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ASTRO–PARTICLE PHYSICS WITH THE ALPHA MAGNETIC SPECTROMETER (AMS)

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Abstract

The Alpha Magnetic Spectrometer (AMS) is a state of the art detector for the extraterrestrial study of antimatter, matter and missing matter. After a precursor flight on STS91 in may 1998, AMS will be installed on the International Space Station Alpha where will operate for three years. In this paper the AMS experiment is described and its physics potential reviewed.

1 Introduction

The disappearance of cosmological antimatter and the pervasive presence of dark matter are two of the greatest puzzles in the current understanding of the universe.

- Antimatter

The Big Bang model assumes that, at its very beginning, half of the universe was made out of antimatter. The validity of this model is based on three key experimental observations: the recession of galaxies (Hubble expansion), the highly isotropic cosmic microwave background and the relative abundances of light isotopes. However, a fourth basic observation, the presence of cosmological antimatter somewhere in the universe, is missing. Indeed measurements of the intensity of gamma ray flux in the MeV region exclude the presence of a significant amount of antimatter up to the scale of the local supercluster of galaxies (tens of Megaparsecs). It follows that, either antimatter has been destroyed immediately after the Big Bang by some unknown mechanism, or matter and antimatter were separated (by some other unknown mechanism) into different region of space, at scales larger than superclusters.

All efforts to reconcile the the absence of antimatter with cosmological models that do not require new physics failed (see Steigmann, 1976, Kolb and Turner,1983, and Peebles, 1993, for a review of these theories).

It follows that we are currently unable to explain the fate of half of the baryonic matter present at the beginning of our universe.

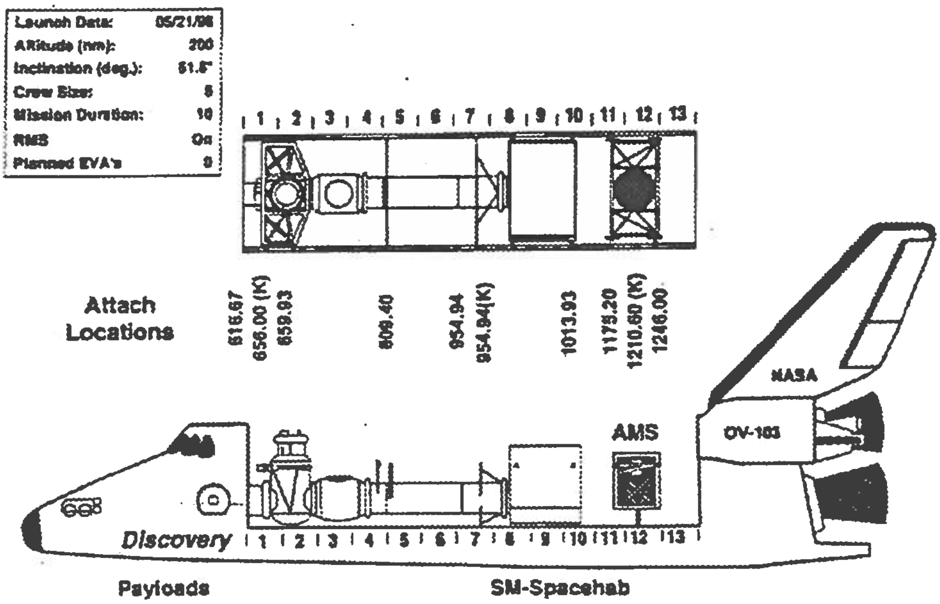

Figure 1: *AMS on STS 91 (Discovery)*

- Dark matter

Rotational velocities in spiral galaxies and dynamical effects in galactic clusters provide us convincing evidence that, either Newton laws break down at scales of galaxies or, more likely, most (up to 90%) of our universe consists of non-luminous (dark) matter. There are several dark matter candidates. They are commonly classified as "hot" and "cold" dark matter, depending on their relativistic properties at the time of decoupling from normal matter in the early universe. As an example, light neutrinos are obvious candidates for "hot" dark matter while Weakly Interacting Massive Particles (WIMP's) are often considered as "cold" dark matter candidates (Ellis et al.,1988; Turner and Wilzek, 1990).

In either cases we are currently unable to explain the origin of most of the mass of our universe.

To address these two fundamental questions in astroparticle physics a state of the art detector, the Alpha Magnetic Spectrometer (AMS) (AMS, 1994) has been recently approved by NASA to operate on the International Space Station Alpha (ISSA). AMS is manifested for a precursor flight with STS91, (Discovery, may 1998, Figure 1), and for a three year long exposure on the ISSA, after its installation during Utilization Flight n.4 (Discovery, december 2000, Figure 2). AMS has been proposed and is being built by an international collaboration involving China, Finland, Germany, Italy, Rumenia, Russia, Switzerland, Taiwan and US.

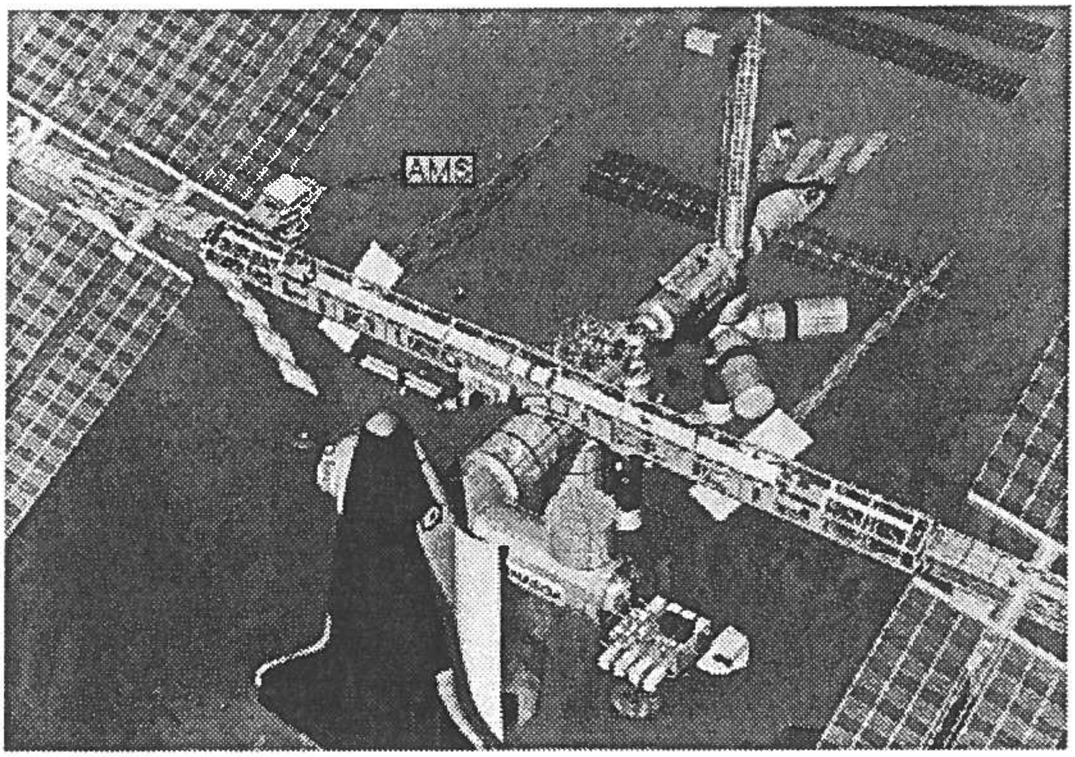

Figure 2: *AMS installed on the main truss of the International Space Station Alpha*

2 Particle physics and antimatter

Particles and antiparticles are connected through three discrete space-time symmetries which are the foundations of relativistic field theory: charge conjugation (C), parity (P) and time reversal (T). We know today that each of these symmetries can be independently violated. Invariance of fundamental interactions under the three combined transformations is, however, always maintained (CPT theorem). The best tests of the CPT theorem are indeed based on the comparison of lifetimes and masses of particle and antiparticles, since the a CPT tranformation links a particle to its antiparticle. An asymmetry between matter and antimatter in our universe would then be strictly related to a violation of these discrete symmetries.

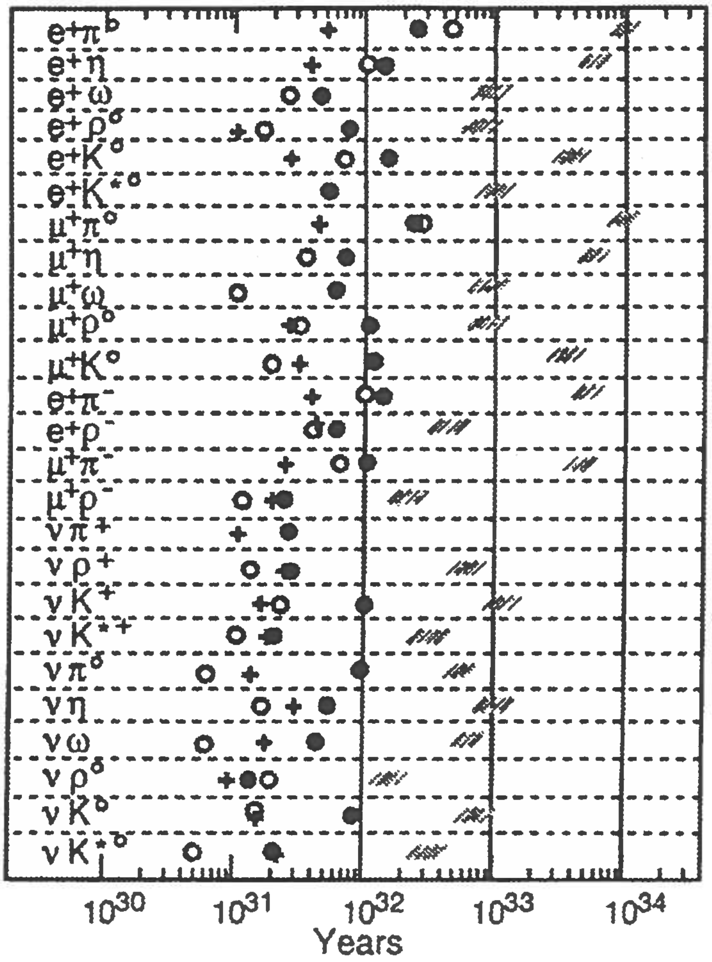

Figure 3: *Sensitivity of Super-Kamiokande (dashes) for different proton decay channels as compared with current experimental limits (90% C.L.) (data:* o *IMB,* • *Kamiokande,*+ *Frejus).*

In 1967, Sakharov noted that baryogenesis, which describes the evolution from a symmetric universe to an asymmetric one, requires four ingredients, three of which, baryon number violation, C and CP violations are fundamental properties of elementary particles (Sakharov 1967). Neither particle acceleration experiments nor proton decay experiments have yet provided evidence for baryon number violation. Figure 3 shows the current status on proton decay searches together with the sensitivity of Super-Kamiokande, the most important next generation experiment in this field (Ting, 1996). However, since there is a long range force associated with baryonic charge, there is no compelling reason for baryon number to be conserved. Nevertheless, until particle physics experimental data provides confirmation of these ideas, the observed lack of antimatter in our part of universe will be the strongest evidence for baryon number violation.

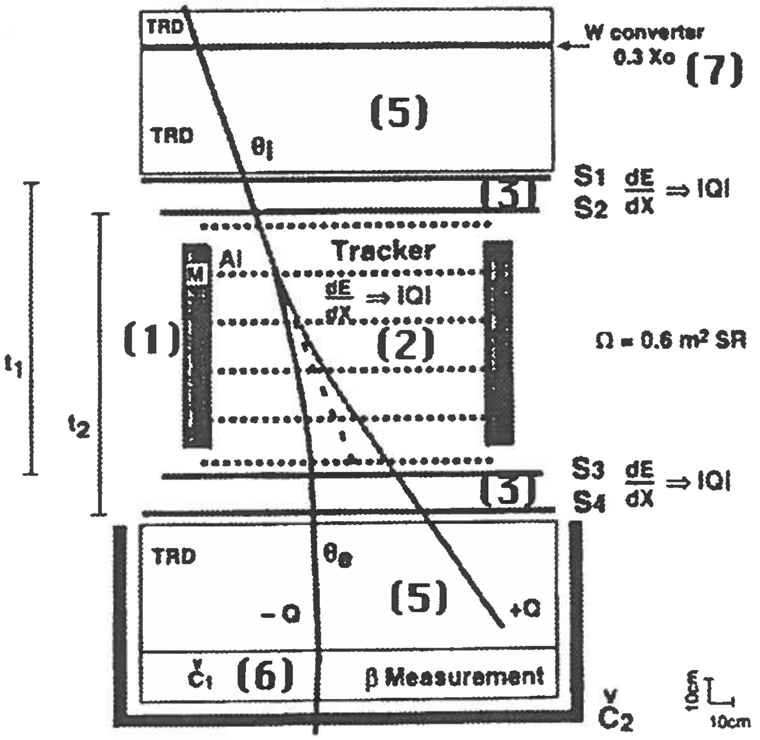

Figure 4: *AMS design principles*

CP violation has been observed directly in three decays of the K_L meson and nowhere else in particle phyisics experiments:

$$K_L \rightarrow \pi^+\pi^-, \quad K_L \rightarrow \pi^o\pi^o, \quad K_L \rightarrow \pi l \nu \tag{1}$$

(l is either an electron or muon). The absence of antimatter in our part of the universe (and perhaps in the entire universe), combined with Sakharov conditions, provides the only other evidence for CP violation.

Since CP violation as the origin of baryogenesis occurs at energy scales much greater and at much greater level than in the in the kaon system, the study of baryon asymmetry in the universe provides crucial informations in attempts to probe beyond the Standard Model of particle physics. Cosmological models that predict baryon symmetry on the scale of the observable universe may involve different sorts of CP violating mechanisms than those models which exclude antimatter altogether. The determination by AMS of whether the universe does or does not contain domains of antimatter beyond our local supercluster of galaxies is of great importance to particle physics.

B-factories currently being developed to study CP violation in the B-meson system may provide information pertaining to baryon asymmetry. However current understanding suggest that CP violation in the B-system is most likely unrelated to the CP violation necessary to produce cosmological baryon asymmetry. In particular, just as CP violation, present in the kaon system from a phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix, is too small to produce the observed cosmic asymmetry, similar conclusions are likely to hold for the B-system. It is possible that CP violation beyond the phase of the CKM matrix is operative in the B-system, and B-factories are likely to reveal whether or not this is the case. However, new sources of CP violation which have been suggested for the origin of the baryon asymmetry do not typically lead to significant new CP violation in the B-system.

3 AMS experiment design principles

Search of antimatter requires the capability to identify with the highest degree of confidence, the type of particle traversing the experiment together with the absolute value and the sign of its electric charge. This can be achieved through repeated measurements of the particle momentum (Spectrometer), velocity (Time of Flight, Transition Radiation detectors) and energy deposition (Ionization detectors).

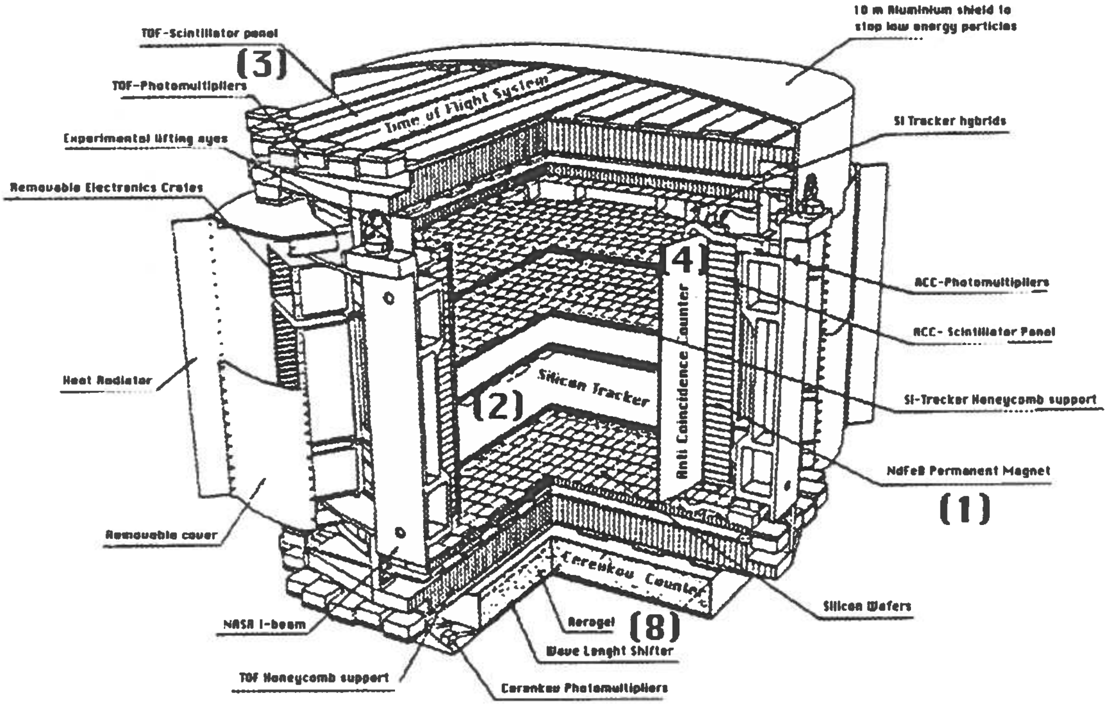

Figure 5: *Detector configuration on STS91 precursor flight*

The design principles of the AMS experiment are shown in Figure 4, while the experiment configuration for the precurson flight is shown in Figure 5. It consist of a large acceptance magnetic spectrometer (about 0.6 m^2sr) made of a new type permanent Nd-Fe-B magnet (1), surrounding a six layer high precision silicon tracker (2) and surrounded by a time of flight scintillator system (ToF) (3). A scintillator anticounter system (4), located on the magnet inner wall, two transition radiation trackers (TRT) located below and above the magnet (5), and a solid state Cherenkov (6) detector, complete the experiment. A thin (0.3 X_o) W converter (7) is located on the upper part the experiment to allow the detection of high energy gamma rays through their conversion in to e^+e^- pairs. While on the Space Station the complete AMS experiment will operate, a reduced configuration (baseline) will be deployed on the precursor flight. The baseline configuration includes the magnet with the anticounter system, the time of flight, the silicon tracker, equipped on 50% of its area and a threshold Cherenkov counter (8).

The magnet is based on recent advancements in permanent magnetic material and technology (Figure 6) which make it possible to use very high grade Nd-Fe-B to construct a permanent magnet with $BL^2 = 0.15\ Tm^2$ weighting ≤ 2 tons. A charged particle traversing the spectrometer will trigger the experiment through the ToF and TRT systems. The ToF will measure the particle velocity with a resolution of ~ 100 ps over a distance of ~ $1.4m$. Figure 7 shows the ToF resolution as measurend on a test beam (Palmonari 1996).

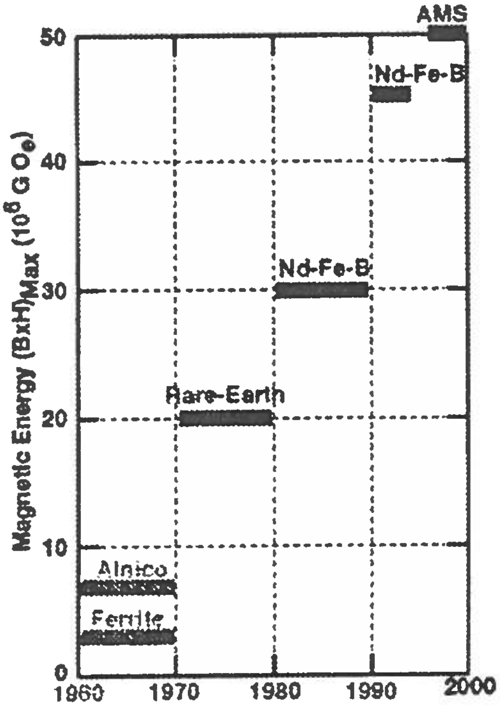

Figure 6: *Avancement of permament magnet materials since 1960*

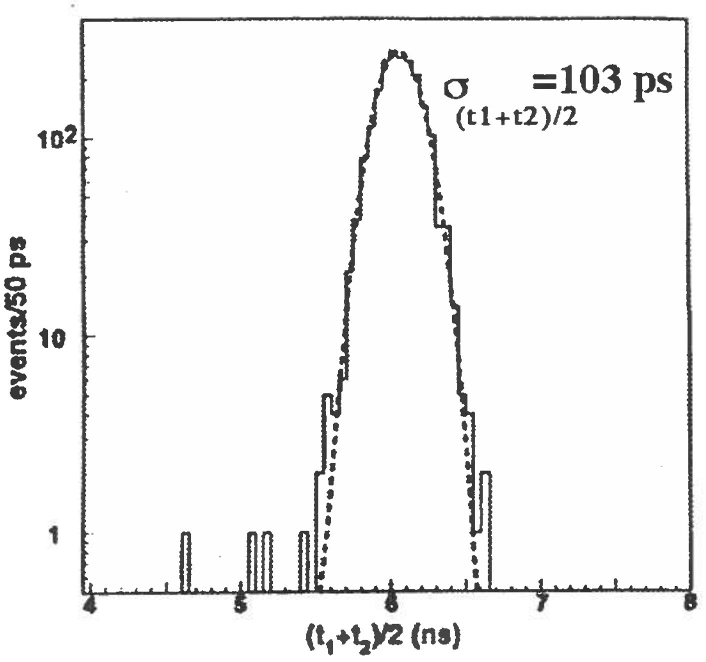

Figure 7: *Time of Flight detector resolution as measured in a test beam*

Figure 8 shows the proton rejection capability of the AMS TRT system (Dolgoshein et al., 1993) at 90% e-detection efficiency, versus particle momentum.

The momentum resolution of the silicon spectrometer is given in Figure 9 (Battiston, 1994): at low rigidities, below 8 GV, its resolution is dominated by multiple scattering ($\frac{\Delta p}{p} \sim 7\%$) while the maximum detectable rigidity is about 500 GV. The parameters of the silicon spectrometer are given in Table 1. Both the ToF scintillators and the silicon layers measure $\frac{dE}{dx}$, allowing a multiple determination of the absolute value of the particle charge.

Table 1: *AMS silicon tracker parameters*

Number of planes	6
Accuracy (bending plane)	10 μm
Accuracy (non bending plane)	30 μm
Number of channels	172000
Power consumption	400 W
Weight	130 kg
Silicon Area (double sided)	6 m^2

By combining the various measurement it is then possible to determine the type of particle traversing the magnet and/or to distinguish interesting particles from background. Let we look at a few examples:

- antimatter: antinuclei heavier than $\bar{H}$ would give the distinct signal of a neg-

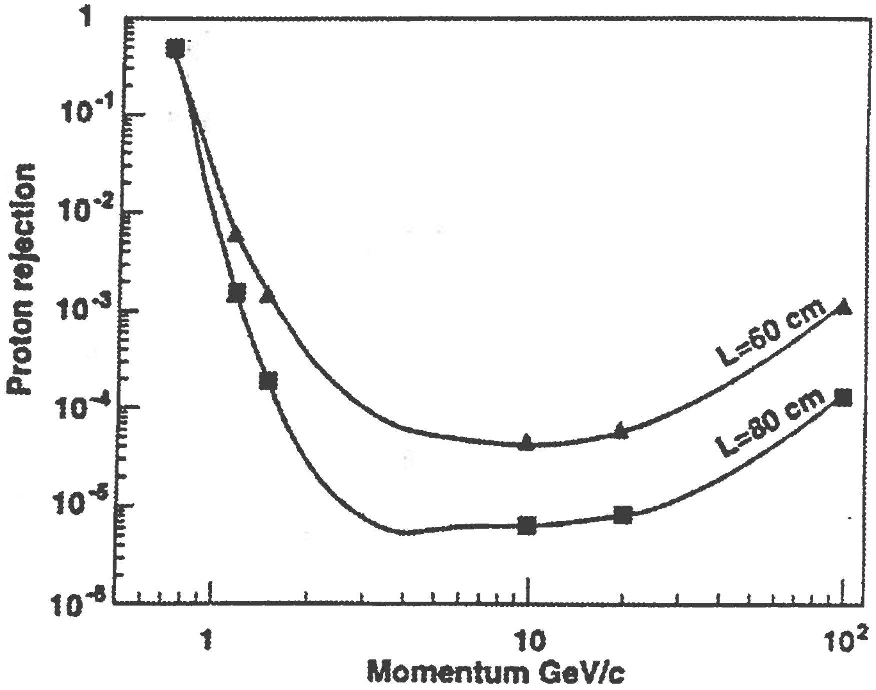

Figure 8: *AMS TRT p-rejection efficiency for* 90% *e-detection efficiency versus particle momentum (MC simulation based on test beam data)*

ative charged particle with $|Z| \geq 2$. The signed momentum measured in the spectrometer toghether with the absolute charge measured by $\frac{dE}{dx}$ are used in this measurement. The most important backgrounds are due to

- albedo nuclei entering the detector from below. This background is rejected by using the signed ToF measurement together with the redundant directional information of the Cherenkov detectors.
- errors in the measurement of the track sign induced by nuclear scattering in the tracker material. These events are rejected by comparing two independent momentum measurements performed in the silicon tracker together with the ToF velocity measurement.

A detailed Monte Carlo simulation has shown that AMS has a 10^{-10} sensitivity ($1\ \sigma$) for finding $\bar{He}$ and $\bar{C}$.

- antiprotons: $\bar{p}$ signal corresponds to a negative charged particle with $|Z| = 1$. Given the relative abundances, the most important physical background to $\bar{p}$ are electrons. Additional backgrounds are given by negative pions and muons produced in the vicinity of the spectrometer and by positive albedo particles entering the spectrometer from below. Detailed simulations have shown that up to about 2.4 GeV/c antiprotons are unambiguously identified using the ToF measurement of their velocity and the signed momentum measured by the spectrometer (the

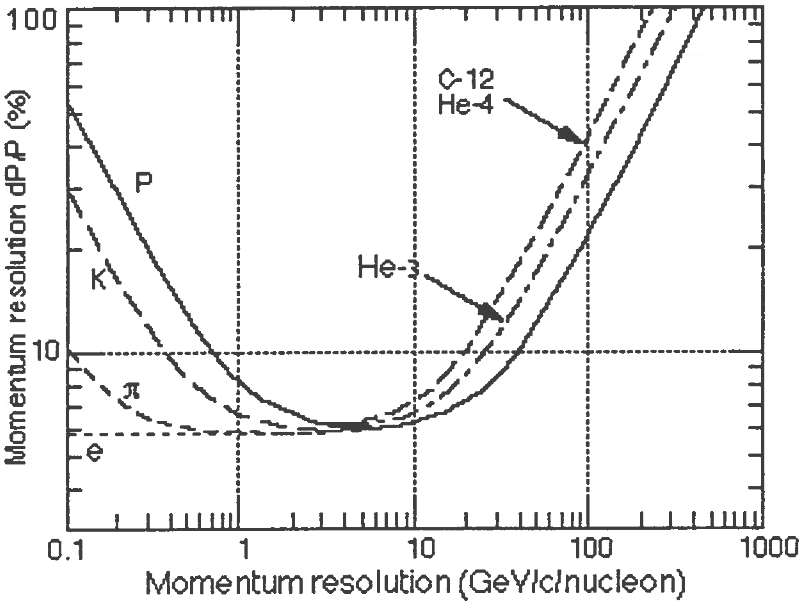

Figure 9: *Expected momentum resolution of the AMS silicon tracker*

absolute value of the charge is given by the $\frac{dE}{dx}$ measurements). In addition during the precursor flight $\bar{p}$ will be identified up to about 5 GeV/c by the threshold Cherenkov detector while on the Station the TRT detectors will allow a rejection of e^- up to much higher energies. Albedo particles will be rejected as before using the ToF and Cherenkov detectors.

- positrons: e^+ signal corresponds to a positive charged particle with $|Z| = 1$. Given the relative abundances, the most important physical background to e^+ are protons followed by positive pions and muons produced in the vicinity of the spectrometer and and by negative albedo particles entering the spectrometer from below. Positrons will be identified using the the spectrometer and ToF together with the threshold Cherenkov counter on the precursor flight and the TRT's on the Station flight, respectively. Albedo particles are rejected as in the previous cases.
- photons: about $\sim 25\%$ of incoming photons will convert in the 0.3 X_o W layer creating an e^+e^- pair. The excellent accuracy and resolving power of the silicon tracker will allow identification of high energy gamma rays from 100's of MeV to 100's of GeV. By measuring independently the e^+e^- quadrimomenta, the energy and the direction of the incoming photon can be measured. Gamma energy resolution is about 25%, dominated by the bremsstrahlung processes in the W converter, while the angular resolution follows the law $\sigma(\psi_{0.68\%}) = 0.96^\circ(\frac{E_\gamma}{1\ GeV})^{-0.92}$.

4 AMS physics potential

The physics objectives of AMS are:

- search for Antimatter ($\bar{H}e$ and $\bar{C}$) in space with a sensitivity of 10^4 to 10^5 better than current limits.

The breakdown of the Time-Reversal symmetry in the early universe might have set different sign for the production of matter and antimatter in different regions of space. Since there are $O(10^8)$ super clusters of galaxies and the observational constraints are limited to the scale of the local supercluster, the universe can be symmetric on a larger scale. The observed matter-antimatter asymmetry is then a local phenomenon. Figure 10a,b shows the sensitivity of AMS, after three years on ISSA, in detecting $\bar{H}e$ and $\bar{C}$ compared to the current limits. In Figure 10a we have included the prediction of $\bar{H}e$ yield as predicted by a model assuming a matter-antimatter symmetric universe at the level of super-cluster of galaxies (Ahlen et al., 1982). As seen from the figure, the current limits are not sensitive enough to test the existence of superclusters of galaxies of antimatter and AMS is 10^3 times more sensitive than this prediction based on matter-antimatter symmetric universe.

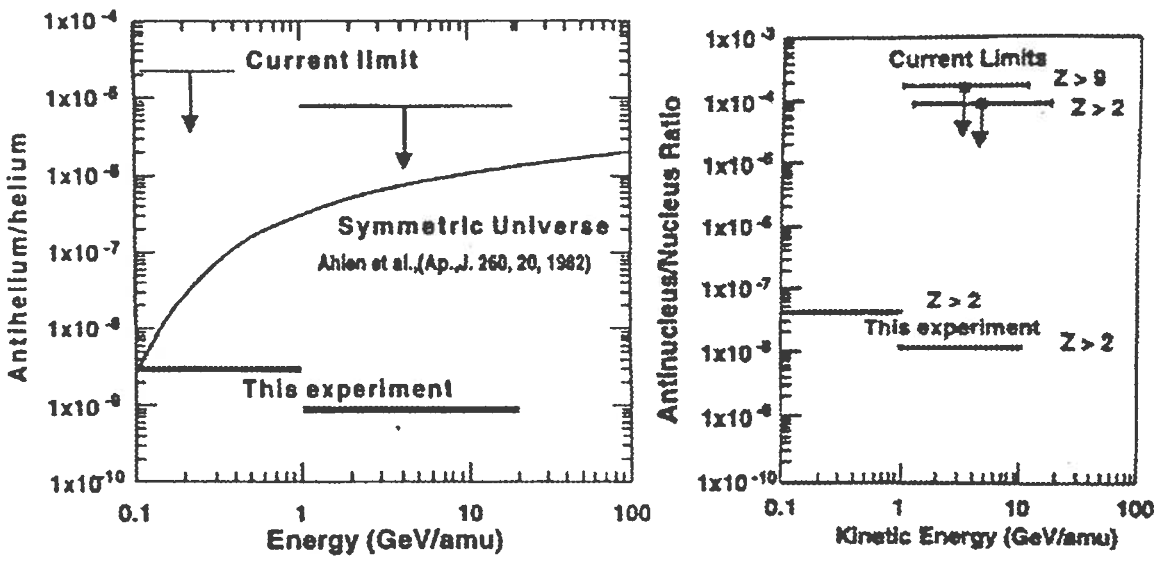

Figure 10: *Sensitivity of AMS (3 years on ISSA) in a search for (a)* $\bar{H}e$*; (b)* $Z > 2$ *antinuclei (95% C.L.).* $\bar{H}e$ *sensitivity is compared to a prediction assuming a matter-antimatter symmetric universe.*

- search for dark matter by high statistics precision measurements of $\bar{p}$, e^+ and γ spectra.

These measurements will allow direct searches for the various annihilation and decay products of WIMP's in the galactic halo:

$$\bar{\chi} + \chi \rightarrow \bar{p} + ..., \quad \bar{\chi} + \chi \rightarrow e^+ + ..., \quad \chi, \bar{\chi} \rightarrow \gamma\gamma \tag{2}$$

Figure 11 shows the simulation of the 100 hour measurement of the $\bar{p}$ flux on the precursor flight compared to a compilation of existing $\bar{p}$ data together with a prediction of the effects of an heavy neutralino (Jungman and Kamionkowski, 1994). Similarly Figure 12 shows the simulation of three years of AMS e^+ data compared to the existing measurements. The accuracy of the AMS measurement of the $\frac{e^+}{e^-}$ spectrum will allow to test the existence of an heavy neutralino ($m_\chi \sim 100\ GeV$) (Kamionkowski and Turner, 1991). Also the measurement of the γ spectrum will test the existence of neutralinos in case of R-parity violating SUSY models, through its decay in two photons with $E_\gamma = m_\chi/2$ (Bergstrom, 1989;Berezinsky, Masiero, Valle, 1991; Stecker, 1996). The number of high energy γ expected for χ ($\bar{\chi}$) decay is given as a function of the neutralino mass in Table 2: above $m_\chi \sim 80\ GeV$ the contributions to the extragalactic γ background due to χ decay would exceed a 5 σ effect.

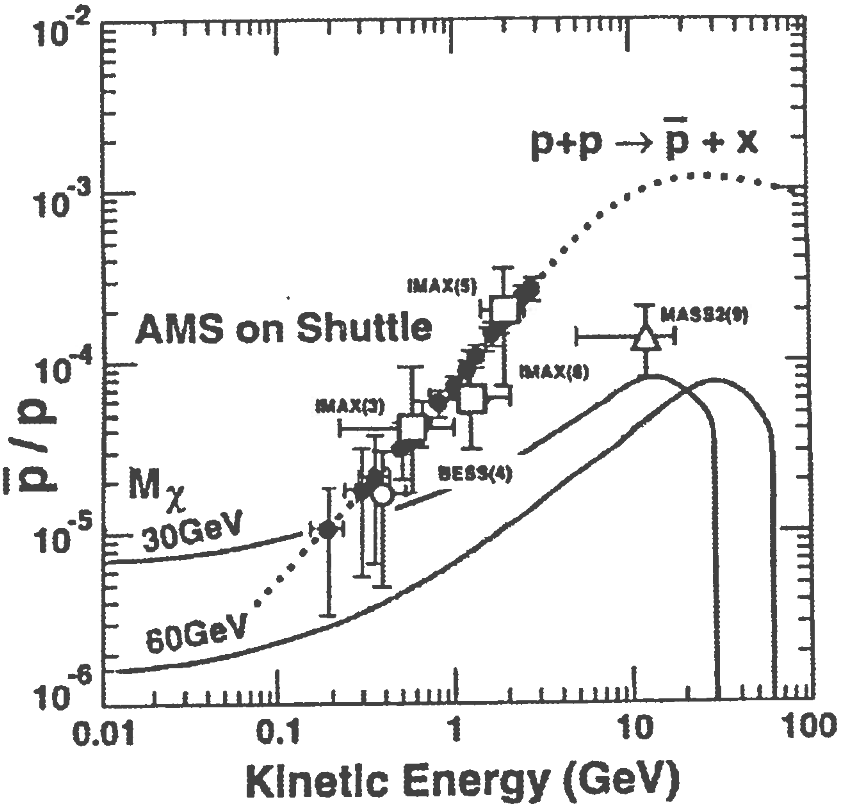

Figure 11: *Simulated 100 hour shuttle flight* $\bar{p}$ *measurement by AMS, compared with a compilation of existing* $\bar{p}$ *data.*

- astrophysical studies by high statistics precision measurements of D, $^3He, B, C$, ^9Be, ^{10}Be spectra.

Precision measurement of isotopes and elemental abundances in Cosmic Rays (CR) give very important informations about CR origin, their galactic confinement time and their propagation inside and between galaxies. This is deeply related to the search for antinuclei, since antimatter particles, to be detected, should excape a region of the universe dominated by antimatter, propagate through the intergalactic void separating superclusters and enter our galaxy. As an example AMS will measure in three months $5\ 10^7$ deuterium events reducing the current uncertainty on D/p by a factor of 100. Similarly, AMS will be able to separe ^3He from ^4He up to 5 GV of rigidity, thus collecting in three years $\sim 4\ 10^8$ ^3He and $\sim 4\ 10^9$ ^4He, reducing the existing uncertainties by a factor 200. The ratio $\frac{B}{C}$, which constrains the parameters regulating the outflowing galactic wind, can be measured by AMS better than the current data within one day and up to 100 GV of rigidity. On the other side, the ratio $\frac{^{10}Be}{^9Be}$ determines the CR confinement time; at present, a dozen of ^{10}Be events have been detected during more than forteen years of observations and the CR galactic confinement time is currently known within a large uncertainty ($\sim 40\%$). With AMS it will be possible to detect tens of ^{10}Be/day in the 1 GV range, thus dramatically reducing the error on CR confinement time.

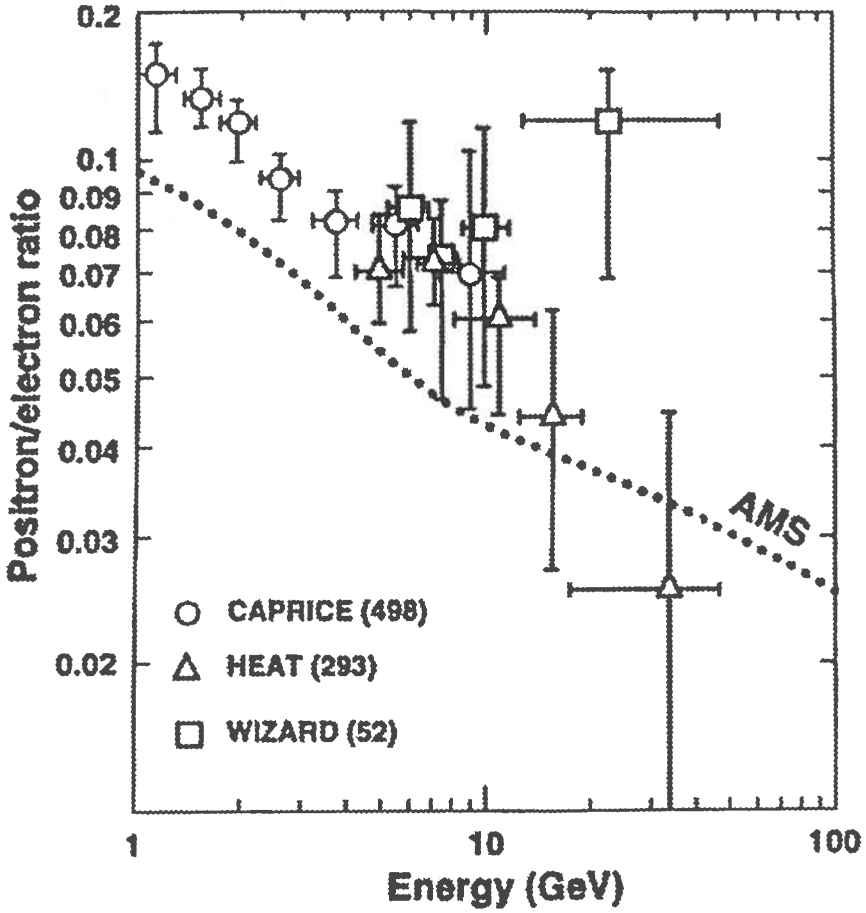

Figure 12: *Simulated 3 years AMS* e^+ *measurement compared with a compilation of existing* e^+ *data.*

Table 2: *Rates for γ rays diffuse extragalactic background for R-parity violating χ decays*

m_χ	E_γ	ΔE_γ	N_{back}	$N_{5\sigma}$	N_χ
6	3	0.6	3250	297	5
20	10	2	970	156	16
60	30	6	300	87	47
100	50	10	170	65	79
200	100	20	83	46	157

Table 3: *Comparison of EGRET and AMS γ detection capabilities*

Parameter	EGRET	AMS
Peak effective area ($cm^2 sr$)	1500	2100
Angular resolution (68%)	$1.7^o(\frac{E_\gamma}{1\ GeV})^{-0.534}$	$0.96^o(\frac{E_\gamma}{1\ GeV})^{-0.92}$
Mean opening angle	$\sim 25^o$	$\sim 27^o$
Total viewing time	$\sim 2.5\ yr$	$\sim 3\ yr$
Source flux sensitivity ($> 100 MeV$)	$1\ 10^{-7} cm^{-2} s^{-1}$	$7\ 10^{-8} cm^{-2} s^{-1}$
Detector energy range (GeV)	$0.02\ to \sim 50$	$0.1\ to \sim 300$

In addition, the capability of AMS of detecting high energy γ rays would make it possible to perform very important observations in gamma ray astrophysics after the turn off of the EGRET experiment (within one or two years). Simulations suggest indeed that the performance of AMS is comparable to if not better than EGRET, in spite of the fact that AMS on the Space Station will not be able to point to targets of opportunity (Fiandrini, 1996). A comparison between the two experiments is shown in Table 3, while the expected sensitivity ratio between one year of AMS data and EGRET total data is shown in Figure 13.

We can see that, integrating over three years, AMS will be about a factor of three more sensitive than EGRET over most of the sky. Before the advent of new gener-

Table 4: *Physics capabilities of AMS after three years on ISSA*

Elements	Yield (or sensitivity)	(Now)	Energy Range (GV)	Physics
e^+	10^8	$(\sim 10^3)$	0.1 – 100	↑
$\bar{p}$	500000	(~ 30)	0.5 – 100	Dark Matter (SUSY)
γ			0.1 – 300	↓
$\bar{He}/He$	$\frac{1}{10^9}$	$(\frac{1}{10^5})$	0.5 – 20	Antimatter
$\bar{C}/C$	$\frac{1}{10^8}$	$(\frac{1}{10^4})$	0.5 – 20	CP vs GUT , EW
D, H_2	10^9		1.0 – 3.0	↑
$^3He/\ ^4He$	10^9		1.0 – 3.0	Astrophysics
$^{10}Be/\ ^9Be$	2%		1.0 – 3.0	↓

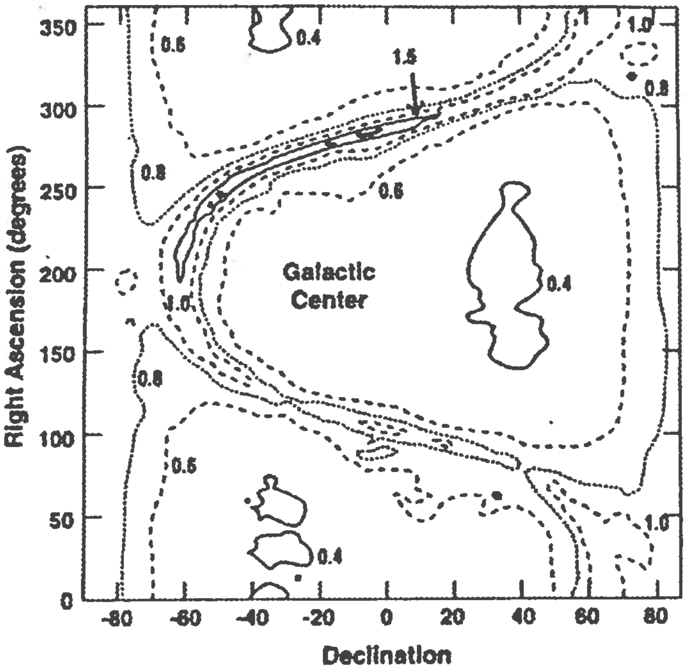

Figure 13: *AMS one year γ flux sensitivity as a function of the position on the celestial sphere. Units=* $10^{-8}\gamma/cm^2s$ *GeV at* 1 *GeV. EGRET flux sensitivity is* 1 *in above units, numbers smaller than* 1 *means AMS sensitivity to lower fluxes*

ation gamma ray space facilities, AMS will then be the only space born experiment to continue the EGRET mission at the beginning of the next century, covering the interesting region $E_\gamma = 30 - 300GeV$. These data will extend our knowledge in key areas of γ astrophysics like: Active Galactic Nuclei (AGN), blazars, γ-bursters. They will also allow a measurement of the extragalactic γ background and of the interaction of high energy γ rays with the black-body microwave background.

The physics capabilities of AMS after three years of exposure on the ISSA are summarized in Table 4.

5 Conclusion

During the past forty years, there have been many fondamental discoveries in astrophysics measuring UV, X-ray and γ-ray photons. There has never been a sensitive magnetic spectrometer in space, due to the extreme difficulty and very high cost of putting a superconducting magnet in orbit. AMS will be the first large acceptance magnetic detector in space. It will allow a measurements of the flux of all kind of cosmic rays with an accuracy orders of magnitude better than before. The large improvement in sensitivity given by this new instrument, will allow us to enter into a totally new domain to explore the unknown.

6 References

AMS Collaboration :1994, Alpha Magnetic Spectrometer for Extraterrestrial Study of Antimatter, Matter and Missing Matter on the International Space Station Alpha, Proposal.

Ahlen, S. et al.: 1982,Ap. J. **260**, p. 20.

Battiston, R. : 1995, Nucl. Instr. and Meth. (Proc. Suppl.) **B44**, p. 274.

Berezinsky, V., Masiero, A., Valle, J.W.F. : 1991, P.L. **B266**, p. 382.

Bergstrom, L.: 1989, P.L. **B225**, p. 372.

Dolgoshein, B. A. et al.: 1993, Nucl. Instr. and Meth.**A336**, p. 434.

Ellis, J. et al.: 1988, Phys. Lett. **B214**, p. 403.

Fiandrini, E.: Proc. 6th Topical Seminar on "Experimental Apparatus for Particle Physics and Astrophysics", San Miniato al Todesco, Italy, 20-24 May 1996, Nucl.Phys. B. Proc. Suppl. in press.

Kamionkowski, M., Turner, M.S. : 1991, P.R. **D43**, p. 1774.

Kolb, E.W., Turner, M.S.: 1983, Ann. Rev. Nucl. Part. Sci. **33** p. 645.

Jungman G., Kamionkowski,M. : 1994, P.R. **D49**, p. 2316.

Palmonari, F. : 1996, private communication.

Peebles, P.J.E.:1993, Principles of Physical Cosmology, Princeton University Press, Princeton N.J.

Sakharov, A.D.: 1967, JETP Lett **5**, p. 24.

Steigmann G.: 1976, Ann. Rev. Astron. Astroph., **14** p. 339.

Stecker, F.W.: Proc. 2nd Int. Symp. on "Sources and Detection of Dark. Matter in the Universe", S. Monica, CA, February 1996, Nucl.Phys. B. Proc. Suppl. in press.

Ting, S.C.C : 1996, Proceedings XVII International Symposium on Lepton-Photon Interactions, Beijing, China, 15 August 1995, CERN-PPE/96-70, 23 may 1996.

Turner, M.S., Wilzek, F.: 1990, Phys. Rev. **D42**, p. 1001.