Signals for new symmetries: Arnowitt's forte, my passion

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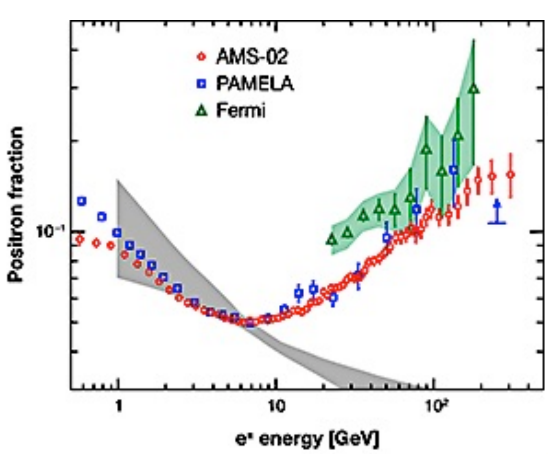
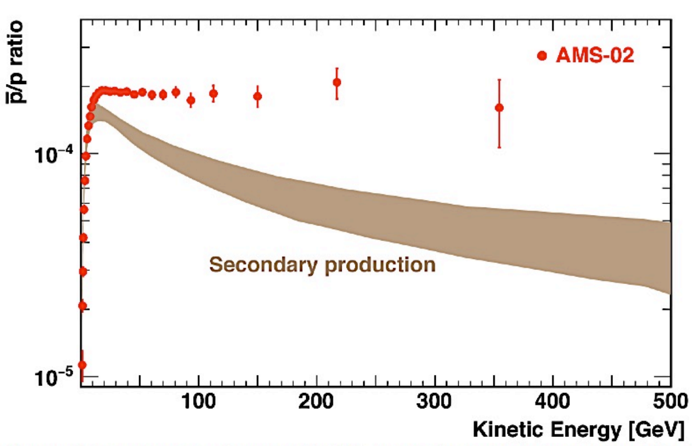
When a particle carrying a flavor under a new symmetry is born, it cannot decay by strong or electromagnetic interactions into lighter particles that do not carry that symmetry. The most likely mechanism for its ultimate decay is the weak interaction, in which it could decay into particles that in turn ultimately decay into a final state involving leptons and neutrinos. For a century signals involving energetic positrons have been the most productive fingerprint for identifying a new flavor of matter: from beta decay of nuclei, to particles carrying strangeness, charm, beauty, and truth, to the weak bosons and the Higgs boson.

In 2013 the Alpha Magnetic Spectrometer reported a broad maximum in the spectrum of energetic positrons (e^+/e^-) peaked at ~350 GeV, which would suggest a possible origin from the decay or annihilation of a new-flavor particle with a mass > TeV.

Astrophysicists suggested the possibility of an alternative origin from acceleration and cascade of electrons in the mantle of a pulsar somewhere in our galaxy. But this year AMS reported a second result: a plateau in the spectrum of antiprotons ($\bar{p}/p$) out to the same energy. Antiprotons could be produced in the decay or annihilation of a massive new-flavor particle, but could not plausibly originate from a pulsar.

Richard Arnowitt was long a leading thinker in devising and analyzing the signals that could most effectively distinguish new flavors and new symmetries of nature. His contributions to phenomenology guided those searches, in particle collider experiments, in rare decay experiments, and in astrophysical observations. At this moment when the AMS results are motivating the next run at LHC, the next generation of dark matter searches underground, and new astrophysical experiments, I feel that Dick's spirit is with us as we strive to find what field of nature is showing its first face to man.





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1934: Fermi theory of beta decay

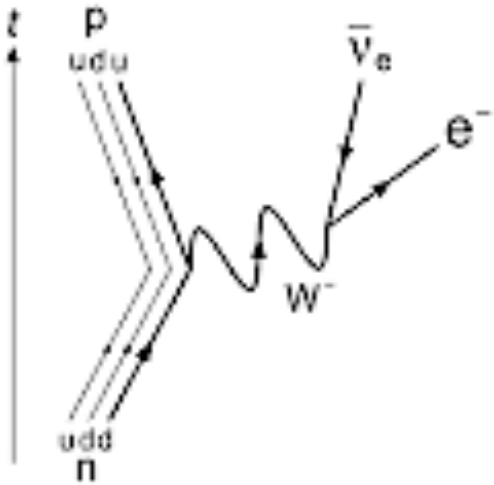
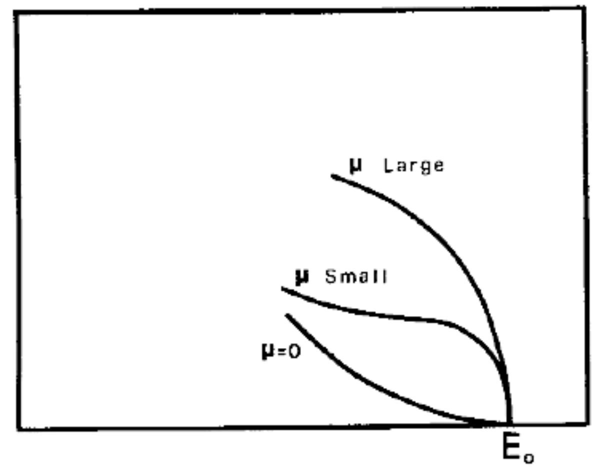
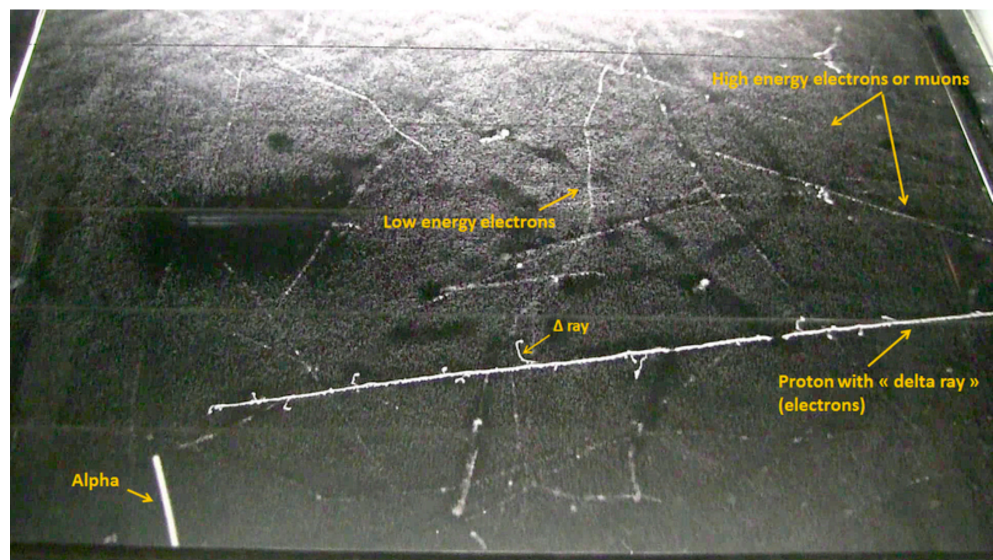


Table I. The value of $F(\eta_0)$ for large values of η_0.

η_0	$F(\eta_0)$
0	$\eta_0^6/24$
1	0.03
2	1.2
3	7.5
4	29
5	80
6	185
7	380

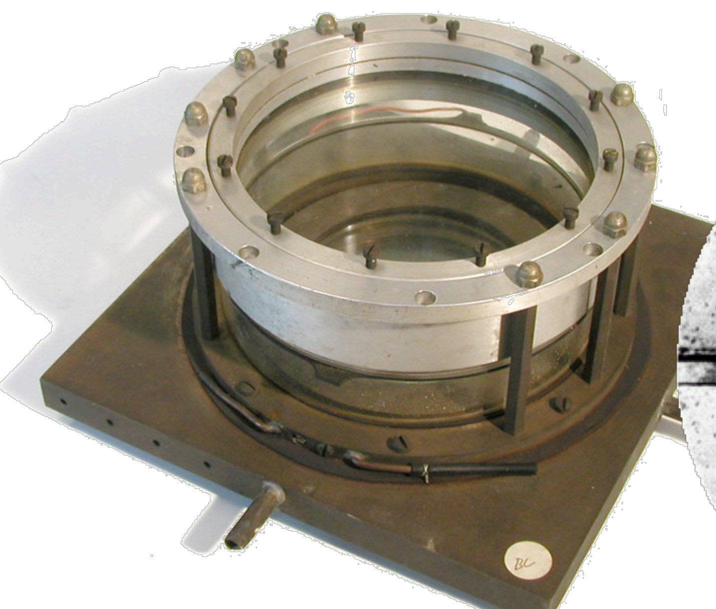


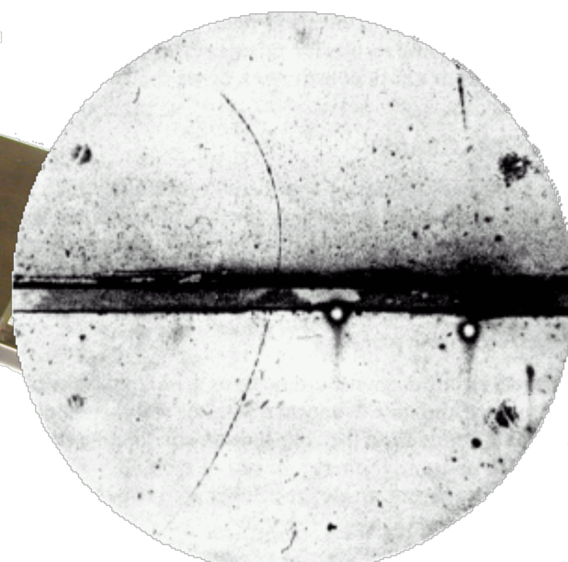
Fermi realized that the systematics of spectra and lifetimes for beta decay of nuclei required an interaction with a near-massless neutrino, and a universal matrix element for a weak interaction.

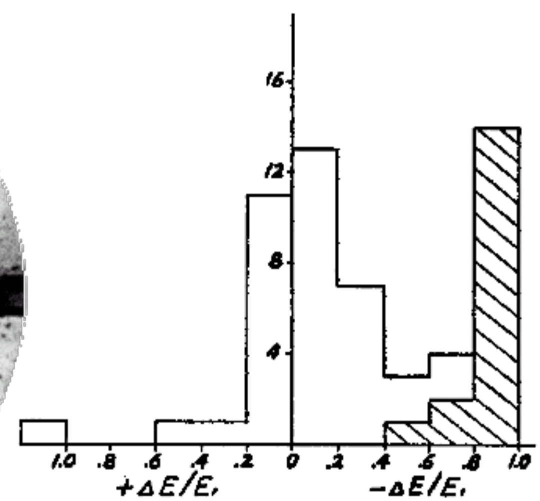


1936: Discovery of the muon

- Anderson and Neddermeyer found tracks of penetrating (electron-like) particles but they had a much larger E/p ratio than electrons.
- Yukawa had predicted the pion with a mass of ~100 MeV, so natural expectation was that it was the carrier of the strong interaction.
- But it did not interact strongly, and it decayed into an electron and missing energy!
- Rabi: 'Who needs a heavy electron?'

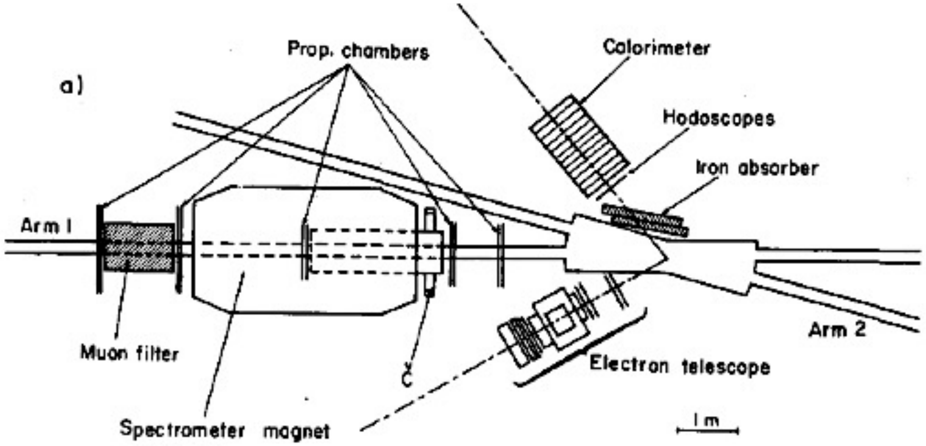


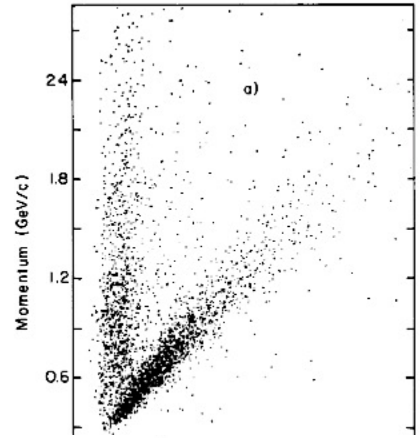


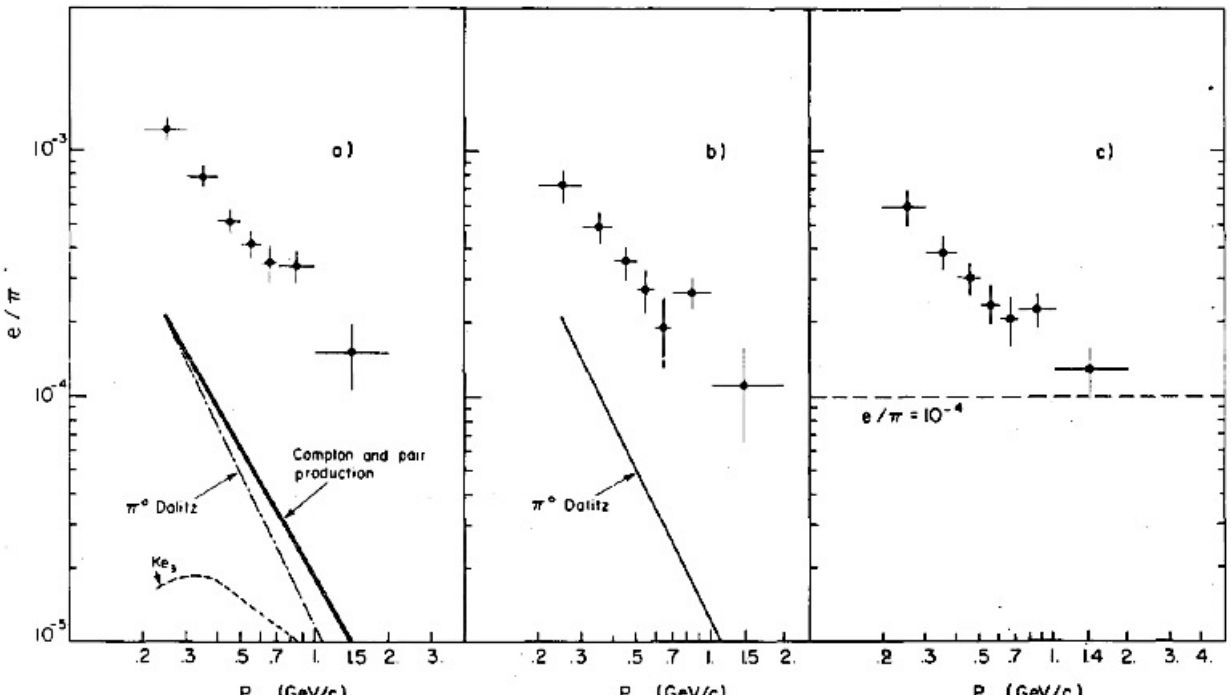


Distribution of fractional losses in 1 cm of platinum.

1975: Single e± signal for charm..

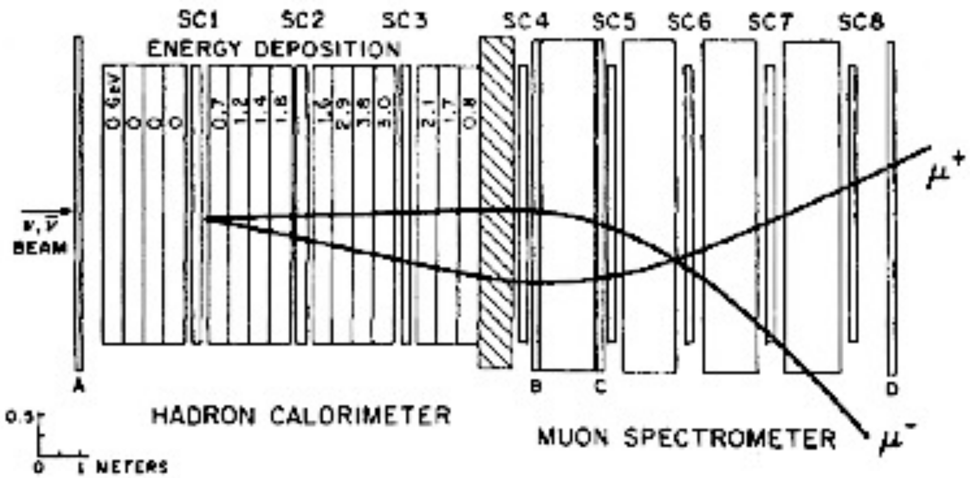






L. Baum *et al.*, 'Experimental observation of a copious yield of electrons with small transverse momenta in pp collisions at high energies', Phys. Lett. B60, 485 (1976).

1977-1980: ν-Produced Dimuon and Trimuon Events: new physics at the lepton vertex -*charm*



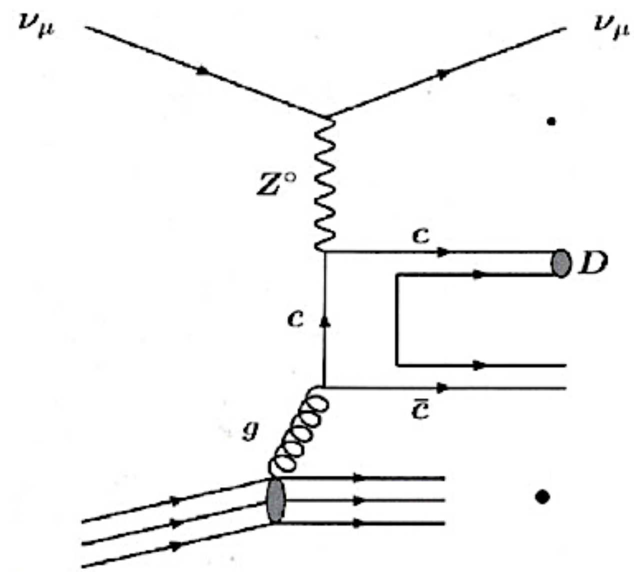


Fig. 4. Gluon-boson fusion graph, NC reaction.

Table 6. Results on trimuon detection.

Experiment	μ_{--+} or μ_{++-}	Ref.	Year
HPFW	39	[Benvenuti 1978a]	1978
FNAL	3	[Barish 1977]	1977
Gargamelle	10	[Aatuft 1983]	1982
CDHS	2	[Holder 1977]	1978
CHORUS	42	[Kayis-Topaksu 2004a]	2003

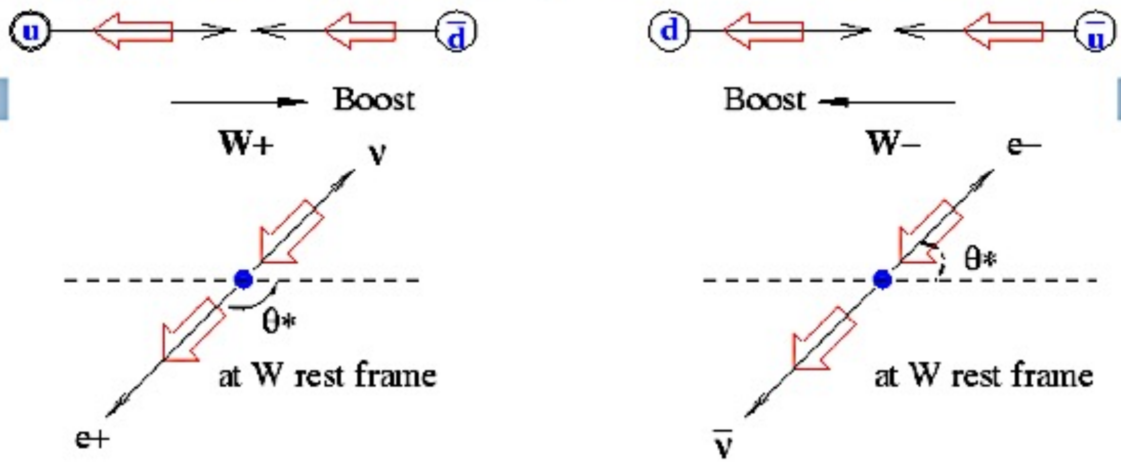
Neutrinos couple to both naked and hidden charm states, and so produce both dimuon and trimuon final states through cascade decays.

Decay modes into electrons cannot be detected since only penetrating particles can be triggered in ν beams.

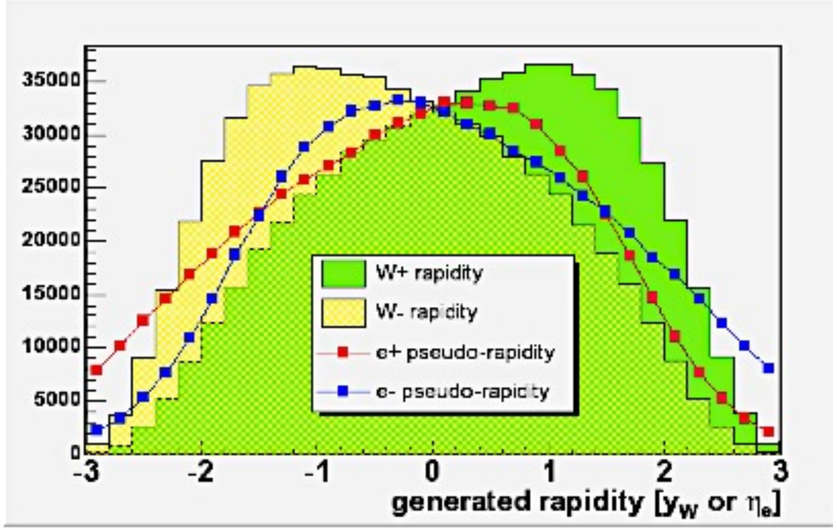
U. Dore, 'Physics with charm particles produced in neutrino interactions. A historical Recollection', Eur. Phys. J. H37 , 115 (2012).

1982-2010: e^+e^- asymmetry for W

W asymmetry in p-pbar collisions



- If u quarks carry more momentum than d quarks, the W^+ will head in the proton direction preferentially.
- Unfortunately, the V-A interaction means that the charged lepton from W decay heads backwards in the W frame

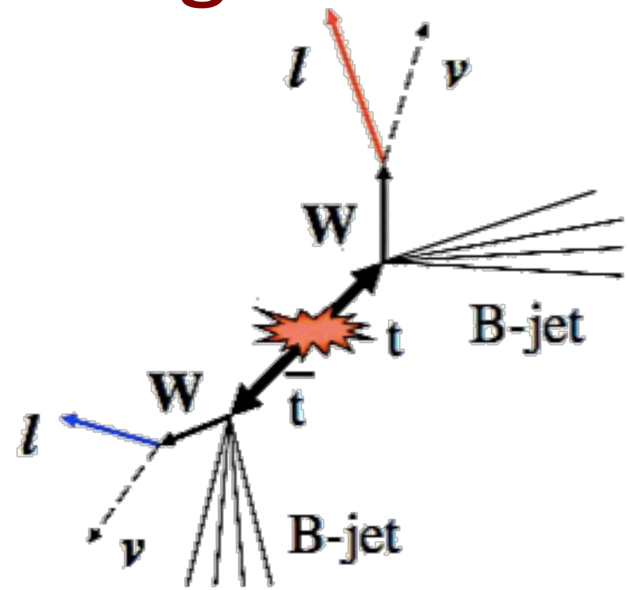


DIS2010 April 19, 2010

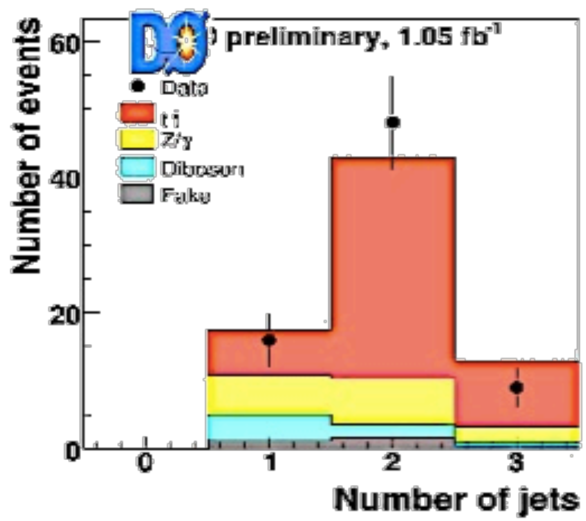
H. Shumann, 'W AND LEPTON ASYMMETRIES AT THE TEVATRON' (2010).

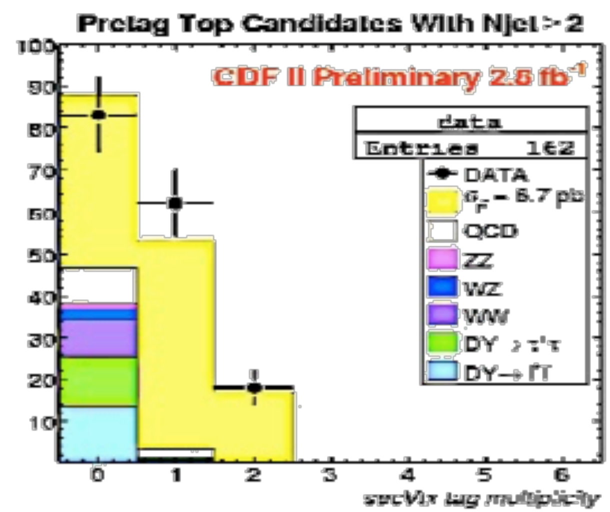
2005-2010: Top quark pairs using $\ell^+ \ell^-$

- Two high p_T leptons (opposite charge) ee, eμ, μμ
- Significant missing transverse momentum
- ≥ 1 jet (eμ), ≥ 2 jets (ee, μμ)



ee,eμ and μμ combined

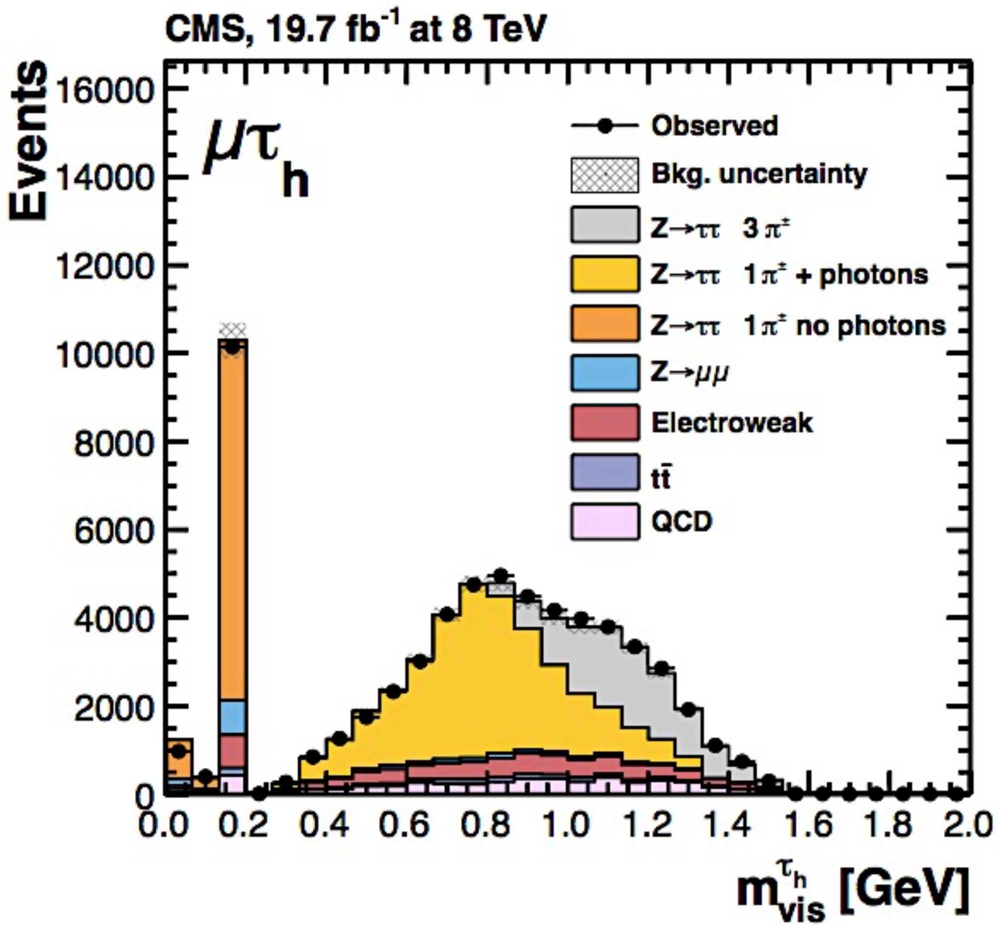




Top quark is needed to describe the b-jet multiplicity distribution in dilepton events

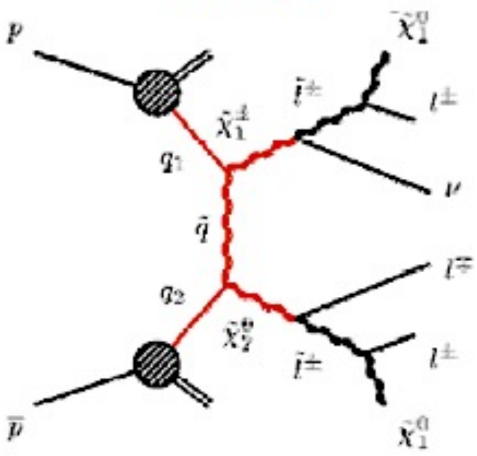
H. Shellmann, 'W AND LEPTON ASYMMETRIES AT THE TEVATRON' (2010).

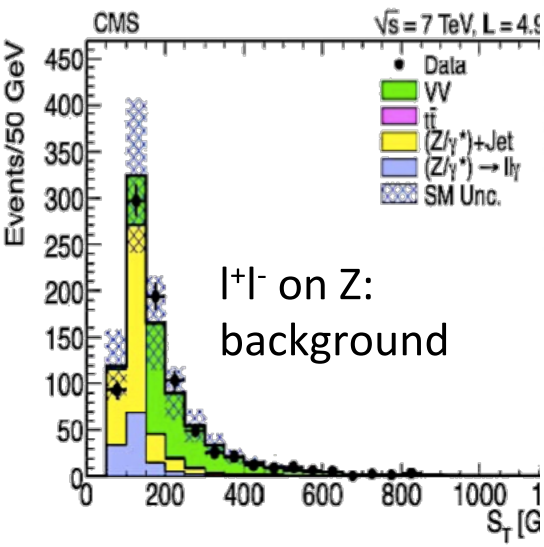
Every rule has an exception:
Higgs couples to mass, couples weakly to *e*

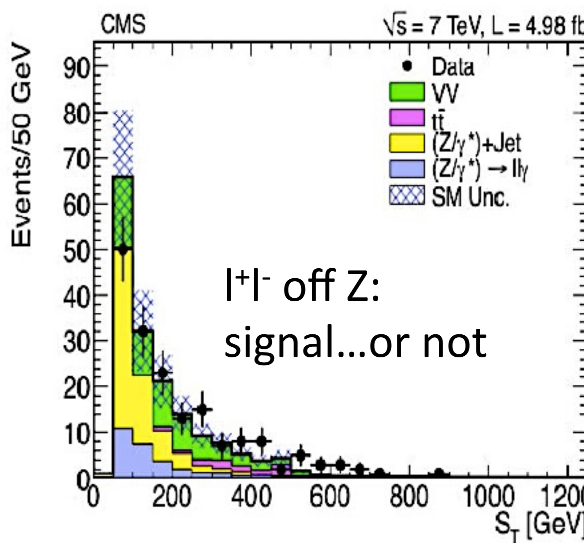


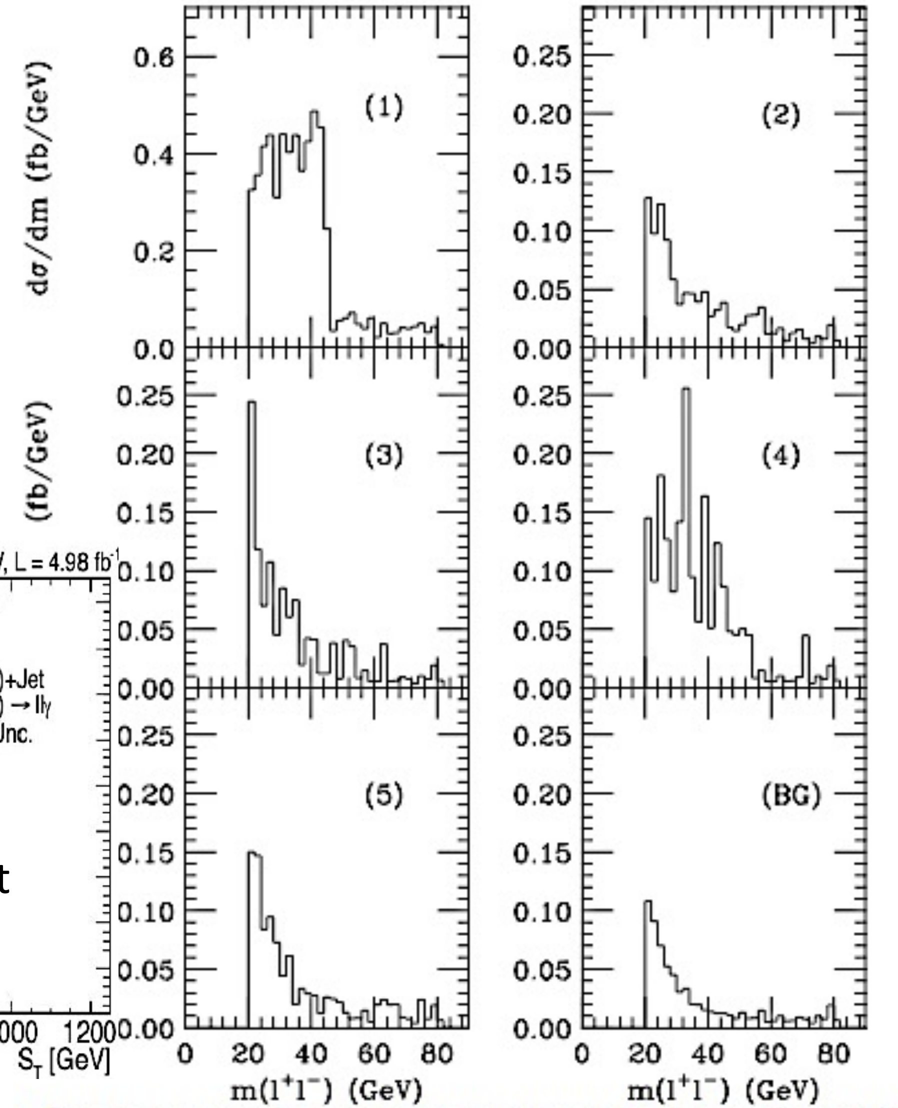
CMS, 'Evidence for the 125 GeV Higgs boson decaying to a pair of τ leptons', arxiv.org/pdf/1401.5041v2.pdf

2012: Searching for SUSY… trileptons







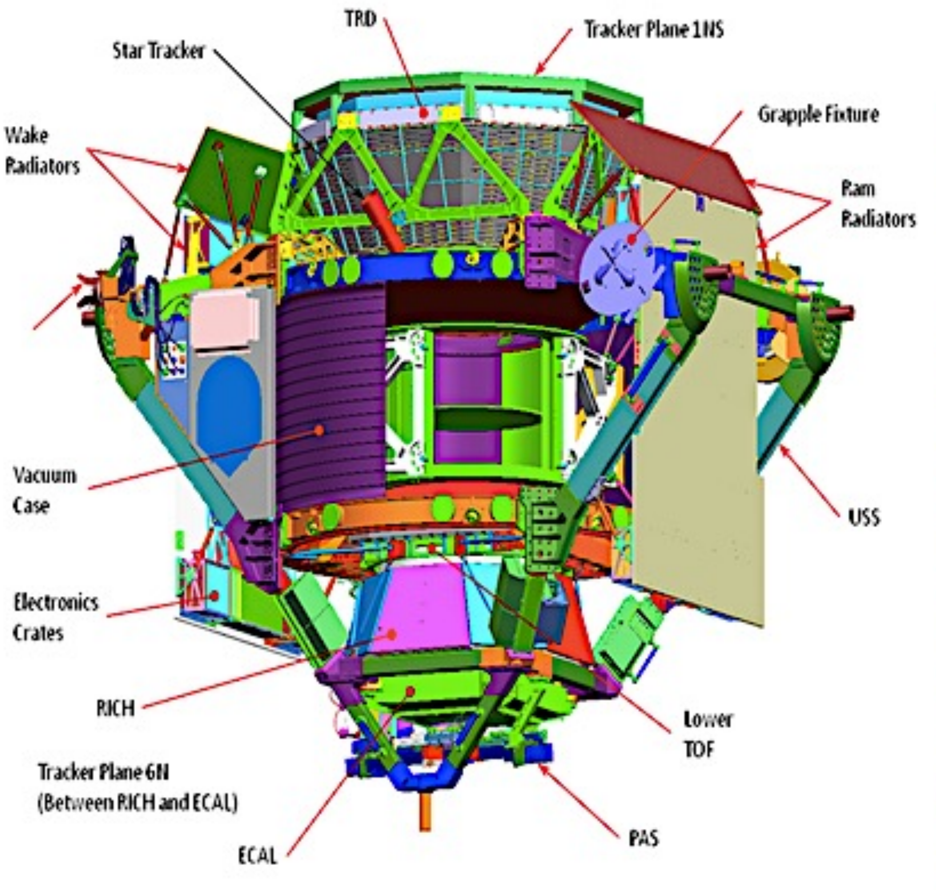


H. Baer *et al*., 'TRILEPTON SIGNAL FOR SUPERSYMMETRY AT THE TEVATRON REVISITED' (2013).
S. Sumalwar, 'Search for anomalous production of multileptons at CMS with 5.0fb^{-1} of 7 TeV data (2012).

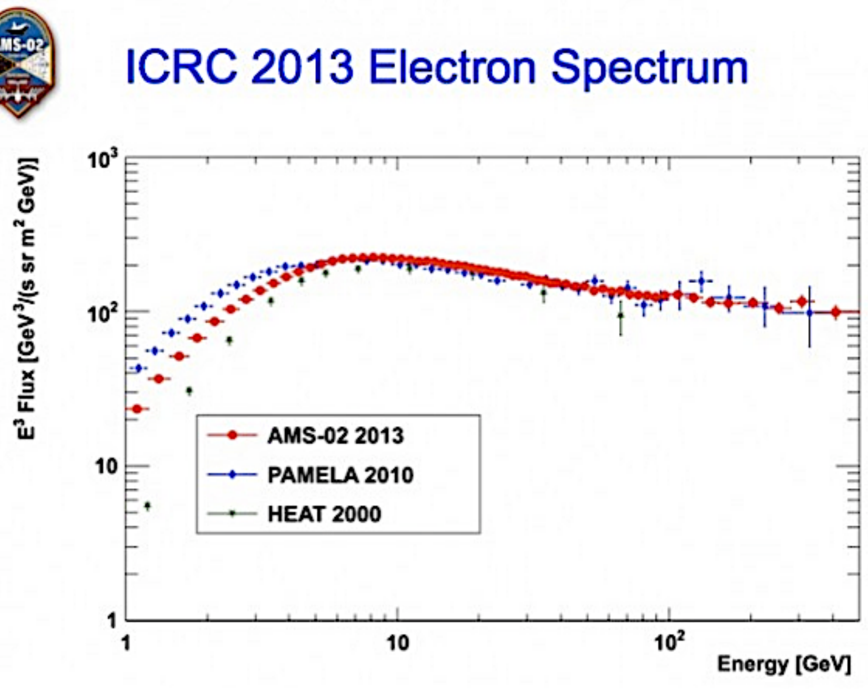
And now AMS…

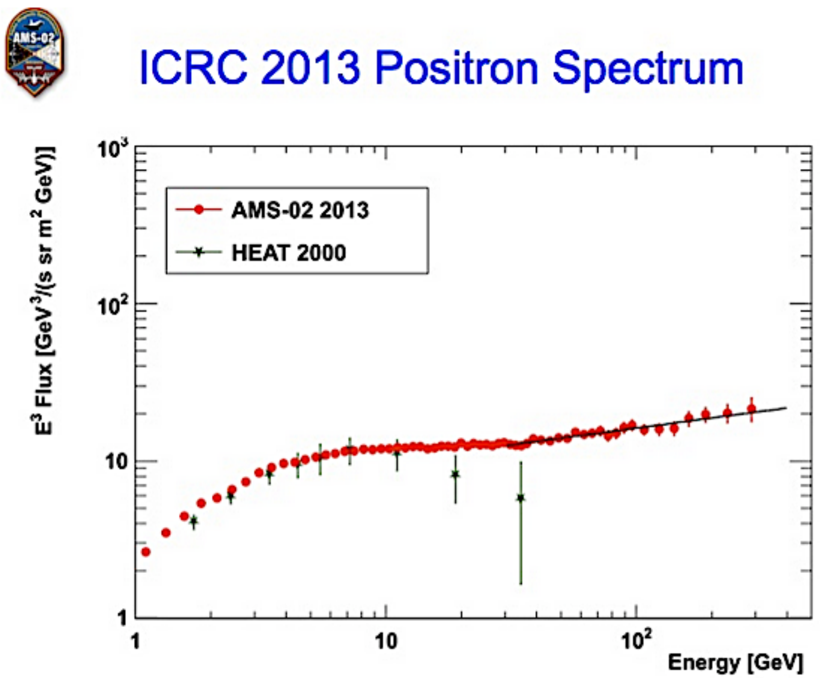
AMS is designed to identify and measure charged particles and photons in primary cosmic rays up to ~500 GeV. Primary objectives:

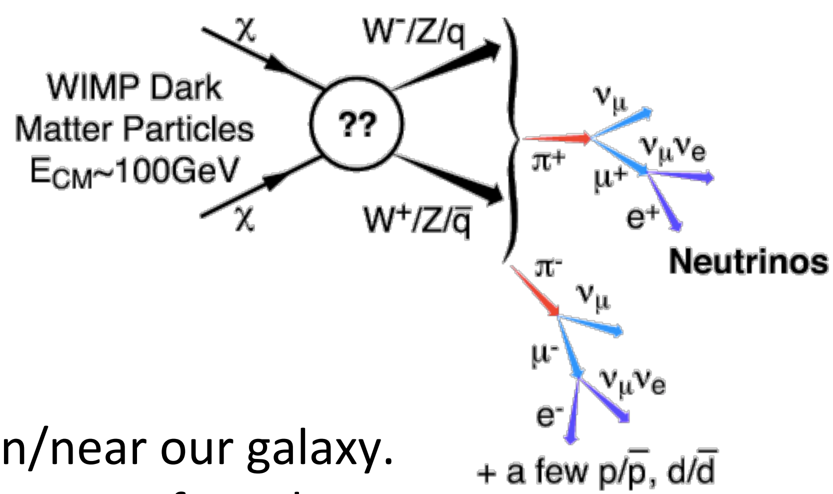
- spectrum of all forms of antimatter (CP puzzle)
- Spectrum of nuclei (baryogenesis)
- spectrum of e^+, e^-, antiprotons from dark matter annihilation



2013: e^+/e^- rises up to 350 GeV

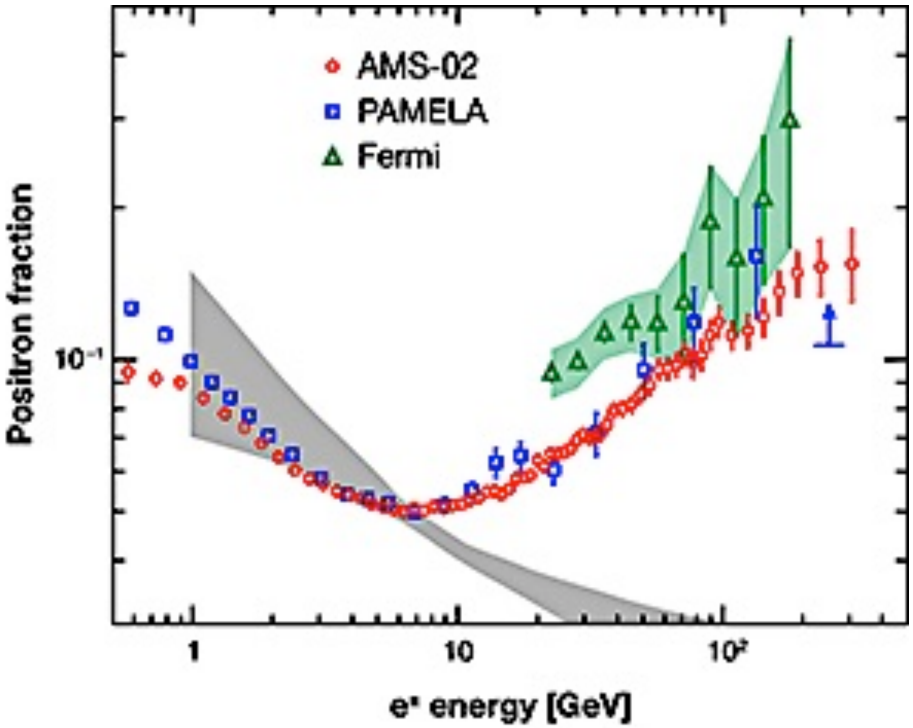


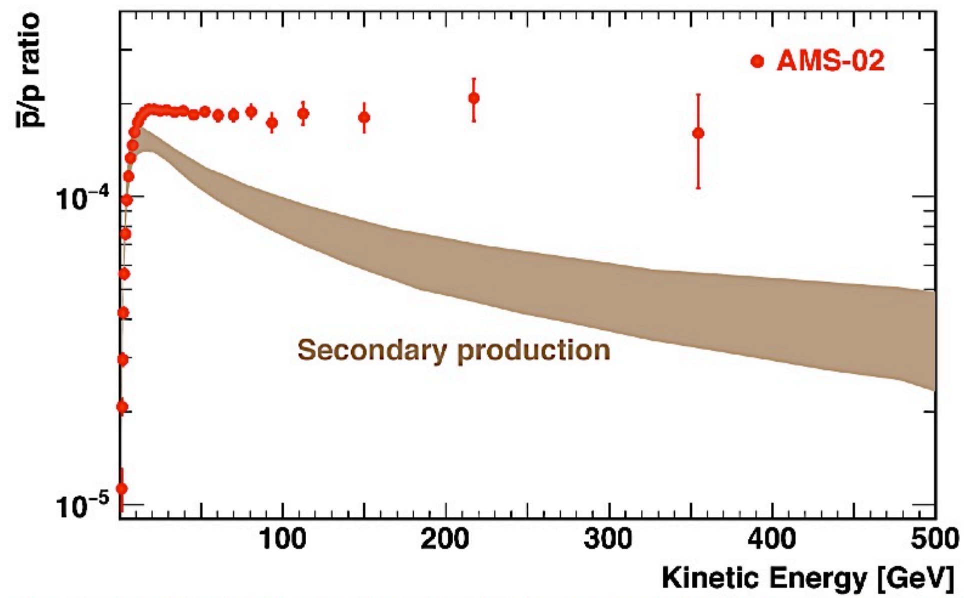




- Could come from annihilation of dark matter in/near our galaxy.
- Could come from pair production in the shock wave of a pulsar.

2015: More statistics on positrons, *antiproton plateau to >350 GeV…*





- Please show me a pulsar that could emit antiprotons...
- And then there is helium….
- AMS asked the questions, and found remarkable answers up to 350 GeV.
- Alas, AMS is running out of acceptance and momentum resolution to extend its results much farther.

An ultimate γ/ X-ray/ $e^{\pm}$ telescope?

From the experience in design, construction, and testing the AMS magnet/cryo systems, I have designed an advanced γ/ X-ray/ $e^{\pm}$ telescope that would be capable of opening a new generation of astrophysics beyond what is possible with SWIFT, FERMI, PAMELA, and AMS.

Three ingredients motivate the design:

➢The *present experiments are starved for acceptance and pointing*, and typically can see only a small portion of the sky at a time (missing most of light curve for GRBs).

➢A few years ago I designed a *superconducting toroid shield* capable of staging on a manned deep-space vehicle to protect astronauts from cosmic rays. Such exploration is not likely to happen soon, but the design was serious and feasible.

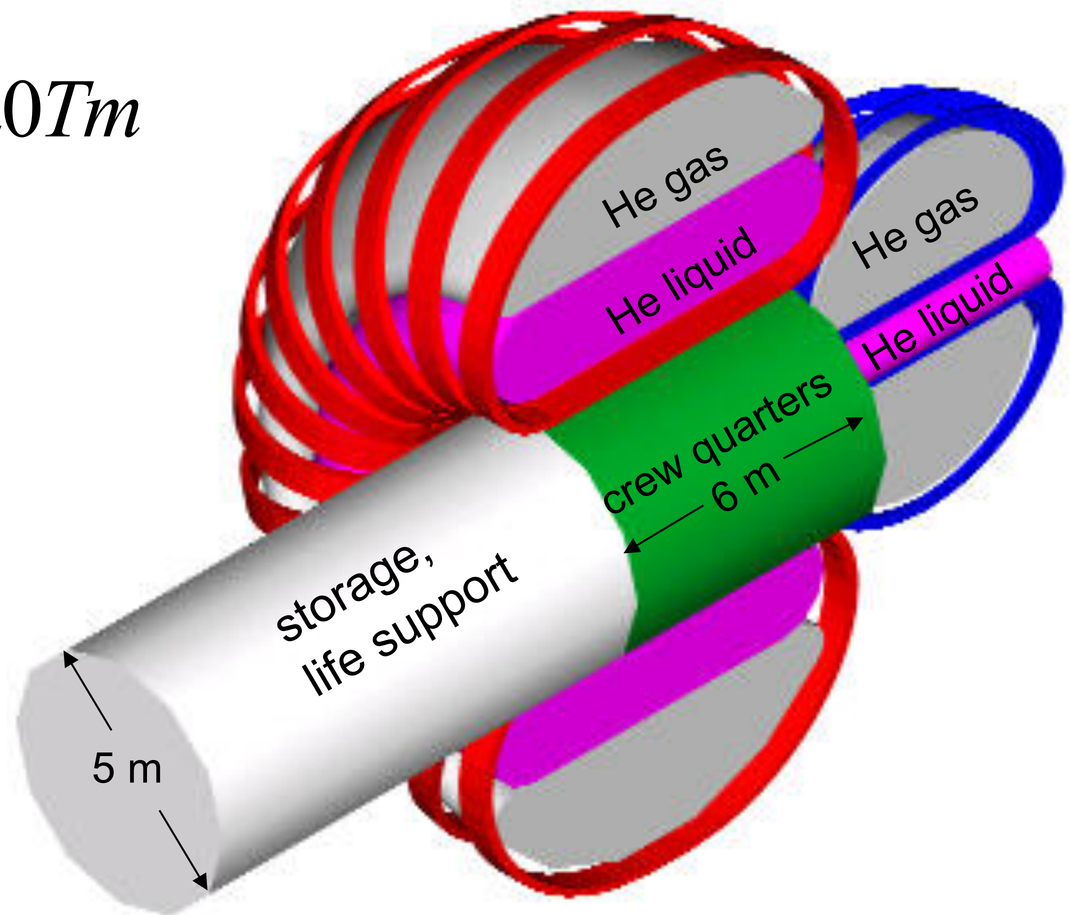
➢There have been suggestions that GRBs might offer a *2nd standard candle*, complementing SN1A. If that could be matured, it might help to extend dark energy resolution at high z.

These thoughts led us to a new concept for particle astrophysics in space:

High Energy Photon and Imaging Spectrometer (HEPHAISTOS)

Background of the technology: Superconducting toroid shield to protect astronauts on deep-space missions

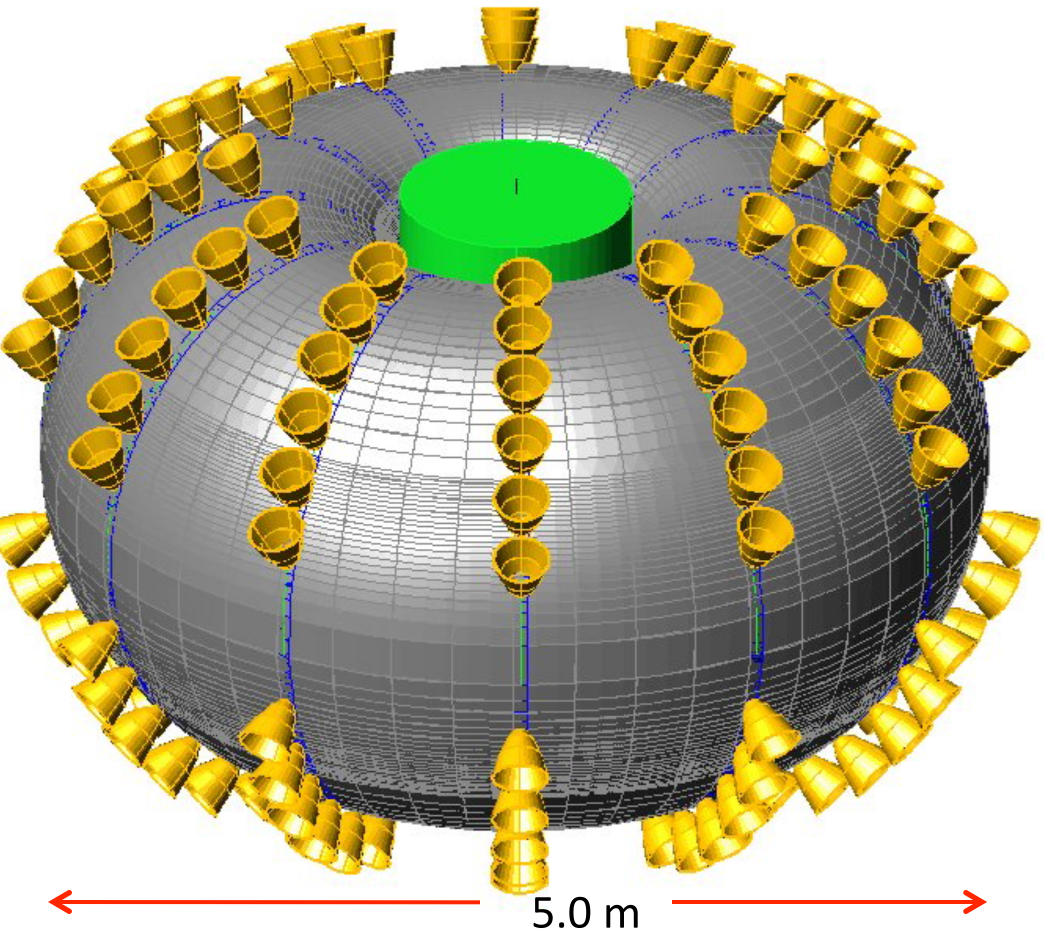
$$\int B d\ell = 20Tm$$

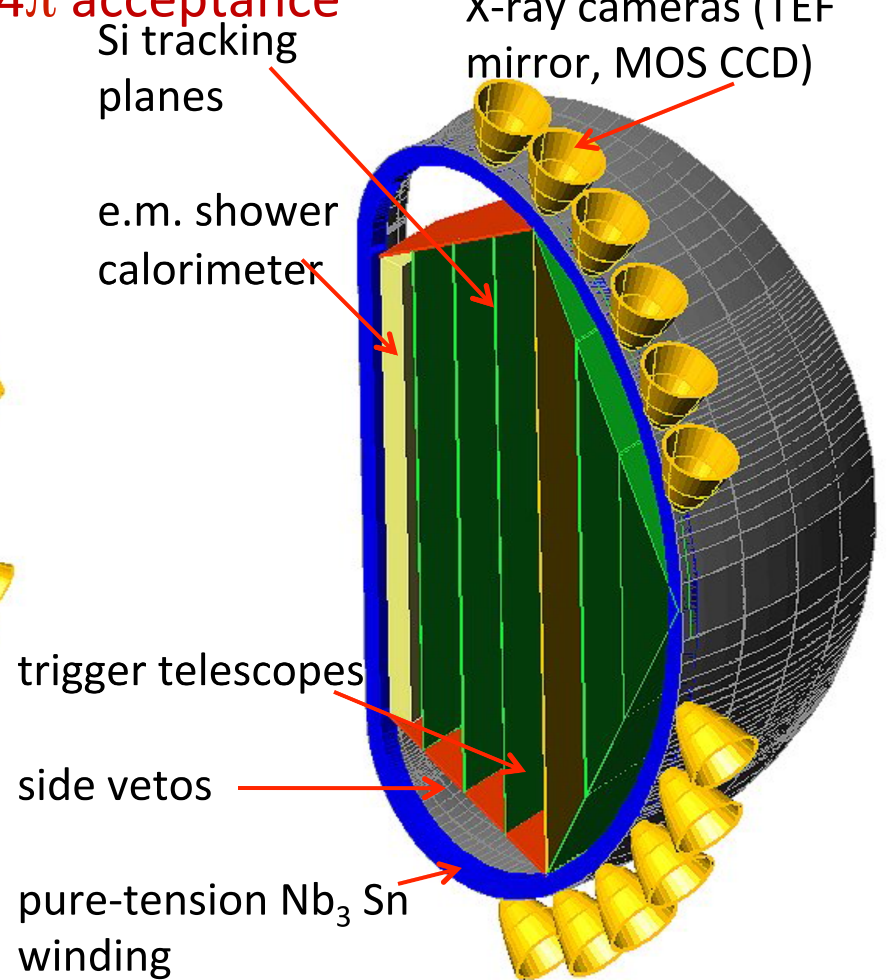


Apply the same concept (smaller scale) to make a wrap-around pointing $\gamma/e^{\pm}$ detector = HEPHAISTOS

HEPHAISTOS

Superconducting constant-tension toroid → 1-3 T
Si tracking planes → hi-res spectroscopy, (4π-2) ster acceptance
Shower calorimetry → e/p ID of $e^{\pm}$
Converter foil → precision pointing for γ' s
Steerable X-ray cameras with continuous 4π acceptance





JAXA H-IIB Launch Vehicle can lift HEPHAISTOS

- Can lift 16.5 metric tons to 200km×300km orbit
- 2nd Stage: No Change
- 1st Stage (Tank):
  - Diameter enhanced from 4m to 5.2m
  - Length: 1m stretched
- 1st Stage (propulsion system):
  - Two LE-7A Engines clustered
  - Dual feed line from tanks
- SRB: No change from H-IIA (SRB-A2)
- Stack all windings, tracking, calorimeters of HEPHAISTOS in one HIIB bus load.
- Assemble on Space Station.
- Tow to high orbit.
- Deploy & charge magnet.

HEPHAISTOS attributes

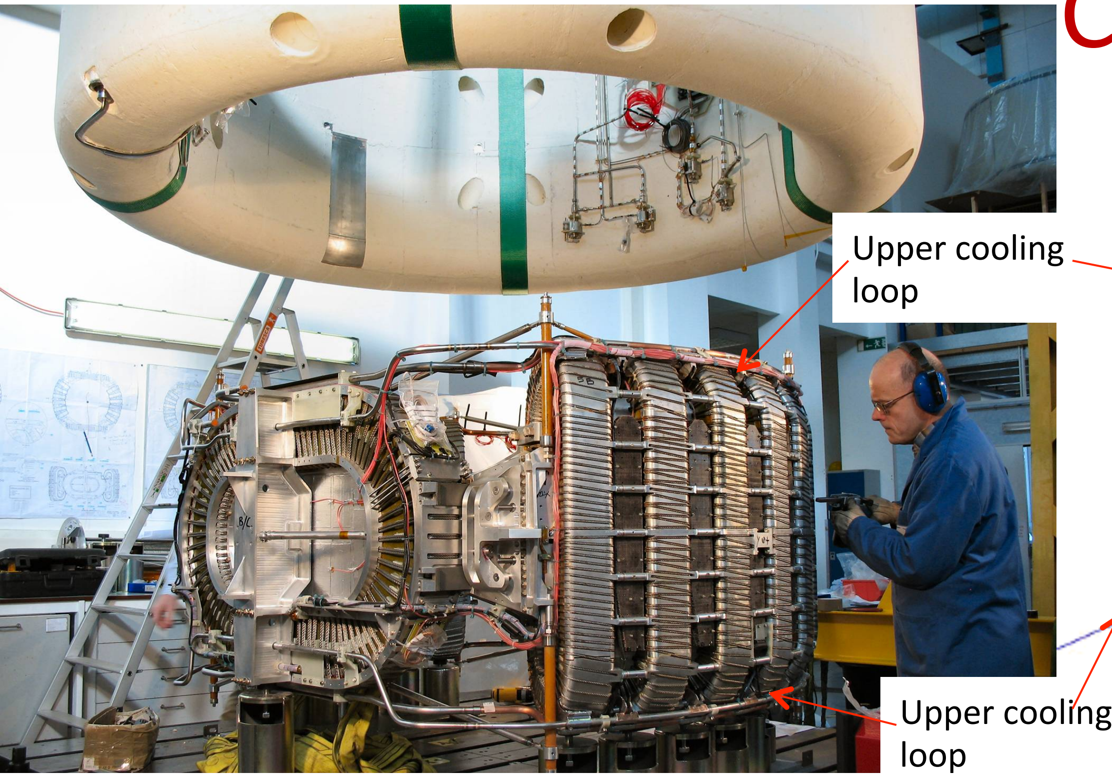
It would have a total acceptance of ~25 m^2 ster, and would look at 80% of the sky at all times.

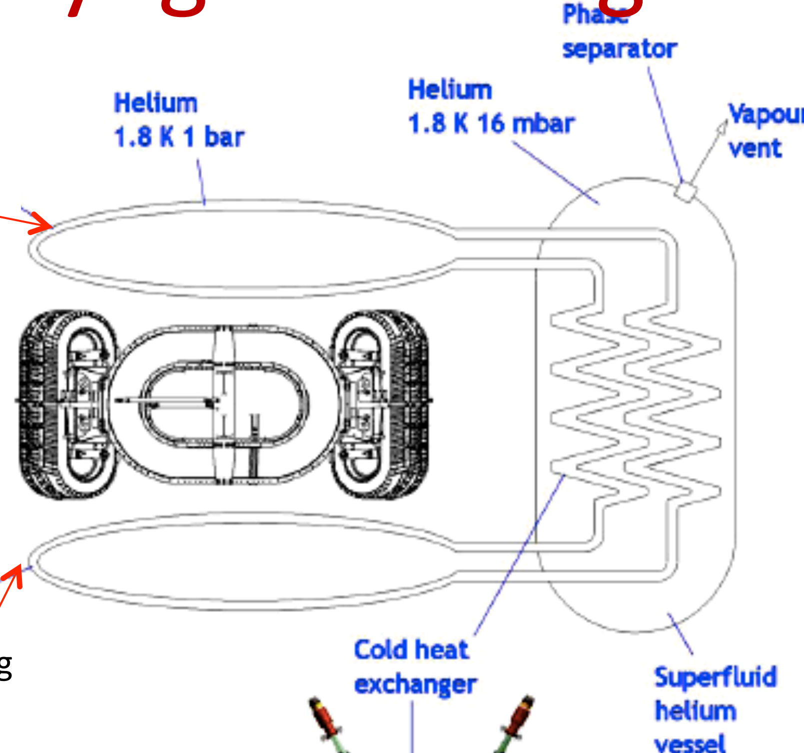
By contrast, the acceptance of FERMI is ~1 m^2 ster, that of AMS is ~0.5 m^2 ster.

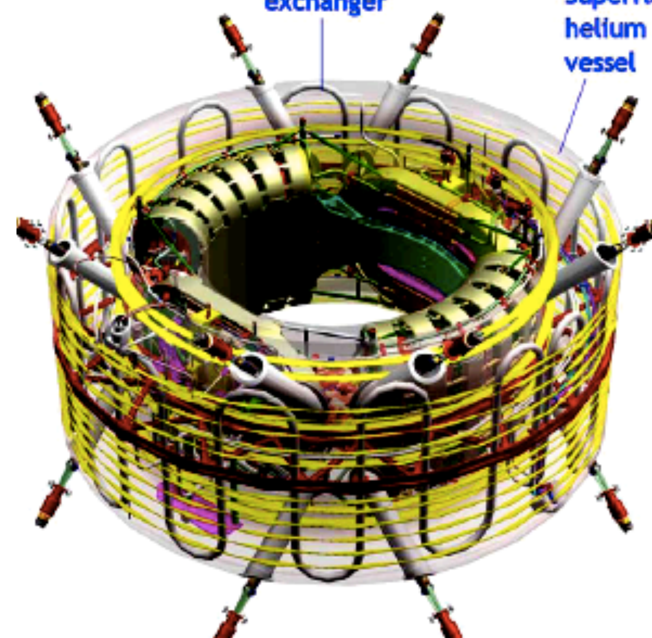
The analyzing field integral $\int B^2 dl \sim 4Tm^2$ combined with the resolution of the Si tracking provides excellent momentum measurement for $e^{\pm}$, excellent pointing accuracy for high-energy γ' s up to > 4 TeV.

An array of steerable X-ray telescopes mounted on the winding assemblies provides 12x the acceptance of SWIFT for any object, and can simultaneously observe multiple objects over the entire sky with that acceptance for each.

Cryogenic Design







We learned a huge amount from building and testing the AMS magnet and its LHe cryogenics. For HEPHAISTOS:

- ➢We can use ReBCO tape conductor @ LN_2
- ➢LN_2 can be pumped, phase-separated, and gathered in zero-g.
- ➢Cryopump 80 K ➔ 300 K ➔radiative shield.

Dick Arnowitt inspired me with tough questions, physics insights, and coupling his brilliant phenomenology with my dirty fingernails to motivate where to look next for signals of new gauge fields.