Precision measurements of the Nucleon Form Factors in the time-like region with FINUDA at DAFNE2

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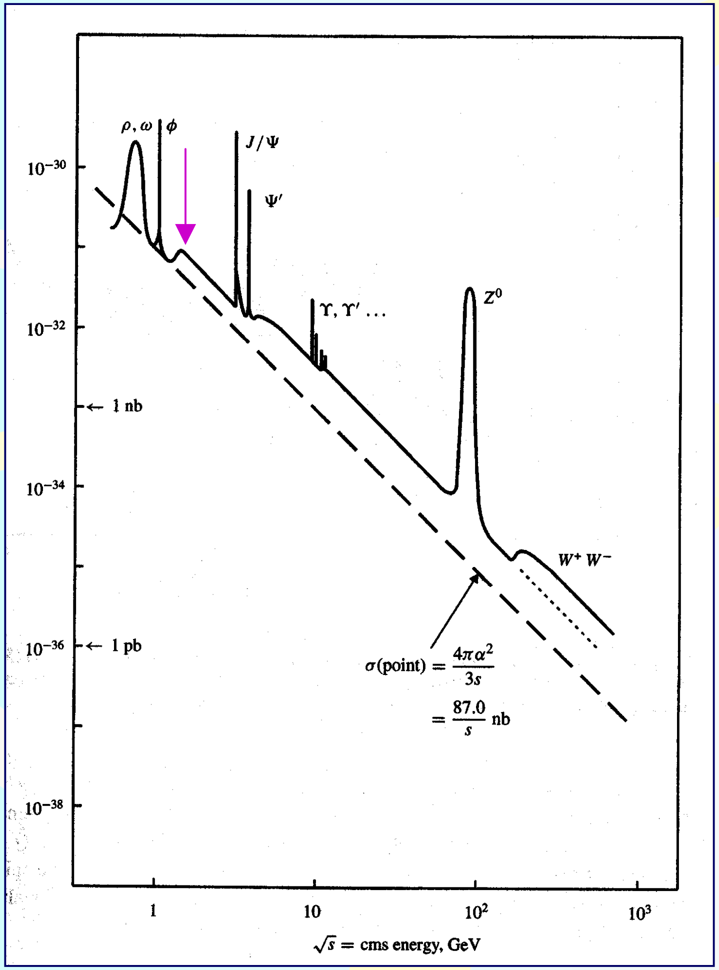
Workshop on e^+e^- in the 1-2 GeV region
Alghero, 12.09.03

Outline of the talk

- Open problems in e^+e^- annihilation around $\sqrt{s}$ = 2 GeV (close to $\bar{N}N$ threshold)
  - Measurements of nucleon time-like form factors

- Study of feasibility with FINUDA
  - $e^+e^- \rightarrow \bar{N}N$ annihilation and form factors evaluations
    - Basic generalities of the experimental setup
    - Apparatus' changes & requirements
    - Expected topologies and detection efficiencies, expected yields per day
    - Backgrounds

Total e^+e^- cross section at ≈2 GeV



- Beyond the φ peak the **total** cross section is about hundreds of nb:
  - $e^+e^- \to \bar{n}n \approx 1$ nb
  - $e^+e^- \to \bar{p}p \approx <1$ nb
  - $e^+e^- \to$ multihadrons ≈ 40-70 nb
  - $e^+e^- \to \gamma\gamma \approx 3 \div 4$ nb
  - $e^+e^- \to \mu^+\mu^- \approx 20$ nb
  - $e^+e^- \to e^+e^- \approx 20$ nb

Measurements of the nucleon form factors in the time-like region

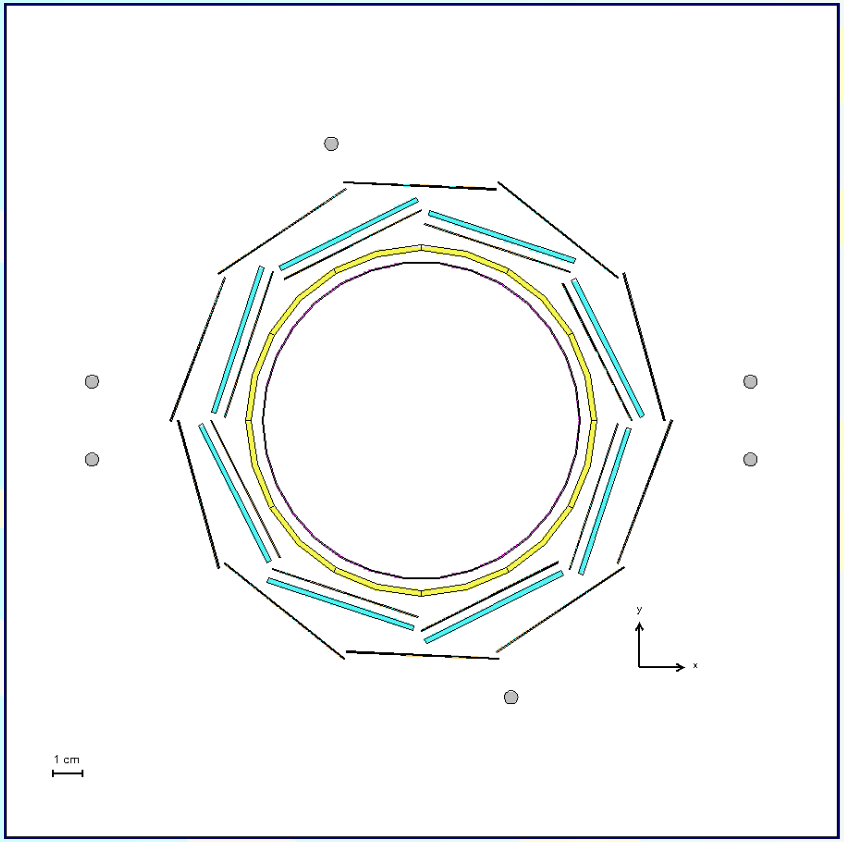
- Based on total and differential cross sections:

$$\sigma = \frac{4\pi\alpha^2\beta}{3s}\left[\left|G_M(s)\right|^2 + \frac{2M_N^2}{s}\left|G_E(s)\right|^2\right]$$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2\beta}{4s}\left[\left|G_M(s)\right|^2\left(1+\cos^2\vartheta\right) + \frac{4M_N^2}{s}\left|G_E(s)\right|^2 \sin^2\vartheta\right]$$

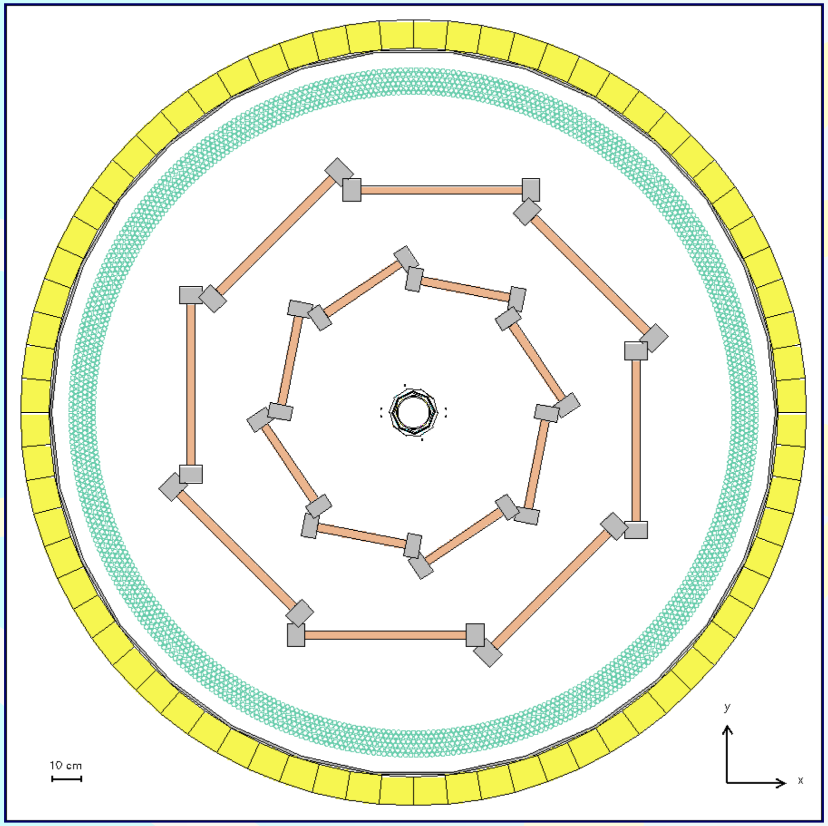
- $G_E = F_1 + (s/4M^2_N)F_2$ $G_M = F_1 + F_2$ (Sachs FF)
- G_E vs G_M can be discriminated via the angular distributions
  - $s >> M^2_N$: only $G_M(s)$ counts
  - $s \approx 4\ M^2_N$ (threshold): $G_E(s) \approx G_M(s)$
    $\Rightarrow$ isotropic distribution

FINUDA present assembly: internal region



- Beam pipe (Be, 0.5 mm thick)
  - R_i = 5.39 cm
- TOFino (12 scintillators, 0.2 cm thick)
  - R_i = 5.8 cm
- ISIM (8 modules, 300 μm thick)
  - Distance= 6.3 cm
- Nuclear targets
- OSIM (10 modules, 300 μm thick)
  - Distance = 8.3 cm

FINUDA present assembly: tracking region + external scintillators



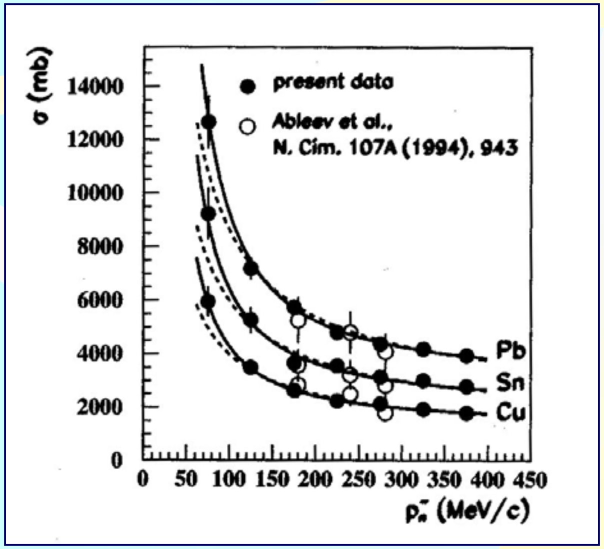
- Two series of 8 drift chambers, 6 cm thick each
  - Distance 1st layer ≈ 43 cm
  - Distance 2nd layer ≈ 75 cm
- 6 layers of straw tubes (total thickness ≈16 cm)
  - R_i = 111 cm
- TOFone (72 scintillators, 10 cm thick)
  - R_i = 127 cm
  - Efficiency for low momentum neutrons detection: ≤ 15%
- Fe magnet coil ⇒ 1.1 T
  - R_i = 138 cm
- He atmosphere:
  - Total radiation length: 1700 m
  - If filled with air: 304 m

New requirements for FF measurements

- **Some converter is needed somewhere!**

$$\sigma_{ann}(p_{\bar{n}}, A) = \sigma_0(p_{\bar{n}})A^{0.65}$$

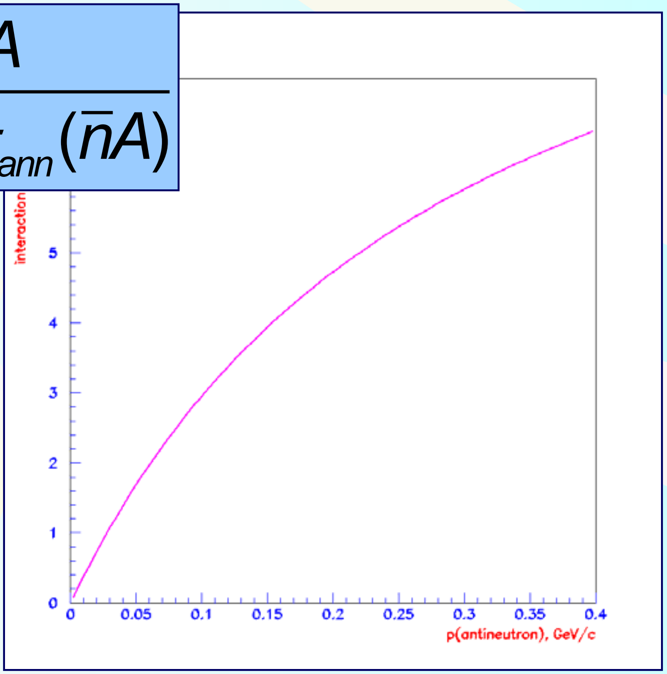
$$\sigma_0(p_{\bar{n}}) = a + b/p_{\bar{n}}$$



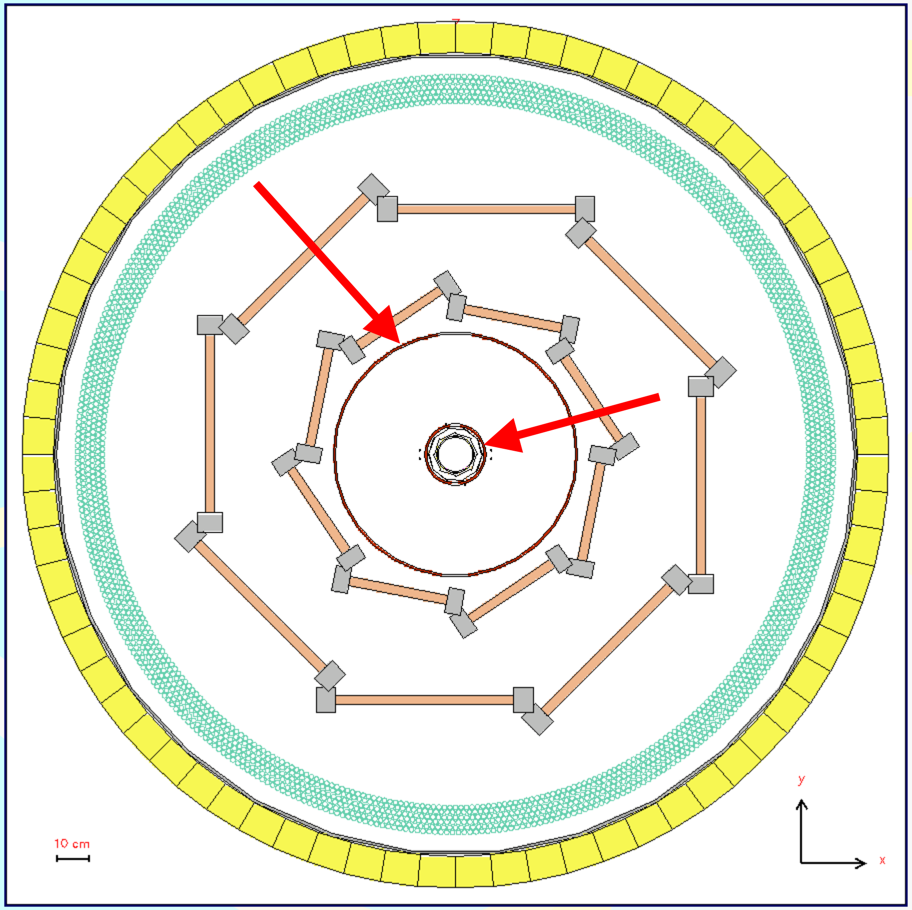
- Criteria for a good converter material:
  - Highest annihilation cross section
  - Low charged π absorption
  - High conversion efficiency for π^0
  - Amagnetic (if B field is required)

$$\lambda = \frac{1}{\Sigma} = \frac{A}{N_{AV}\rho\sigma_{ann}(\bar{n}A)}$$

- Copper
  - A= 63.5, Z=29
  - ρ=8.96 g/cm^3
  - X_0 = 1.43 cm



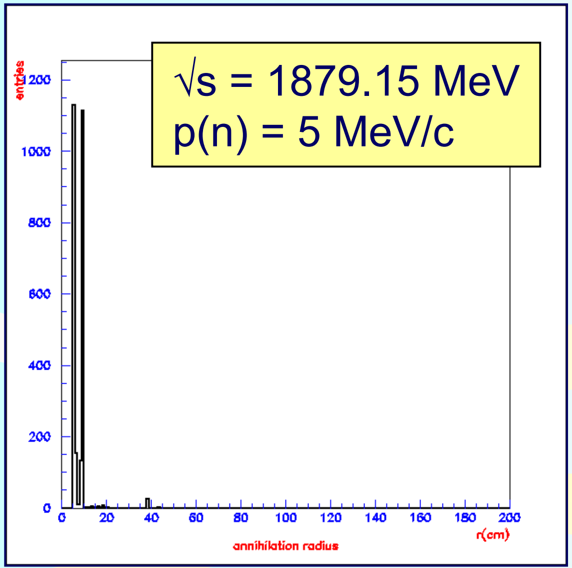
Converter(s) positioning: most convenient placements

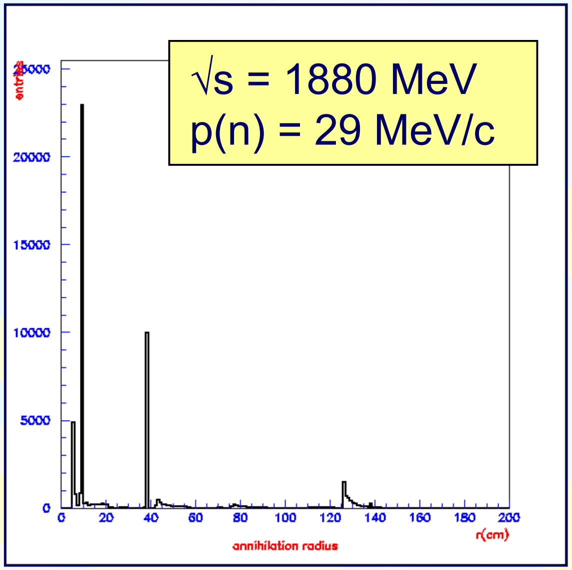


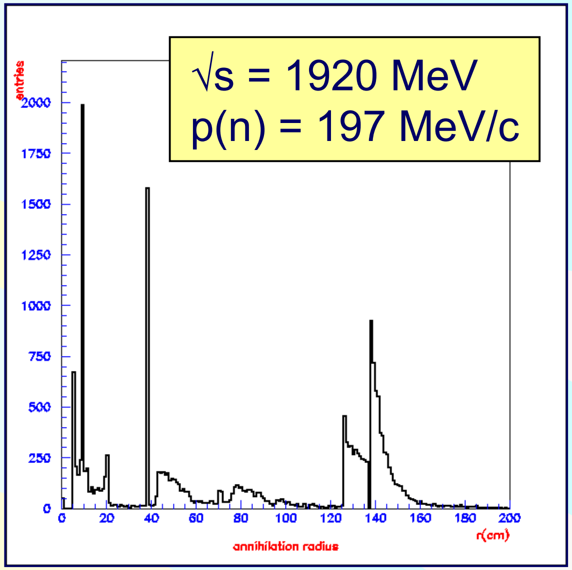
- 1^{st} converter beyond OSIM
  - Possibility of $p\bar{p}$ tracking in the inner region
  - 7 mm thick tube, 20 cm long, R_i=9 cm
  - Thickness corresponding to
    - ≈ 4 interaction lengths for 5 MeV/c antineutrons
    - ≈ 1 interaction length for 25 MeV/c antineutrons

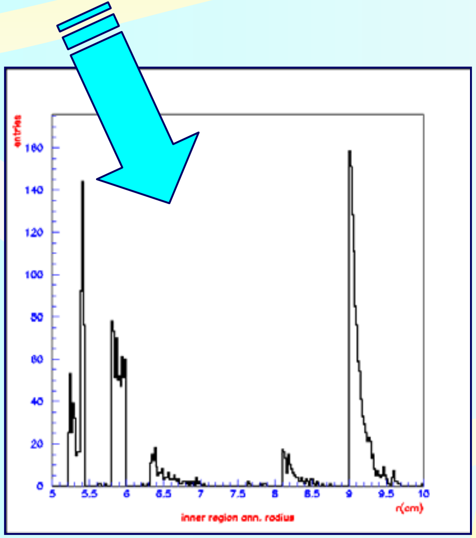
      ($\sqrt{s}$ = 1879.89 MeV)
    - 0.5 X_0
  - For 340 MeV/c antineutrons ($\sqrt{s}$ = 2 GeV)
    - λ = 5.88 cm ≡ 4 X_0
- 2^{nd} converter before the first DC layer
  - 7 mm thick tube:
    - one interaction length for 50 MeV/c antineutrons

n̄-Nucleus annihilation vertex position inside the apparatus



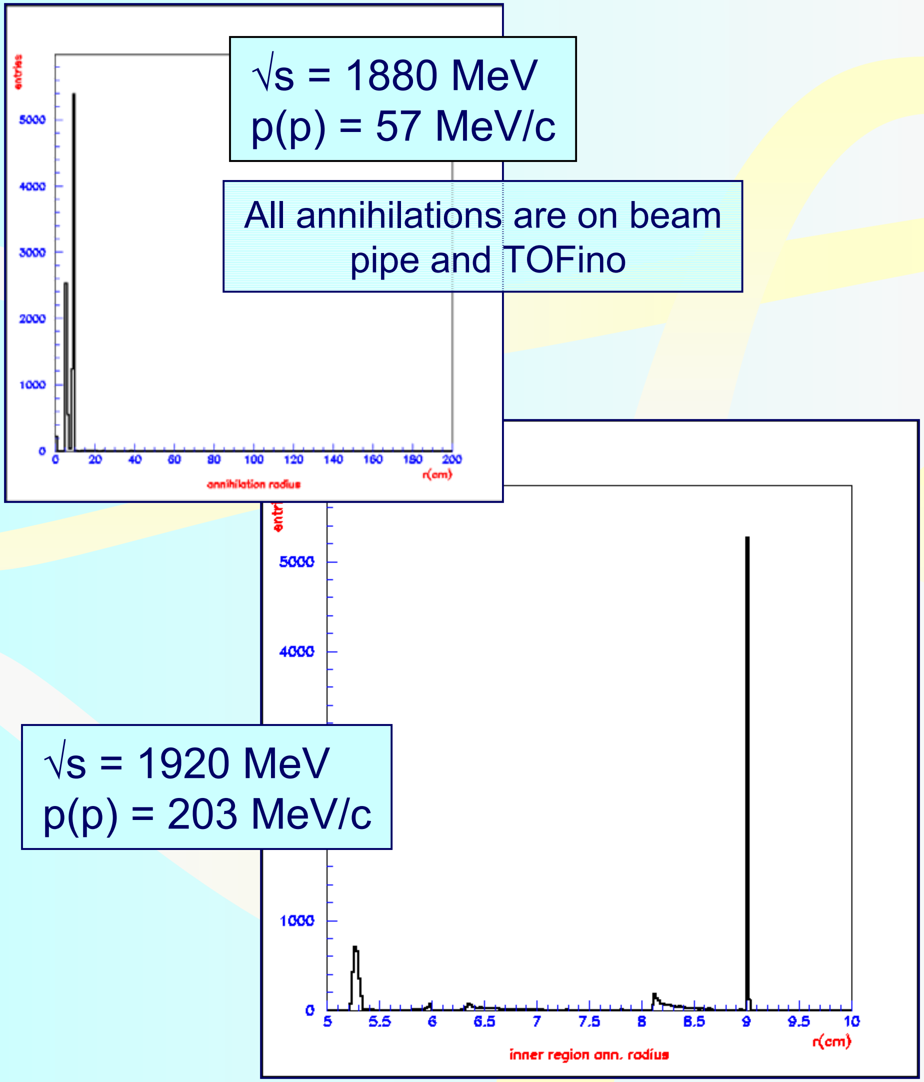






- 5 MeV/c n̄s annihilate completely on beam-pipe, TOFino and 1st converter
- 29 MeV/c n̄s annihilate for the 44% on first converter, 20% on the second one
- 197 MeV/c n̄s annihilate for the 13% on the first converter, 8% on the second one, 22% on drift chambers, 16% on TOFone, 28% on magnet coil

$\bar{p}$-Nucleus annihilation vertex position inside the apparatus



$\sqrt{s}$ = 1880 MeV
p(p) = 57 MeV/c

All annihilations are on beam pipe and TOFino

$\sqrt{s}$ = 1920 MeV
p(p) = 203 MeV/c

- 300 MeV/c ($\sqrt{s}$ = 1970 MeV) protons/antiprotons range in Cu is
  - R = 1.88 g cm^{-2}
  - l = 2.1 mm
- All protons/antiprotons stop at most on first converter
  - Insensitive to the presence of the second converter
- At $\bar{n}n$ threshold ($\sqrt{s}$ = 1879.13 MeV) the outgoing $\bar{p}$/p momentum is ≈ 48 MeV/c:
  - Never spiralize before reaching the beam pipe, not even for B = 1.1 T

Use of magnetic field: pro’s and con’s

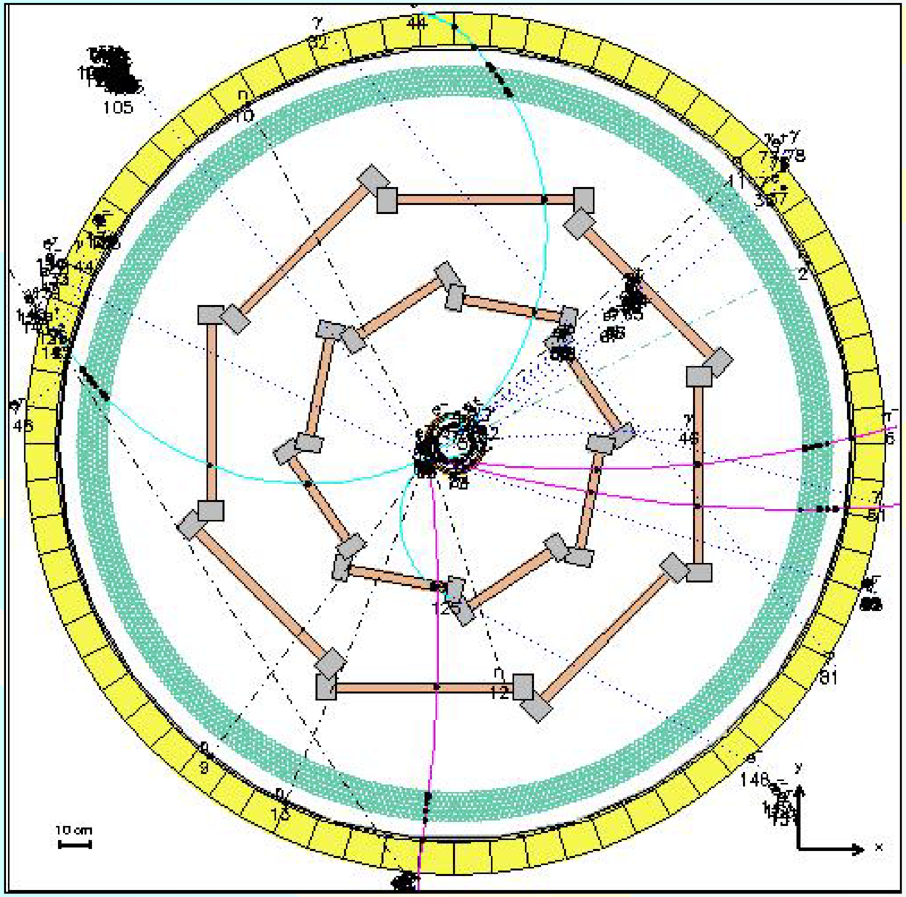
- PRO’S:
  - Easier spurious tracks (cosmic rays) rejection
  - Helps to confine background (Touscheck, and even Bhabha) events within the first converter
  - Track momentum measurement possible
    - Not essential for this kind of physics measurements, only interested in event topology

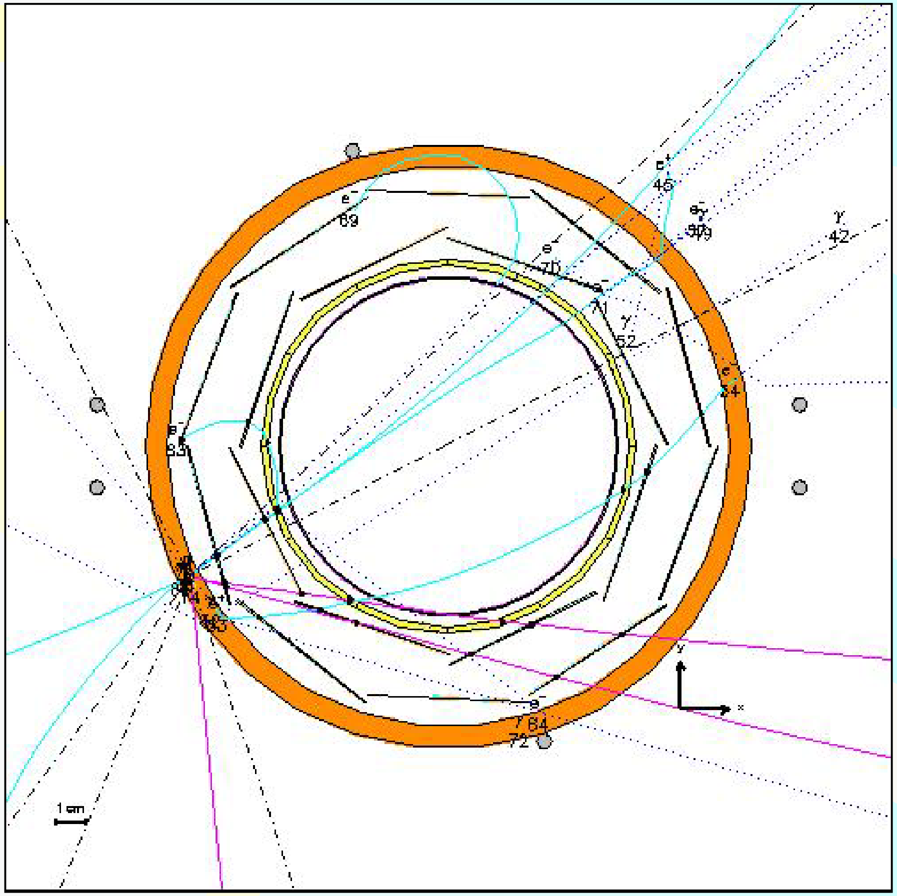
A field of moderate intensity (0.2 T) seems to be a good compromise solution

- CON’S:
  - Iron cannot be used as a converter
  - Lower reconstruction efficiency of the annihilation star
    - The higher the field, the more e^+e^- pairs from π^0 conversion are lost
  - Less difficulty on the star topology reconstruction
    - Two hits per track are enough
  - No perturbations on beam optics

$e^+e^-\rightarrow\bar{n}n$ with FINUDA: typical topologies

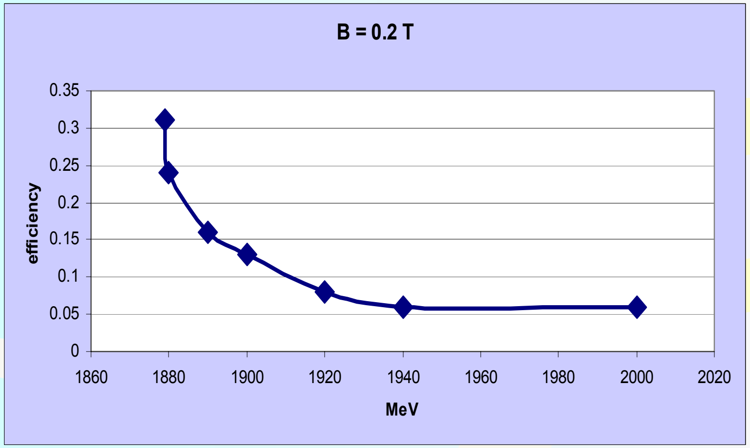
Configuration with a single copper converter (7 mm thick, 1 interaction length for 25 MeV/c $\bar{n}\equiv 0.5X_0$), beyond the inner region





$\sqrt{s}$ = 1890 MeV, B = 0.2 T

Tentative events yields/day, $e^+e^- \to \bar{n}n$



1 converter only

$\mathbf{L} \approx 5\times10^{31}$ cm^{-2} s^{-1}

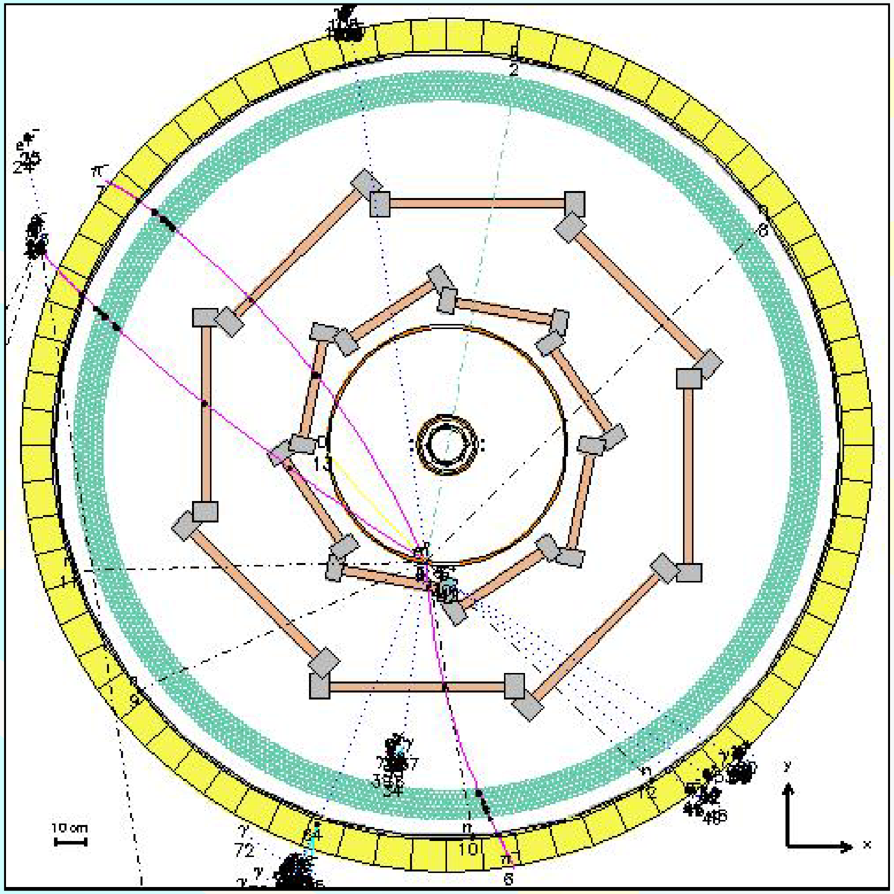
$L_{day} \approx 4$ pb^{-1}; $\sigma_{Ann} \approx 1$ nb

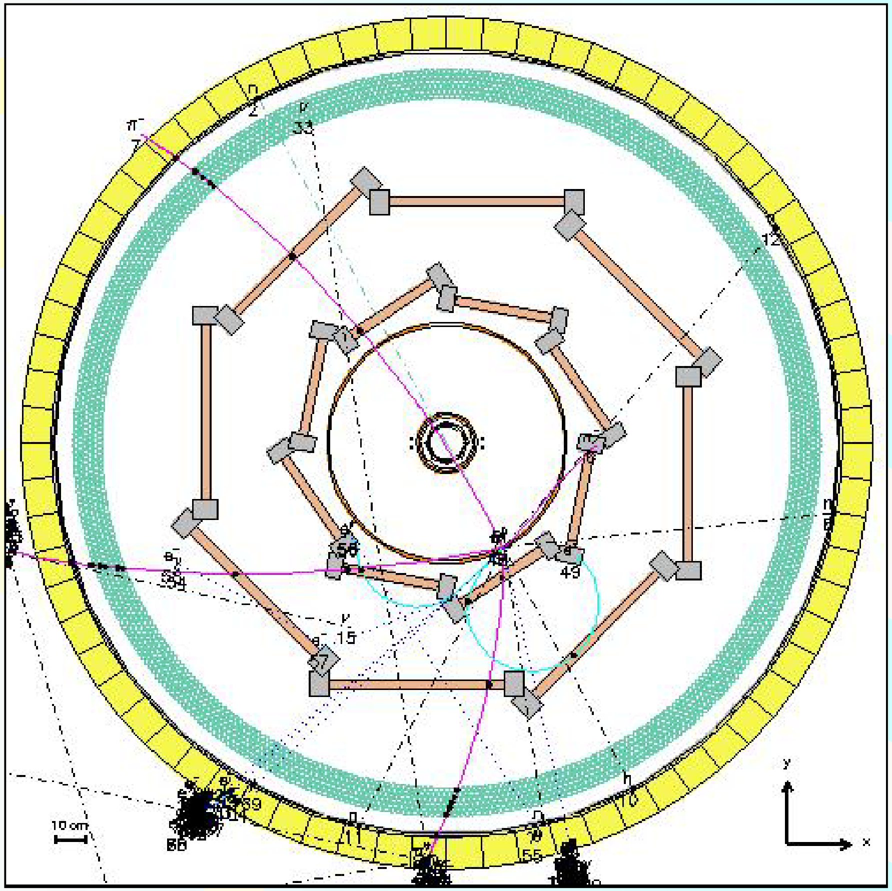
B = 0.2 T

Chamber transparency: 85%

√s (MeV)	ε	L_{day}(pb^{-1})	# events	# events w. n coincidence
1879	.31	4	1054	158
1880	.24	4	816	122
1890	.16	4	640	96
1900	.13	4	442	66
1920	.08	4	272	41
1940	.06	4	204	31
2000	.06	4	204	31

$e^+e^-\to\bar{n}n$ with FINUDA: two converters?





$\sqrt{s}$ = 1900 MeV, B = 0.2 T

Tentative events yields/day, $e^+e^-\to\bar{n}n$

2 converters

L $\approx 5\times10^{31}\ \mathrm{cm^{-2}\ s^{-1}}$

$L_{day} \approx 4\ \mathrm{pb^{-1}}$; $\sigma_{Ann} \approx 1$ nb

B = 0.2 T

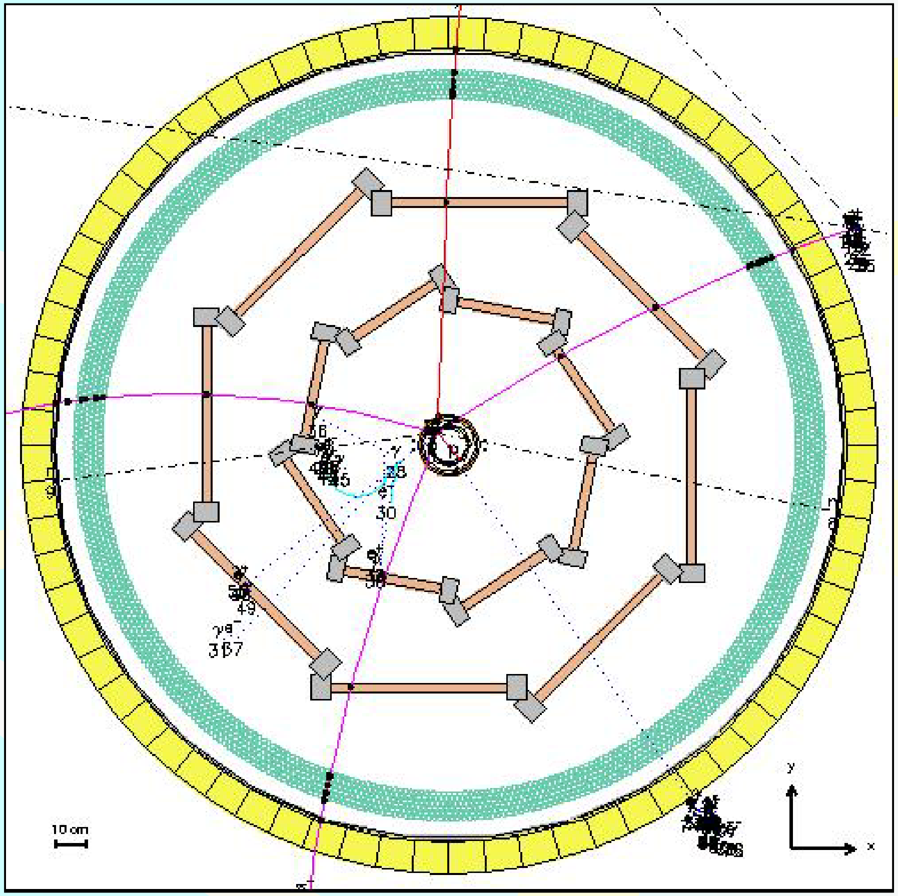
Chamber transparency: 85%

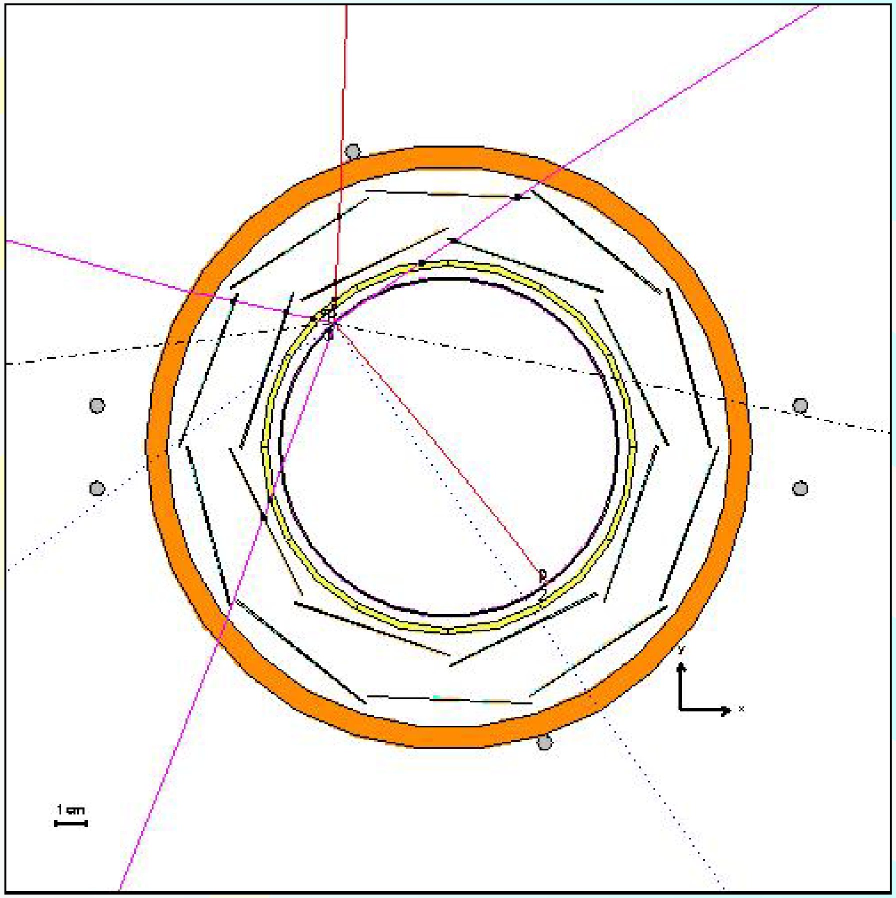
The second converter enhances the number of annihilations (and useful events) from 20 to 60%

$\sqrt{s}$ (MeV)	1st/2nd converter annihilation ratio	ε	$L_{day}(\mathrm{pb^{-1}})$	# events	# events w. n coincidence
1879	4.94	.31	4	1265	190
1880	3.39	.24	4	1053	157
1890	1.97	.15	4	966	119
1900	1.81	.13	4	685	102
1920	1.44	.08	4	460	66
1940	1.66	.06	4	326	50
2000	1.56	.06	4	335	51

$e^+e^- \to \bar{p}p$ with FINUDA: typical topologies

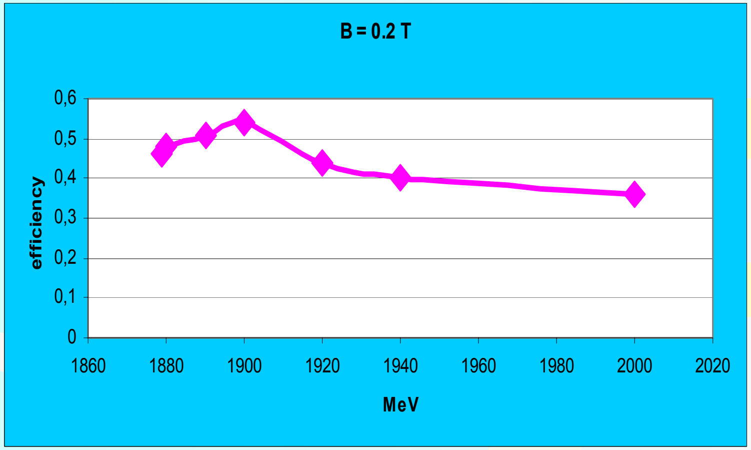
Antiprotons get always stopped in the copper layer





$\sqrt{s}$ = 1890 MeV, B = 0.2 T

Tentative events yields/day, $e^+e^- \to \bar{p}p$



1 converter only

L ≈ 5×10^{31} cm^{-2} s^{-1}

$L_{day} \approx 4\ pb^{-1}$; $\sigma_{Ann} \approx 1$ nb

B = 0.2 T

Chamber transparency: 85%

√s (MeV)	ε	L_{day}(pb-^{1})	# events
1879	.46	4	1564
1880	.48	4	1632
1890	.51	4	1734
1900	.54	4	1836
1920	.44	4	1496
1940	.40	4	1360
2000	.36	4	1224

How to distinguish $e^+e^- \to \bar{n}n$ from $e^+e^- \to \bar{p}p$?

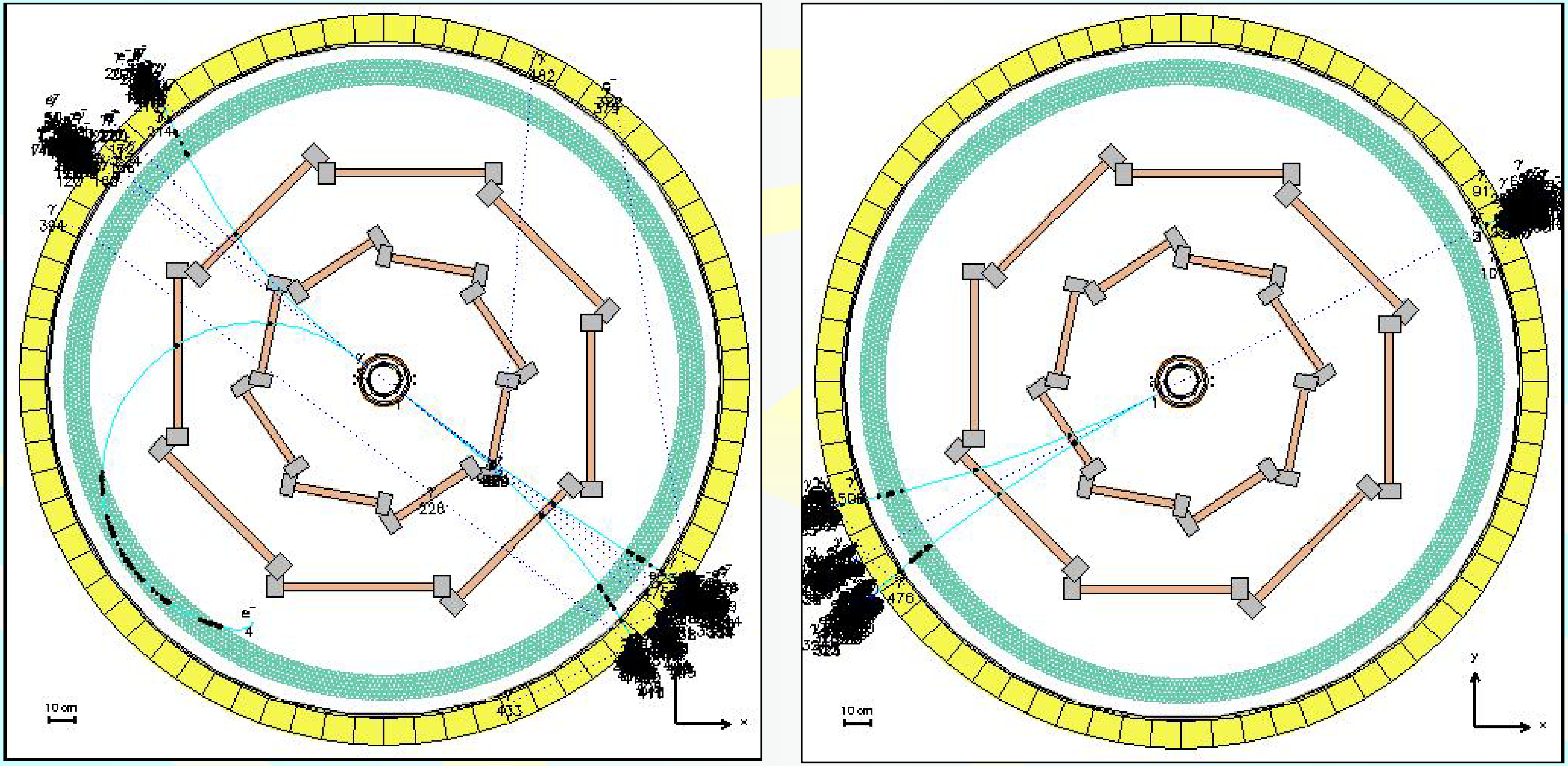
- If all $\bar{p}$'s stop on beam pipe the event topology for the antinucleon "prong" is the same in the two cases
    - But the proton leaves hits on the tracking devices, and the neutron hits the outer scintillator hodoscope
    - If the reconstructed vertex is on the beam pipe one can assume it's a $\bar{p}p$ event
    - The probability that a few MeV/c antineutron annihilates in this place is about 9%

Faster $\bar{p}$'s

- They hit tofino allowing a back-to-back trigger
- If just a hit is left by each track on ISIM or OSIM the $\bar{p}$/p tracks may be completely reconstructed
- The $\bar{p}$ track points as well to the annihilation vertex
    - Higher efficiency
        - Looser criteria to identify the annihilation star

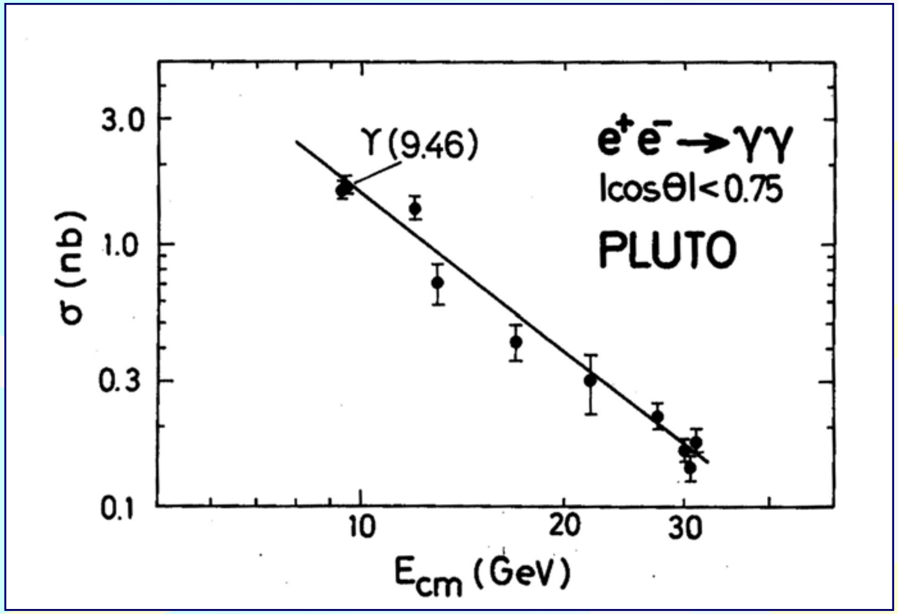
Background I: $e^+e^- \to \gamma\gamma$

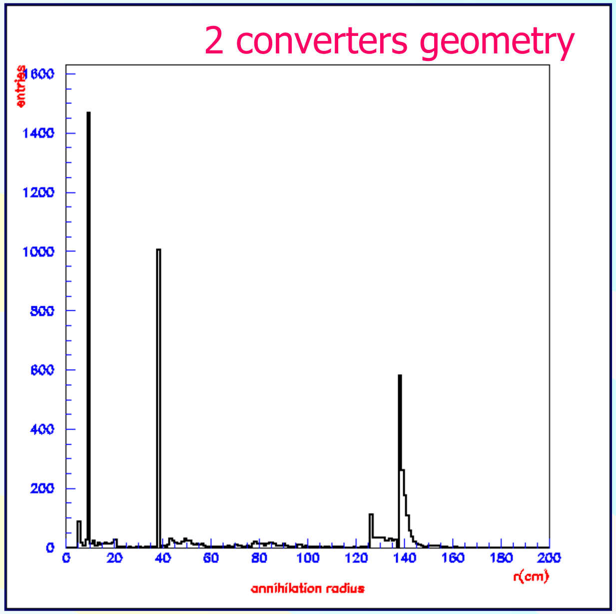
Events with 2 (electron) prongs can fake annihilation stars



$\sqrt{s}$ = 1900 MeV, B = 0.2 T

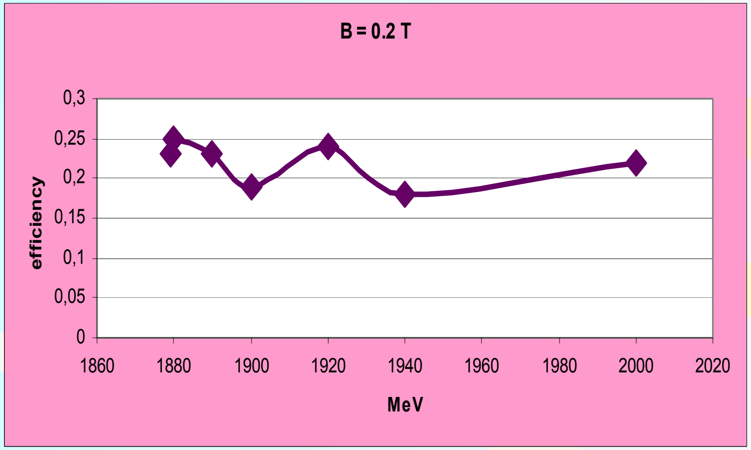
Background I: $e^+e^- \to \gamma\gamma$





- Two 7 mm thick Cu converters provide one radiation length
- Events topology is very similar if only two tracks out of the interaction point are required
  - Without magnetic field it's easier to discriminate them since the opening angle of e^+e^- pairs is very tight, and fixed at any beam energy
  - In these conditions the detection efficiency for a $\gamma\gamma$ event is 20-25%, which means about 2000-2500 events that can fake true annihilations, with $L_{day} \approx 4\ pb^{-1}$ and $\sigma_{\gamma\gamma} \approx 3\ nb$

Tentative events yields/day, $e^+e^-\to\gamma\gamma$



1 converter only

$\mathbf{L} \approx 5\times10^{31}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

$L_{day} \approx 4\ \mathrm{pb}^{-1}$; $\sigma_{\gamma\gamma} \approx 3$ nb

B = 0.2 T

Chamber transparency: 85%

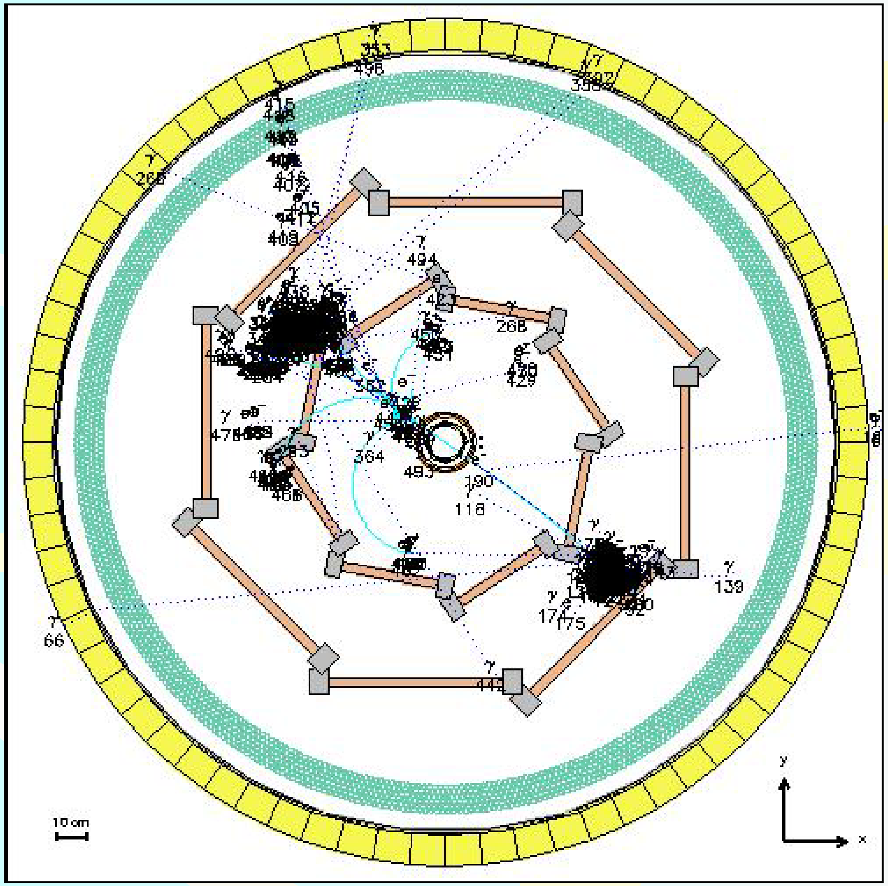
√s (MeV)	ε	L_{day}(pb-^{1})	# events
1879	.23	4	2346
1880	.25	4	2550
1890	.23	4	2346
1900	.19	4	1938
1920	.24	4	2448
1940	.18	4	1836
2000	.22	4	2244

Background II: cosmic ray rejection

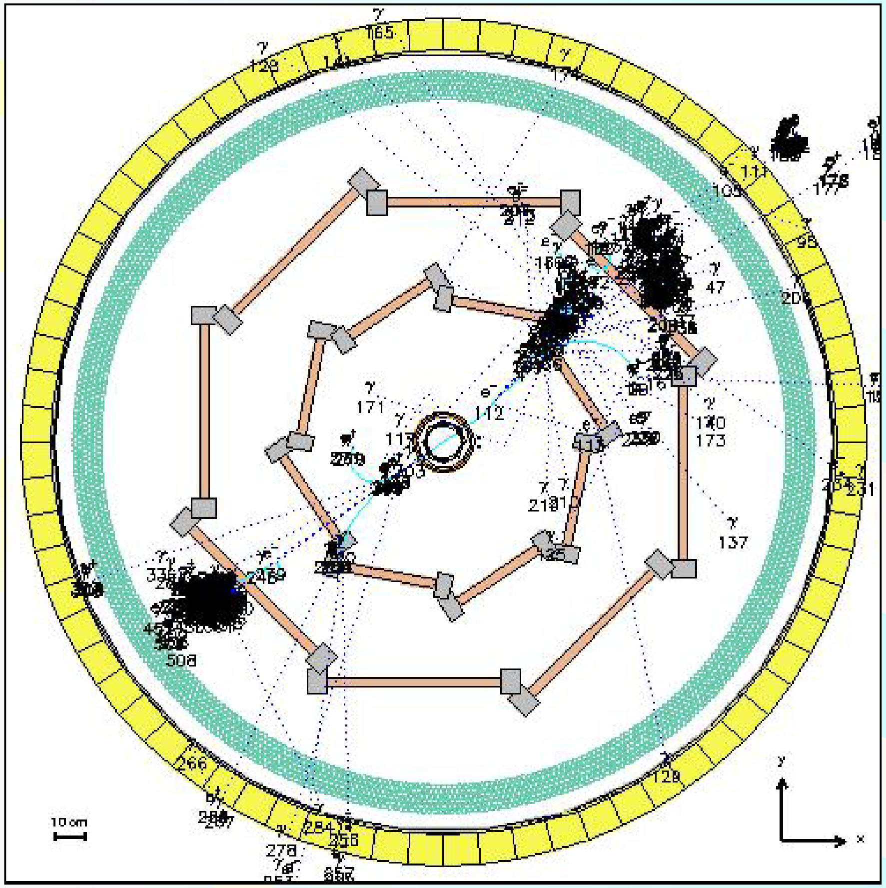
- Maximum expected cosmic rays events (OR Tofino):
  - 50 Hz
- To be compared with:
  - #ev/s = σ * **L** = 1 nb * 5×10^{31} cm^{-2} s^{-1} = 5×10^{-2} Hz
- Cosmic rays can give spurious tracks passing through $e^+e^-\rightarrow\bar{p}p$ annihilation vertex
- With a magnetic field spurious tracks are deviated and don’t pass anymore through the apparatus’ center

Background II: $e^+e^- \to e^+e^-$ Bhabha events

Topology very different from an annihilation star



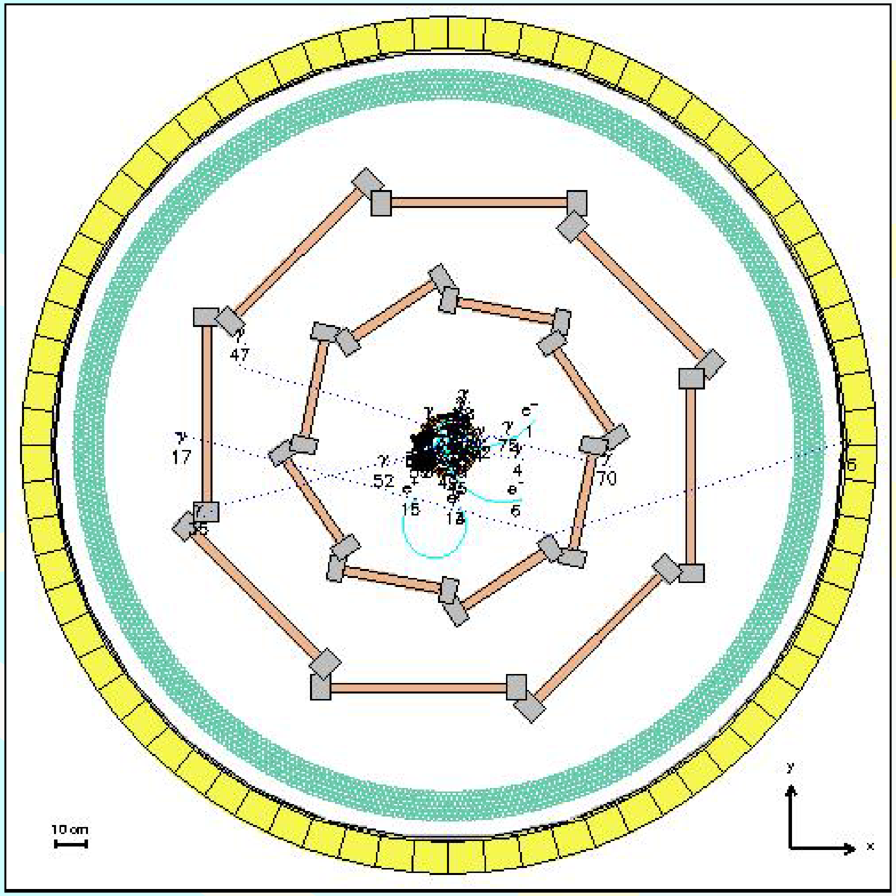
$\sqrt{s}$ = 1900 MeV, B = 0.2 T

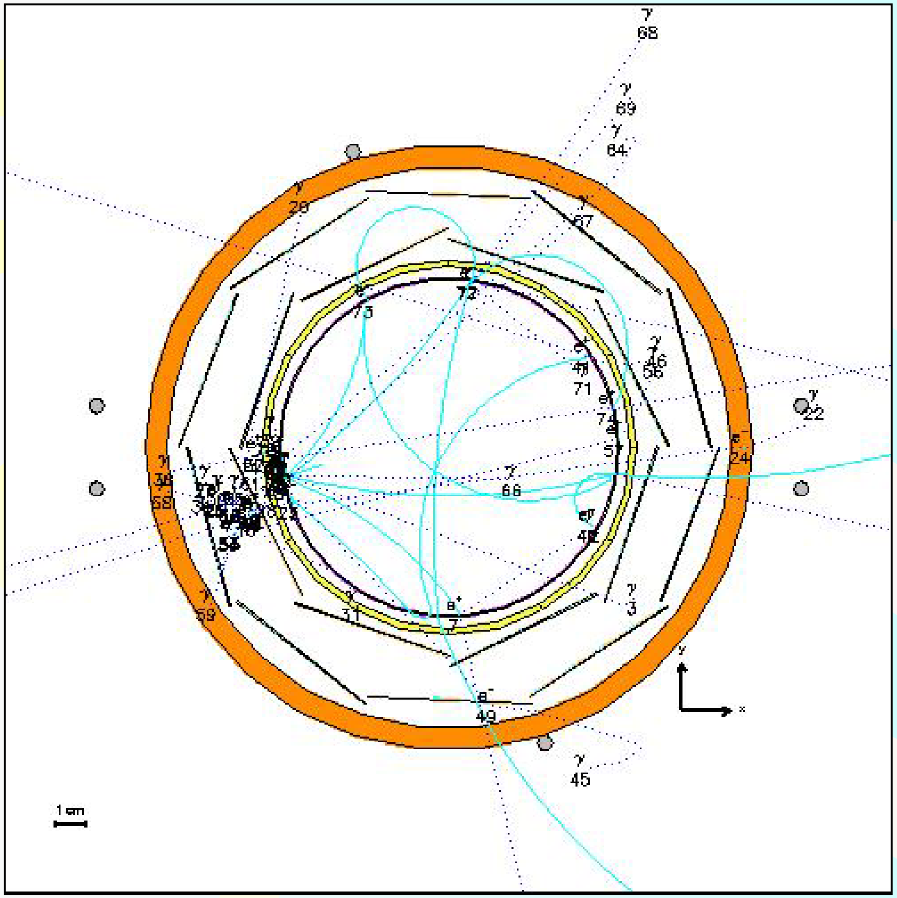


$\sqrt{s}$ = 2000 MeV, B = 0.2 T

Background III: Touscheck events

Confined inside beam pipe and inner region





√s = 1890 MeV, B = 0.2 T

Advantages and drawbacks with FINUDA

- Total cross sections can be measured with fair efficiency

- Some problems for the differential cross sections due to the apparatus’ limited acceptance
  - Something to improve the angular coverage needed

- Further checks: possibility to measure the proton and (more difficult, but feasible) the neutron polarization
  - Enough room is available to place suitable polarization filters: carbon converter
    - Method: measure a left/right asymmetry for the emitted nucleon
    - Tool to get the relative phase and infer something more about G_M and G_E, that in the time-like region are complex

Conclusions

- The cross section measurements for both $e^+e^- \to \bar{n}n$ and $e^+e^- \to \bar{p}p$ seems to be feasible
  - maximum efficiency: 30% close to threshold
  - Most important problem: reduced FINUDA angular acceptance!!
- $\gamma\gamma$ background rejection strong enough if event reconstruction requires
  - A more-than-two-prong annihilation star
  - A signal on TOFone by a neutron within a definite time gate
- Possibility to reconstruct with a ~20% efficiency multihadronic events like $e^+e^- \to 4\pi$, $\to 6\pi$ to search for possibile new structures in formation
- Possibility to perform polarization measurements