# Searches for Continuum and Resonant Production of Z Boson Pairs Using the ATLAS Detector

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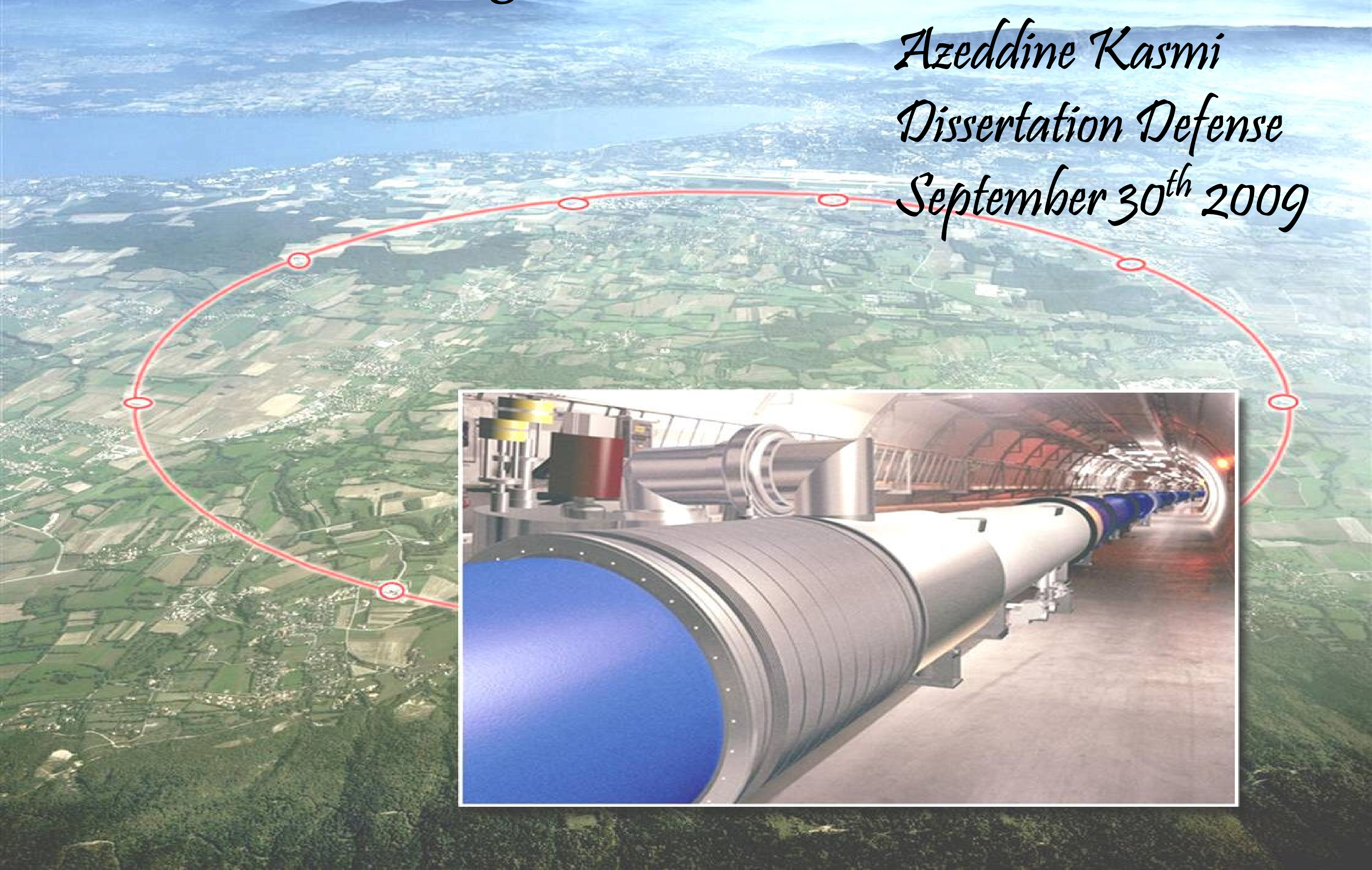
*Dissertation Defense*
*September 30th 2009*



# OUTLINE

- Theoretical motivation
- The ATLAS detector at the Large Hadron Collider
  - Electronics calibration of calorimeter*

- Reconstruction and Particle Identification
  - Photon conversion*
  - Lepton ID and optimization*
  - techniques for partially reconstructed "*e*"*

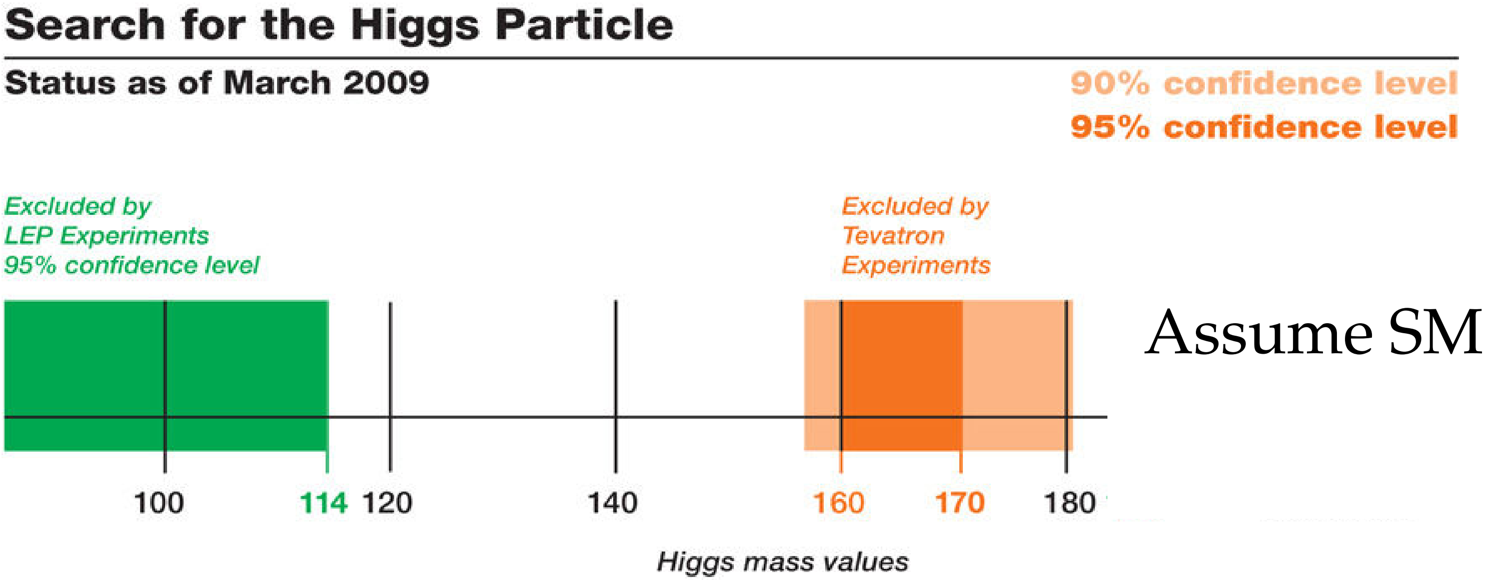
- Z Pair Production Search*
- Higgs Search*
- Conclusion

*My contributions

# Open Question in the SM: Origin of Mass

- Origin of mass: still unresolved question
- Current explanation: based on symmetry breaking
  - $SU(2)_L x U(1)_Y$ spontaneously broken symmetry
  - Generates masses for the weak bosons ($W^{\pm}$,Z) and the fermions
  - Particles gain mass via interaction with the "Higgs field"
  - Predicts a scalar particle: the Higgs boson
  - Fermion masses unpredicted

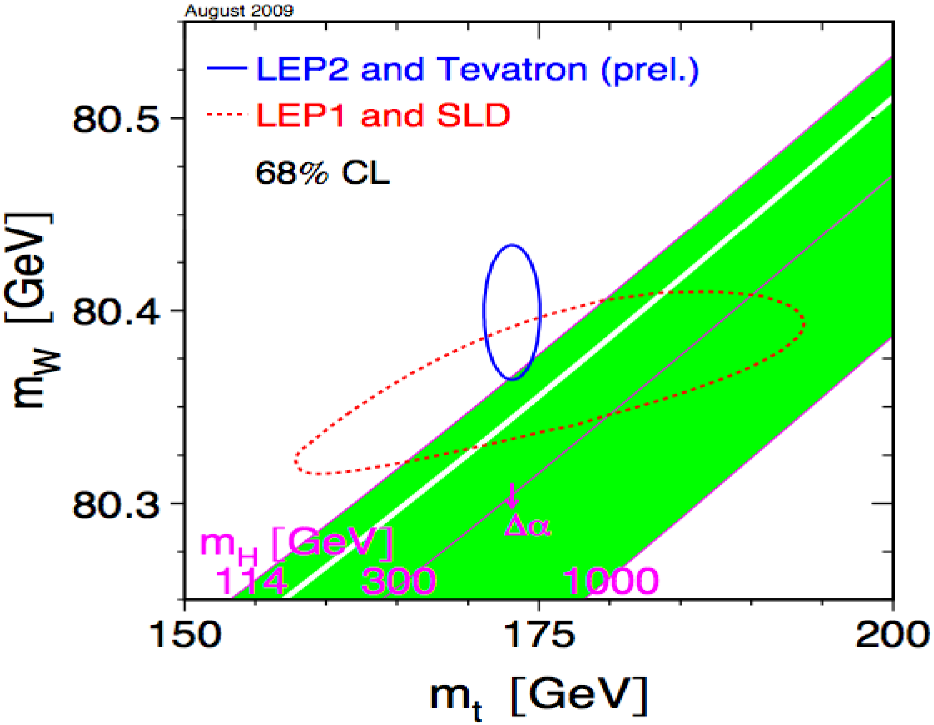
LEP/Tevatron Limits on the Higgs mass $m_H$

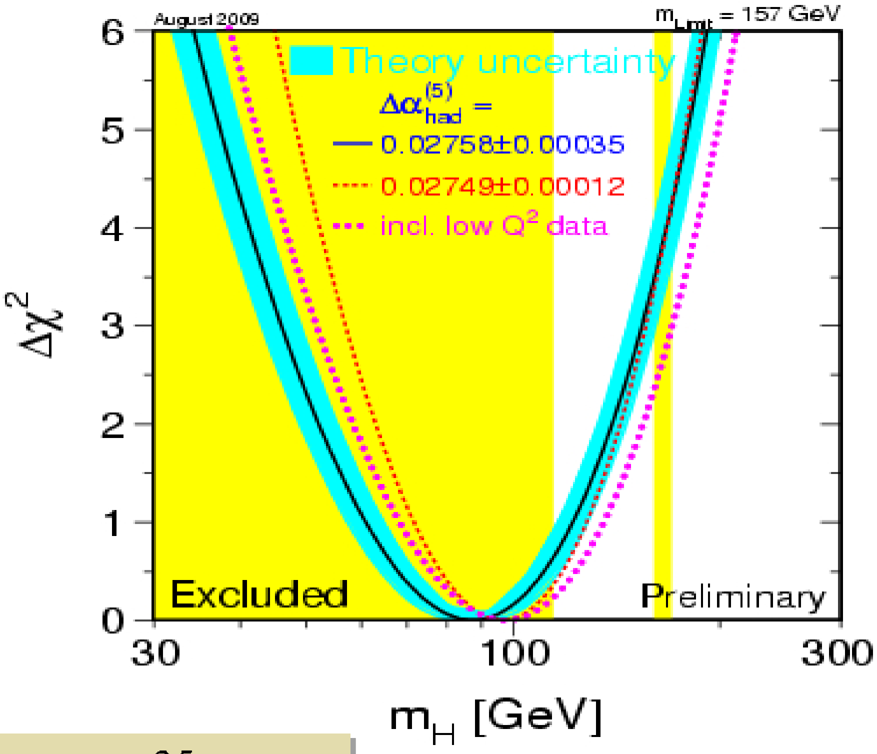


Assume SM Higgs

# Electroweak fits

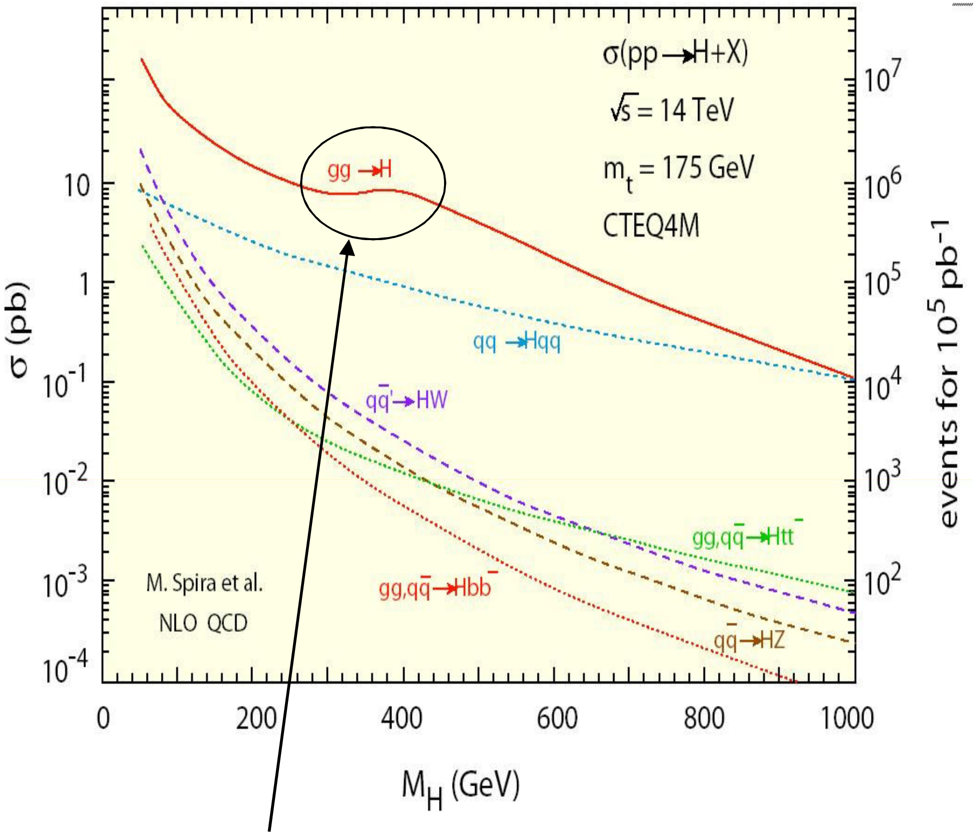
**Radiative corrections for $M_W$ go as $m_t^2$, $\log(m_H)$**



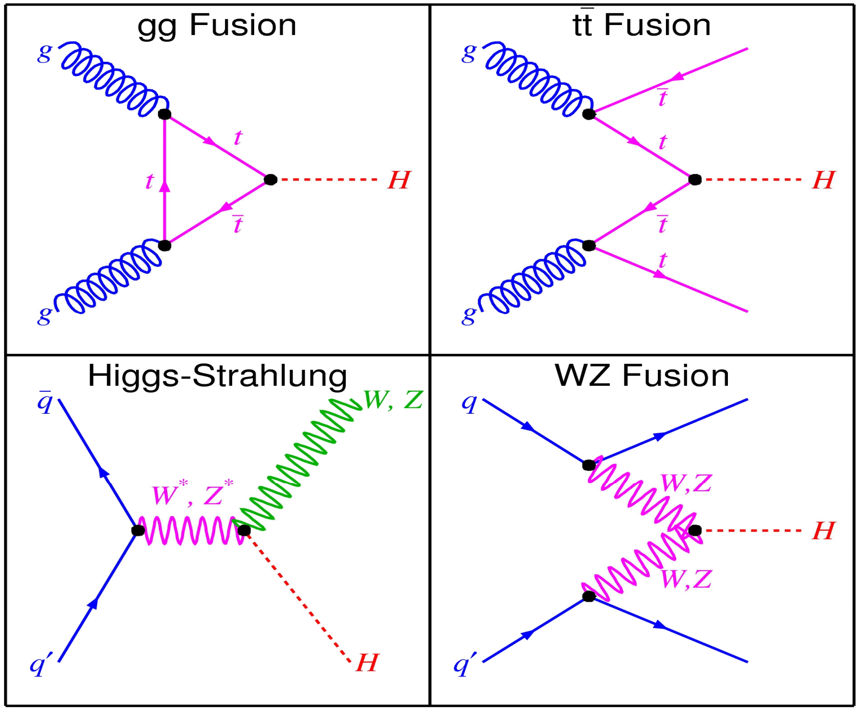


$$m_H = 87^{+35}_{-26}\,\mathrm{GeV}$$

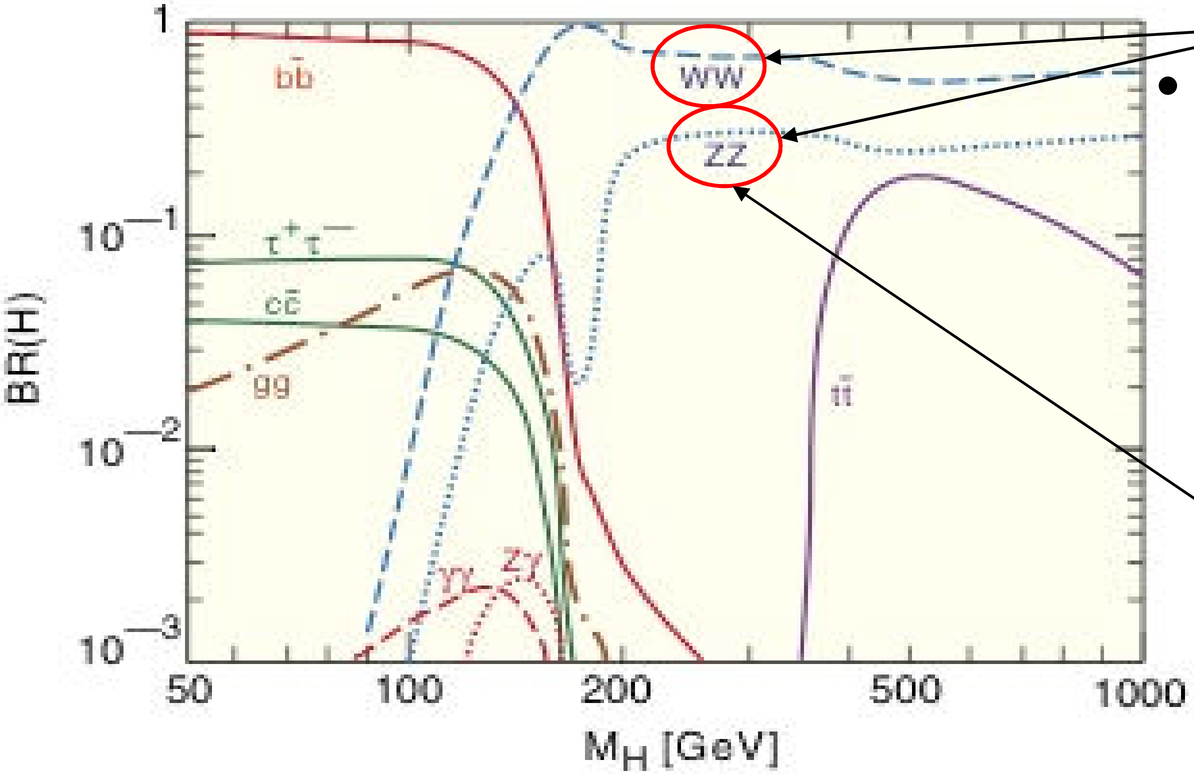
# Higgs Production



Focus on that process



# Higgs decay modes

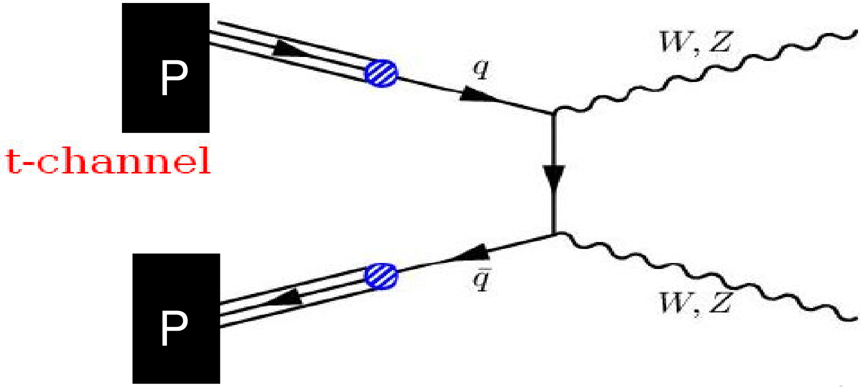


- Heavy Diboson decay mode
  - Dominates at medium to high masses

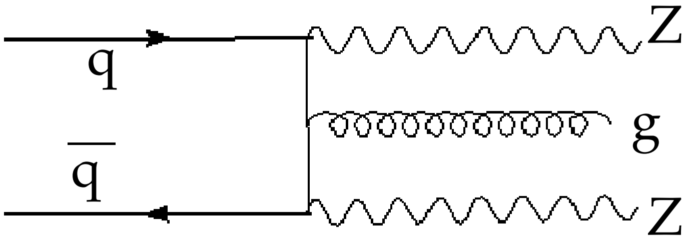
My focus

- Z boson pair production is an important background for the Higgs searches

# Z Pair Production and Final States

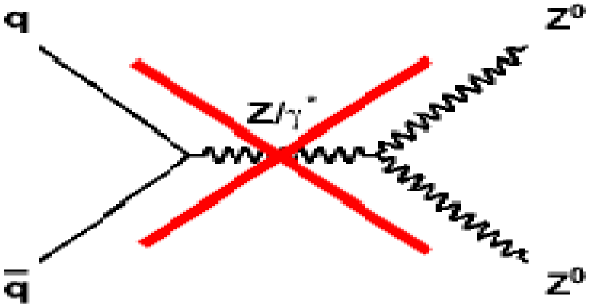


<u>NLO</u>



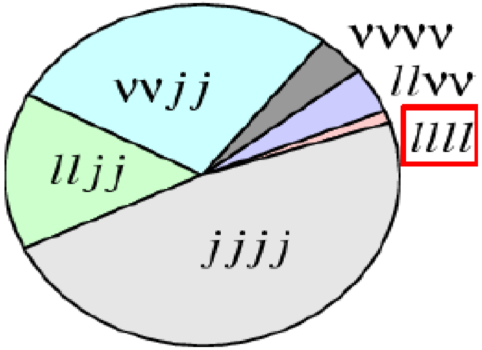
NNLO

Contribution from gluon-fusion ~15% of the total cross section



**ZZZ and ZZγ are absent in the SM**

- Boson pair production probes gauge boson self-interaction
- Sensitive to new physics in trilinear gauge couplings (TGC)

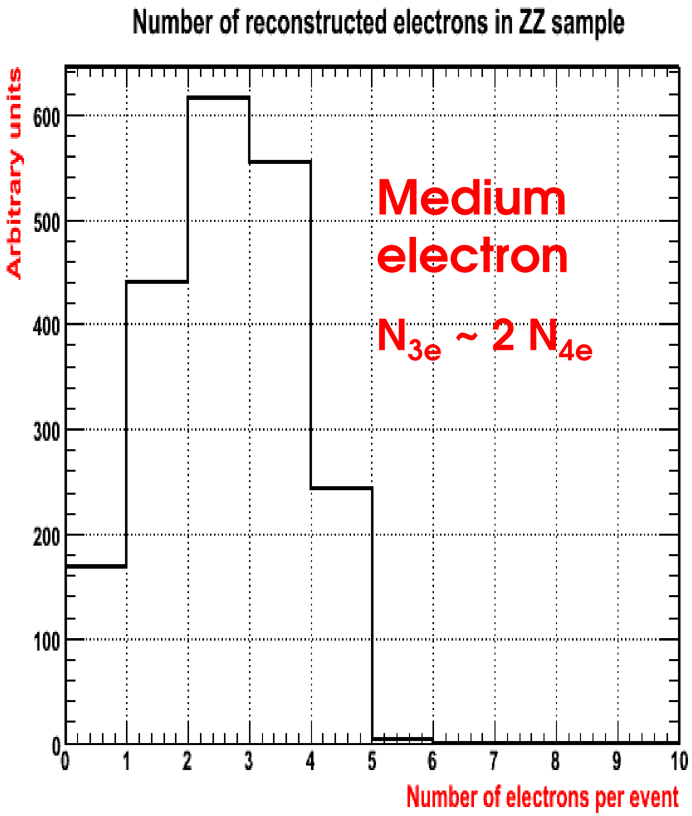


- Despite the small BR, the 4 lepton channel is a clean signature

$BR(ZZ \rightarrow 4\ell, \ell = e, \mu) = 0.5\ \%$

# The signature of the search

- In ZZ→ 4leptons
  - 4 leptons are produced
  - Inefficiencies in electron reconstruction
    - Number of events with 3 reconstructed leptons is higher than events with 4 reconstructed leptons.

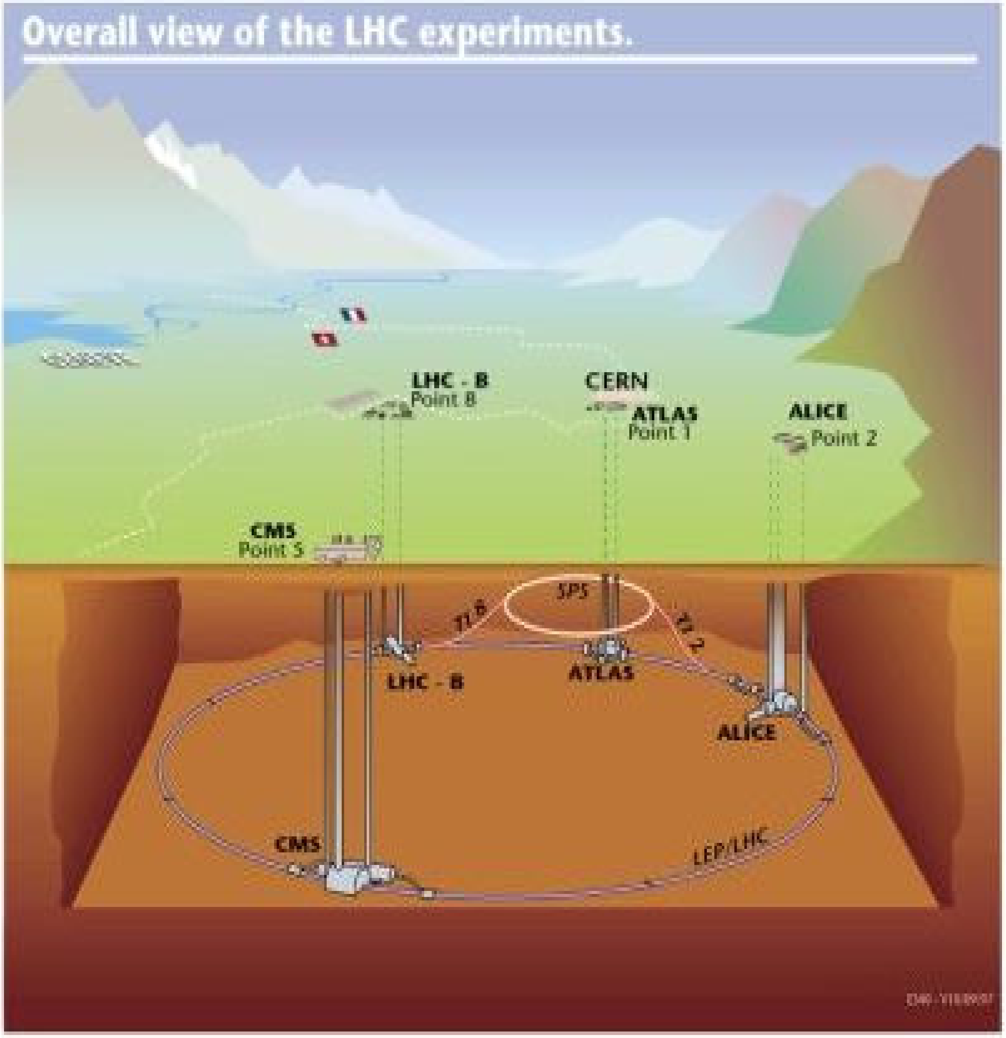

Number of reconstructed electrons in ZZ sample

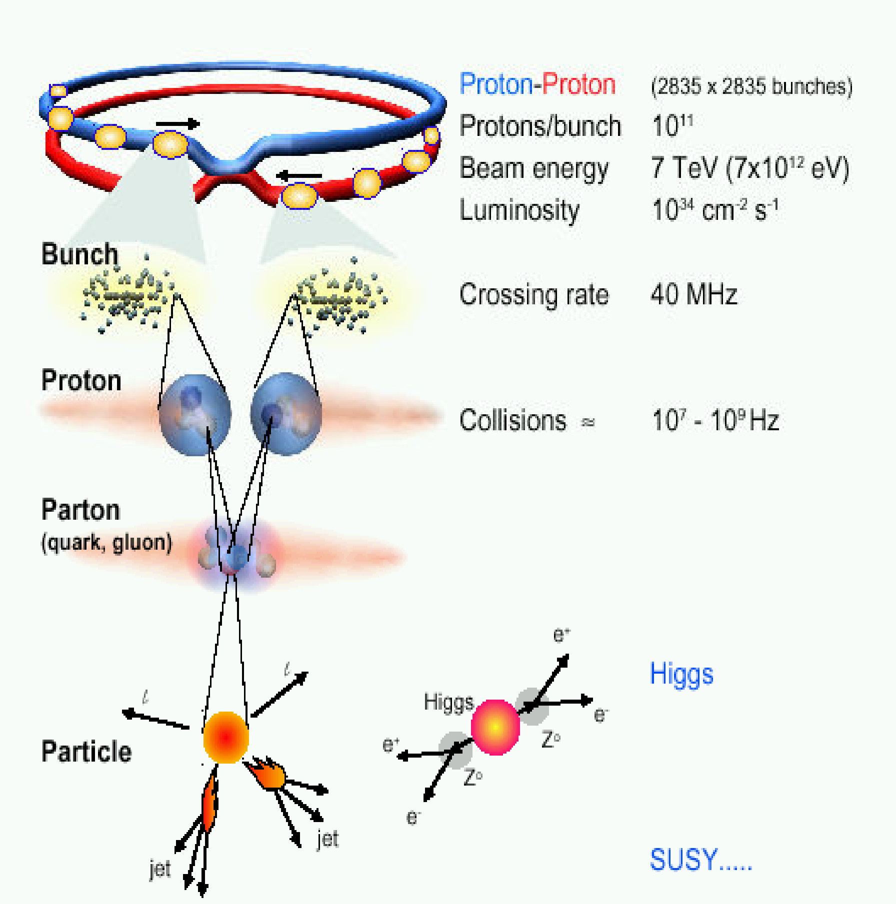
**Medium electron**

$N_{3e} \sim 2\,N_{4e}$

- Strategy
  - Fully identify 3 leptons (Ryszard/Julia)
  - Partially identify unfound electron
    - eg. $4e \rightarrow 3e$+"e", $2\mu 2e \rightarrow 2\mu 1e$+ "e"
    - My approach: ignore tracking, sliding window electron algorithm
    - Maximize acceptance with calorimeter
    - Try to reduce BG to acceptable level

# The Large Hadron Collider (LHC) at CERN



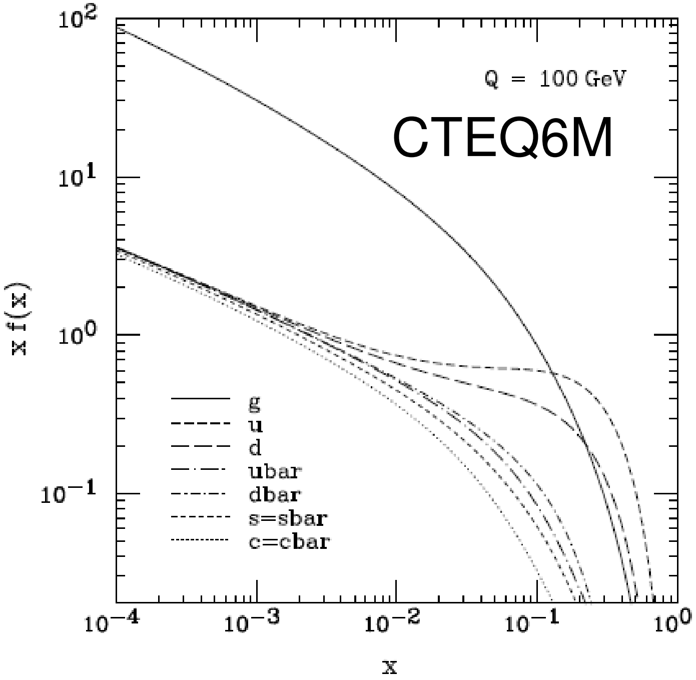


| | |
|---|---|
| Proton-Proton | (2835 x 2835 bunches) |
| Protons/bunch | $10^{11}$ |
| Beam energy | 7 TeV ($7 \times 10^{12}$ eV) |
| Luminosity | $10^{34}$ cm$^{-2}$ s$^{-1}$ |
| Crossing rate | 40 MHz |
| Collisions ≈ | $10^{7}$ - $10^{9}$ Hz |

Selection of 1 in 10,000,000,000,000

# LHC Parton Kinematics

- Protons made of 3 valence quarks in a sea of gluons, quarks and anti-quarks
- Each parton carries only a fraction of the proton momentum
- $f_a$ and $f_b$ are parton distribution functions



$$\sigma_X = \sum_{a,b}\int_0^1 dx_a dx_b f_a(x_a,\mu_F^2) f_b(x_b,\mu_F^2)$$

$$\times \hat{\sigma}_{ab\to X}(x_a,x_b,\{p_i^\mu\};\alpha_s(\mu_R^2),\alpha(\mu_R^2),\frac{Q^2}{\mu_R^2},\frac{Q^2}{\mu_F^2})$$

where X=W, Z, H, high-$E_T$ jets, … and $\hat{\sigma}$ calculated via perturbation theory

LHC will run Nov. 2009 @7 TeV L = $10^{31}$ cm$^2$ s$^{-1}$

This analysis assumes 14 TeV center of mass

# The ATLAS Detector at CERN

## Inner Detector:

- Momentum measurement
- Solenoidal magnetic field of 2 T
- Covers region of $|\eta| < 2.5$

## ATLAS coordinate system

Polar coordinates: $\theta$ and $\varphi$

z is beam axis

Pseudo rapidity: $\eta = -\ln\tan(\theta/2)$

## Calorimeters:

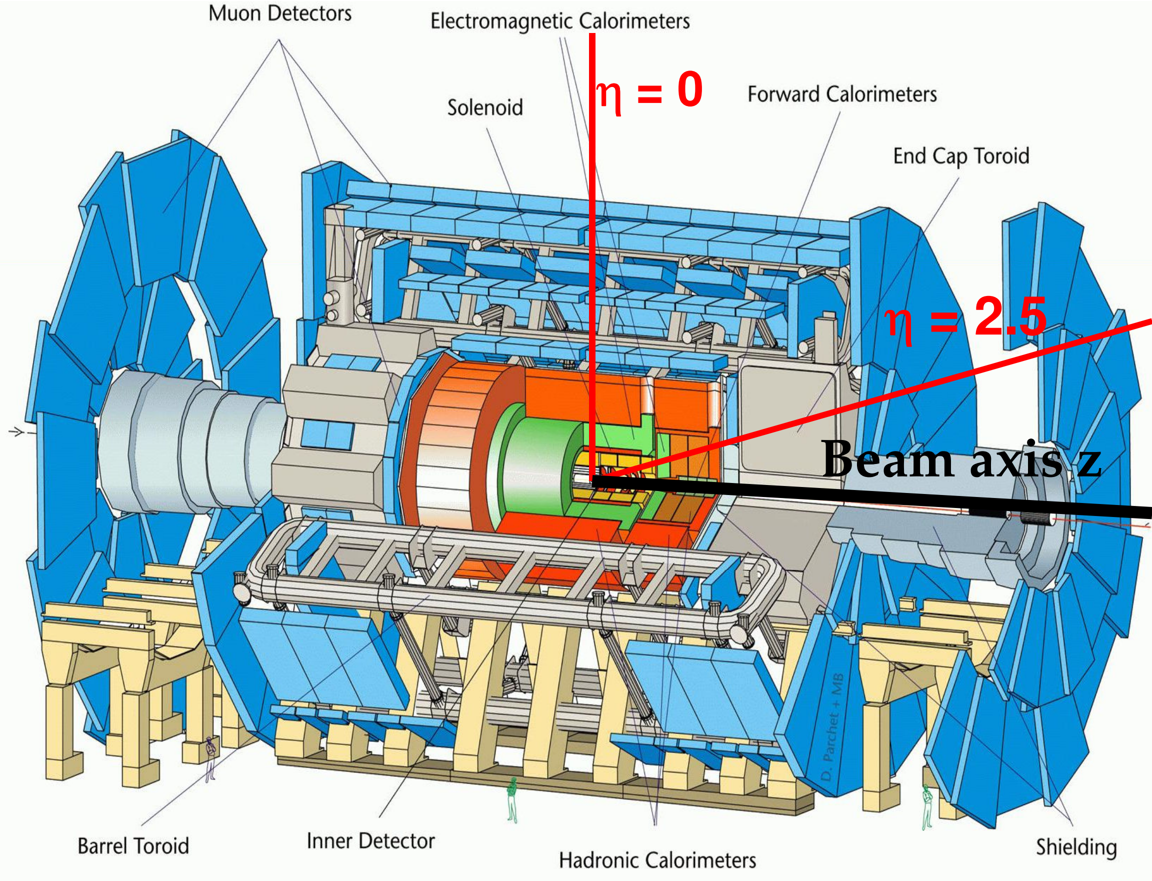
Absorber: lead/stainless-steel

Active medium: Liquid Argon

- Energy measurement
- Covers region $|\eta| < 4.9$

Electromagnetic: $\gamma$, $e$

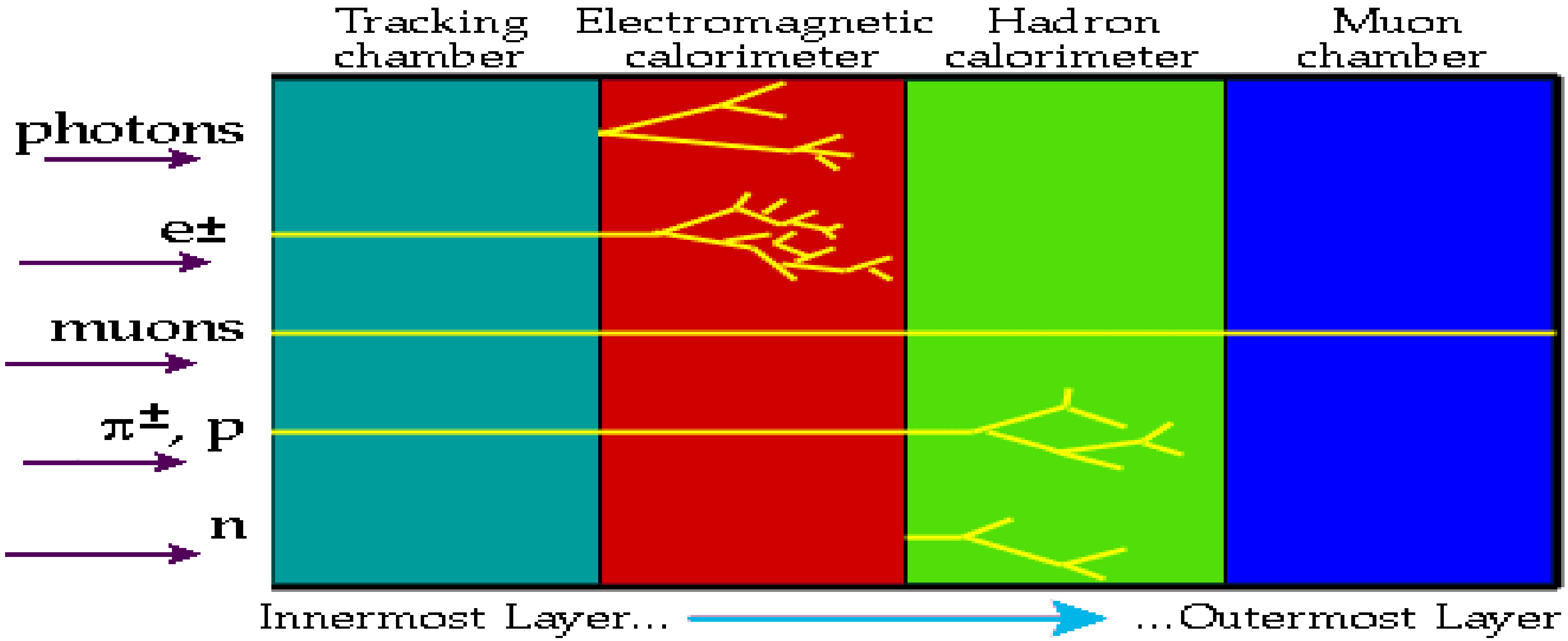
Hadronic: jets, $E_T^{Miss}$



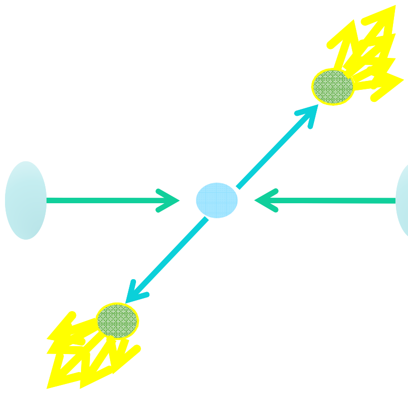
## Muon Spectrometer:

- Muon identification
- $P_T$ measurements
- Toroid B field
- Inner detector $|\eta| < 2.5$

# General Principle for Particle Detection



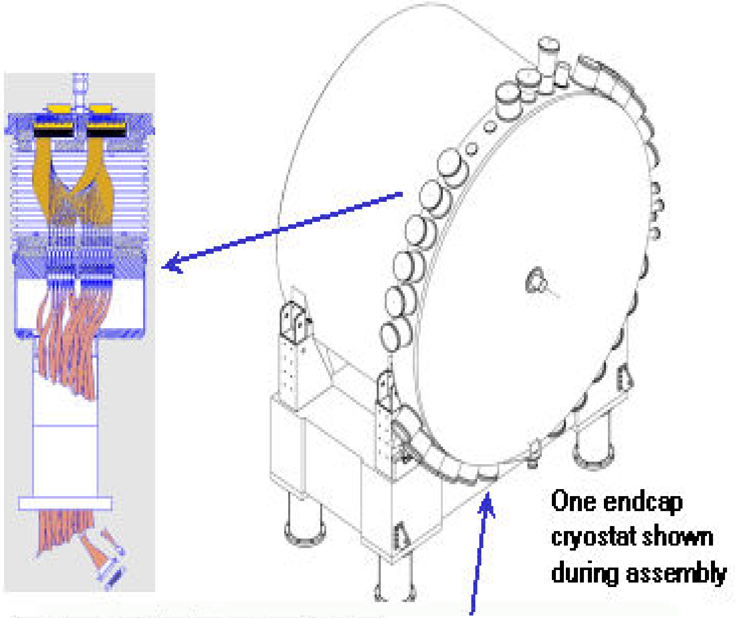
- Charged particles (μ, *e*) leave a track
- Colored objects can not be observed due to confinement
  - Fragmentation is when colored objects create a spray of collimated particles which is known as "jets"

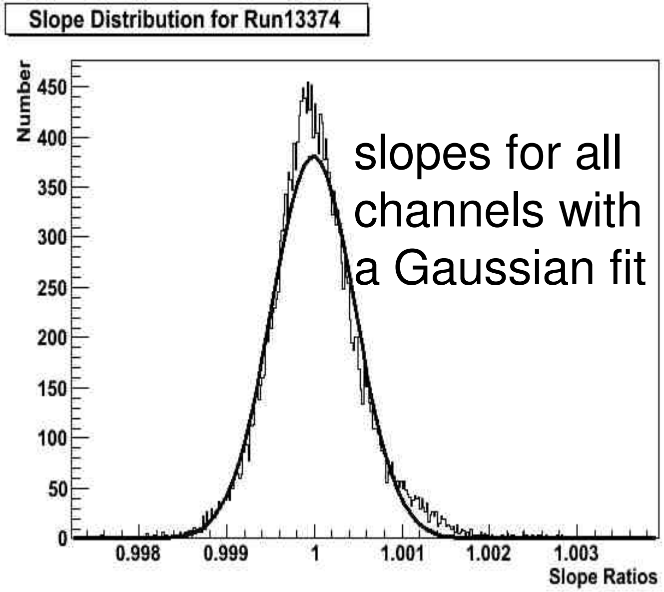


# Calibration of Electronics

- A ramp run simulates passage of particles through detector by injecting a charge by DAC (Digital-to-analog converter)
- Modification the signal goes through in Front End Boards should be taken into consideration,

  the ramp factor, the slope of ADC vs. DAC.
- The slope is defined as $\dfrac{Ramp_{run\ \ channel}}{Ramp_{reference\ \ channel}}$
- My task was
  - analyze the slopes and identify bad channels in crates in end cap (4 in each end cap)
  - One Feed-through (FT) has 15 FEB's and another has 8 FEB's
  - One crate reads out 1792 EMEC outer wheel channels, 112 EMEC inner wheel channels and 704 HEC channels

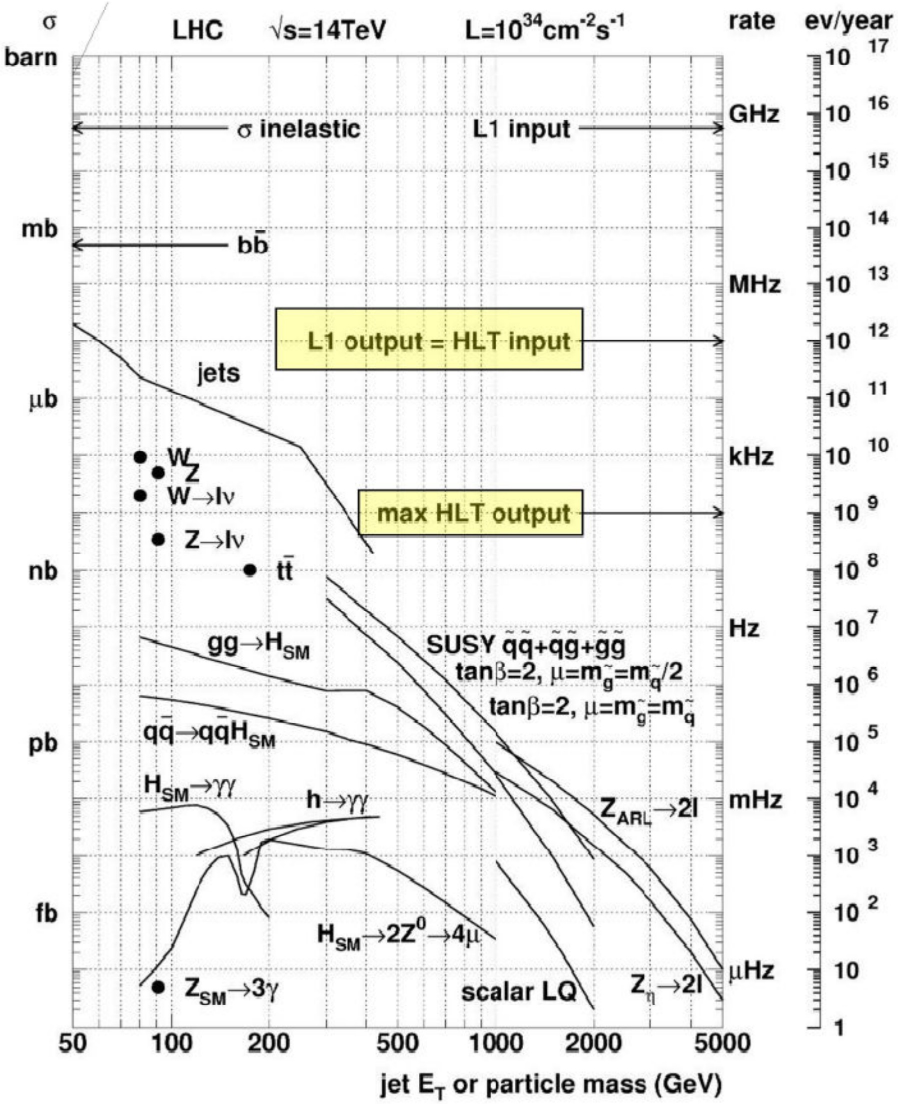

One endcap cryostat shown during assembly



slopes for all channels with a Gaussian fit

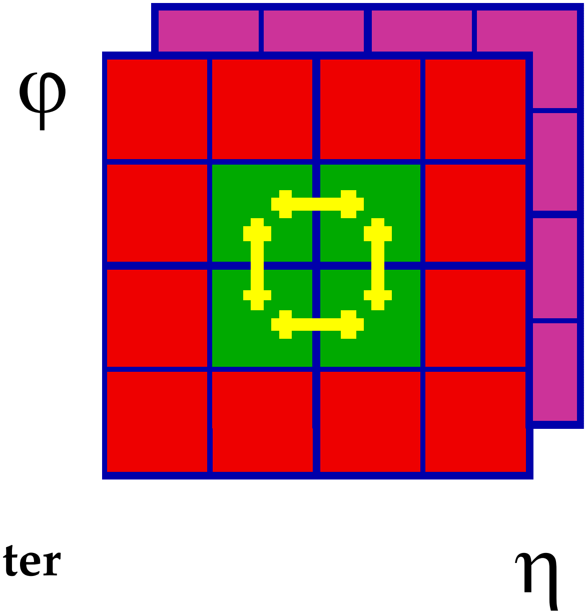
# Trigger and DAQ

- Level 1 (hardware) trigger
  - Event rate from 40MHz down to 100kHz
  - Uses calorimeters & muon chambers
- Level 2 (software) trigger
  - Event rate down 2.5kHz
  - Input from Level 1 trigger
- Event Filter (software) trigger
  - Event rate down to 200Hz
  - Reconstruct full event and makes decision



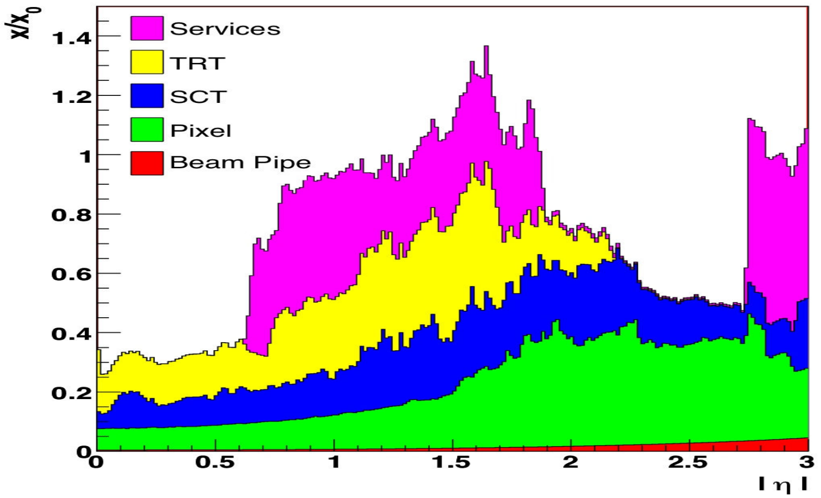
# Data Collection and Reconstruction

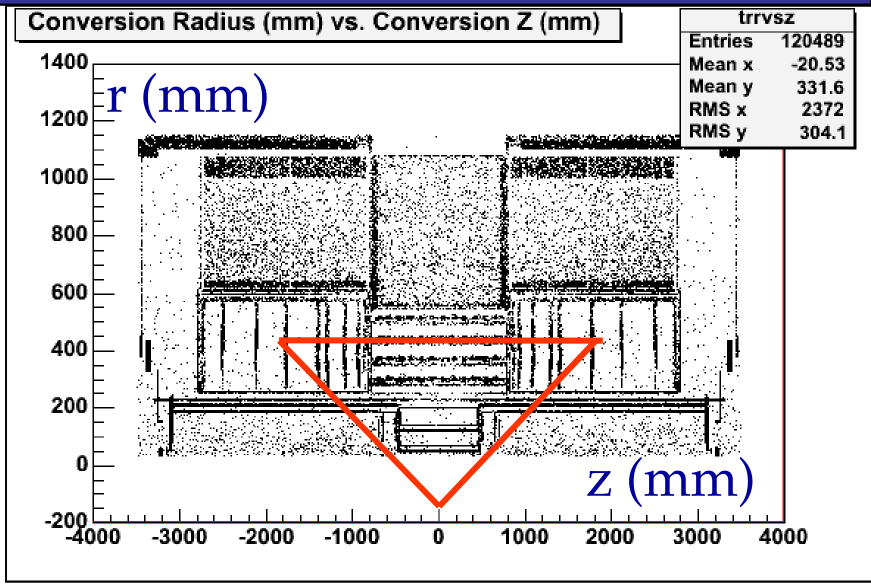
- **Standard Electron/Photon Identification**
  - **Uses a sliding window**
  - The space of $\eta$ and $\varphi$ is divided into a grid each of size $\Delta\eta$ , $\Delta\varphi$.
  - Drawbacks
    - **covers $|\eta| < 2.5$**
    - **Makes the assumption of the width of the cluster**
    - **splits the cluster in crack region**



- **Muon Identification**
  - Combination of tracks from the inner tracker & spectrometer
  - Minimum $\chi^2$ between tracks from inner tracker and spectrometer

# Photon Conversion





- Photon conversion occurs at the presence of material
- I found that reconstruction efficiency is 80%
  - for conversions that occur up to a distance of 800mm from the beam axis
- The effective angle range of the conversion finder is $-2.5 < \eta < 2.5$
- For the current software
  - Any electron which forms an 0 opening angle with an opposite charge electron is considered as conversion

# Signal and Background Modeling

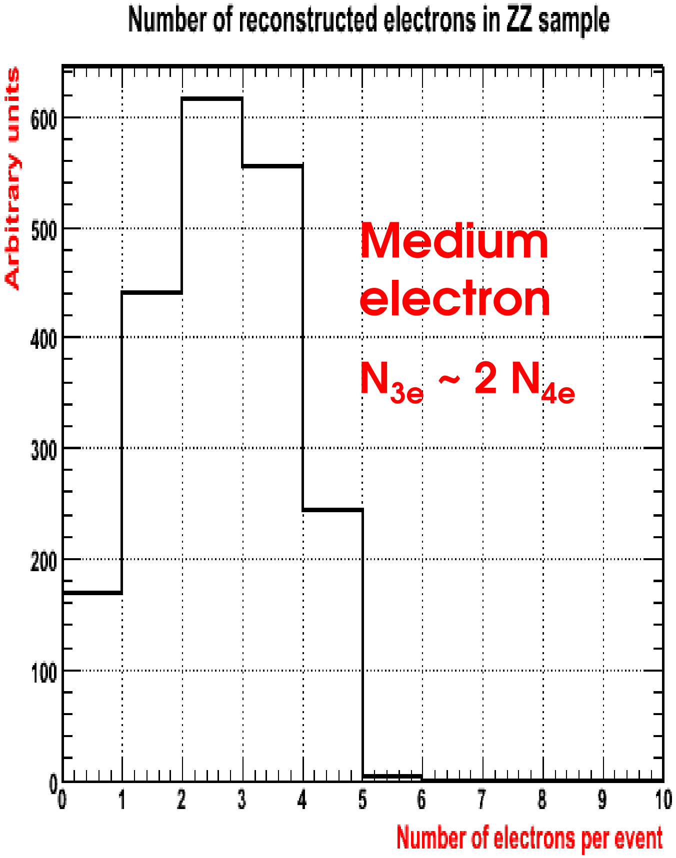
| Samples | ZZ→4ℓ | H→ZZ →4ℓ 180 GeV | H→ZZ →4ℓ 200 GeV | H→ZZ →4ℓ 300 GeV | Zbb→ 3ℓ | Zb→ 3ℓ | WZ→3ℓ | tt→4ℓ |
|---|---|---|---|---|---|---|---|---|
| Generator | MC@NLO | Pythia | Pythia | Pythia | AcerMC | AcerMC | Herwig - Jimmy | MC@NLO |
| pdf | CTEQ6M | CTEQ6M | CTEQ6M | CTEQ6M | CTEQ6L | CTEQ6L | CTEQ6M | CTEQ6M |
|  | 66.8 fb (NLO) | 5.38 fb (NLO) | 20.53 fb (NLO) | 13.32 fb (NLO) | 12663 fb (NLO) | 14000 fb (NLO) | 807 fb (NLO) | 6064 fb (NLO) |

$\sigma_s/\sigma_B \sim 10^{-3}$

Simulated in GEANT-4 for the ATLAS detector

# 3l + "e" selection: Motivation

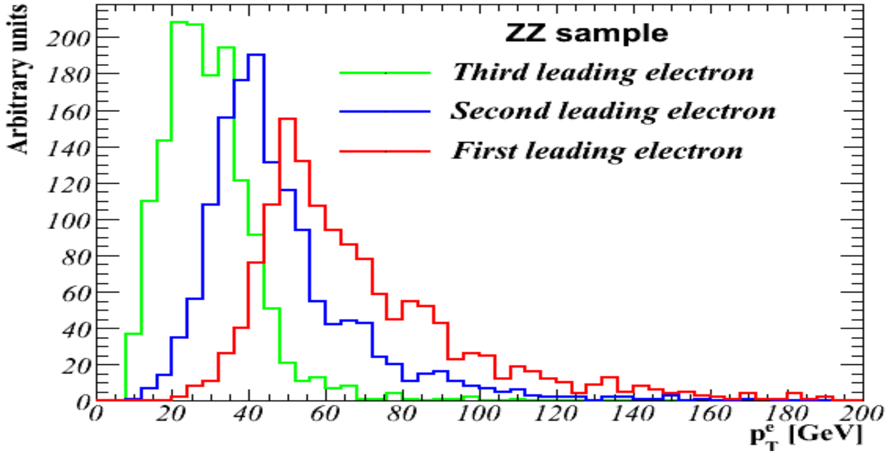
- Why channel with 1 unidentified "e" ?
  - Calorimeter can find it: complete acceptance
  - Tracking available only in $|\eta| < 2.5$
  - Clustering available only in $|\eta| < 2.7$
  - Detector cracks
  - I will avoid the sliding window algorithm
- What does reconstructed lepton multiplicity in ZZ→4e look like ?
  - 3*e* has higher acceptance than 4*e* reconstructed
- This Analysis exclusive 3l+"*e*" (4l excluded)
  - Current analysis includes ZZ→3*e* +"*e*" ZZ→2μ1*e* +"*e*", and analogous Higgs channel
  - I developed 2 different techniques for finding the unidentified electron

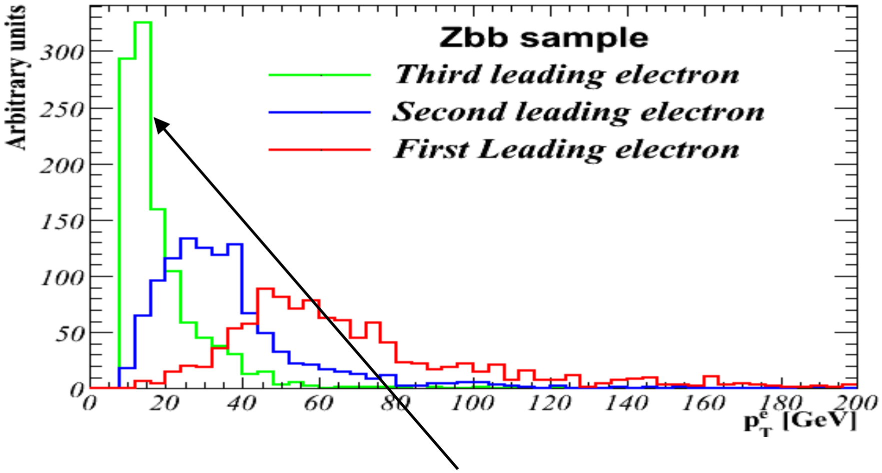

Number of reconstructed electrons in ZZ sample

**Medium electron**

$N_{3e} \sim 2\, N_{4e}$

# Pre-selection: lepton $P_T$ and trigger efficiencies





In Zbb, the third-leading electron has low $P_T$

Require $P_T$ > 10 GeV

Trigger efficiencies

3e channel

Trigger efficiency is ~100%

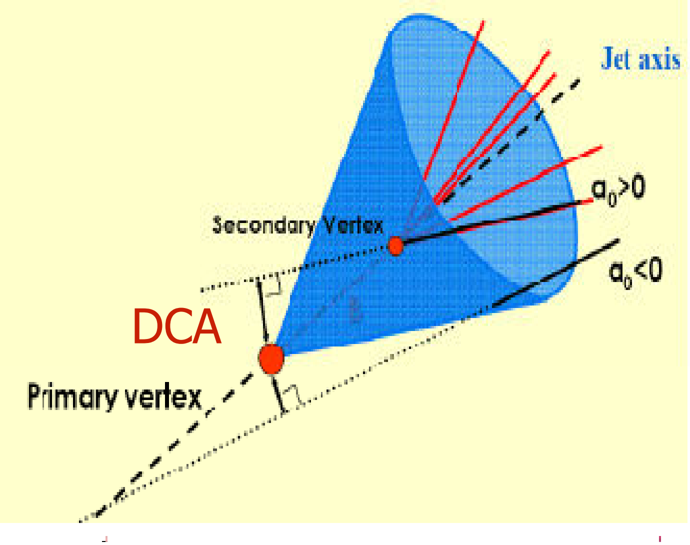
| Trigger item | $ZZ$ | H (180) | H (200) | H (300) |
|---|---|---|---|---|
| **EF_e10** | 0.997 ± 0.001 | 0.998 ± 0.001 | 0.998± 0.001 | 0.997± 0.001 |
| **EF_2e25i** | 0.869 ± 0.006 | 0.774 ± 0.008 | 0.816±0.007 | 0.915±0.005 |

2μ1e channel

| Trigger item | $ZZ$ | H (180) | H (200) | H (300) |
|---|---|---|---|---|
| **EF_e10** | 0.963 ± 0.002 | 0.977 ± 0.002 | 0.975± 0.002 | 0.978± 0.002 |
| **EF_mu6** | 0.954 ± 0.003 | 0.967 ± 0.003 | 0.971± 0.002 | 0.963± 0.003 |

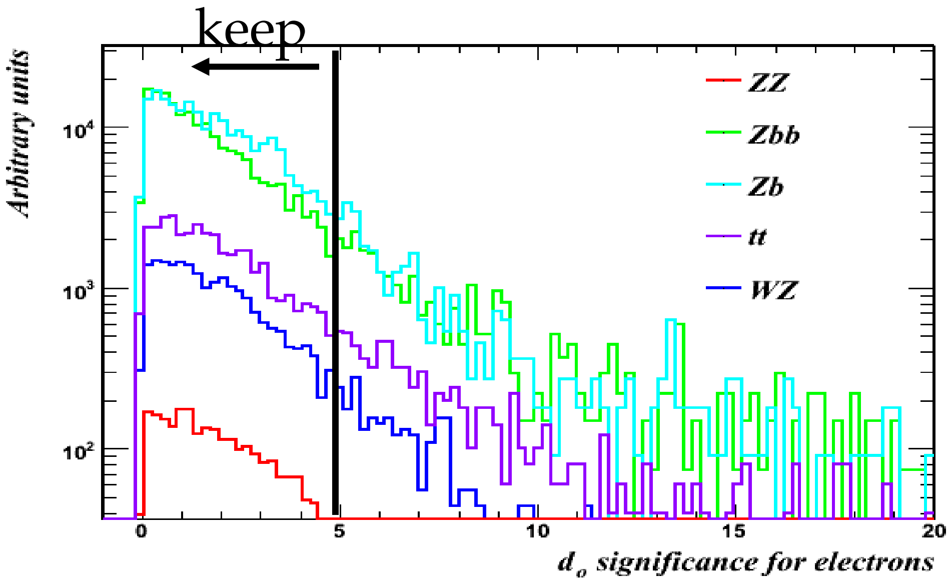
Can use "OR"

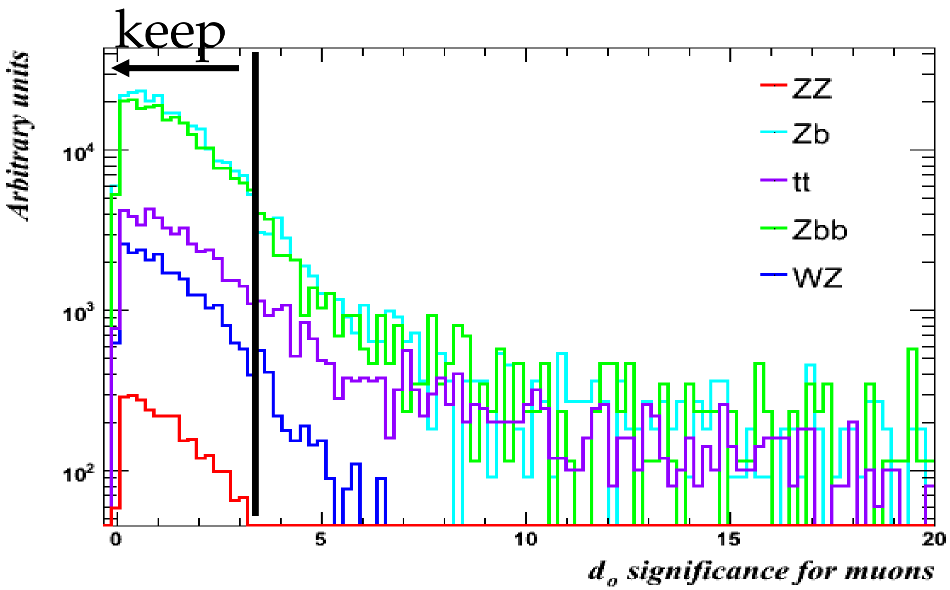
# Impact parameter significance



DCA is Distance of Closest Approach.

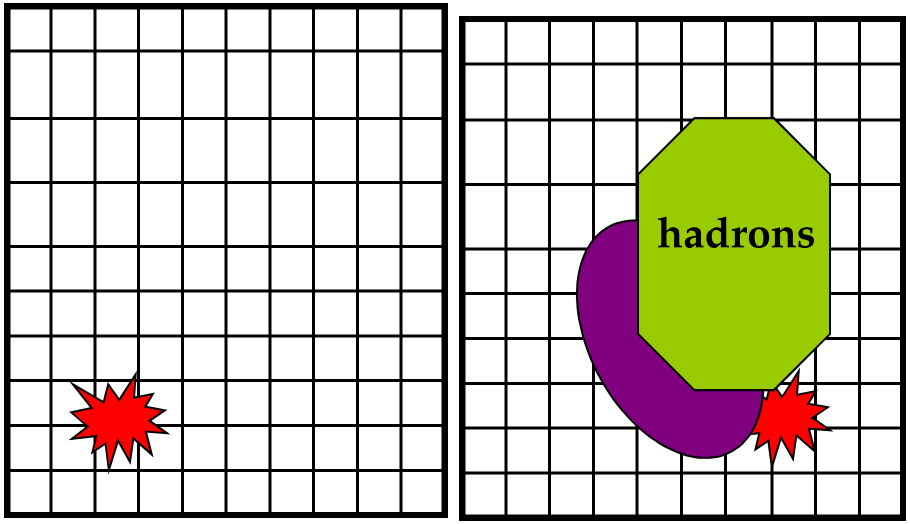
- Zbb, Zb and tt are most likely to have tracks originating from displaced vertices.
- To select only prompt lepton
  - Reject when $DCA/\sigma_{DCA}$ is large

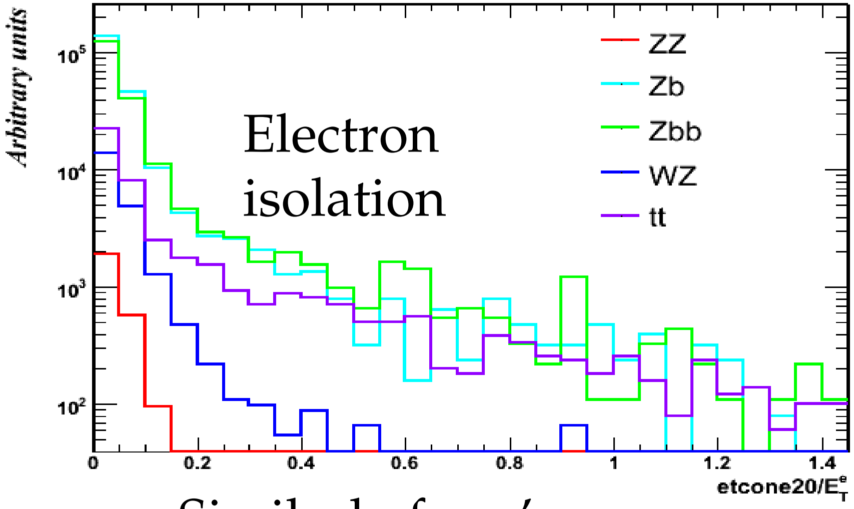




# Isolation in signal and background

- Leptons originating from the signal are isolated from hadronic energy.
- In background events at least one lepton non-isolated.
- $E_T$ evaluated in cone of $\Delta R = 0.2$ around the lepton
  - subtraction of the energy of the lepton itself.
- I defined isolation to be the ratio of energy in cone to energy of lepton





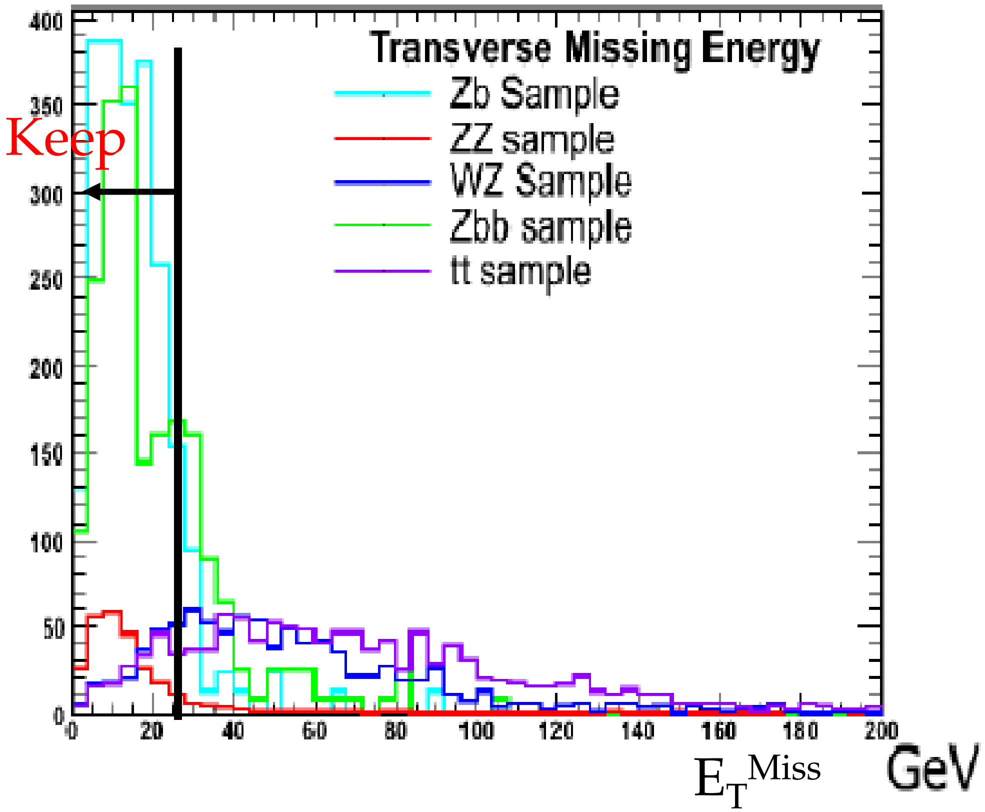
Similarly for μ's

# Transverse Missing Energy

- Transverse missing energy
  - Neutrino, (real $E_T^{Miss}$)
  - Bad measurements of jets ( "instrumental" $E_T^{Miss}$ )

- The signal events, Zbb, and Zb have no ν's but the low $E_T^{Miss}$ is due to detector resolution

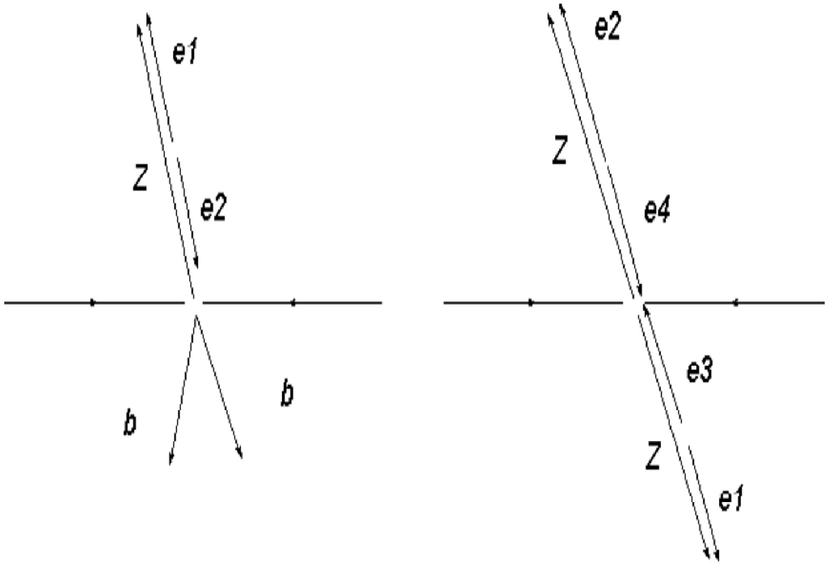
- BG with true $E_T^{Miss}$ WZ and tt are have neutrinos

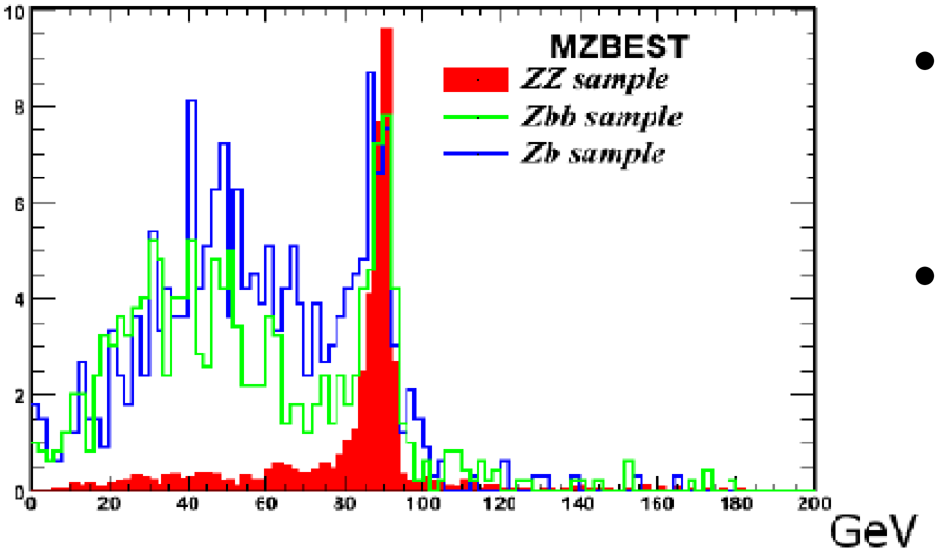


Use an $E_T^{Miss}$ < 24 GeV

# Use Z mass as a cut

- Electrons are $P_T$ ordered
- Require opposite sign
- I define a variable $M_{Zbest}$
  - Make invariant masses of M13 and M23
  - Check which one is closest to nominal Z mass → $M_{Zbest}$
  - This issue of combinatorics does not appear in 2μ1*e*





- Consider a cut:
  - 75< $M_{Zbest}$ < 100 GeV
  - S:B :: 1:25 (for both channels)
- Need two orders of magnitude increase in S/B
  - Need the unfound electron

# Partially reconstructed electron

- I looked for an algorithm which
  - does not assume or require a track
  - does not have a restriction in $|\eta|$
  - no shower shape requirements
  - I define the efficiency of an algorithm as

$$\varepsilon = \frac{N^{cluster}\ (\Delta R < 0.2)}{N^{ue}}$$

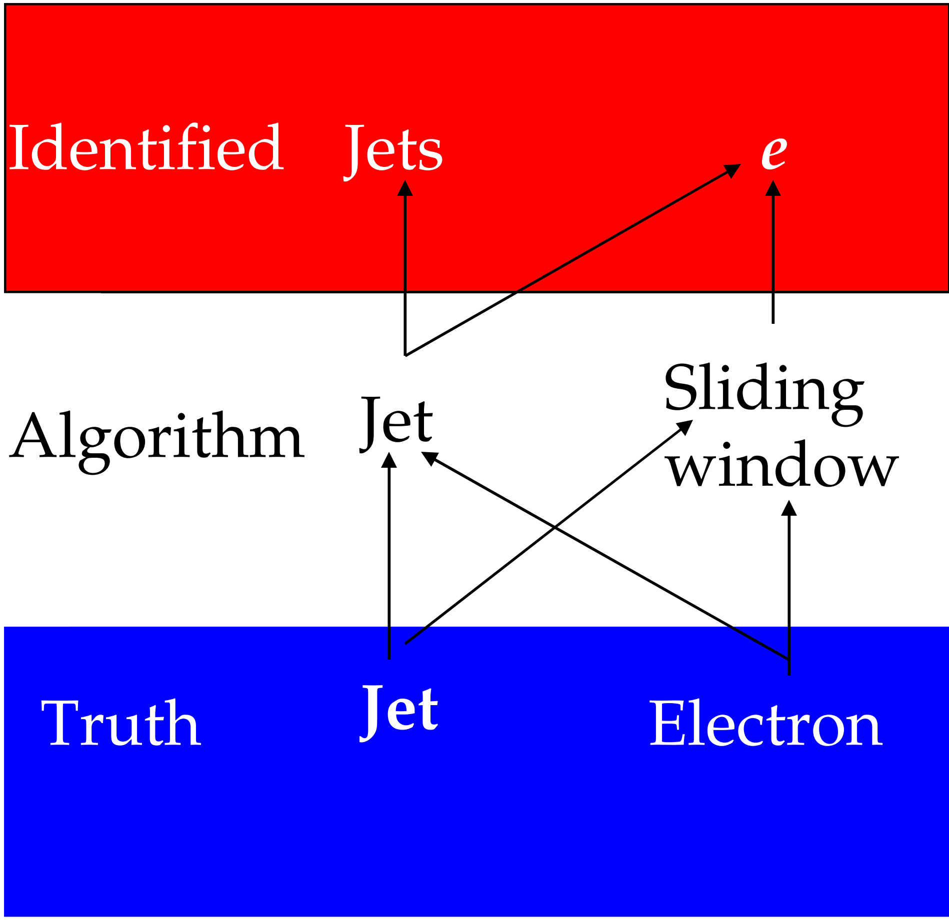
$N^{cluster}$ ($\Delta$R) = number of reconstructed clusters matching a number of truth unidentified electrons $N^{ue}$

- The $p_T$ resolution is defined as

$$P_T^{resolution} = \frac{P_T^{truth} - P_T^{reco}}{P_T^{Truth}}$$

# Partially reconstructed electron

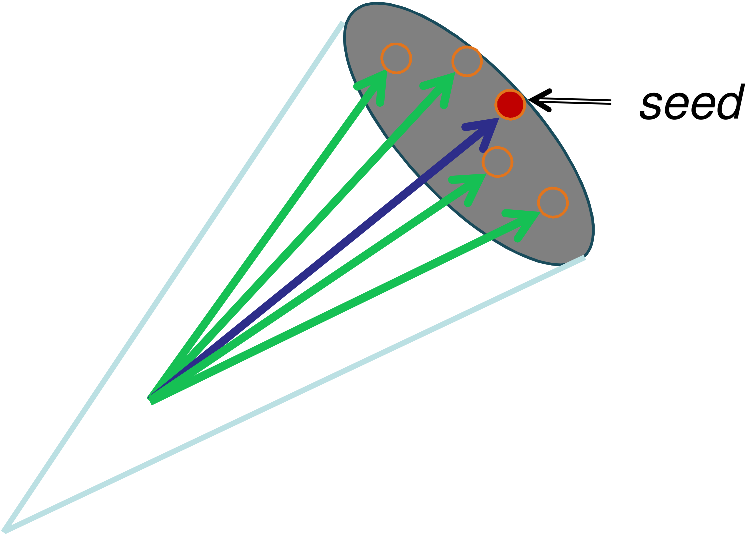
- These algorithms designed for different processes
- When I started
  - Only one algorithm covering the forward region existed jet algorithm
  - Valuable proof-of-principle to show competitive result with modest rejection (i.e. don’t need $10^{-4}$)
- In this talk
  - Truth is the event that happen in nature
  - three levels
    - Truth electrons
    - Jet, and electron algorithms
    - identified electrons



# Jet algorithm

Nearness in angle =>Cone Algorithm

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$ (Use ΔR= 0.4)

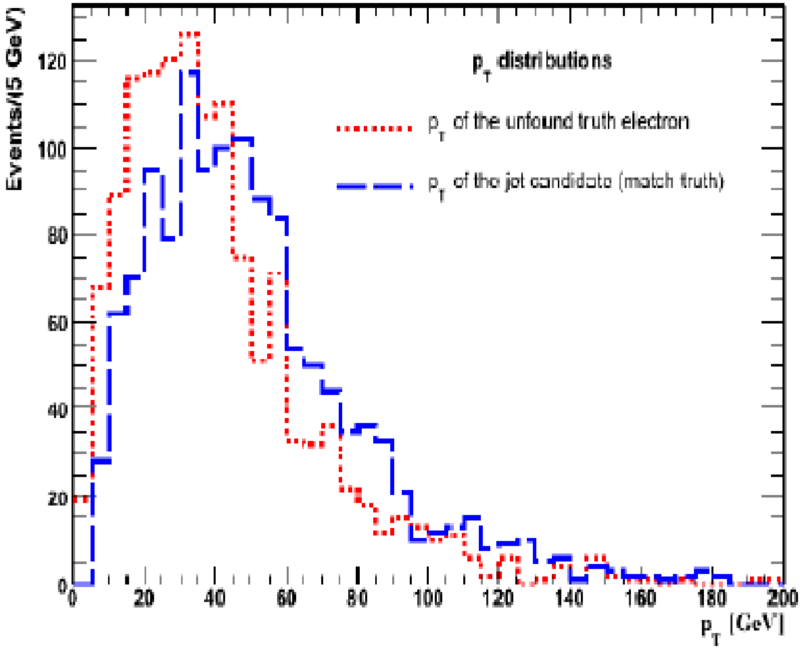


Advantages for identifying electron

- No assumption on the shower shape
- No eta limitation
- No cluster splitting

Disadvantage

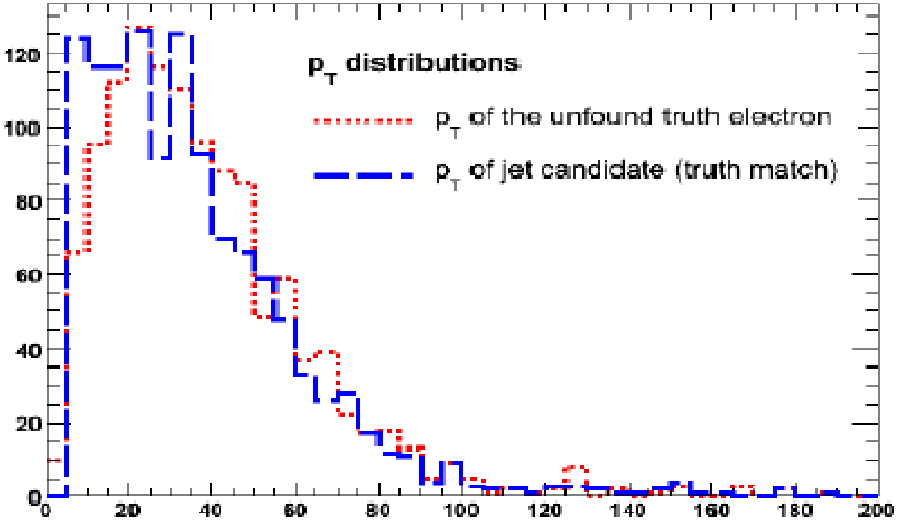
- Not tuned to give electron ID info.
- No shower shape info. is available (except EM fraction)



# Topological cluster algorithm

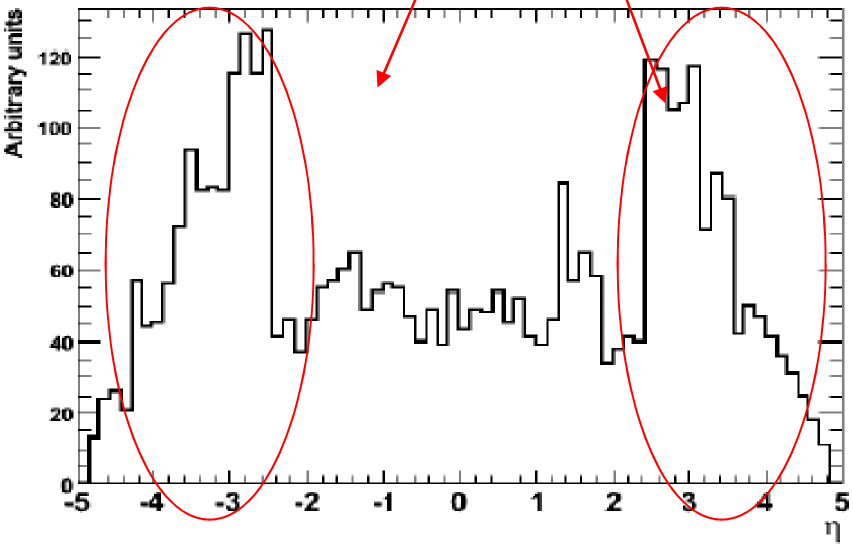
3D nearest neighbor algorithm

- Designed for single particle
- Seeded algorithm
- Includes all neighboring cells in 3D if above threshold



Similar $P_T$ spectra for topological cluster algorithm and truth

Wide range in eta coverage



η of electrons reconstructed with topological cluster matched to the unfound Z electron.

# Summary table of performances for ZZ Sample

Efficiency in finding the unfound "*e*" of different clustering algorithm

| Algorithm | ~~Sliding Window~~ | Jet cone algorithm | Topological cluster | ~~Topological cluster (EM)~~ | ~~Tau~~ |
|---|---|---|---|---|---|
| Efficiency (%) | ~~60± 1.1~~ | 92 ± 0.4 | 96 ± 0.3 | ~~75 ± 0.6~~ | ~~54 ± 1.1~~ |

$P_T$ resolution and position resolution for best algorithms compared to sliding window

| Algorithm | Jet cone algorithm | Topological cluster | Sliding Window |
|---|---|---|---|
| $P_T$ resolution | 0.25 | 0.22 | 0.19 |
| $\Delta\phi$ Resolution | 0.02 | 0.02 | 0.009 |
| $\Delta\eta$ Resolution | 0.028 | 0.023 | 0.018 |

Similar performances to sliding window

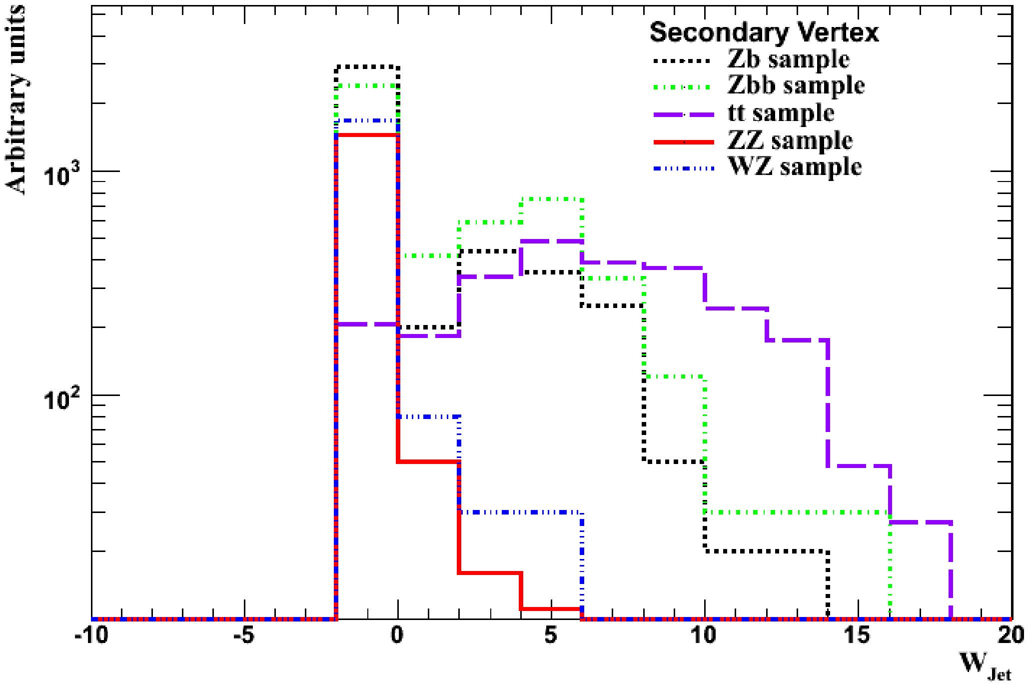
# Partial “*e*” Identification

For a better background rejection

- Apply particle identification on partially reconstructed “*e*”
- Need set of criteria to identify partially reconstructed electron candidates

# *b*-jet Rejection

- Only with jet algorithm
  - The secondary vertex SV2 measures the likelihood of a jet to be a *b*-jet or not using a track

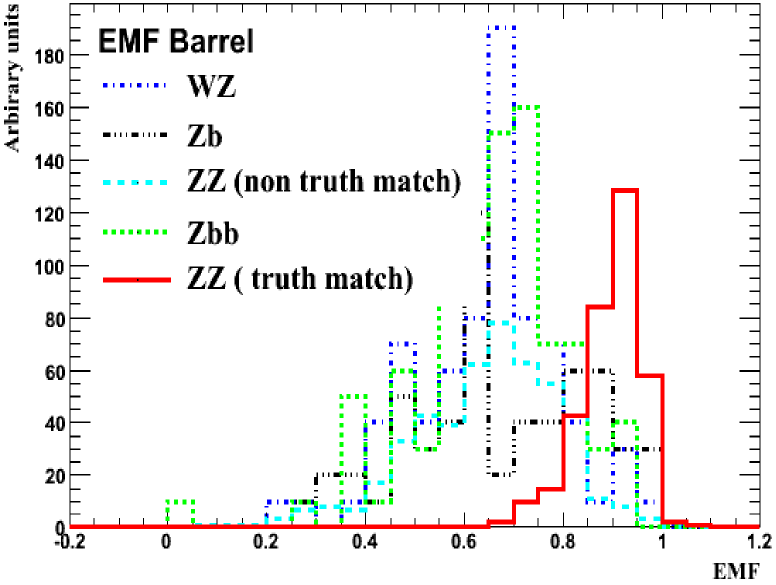


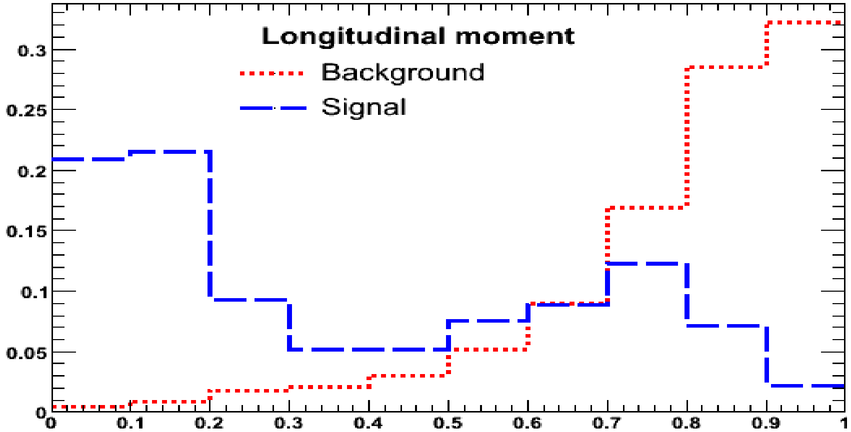
| Process | $b$-tagging veto efficiency (%) |
|---|---|
| $ZZ$ | 95±0.1 |
| $Zb\bar{b}$ | 49±0.3 |
| $Zb$ | 56±0.4 |
| $t\bar{t}$ | 20±0.06 |
| $WZ$ | 92±0.2 |

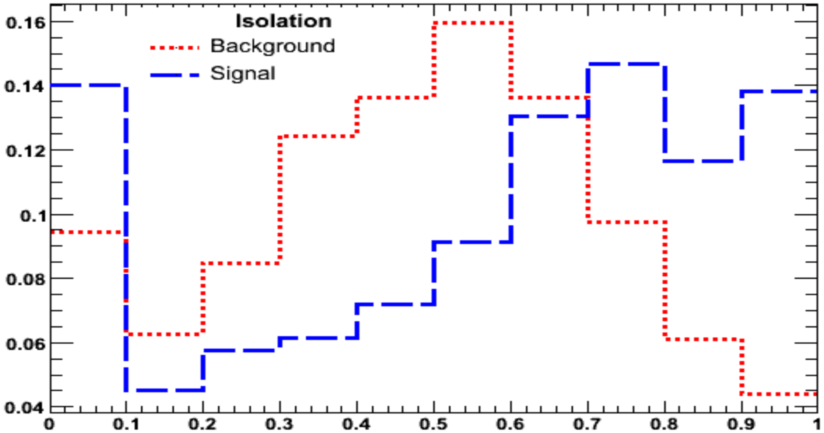
If SV2 < 0, the jet is a light jet

# Shower Shape Parameter

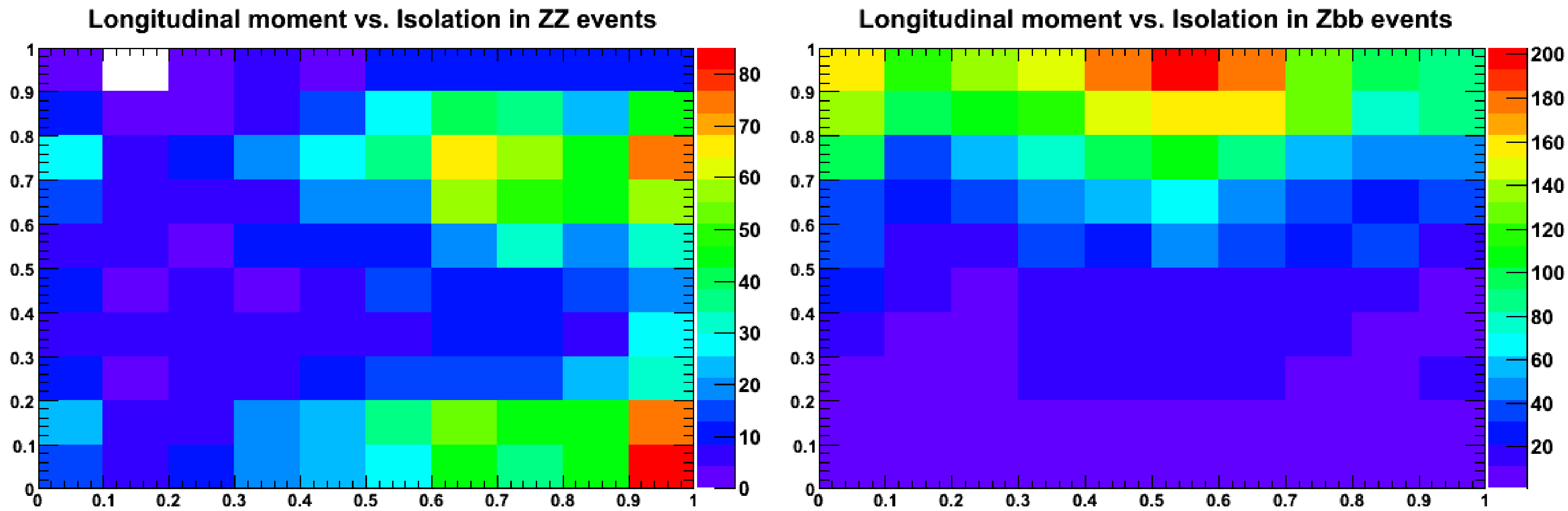
- Jet algorithm
  - EM fraction : the fraction of the energy left in the Electromagnetic calorimeter
    - EMF > 0.8 (barrel)
    - EMF >0.85 (end cap)
- Topological cluster
  - Longitudinal moment
    - Short showers (0)
    - Long showers (1)
  - Isolation







# Longitudinal moment vs. Isolation



- The signal and background are found in different areas
- It is difficult to design an efficient 2D cut with these two variables
- For optimal discrimination power, I combined various variables and use the likelihood method.

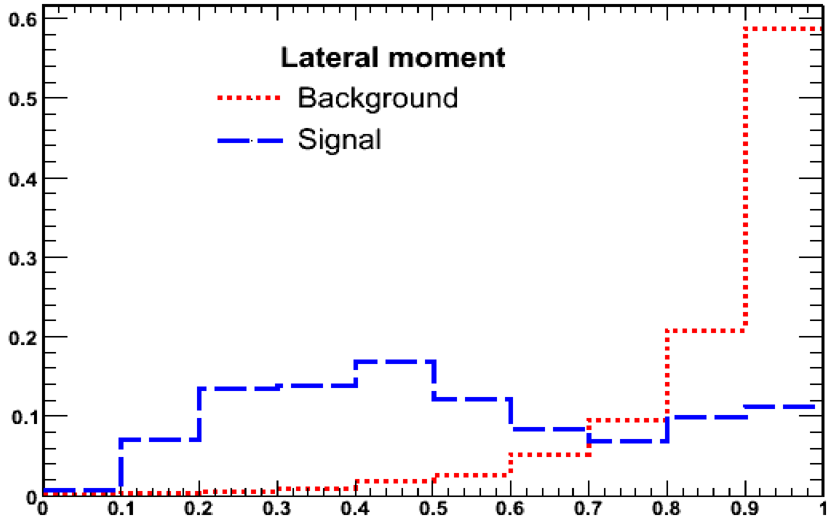
# Shower shape variables in topological cluster

## Lateral moment

Normalized distributions (0-1)

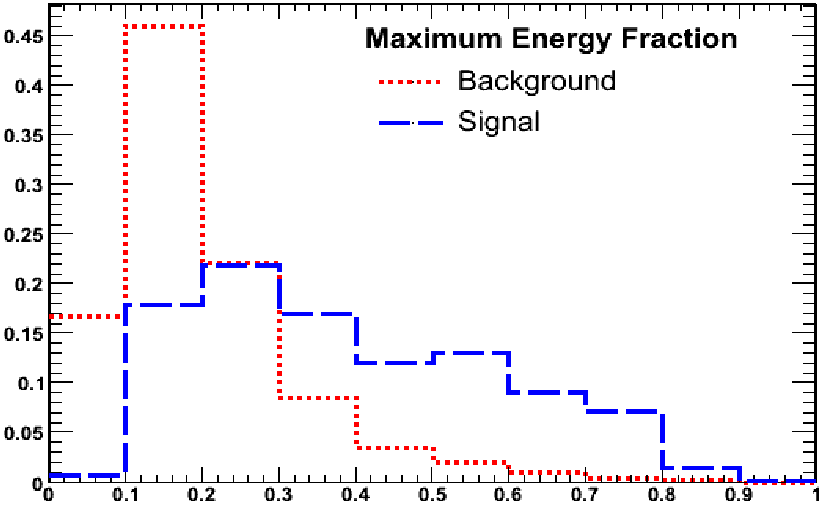
1 wide showers

0 narrow showers



## Max Energy fraction

Energy fraction in cells of a segmented calorimeter



# The topological likelihood

I used theses distributions to assign a probability for a given topological cluster to be signal or background

$P_s(x)$ from Z→ ee sample and $P_b(x)$ from ttbar sample

Multiplication of these variables gives the overall probability for the event.

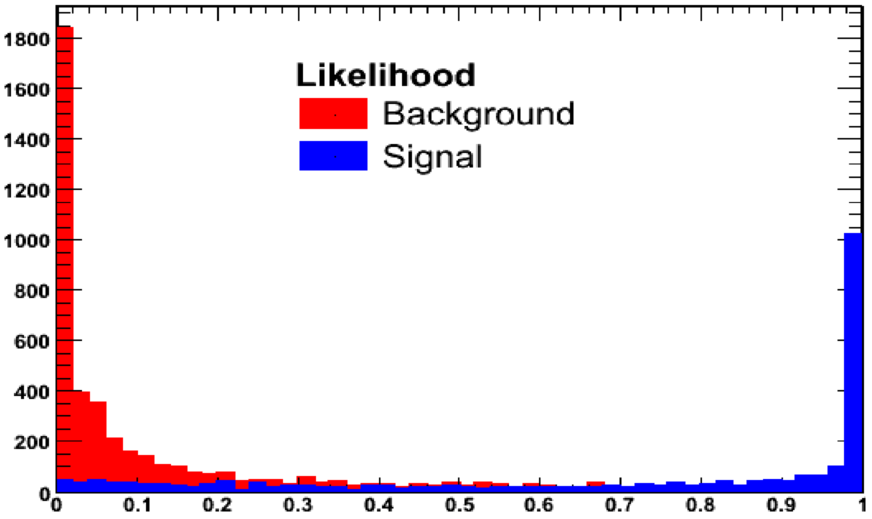
$$P_s(x) = \prod_i P_{s,i}(x_i) \quad \text{and} \quad P_b(x) = \prod_i P_{b,i}(x_i)$$

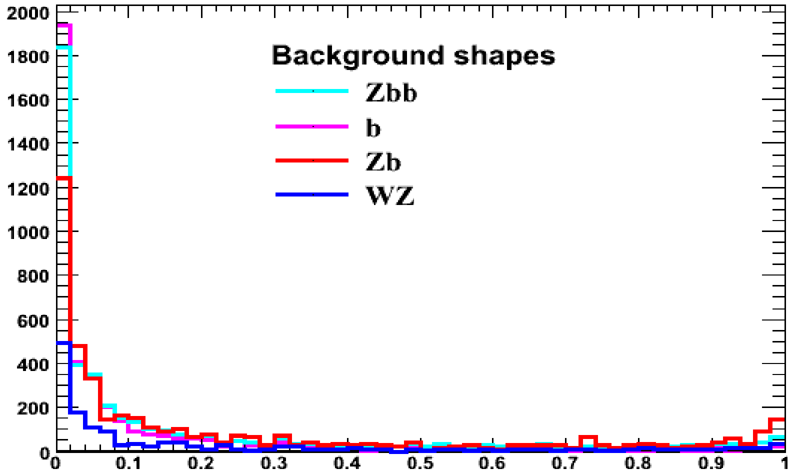
i = {longitudinal, lateral, isolation, Max energy fraction}

I defined the likelihood discriminant as

$$L(x) = \frac{P_s(x)}{P_s(x) + P_b(x)}$$

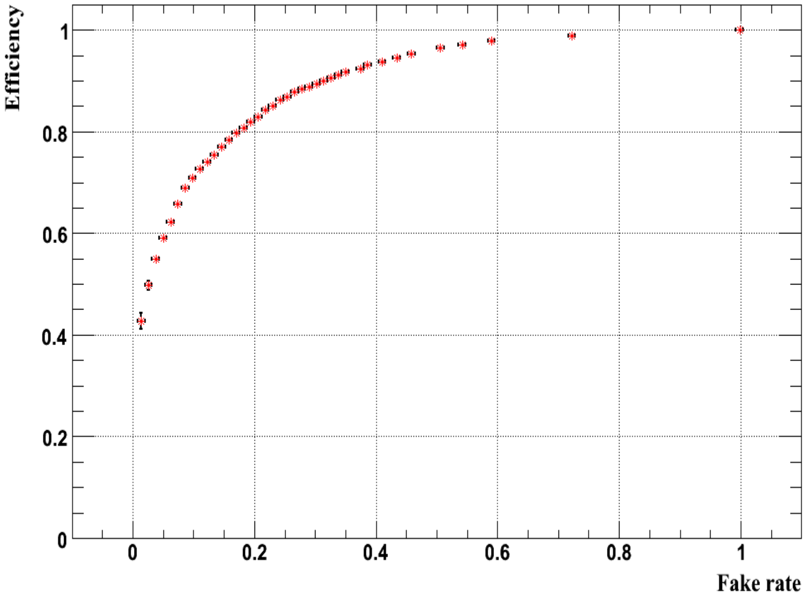
# Likelihood: Signal is ZZ and Background is Zbb





$$\varepsilon = \frac{N_S^{\text{passing clusters}}}{total\ N_S^{\text{clusters}}}$$

$$Fake = \frac{N_B^{\text{passing clusters}}}{total\ N_B^{\text{clusters}}}$$



# Likelihood dependence on η

- The pdf's are strongly η dependent (ε + fake rate are not)

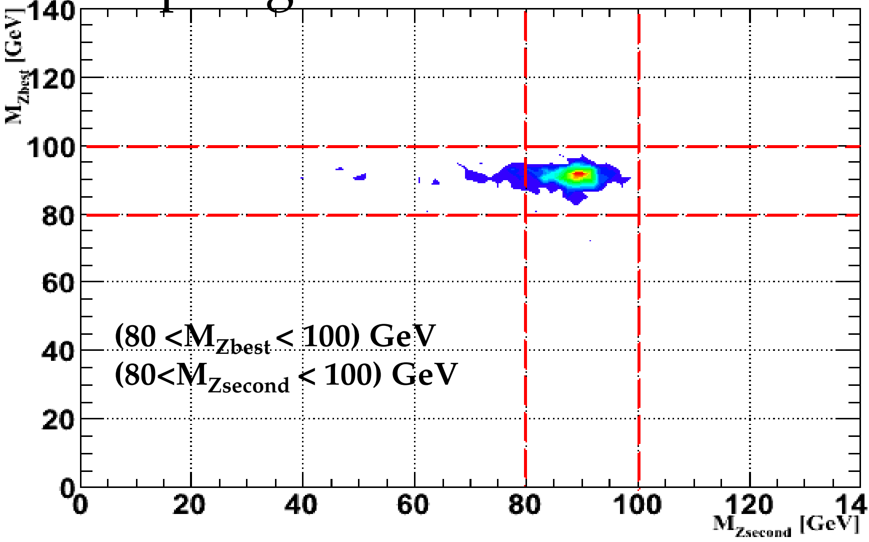
| Eta range | Signal efficiency (%) | Zbb fake rate(%) | WZ fake rate(%) |
|---|---|---|---|
| $\|\eta\| < 0.7$ | 84 | 20 | 18 |
| $\|\eta\| > 0.7$ and $\|\eta\| < 1$ | 83 | 16 | 16 |
| $\|\eta\| > 1$ and $\|\eta\| < 1.375$ | 86 | 18 | 17 |
| $\|\eta\| > 1.375$ and $\|\eta\| < 1.9$ | 83 | 21 | 21 |
| $\|\eta\| > 1.9$ and $\|\eta\| < 2.5$ | 90 | 13 | 12 |
| $\|\eta\| > 2.5$ and $\|\eta\| < 3.2$ | 95 | 4 | 2 |
| $\|\eta\| > 3.2$ | 89 | 7 | 2 |

Signal efficiency and fake rates for L > 0.5

# Second Z and 2 Dimensional cut

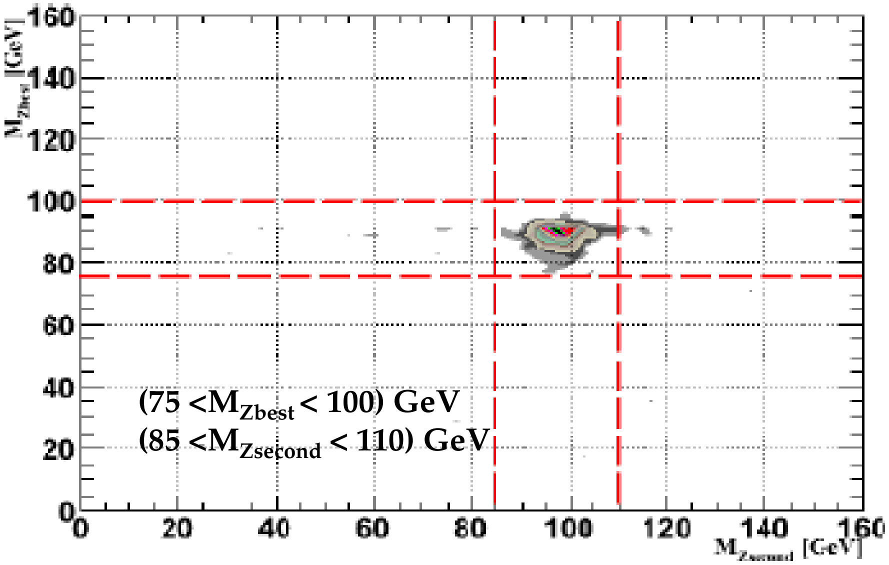
- Second Z peak :
  - The electron that did participate in $M_{Zbest}$ forms with partially reconstructed "*e*"
  - In 2μ1*e*, $M_{Zbest}$ is from 2 μ's
- 2D cut
  - 2 Z's are required in the event

Topological cluster

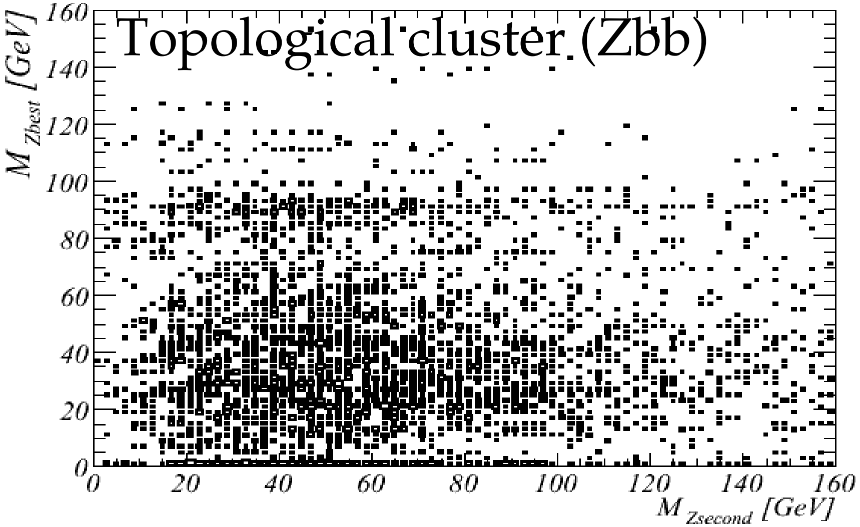


$(80 < M_{Zbest} < 100)$ GeV
$(80 < M_{Zsecond} < 100)$ GeV

Jet algorithm



$(75 < M_{Zbest} < 100)$ GeV
$(85 < M_{Zsecond} < 110)$ GeV



Topological cluster (Zbb)

cuts are very loose to illustrate the point

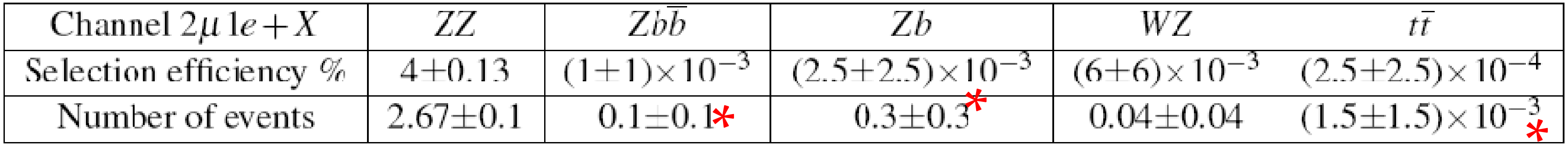
# Final Selection cuts

| | |
|---|---|
| Electrons | Medium |
| Muons | combined |
| IP significance | <5 for electrons , <3 for muons |
| Isolation (etcone20/et) | 0.14 |
| $E_T^{Miss}$ | 24(GeV) |

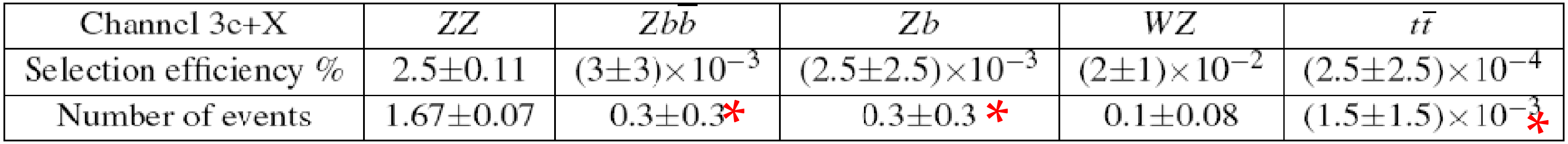
| Cut | Jet cone DR = 0.4 | Topological Cluster |
|---|---|---|
| anti b-tagging SV2 | <0 | N/A |
| EMF | 0.8 B 0.85 EC | N/A |
| likelihood | N/A | 0.5 |
| $M_{Zbest}$ | 75-100 (GeV) | 80-100 (GeV) |
| $M_{Zsecond}$ | 85-110 (GeV) | 80-100 (GeV) |

# Results ($1fb^{-1}$) for the Jet Algorithm and Topological Cluster (14 TeV)

## Jet Algorithm



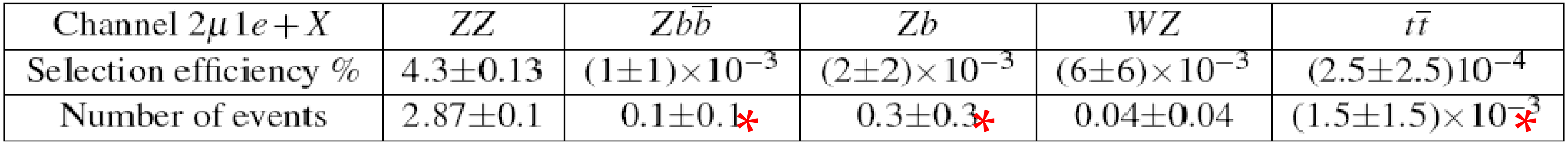
| Channel $2\mu\, 1e+X$ | $ZZ$ | $Zb\bar{b}$ | $Zb$ | $WZ$ | $t\bar{t}$ |
|---|---|---|---|---|---|
| Selection efficiency % | $4+0.13$ | $(1+1)\times10^{-3}$ | $(2.5+2.5)\times10^{-3}$ | $(6+6)\times10^{-3}$ | $(2.5+2.5)\times10^{-4}$ |
| Number of events | $2.67\pm0.1$ | $0.1\pm0.1$* | $0.3\pm0.3$* | $0.04\pm0.04$ | $(1.5\pm1.5)\times10^{-3}$* |



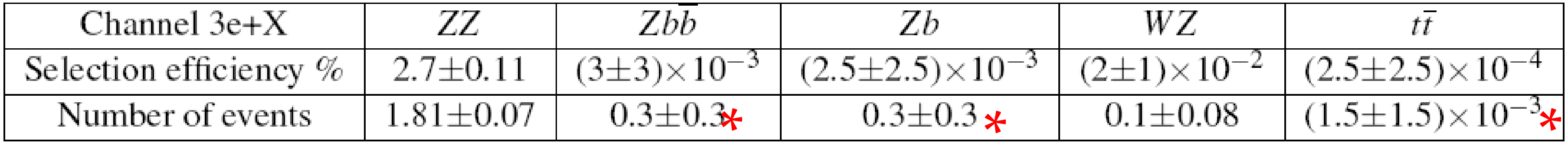
| Channel 3e+X | $ZZ$ | $Zb\bar{b}$ | $Zb$ | $WZ$ | $t\bar{t}$ |
|---|---|---|---|---|---|
| Selection efficiency % | $2.5\pm0.11$ | $(3\pm3)\times10^{-3}$ | $(2.5\pm2.5)\times10^{-3}$ | $(2\pm1)\times10^{-2}$ | $(2.5\pm2.5)\times10^{-4}$ |
| Number of events | $1.67\pm0.07$ | $0.3\pm0.3$* | $0.3\pm0.3$ * | $0.1\pm0.08$ | $(1.5\pm1.5)\times10^{-3}$* |

$N_{ZZ} = 4.4 \pm 0.1$ $N_{BG} = 1.1 \pm 0.5$

## Topological cluster Algorithm



| Channel $2\mu\, 1e+X$ | $ZZ$ | $Zb\bar{b}$ | $Zb$ | $WZ$ | $t\bar{t}$ |
|---|---|---|---|---|---|
| Selection efficiency % | $4.3\pm0.13$ | $(1\pm1)\times10^{-3}$ | $(2\pm2)\times10^{-3}$ | $(6\pm6)\times10^{-3}$ | $(2.5\pm2.5)10^{-4}$ |
| Number of events | $2.87\pm0.1$ | $0.1\pm0.1$* | $0.3\pm0.3$* | $0.04\pm0.04$ | $(1.5\pm1.5)\times10^{-3}$* |



| Channel 3e+X | $ZZ$ | $Zb\bar{b}$ | $Zb$ | $WZ$ | $t\bar{t}$ |
|---|---|---|---|---|---|
| Selection efficiency % | $2.7\pm0.11$ | $(3\pm3)\times10^{-3}$ | $(2.5\pm2.5)\times10^{-3}$ | $(2\pm1)\times10^{-2}$ | $(2.5\pm2.5)\times10^{-4}$ |
| Number of events | $1.81\pm0.07$ | $0.3\pm0.3$* | $0.3\pm0.3$ * | $0.1\pm0.08$ | $(1.5\pm1.5)\times10^{-3}$* |

$N_{ZZ} = 4.7 \pm 0.1$ $N_{BG} = 1.1 \pm 0.5$

- 0 event passed, assume 1 event
- BG may be overestimated

# Higgs Searches in High mass range

- At high mass Higgs ($m_H \geq 180$ GeV )
  - Many Models predicts high mass Higgs
    - Top color model (Higgs is made of top and anti-top)
    - Little Higgs model does not restrict the mass of the Higgs

  - $H \rightarrow ZZ \rightarrow 4l$
  - Use the same selection criteria as in ZZ analysis

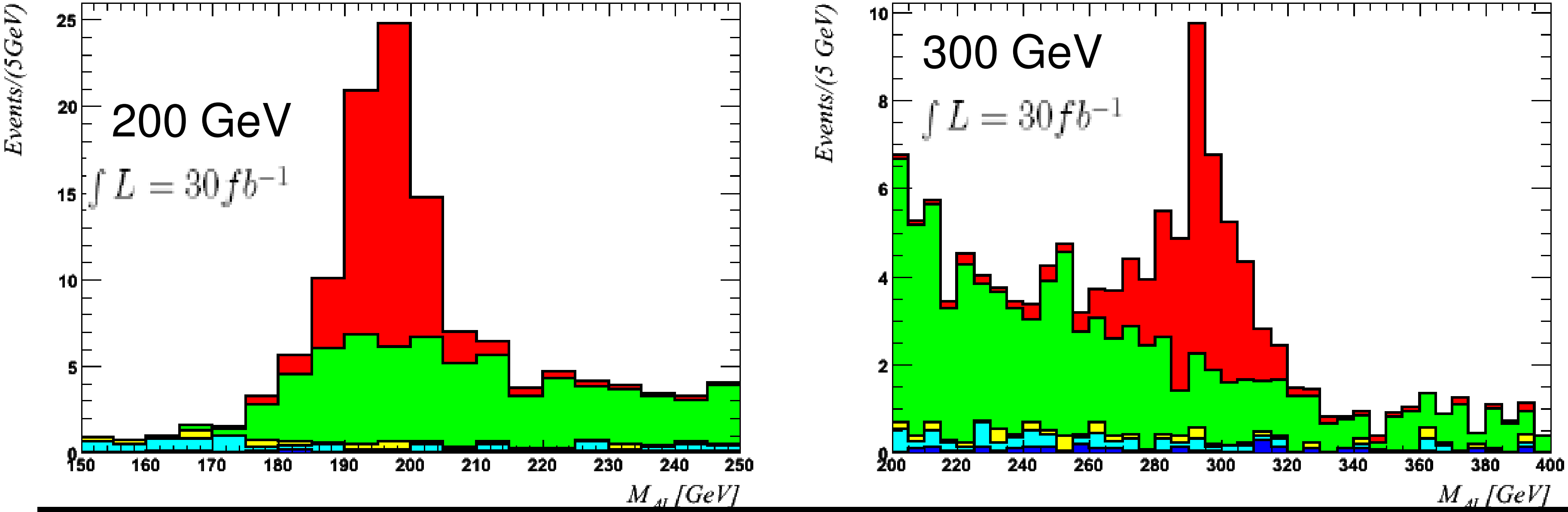
- Higgs analysis, consider 3 mass points
  - $M_H = 180$ GeV
  - $M_H = 200$ GeV
  - $M_H = 300$ GeV

# Selection Efficiencies

| Selection | Selection efficiency (%) Jet algorithm | Selection efficiency (%) Topological cluster |
|---|---|---|
| **180 GeV** | | |
| 3e+X | 2.1 | 2.3 |
| 2m1e+X | 3.3 | 3.4 |
| **200 GeV** | | |
| 3e+X | 2.62 | 4.05 |
| 2m1e+X | 4.17 | 4.95 |
| **300 GeV** | | |
| 3e+X | 3.1 | 4.3 |
| 2m1e+X | 4.4 | 4.7 |

The efficiency is mass dependent, we emphasize the high mass region

# Higgs: invariant masses



| Mass (GeV) | | 180 | 200 | 300 |
|---|---|---|---|---|
| Selection (to gauge relative sensitivity) | | 175-187 | 190-210 | 290-310 |
| 3*e*+"*e*"&<br>2μ1*e*+"*e*" | Higgs | 1.55 | 14 | 6.2 |
| | BG | 2.53 | 8.26 | 2.46 |
| S::B | | 1::1.5 | 2::1 | 3::1 |

# Normalization

- Theoretical uncertainties : pdf uncertainties
  - Cross section: 4% difference in ZZ production
    - 14.74 pb in CTEQ6M
    - 15.32 pb in MRST03
- Luminosity
  - Precise determination of the luminosity is to use the W and Z production and leptonic decays.
  - Luminosity uncertainties ~5%*

*(M. Dittmar, F. Pauss, D. Zuercher, Phys. Rev. D 56 (1997) 7284-7290)

# Experimental Systematics

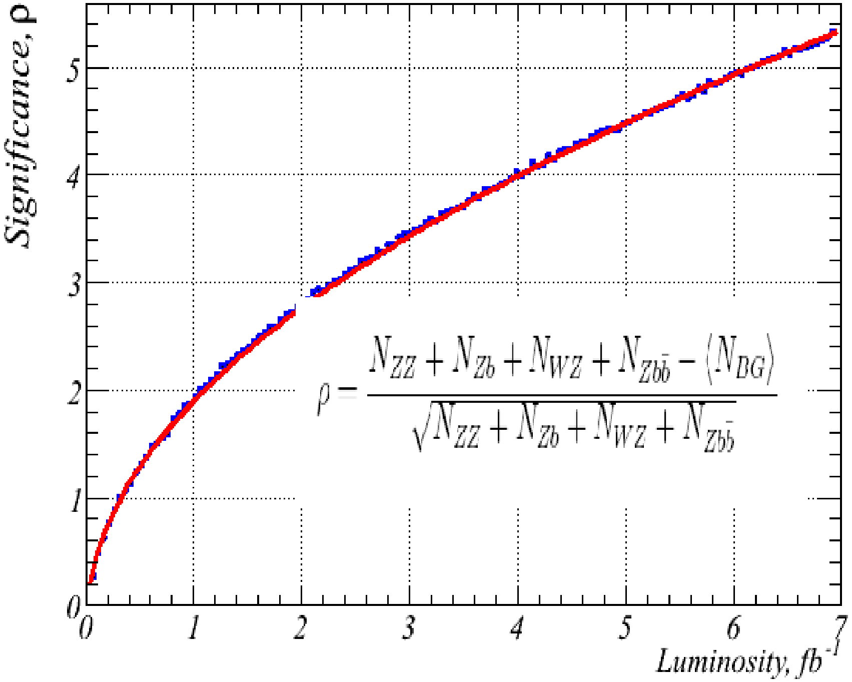
- Lepton uncertainties
  - Lepton energy scale
    - arises from EM calibration
    - To estimate its impacts, varied $E_T$ by ±1%
  - Lepton energy resolution
    - Reconstructed electron energy are smeared using a Gaussian
      - $smearE_T = 0.1 * a.Gauss$
      - $E_T^{new} = E_T (1+smearE_T)$
  - Material effects in electron efficiency
    - direct effect on shower shape discriminants
    - found to be small 2%

Impact (in %) of lepton uncertainties on my selection criteria

| | H (200 GeV) | H (300 GeV) | ZZ | Zbb |
|---|---|---|---|---|
| Energy scale (1%) | ± 2.2 % | ± 0.2 | ± 2.9% | ± 4.7% |
| Resolution (%) | -6.6% | -5.3% | -2.2% | -2.1% |

# The significance of ZZ analysis for 1 $fb^{-1}$

- Run pseudo-experiments
  - Poisson distribution
- 3l + X channel
  - 4.7 signal event and 1.1 BG event
- 4l channel
  - 13.3 ±0.09 signal events and 0.2±0.07 BG event
  - Significance $\frac{S}{\sqrt{S+B}} = 3.6$
- 3l+X & 4l combined
  - Acceptance gain of 38%
  - Significance = 4.07-4.11 (~4.09)

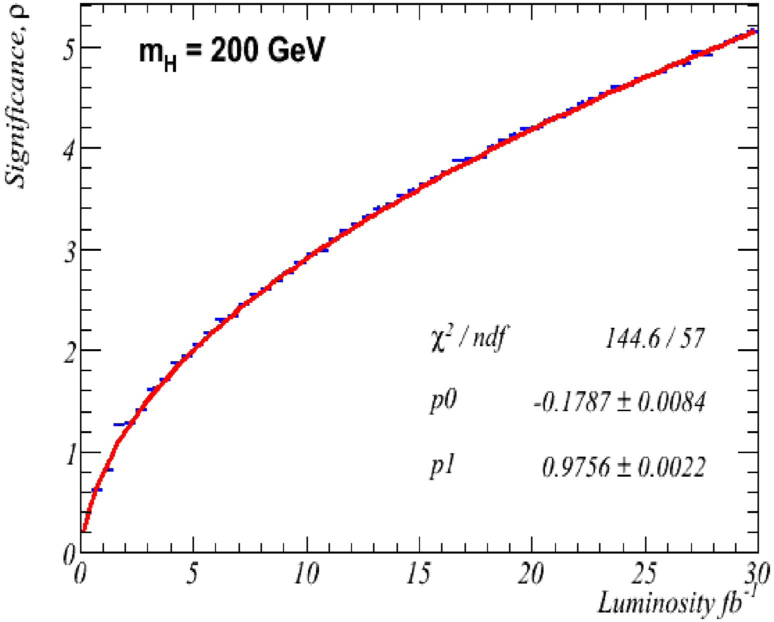


$$\rho = \frac{N_{ZZ} + N_{Zb} + N_{WZ} + N_{Zb\bar{b}} - \langle N_{BG} \rangle}{\sqrt{N_{ZZ} + N_{Zb} + N_{WZ} + N_{Zb\bar{b}}}}$$

# Significance for Higgs

For $L = 10\ fb^{-1}$

| Higgs mass (GeV) | 200 | 300 |
|---|---|---|
| Significance (3ℓ+"*e*" channel alone) | 2.96 | 2.11 |
| Significance (4ℓ channel) | 6.19 | 4.88 |
| Significance (4ℓ and 3ℓ+"*e*") | 7.07 | 5.45 |



When one can reach 5 "σ"

- To reach 5σ with 4l channel, need a luminosity of $6.8\ fb^{-1}$

Combination of 3l & 4l channels: Significance: 5.06-5.11 (~5.10) @ $5.4\ fb^{-1}$

21% less data needed

# Conclusion

- An exclusive ZZ → 3l+"*e*" and H→ ZZ → 3l+"*e*"($m_H \geq 180$ GeV) analysis conducted on MC @ 14 TeV
  - Two approaches with clustering and particle identification
  - Substantial improvement over 4 lepton channel
    - Topological cluster is slightly better than the jet algorithm
- Results
  - In ZZ analysis,
    - A gain in acceptance of 38% (from 13 signal events to 18 for $1fb^{-1}$)
    - Significance (3l+X and 4l combined) from 3.6 to 4.1 for $1fb^{-1}$
      - ATL-COM-PHYS-2009-433 (in referee process )
  - Higgs analysis (if 3l+X and 4l are combined)
    - $m_H$=200GeV, 5σ can be reached at L= 5.4 fb-1 instead of 6.8 fb-1
    - $m_H$=300GeV, 4.88σ increases to 5.45σ at L = $10fb^{-1}$
  - Searches in low mass Higgs range require more BG rejection
  - This work shows
    - topological clusters valuable for electron identification
    - Used to justify this algorithm (Leysin August09)
    - Default algorithm beyond $|\eta| > 2.5$

# BACK UP SLIDES

# Data Collection and Reconstruction 1

## Sliding window algorithm (Standard)

Uses a sliding-window cluster to find electron and photon.

- **The tower building**

In h and j space ( | h | < 2.5) is divided into a grid each of size Δη , Δφ.

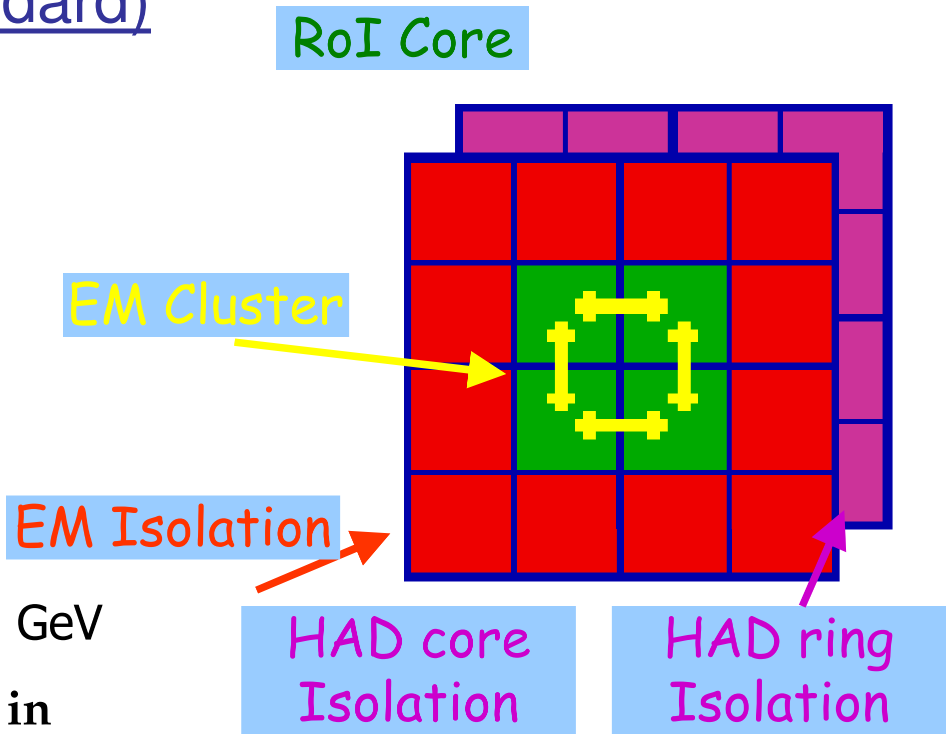
- **The pre-cluster (seed) finding**

In the window **Dh , Dj** (5x5) $E_T^{threshold} > 3$ GeV

**The position of cluster should be usually in smaller window (3x3) (less sensitive to noise)**

- **The cluster filling (EM)**

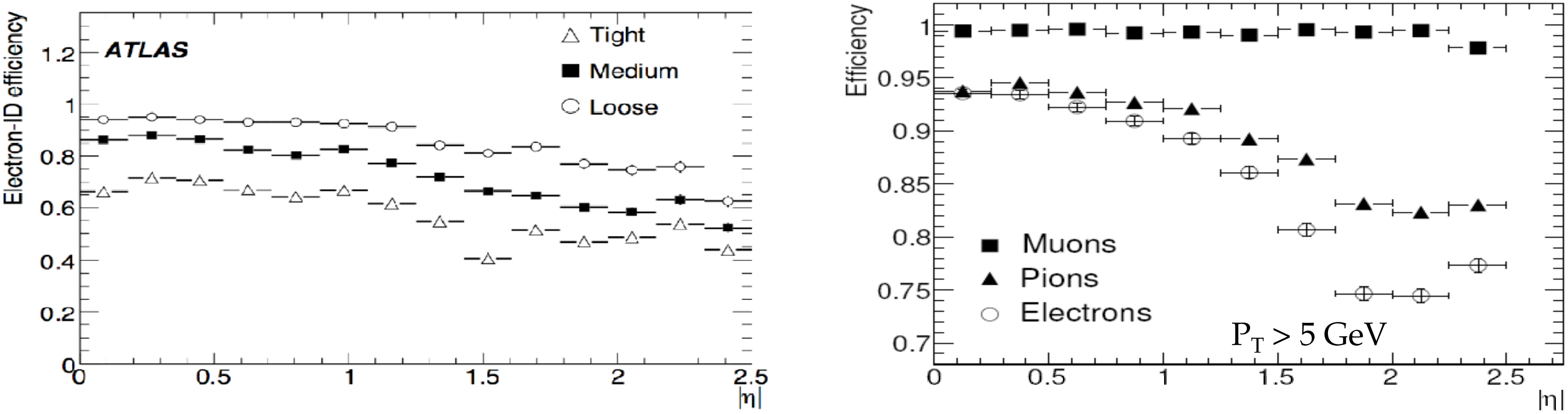
**The positions of pre-clusters are used as seeds around which final clusters are subsequently filled. Release 12, (3x5, 3x7 and 5x5, thus leading to 3 cluster collections)** ⎝ **egamma candidates**



Disadvantages:

- Assumption on cluster width.
- Limited Eta range
- Splitting of cluster in crack regions

# The ATLAS standard electron definitions



- ElectronLoose: had + middle, no refined tracking
- ElectronMedium: had + middle + strips + calo Iso + tighter tracking
- ElectronTight: had + middle + strips + calo Iso, even tighter tracking

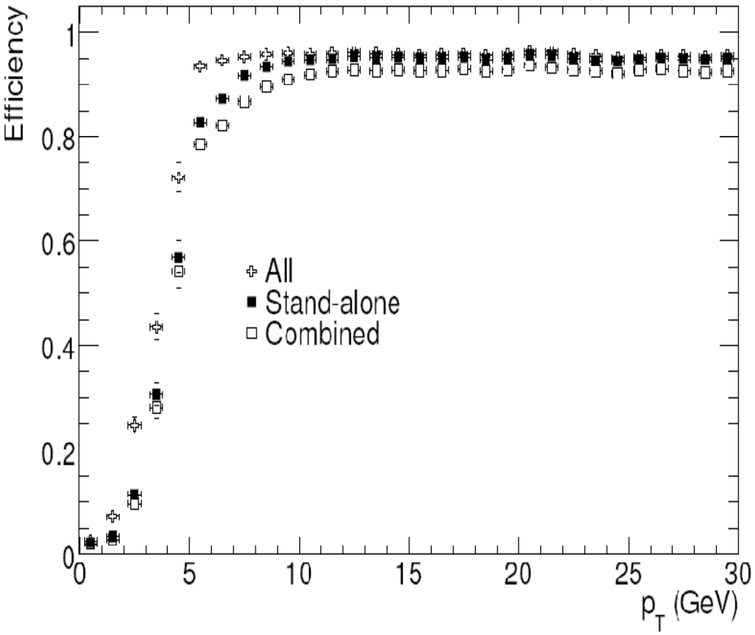
# Data Collection and Reconstruction 2

## Muon reconstruction

- Stand-alone: Spectrometer info. only
- Combined: combination of track from the inner tracker & a track from spectrometer
- Combination with minimum $\chi^2$ between

a track from the inner tracker and

the spectrometer (STACO)

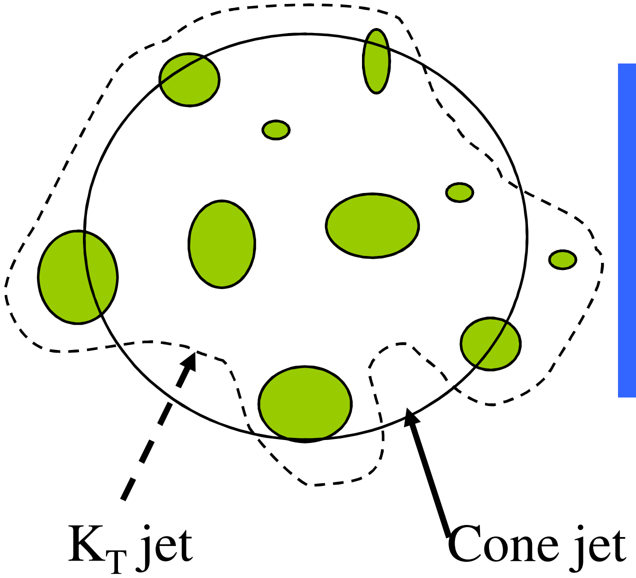


- Origin of Transverse Missing Energy $E_T^{Miss}$
- Neutrino, LSP, gravitino (real $E_T^{Miss}$)
- Bad measurements of jets (fake $E_T^{Miss}$)
- $E_T^{Miss}$ measurement: Cell Based method
- \- $P_T^{miss}$ = S $P_T$(cell) + S$P_T$(m) + S$P_T$ (loss in cryostat (dead material))

Dead/hot/noisy cell , Energy calibration (nonlinearity, resolution)

# Data Collection and Reconstruction 3

## Jet cone reconstruction algorithms



Nearness in angle =>Cone Algorithm

D$\mathcal{R}$ = □□□2 □□□2

Possible to produce overlapped cones, Needs a Split-Merge step.

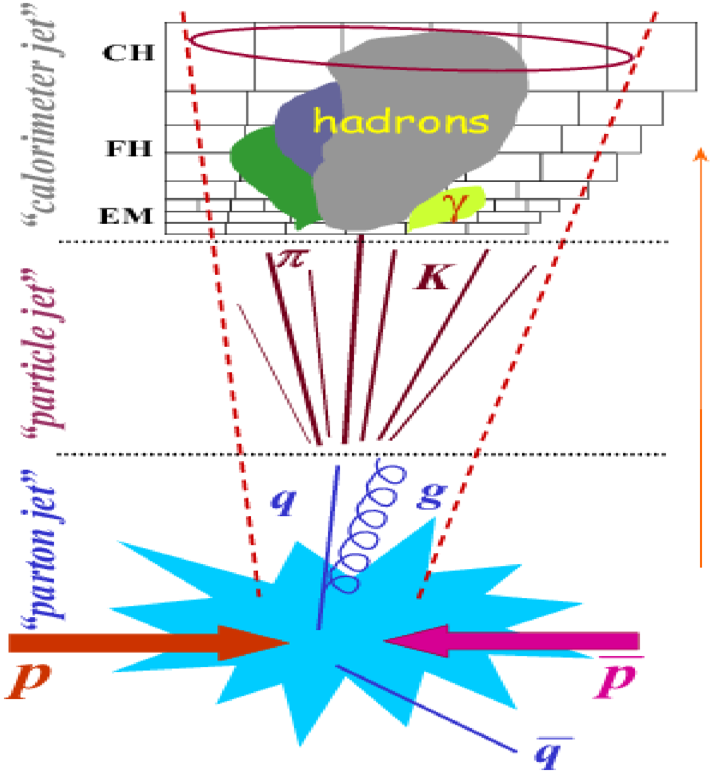
It's clustering algorithm.

Advantages for identifying electron

- No assumption on the shower shape
- No eta limitation
- No cluster splitting

Disadvantage

- Not tuned to give electron ID information.
- No shower shape information is available



Historically, hadron collider use cone algorithms :easier calibration

Use DR= 0.4 cone Algorithm

# Data Collection and Reconstruction 4

## 3D nearest neighbor algorithm (Topological Cluster)

- **Seed Threshold:**

  $|\text{energy}|/\sigma_{\text{noise}} > 4$
- **Neighbor Threshold (2D):**

  Cells with $|\text{energy}|/\sigma_{\text{noise}} > 2$
- **Cell Thresholds (3D):**

  Cells with $|\text{energy}|/\sigma > 0$

Some shower shape information are

### Longitudinal moment

l is the distance of the cell from the shower center along the shower axis

- $long_2 = \langle l^2 \rangle$, with $l = 0$ for the two most energetic cells
- $long_{\max} = \langle l^2 \rangle$, with $l = 10$ cm for the two most energetic cells and $l = 0$ for all other cells

$$longitudin\,al = \frac{long_2}{(long_2 + long_{\max})}$$

### Lateral moment

In a similar fashion, but $lat_{\max}$ is at r = 4 cm from the shower axis

$$lateral = \frac{lat_2}{(lat_2 + lat_{\max})}$$

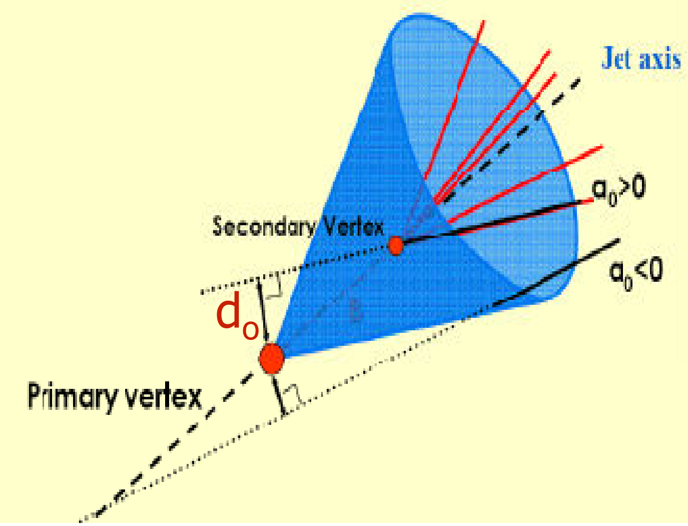
### Max Energy fraction

Energy fraction of the most energetic cell

### Isolation

The layer energy weighted fraction of non-clustered neighbor cells on the outer perimeter of the cluster

# B tagging



- B tagging means identification of jets which contains a b quark.
- Lifetime ~ 1.5 ps i.e. flight distance ~4mm for 50 GeV particle.

Possible b tagging methods

- Lifetime tag (impact parameter)

$d_o$ is the track impact parameter in the

transverse plane (r- f).

$z_o$ is the track impact parameter in the longitudinal plane (r-z).

Secondary vertex:

1) The invariant mass of all tracks associated to the vertex.

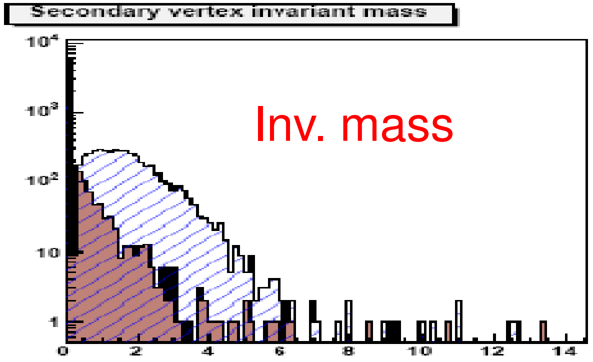
2) $$Energy_{ratio} = \frac{\sum E^{tracks\ of\ vertex}}{\sum E^{all\ tracks\ in\ the\ jet}}$$

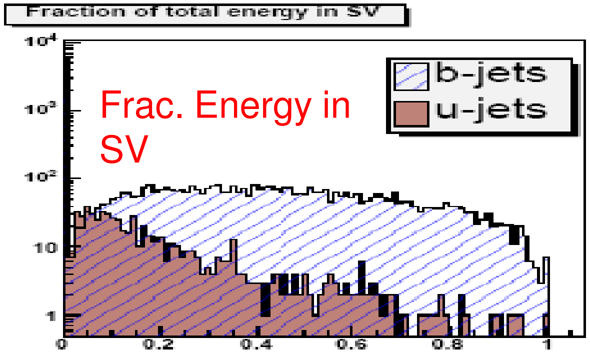
3) Number of two-track vertices

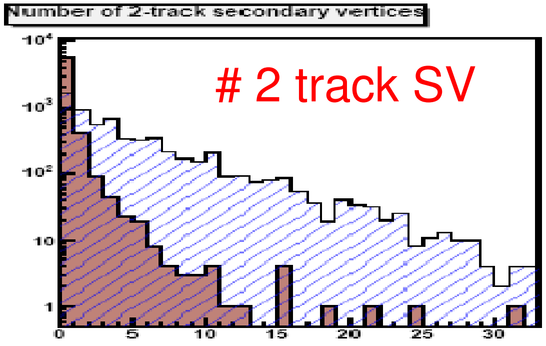
# B-tagging Secondary vertex

- Comparison of measured value $S_i$ to a pre-defined smoothed and normalized distributions for both the b- and light jet hypothesis, $b(S_i)$ and $u(S_i)$.
- 2D or 3D pdf are used
- The ratio $b(S_i)/\ u(S_i)$ defines the track or vertex weight.
- SV1 : 2D distribution of the two first variables and a 1D distribution of the number of two-tracks
- SV2 : 3D-histogram of the three properties

$$W_{jet} = \sum_{i=1}^{N_T} \ln W_i = \sum_{i=1}^{N_T} \ln \frac{b(S_i)}{u(S_i)}$$

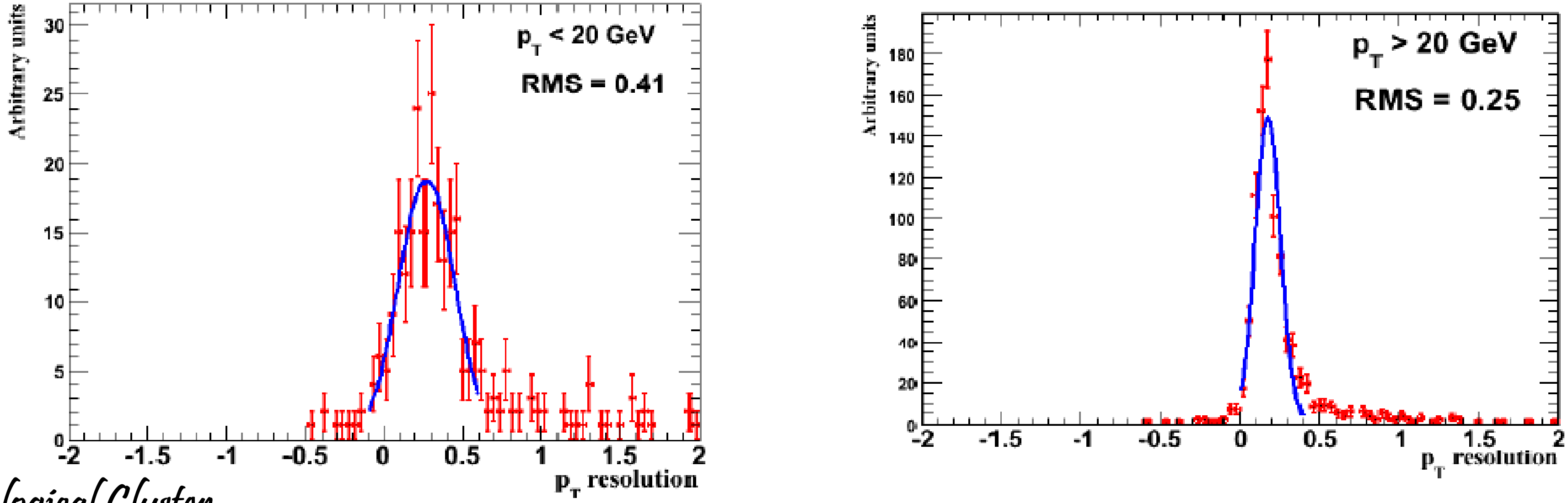




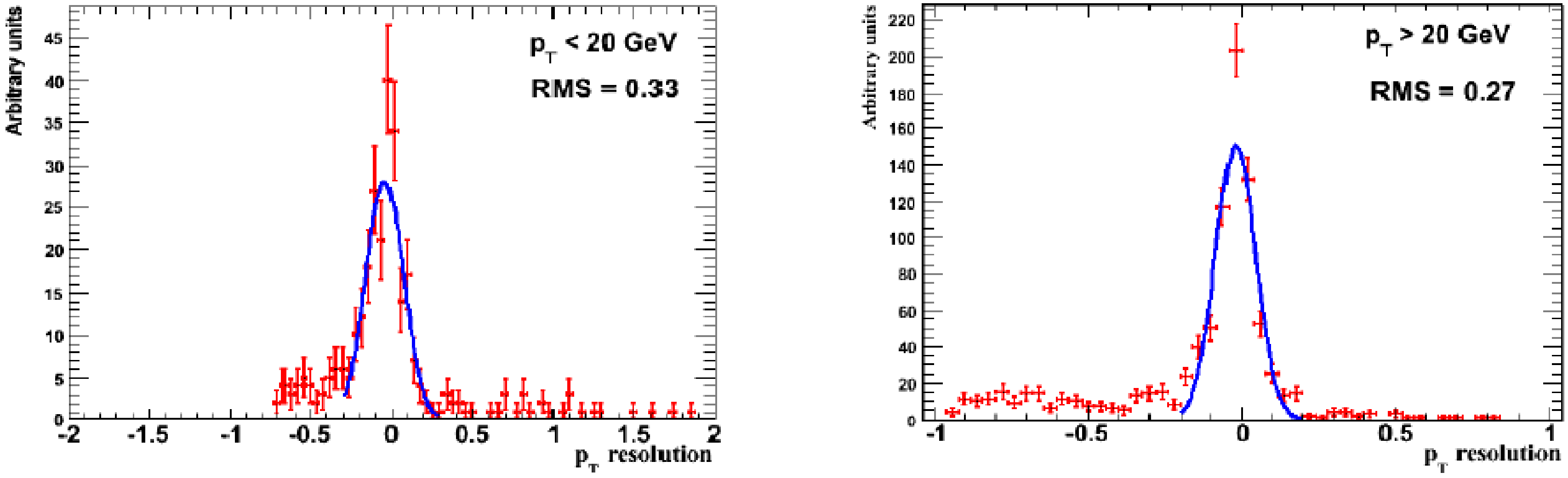


# $P_T$ resolution of topological cluster and jet algorithms

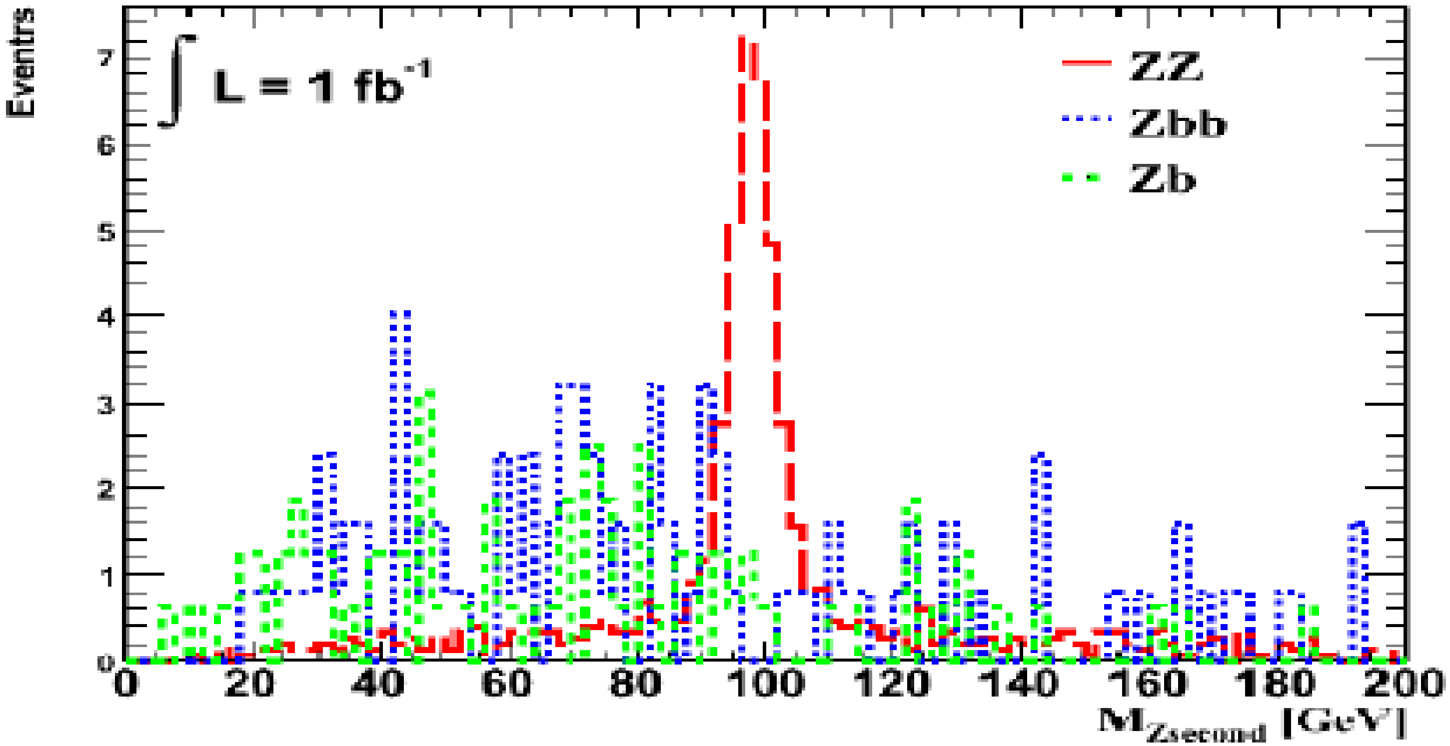
*Jet C4 algorithm*



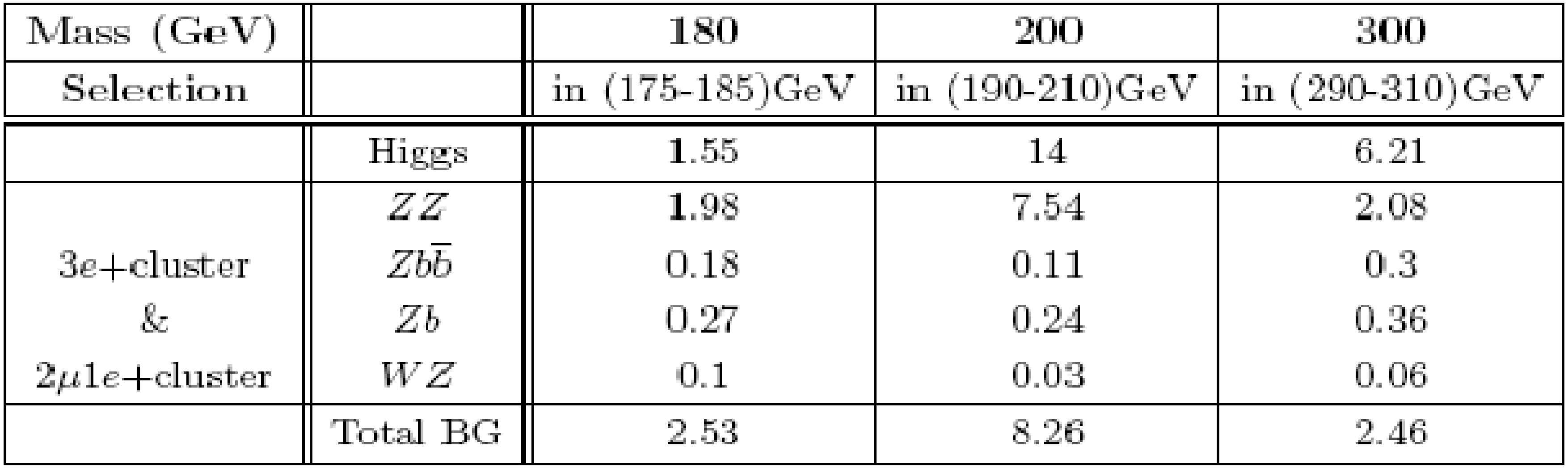
*Topological Cluster*



# Z second


Eventrs
$\int L = 1\ fb^{-1}$
ZZ
Zbb
Zb
0
1
2
3
4
5
6
7
0
20
40
60
80
100
120
140
160
180
200
$M_{Zsecond}$ [GeV]

# Higgs in mass window and systematics



| Mass (GeV) | | 180 | 200 | 300 |
|---|---|---|---|---|
| Selection | | in (175-185)GeV | in (190-210)GeV | in (290-310)GeV |
| | Higgs | 1.55 | 14 | 6.21 |
| $3e$+cluster<br>&<br>$2\mu1e$+cluster | $ZZ$ | 1.98 | 7.54 | 2.08 |
| | $Zb\bar{b}$ | 0.18 | 0.11 | 0.3 |
| | $Zb$ | 0.27 | 0.24 | 0.36 |
| | $WZ$ | 0.1 | 0.03 | 0.06 |
| | Total BG | 2.53 | 8.26 | 2.46 |

Event yields for 10 $\text{fb}^{-1}$ in signal events and backgrounds

S:B 1:1.5 2:1 3:1

| | H (200 GeV) | H (300 GeV) |
|---|---|---|
| Energy scale (1%) | +/-2.2 % | +/-0.2 |
| Resolution (%) | -6.6% | -5.3% |

# Systematic Effects and Significance

For L = 10 fb$^{-1}$

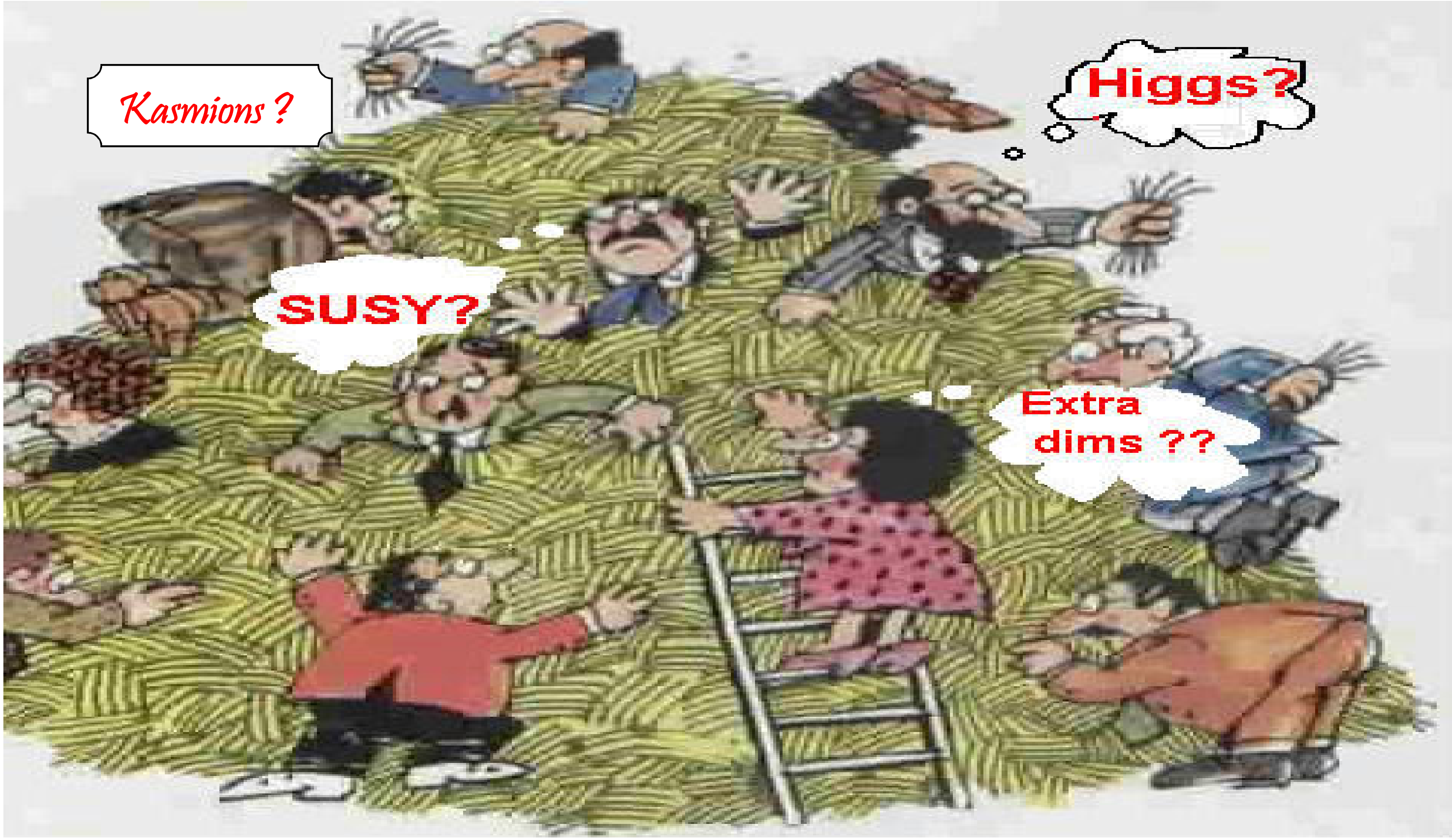
| Higgs mass (GeV) | 180 | 200 | 300 |
|---|---|---|---|
| Expected signal events (4lepton channel) | 13.2 | 56.6 | 31.5 |
| Expected background events (4lepton channel) | 8.9 | 26.77 | 10.1 |
| Significance (4lepton channel) | 2.80 | 6.19 | 4.88 |
| Combined significance (4l and 3l+"$e$") | 2.88 | 7.07 | 5.45 |

When one can reach 5σ ?

For L = 6 fb$^{-1}$

- 4 lepton channel: 33.96 signal events,16.06 BG events, Significance: 4.8
- 3 lepton channel: 8.4 signal events, 4.95 BG events
- Combination of 3l & 4l channels: Significance: 5.3 @ 6 fb$^{-1}$ instead of 7 fb$^{-1}$

# Stay tuned



THANK YOU