A SEARCH FOR AN EXOTIC Θ^+ BARYON IN INCLUSIVE NEUTRINO-NUCLEON INTERACTIONS IN THE NOMAD EXPERIMENT

Vincenzo Cavasinni [a], Dmitry Naumov [b], **Oleg Samoylov** [b]
(on behalf of the NOMAD Collaboration)

[a] Univ. of Pisa and INFN, Pisa, Italy
[b] JINR, Dubna, Russia

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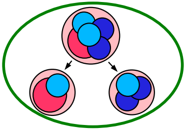

Outline

1. Introduction
   - Motivation of searches
   - Experimental review
   - NOMAD experiment
2. Analysis tools
   - Particles identification
   - What we can get from NOMAD data
   - The Background Estimation
   - Invariant Mass Resolution
   - ”Sensetive” analysis strategy
   - Statistical analysis
   - Results
3. Conclusions

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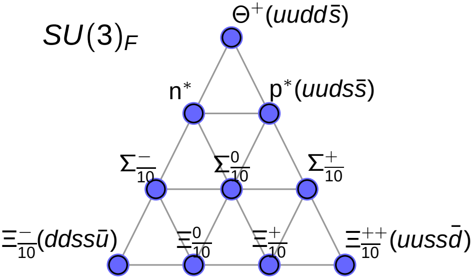
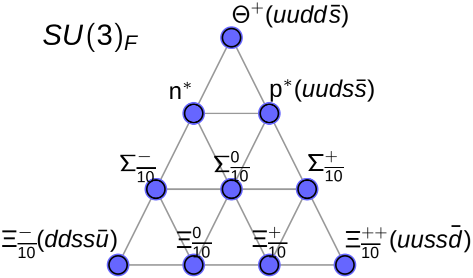


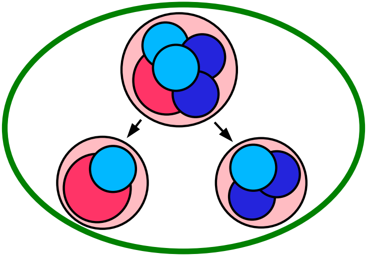
Quark Model

1. $M_\Theta \simeq 2m_u + 2m_d + m_s \simeq$ $\simeq 4 \cdot 300$ MeV $+ 500$ MeV $=$ $= 1700$ MeV
2. $\Gamma_\Theta \simeq \Gamma_\Delta \simeq 100$ MeV

Soliton Model (1997 Diakonov at al.)

1. Low Mass: $M_\Theta = 1530$ MeV
2. Narrow Width: $\Gamma_\Theta \lesssim 15$ MeV





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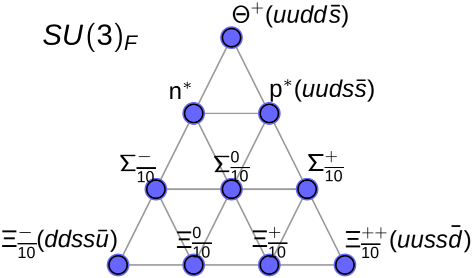

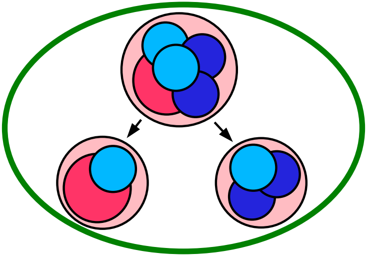

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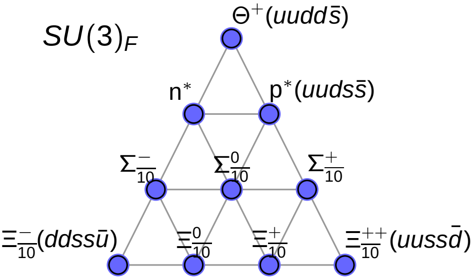

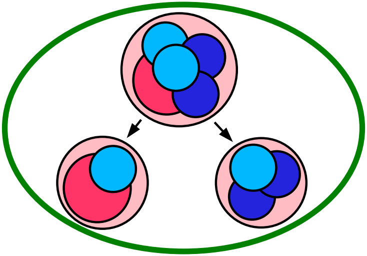

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Positive Signals for Θ^+

Experiment	Reaction	Mode	S	B	Sign. Pub.	$\frac{S}{\sqrt{B}}$	$\frac{S}{\sqrt{B+S}}$
LEPS(1)	$\gamma C_{12} \to K^+K^-X$	nK^+	19	17	4.6	4.6	3.2
LEPS(2)	$\gamma d \to K^+K^-X$	nK^+	56	162	-	4.4	3.8
CLAS(d)	$\gamma d \to K^+K^-np$	nK^+	43	54	5.2	5.9	4.4
CLAS(p)	$\gamma p \to K^+K^-n\pi^+$	nK^+	42	35	7.8	6.9	4.7
SAPHIR	$\gamma p \to K_S^0K^+n$	nK^+	55	56	4.8	7.3	5.2
COSY	$pp \to \Sigma^+K_S^0p$	pK_S^0	57	95	4-6	5.9	4.7
JINR	$p(C_3H_8) \to K_S^0pX$	pK_S^0	88	192	5.5	6.4	5.3
SVD	$pA \to K_S^0pX$	pK_S^0	35	93	5.6	3.6	3.1
DIANA	$K^+Xe \to K_S^0pXe'$	pK_S^0	29	44	4.4	4.4	3.4
νBC	$\nu A \to K_S^0pX$	pK_S^0	19	8	6.7	6.7	3.7
HERMES	quasi-real photoproduction	pK_S^0	51	150	4.3-6.2	4.2	3.6
ZEUS	$ep \to K_S^0pX$	pK_S^0	230	2080	4.6	7.0	6.4

1. Experiments with various beams
2. Both Decay Modes of Θ^+
3. Small Statistics: $\lesssim$ 100 Signal Events
4. Statistical Significance ranging from 4 to 7 σ

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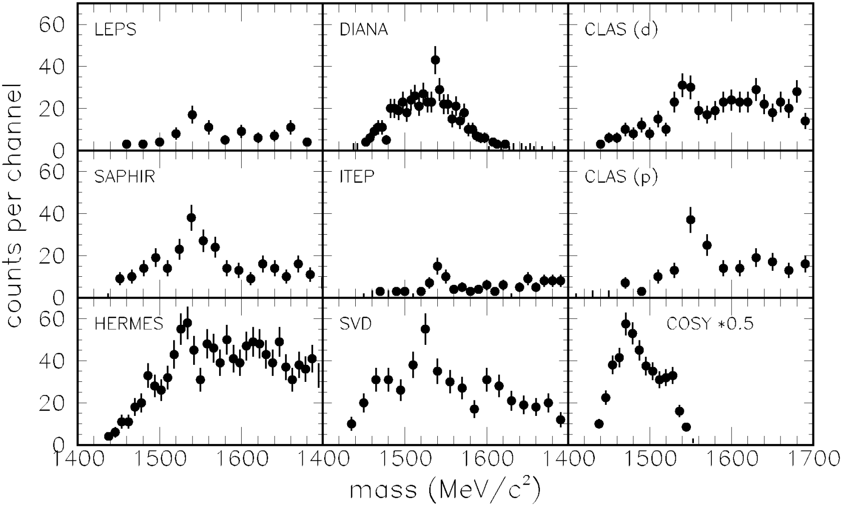

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PDG 2004

EXOTIC BARYONS

Minimum quark content: $\Theta^+ = uudd\bar{s}$, $\Phi^{--} = ssdd\bar{u}$, $\Phi^+ = ssuu\bar{d}$.

$\Theta(1540)^+$ $I(J^P) = 0(?^?)$

It is difficult to deny a place in the Summary Tables for a state that six experiments claim to have seen. Nevertheless, we believe it reasonable to have some reservations about the existence of this state on the basis of the present evidence.

Mass $m = 1539.2 \pm 1.6$ MeV
Full width $\Gamma = 0.90 \pm 0.30$ MeV

NK is the only strong decay mode allowed for a strangeness S=+1 resonance of this mass.

$\Theta(1540)^+$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)

Negative Results of Searches for Θ^+

Experiment	Reaction	Experiment	Reaction
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BELLE	$KN \to PX$	BES	$e^+e^- \to J/\psi(\psi(2S) \to \theta\bar{\theta})$
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DELPHI	Hardronic Z dacays	E690	$pp \to PX$
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L3	$\gamma\gamma \to \theta\bar{\theta}$	PHENIX	$AuAu \to PX$
SELEX	$(\pi, p, \Sigma)p \to PX$	SPHINX	$pC(N) \to \theta^+C(N)$

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2. No signal

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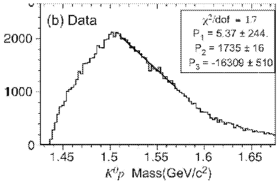

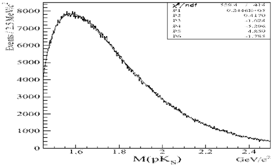

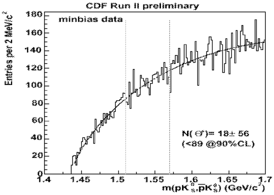

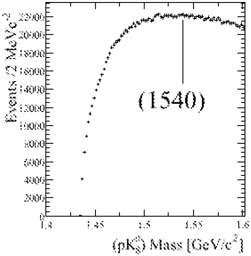

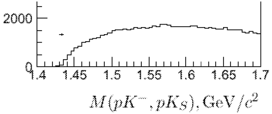

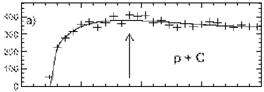

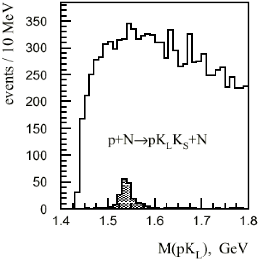

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PDG 2005

$\Theta(1540)^+$ $I(J^P) = 0(?^?)$ Status: $**$

A REVIEW GOES HERE – Check our WWW List of Reviews

$\Theta(1540)^+$ MASS

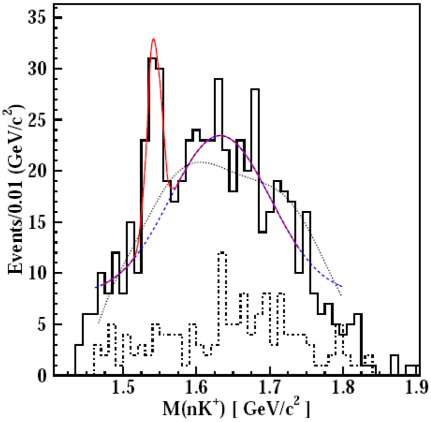
As is done through the *Review*, papers are listed by year, with the latest year first, and within each year they are listed alphabetically. NAKANO 03 was the earliest paper.

Since our 2004 edition, there have been several new claimed sightings of the $\Theta(1540)^+$ (see entries below marked with bars to the right), but there have also been several searches with negative results:

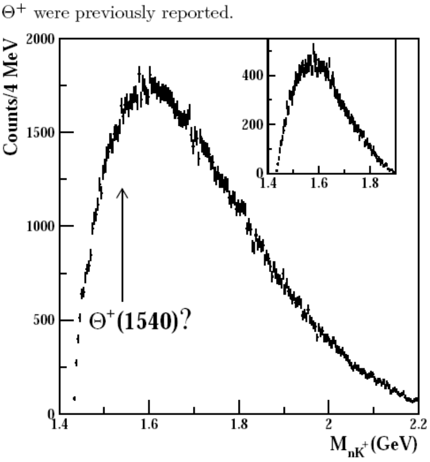
- ANTIPOV 04 (SPHINX Collab.) in $pN \to (nK^+, pK^0_S,$ or $pK^0_L)\ \overline{K}^0 N$ in proton–carbon reactions at 70 GeV/c;
- BAI 04G (BES Collab.) in J/ψ and $\psi(2S)$ decays;
- SCHAEL 04 (ALEPH Collab.) in Z decays;
- ABT 04A (HERA-B Collab.) in p nucleus reactions at midrapidity and $\sqrt{s}$=41.6 GeV;
- LONGO 04 (HyperCP Collab.) in interactions of a high-energy beam of π^+, K^+, p, and charged hyperons with tungsten.

In general, these experiments with negative results have many more events than do the experiments with positive results. (Against this, however, it may be argued that the recent negative results are often from experiments with different reactions or at different energies from the experiments with positive results.)

Furthermore, the $\Theta(1540)^+$ finds almost no support from the claimed observations of other pentaquarks, the $\Phi(1860)$ and the $\Theta_c(3100)$, for which the evidence is very weak. (See the Listings following the $\Theta(1540)^+$.) Thus we have reduced the status of the $\Theta(1540)^+$ to two stars.

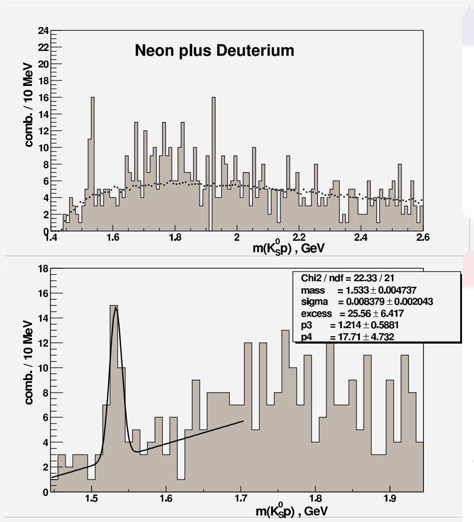


CLAS Results 2003



CLAS Results 2005

ANALYSIS OF ITEP GROUP ON νN IN BUBBLE CHAMBER



THEY PUBLISHED

1. Signal and Background Events: $S = 19$, $B = 8$
2. Significance: 6.7σ
3. Appearance: $N_\Theta = C \cdot 10^{-3} N_\nu$

NOTATIONS

1. $\sqrt{19}/\sqrt{8} = 6.7$
2. $\sqrt{19}/\sqrt{8+19} = 3.7$
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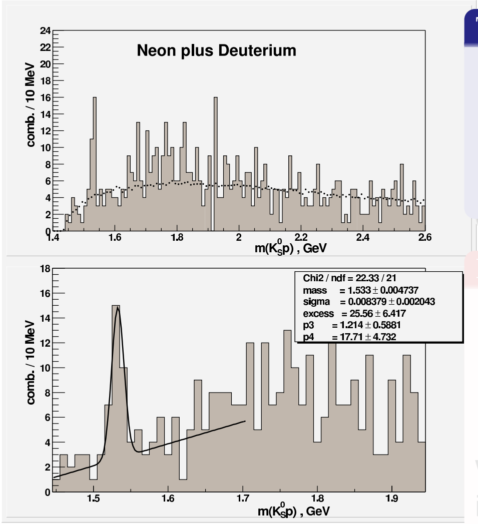
We have 1500k neutrino events instead of 113k of the ITEP group.

Analysis of ITEP group on νN in Bubble Chamber



They published

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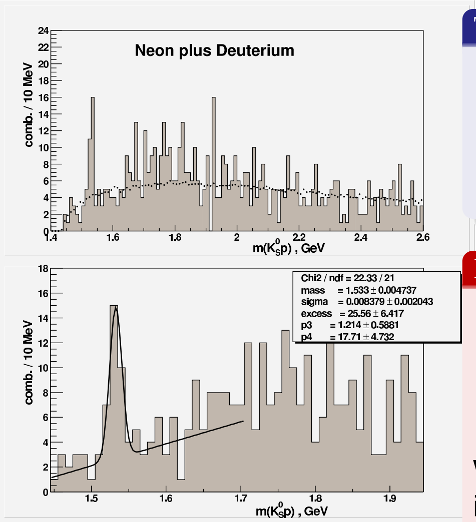

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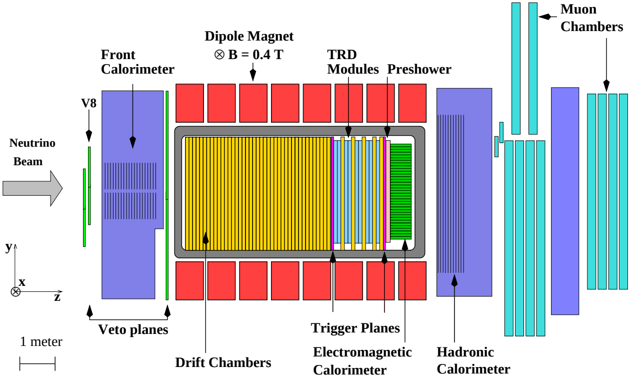

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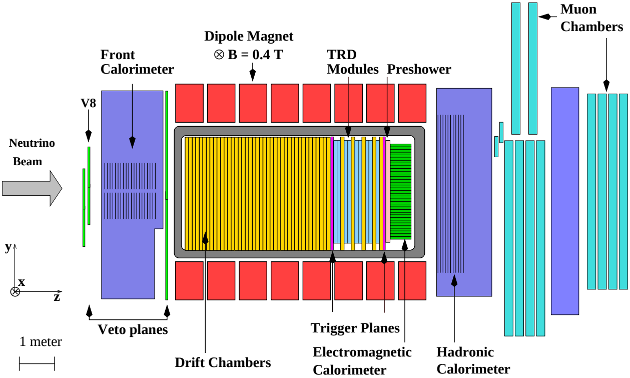

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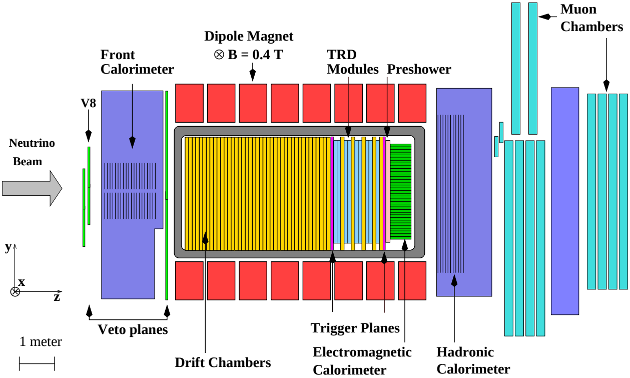

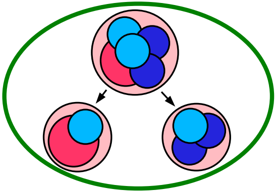

$$\Theta^+ \to pK^0_S$$
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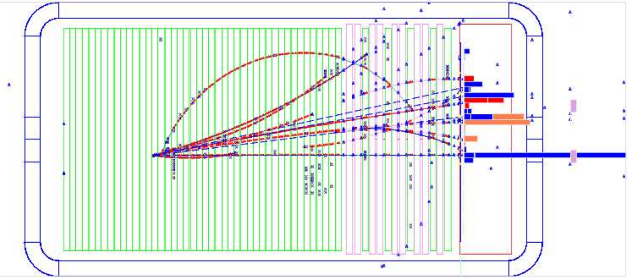
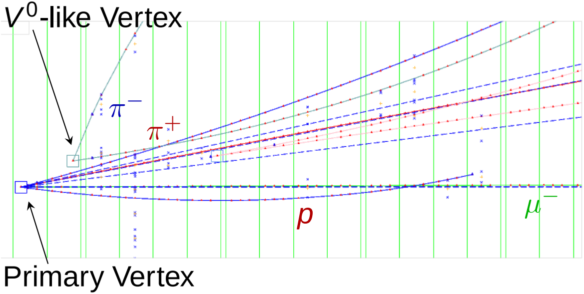
Θ^+ CANDIDATE





Event's information:

- $E_\nu = 106.9$GeV
- $E_\mu = 73.1$GeV
- $p_p = 492$MeV/c
- $p_K = 764$MeV/c
  $p_{\pi^+} = 581$MeV/c
  $p_{\pi^-} = 284$MeV/c
- $M_{inv}(pK) = 1535$MeV/c^2

OUTLINE

1 INTRODUCTION
- Motivation of searches
- Experimental review
- NOMAD experiment

2 ANALYSIS TOOLS
- Particles identification
- What we can get from NOMAD data
- The Background Estimation
- Invariant Mass Resolution
- ”Sensetive” analysis strategy
- Statistical analysis
- Results

3 CONCLUSIONS

"Blind analysis" strategy

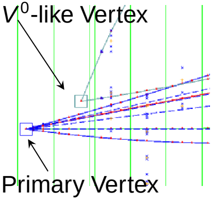
"Blind" analysis

1. Particles identification
2. Estimation of Signal events from NOMAD data
3. The Background calculation
4. Invariant Mass Resolution
5. Finding of selection criteria to most sensitive for Θ^+ search
6. Statistical analysis

"Opening the Box"

1. The Results.
2. Conclusions, Discussions ...

K_S^0 identification from the Kinematic Fit



Kinematic Fit procedure

1. V^0-like vertex can be: $K_S^0 \to \pi^+\pi^-$, $\Lambda \to p\pi^-$, $\bar{\Lambda} \to \pi^+\bar{p}$, $\gamma \to e^+e^-$.
2. The NOMAD experiment does not contain a dedicated detector for proton identification.
3. We computed $\chi^2_\alpha = \chi^2_0(g - f) + \sum_i 2\lambda_i F_i(g, p_\alpha)$

   f - a vector of the reconstructed parameters (momenta, angles), g - a vector of the fitted parameters, p_α - a four-vector of the decaying particle α, F_i- a vector of the momentum-energy conservation.

Reconstructed $K_S^0 \to \pi^+\pi^-$ invariant mass distribution in the ν_μ CC (left) and ν_μ NC (right) sets of the data.

We identify

1. ~ 23.6 kK_S^0 (both in CC and NC);
2. $M = 497.9$MeV/c^2;
3. $\sigma = 9.5$MeV/c^2;
4. Efficiency of 24%;
5. Purity of 97%.

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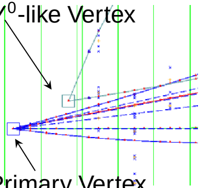

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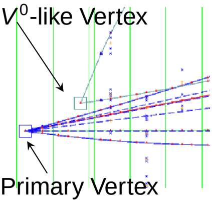

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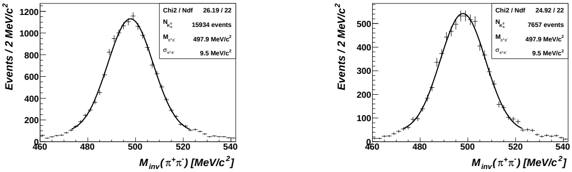

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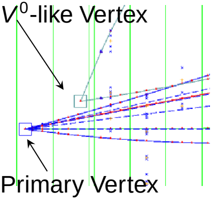

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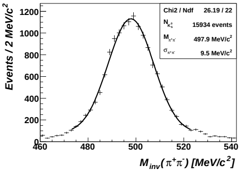

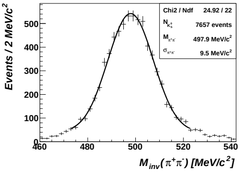

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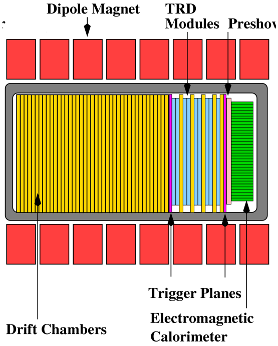
PROTON IDENTIFICATION BY LIKELIHOOD FUNCTIONS



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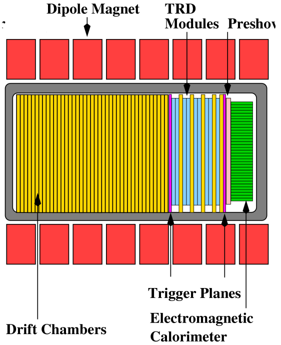

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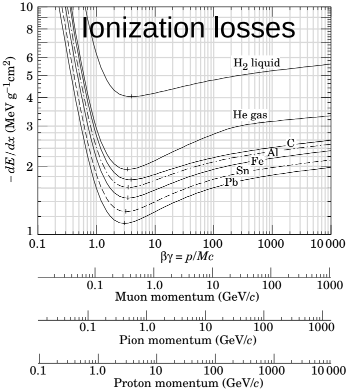

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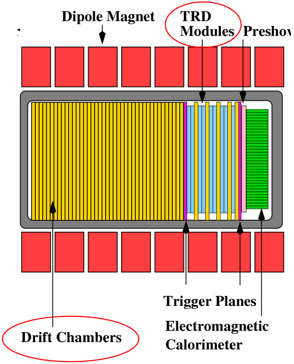

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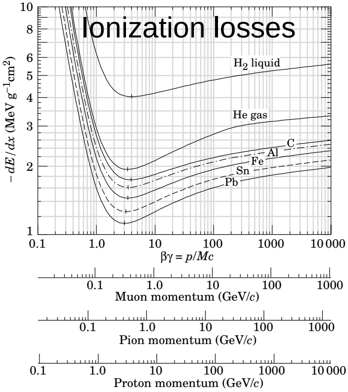

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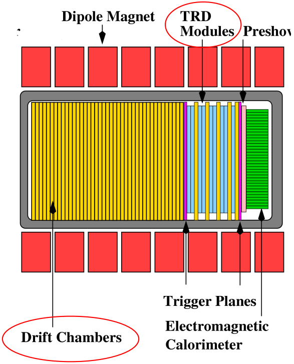

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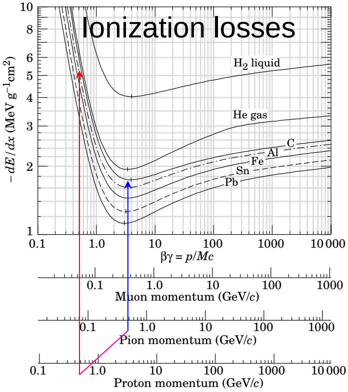

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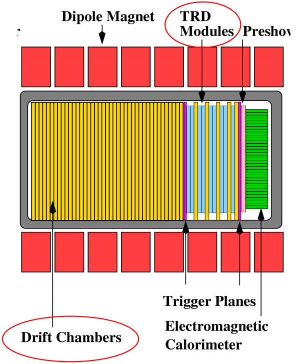

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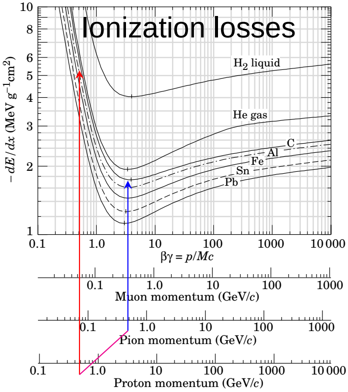

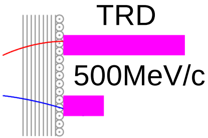

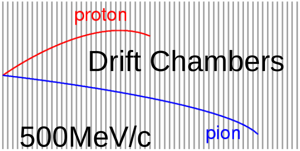

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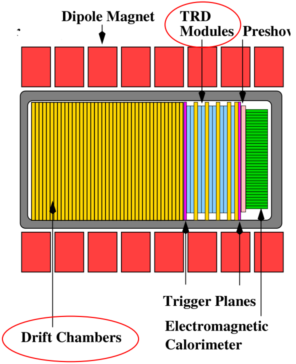

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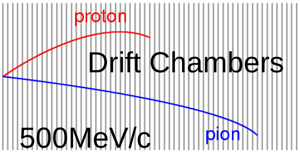

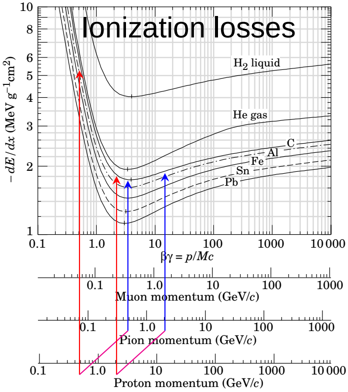

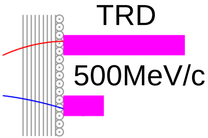

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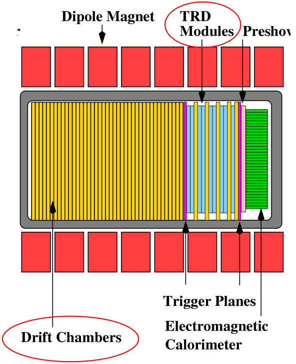

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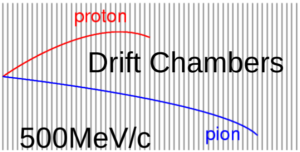

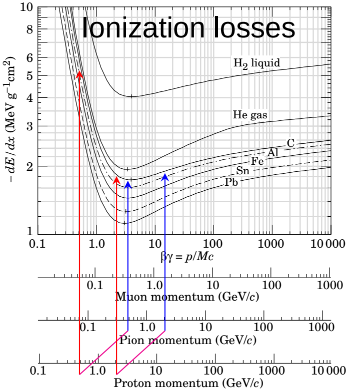

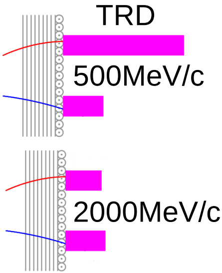

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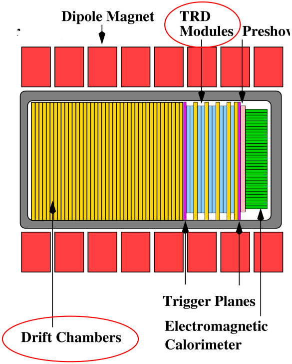

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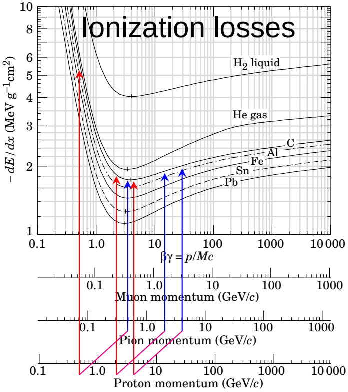

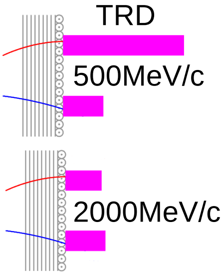

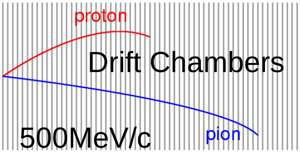

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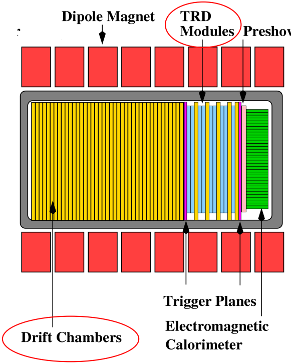

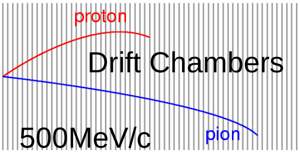

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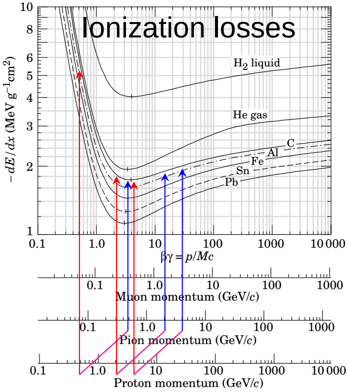

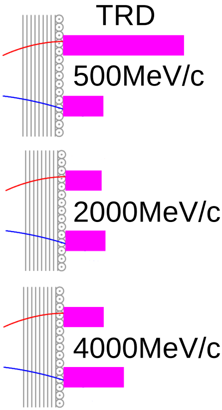

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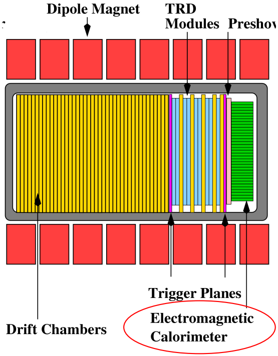

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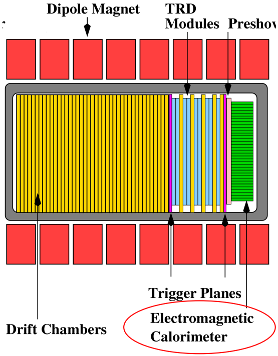

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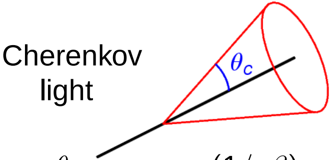

$$\theta_C = \arccos(1/n\beta)$$

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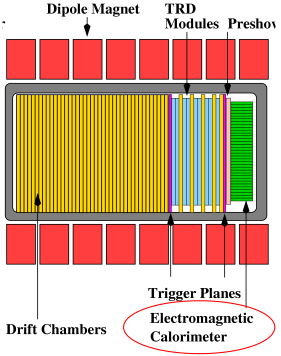

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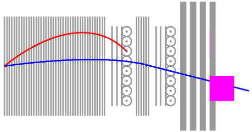
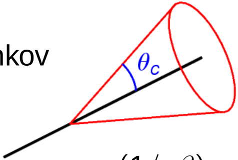


500MeV/c

Cherenkov light



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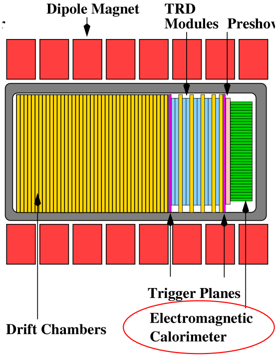

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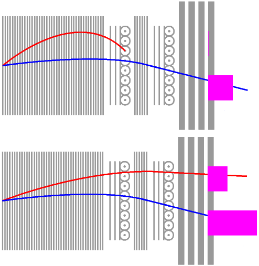

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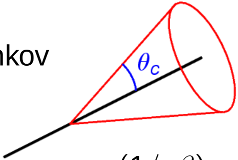
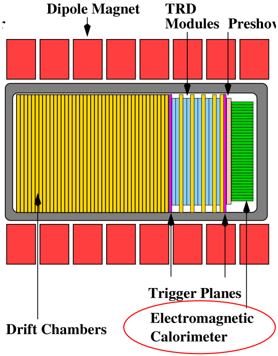
2000MeV/c

Cherenkov light

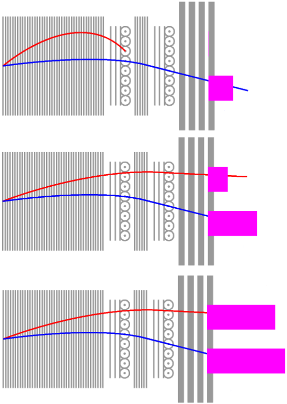


$$\theta_C = \arccos(1/n\beta)$$

Proton identification by Likelihood functions



NOMAD experiment does not contain a dedicated detector for proton identification, but a substantial rejection against pions can be obtained using:

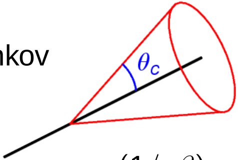


500MeV/c

2000MeV/c

4000MeV/c

Cherenkov light



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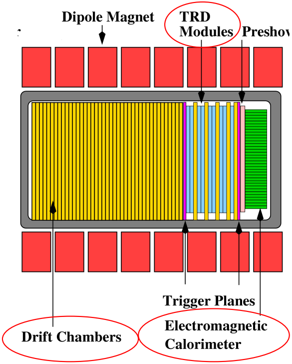
PROTON IDENTIFICATION BY LIKELIHOOD FUNCTIONS



CLEANEST PROTON SAMPLE IS GOTTEN

1. The Drift Chambers (DC): at a given momentum protons range out faster than pions, usable for $p < 1000$MeV/c;
2. The Transition Radiation Detector (TRD): at $0.4 < p < 1.6$GeV/c proton ionization loss larger than that of pions;
3. The Electromagnetic Calorimeter (ECAL): difference of Cherenkov light emitted by protons and pions: useful for $1 < p < 3$GeV/c.

LIKELIHOOD FUNCTIONS

1. We constructed three Likelihood functions for three detectors: $\mathrm{Lh}_{DC}(L, p)$, $\mathrm{Lh}_{TRD}(<\epsilon>, p)$, $\mathrm{Lh}_{ECAL}(\epsilon, p)$

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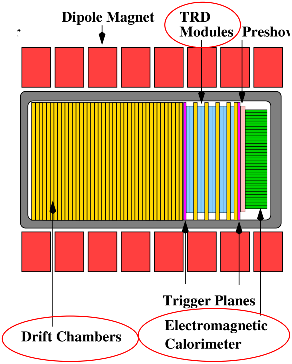

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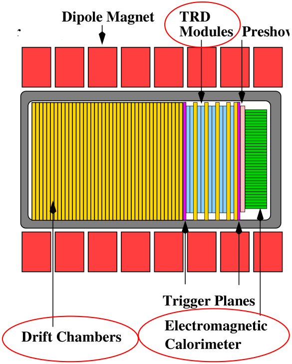

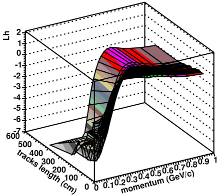

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Comparison with ITEP group results

Experiment Chamber Fill	WA21 BEBC Hydrogen	WA25 BEBC Deuterium	WA59 BEBC Neon–H_2	E180 15' B.C. Neon–H_2	E632 15' B.C. Neon–H_2
Neutrinos:					
Mean E_ν, GeV	48.8	51.8	56.8	52.2	136.8
Mean momentum of detected K^0_S, GeV	5.7	5.7	4.5	3.4	7.7
All measured CC events	18746	26323	9753	882	5621
CC events with K^0_S	1050	1279	561	21	587
CC events with K^0_S and identified protons	82 (78)	307 (128)	193 (193)	9 (8)	229 (157)
Antineutrinos:					
Mean E_ν, GeV	37.5	37.9	39.5	33.8	110.0
Mean momentum of detected K^0_S, GeV	4.2	4.2	3.5	3.4	7.6
All measured CC events	13155	16314	15693	5927	1190
CC events with K^0_S	702	761	631	231	123
CC events with K^0_S and identified protons	45 (43)	116 (57)	185 (185)	56 (54)	49 (28)

	ITEP	NOMAD
N_{ν_μ}	113k	1500k
$N_{K^0_S}$	5946	23591
$N_{pK^0_S}$	1271	12k
N_{Θ^+}	19	$\simeq 200$

We studied this background in three different ways:

1. MC events contain no Θ^+.
   This requires a large sample of MC events to reduce statistical fluctuations and depends on a used model.
2. Fake-pair technique: combinations protons and K_S^0's from different events in the data.
   It reproduces data distributions such as a resolution, an efficiency, an acceptance. But it also can bias the data. We solved this problem paying special attention that ...
3. A polynomial fit to the M distribution of the data themselves, excluding the Θ^+ mass region, can also be used to describe the background for the Θ^+ search.
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Fake Pair Technique

$$M_{inv}^2 = m_1^2 + m_2^2 + 2(\mathbf{E_1}\mathbf{E_2} - \mathbf{p_1}\mathbf{p_2}\ cos\theta)$$

We take into account

1. Magnitude and direction of the hadronic jet momentum
2. Momentum and Angular distributions of decays particles
3. Multiplicity of decays particles

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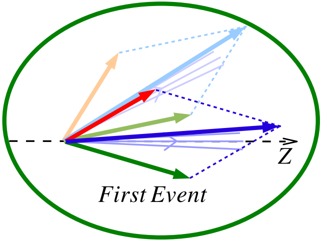

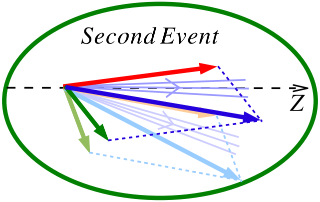

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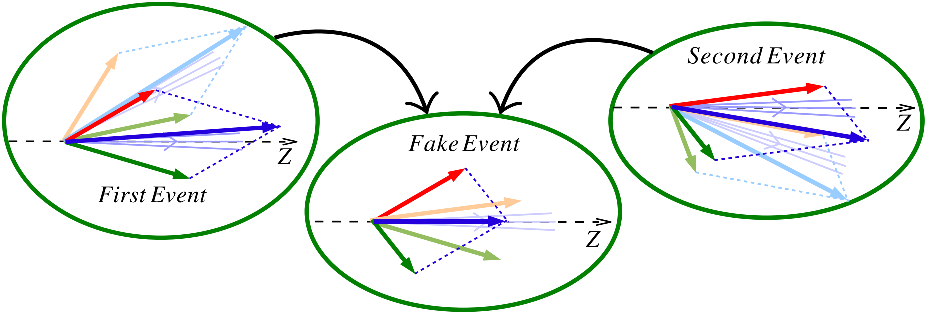

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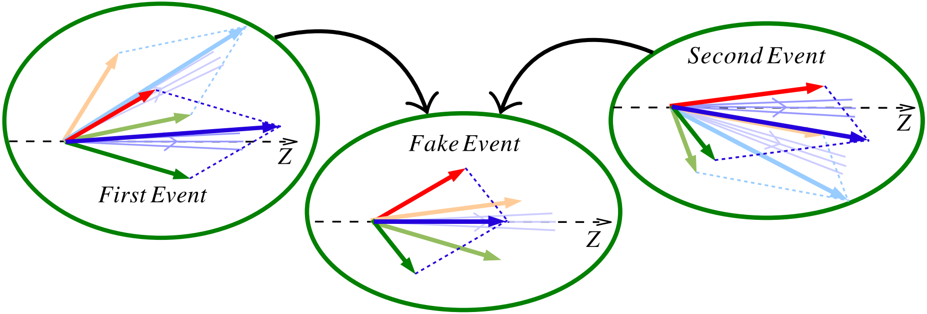

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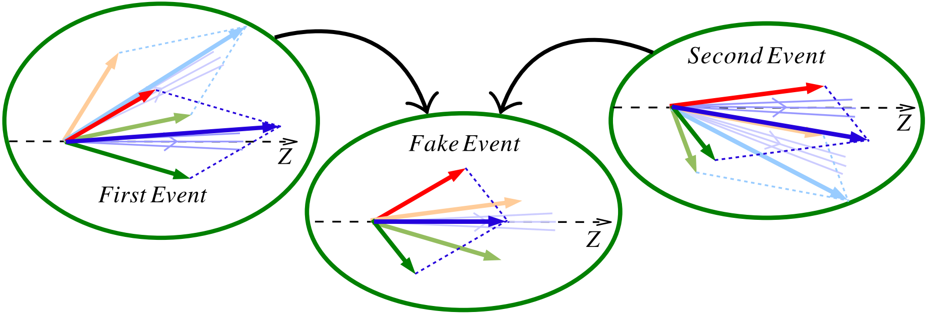

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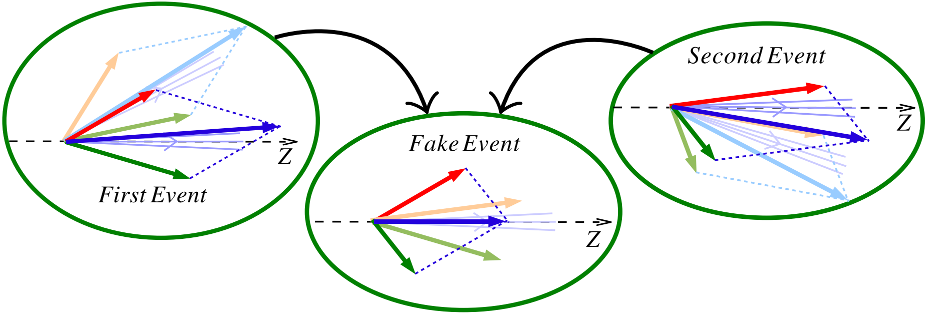

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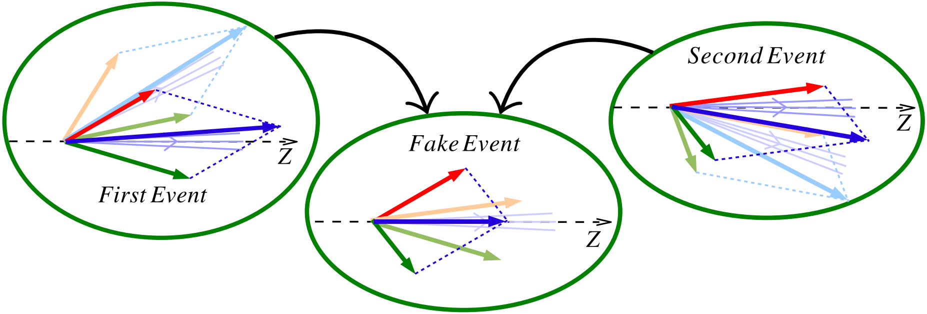

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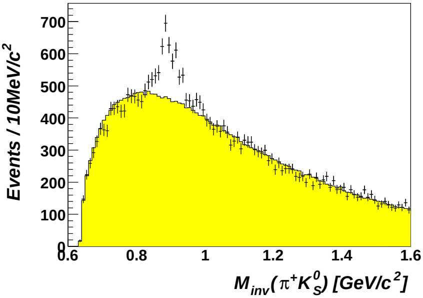
Fake Pair Technique

Check on $K^* \to \pi^+ K^0$ resonance

1. Clear K^* peak and good agreement with the Background



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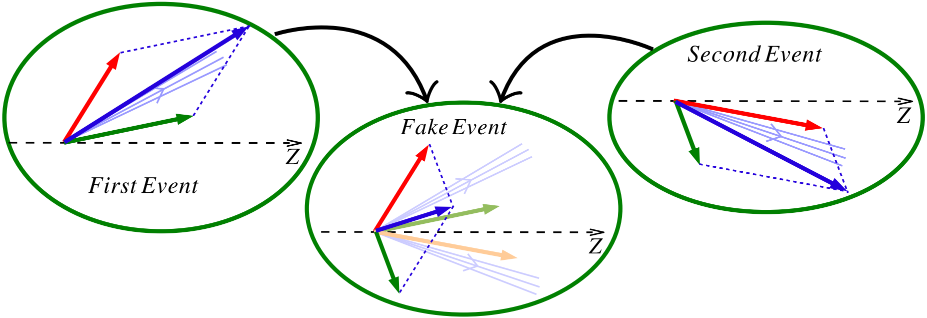


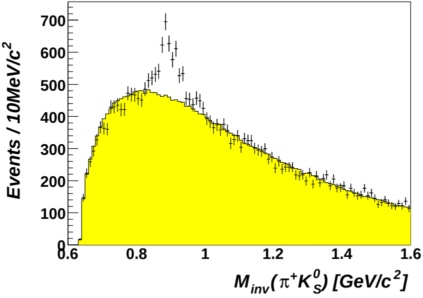
If not considered the following:

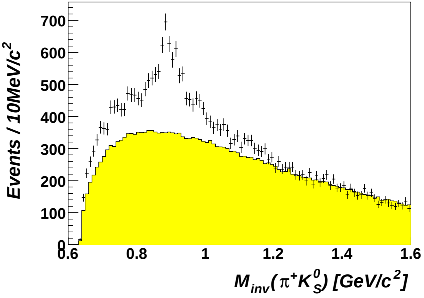
1. Hadronic jet momentum
2. Momentum and Angular distributions of Decays Particles

Fake Pair Technique

Check on $K^* \to \pi^+ K^0$ resonance

1. Good agreement with the Background
2. Underestimation at low values of Invariant Mass





Rotation needed!!!

Verify background also with : $\Lambda \to p\pi^-$, $K_S^0 \to \pi^+\pi^-$ decaying at Primary Vertexes.

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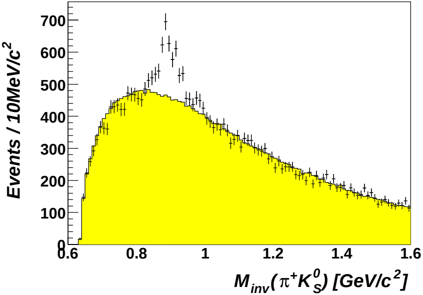

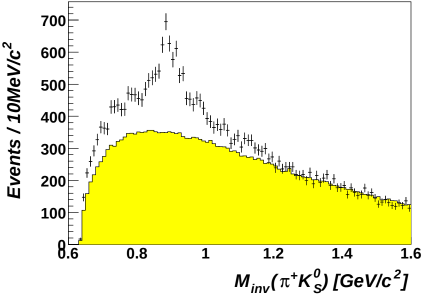

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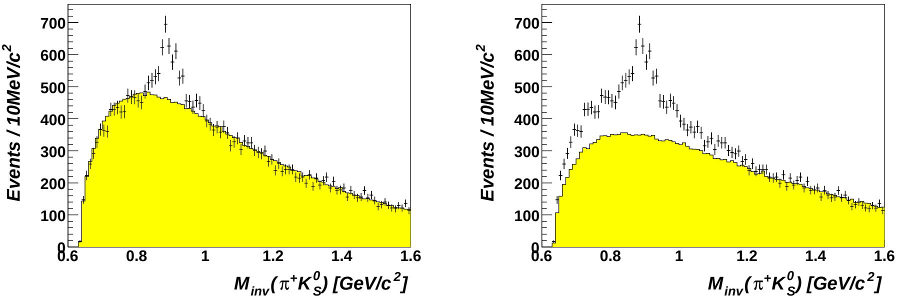

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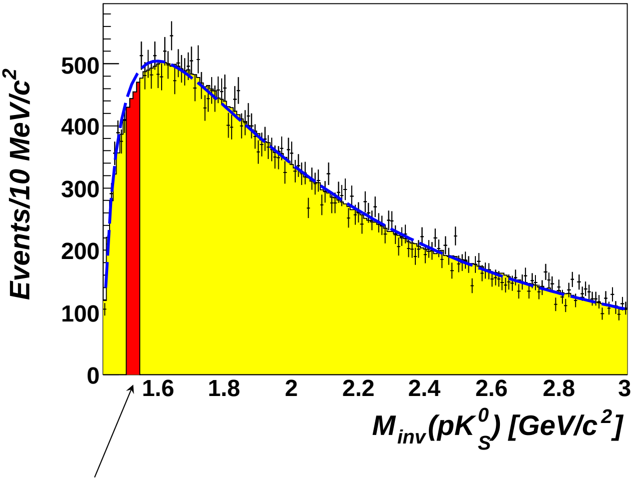
THE BACKGROUND IN THE DATA



$1510 < M(pK^0_S) < 1550$ MeV/c^2 (Θ^+-region) excluded

We calculated

1. Simulated and Reconstructed invariant mass ("A"): $\sigma\left(M_{inv}^{gen} - M_{inv}^{rec}\right)$
2. using of resolution on measured decays particles momenta ("B"):

$$M_{inv}^{2}\ \sigma^{2}(M_{inv}) = \left(\frac{E_2}{E_1}p_1 - p_2\ cos\theta\right)^{2}\sigma^{2}(p_1) + \left(\frac{E_1}{E_2}p_2 - p_1\ cos\theta\right)^{2}\sigma^{2}(p_2)$$

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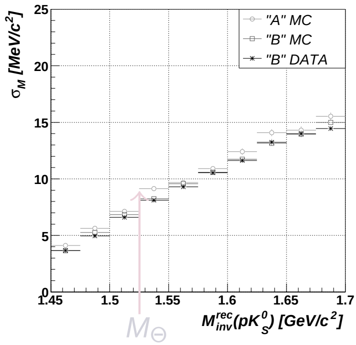

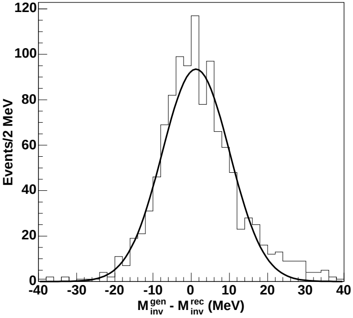

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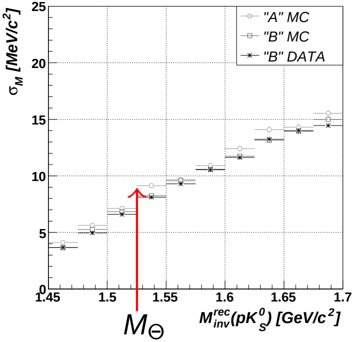

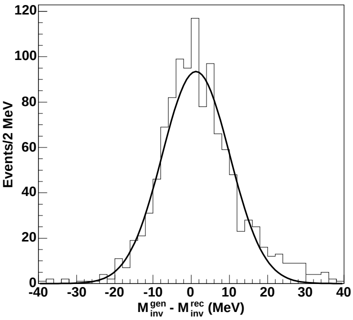

An example

Cleanest sample

The idea behind this approach to find such rare process like $\Theta^+ \to pK_S^0$ one has to provide first the cleanest samples of both kaons and protons.

"Sensetive" sample

The idea behind this approach to find such identification criteria which maximize the sensitivity to the Θ^+ signal relying on the statistical basis.

Sample	No identification	Cleanest	Sensetive
N_S	500	80	300
N_B	10000	400	2500
Purity	4.8%	16.7%	10.7%
Efficiency	100%	16.0%	60.0%
Contamenation	100%	4.0%	25.0%
Significance $N_S/\sqrt{N_B}$	5σ	4σ	6σ

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We optimize the sriteria for the proton identification likelihood ratios maximizing the sensitivity to the expected Θ^+ signal.

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"Sensetive" sample

The procedure of tuning the proton identification cuts is then as follows:

- MC "signal" is K_S^0-proton pair with $1510 < M < 1550$ MeV$/c^2$. We also assume no Θ^+ polarization, a flat distribution of $\cos\theta^*$.
- MC "background" is pair K_S^0 and a positive track not identified as a proton.
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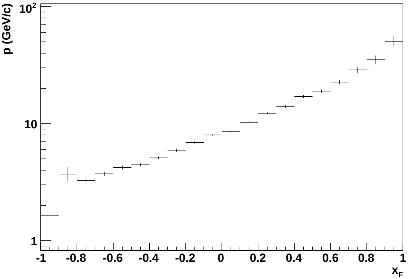
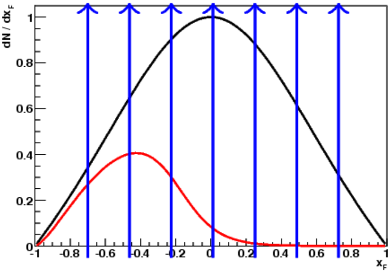
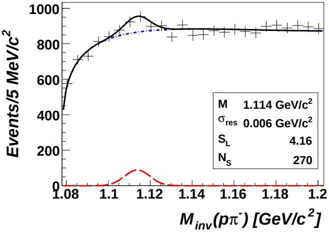
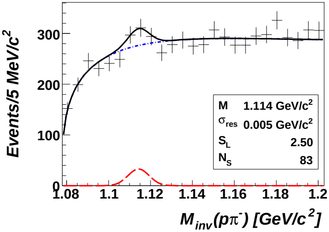


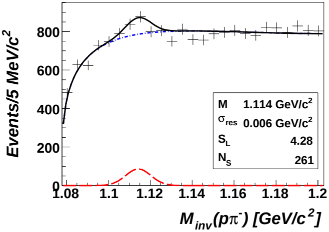


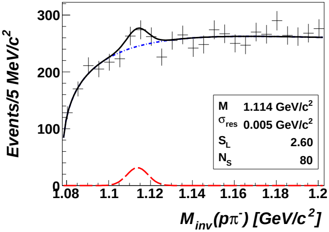
Check on $\Lambda \to p\pi^-$ invariant mass distributions. $-0.6 < x_F < -0.3$





MC | No proton identification | DATA





"Sensetive" proton sample

SIGNIFICANCE CALCULATION

1. Split the data points into 10 intervals: 5 mass intervals with proton decay cosine in the Θ^+ rest frame belonging to the interval $[-1, -0.5)$ and other 5 mass intervals with proton decay cosine in the Θ^+ rest frame belonging to the interval $[-0.5, 1]$
2. Compute two likelihoods:
$$\ln L_B = \sum_{i=1}^{10} (-b_i + n_i \cdot \ln b_i)$$
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b_i, s_i, n_i are the number of predicted background and signal events and observed data events in the i-th bin
3. Compute the signal statistical significance as:
$S_L = \sqrt{2 (\ln L_{B+S} - \ln L_B)}$
4. Find the resonance mass position M and Breit-Wigner width Γ and number of signal events N_s yielding maximum of S_L
5. Repeat the process at $5 x_F$ intervals:
$[-1.0, -0.6), (-0.6, -0.3), (-0.3, 0.0), (0.0, 0.4), (0.4, 1.0]$.

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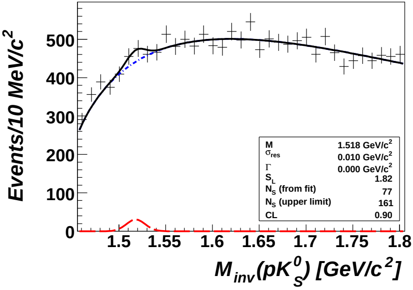
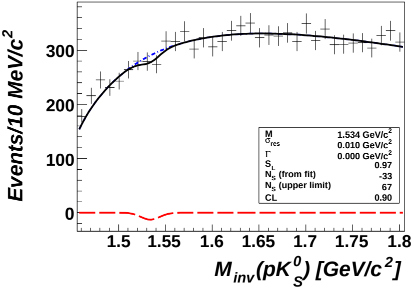
"Opening the BOX"

$\Theta^+ \to pK_S^0$ invariant mass distributions. $-1.0 < x_F < 1.0$





No proton identification

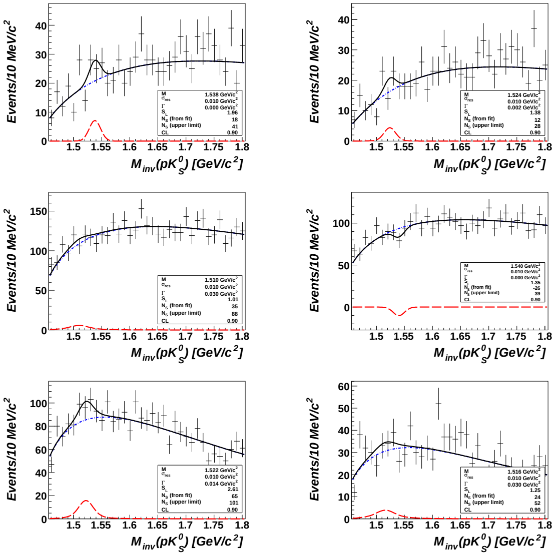
"Sensetive" proton sample

"Opening the BOX"

$-1.0 < x_F < -0.6$

$-0.3 < x_F < 0.0$

$0.4 < x_F < 1.0$

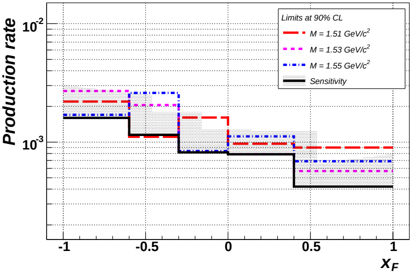


No proton identification

"Sensetive" proton sample

Θ^+ production

x_F interval	$[-1,-0.6)$	$(-0.6,-0.3)$	$(-0.3,0)$	$(0,0.4)$	$(0.4,1]$	all
no ID						
N_s (fit)	18	26	35	30	65	77
SL	1.96	1.49	1.01	1.18	2.61	1.82
N_s^{up}	41	61	88	81	101	161
R^{up}	*3.84*	*2.18*	*1.74*	*1.37*	*0.83*	*4.36*
optimal ID						
N_s (fit)	12	29	-26	-34	24	-33
SL	1.38	1.72	1.35	1.85	1.25	0.97
N_s^{up}	28	68	39	36	52	67
R^{up}	*2.80*	*2.60*	*0.84*	*0.79*	*1.00*	*2.13*



We observed no Θ^+

Upper limit (90%CL)

in the full x_F interval:

$2.13 \cdot 10^{-3}$ to $\nu_\mu N$-interaction

A potential Θ^+ signal

x_F distribution

1. Use the background from the two side-bands: $1460 < M < 1500$, $1580 < M < 1650\mathrm{MeV/c}^2$;
2. Normalize the average of the two side-band distributions to the expected number of background events build with fake pairs in the signal region: $1510 < M < 1550\mathrm{MeV/c}^2$;
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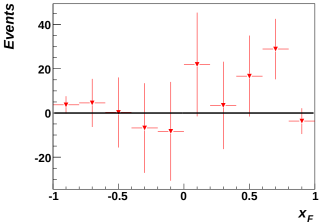
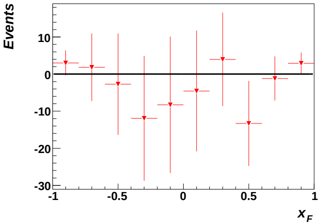


No proton identification



"Sensetive" proton sample

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$\cos\theta^*$ distribution

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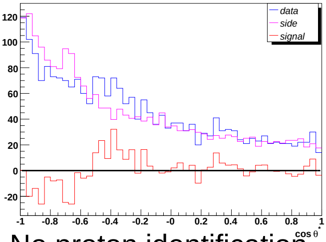

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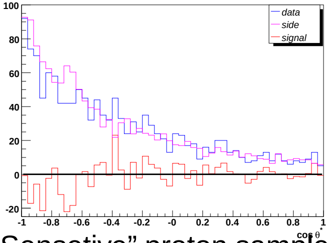

"Sensetive" proton sample

OUTLINE

1. INTRODUCTION
   - Motivation of searches
   - Experimental review
   - NOMAD experiment
2. ANALYSIS TOOLS
   - Particles identification
   - What we can get from NOMAD data
   - The Background Estimation
   - Invariant Mass Resolution
   - ”Sensetive” analysis strategy
   - Statistical analysis
   - Results
3. CONCLUSIONS

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