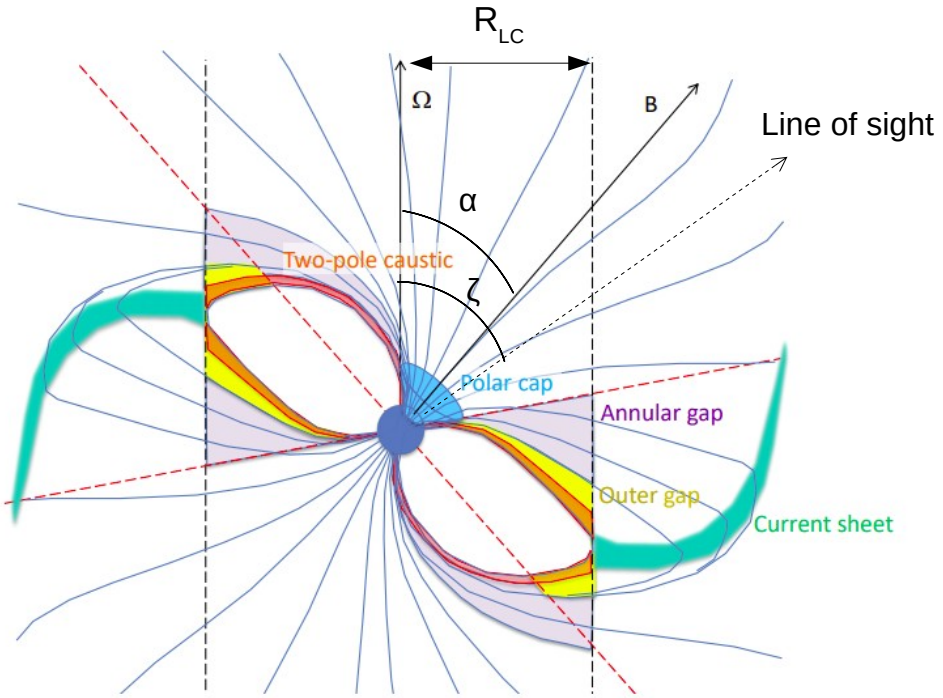
Polarimetry of the Vela pulsar with the *Fermi*-LAT: A sensitivity estimate

Adrien Laviron, Denis Bernard, Philippe Bruel,
Laboratoire Leprince-Ringuet, Palaiseau, France

on behalf of the *Fermi*-LAT collaboration

11th Fermi Symposium
September 12th, 2024

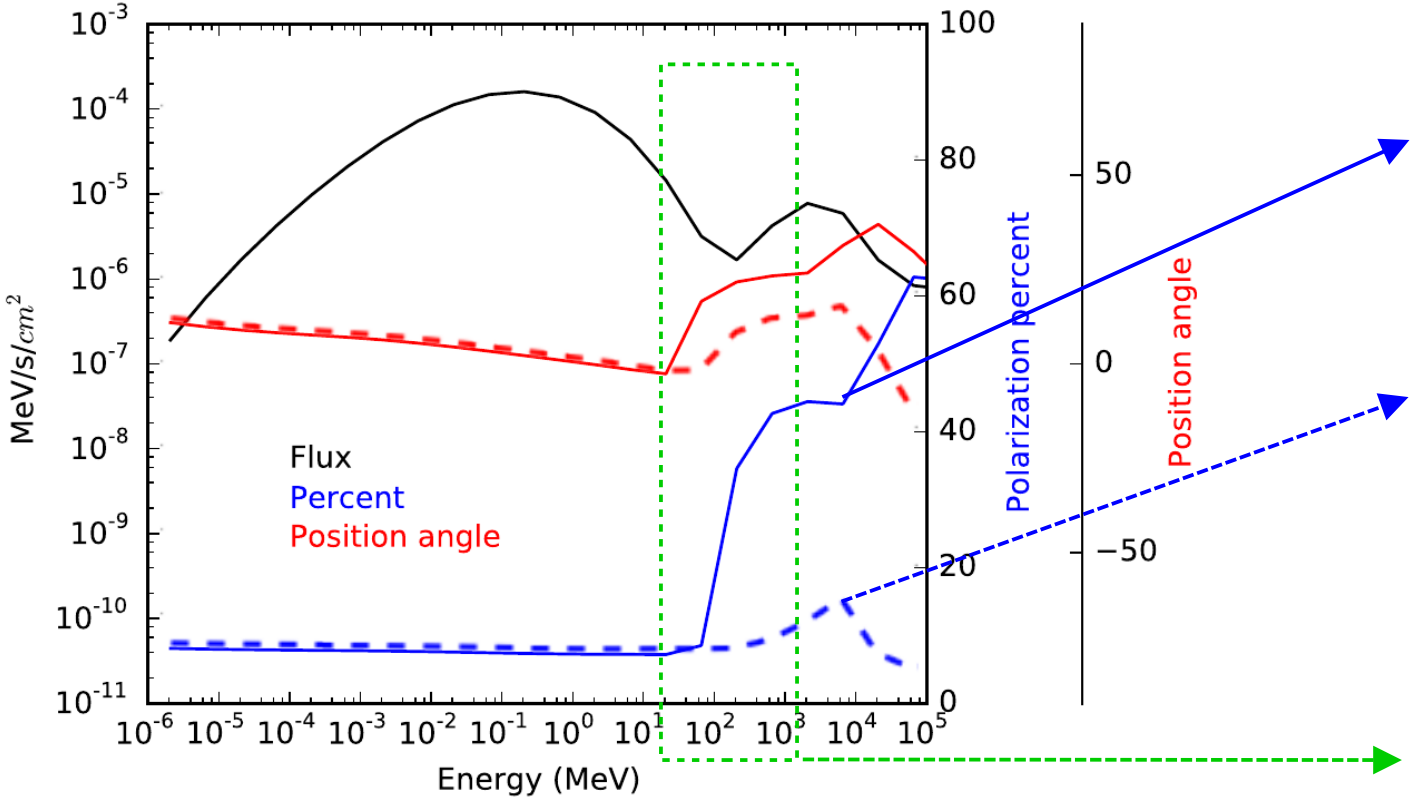
Gamma-ray pulsars with the *Fermi*-LAT



From: Harding 2021

- Detected >300 pulsars [Smith et al. 2023, 3PC catalog]
  - since 2008
  - in the 20 MeV - 300 GeV energy range
- Pulsed gamma-ray emission (outer magnetosphere)
- Gamma-ray polarimetry is an independent probe of
  - emission processes
  - emission region

Pulsar polarization model



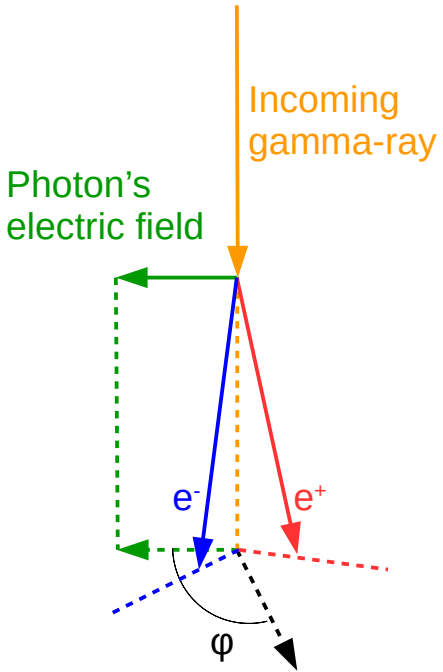
Curvature radiation:
High polarization fraction

Synchrotron radiation:
Low polarization fraction

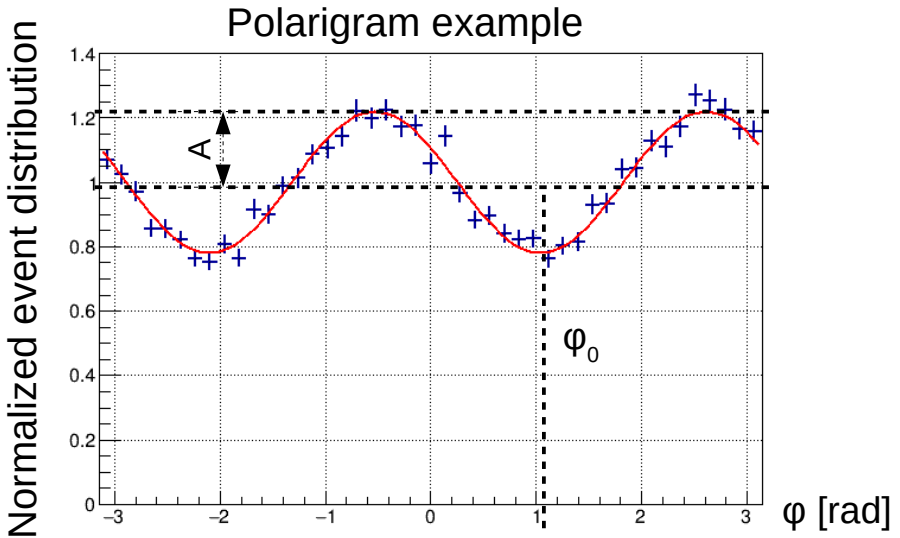
Energy range of
Fermi-LAT polarimetry
uniquely suited

From: Harding & Kalapotharakos, 2017

Pair-production polarimetry: the general principle



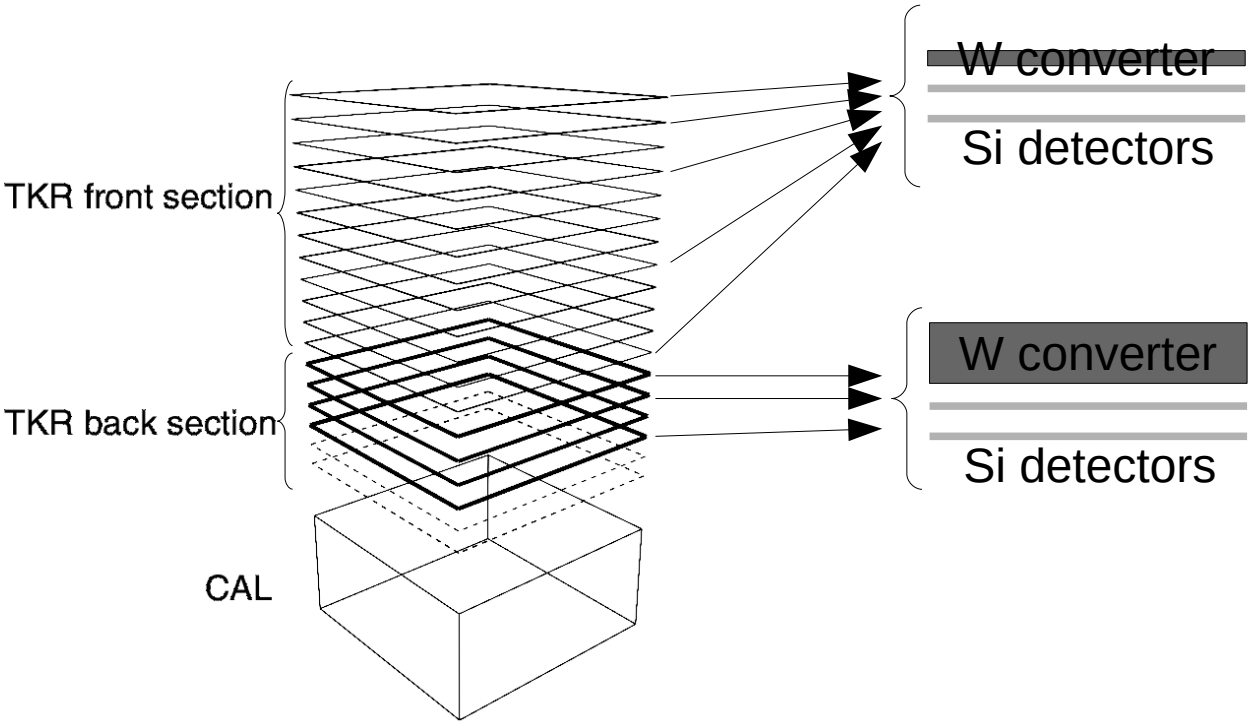
$$\varphi = \frac{\varphi_{e^+} + \varphi_{e^-}}{2}$$



- Precise measurement of the e^+ and e^- direction needed to perform polarimetry
- Theoretical modulation amplitude A≈0.2 for a 100 % polarized source

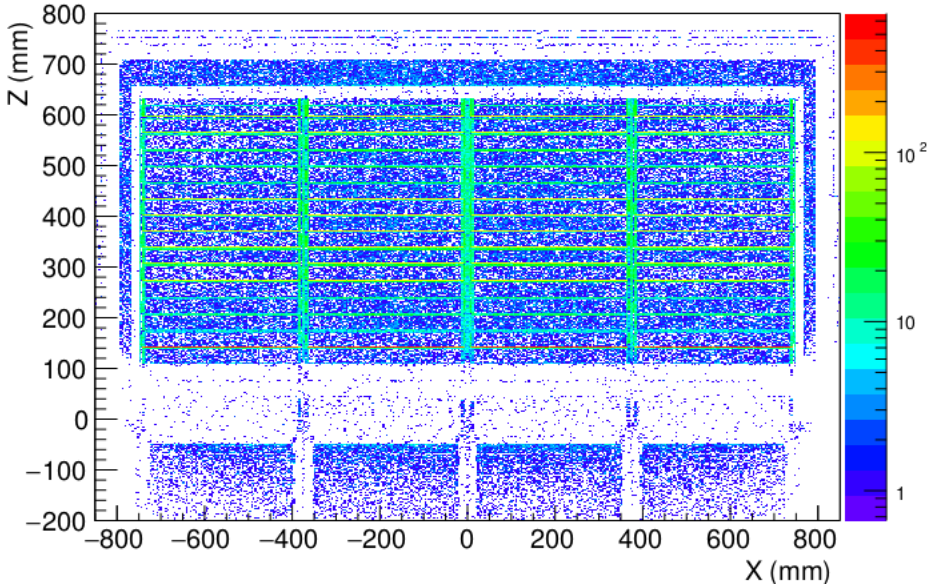
Polarimetry limiting factor: Multiple scattering

- Scattering of the e^+-e^- pair as it propagates through matter
  - The LAT was not designed with polarimetry in mind.
- Previous polarimetry attempt by Giomi et al., 2017 using Pass 8 data was inconclusive.
  - Need to revert to **raw LAT data**
- *Fermi*-LAT simulation software `Gleam` modified with `G4BetheHeitler5DModel` polarized gamma conversion model

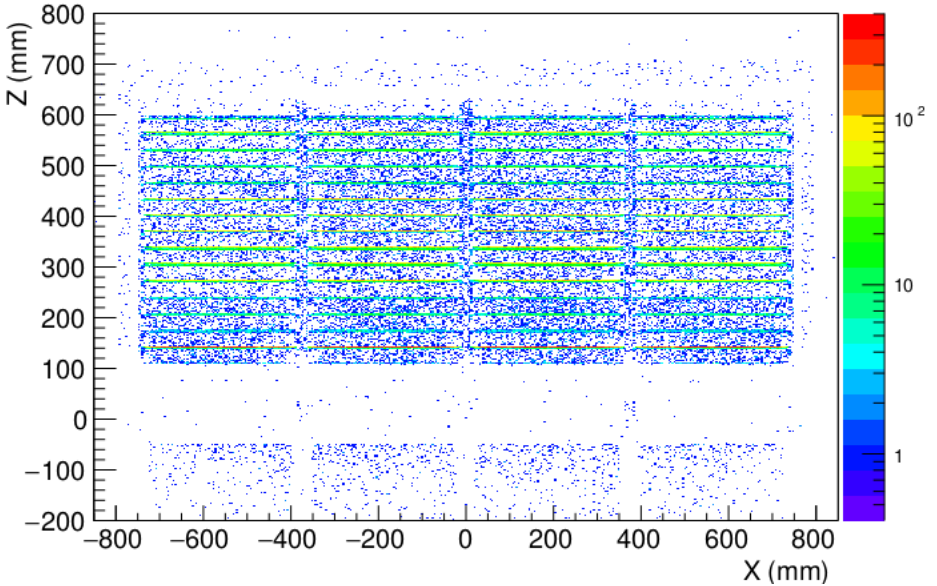


Event selection dedicated to polarimetry

All transient events

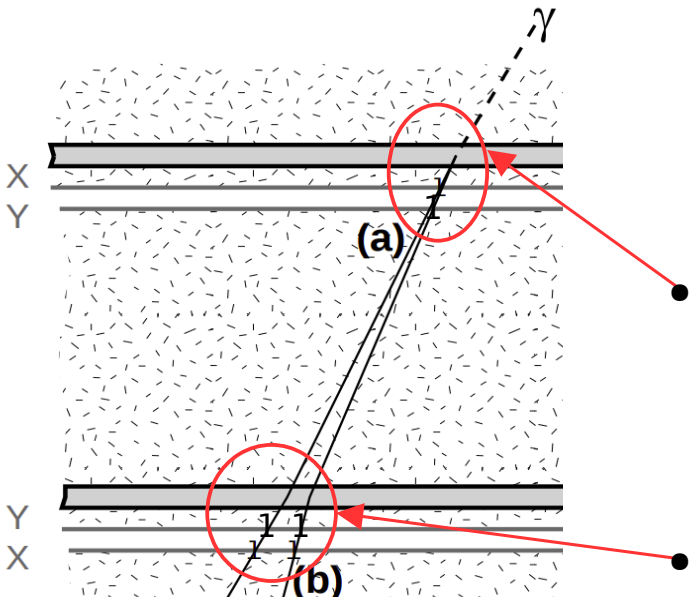


Selected events



- Monte-Carlo point of first gamma-ray interaction, for transient events (evclass=16), XZ plane
- Remove events for which the Pass 8 track
  - conversion point is too close (< 12mm) to the tower edges
  - come from or go towards non-sensitive parts of the tracker
  - events which triggered the first silicon plane of the topmost layer
- 61 % of events are selected at 100 MeV.

An event reconstruction dedicated to polarimetry



Analysis with only the first two layers

- Limits multiple scattering

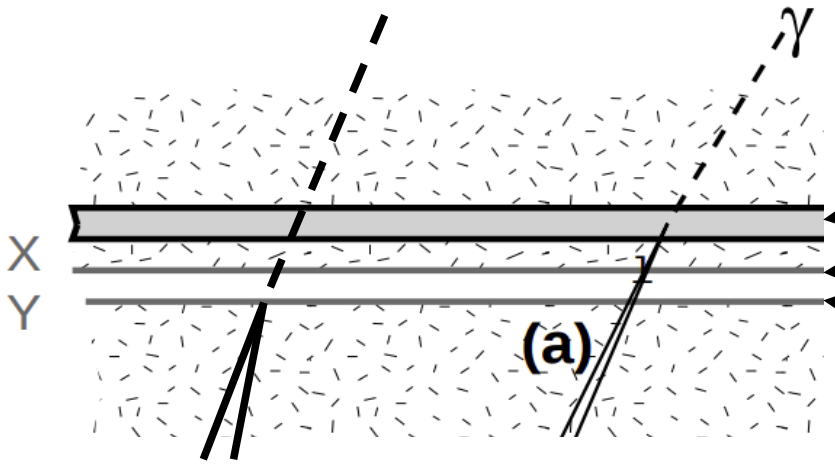
(a) Conversion layer

- Gives the conversion point
- Multiple scattering much larger in tungsten

(b) Gives the azimuthal information

- Only if the electron and positron are separated enough
- Different event morphologies

An event reconstruction dedicated to polarimetry

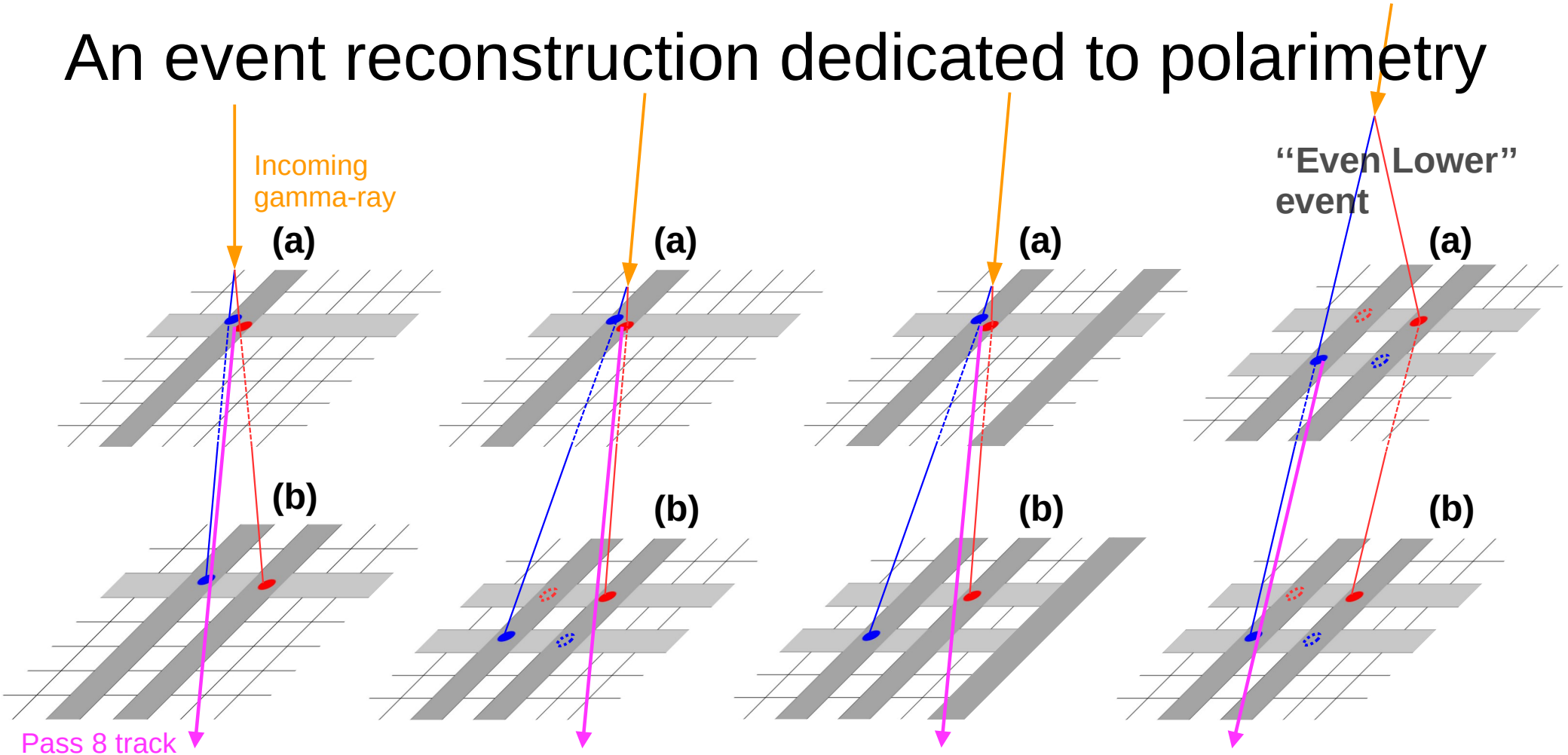


(a) Conversion layer

- Tungsten converter
- Upper silicon detector
- Lower silicon detector

- Conversions in silicon
  - Less multiple scattering
  - May only trigger the lower silicon detector => ‘‘Lower’’ events
- Conversions in the tungsten
  - Trigger both silicon detectors => ‘‘Upper’’ events

An event reconstruction dedicated to polarimetry



Morphology 01
(High energy)

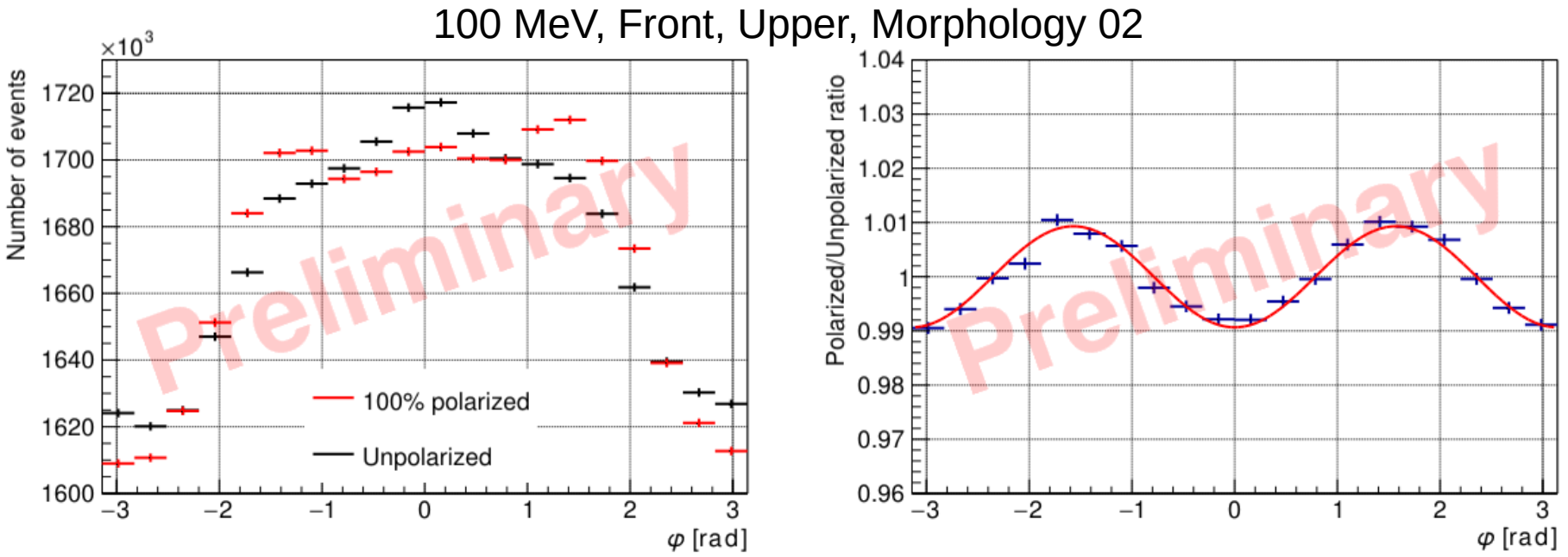
Morphology 02
Pass 8 track used
to remove the ambiguity

Morphology 14
Extra clusters
not used

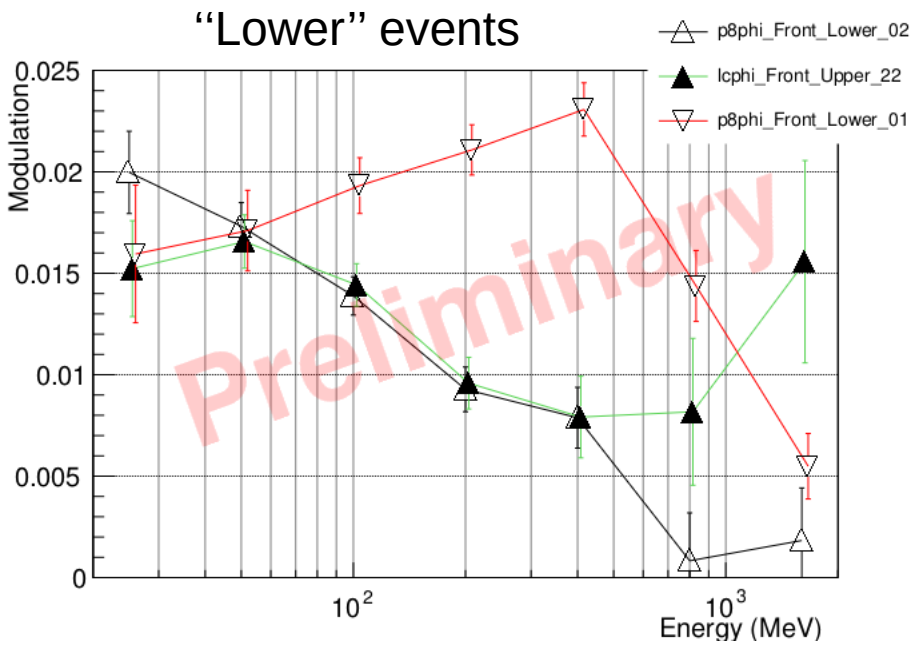
Morphology 22 (1% of events)
Azimuthal information
in conversion layer **(a)**

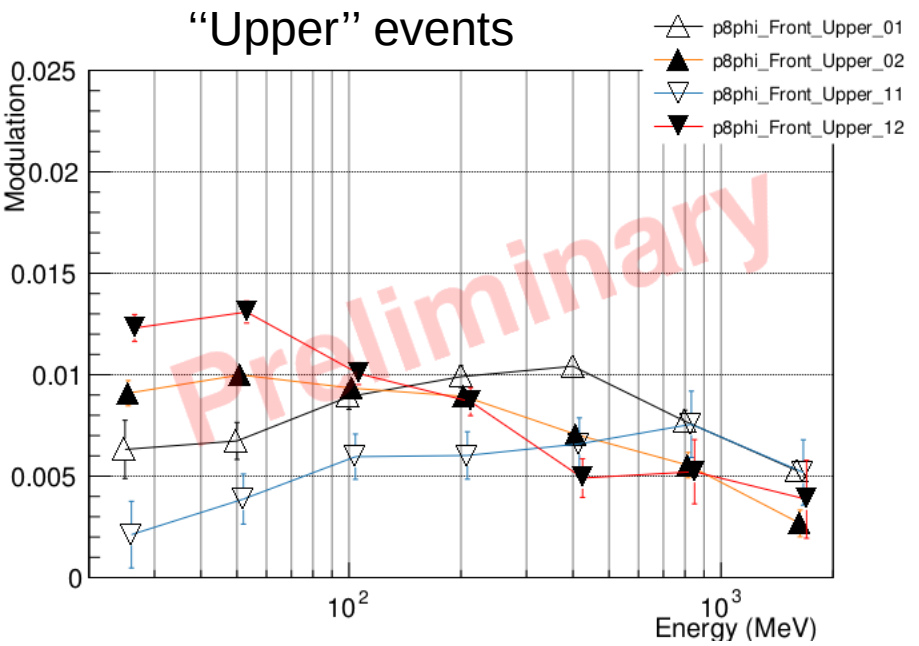
100 MeV simulated polarization signal

- Monte-Carlo simulations of a high-flux, mono-energetic, 100 MeV source located at Vela's pulsar's coordinates (using 15 years of *Fermi*-LAT attitude)
  - Not polarized (left, black)
  - 100 % polarized (left, red)
- The division (right) shows the polarization signal: ~1 % modulation (instead of 20%, because of multiple scattering)



Modulations



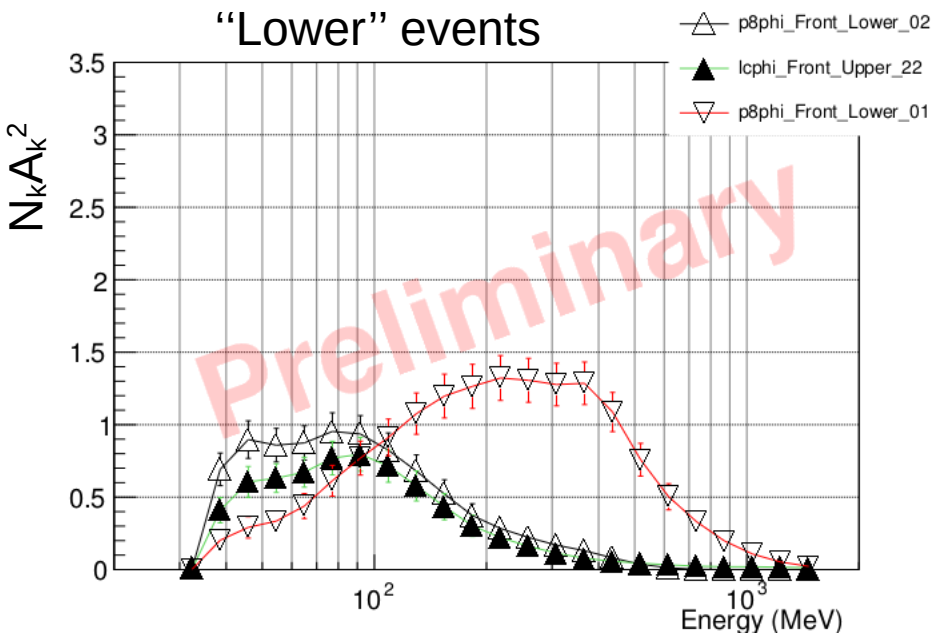


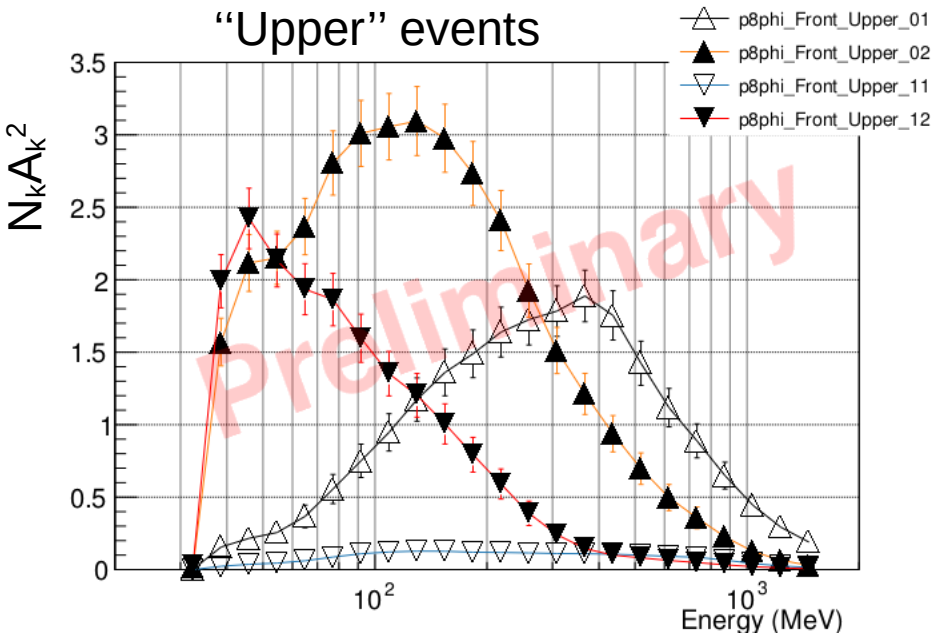
- Higher for ‘‘Lower’’ events (~ 2%) than for ‘‘Upper’’ events (~ 1%)
- Morphologies 01 and 11 peak at ~400 MeV
- Morphologies 02, 12, 22 peak at ~ 50 MeV.

Optimal weighting scheme

- Event category means
  - Energy bin
  - ‘‘Upper’’ or ‘‘Lower’’
  - Event morphology
- Weight each category *k* with its modulation A_k
  - Figure of merit of a category *k* is $N_k A_k^2$
  - Represents the statistical weight of the category
- Uncertainty on polarization fraction is $\sigma_P = \sqrt{\frac{2}{\sum_{k \in \{Categories\}} N_k A_k^2}}$

Sensitivity estimate for the Vela pulsar





- Calculated using a fitted Vela pulsar spectrum (Transient020, 30 MeV – 1600 MeV)
- The “Upper” events dominate the measurement because much more numerous.
- Background-free uncertainty on the polarization fraction is $\sigma_P \approx 13\,\%$

Sensitivity estimate for the Vela pulsar with galactic background

- Uncertainty on polarization fraction (with unpolarized galactic diffuse background)

$$\sigma_P = \sqrt{\frac{2}{\sum_{k \in \{Categories\}} N_k A_k^2}} \sqrt{\frac{S+B}{S}}$$

  - S: source counts, B: background counts (no polarimetry selection)
  - $S \times \varepsilon = \sum_{k \in \{Categories\}} N_k$

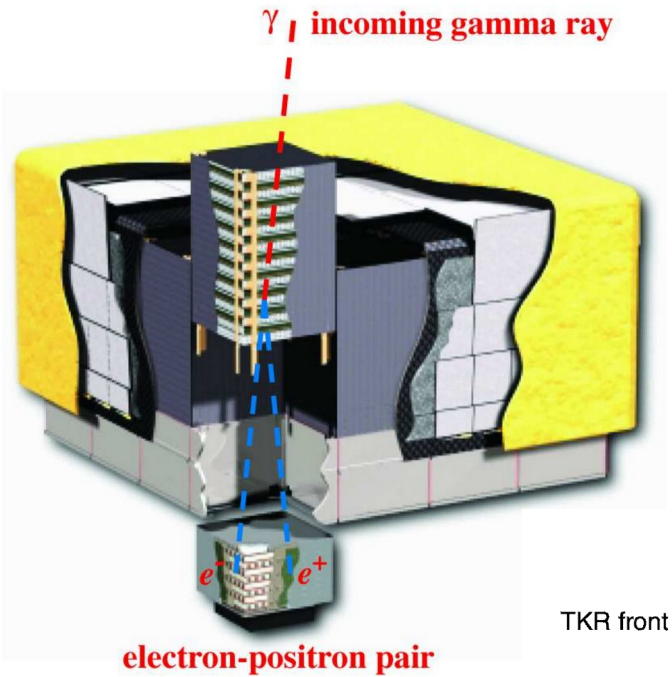
    where ε is the polarimetry selection efficiency
- Estimate S and B in each energy bin from the fitted ROI
  - Events within the 95 % containment angle of the PSF
- We obtain a preliminary uncertainty on the Vela polarization fraction $\sigma_P \approx 19\,\%$

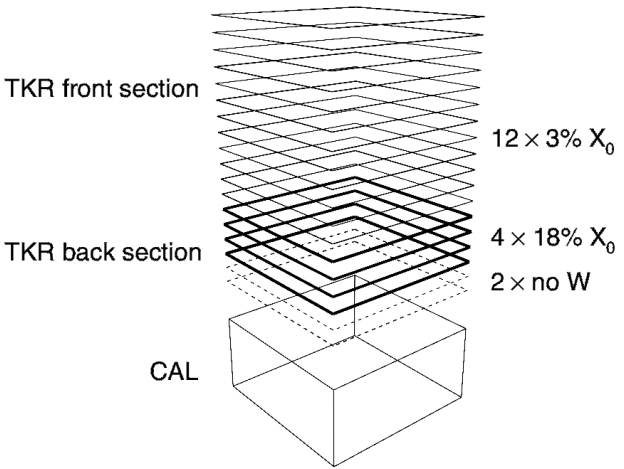
Conclusions and future prospects

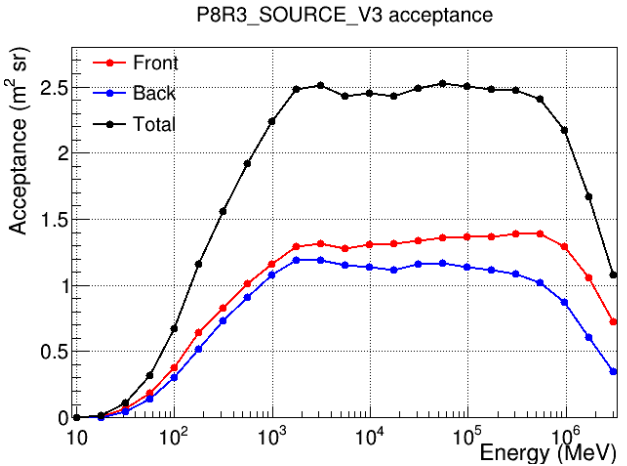
- Conclusions:
  - *Fermi*-LAT is sensitive to the polarization of the Vela pulsar
  - Preliminary sensitivity estimate $\sigma_P \approx 19\,\%$
  - Results in good agreement with the toy-model study [Bernard 2022].
- Next steps:
  - Data / Simulation comparison (work in progress)
  - Perform the measurement

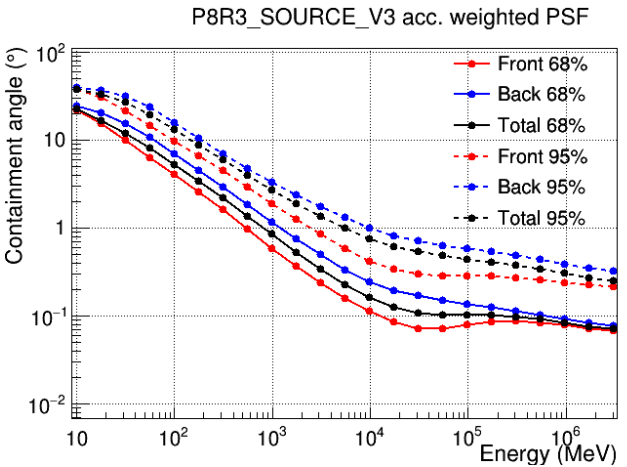
Backup

The *Fermi*-LAT









Preliminary performance of the Back section