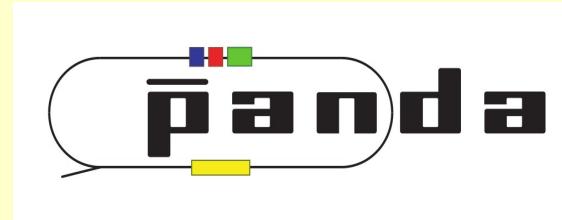


October 7th 2014



Workshop of the GDR-PH-QCD Groupe II at IPN Orsay  
October 6-7, 2014

Simulation studies concerning the  
measurement of the time-like form factors in  
reactions of

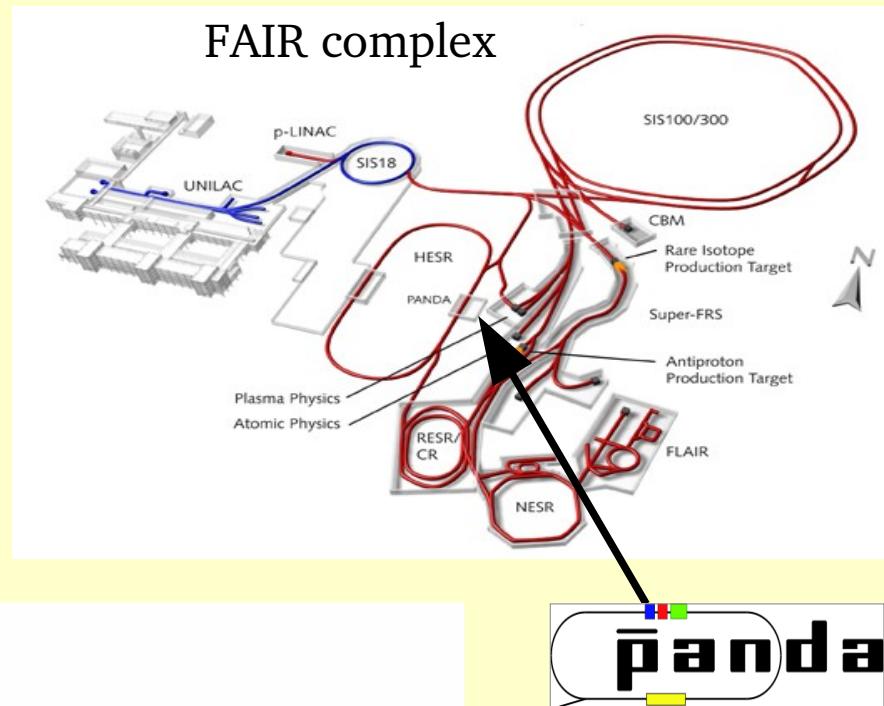
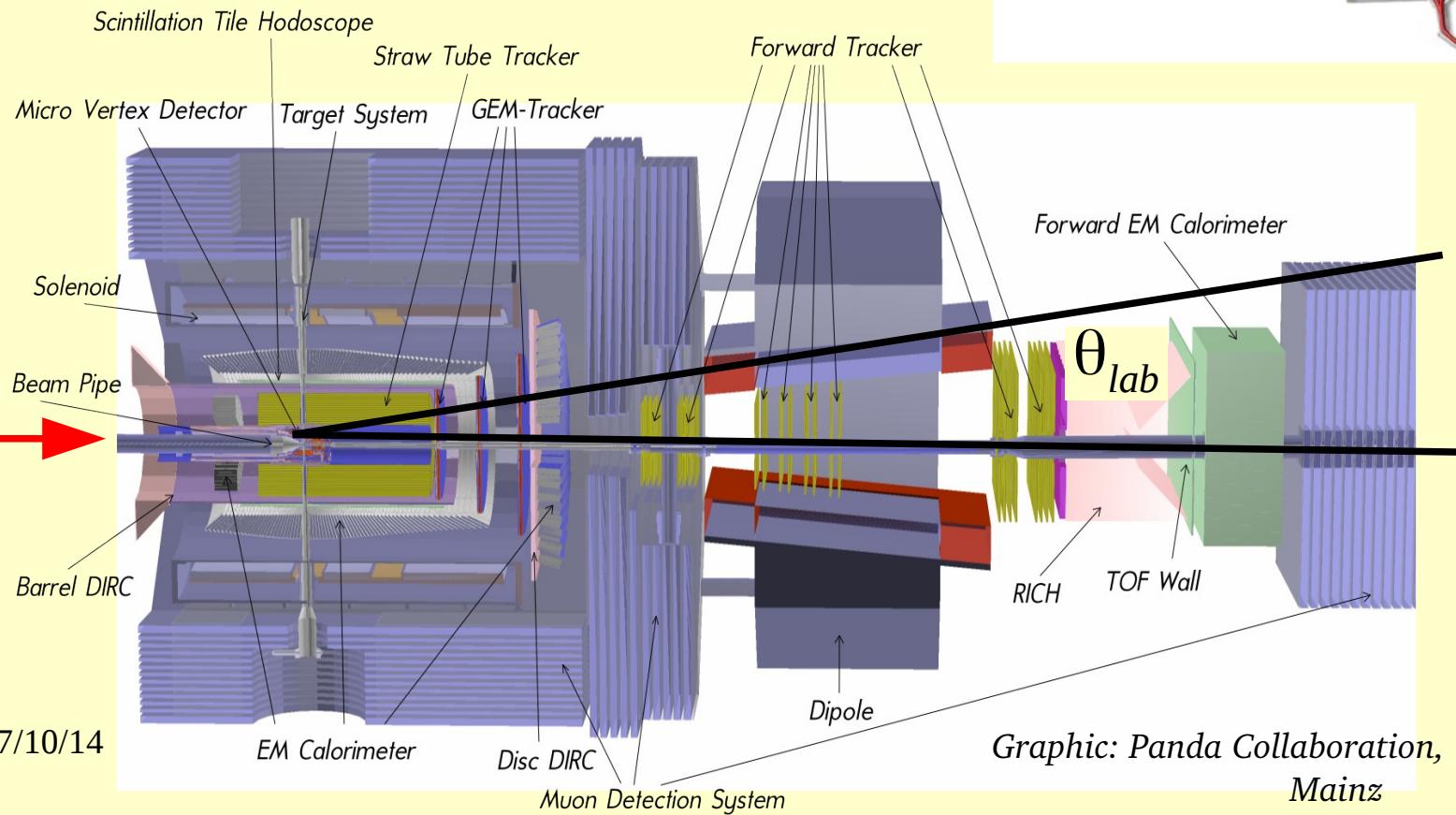
$$\bar{p} p \rightarrow \mu^+ \mu^-$$

Iris Zimmermann

Johannes-Gutenberg Universität Mainz, Helmholtz Institut Mainz

# The PANDA-Experiment at HESR (@FAIR, Darmstadt)

- Fixed target experiment
- High energy antiproton beam in the momentum range from **1.5 GeV/c up to 15 GeV/c**
- High luminosity:  **$2 \cdot 10^{31} - 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$**
- Nearly  $4\pi$  acceptance
- Good energy and momentum resolution
- **Start of data taking: 2019**



Graphic: Panda Collaboration, A. Karavdina,  
Mainz

# Motivation for measuring $\bar{p} p \rightarrow \mu^+ \mu^-$

- Differential cross section<sup>1</sup> of the reaction  $\bar{p} p \rightarrow \mu^+ \mu^-$   
→ access to the **time-like, electromagnetic form factors of the proton  $G_E$  and  $G_M$** :

$$\frac{d\sigma}{d \cos \theta_{CM}}(s, \theta) = \frac{\alpha^2 \pi}{2 \cdot s} \cdot \frac{p_{l^-}}{\bar{p}} \cdot |G_M|^2 \left[ \frac{4M_p^2}{s} \left( 1 - \beta^2 \cos^2 \theta_{CM} \right) \cdot R^2 + \left( 1 + \frac{4m_l^2}{s} + \beta^2 \cos^2 \theta_{CM} \right) \right]$$

- High luminosity at PANDA

→ Individual measurement of  $|G_E|$  and  $|G_M|$

$$R = \frac{|G_E|}{|G_M|}$$

# Motivation for measuring $\bar{p} p \rightarrow \mu^+ \mu^-$

- First time measurement of **time-like electromagnetic form factors using muons**
- **Radiative corrections** (final state radiation) are **suppressed** by the mass of the muon
- Consistency check of time-like form factor data from  $e^+e^-$
- Using muon pairs → **Challenge: Strong hadronic background**, mainly

$$\bar{p} p \rightarrow \pi^+ \pi^-$$

- In case of  $e^+e^-$ :  $e/\pi$  are easier to separate  
(background suppression factor  $\sim 10^{-8}$  already achieved)

$$\frac{\sigma(\mu^+ \mu^-)}{\sigma(\pi^+ \pi^-)} \propto 10^{-6}$$

→ Good muon-pion separation needed!

# Simulation & Analysis

- Simulations for both **signal and background** at beam momentum of 1.7 GeV/c (3.3 GeV/c)
    - PandaRoot package
- Event generation\*:
- Signal:**  $\bar{p} p \rightarrow \mu^+ \mu^-$   $10^6$  events (expected:  $\sim 0.83 * 10^6$  events)
- Background:**  $\bar{p} p \rightarrow \pi^+ \pi^-$   $10^8$  events (expected:  $\sim 1.63 * 10^{11}$  events)
- $|\cos(\theta_{CM})| < 0.8$
- Analysis:
    - Preselection of the data
    - Application of hard cuts
    - Multivariate Analysis (TMVA toolkit of ROOT)

# 1) Analysis: Data Preselection

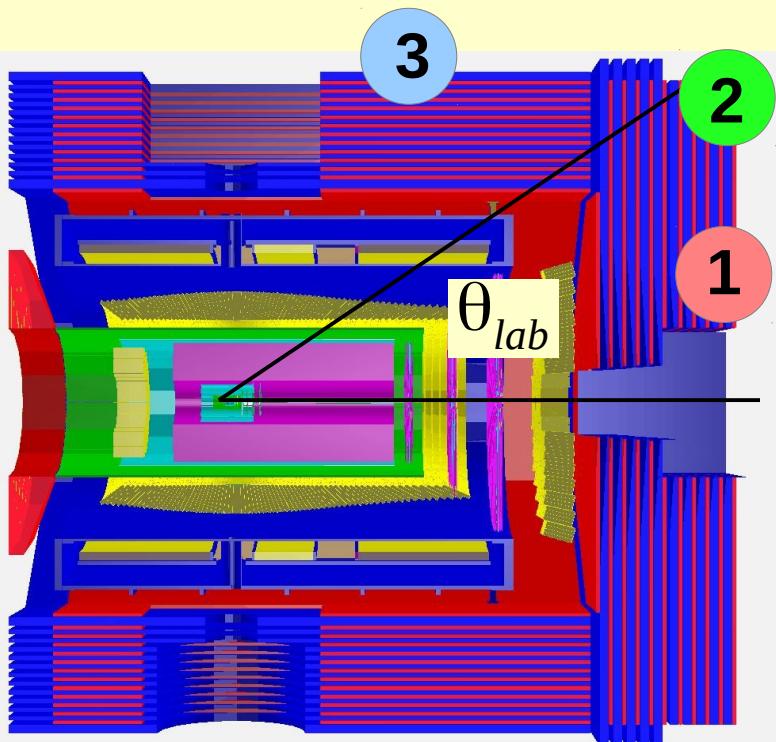
Signal:  $p \bar{p} \rightarrow \mu^+ \mu^-$

Background:  $p \bar{p} \rightarrow \pi^+ \pi^-$

**For each event:**

- Combination of pairs of the reconstructed tracks containing 1 positive & 1 negative charge
- If more than one possible pair: accept only the pair with closest to 180° back-to-back production in center-of-mass system
- Both candidates must have hits in Muon System (MDT)

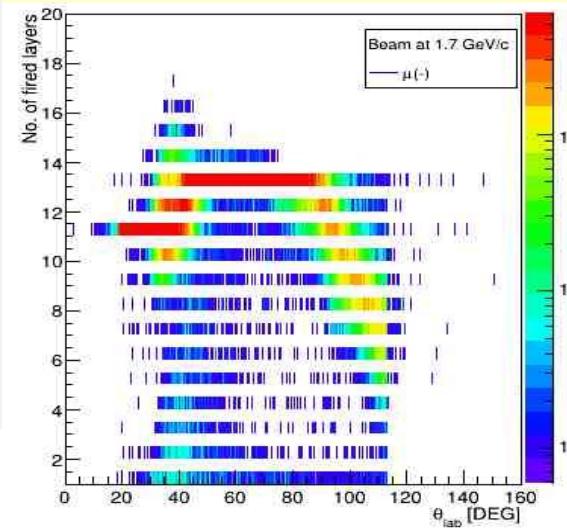
# Muon System of PANDA



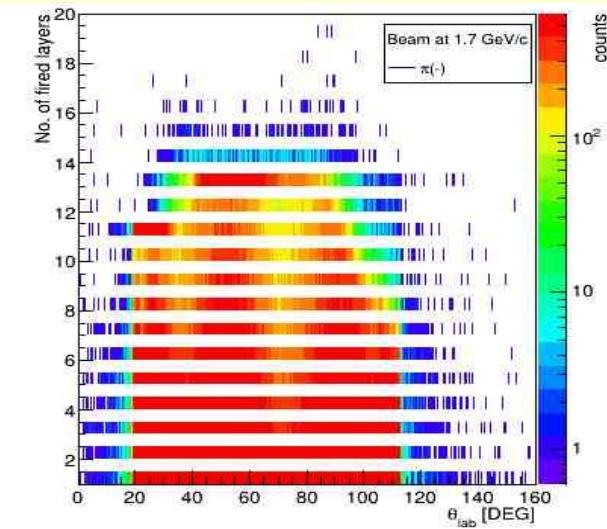
- 1** Endcap & Muon filter:  
11 detection layers
- 2**  $\sim 40^\circ$  polar production angle:  
Overlap of Barrel & Endcap
- 3** Barrel: 13 detection layers
- 4** Forward Range System (FRS)  
(not shown): 16 detection layers

Number of fired detection layers vs. polar production angle (lab frame)

Signal:  $p \bar{p} \rightarrow \mu^+ \mu^-$



Background:  $p \bar{p} \rightarrow \pi^+ \pi^-$

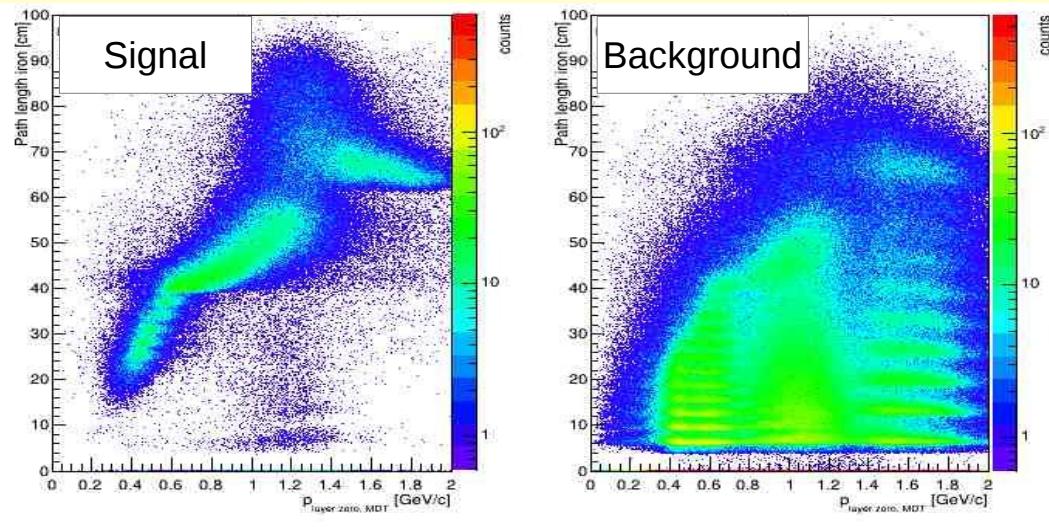


- Reconstructed events after preselection
- Beam momentum 1.7 GeV/c
- $\cos(\theta_{CM}) \in [-0.8; +0.8]$

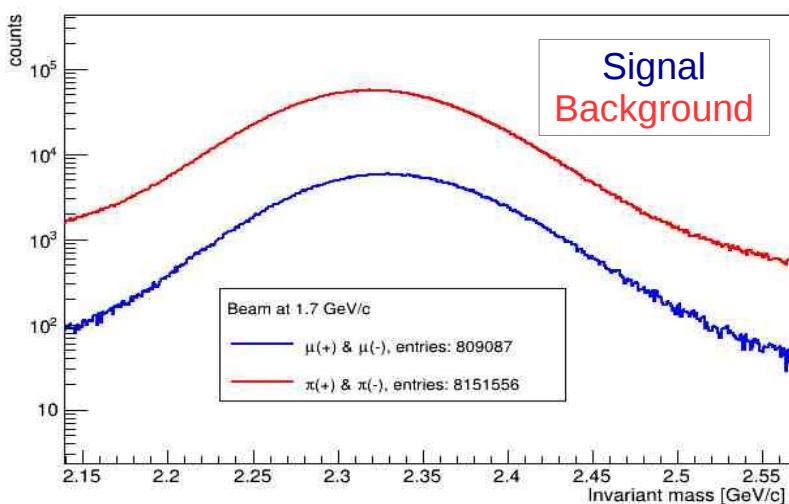
# 1) Analysis: Preselected Data

## Muon System

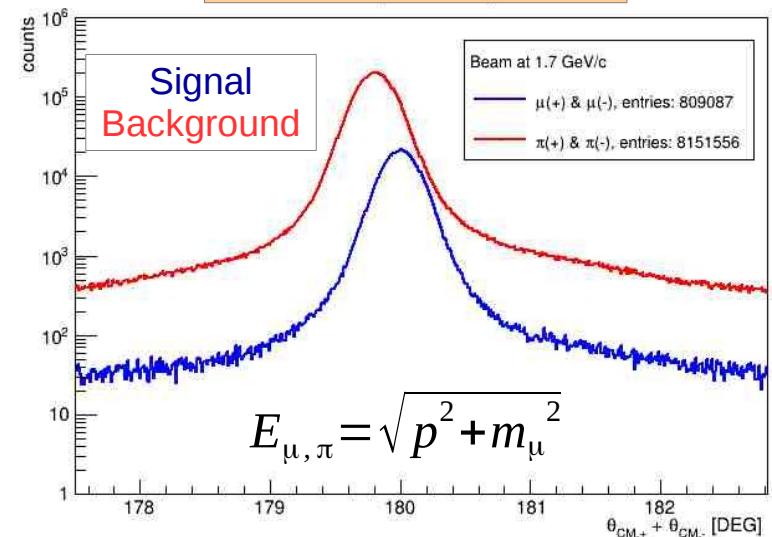
Path length inside iron absorber vs initial momentum MDT



## Invariant Mass

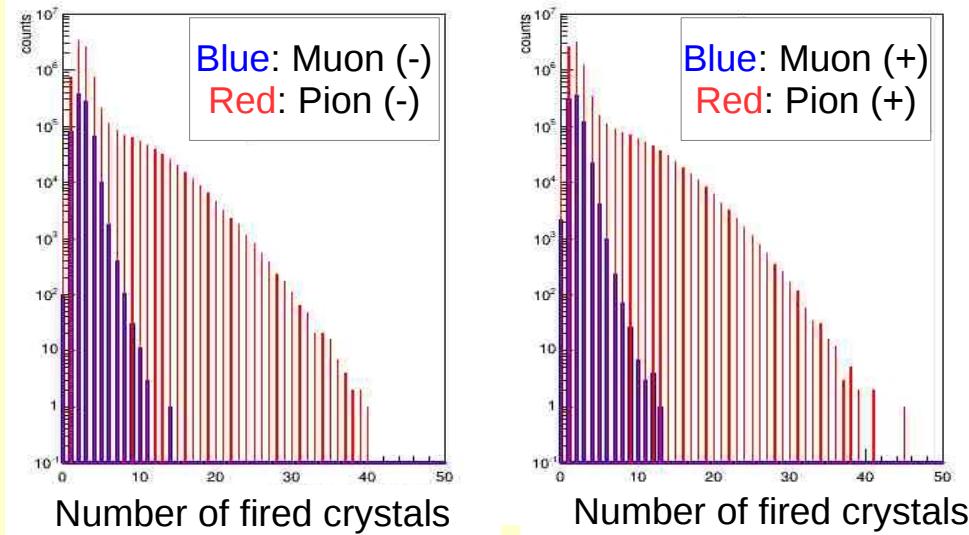


## $\theta_{CM}^+ + \theta_{CM}^-$



## Electromagnetic Calorimeter

### Number of fired crystals



## 2) Analysis: Hard Cuts

First scenario: Application of cuts

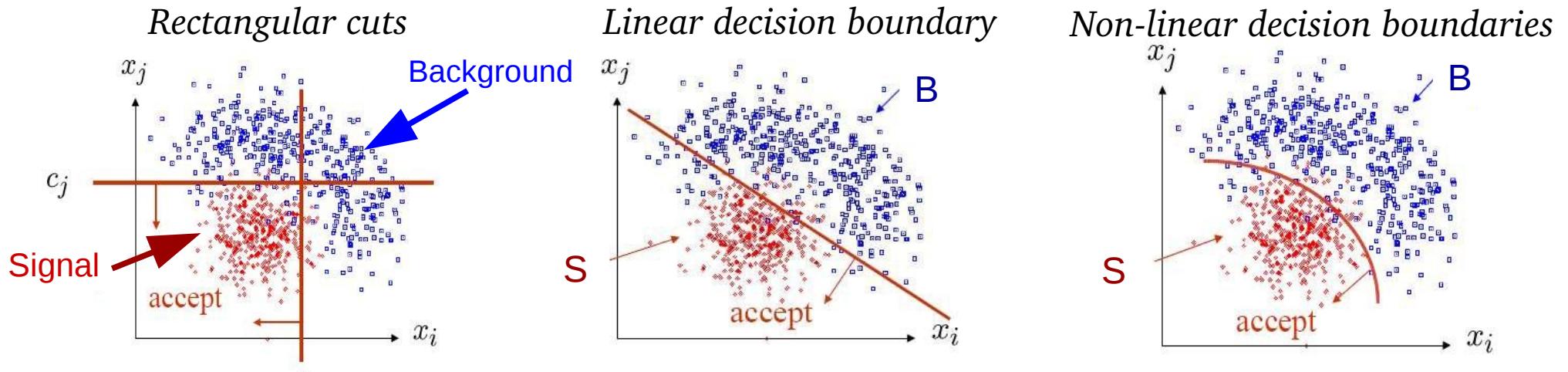
Invariant mass [GeV/c]	] 2.3 , 2.38 [
$\theta_{CM}^+ + \theta_{CM}^-$ [DEG]	] 179.95 , 180.5 [
Path length inside absorber of muon system [cm]	> 42.0
$P(\mu^+)_{MDT}; P(\mu^-)_{MDT}$	> 0.99
$P(\mu^+)_{EMC}; P(\mu^-)_{EMC}$	> 0.05

Beam momentum: 1.7 GeV/c	#Events: Signal	#Events: Background
Monte-Carlo Simulation	$10^6$	$1.0425 * 10^8$
After Preselection	809087 (~80.9 %)	8151556 (~ 8.2%)
After Preselection & Hard Cuts	112278 (~11.2 %)	1660

Background suppression factor  $\sim 2 * 10^{-5} \rightarrow$  could this be improved?

# 3) Analysis: Multivariate data classification (Toolkit for Multivariate Analysis )

How to find an optimal decision boundary?



**Goal of Multivariate Analysis:** Find *optimal decision boundary* using *many variables*,  
→ optimal signal/background separation.

**TMVA:** Root-integrated software package for processing and evaluation of multivariate classification methods.



For instance:

- Boosted Decision Trees (**BDT**)
- Artificial neural networks (**Multilayer Perceptron**)
- Support Vector Machine (**SVM**)
- ...

### 3) Analysis: Multivariate data classification (Toolkit for Multivariate Analysis )

#### 1) Training phase

**Signal data sample:**  
Set of input variables  
(X<sub>1</sub>, X<sub>2</sub>, X<sub>3</sub>, ..., X<sub>n</sub>)

**Background data sample:**  
Set of input variables  
(X<sub>1</sub>, X<sub>2</sub>, X<sub>3</sub>, ..., X<sub>n</sub>)

- Set of **input variables** can be optimized:  
Ranking, Linear correlation between variables
- **Additional cuts** on the input variables can improve performance

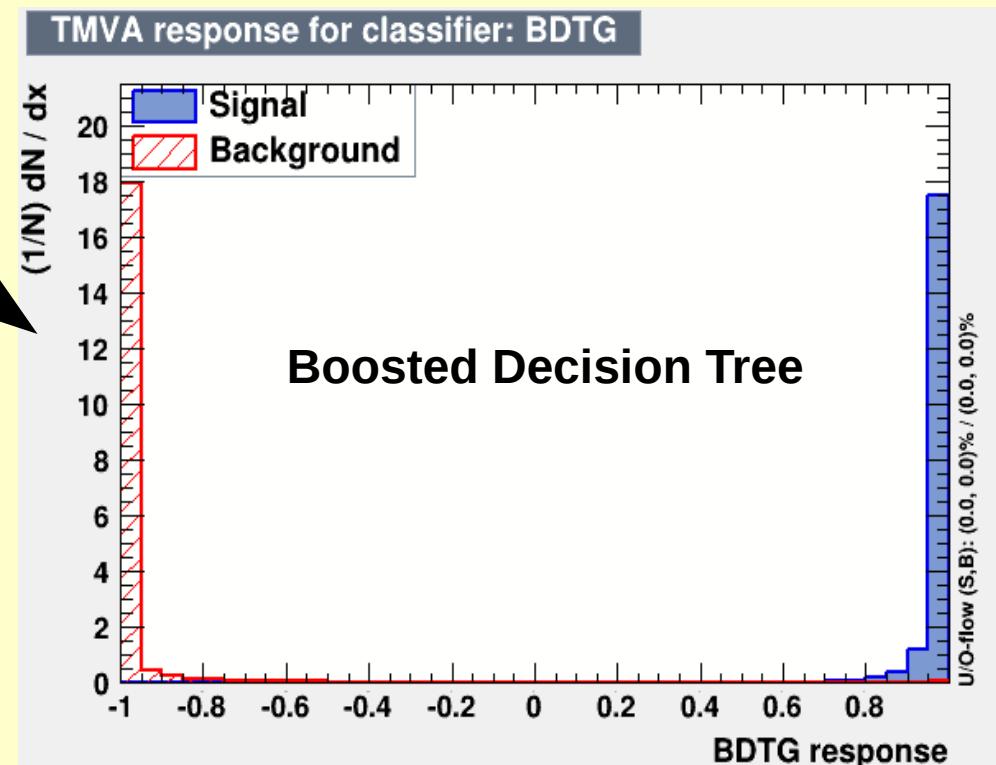
  
Training, Testing &  
Evaluation of classifiers

TMVA output: Weight files  
in xml format

Data to be  
analyzed

#### 2) Application phase

Analysis of data:  
→ Cuts on classifier  
output



Training input variables from Muon System, Straw Tube Tracker and EMC

# Separation of signal & background

Beam momentum: 1.7 GeV/c	#Events: Signal	#Events: Background
Monte-Carlo Simulation	$10^6$	$1.0425 \cdot 10^8$
After Preselection	809 087 (~80.9 %)	8 151 556
After Preselection & Hard Cuts	112278 (~11.2 %)	1660
MVA & cuts*	(~10.1 %)	260

\* Applied cuts:

- Boosted Decision Tree (BDT response > 0.375)
- BDT Gradient Boost (BDTG response > 0.998)
- Invariant Mass  $\sqrt{s} \in [2.23 ; 2.45]$
- $\theta_{CM}^+ + \theta_{CM}^- > 179.99$

Current status:  
**Background suppression factor**  
 $\sim 2.5 \cdot 10^{-6}$

# What can be achieved?

- Assumptions:
  - Integrated luminosity:  $2 \text{ fb}^{-1}$
  - $|G_E| = |G_M|$ , for  $|G_M|$  a modified dipol parametrization<sup>1</sup> has been used

→ At 1.7 GeV/c calculate the expected number of events:

Signal:	$N \sim 0.83 * 10^6$	events of	$\bar{p} p \rightarrow \mu^+ \mu^-$	$ \cos(\theta_{CM})  < 0.8$
Background:	$N \sim 1.63 * 10^{11}$	events of	$\bar{p} p \rightarrow \pi^+ \pi^-$	

- Analysis shows currently
  - signal efficiency  $\sim 10.1\%$
  - background suppression factor  $\sim 2.5 * 10^{-6}$  (in case of  $e^+e^- \sim 10^{-8}$ )

Rough estimation of the expected signal/background ratio:

- Signal:  $N(\text{after analysis}) \sim 83830$  events
  - Background:  $N(\text{after analysis}) \sim 407500$  events
- Signal-to-background ratio  $\sim 1 : 5$

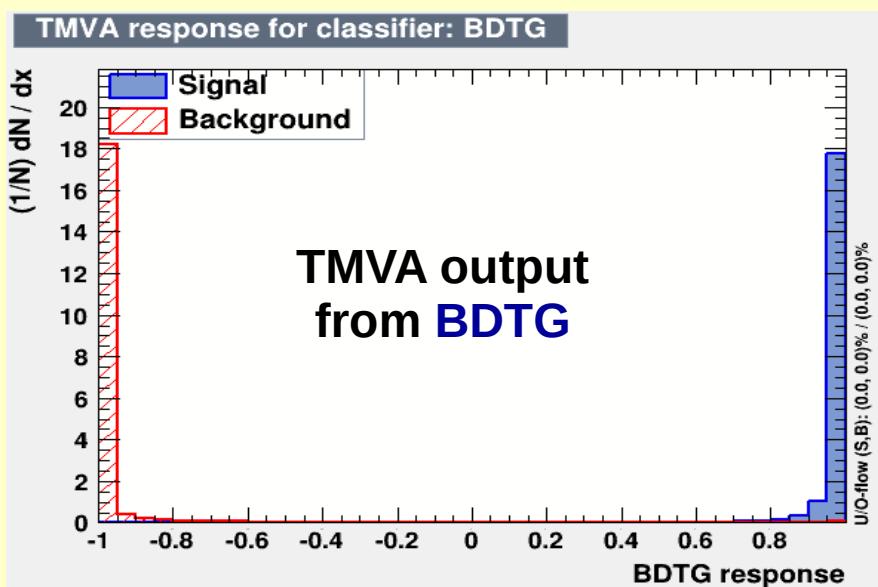
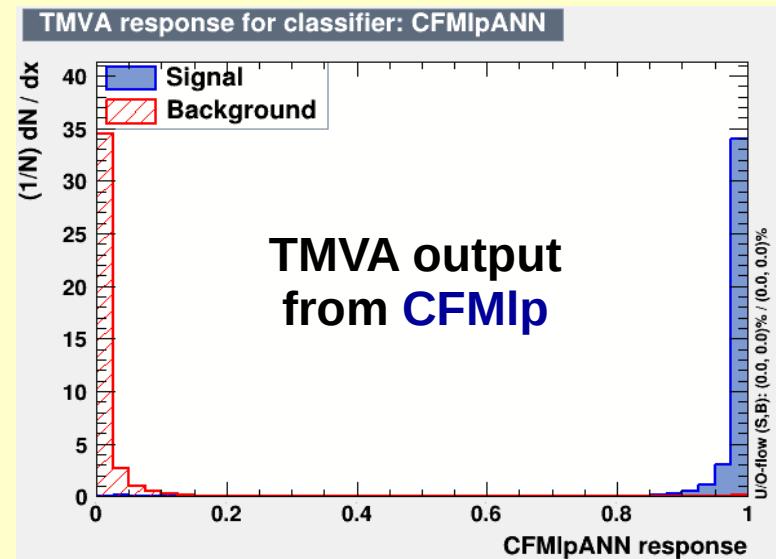
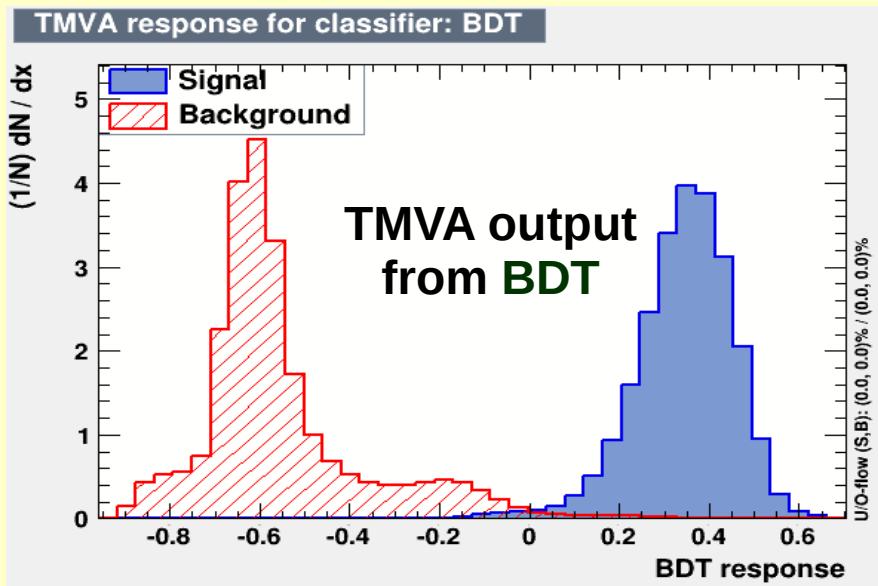
# Summary & Outlook

- **Simulation & Analysis** for beam momentum of 1.7 GeV/c (3.3 GeV/c):
  - *Signal:*  $p \bar{p} \rightarrow \mu^+ \mu^-$  **10<sup>6</sup> events**
  - *Background:*  $p \bar{p} \rightarrow \pi^+ \pi^-$  **10<sup>8</sup> events**
  - Analysis: Comparison of hard cuts and multivariate classification methods (TMVA toolkit in ROOT) for signal/background separation.
- **Hard Cuts:** Signal efficiency  $\sim 11.2\%$ , background suppression  $\sim 2 * 10^{-5}$
- **TMVA:** Signal efficiency  $\sim 10.1\%$ , background suppression  $\sim 2.5 * 10^{-6}$  could be obtained using MVA methods → Signal extraction by background subtraction might be possible.
- Optimization of MVA: Test of different sets of variables/cuts using different TMVA classification methods is under investigation

# Backup

### 3) Analysis: Multivariate data classification (Toolkit for Multivariate Analysis )

#### TMVA Classifier output distributions



**Decision Tree:** Sequential application of cuts splits the data into nodes, where the final nodes (leafs) classify an event as **signal** or **background**

**BDT:** Boosted Decision Tree: combine a forest of Decision Trees derived from the same sample, e.g. using different event weights.

**CFMlpANN:** Neural Network (Multilayer Perceptron)

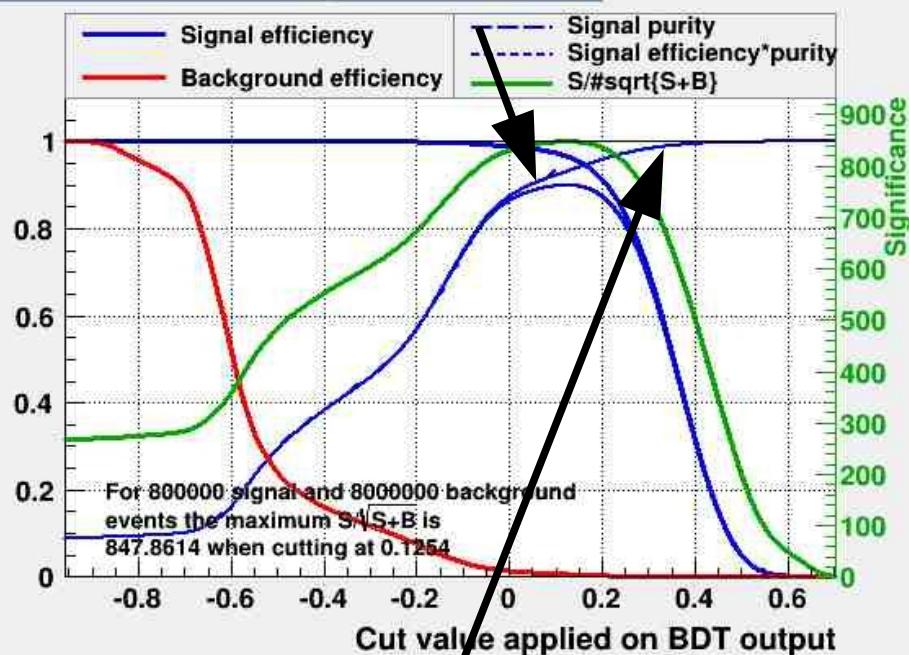
### 3) Analysis: Multivariate data classification (Toolkit for Multivariate Analysis )

Finding the optimal classification method & cut values

Cut efficiencies

Receiver operating characteristic (ROC curve)

Cut efficiencies and optimal cut value



High signal purity needed

Background rejection versus Signal efficiency

