

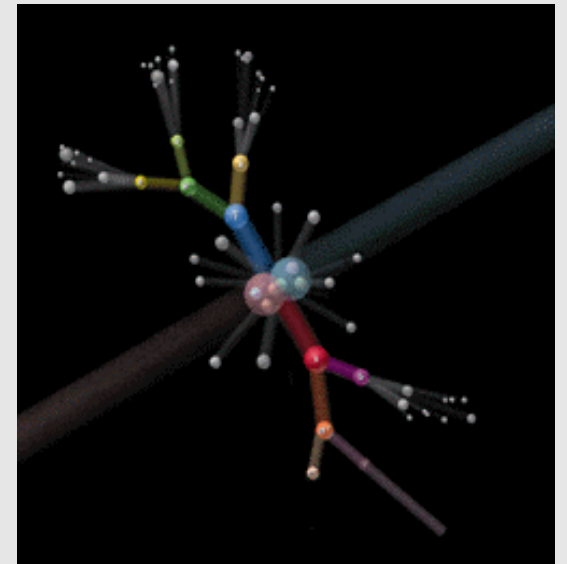
# Neural Network Applications for the Analysis of LEP data

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Borut Paul Kersevan

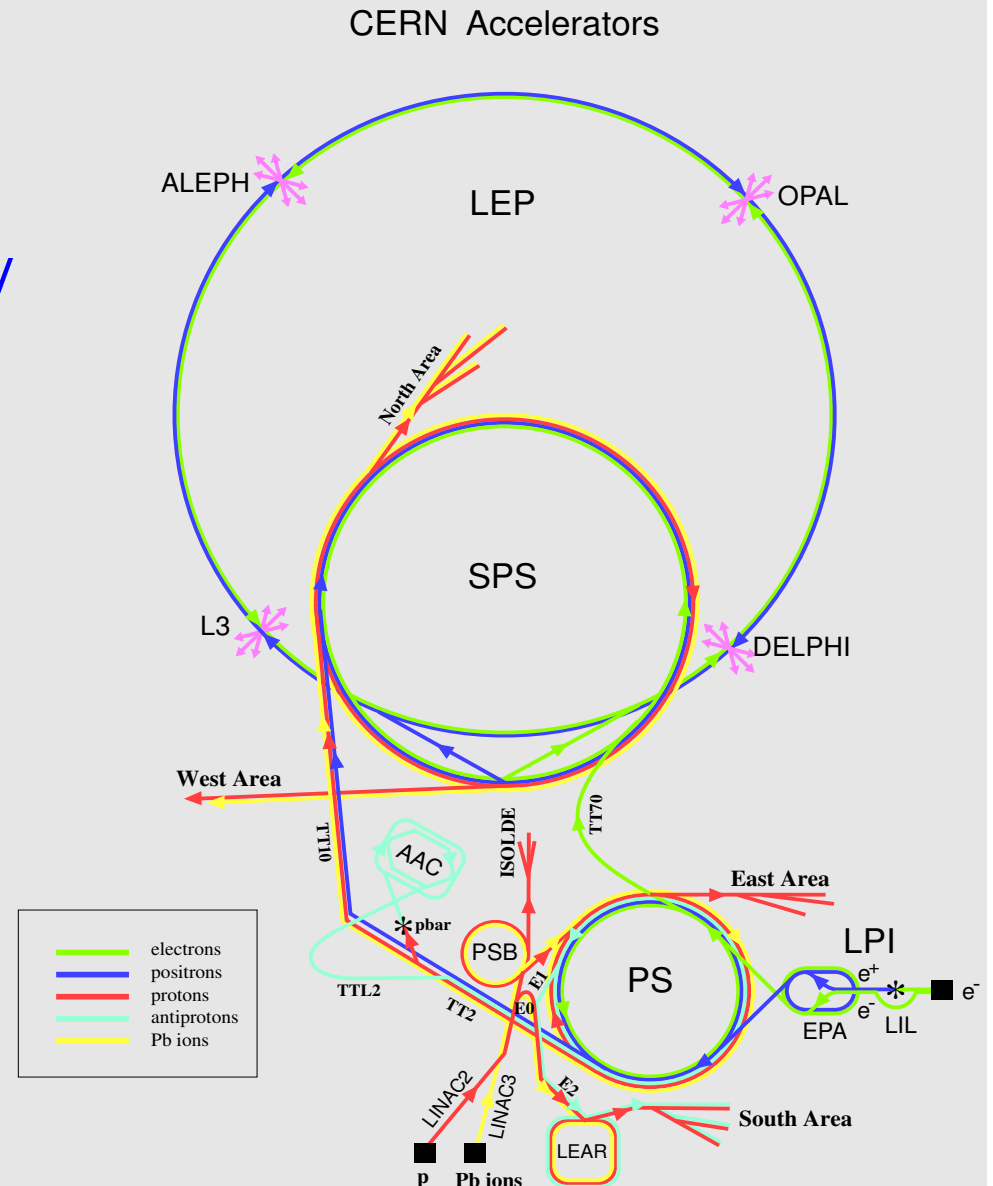
Faculty of Mathematics and Physics  
University of Ljubljana  
and  
“Jozef Stefan” Institute

- Measurements at **LEP**
- Application of the **Artificial Neural Networks**
- **LEP** experience with **ANN-s**



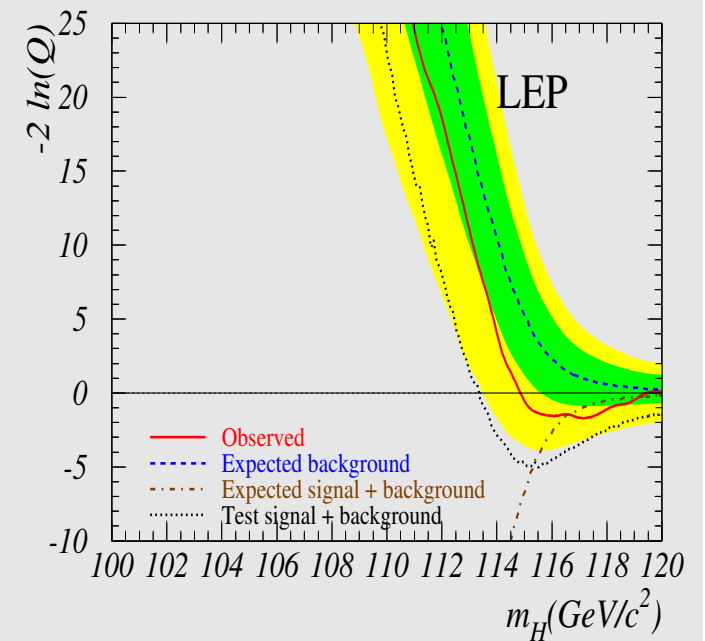
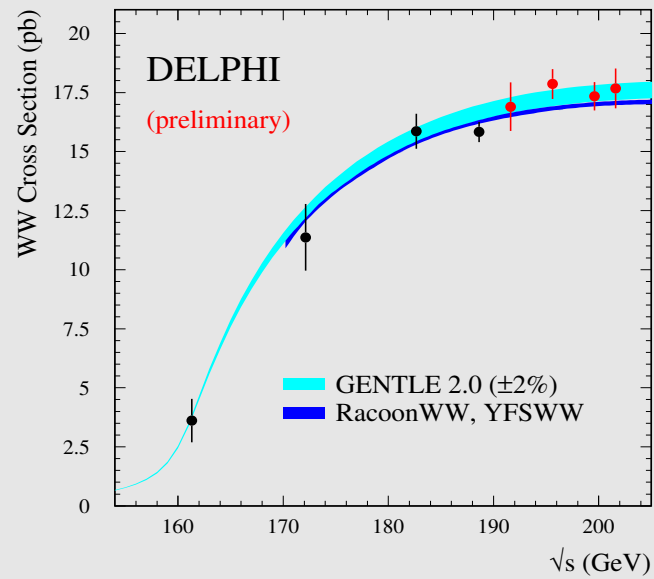
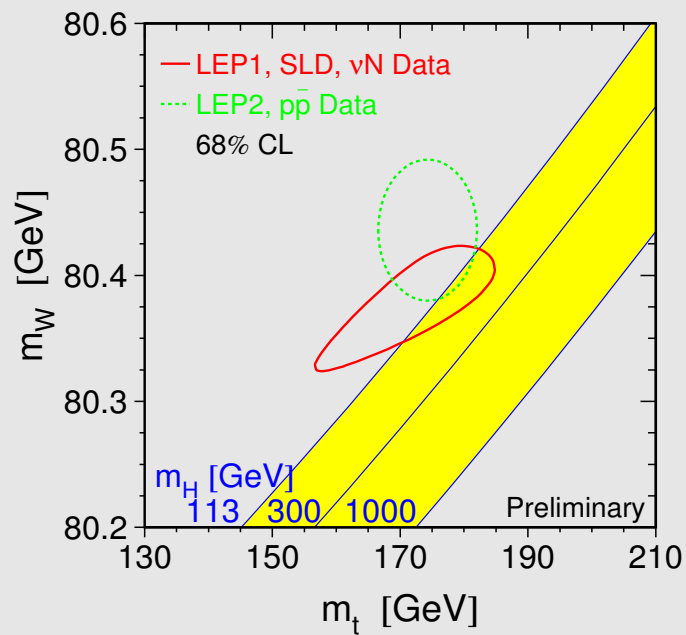
# LEP & Experiments at CERN

- Large Electron Positron collider operated at CERN in period 1989–2000
  - LEP I:  $e^+e^-$  beams collided at  $\sqrt{s}=91$  GeV
    - About 4 million  $Z^0$  events/experiment recorded
  - LEP II:  $e^+e^-$  beams accelerated up to  $\sqrt{s}=210$  GeV
- Four multi-purpose detectors:
  - ALEPH
  - DELPHI
  - L3
  - OPAL



# What was measured?

- Precision measurements of the Standard Model
- Tests of the Standard Model predictions
- New physics searches



# What are we interested in?

- Typical process:

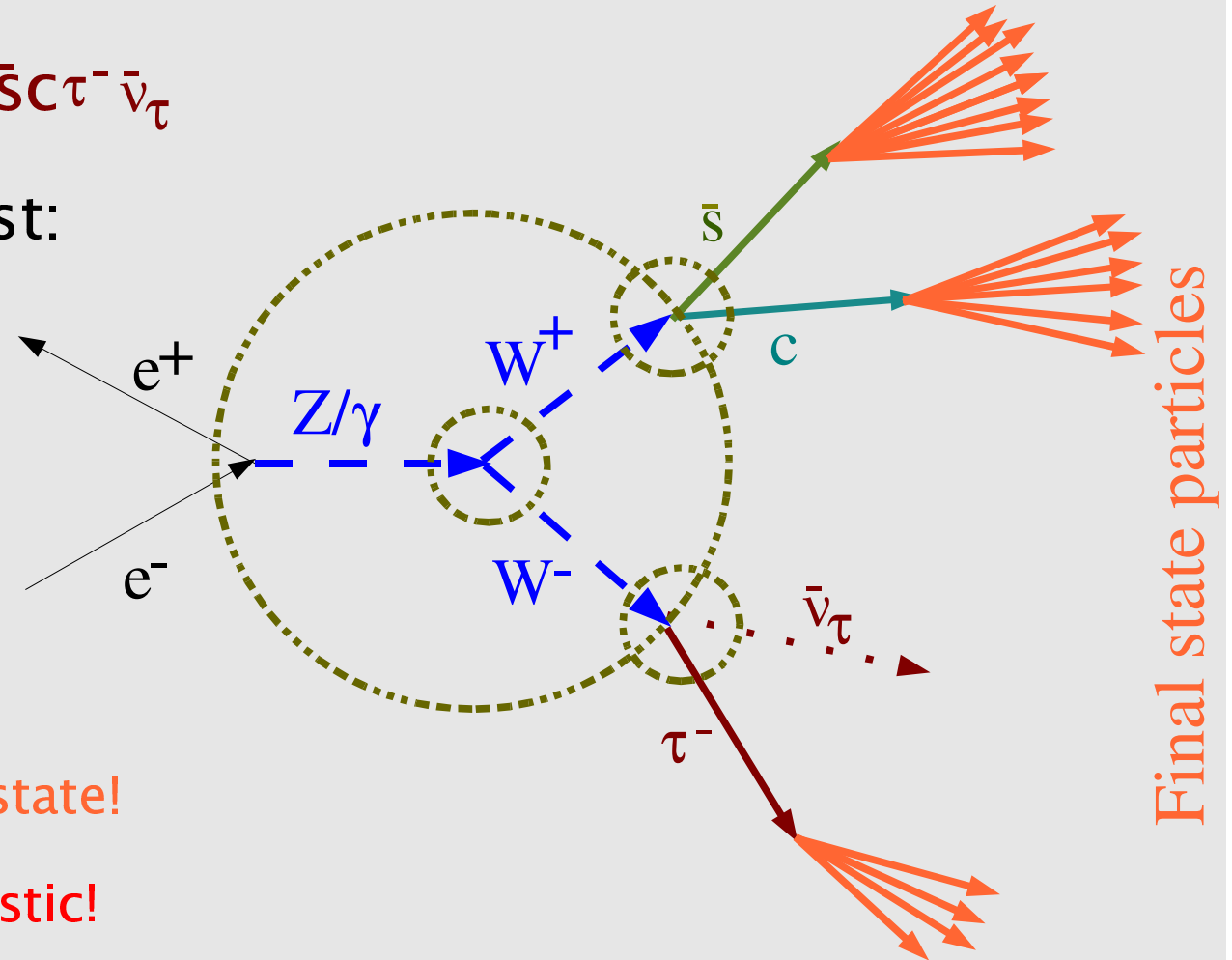
$$e^+e^- \rightarrow (Z^0/\gamma^*) \rightarrow W^+W^- \rightarrow \bar{s}c\tau^-\bar{\nu}_\tau$$

- Many items of interest:

- Resonances
- Cross-sections
- Couplings

- Keep in mind:

- we see only the **final state!**
- The process is **stochastic!**



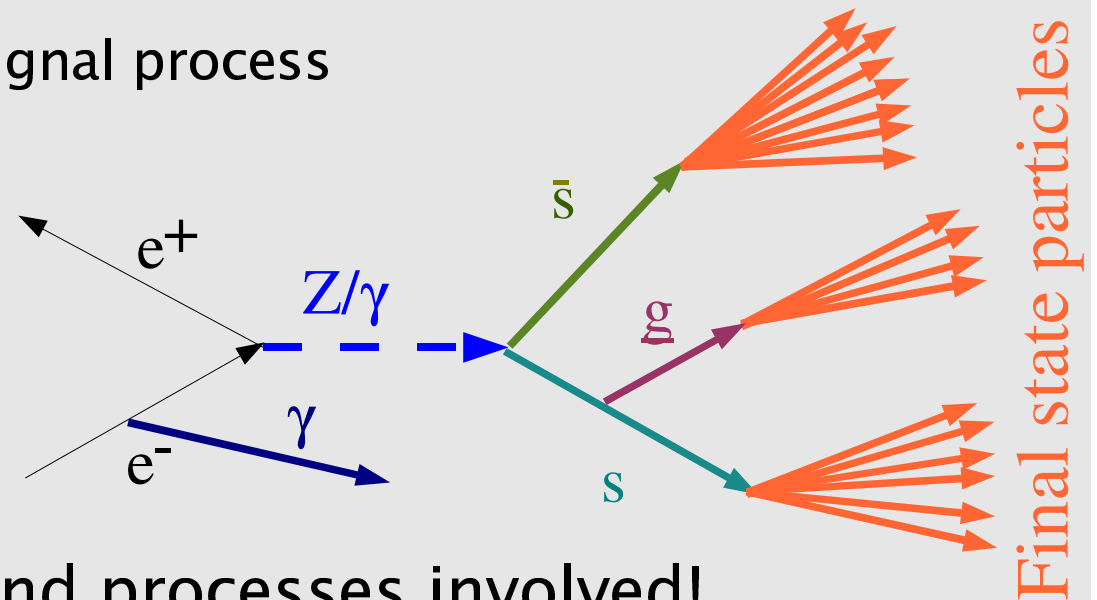
## Then There is **Background**...

- A background process to the previous one:

$$e^+e^- \rightarrow (Z^0/\gamma^*) \rightarrow s\bar{s}$$

- Background in what sense?

- Similar **kinematic signature** to the signal
- we know it better than the signal process



- In practice **many** background processes involved!

# And the **Detector**...

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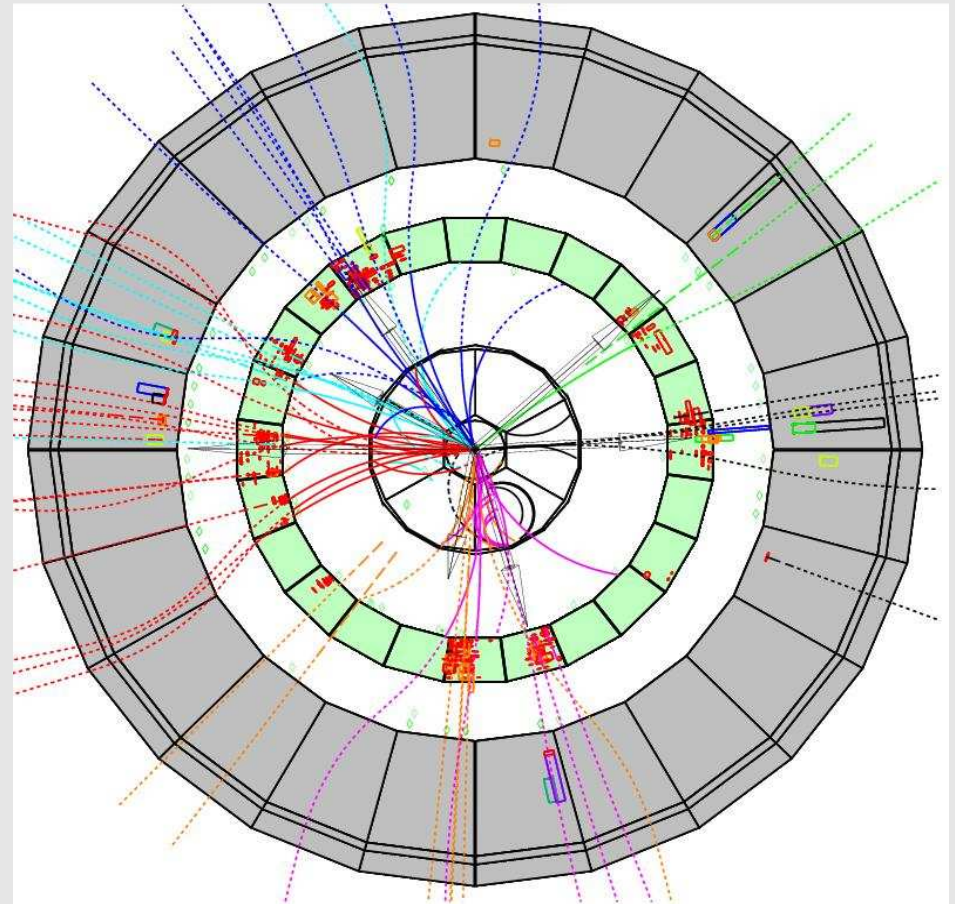
- Necessarily **imperfect** detection:

- **Finite** measurement precision
- (Partially) **blind** to some particles/parameters:
  - Neutrinos
  - Particle flavour
  - etc..

- **Multipurpose** detectors at LEP:

- **no** background rejection

Example: a **4-jet event** in the DELPHI detector



# What next?

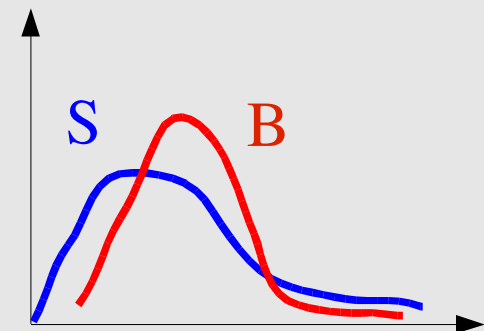
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- What we are left with in a data sample:
  - backgrounds and (**maybe**) signal
  - **smeared** and/or **partially reconstructed** topologies
- How do we proceed?
  - **Filter** out the signal candidate events
  - **Extract/reconstruct** the interesting quantity
  - At **LEP** one has to be **good at it** → **precision** measurements!

# Event filtering

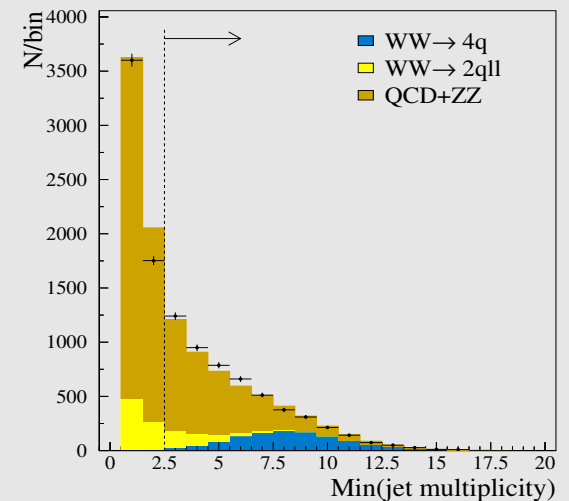
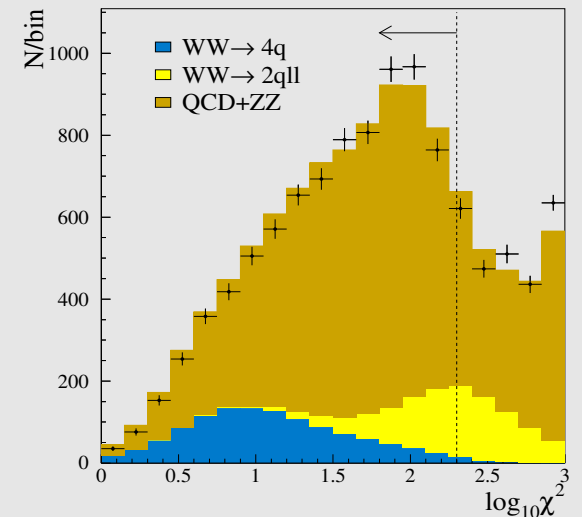
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- Use the **prior** knowledge/assumptions about the detector and the processes involved:
  - we can **predict** the kinematic/topological quantities that separate **signal** from **background**
- To **quantify** them is more difficult:
  - Theoretical predictions of event rates and shapes
  - Description of detector effects
- Bottom line is we need an accurate **Monte-Carlo simulation** for **PDF-s**  
**Cracow** group famous: **KoralZ,KoralW,YfsWW,Tauola,Bhlumi...**



# Event filtering II

- The **easiest** approach:
  - Find an signal-sensitive variable
  - Determine the distributions of signal and background on that variable (**projection of the PDF**)
  - make a **cut** that gives optimal **background rejection** and still **retains as much signal as possible**
    - **purity**  $\otimes$  **efficiency**
  - **Repeat** the procedure until the options are exhausted
- At **LEP** this considered as the **standard/robust** approach



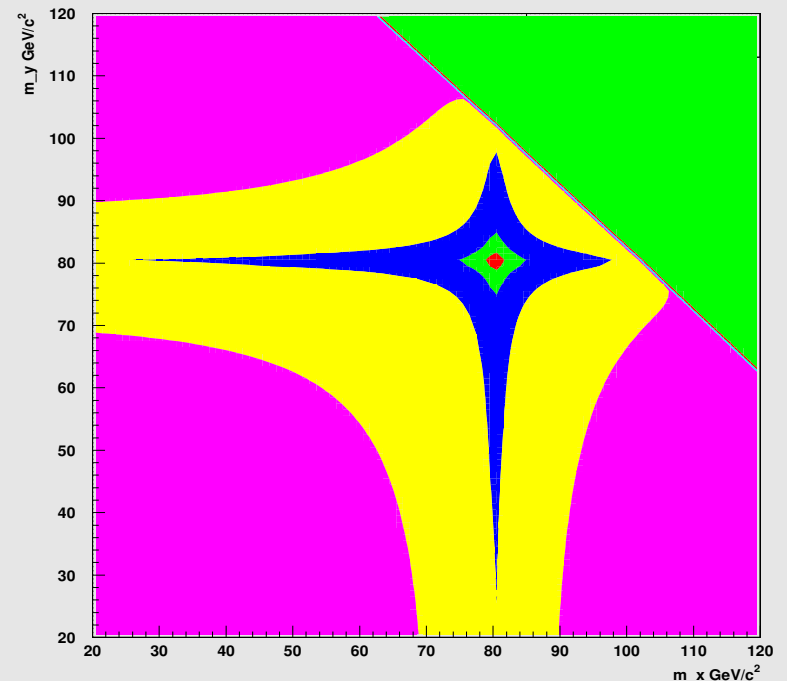
# Event Filtering III

- **Caveats** of the cut-based analysis at **LEP**:
  - **Many cuts needed** to get an efficient filter
  - Variables often **correlated/non-orthogonal**
  - In effect isolating a rectangular N-dimensional hypercube around a **complex signal PDF**
- Clearly one can do better:
  - High quality data of **LEP** experiments
  - Very accurate simulations
- Indeed many advanced techniques developed
  - Use of **neural networks (ANN)** is one of them

Example:

Reconstructed  $M_W$  of  $WW$  pairs

*DELPHI183 GeV*

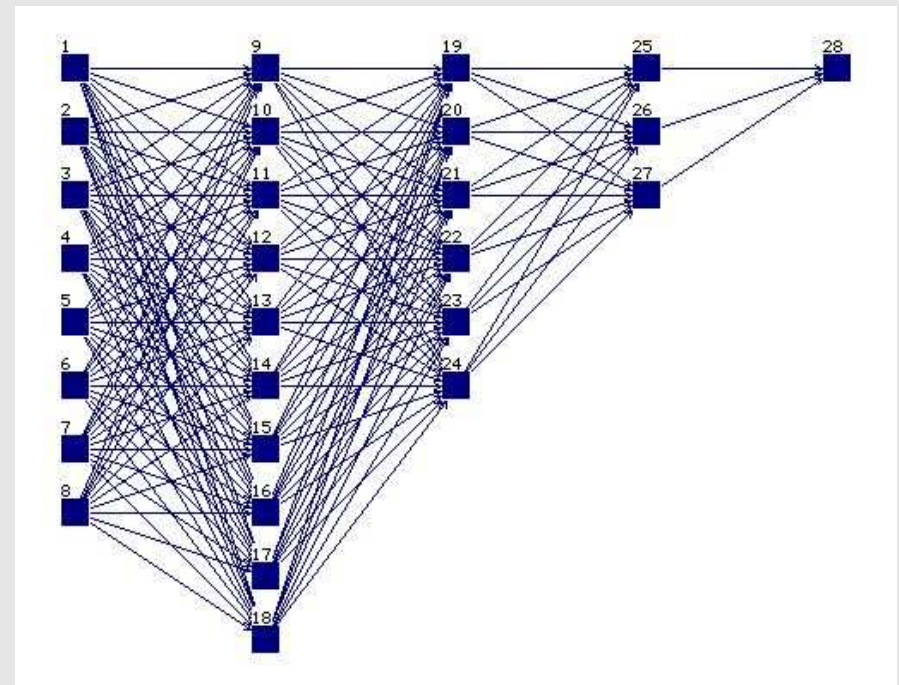


# Event Filtering IV

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- Various ANN programs:
  - SNNS (IPVR Stuttgart)
  - JETNET (Lund University)
  - Sometimes custom made
- General strategy in common:
  - Some preliminary cuts
  - Use feed-forward ANN-s
  - Sensitive variables on input neurons
  - A few hidden layers
  - One output neuron as the signal probability
  - Train on MC for signal (out=1) and background (out=0)

Example:  
a SNNS feed-forward ANN



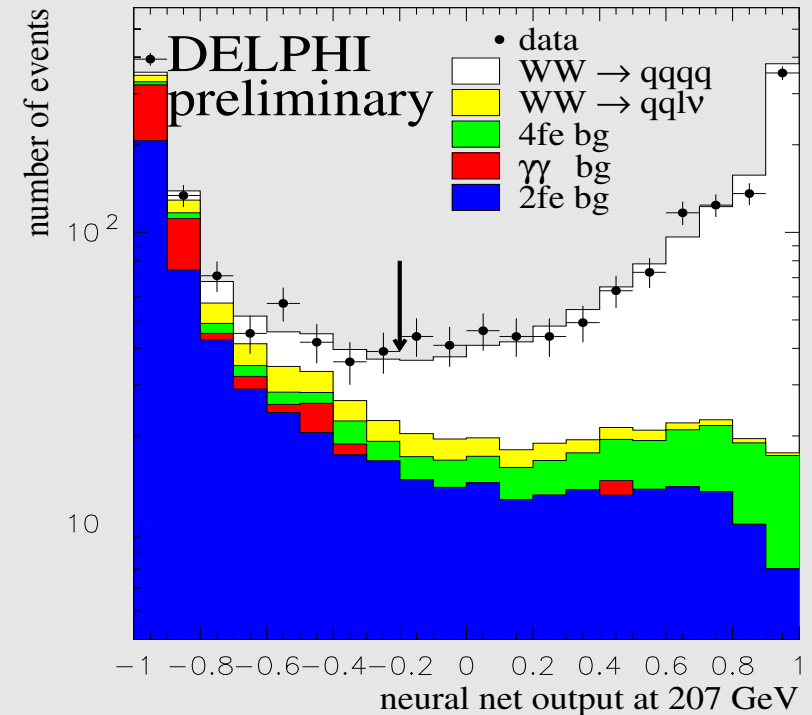
# Event Filter – Example I

- DELPHI measurement of the production rate

$$\sigma(e^+e^- \rightarrow W^+W^- \rightarrow qq\bar{q}\bar{q})$$

- JETNET package used
- 10 input variables (neurons)
- One hidden layer with 8 neurons
- Standard backpropagation algorithm
- Resulting in efficiency  $\sim 90\%$ , purity  $\sim 75\%$

- A comparative cut analysis: efficiency  $\sim 85\%$ , purity  $\sim 75\%$



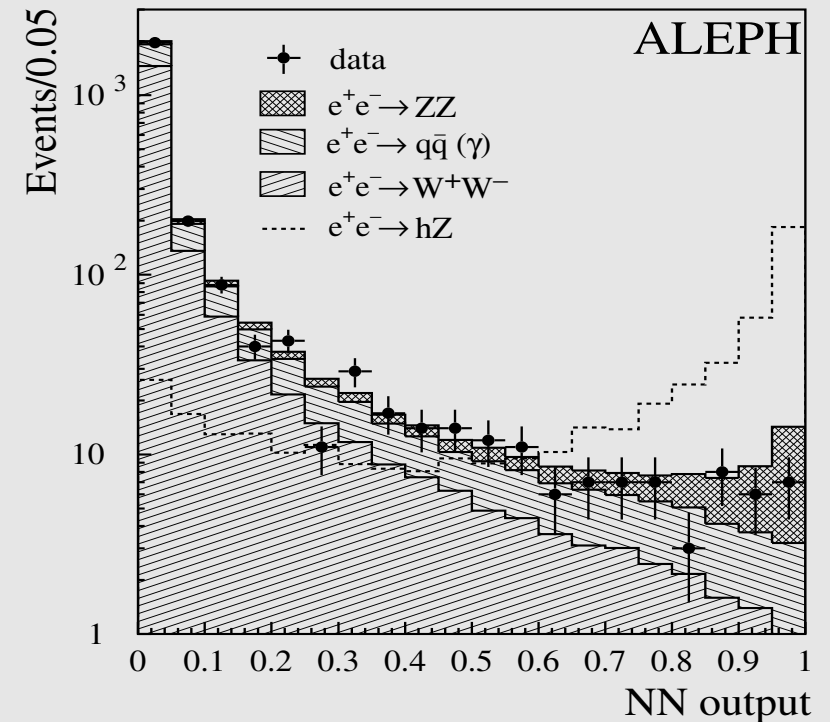
# Event Filter – Example II

- ANN-s used by all LEP experiments in Higgs boson searches
- ALEPH measurement of the Higgs boson mass

$$e^+e^- \rightarrow HZ^0 \rightarrow b\bar{b}q\bar{q}, b\bar{b}b\bar{b}, \dots$$

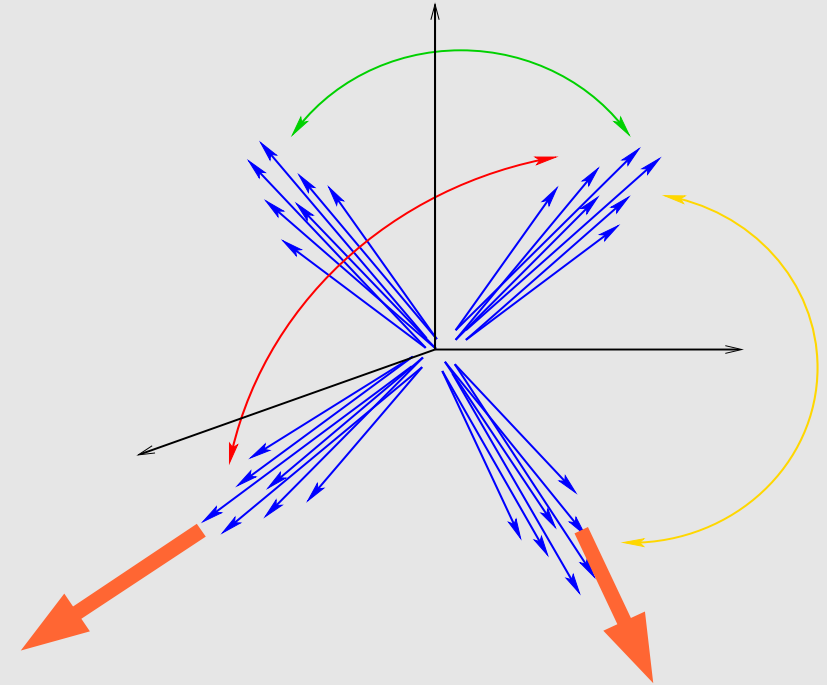
- SNNS and JETNET packages used
- 14–22 input variables (neurons)
- One or two hidden layers with 8–10 neurons
- One to three output neurons
- Standard backpropagation algorithm
- Additional ANN used for jet b-tag

Example:  
Higgs search in 2000



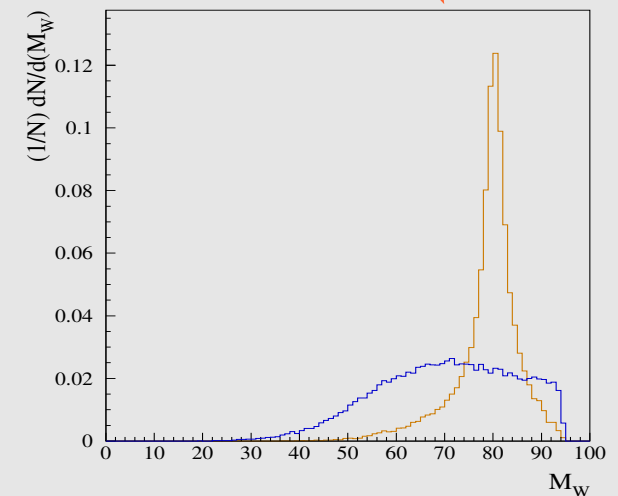
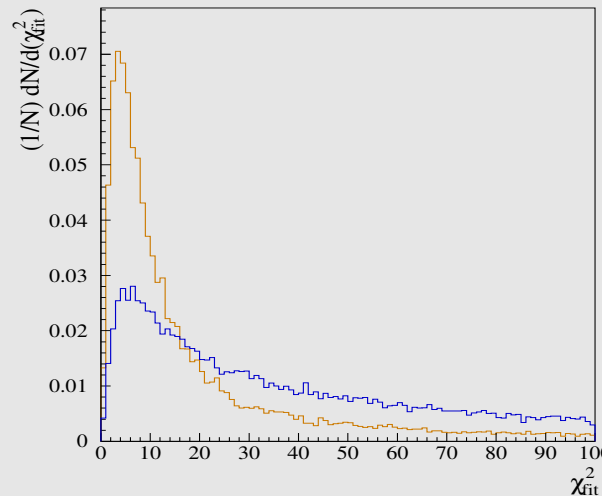
# Kinematic Reconstruction

- Reconstruction of interesting quantities often more taxing than event filtering
  - We are trying to **reconstruct** a quantity **inside a complex event**
  - Disentangle **minuscule signatures** to tag the quantity of interest
  - **ANN-s** one of the obvious choices



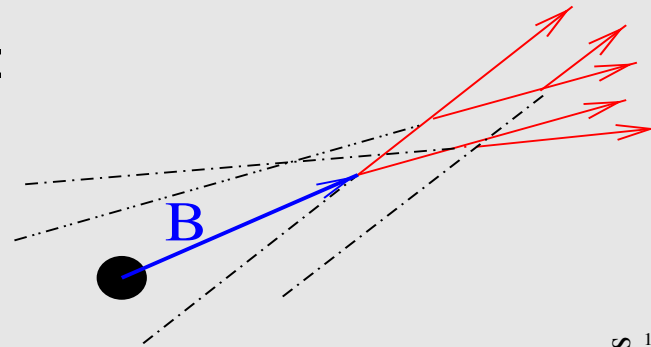
Example:

Jet pairing in  
 $e^+e^- \rightarrow W^+W^- \rightarrow qqqq$

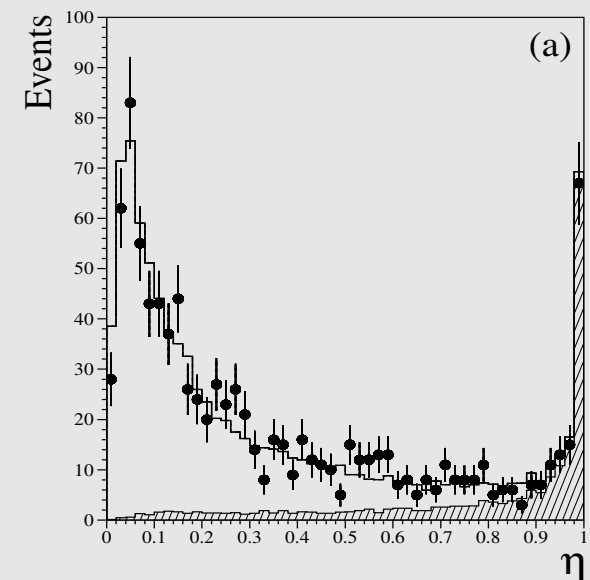


# Reconstruction – Example I

- ANN-s used by all LEP experiments in b-tagging procedures:
  - identify the jets which originate in b-quark fragmentation
- ALEPH b-tagging procedure:
  - JETNET package used
  - 6 input variables(neurons)
  - Two hidden layers
  - One output neuron output as b-tag probability
  - Standard backpropagation algorithm
  - non b-jet rejection ~ 85 %, b-jet efficiency ~ 85 %

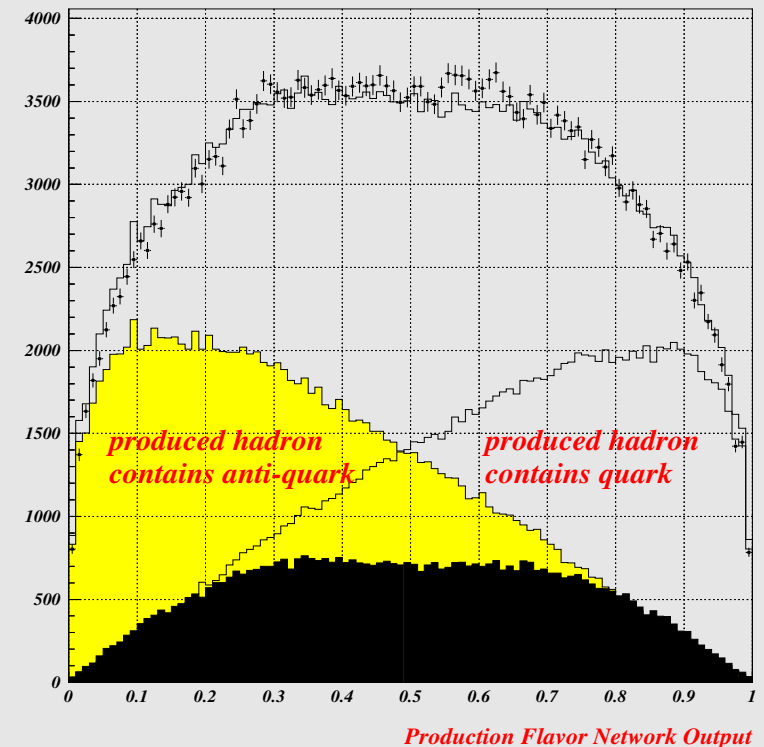


Example:  
ALEPH b-tag at 161 GeV



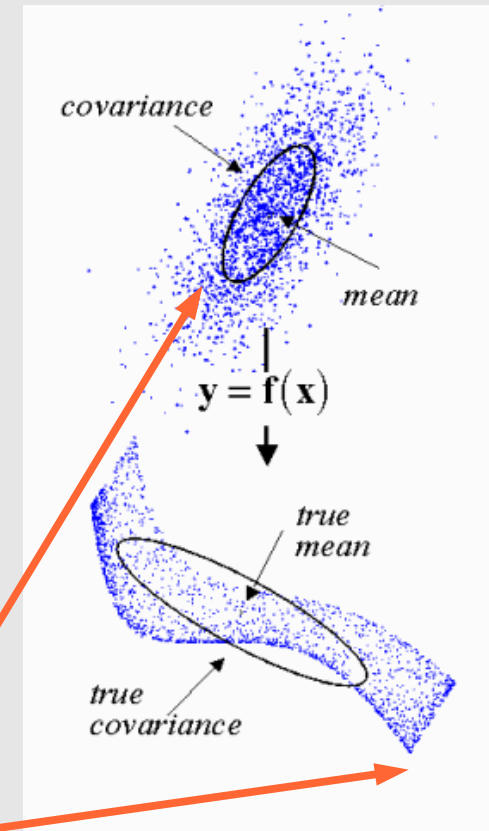
# Reconstruction – Example II

- **BSAURUS** package used at the **DELPHI** experiment for inclusive reconstruction of **B-hadrons** in  $e^+e^- \rightarrow Z^0 \rightarrow b\bar{b}$ 
  - Possibly **the most complex ANN** setup at **LEP**
- Several **ANN**-s used in various stages: **vertex**, **B-meson flavour**, **b-quark flavour**
  - **JETNET** package used
  - **At least 10 input variables**(neurons)
  - **One hidden layer with  $N=\text{input variables}+1$**
  - **One output neuron**
  - **Standard backpropagation** algorithm



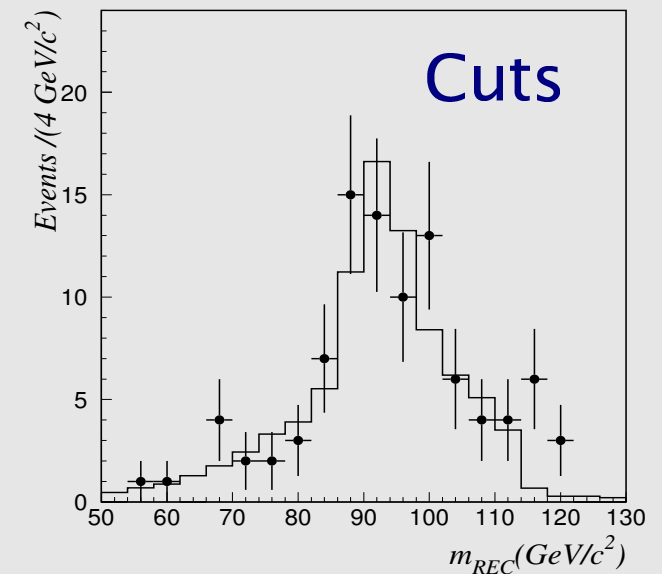
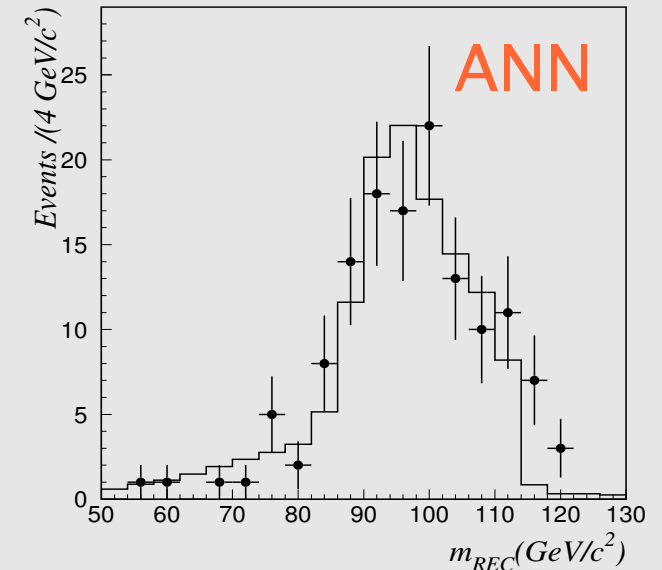
# LEP Experience with ANN-s

- ANN often considered as a **black box tool**, well...
- Somewhat of a **dogma**: cannot do uncertainty estimation properly because of **non-trivial error propagation**...
  - In fact **the same** holds for **any complicated PDF**
  - Uncertainty can still be propagated by smearing the input quantities
- The **true problem** are possible **biases** due to the non-linear response of the ANN-s:
  - Can **small variations** in the tails be **pushed too far** away?



# LEP Experience with ANN-s II

- Origins of (possible) biases in ANN :
  - One relies heavily on the simulation predictions which are certainly not perfect
    - we still need measurements..
  - Extremely large MC samples are needed to cover the whole phase space of interest
    - millions of events needed
  - Danger of even slight overtraining..
    - potentially disastrous for particle searches
- Generic LEP solution:
  - Run a robust (cut based) procedure in parallel
  - Example: ALEPH observation of Higgs candidates
    - Phys. Lett., B 495 (2000) 1



# LEP Experience with ANN-s III

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- Additional (minor) grudges regarding ANN-s
  - The ANN topology not a-priori obvious
    - Number of hidden layers, connections
  - The input parameters in ANN training unknown
    - a lot of guesswork and iterations
  - The ANN analyses still quite time consuming
    - still a net gain compared to cut-based analyses
- Nevertheless, the ANN applications at LEP have clearly shown the ANN-s to be a superior tool