Detection principle: the concept of a pair conversion telescope.
  - basic design drivers.

The Large Area Telescope:
  - silicon tracker (TKR);
  - electromagnetic calorimeter (CAL);
  - anti-coincidence detector (ACD).

Detection principle revisited.

Orbital environment.
  - (And instrumental pile-up, aka ghost effect.)

Event triggering and filtering.

Event-level analysis:
  - event reconstruction;
  - background rejection.

Conclusions.

All is very IRF-oriented!

There are a few Exercises for you to solve in the following slides.
Detection principle

Photon Energy

1 Mb
1 kb
1 b
10 mb
10 eV 1 keV 1 MeV 1 GeV 100 GeV

(b) Lead (Z = 82)
- experimental \( \sigma_{\text{tot}} \)

(a) Carbon (Z = 6)
- experimental \( \sigma_{\text{tot}} \)

Cross section (barns/atom)

\( \sigma_{\text{p.e.}} \)
\( \sigma_{\text{Rayleigh}} \)
\( \sigma_{\text{Compton}} \)
\( \kappa_{\text{nuc}} \)
\( \kappa_{e} \)

\( \gamma \) ray

Conversion plane
Tracking plane

Tracker/converter

Calorimeter

- Pair production is the dominant interaction process for photons in the LAT energy range;
- \( e^+ e^- \) pair provides the information about the \( \gamma \)-ray direction/energy;
- \( e^+ e^- \) pair provides a clear signature for background rejection (really?).

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Science design drivers

- **Effective area and Point Spread Function:**
  - thickness and layout of conversion layers;
  - PSF also drives the design of the sensors, the spacing of the detection planes and the overall TKR design.

- **Energy range and resolution:**
  - thickness and design of the calorimeter;

- **Field of view:**
  - determined by the aspect ratio of the instrument;

- **Charged particle background rejection:**
  - mainly drives the ACD design;
  - also impacts the TKR and CAL design (which are needed for the background rejection);
  - need for a flexible triggering and event filtering system.
Mission design drivers

- Launcher type and allocated space:
  - maximum possible lateral dimensions of the instruments (i.e. geometric area);
  - about $\sim 1.8 \times 1.8$ m$^2$ for Fermi (the LAT footprint is actually $\sim 1.5 \times 1.5$ m$^2$).

- Power budget:
  - number of electronics readout channels in the tracker (i.e. strip pitch, number of layers);
  - about 650 W overall for Fermi;

- Mass budget:
  - essentially limits the total depth of the calorimeter (once the footprint is fixed);
  - 3000 kg for Fermi.

- Telemetry bandwidth:
  - need onboard filtering.

- Launch and operation in space:
  - sustain the vibrational loads during the launch;
  - operate in vacuum, sustain thermal gradients.
The Large Area Telescope

- Overall modular design.
- $4 \times 4$ array of identical towers (each one including a tracker and a calorimeter module).
- Tracker surrounded by and Anti-Coincidence Detector (ACD).
- “It uses less power than a toaster and we talk to it over a telephone line.” (Bill Atwood)

Tracker
- Silicon strip detectors, W conversion foils; 1.5 radiation lengths on-axis.
- $\sim 10k$ sensors, $73 \text{ m}^2$ of silicon active area, $\sim 1\text{M}$ readout channels.
- High-precision tracking, short dead time.

Anti-Coincidence Detector
- Segmented (89 tiles) as to minimize self-veto at high energy.
- 0.9997 average detection efficiency.

Calorimeter
- 1536 CsI(Tl) crystal; 8.6 radiation lengths on-axis.
- Hodoscopic, 3D shower profile reconstruction for leakage correction.
Silicon Tracker/Converter (1/2)

- Primary roles:
  - convert $\gamma$ rays into electron/positron pairs;
  - main event trigger (more on this later);
  - direction reconstruction.

- Also important for:
  - background rejection (SSD veto, hit counting);
  - energy measurement at low energy (i.e., below a few hundred MeV).

- Use of Silicon Strip Detector (SSD) technology:
  - precise tracking with $\sim$ no detector-induced deadtime;
  - self-triggering.

- Key features:
  - $\sim 73 \text{ m}^2$ of single-sided SSDs (400 $\mu\text{m}$ thickness, 228 $\mu\text{m}$ pitch);
  - 884,736 independent readout channels ($\sim 200 \mu\text{W}$ per channel);
  - digital readout (plus layer OR time over threshold);
  - $\sim 10^{-6}$ noise occupancy at the nominal 1/4 of a Minimum Ionizing Particle (MIP) threshold (providing $\sim 100\%$ detection efficiency).

- Exercise: Estimate the average number of noise hits per event in the full LAT.
Tradeoffs in the design of the tracker converter:

- overall thickness of the converter foils: conversion efficiency vs. multiple scattering (limiting the angular resolution at low energy);
- number and spacing of the planes: energy dependence of the PSF;
- strip pitch: hit resolution vs. power consumption.

18 paired x−y layers (∼ 36 cm on a side, spaced by ∼ 3.5 cm) in two distinct sections:

- front has better PSF and lower background contamination;
- 1.5 $X_0$ on axis—that’s a lot for a tracker!

Exercise: What’s the maximum off-axis angle the TKR will trigger?
Electromagnetic Calorimeter (1/2)

- Primary roles:
  - energy reconstruction;
  - contribution to the event trigger (more on this later);

- Also important for:
  - background rejection (shower shape);
  - seeding the tracker reconstruction.

- Crystal detector elements:
  - 8 layers of 12 CsI(Tl) crystals \((27 \times 20 \times 326 \text{ mm}^3)\) per tower;
  - hodoscopic stacking (alternating orthogonal layers);
  - \(8.6 \times X_0\) on-axis.

- Readout electronics:
  - dual PIN photodiode on each crystal end;
  - each one processes by two electronics chains \((\times 1, \times 8)\);
  - four readout ranges, dynamic range 2 MeV–70 GeV per crystal.

Exercise: How much energy does a MIP on-axis release in the CAL?
Electromagnetic Calorimeter (2/2)

- CAL xtals with readout at each end:
  - measure longitudinal position of the energy deposition from light asymmetry;
  - provide a full 3-dimensional image of the EM shower;
- CAL imaging capabilities are crucial for both background rejection and energy reconstruction at high energy:
  - remember, the LAT is $\sim 10 \times X_0$ on axis, so there is a significant shower leakage out the back of the CAL.

**Exercise:** What is the fraction of energy escaping out the back of the CAL for a 500 GeV photon on-axis?
Primary roles:

- event triggering and onboard filter (more on this later);
- background rejection.

Also important for:

- identifying heavy ions for CAL calibration purposes.

One important lesson learned from the previous mission:

- backsplash from the CAL in high-energy event can hit the ACD;
- can cause self-veto, especially for monolithic shields.

The LAT ACD is segmented:

- 89 tiles (overlapping in one dimension) plus 8 ribbons (covering the gaps in the other);
- can extrapolate tracks to specific tiles;
- this also makes complete hermeticity more difficult to achieve.
The LAT shows no significant degradation in time over the first \( \sim \) three years of mission.

- drift of the light yield in the CAL expected from radiation damage.
A “gold-plated” simulated 360 MeV \( \gamma \)-ray...

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Monte Carlo \( \gamma \)-ray direction

Event topology
- two clear tracks;
- tracks point to energy deposits in the CAL;
- no ACD hit tiles;
- tracks start in the middle of the instrument.
...AND A "GOLD-PLATED" BACKGROUND EVENT

Event topology

- one track;
- track points to a hit tile in the ACD;
- (with > 25 MIPs signal, so this is actually a heavy ion);
- track starts in uppermost TKR layer (i.e., at the edge of the instrument).
A $\sim 100$ MeV simulated $\gamma$-ray...

Event topology

- no ACD hit tiles (good);
- but this time we only have one track;
- where's the other guy (aren't we supposed to detect electron-positron pairs)?
...and a $\sim 40$ MeV simulated $\gamma$-ray

Event topology
- no ACD hit tiles (good);
- we still only have one track;
- and even worse: it doesn’t even make it to the CAL!
- Can we estimate the energy for this one?
e^+ and e^- split the energy equally on average;
   not uncommon that one takes the vast majority.
   . . . at the level that the other track can die in the tungsten.

At high energy the opening angle is small:
   at some point we don’t resolve the two tracks anymore (back into
   the one-track case).

Except for the stray tracks from CAL backsplash!

Exercise: Give a rough estimate of the maximum energy at which
the TKR is able to resolve the two tracks in the pair.
Event topology

- no ACD hit tiles (good);
- one track (can happen);
- corresponding energy deposit in the CAL (good);
- believe it or not this is a back-entering CR proton 😊
A simulated 540 GeV $\gamma$-ray

Event topology

- (potentially) many many tracks;
- lots of CAL back-splash;
- tracks point just about everywhere;
- many hits in the ACD;
- still we get energy and direction right (for this particular event).
And finally: a (real) TGF

Event topology

- Pretty much the entire detector is on (many many low-energy photons);
- standard event reconstruction can’t do much, here.
- (The instrument was in a special configuration/orientation; this would not pass the gamma onboard filter.)
Now let’s stop with event display but...

- γ-ray event topology varies a lot across the instrument phase space:
  - can have (zero), one, two or many tracks;
  - can have hits in the ACD (here is where we take advantage of the segmentation);
  - from “no energy deposit” to a “fully developed em shower” in the CAL.

- Background event topology varies a lot across the instrument phase space:
  - some of them are easy to identify;
  - some are hard;
  - some are impossible (e.g., the irreducible background).

- Take-away message 1: event reconstruction is challenging.
- Take-away message 2: background rejection is challenging.
Relevant γ-ray and primary CR spectra (not taking into account the effect of the geomagnetic field):

- up to $10^6$ background rejection power required;
- running out of photons above a few TeV with $\sim 2 \text{ m}^2 \text{ sr}$ acceptance.
CR-induced background level in low-Earth orbit depends on the local geomagnetic conditions:

- low-energy CRs effectively shielded by the Earth’s magnetic field;
- how low is low depends on the position (a).

Most of the charged particles crossing the LAT generate a treq;
- trigger request rate also varies across the orbit (b).

Celestial $\gamma$-rays are unaffected by magnetic fields:
- the rates of the cleanest event classes (c) should not depend on the local geomagnetic conditions; however.

Exercise: Estimate the vertical rigidity cutoff at the equator.
**Instrumental pile-up (aka “ghost” effect)**

The **persistence** time of the electronics signals in the detector is of the order of $\sim 10 \, \mu s$:

- if two events happen to be that close in time (and we happen to trigger on one) we’re effectively reading out both.
- Ghost signals can cause good $\gamma$ rays to be misclassified as background (i.e., loss of effective area).

**Exercise:** estimate the fraction of events affected by ghosts.
Trigger and onboard filter basics

- Ideally we would like to be able to:
  - read out all the events (i.e., all particles crossing the detector);
  - down-link all the events to the ground;
  - postpone all the decisions (is the event a $\gamma$ ray?) to the offline data analysis phase.

- Unfortunately that's generally impossible in high-energy physics experiments:
  - reading out an event takes time (at least $26.5 \text{ \mu s}$ for the LAT); during this deadtime the instrument is blind;
  - the bandwidth for transmitting data to ground is limited ($\sim 1 \text{ Mb/s}$)—and expensive.

- Bottom line: we do have to take decisions onboard about:
  - which events we want to read out;
  - which events (among those that we read out) we want to transmit to ground.

- Exercise: estimate the deadtime fraction if we were to read out all the events causing a trigger request (take $\sim 8 \text{ kHz treq rate}$).
Use fast (< 1 μs) signals to trigger readout;
- as opposed to ground analysis using slower (∼ 10 μs) signals.

Each subsystem generates one or more trigger primitives:
- TKR: three adjacent tracker x-y layers above threshold;
- CAL_LO: any single CAL channel above 100 MeV (adjustable);
- CAL_HI: any single CAL channel above 1 GeV (adjustable);
- ROI: one or more ACD tile(s) over veto threshold (nominally 0.45 MIP) in proximity of a triggering TKR tower;
- CNO: signal in any of the ACD tiles above the CNO (Carbon Nitrogen Oxygen) threshold (nominally 25 MIPs);
- PERIODIC: 2 Hz synchronous (for minimum bias event sample).

Some of the trigger primitives can open a 700 ns trigger window;
- collect all the asserted primitives when the window is closed;
- map each combination into a look-up table;
- decide whether to read out the event or not.

If the trigger request is accepted, the full LAT is read out.
- (It takes < 2 μs to take the decision.)

Exercise: Does a MIP 45° off-axis generate a CAL_LO?
Some trigger primitive combinations are prescaled.

Consider trigger engine 10 for example:

- \((\text{TKR} \&\& \text{ROI}) \&\& !((\text{CNO} \&\& \text{CAL}_\text{LO}) \&\& \text{CAL}_\text{HI})\)
- This is most likely to be a MIP and very unlikely to be a \(\gamma\) ray;
- there are many of them: we only read out 1 every 50.

Prescaling reduces deadtime:

- we don’t actually read out the event (which takes at least 26.5 \(\mu s\)).

5–10 kHz trigger request rate \(\rightarrow\) 2–3 kHz event readout rate.

Exercise: estimate the deadtime fraction for a 2.2 kHz readout rate.
We’re down to 2.2 kHz average event readout rate;
  - with an average compressed event size of \( \sim 500 \) bytes that’s still too much;
  - need further onboard event filtering to reduce the rate of events to be transmitted to ground.

Onboard filter: configurable, has access to the full event information;
  - hierarchical set of conditions with the fastest being applied first.

Multiple coexisting filtering algorithms running:
  - gamma filter: keep whatever might possibly be a \( \gamma \) ray;
  - HIP filter: select heavy ion events for CAL calibration;
  - diagnostics filter: provide a prescaled unbiased sample of all trigger types.

2–3 kHz event readout rate \( \rightarrow \) 300–500 Hz downlink rate.

Exercise: estimate the necessary average downlink bandwidth for 2.2 kHz and 400 Hz event readout rate.
Almost all the particles (∼99%) downlinked to ground are still charged background.

(Though there is still interesting science in there.)

The onboard filter is highly efficient for $\gamma$ rays.

The remaining data reduction steps are performed as part of the offline ground processing.
Event selection analysis overview

Trigger
- Trigger (§ 3.1.1)
- On-board filter (§ 3.1.2)

Event reconstruction
- CAL recon (§ 3.2.1)
- TKR recon (§ 3.2.2)
- ACD recon (§ 3.2.3)

Event-level analysis
- Merit (§ 3.3.1)
- Energy analysis (§ 3.3.2)
- PSF analysis (§ 3.3.3)
- CPF analysis (§ 3.3.5)
- TKR topology (§ 3.3.6)
- CAL topology (§ 3.3.7)
- Event classification (§ 3.3.8)

Definition of standard photon classes (§ 3.4)

(Disregard the section numbers for the purpose of this presentation.)
CAL reconstruction overview

- Apply xtal calibrations (i.e., convert ADC counts to MeV).
- Iterative moments analysis (i.e., calculate the principal axes of the inertia tensor associated with the energy deposition):
  - shower centroid;
  - shower direction ($\sim 1^\circ$ resolution above $\sim 10$ GeV);
  - shower transverse/longitudinal spread (background rejection).
- Energy reconstruction:
  - much, much more than summing up the xtal energies;
  - three different reconstruction algorithms;
  - different performance in different parts of the phase space.
- Note that we don’t currently attempt to identify separate clusters of hit logs.
TKR reconstruction overview

- Combine adjacent hit strips to form clusters.
- Seed the track-finding stage with the CAL information, if available.
- Combinatoric search for tracks through a Kalman fit/filter technique:
  - start from a seed;
  - propagate to next plane based on the expected multiple scattering (need particle/energy hypothesis) and add hits as possible;
- Order tracks by quality (longest, straightest: best).
- Vertexing: combine the two best tracks when possible.
- (Much more complicated than this in real life.)
- Apply tile/ribbon calibrations (i.e., convert ADC counts to MeV).
- Look for reasons to veto the event:
  - (i.e., decide it’s a charged particle, as opposed to a $\gamma$ ray).
- Much, much more complicated than requiring that there is no energy in the ACD:
  - a lot of phase space for weird things to happen;
  - (as you have seen before in the event displays).
- Extrapolate TKR tracks to the ACD:
  - is there any signal in the tile the track points to?
- But there are many ways we can potentially go wrong:
  - did we pick the right track?
  - did we happen to pass through inactive (or not fully efficient) areas in the ACD (i.e., ribbons, corners)?
  - are we affected by the backsplash (the energy deposited in the CAL is a good proxy for that).
Event-level analysis overview

- Complex multivariate analysis:
  - uses Classification Trees in conjunction with plain cuts;
  - a huge amount of work went into defining relevant classification variables.

- PSF analysis:
  - determine the best direction estimate (1\textsuperscript{st} track, vtx, neutral vtx);
  - along with a reconstruction quality indicator.

- Energy analysis:
  - select the best energy method (+ quality indicator).

- “Charged Particle in the Field of view” analysis:
  - identify events which are clearly charged particles in the FOV.

- TKR and CAL topology analysis:
  - probability of an event being a $\gamma$ ray using CAL/TKR information.

- Event classification:
  - combine all the previous information.

- Definition of the photon classes.
How different photon classes differ?

- Primarily in the level of background contamination;
- and, since you don’t get anything for free, in the $\gamma$-ray efficiency too.
- So we have (form dirtiest to cleanest) P7TRANSIENT, P7SOURCE, P7CLEAN, P7ULTRACLEAN.

Why different photon classes?

- Because different analyses require different signal-to-noise ratios.
- (Or, phrased in a different way: different analyses might provide additional handles to reject background).

Point source analysis:

- cut on the ROI;
- is it a pulsar? Even better, can use the pulse phase, too!

Isotropic background:

- no obvious spatial or temporal signatures to distinguish signal and background.

Exercise: how much background do you remove by selecting events in a 5° ROI?
Future developments in the event-level analysis

- The LAT provides a huge amount of information on an event-by-event basis.

- The instrument performance is not “once and forever”:
  - you can improve by being more clever in the event reconstruction and in the background rejection;
  - even now that the LAT is built and up in space we can improve.

- Ongoing long-term effort to revisit all the aspects of the event-level analysis:
  - make use of the lessons learned operating the LAT;
  - new pattern recognition in the TKR;
  - clustering stage in the CAL;
  - new energy reconstruction at high energy;
  - new ACD reconstruction;
  - new event classification...
The LAT is essentially a particle-physics instrument.

Huge amount of information available on an event-by-event basis:
- event reconstruction and background rejection can be very hard;
- understanding the instrumental effects can also be very hard;
- we always have room for improving the performance!

Large dynamic range and field of view:
- large variations in the event topology;
- parametrizing the instrument response is challenging.

There’s a lot of stuff going on to get the photon energy, direction and arrival time from the raw detector information!