Measurement of $\bar{p}p \to e^+e^-$ and $\bar{p}p \to e^+e^-\pi^0$ with $\overline{\text{P}}$ANDA Simulations with BaBar-like framework

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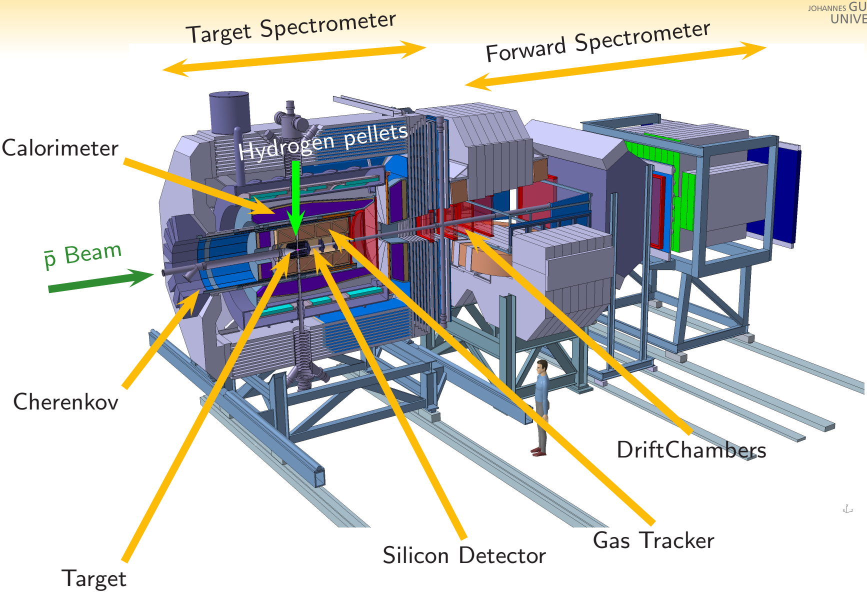
$\overline{\text{P}}$ANDA



$\overline{\text{P}}$ANDA challenges and capabilities

1.- Nucleon structure studies: Measurement of FF in time-like region.

2.- Study the validity of the TDA approach.

3.- Physics cases:

- Study of the signal channels: $\bar{p}p \to e^+e^-$ and $\bar{p}p \to e^+e^-\pi^0$.
- Main background channels: $\bar{p}p \to \pi^+\pi^- \to$ and $\bar{p}p \to \pi^+\pi^-\pi^0$ respectively.

  $\Rightarrow 10^6$ times higher than signal in average.
- Challenge: Good suppression of pions as background.

4.- $\overline{\text{P}}$ANDA Detector:

- High Luminosity: $L = 2 \cdot 10^{32}\,\text{cm}^{-2}\text{s}^{-1}$
- Good tracking system.
- Good PID capabilities.

$\boxed{\to \text{SIMULATION}}$

Electromagnetic Form Factors in time-like region

Electromagnetic Form Factors

Parameterize the hadronic current in the matrix element for elastic electron scattering and its crossed process annihilation.

Matrix element for e-p scattering:

$$M = \frac{e^2}{q^2}\bar{u}(k_2)\gamma^{\mu}u(k_1)\bar{u}(p_2)\left[F_1(q^2)\gamma_{\mu} + i\frac{\sigma_{\mu\nu}q^{\nu}}{2M}F_2(q^2)\right]u(p_1)$$

F_1: Dirac FF
F_2: Pauli FF

One can define the Sachs Form Factors as:

$$G_E = F_1 + \tau F_2 \qquad \text{where } \tau = \frac{q^2}{4M^2c^4}$$

$$G_M = F_1 + F_2$$

- G_E and G_M depend on transferred momentum, q^2.
- We are interested in the measurement of the Electromagnetic Form Factors, G_E and G_M in the time-like region.

Access to time-like form factors

We can access via the reactions $\bar{p}p \rightarrow \ell^+\ell^-$

Cross Section $\bar{p}p \rightarrow \ell^+\ell^-$

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2(\hbar c)^2}{8M_p\sqrt{\tau(\tau-1)}}\left[|G_m|^2\left(1+\cos^2\theta\right)+\frac{|G_e|^2}{\tau}\left(1-\cos^2\theta\right)\right]$$

- With high statistics one can measure the angular distribution.
- Knowing the luminosity one can calculate the diferential cross section.

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{L}\frac{d^2N}{dt\cdot d\cos\theta}$$

- The total cross section can be calculated from the total number of signal events.

Signal and background simulation

- Signal ($\bar{p}p \to e^+e^-$):
  - Using the cross section formula for three FF hypotheses:
    - $G_E = 0$
    - $G_E = G_M$
    - $G_E = 3 \cdot G_M$
  - Integrating for:
    - full luminosity ($\mathfrak{L} = 2 \cdot 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)
    - 10^7 s ($\sim$116 days) of measurement time

- Major Background ($\bar{p}p \to \pi^+\pi^-$):
  - The background cross section is not well known.
  - A symmetrized model fitting the existing experimental data has been done as imput for the simulation.
  - Background cross section known to be 10^6 times higher than the signal in average.
- Minor Background ($\bar{p}p \to \pi^0\pi^0$):
  - The π^0 can decay via Dalitz decay ($\pi^0 \to \gamma e^+e^-$) and give the same signature than the signal.
  - The probability of this possibility is of the order of 10^{-4} .

Number of events simulated

Signal:

10^6 events simulated at each energy for each hypothesis ($G_E = 0$, $G_E = G_M$ or $G_E = 3 \cdot G_M$)

For analysis:

$q^2 (GeV/c)^2$	Expected statistics
5.40	$1.07 \cdot 10^6$
7.43	$1.24 \cdot 10^5$
7.64	$1.03 \cdot 10^5$
8.20	$6.47 \cdot 10^4$
11.03	9078
12.90	3204
13.86	1985
16.69	572
22.29	81

Background:

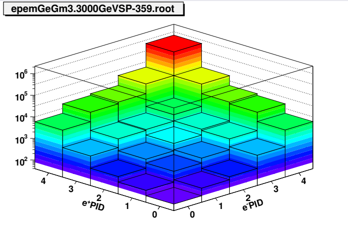
q^2 [$(GeV/c)^2$]	8.2	12.9	16.7
$\pi^+\pi^-$	10^8	10^8	$2 \cdot 10^8$
$\pi^0\pi^0 \to$			
$\gamma\gamma + \gamma\gamma$	10^6	10^6	10^6
$\gamma\gamma + \gamma e^+e^-$	10^6	10^6	10^6
$\gamma e^+e^- + \gamma e^+e^-$	10^6	10^6	10^6

1 event - 2 s cpu time $\to \approx$ 6 cpu years in only 1 machine for 1 channel background simulation.

Reaction reconstruction

Event selection: Combinations of e^+e^- candidates per event

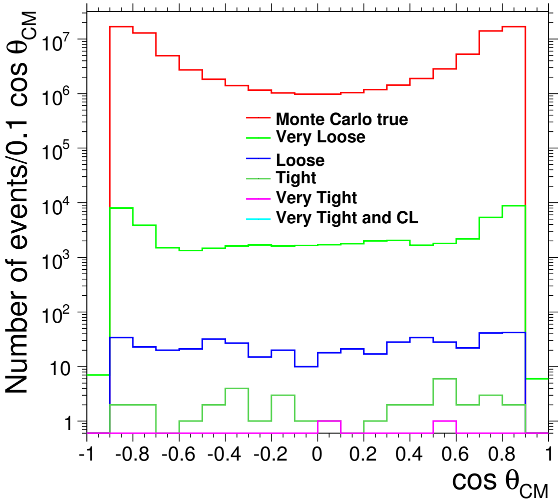
- PID cuts:



- (0) Charged particles
- (1) Very Loose (VL) $>$ 20%
- (2) Loose (L) $>$ 85%
- (3) Tight (T) $>$ 99%
- (4) Very Tight (VT) $>$ 99.8% + 10%/detector

- Kinematic fit cuts - (CL):
  - E and p have been measured for each track.
  - 4-constraints fit (E, p, m, r_0) performed with some particle hypothesis (e, μ, p, π and K).
  - Calculated the fit confidence level for each hypothesis.
    - $CL(e^+e^-) > 10 \cdot CL(\pi^+\pi^-)$
    - $CL(e^+e^-) > 10^{-3}$ $\rightarrow$ Necessary to suppress the whole π^0 background

Test of background suppression: $\bar{p}p \to \pi^+\pi^-$



$p = 3.3\,\text{GeV/c};\ q^2 = 8.2\,(\text{GeV/c})^2$

Angular distribution of charged pions:

Background suppression with cuts:

- PID constraints: 2 misidentified pions.
- CL and PID constraints: Background suppression of 10^8

Signal reconstruction efficiency

$G_e = G_m$; $p = 3.3\,\mathbf{GeV/c}$; $q^2 = 8.2\,\mathbf{(GeV/c)}^2$

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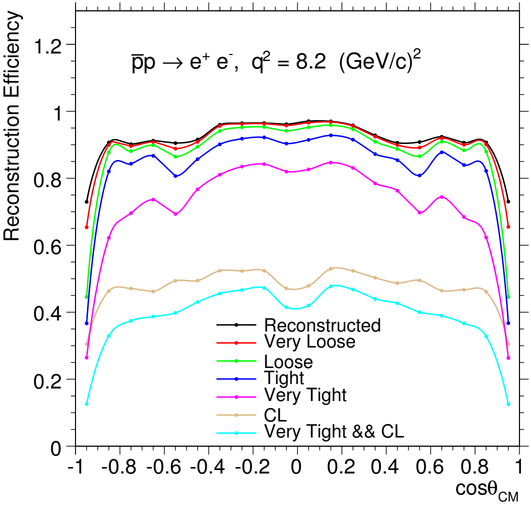
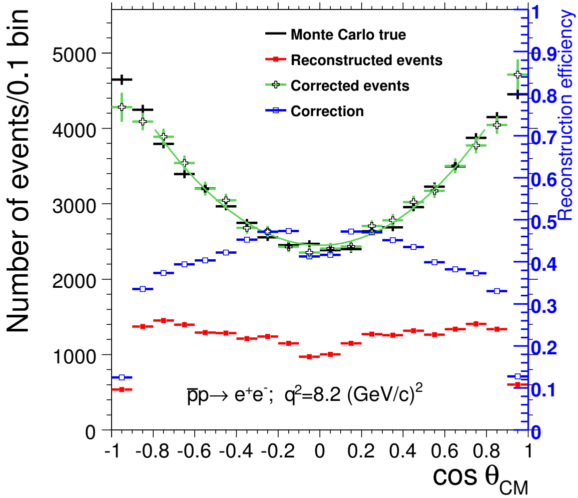


- PID cuts don't represent a big suppression in efficiency.
- CL cut represents about 50% of signal reduction.
- After combination of PID and CL cuts the efficiency is about 40%.

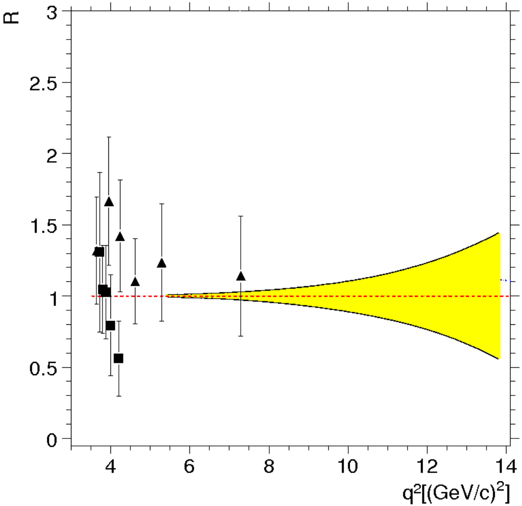
Signal angular distribution



$G_e = 0;$
$p = 3.3\,\mathrm{GeV/c};$
$q^2 = 8.2\,(\mathrm{GeV/c})^2$

- Realistic statistics: 64 000 events.
- Good angular distribution reconstruction after acceptance correction.
- The acceptance correction have been calculated using 1 000 000 events and isotropical distribution simulation.

Results for G_e/G_m

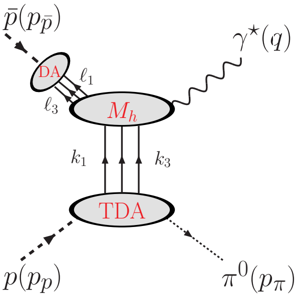


- Squares and triangles represent the values calculated in BABAR and PS170 experiments.
- Our results (for the case of $G_e = G_m$) will be distributed around the red horizontal dashed line.
- The error bars of our calculations (only statistical) are represented by the yellow band.
- The errors are a factor 10 smaller than those calculated up to now.

Validity of Transition Distribution Amplitudes (TDA)

Introduction to the TDA approach[a]:

[a] J. P. Lansberg et al., Phys Rev D 76, 111502(R) (2007)



- Transition Distribution Amplitudes new mathematic objects describing the transition between a barion and a meson.
- Useful to calculate cross sections of hard exclusive processes.
- Approach valid at higher energies.
- Study the validity of TDA approach: Measuring the cross section of $(\bar{p}p \to e^+e^-\pi^0)$ and comparing it with the theory.

Signal and background simulation

- Signal ($\bar{p}p \to e^+e^-\pi^0$)[a]:
  - W^2=5 GeV^2 and 10 GeV^2 (W^2=s)
  - π^0 Forward and Backward
    $\to$ 4 simulations
  - Theoretical cross section calculated for $\Delta_{T_{\pi^0}} = 0$...
  - ... integrating over a $\Delta_{T_{\pi^0}} < 0.5$ GeV and $[Q_{min}, Q_{max}]$[b]

[a] Based on J.P. Lansberg Phys Rev D 76, 111502(R) (2007)
[b] Values for Q_{min} and Q_{max} are shown later in slide 22

- Background ($\bar{p}p \to \pi^+\pi^-\pi^0$):
  - $\pi^+\pi^-\pi^0$ the same angular distribution as the signal.
  - We assume a background cross section 10^6 times higher than signal

Number of events simulated

	Reaction	W^2 (GeV^2)	π^0	N_{events}
Background suppression	$\pi^+\pi^-\pi^0$	5	forward	$\approx 10^8$
	$\pi^+\pi^-\pi^0$	5	backward	$\approx 10^8$
	$\pi^+\pi^-\pi^0$	10	forward	$\approx 10^8$
	$\pi^+\pi^-\pi^0$	10	backward	$\approx 10^8$
Efficiency studies	$e^+e^-\pi^0$	5	forward	$\approx 10^6$
	$e^+e^-\pi^0$	5	backward	$\approx 10^6$
	$e^+e^-\pi^0$	10	forward	$\approx 10^6$
	$e^+e^-\pi^0$	10	backward	$\approx 10^6$
Expected statistics	$e^+e^-\pi^0$	5	forward	150 000
	$e^+e^-\pi^0$	5	backward	150 000
	$e^+e^-\pi^0$	10	forward	6 000
	$e^+e^-\pi^0$	10	backward	6 000

Reaction reconstruction

Event selection: Combinations of $\pi^0 + e^+ + e^-$ candidates per event

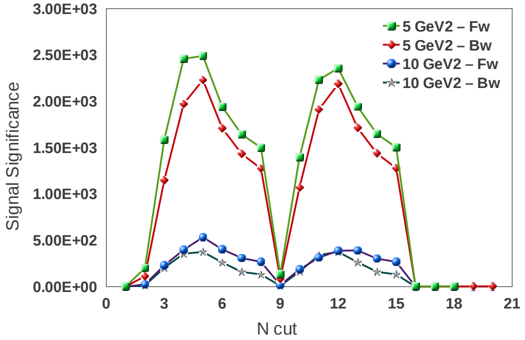
- Particle identification cuts (PID):
  - Only 2 tracks (+ and -) and very loose electrons (+ and -) per event
  - Only 2 tracks (+ and -) and loose electrons (+ and -) per event
  - Only 2 tracks (+ and -) and tight electrons (+ and -) per event
  - Only 2 tracks (+ and -) and very tight electrons (+ and -) per event
  - At least 2 tracks (+ and -) with 2 very loose electrons (+ and -) per event
  - At least 2 tracks (+ and -) with 2 loose electrons (+ and -) per event
  - At least 2 tracks (+ and -) with 2 tight electrons (+ and -) per event
  - At least 2 tracks (+ and -) with 2 very tight electrons (+ and -) per event

- Kinematic fit cuts - Confidence level (CL):
  - $\mathrm{CL}(e^{+/-}) > 10^{-3}$
  - $\mathrm{CL}(e^{+/-}) > 10^{-3}$ and $\mathrm{CL}(e^{+/-}) > \mathrm{CL}(\pi^{+/-})$
  - $\mathrm{CL}(e^{+/-}) > 10^{-3}$ and $\mathrm{CL}(e^{+/-}) > 2 \cdot \mathrm{CL}(\pi^{+/-})$
  - $\mathrm{CL}(e^{+/-}) > 10^{-3}$ and $\mathrm{CL}(e^{+/-}) > 3 \cdot \mathrm{CL}(\pi^{+/-})$

Kinematic region selection (Only for analysis)

- Q^2 cuts in the region in which the cross section is integrated
- $\Delta_{T_{\pi^0}} < 0.5\,\mathrm{GeV}$

Best Cut Selection



Best cut maximizes the
Signal Significance

$$S_{Sg} = \frac{N^{Sg}_{Cut}}{\sqrt{N^{Sg}_{Cut} + N^{Bg}_{Cut}}}$$

$$\mathrm{Eff}_{Bg} = \frac{N^{Bg}_{Cut}}{N^{Bg}_{True}};\ \mathrm{Eff}_{Sg} = \frac{N^{Sg}_{Cut}}{N^{Sg}_{True}};$$

$$N^{Sg}_{True} = 10^6 \cdot N^{Bg}_{True}$$

$$S_{Sg} = \frac{\mathrm{Eff}_{Sg} \cdot N^{Sg}_{True}}{\sqrt{\mathrm{Eff}_{Sg} \cdot N^{Sg}_{True} + \mathrm{Eff}_{Bg} \cdot \frac{N^{Sg}_{True}}{10^6}}}$$

Best cut: $N_{cut} = 5$
Only 2 tracks (+ and -) and very tight electrons (+ and -) per event

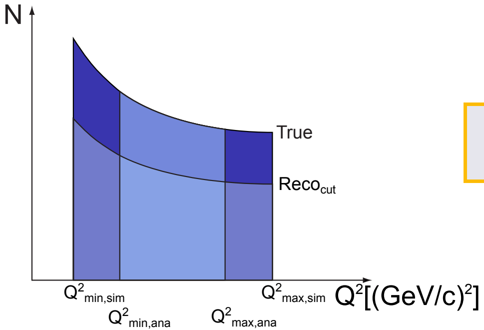
Background contamination fraction

W^2	Forward		Backward	
	Signal	Background	Signal	Background
	Expected number of true events (Calculated)			
	N^{Sg}_{True}	N^{Bg}_{True}	N^{Sg}_{True}	N^{Bg}_{True}
5	150000	$1.5 \cdot 10^{11}$	150000	$1.5 \cdot 10^{11}$
10	6000	$6 \cdot 10^{9}$	6000	$6 \cdot 10^{9}$
	Efficiencies [%] (From Simulations with high statistics)			
	Eff_{Sg}	Eff_{Bg}	Eff_{Sg}	Eff_{Bg}
5	43.28 ± 0.05	$(2.0 \pm 1.8) \cdot 10^{-6}$	34.09 ± 0.05	$(1.0 \pm 1.4) \cdot 10^{-6}$
10	47.24 ± 0.05	$(0.9 \pm 1.3) \cdot 10^{-6}$	26.04 ± 0.04	$(2.8 \pm 1.9) \cdot 10^{-6}$
	Reconstructed events after efficiencies (True·Efficiency)			
	N^{Sg}_{Reco}	N^{Bg}_{Reco}	N^{Sg}_{Reco}	N^{Bg}_{Reco}
5	64916	3023	51134	1449
10	2834	55	1562	166
	Background Contamination [%] $\left(\frac{N^{Bg}_{Reco}}{N^{Bg}_{Reco}+N^{Sg}_{Reco}}\right)$			
	$\mathrm{Cont}_{Bg,\,Fw}$		$\mathrm{Cont}_{Bg,\,Bw}$	
5	4.4 ± 3.7		2.8 ± 3.8	
10	1.9 ± 2.7		9.6 ± 5.8	

Kinematic region cuts

	$W^2 = 5\,\mathrm{GeV}^2$	$W^2 = 10\,\mathrm{GeV}^2$
Simulation limits	$3.61 < Q^2 < 5.29$	$5.76 < Q^2 < 9.18$
Analysis limits	$3.8 < Q^2 < 4.2$	$7.00 < Q^2 < 8.00$

In addition: $\Delta_{T_{\pi^0}} < 0.5\,\mathrm{GeV}$



$$\mathrm{Corr} = \frac{\mathrm{N_{Reco}}[Q^2_{\text{min, ana}}, Q^2_{\text{max, ana}}]}{\mathrm{N_{True}}[Q^2_{\text{min, ana}}, Q^2_{\text{max, ana}}]}$$

Analysis without taking background contamination into account

Selection cut

Only 2 tracks (+ and -) and very tight electrons (+ and -) per event

Kinematic region cut

$3.8 < Q^2 < 4.2$ at $W^2 = 5\,\mathrm{GeV}^2$;
$7.00 < Q^2 < 8.00$ at $W^2 = 10\,\mathrm{GeV}^2$;
$\Delta_{T_{\pi^0}} < 0.5\,\mathrm{GeV}$

Simulation	$N_{True\ \mathrm{w/o}\ Bg}$	$N_{Reconstructed\ \mathrm{w/o}\ Bg}$	$N_{Corrected\ \mathrm{w/o}\ Bg}$	$\epsilon_{rel}[\%]$
5 GeV - fw	72263 ±269	30661 ± 175	72732 ± 433	0.6
5 GeV - bw	72405 ±269	25386 ± 159	73164 ± 488	0.7
10 GeV - fw	1336 ±37	662 ± 26	1319 ± 51	3.9
10 GeV - bw	1313 ± 36	394 ± 20	1312 ± 66	5.0

Analysis taking background contamination fraction into account

$$\boxed{N_{Reconstructed} = N_{Background\ fraction} + N_{Reconstructed\ \text{w/o}\ Bg}}$$

Simulation	$N_{Reconstructed}$	$N_{Signal\ fraction}$	$\epsilon_{rel}(N_{Signal\ fraction})[\%]$
5fw	31967 ± 179	30544 ± 1190	4
5bw	26067 ± 162	25348 ± 1601	4
10fw	674 ± 26	661 ± 31	5
10bw	429 ± 21	387 ± 31	8
		$N_{Corrected}$	$\epsilon_{rel}(N_{Corrected})[\%]$
5fw		72454 ± 2825	4
5bw		73055 ± 2889	4
10fw		1317 ± 62	5
10bw		1289 ± 104	8

Conclusions

- $\bar{p}p \to e^+e^-$
  - The measurement of this reaction with $\overline{\text{P}}$ANDA is feasible.
  - A separation of G_E and G_M will be possible.
  - The error bars are improved in a factor 10 with respect to other experiments.

- $\bar{p}p \to e^+e^-\pi^0$
  - The first results are promising and show that the reaction would be measurable with $\overline{\text{P}}$ANDA.
  - A first sight on the TDAs will be possible.

  ## Outlook:
  - More realistic event generators for signal and background are needed.


Thank you!

Cut number definitions

1 : No additional cuts, only event selection cuts involved
2 : Only one electron and one positron (2 tracks) with Very Loose probability.
3 : Only one electron and one positron (2 tracks) with Loose probability.
4 : Only one electron and one positron (2 tracks) with Tight probability.
5 : Only one electron and one positron (2 tracks) with Very Tight probability.
6 : Cut 5 and Cut 17
7 : Cut 5 and Cut 18
8 : Cut 5 and Cut 19
9 : At least one electron and one positron with Very Loose probability.
10 : At least one electron and one positron with Loose probability.
11 : At least one electron and one positron with Tight probability.
12 : At least one electron and one positron with Very Tight probability.
13 : Cut 12 and Cut 17
14 : Cut 12 and Cut 18
15 : Cut 12 and Cut 19
16 : Confidence level for the fit with $e^+e^-\pi^0$ hypothesis greater than 10^-3
17 : Cut 16 and Confidence level for the fit with $e^+e^-\pi^0$ hypothesis greater than the confidence level of the fit with $\pi^+\pi^-\pi^0$ hypothesis
18 : Cut 16 and Confidence level for the fit with $e^+e^-\pi^0$ hypothesis greater than two times the confidence level of the fit with $\pi^+\pi^-\pi^0$ hypothesis
19 : Cut 16 and Confidence level for the fit with $e^+e^-\pi^0$ hypothesis greater than three times the confidence level of the fit with $\pi^+\pi^-\pi^0$ hypothesis
20 : Cut 16 and Confidence level for the fit with $e^+e^-\pi^0$ hypothesis greater than four times the confidence level of the fit with $\pi^+\pi^-\pi^0$ hypothe