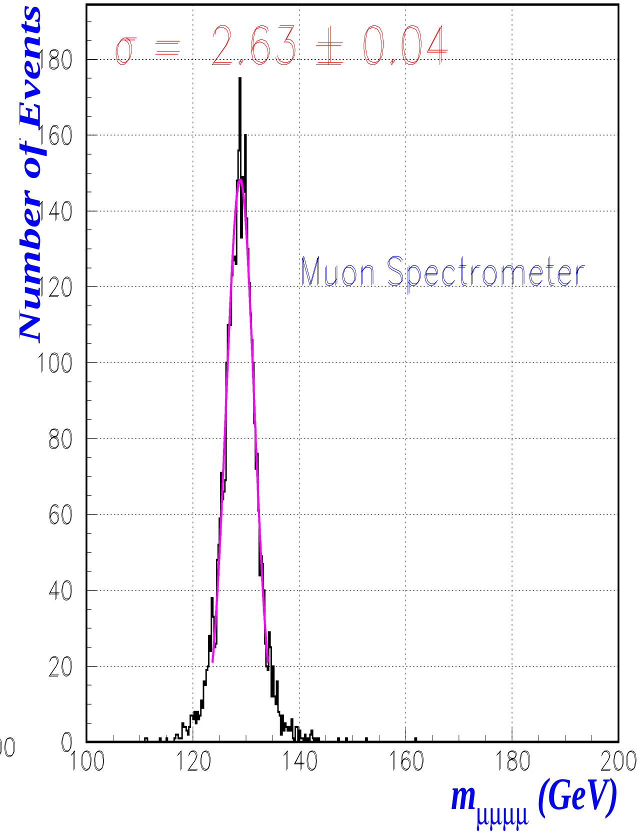
    A 10 parameter fit

# 2) Analysis: Higgs mass resolution $m_H$=130GeV

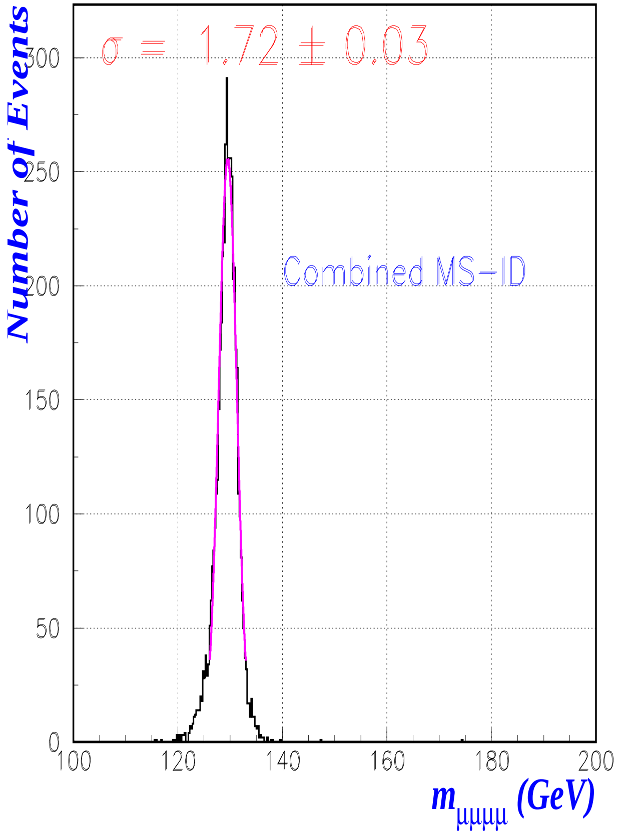
Inner Detector




Standalone Muon system




Combination(ID+μSyst)



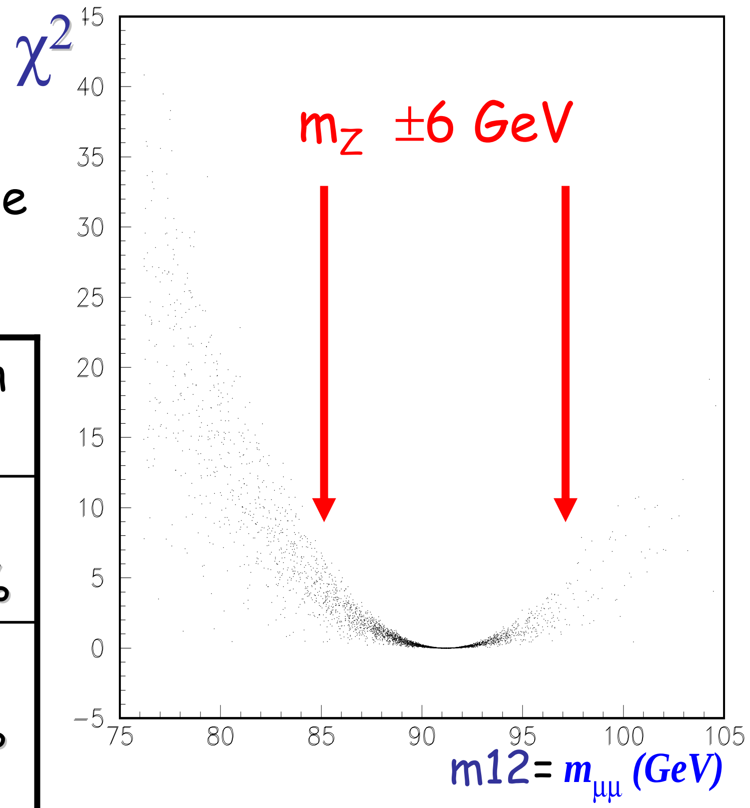

The combination improves the mass resolution by ~20-35% w.r.t ID/μSyst separately and reduces the non-Gaussian tails

# 2) Analyse: $Z^0$ mass constraint ($m_H$=130GeV)

- $\chi 2$ minimization (input: track parameters, covariance matrices, constraints: Z mass and width.) A 10-parameter fit

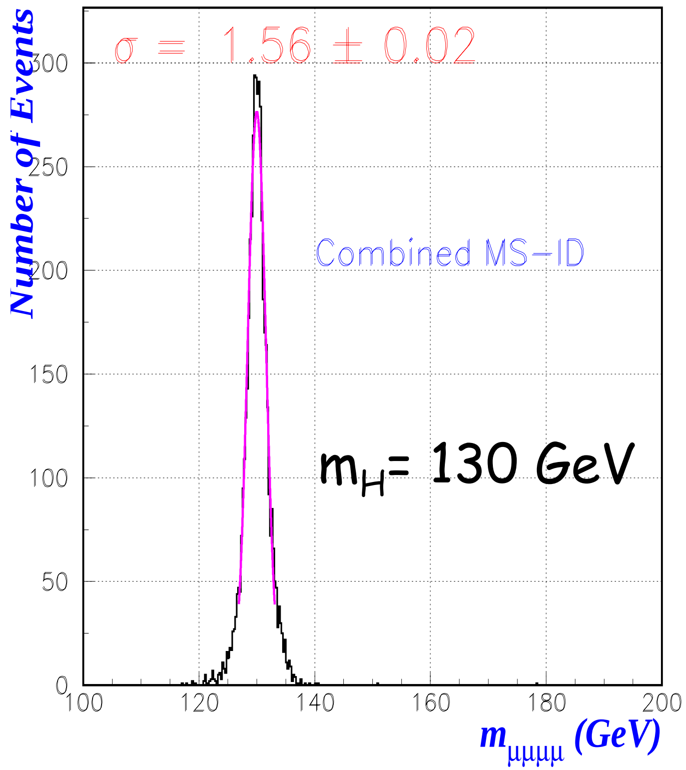
- Only events with $|m(\mu+\ \mu-) - mZ| < 6$ GeV are kept

| Resolution σ (GeV) | Before Z constraint | After Z constraint | Gain (%) |
|---|---|---|---|
| Muon System σ (GeV) | 2.63 ± 0.04 | 2.11 ± 0.04 | 20% |
| Inner Detector σ (GeV) | 2.18 ± 0.03 | 1.71 ± 0.03 | 21% |
| Combination ID + μSyst σ(GeV) | 1.72 ± 0.03 | 1.56 ± 0.02 | 10% |



# 2) Analyse: Higgs mass resolution

Combination of tracks in the inner detector and the Muon system
+ Z mass constraint




| $m_H$ (GeV) | σ (GeV) | σ (GeV) TDR |
|---|---|---|
| 130 | 1.56 ± 0.02 | 1.42 ± 0.06 |
| 150 | 1.81 ± 0.01 | 1.62 ± 0.06 |
| 180 | 2.22 ± 0.02 | 2.20 ± 0.06 |

$$\frac{\sigma}{m_H} \approx 1.2\%$$

Mass resolution worsen by ~ 10% wrt TDR
cracks in Muon System and
more realistic simulation of Inner Detector (material +field)

# 2) Analyse: Background rejection

- Signal and backgrounds after kinematic cuts ( integrated over a mass window of ± 5 GeV around $m_H$=130 GeV)

| process | σXBR(fb) |
|---|---|
| Signal : $H \rightarrow 4\,\mu$ ($m_H$=130 GeV) | **0.10** |
| Irreducible : $(Z/\gamma^*)(Z^*/\,\gamma^*) \rightarrow 4\,\mu$ | **0.04** |
| Irreducible : $(Z/\gamma^*)(Z^*/\,\gamma^*) \rightarrow 2\mu 2\tau$ | **0.01** |
| Reducible : $(Z/\gamma^*)$bb | **0.40** |
| Reducible : tt | **0.27** |

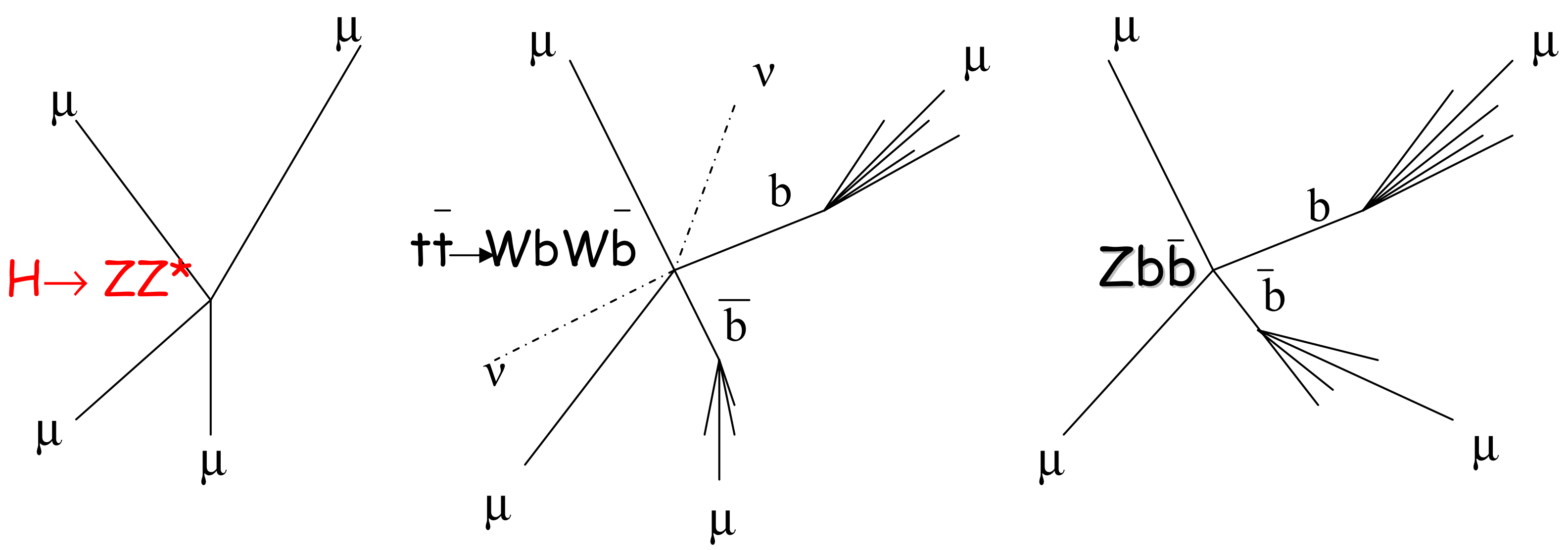
1) Rejection of reducible background

Aim : Bring the reducible bkg down to ~ 10% of irreducible bkg (protection vs theoretical uncertainties) ⇒ Rejection ~ 100 is needed

2) Rejection of irreducible background

Use Likelihood function & Neural Network with discriminating variables based on Higgs properties

# 2) Analyse: Rejection of reducible background




- Isolation Cuts

  In Zbb and ttbar bkg, 2 $\mu$ out of 4 are produced in b quark decay. They are less isolated than direct $\mu$

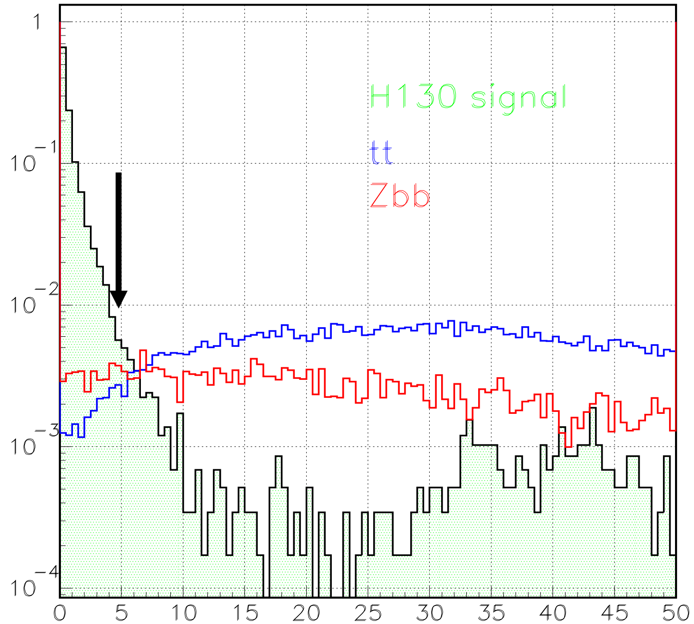
  - isolation in the Inner Detector
  - isolation in the Calorimeters

- Vertexing Cuts

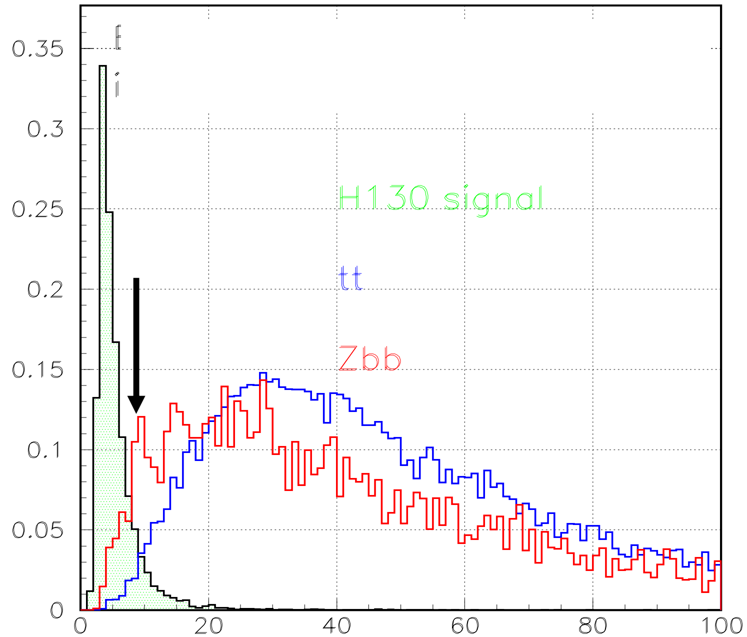
  In Zbb and ttbar bkg, 2 $\mu$ originate from the displaced vertex

  - impact parameter
  - quality of common vertex fit

# 2) Tracker and Calorimeter Isolation




Sum of $P_t$ of tracks around each μ in GeV




Σ of calo energy around each μ in GeV

*Variable* : Sum of the Pt of all tracks in the Inner Detector in a cone of $\Delta R=\sqrt{(\Delta\eta^2+\Delta\varphi^2)}= 0.2$ around each μ condidate

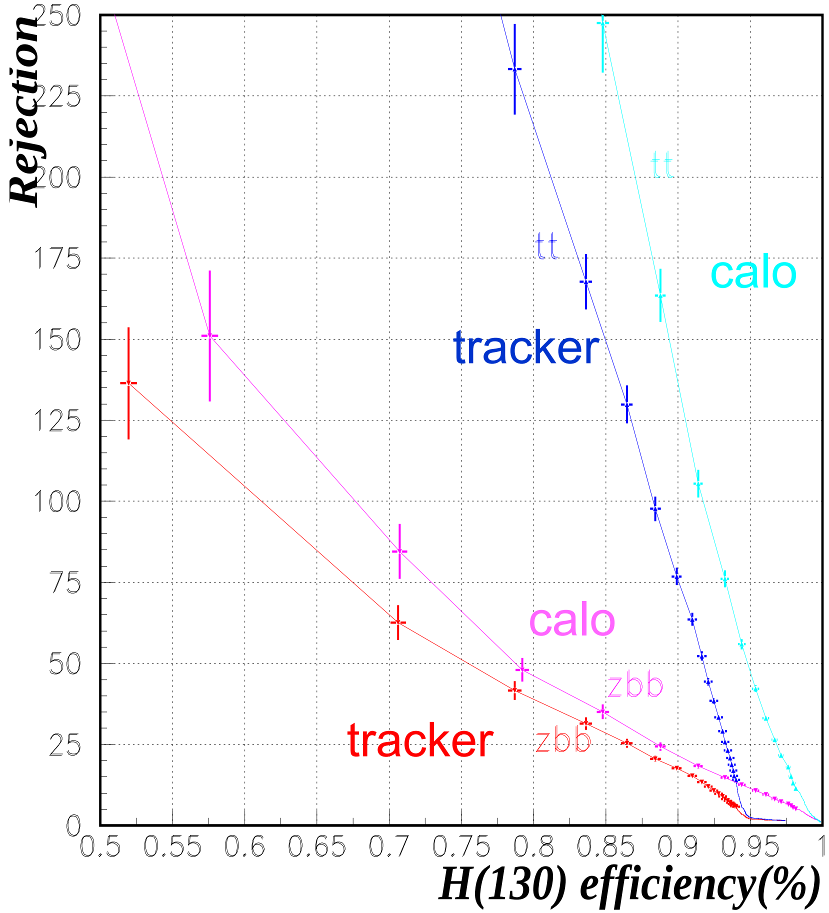
*Cut* < 5 GeV

*Variable* : Sum of the transverse energy deposition in the calorimeters (EM + Tile +LarHEC) in cone $\Delta R=\sqrt{(\Delta\eta^2+\Delta\varphi^2)}= 0.3$ around eacl μ candidate

*Cut* < 9 GeV

( pile-up and noise effects are not simulated)

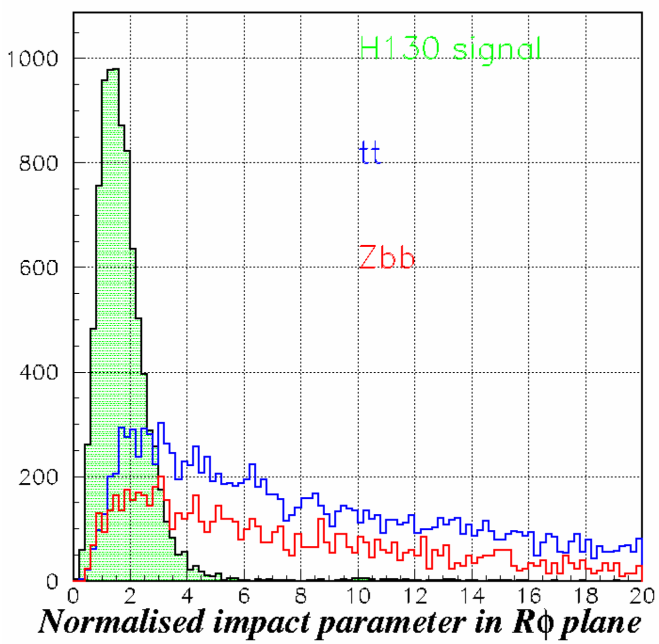
# 2) Calorimeter isolation versus Tracker isolation

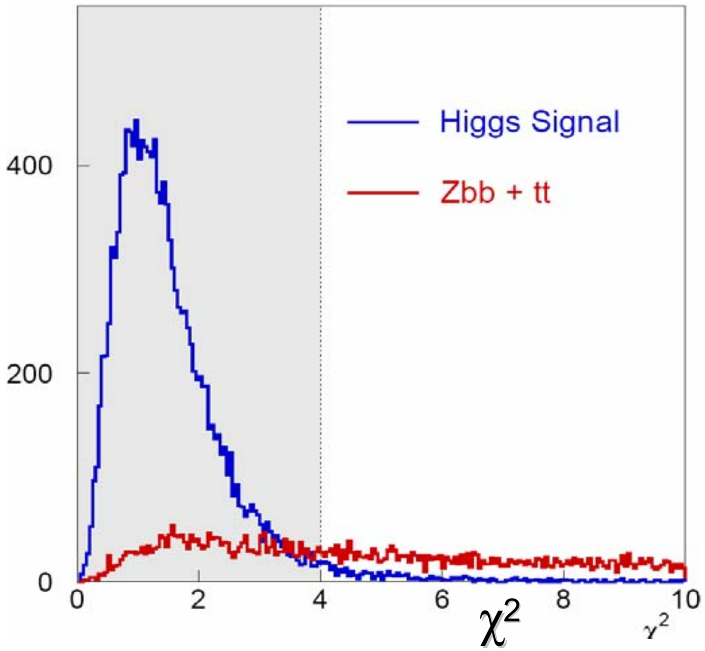



| Isolation | eff % $m_H$=130 | rejection tt | rejection Zbb |
|---|---|---|---|
| Calorimeters | 89 ±0.4 | 163 ±8 | 24 ± 2 |
| Tracker | 90 ±0.4 | 98 ± 5 | 22 ± 2 |

- The calorimeter criteria is more efficient than the tracker
- The isolation cuts are much less effective for Zbb events because of the softer pT spectrum of the b decay's products.

# 2) Vertexing : Impact parameter & Common Vertex fit




*Variable* : Largest of the normalized Impact Parameter of the μ candidates

*Cut* : Normalized IP < 3

Try to fit a common vertex with all the μ

*Variable* : $\chi^2$ of the vertex fit

*Cut* : $\chi^2$ of fit< 4

| Vertexing | eff % $m_H$=130 | Rejection tt | Rejection Zbb |
|---|---|---|---|
| Common Vertex | 89 ± 0.4 | 5.3 ± 0.6 | 4.9 ± 0.6 |
| Impact Parameter | 90 ± 0.4 | 3.2 ± 0.6 | 5.0 ± 1.2 |

The common vertex fit is more efficient than the impact parameter cut

# 2) Combined rejection : Isolation +Vertexing

| | Variable | eff % $m_H$=130 | rejection tt | rejection Zbb |
|---|---|---|---|---|
| Current analysis | Calorimeter info + vertex fit | 79 ± 0.5 | 879 ± 102 | 121 ± 15 |
| TDR | Tracker info + impact parameter | 81 | 1200 ± 350 | 105 ± 50 |

- The goal of 100 rejection of Zbb background is achieved
- The dominant reducible background after rejection is Zbb (softer $p_T$ spectrum, hence isolation and vertexing are less efficient)
- Likelihood and neural network with 6 variables give similar results
  - ✓the 2 largest normalized impact parameters(IP) in transverse plane of the 4 IP
  - ✓the 2 largest pT reconstructed inside a cone of R=0.2 around the 4 $\mu$ tracks
  - ✓the 2 largest total transverse energy depositions in calorimeters in a cone of R=0.2 around the 4$\mu$ tracks

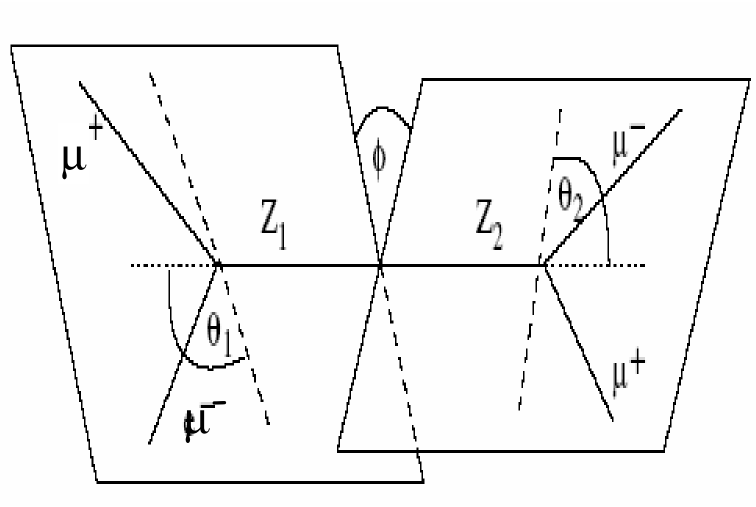
# 2) Analyse: Rejection of irreductible background

- Variables that help to reject irreducible **ZZ*->4μ** bkg are:
  - invariant masses (M12, M34), $p_T$ of 4 μ
  - angular distribution (if Higgs has Spin 0 and CP even)

- Likelihood function (and neural network) with 6 variables:

- Angle between the decay planes of the two Z in Higgs condidate rest frame

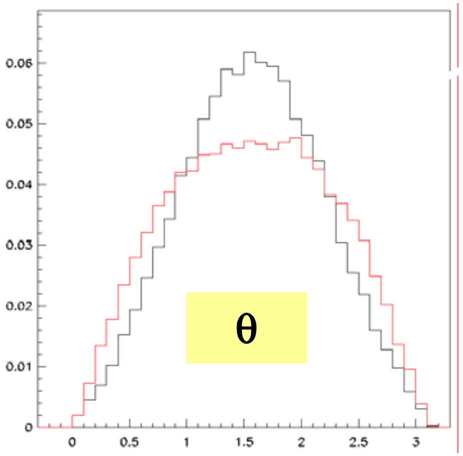
- Angle between μ- in Z rest frame and Z boost in Higgs rest frame (both for on-shell Z and off-shell Z)
  (see ATL-COM-PHYS-2003-001,Buszello et al.)

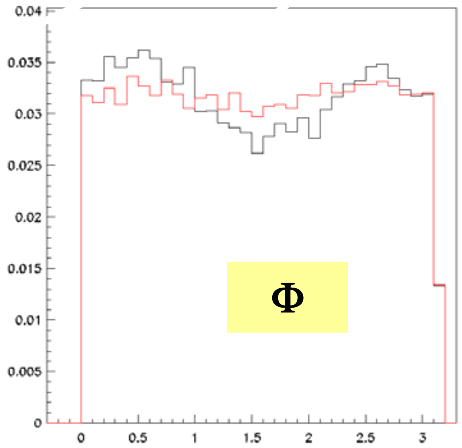


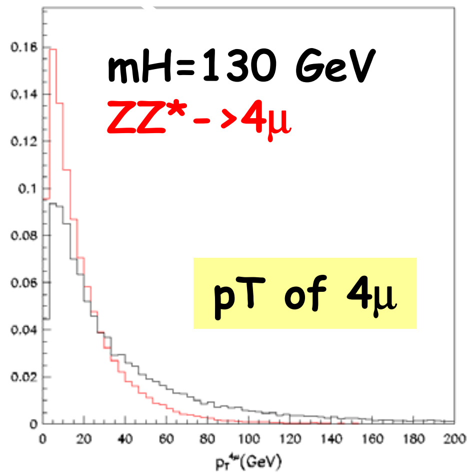

- $p_T$ of 4 μ

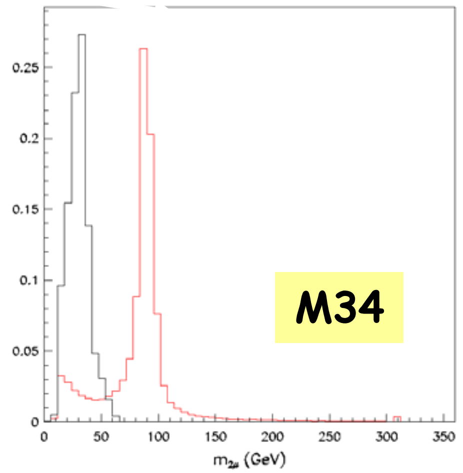
- Invariant mass of the two μ+ μ- paires (M12 and M34)

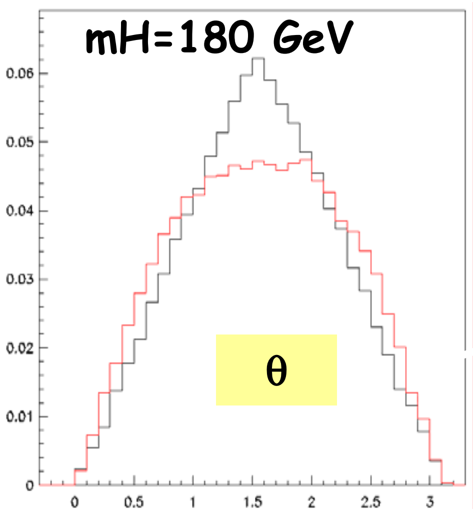
# 2) Analyse: Rejection of irreductible background



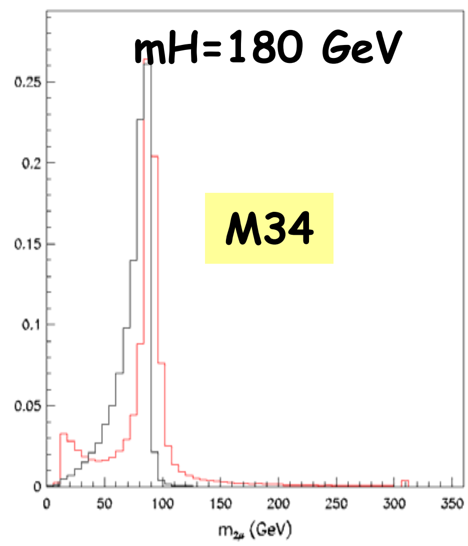




| MH (GeV) | Rejection ZZ LIK | Rejection ZZ NN |
|---|---|---|
| 130 | 1.53 ±0.04 | 1.69±0.05 |
| 150 | 1.57±0.04 | 1.70±0.06 |
| 180 | 1.38±0.02 | 1.41±0.02 |



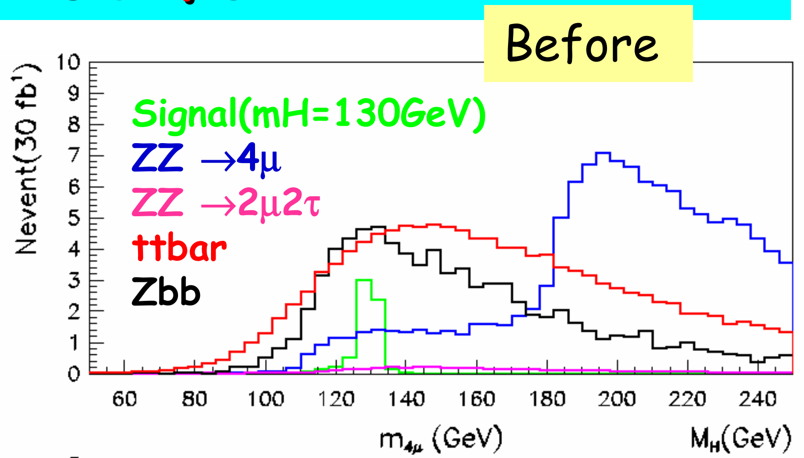

- At higher masses, angular distributions are more different between signal and bkg, but mass distributions are more similar

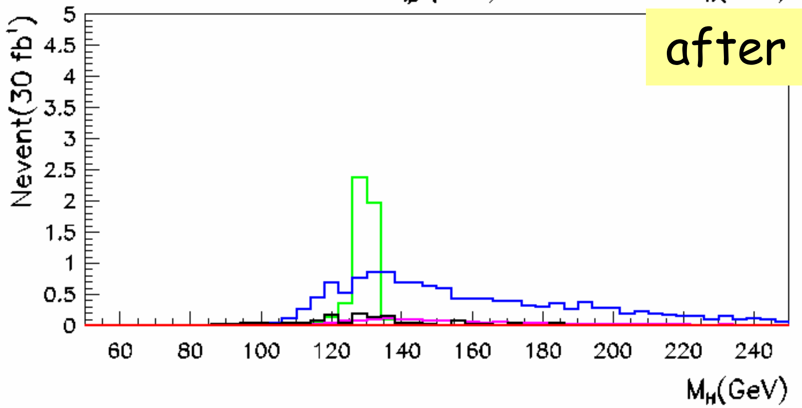
# 3) Results for L=30 $fb^{-1}$

Signal and background rates after overall analysis in mass window ±5 GeV around mH

| | |
|---|---|
| Signal (mH=130GeV) (eff=81.2%) | 4.16 |
| $ZZ \to 4\mu$ | 1.36 |
| $ZZ \to 2\mu 2\tau$ | 0.15 |
| $Zbbar \to 4\mu$ | 0.31 |
| $ttbar \to 4\mu$ | 0.01 |
| BKG | 1.83 |

| Higgs Mass (GeV) | Significance (Poisson) |
|---|---|
| 130 | 2.32 |
| 150 | 5.12 |
| 180 | 2.24 |




By combining the channels $H\to ZZ^*\to 4\mu$, $H\to ZZ^*\to 4e$, $H\to ZZ^*\to 2e2\mu$, the Higgs signal can be observed with a better than $5\sigma$ significance over most of the range $130<m_H<180$ GeV for an integrated luminosity of 30 $fb^{-1}$

# Summary

- This analysis aimed at the:
  - Validation of the reconstruction software within Athena framework with the Data Challenge 1 samples (~1M fully simulated events)
  - Performance of muon $\mu$ detection
    - ~9% loss w.r.t TDR in $H \rightarrow 4\mu$ efficiency due to the new Muon System layout
- **Mass resolution** worse than in TDR at level of 10% because of cracks in Muon System and more realistic simulation of Inner Detector (material +field)
- In spite of slight deterioration in expected performance, improved analysis techniques leads to results consistent with TDR results