Detectors for spaceborne gamma-ray telescopes and polarimeters: state of the art and perspectives

Focus on the angular resolution of e^+e^- pairs telescopes

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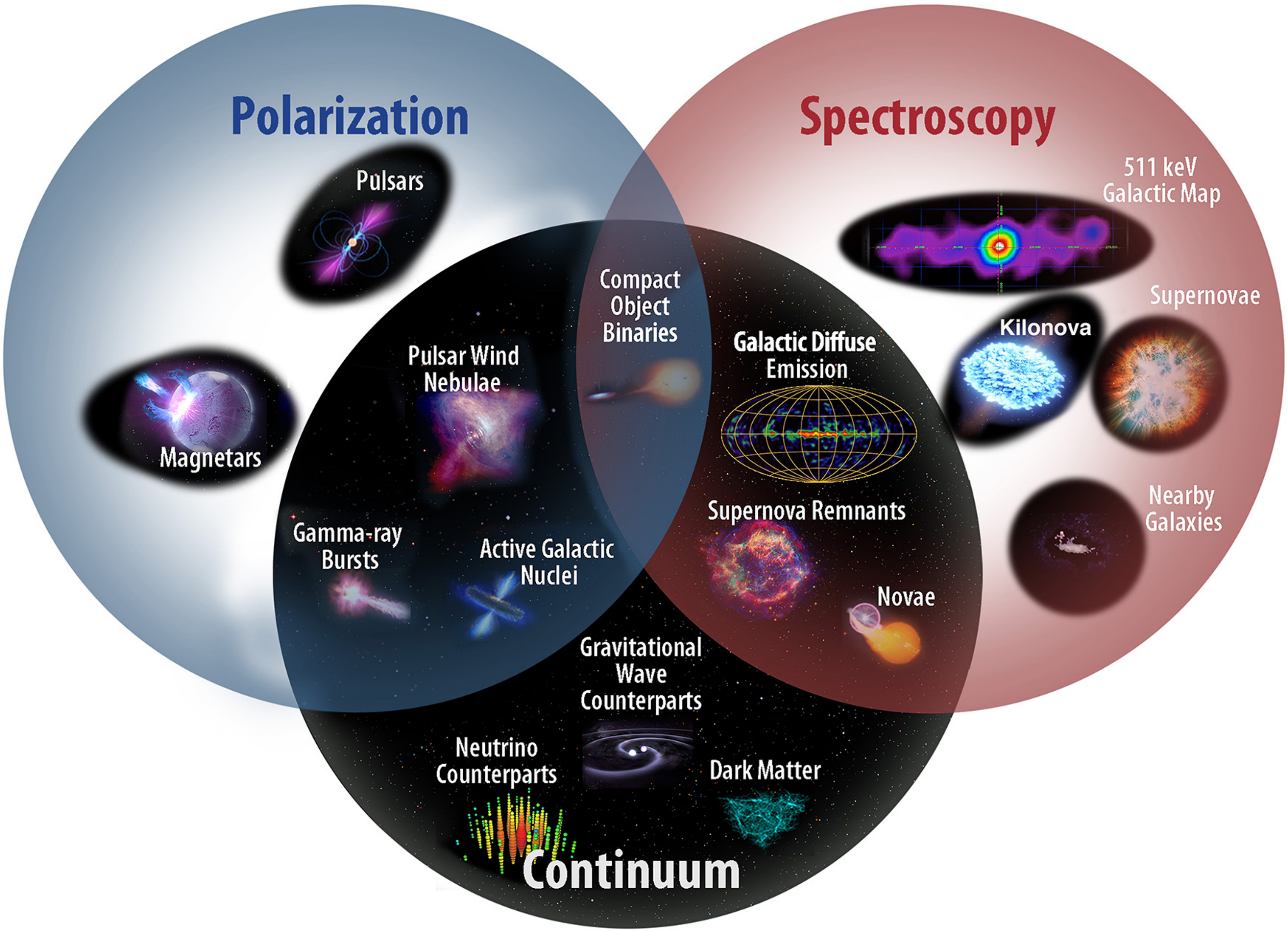
S14, Future spaceborne MeV detectors and related astrophysics

International Conference of Deep Space Sciences, April 2023, Hefei, China

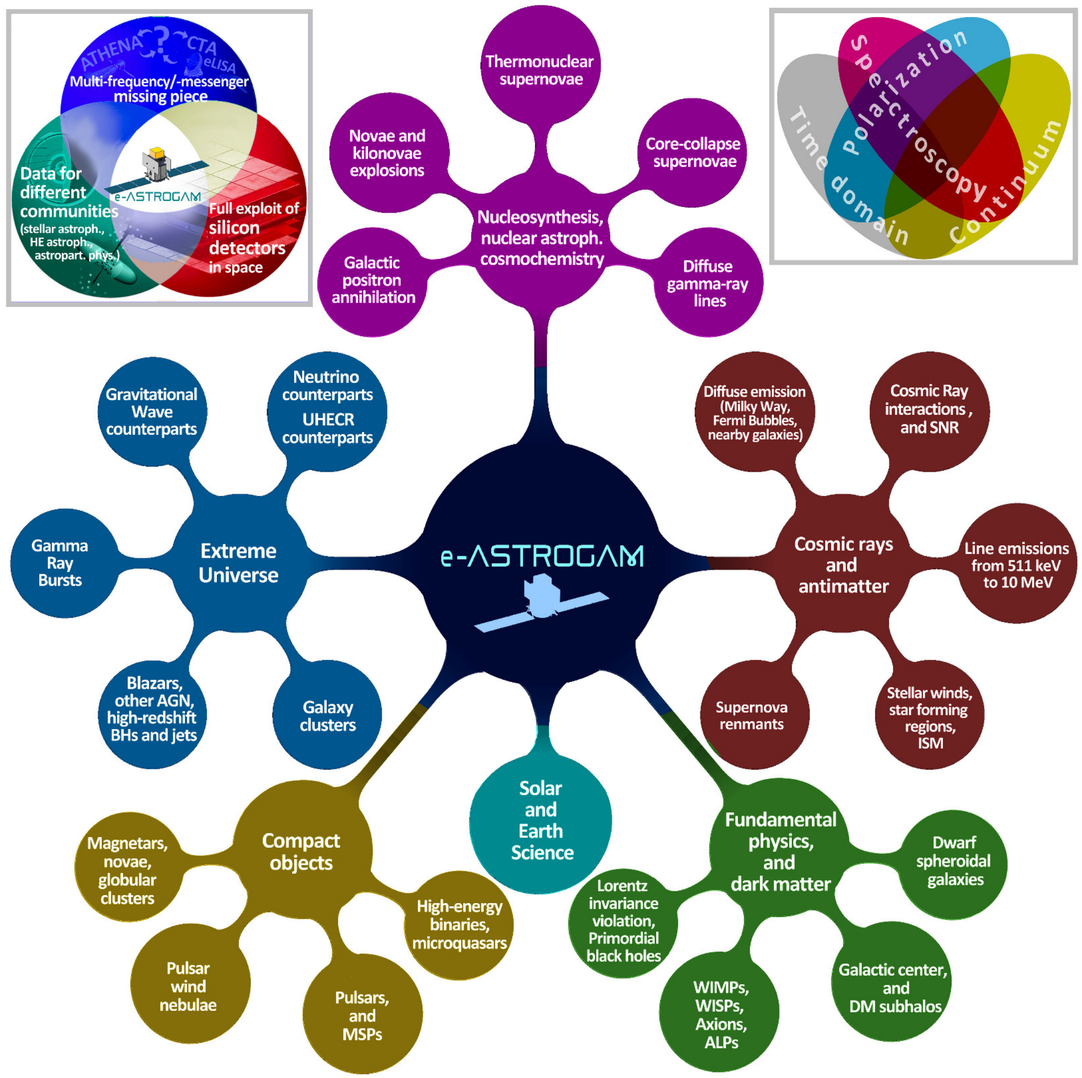
Next MeV gamma-ray spece mission: Scientific programme



R. Caputo *et al.*, J. Astron. Telesc. Instrum. Syst. **8** (2022) no.4, 044003

AMEGO-X (The All-sky Medium Energy Gamma-ray Observatory eXplorer) is a combined (Compton + pairs) telescope project

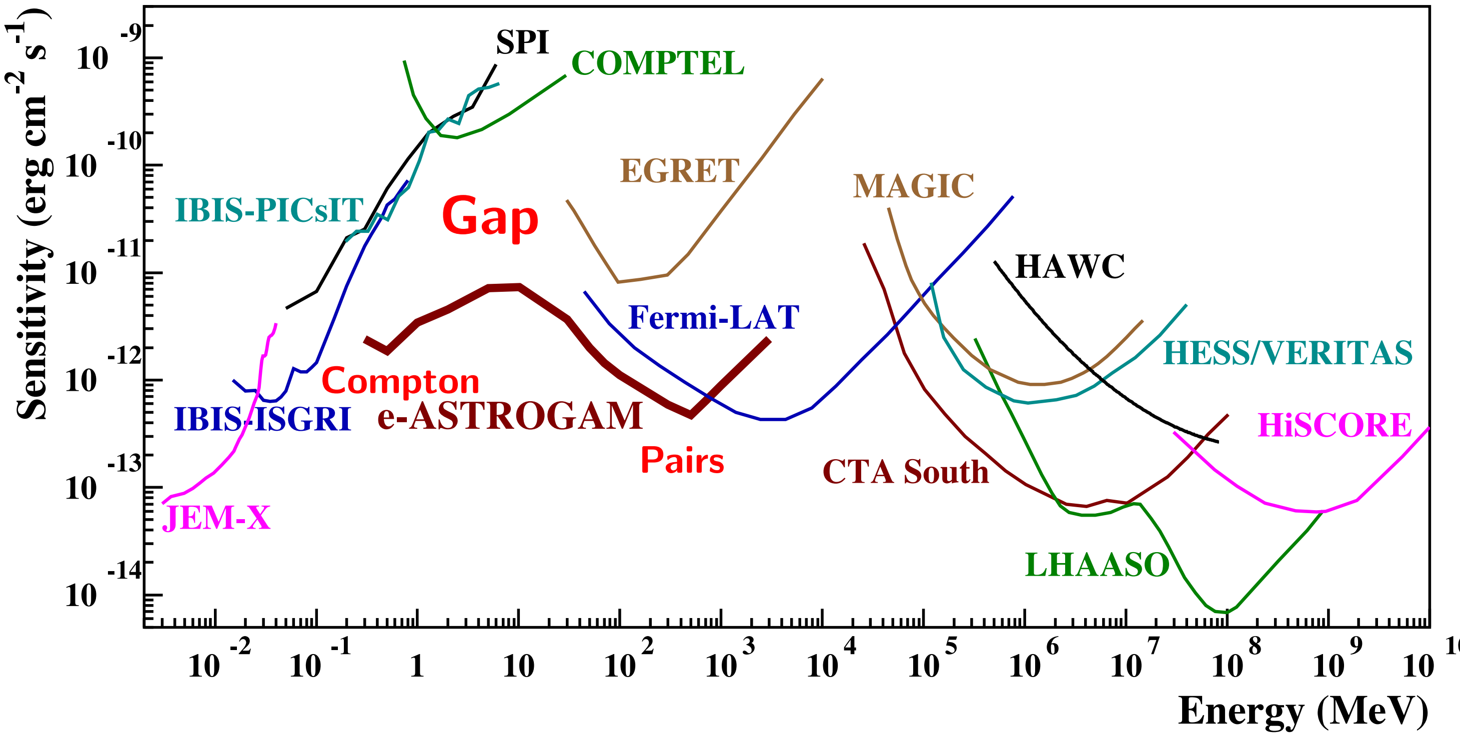
Next MeV gamma-ray spece mission: Scientific programme



A. De Angelis *et al.* [e-ASTROGAM], JHEAp **19** (2018) 1-106

ASTROGAM is a combined (Compton + pairs) telescope project

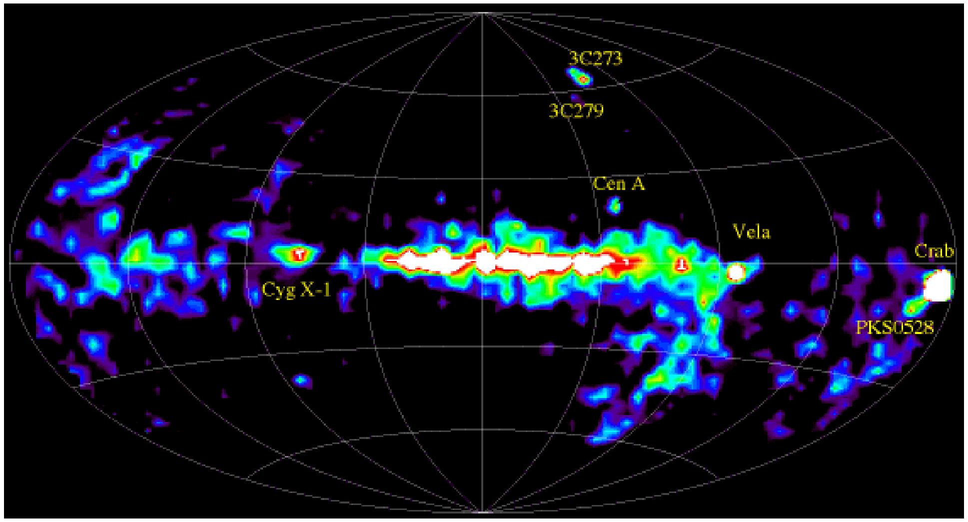
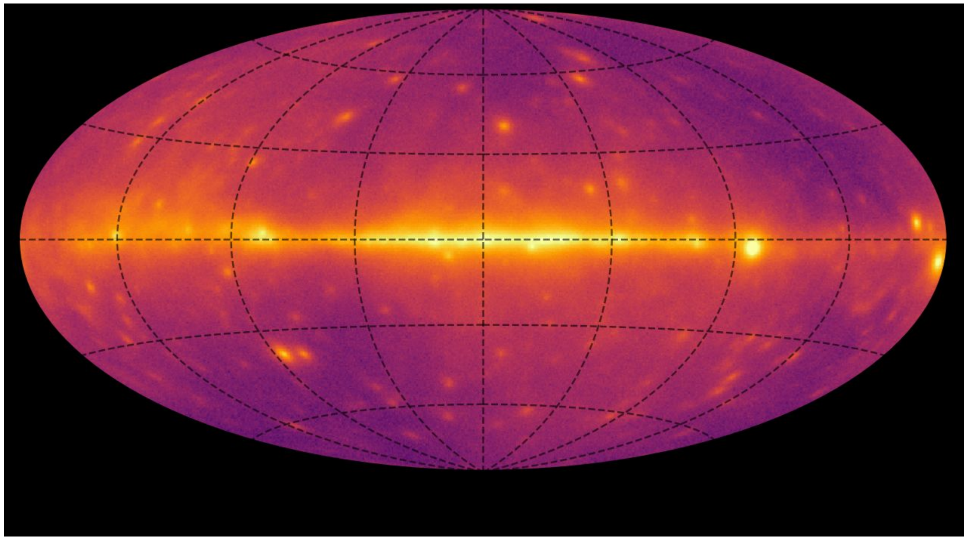
"**Sensitivity gap**" in the MeV energy range



A. De Angelis *et al.* [e-ASTROGAM], JHEAp **19** (2018) 1-106

Differential flux sensitivity: Minimum flux needed to obtain a n-standard-deviation detection from a point-like gamma-ray source, ASTROGAM: $n = 3$, T = 1 year.

ASTROGAM is a combined (**Compton** + **pairs**) telescope project

COMPTEL (Compton)	*Fermi* LAT (Pairs)
	
1 – 30 MeV 9 years heasarc.gsfc.nasa.gov	20 – 200 MeV 13 years 10th Fermi Symposium

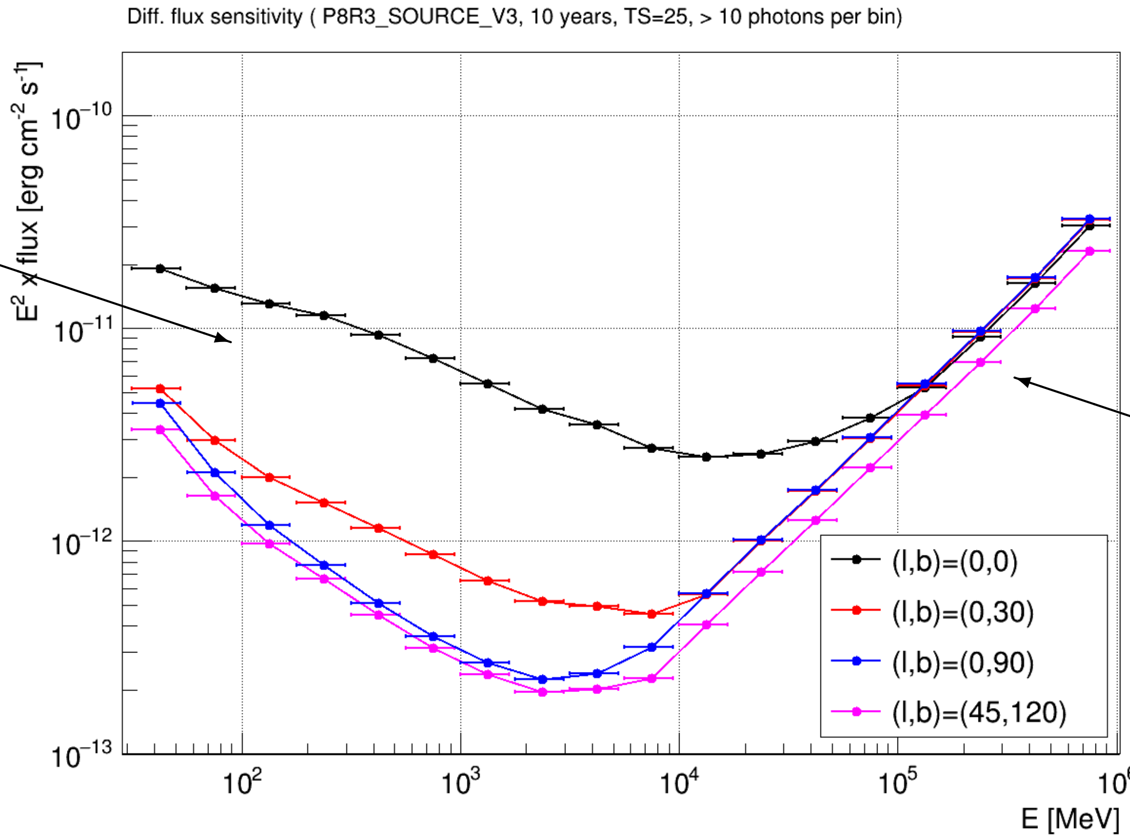
"We are not facing a sensitivity wall, we are facing an angular resolution wall"
I. Grenier (2016)

Limited by background rejection

$$s \approx \frac{n\ \sigma_\theta\ E^2}{\Delta E}\sqrt{\frac{\pi \int B(E)\ \mathrm{d}E}{T\ A_{\text{eff}}}}$$

A_{eff}, effective area

T, duration



Limited by photon statistics

$N_\gamma > 10$

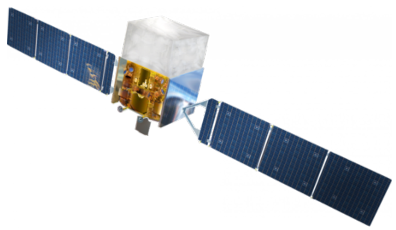
b galactic latitude

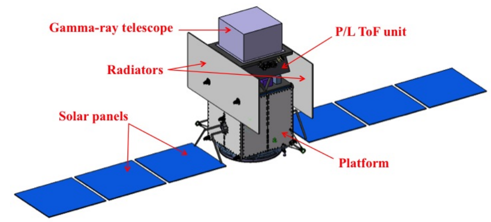
Fermi LAT (Large Area Telescope) performance.html

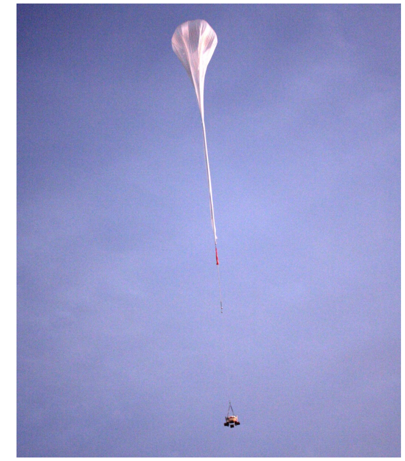
- In this talk I focus on the angular resolution, σ_θ.

Differential flux sensitivity: Minimum flux needed to obtain a n-standard-deviation detection from a point-like gamma-ray source, (here for 4 energy bins / decade, $n = 5$)

Test Cases







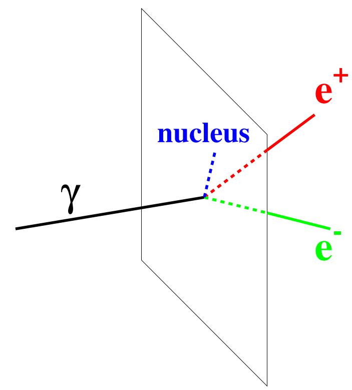
	Fermi-LAT	AMEGO-X / ASTROGAM	GRAINE
Converter / Tracker	Si + W foils	“Pure” Si	film (emulsion+”base”)
Carrier	satellite	satellite	balloon
Status	**In orbit** (2008)	**projects**	project **prototype flown**
	Astrophys. J. **697** (2009) 1071	J. Astron. Tel. Instr. Syst. **8** (2022) 044003 JHEAp **19** (2018) 1-106	Adv. Space Res. **62** (2018) 2945

Photon angular resolution

$$\gamma\ Z \rightarrow e^+\ e^-\ Z$$
$$\vec{k} = \vec{p_{e^+}} + \vec{p_{e^-}} + \vec{p_r}$$

Contributions:

- (a) Un-measured nucleus recoil momentum
- (b) Single-track momentum resolution
- (c) Single-track angular resolution,



Results obtained with the full, 5D, Bethe-Heitler differential cross section

- Includes exact recoil momentum, $\vec{p}_r$, (angle, magnitude) distributions
- 3D final state (NOT a coplanar conversion)
- Energy-momentum strictly conserved

H. Bethe and W. Heitler, Proc. R. Soc. Lond. A, **146** (1934) 83

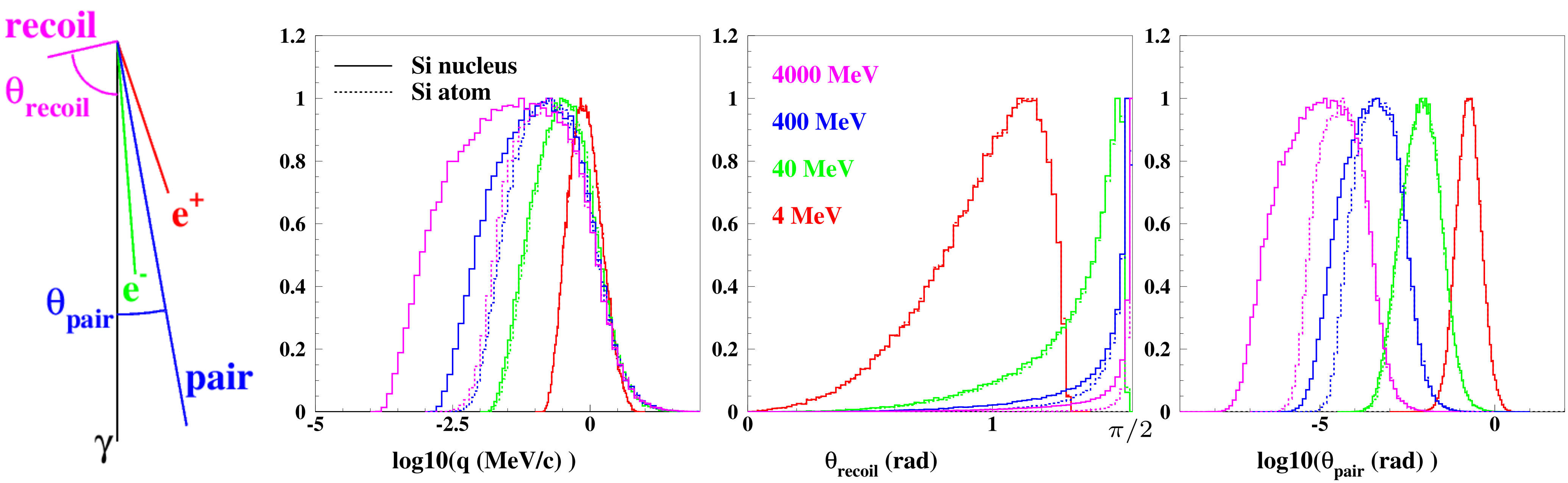
D. Bernard, Nucl. Instrum. Meth. A **899** (2018), 85

In Geant4 as *G4BetheHeitler5DModel* ,

default for high-precision EM physics (Opt 4) since release 10.6 (Dec. 2019)

V. Ivanchenko *et al.* [Geant4], EPJ Web Conf. **214** (2019), 02046

(a) Unmeasured nucleus recoil momentum

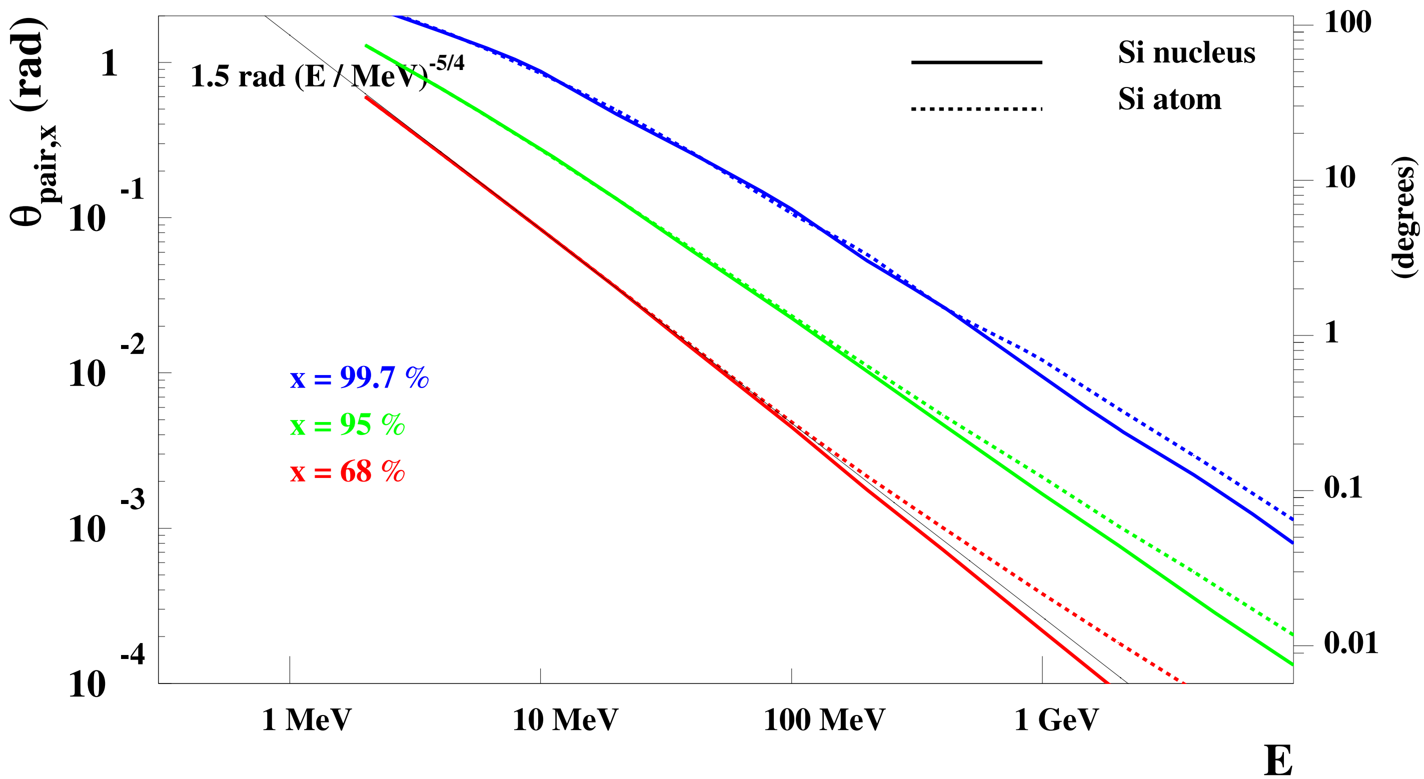


- Conversion on nuclei, recoil momentum distribution extends to $q_{\min} \propto 1/E$
- Conversion on atoms (not on isolated nucleus) & $E > 100\,\mathrm{MeV}$, low-q tail cut by screening
- Recoil direction asymptotically transverse, $\theta_{\mathrm{recoil}} \approx \pi/2$
- Angular resolution, θ_{pair}, scales asymptotically like q/E

D. Bernard, NIM A 729 (2013) 765

P. Gros et al., Astroparticle Physics 88 (2017) 60

Unmeasured nucleus recoil momentum: angular resolution "containment" value



@ $100\,\mathrm{MeV}$, $\theta_{\mathrm{pair},68\%} = 0.27^\circ$, $\theta_{\mathrm{pair},95\%} = 1.35^\circ$ and $\theta_{\mathrm{pair},99.7\%} = 6.56^\circ$

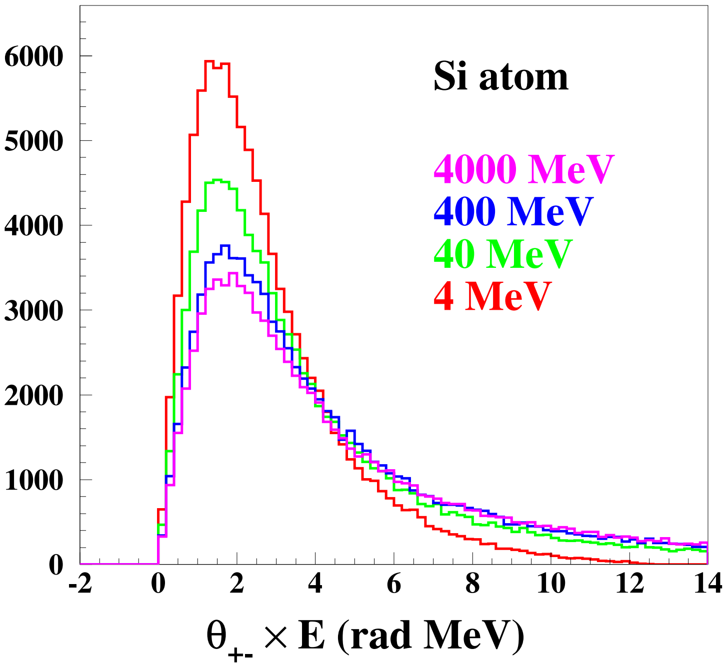
An unavoidable kinematic limit ; Scales like $E^{-5/4}$

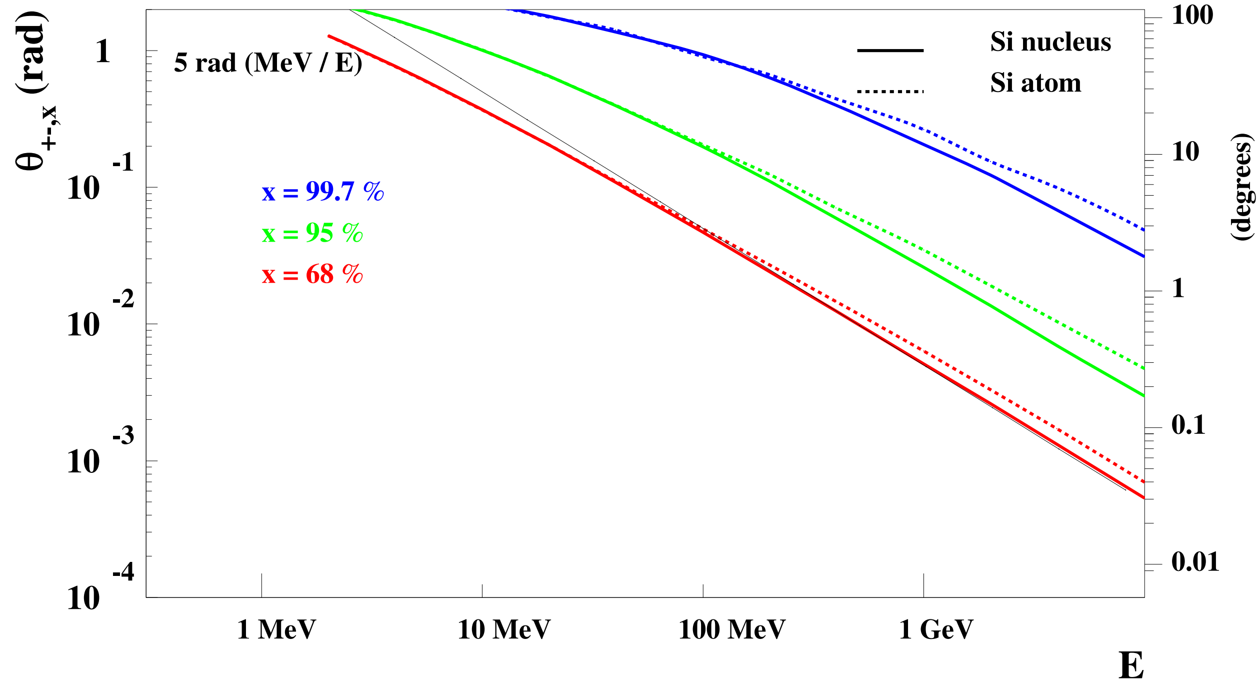
Adapted from

D. Bernard, NIM A 729 (2013) 765

P. Gros et al., Astroparticle Physics 88 (2017) 60

(b) Single-track momentum resolution; Pair opening angle, θ_{+-}

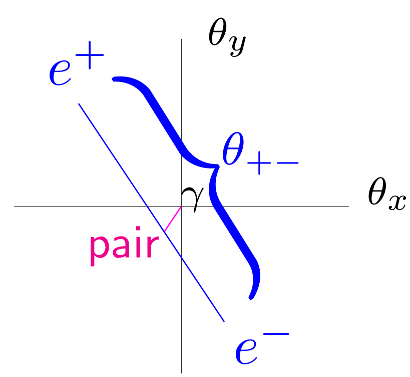




Scales like E^{-1} ; (opening angle) $\theta_{+-,x} \gg \theta_{\text{pair},x}$ (pair polar angle)

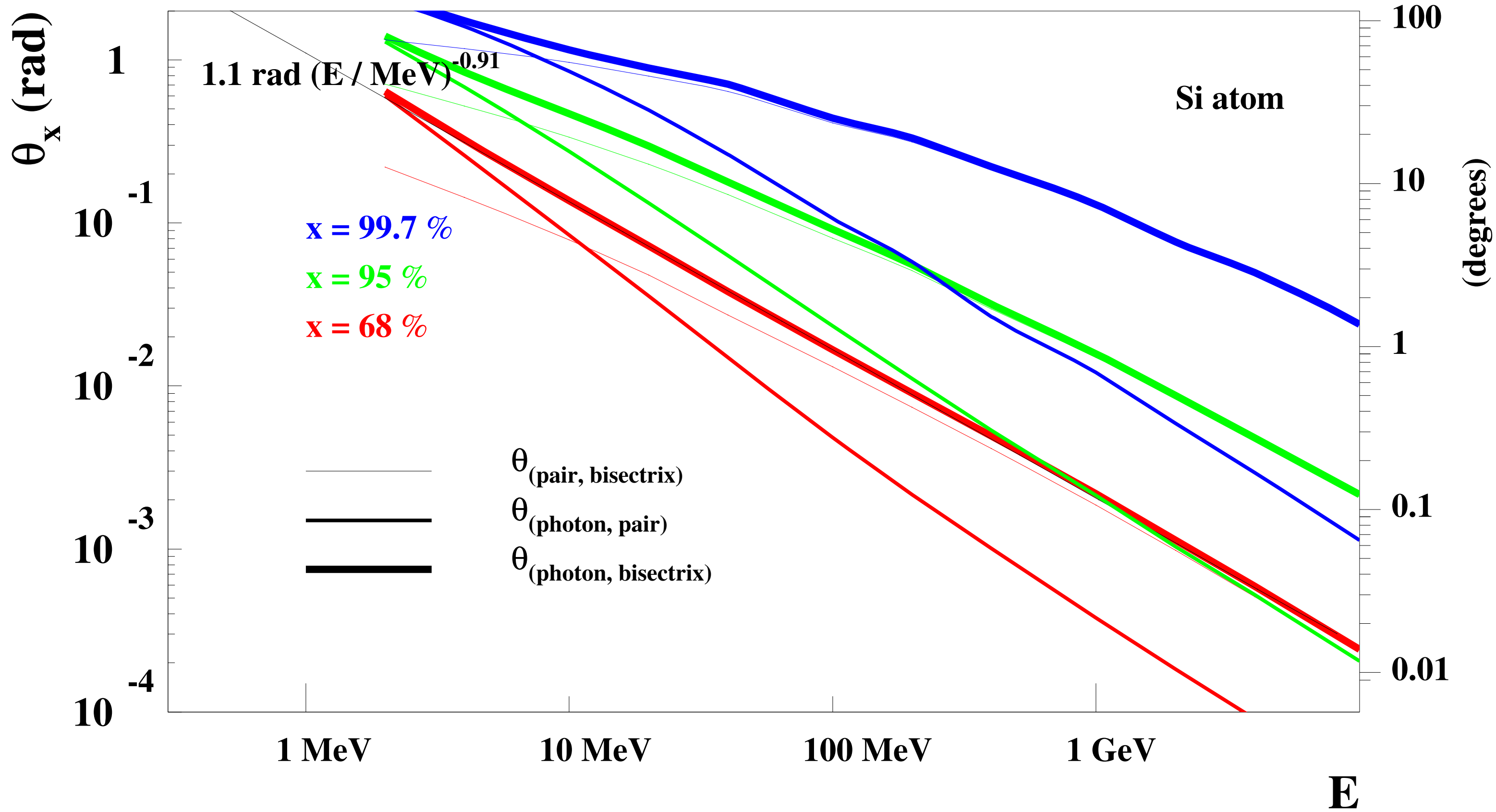
High-energy asymptotic expressions — H. Olsen, Phys. Rev. 131 (1963) 406

Full analysis — D. Bernard, NIM A 729 (2013) 765



e^+ / e^- momentum share ?

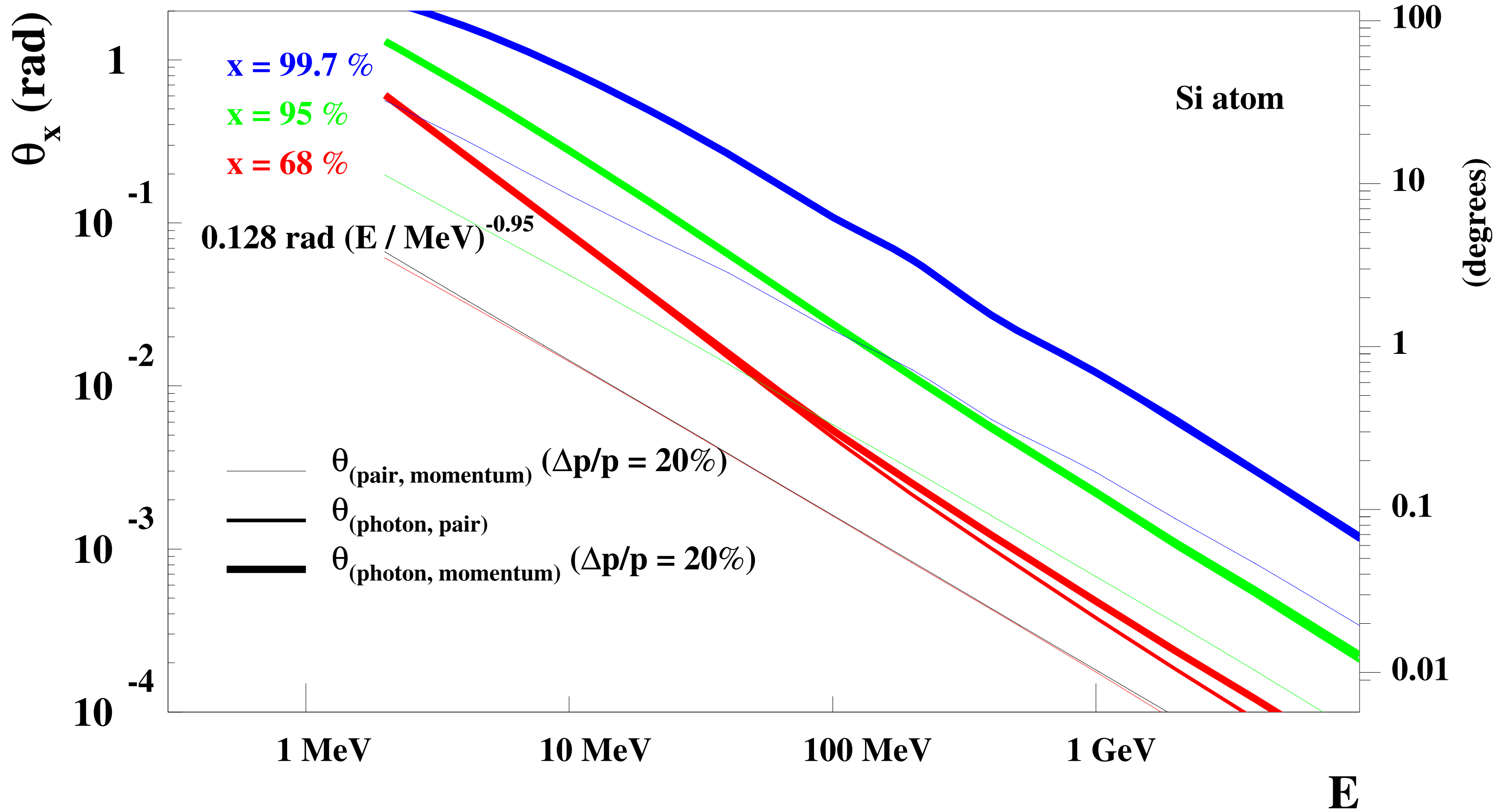
Track momentum measurement ; opening angle ; (1) bisectrix



Assume equipartition: $p_+ = p_- = E/2$. Photon direction "bisectrix" of e^+, e^-

$\theta_{(\text{pair,bisectrix})}$ dominates over $\theta_{(\text{photon,pair})}$, for $E > 10\,\text{MeV}$

Track momentum measurement ; opening angle ; (2) with momentum



Contribution to the angular resolution induced by a $\sigma_p/p\ = 20\%$ momentum resolution

Scales like $0.64\,\mathrm{rad}\,\dfrac{\sigma_p}{p}\left(\dfrac{E}{\mathrm{MeV}}\right)^{-0.95}$; negligible compared to recoil

Track Momentum Measurement ; (1) External (to the tracker)

Calorimeter	**Magnetic spectrometer**
Fermi LAT	AMS-02
CsI(Tl) $(8.6\,X_0)$	Magnet + Si tracker
$\Delta E/E = 20\,\%$ (68 %) @ 100 MeV	$\Delta E/E = 14\,\%$ @ 200 MeV
Fermi LAT Performance	B. Beischer Ph D (2020)

A major impact on the mission mass budget

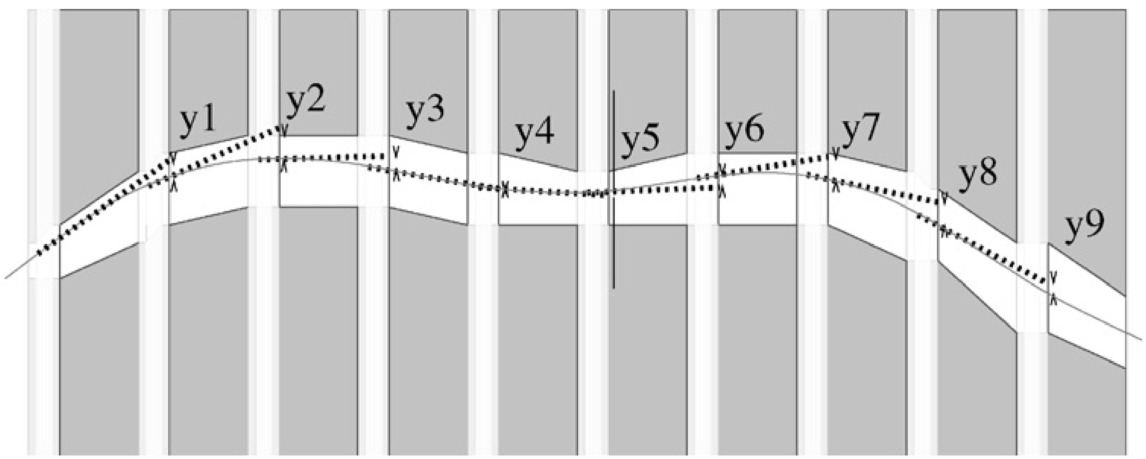
Track Momentum Measurement ; (2) Internal (in the tracker)

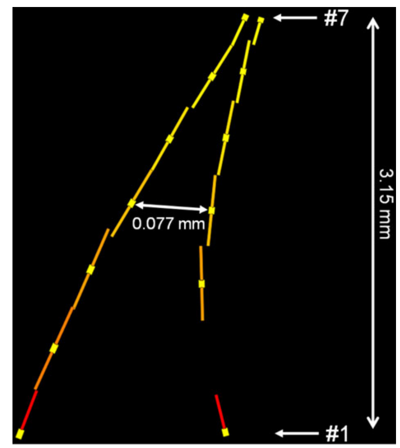
Multiple scattering of relativistic $z = 1$ charged particle through thickness Δ

$$\theta_0 \approx \frac{p_0}{p}\sqrt{\frac{\Delta}{X_0}}\left(1 + \epsilon \log(\Delta/X_0)\right) \qquad , \qquad p_0 = 13.6\,\mathrm{MeV}/c$$

R.L. Workman et al. (PDG) Prog. Theor. Exp. Phys. 2022, 083C01 (2022) (pdf)

$$\Rightarrow \sqrt{\langle y^2 \rangle} \propto \frac{p_0}{p}$$





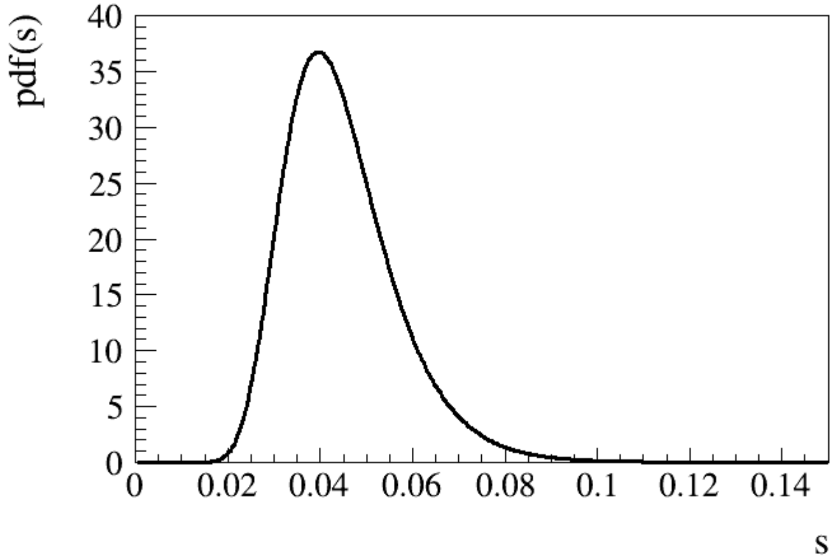
GRAINE: Typical relative precision, $\sigma_p/p = 10 - 20\,\%$

G. Molière Z. Naturforschung A 10 (1955) 177

K. Kodama *et al.* The DONUT (Direct Observation of the NeUtrino Tau) Collaboration, Nucl. Instrum. Meth. A **493** (2002) 45

S. Takahashi *et al.*, The GRAINE (Gamma-Ray Astro-Imager with Nuclear Emulsion) Collaboration, PTEP **2015** (2015) no.4, 043H01

- Apply Kalman filter with track momentum hypothesis p



- A Bayesian analysis of the filtering innovations of s-indexed Kalman filters yields an optimal, unbiased, estimate of the momentum from multiple measurements of multiple-scattering (and of the other track parameters, BTW).

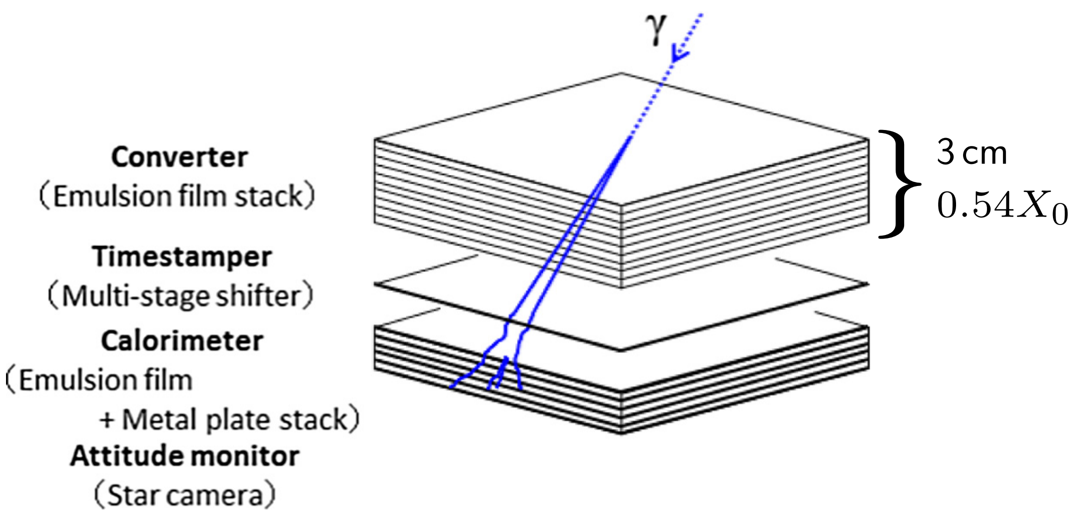
  s, average multiple-scattering angle variance per unit track length, $s, \equiv \left(\frac{p_0}{p}\right)^2 \frac{\Delta}{l X_0}$

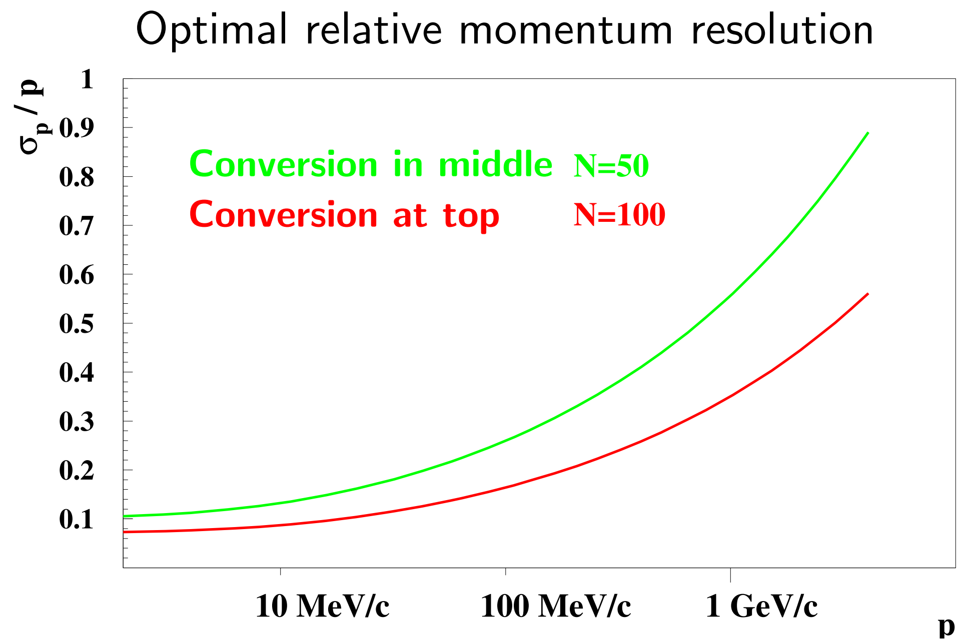
M. Frosini et al., Nucl. Instrum. Meth. A 867 (2017) 182

(l longitudinal measurement sampling, $l = \Delta$ for homogeneous detectors)

Caveat: no BremsStrahlung nor dE/dx here; just multiple scattering

Track Momentum Measurement ; (2) Internal: Optimality: GRAINE





S. Takahashi *et al.*, Adv. Space Res. **62** (2018) 2945

S. Takahashi *et al.*, PTEP **2015** (2015) no.4, 043H01

Computed from M. Frosini et al., Nucl. Instrum. Meth. A 867 (2017) 182

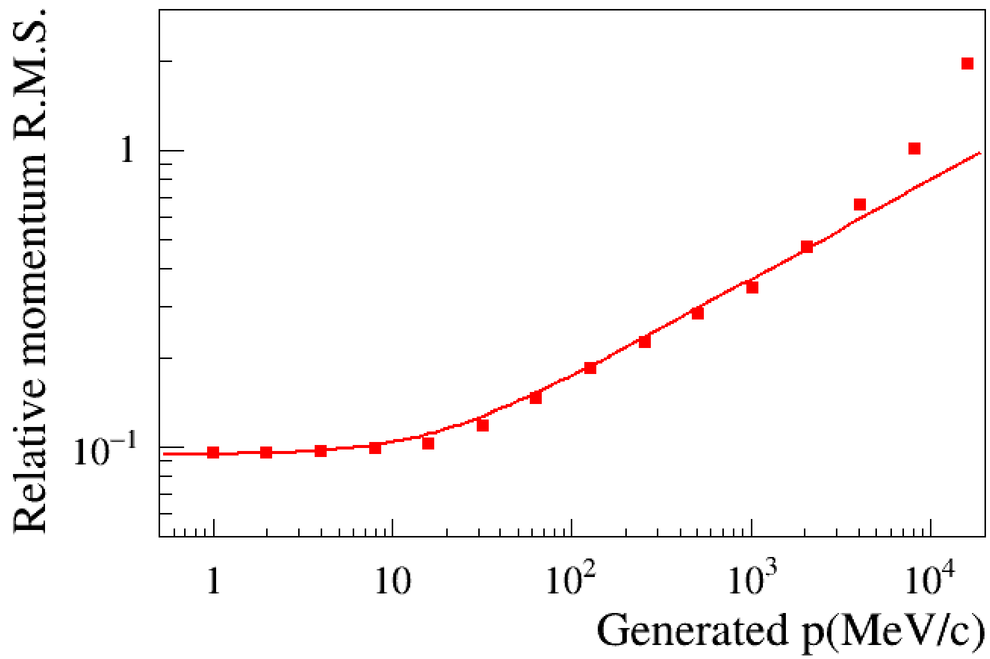
Converter:

- $N \approx 100$ layers (emulsion film)
- Total thickness $L \approx 3\,\text{cm}$, $l = L/N = 0.03\,\text{cm}$
- Total number of radiation lengths $L/X_0 \approx 0.53$,
  Number of radiation lengths per layer $t = l/X_0 \approx 0.0053$,
  Average radiation length $X_0 \approx L/0.53 = 5.66\,\text{cm}$,
- Single layer spatial resolution, $\sigma = \mathbf{0.42}\,\mu\text{m}$!

"Pure" (no W foil), Double-sided silicon strip detector (DSSSD) trackers + Calorimeter

- ASTROGAM, A. De Angelis *et al.* [e-ASTROGAM], Exper. Astron. **44** (2017) no.1, 25
- AMEGO-X. R. Caputo *et al.*, J. Astron. Telesc. Instrum. Syst. **8** (2022) no.4, 044003

- $X_0 = 9.4\,\mathrm{cm}$, radiation length
- $N = 56$ layers
- $\Delta = 500\,\mu\mathrm{m}$, wafer thickness
- $l = 1\,\mathrm{cm}$, layer spacing
- $\sigma = 240/\sqrt{12} \approx 70\,\mu\mathrm{m}$
  single measurement space precision

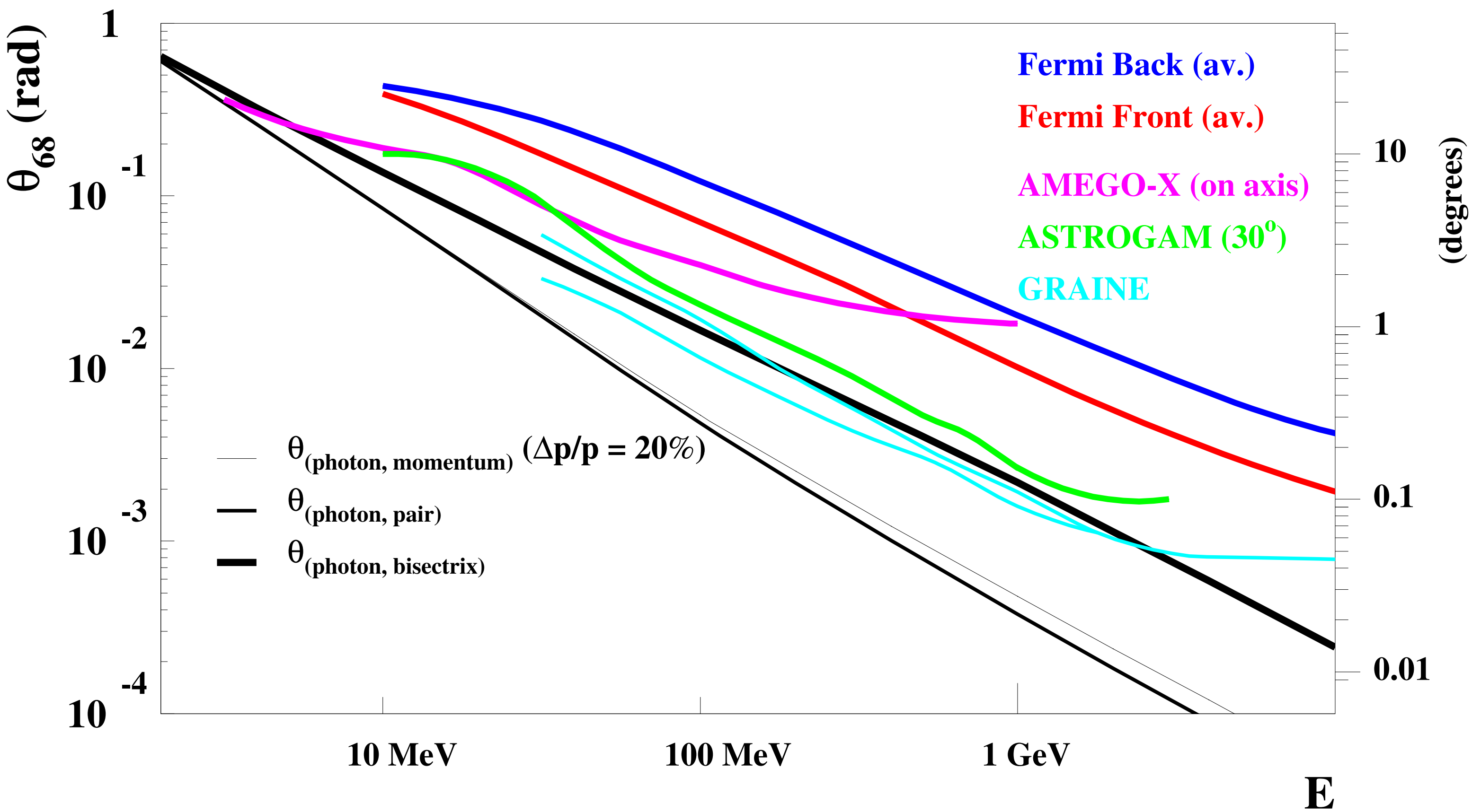


Usable method in the MeV energy range

M. Frosini et al., Nucl. Instrum. Meth. A 867 (2017) 182

Calorimetry in the tracker silicon too ($\approx 11\,\mathrm{MeV}$ loss per track, through 56 wafer pile @ 0°)

Angular resolution: interim wrap-up (a)+(b)



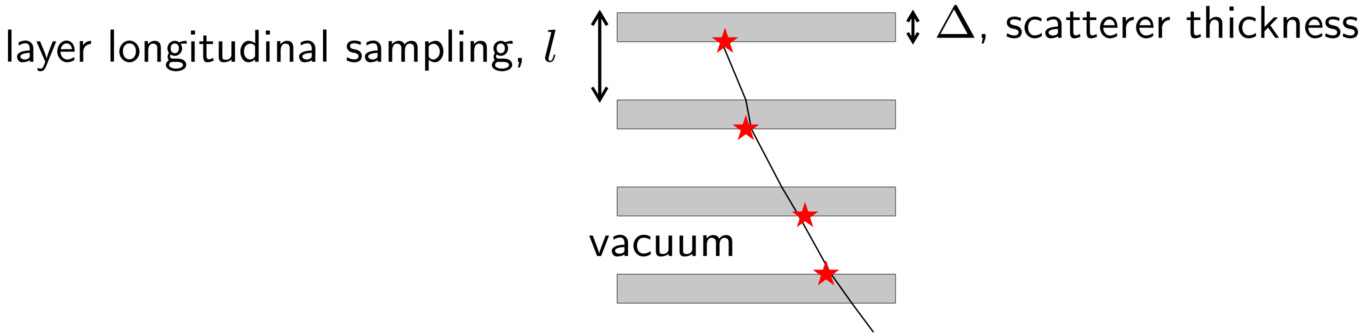
Fermi LAT Performance, Pass 8 Release 3 Version 3

GRAINE, Adv. Space Res. **62** (2018) 2945

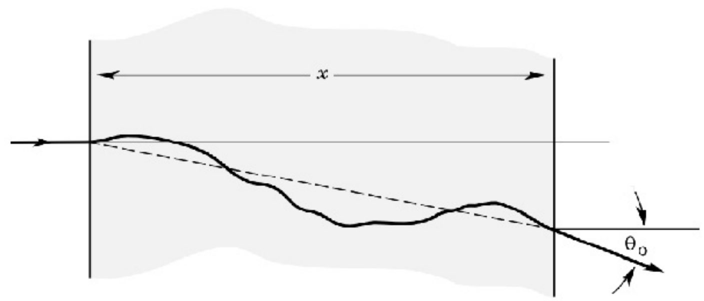
AMEGO-X, J. Astron. Telesc. Instrum. Syst. **8** (2022) no.4, 044003

ASTROGAM, Exper. Astron. **44** (2017) no.1, 25

- Typical tracker consisting of N plane "layers", each with measurement precision σ



- Multiple scattering of charged particles in their way through matter



Deflection polar angle, θ_0, Gaussian distributed,

$$\theta_{\rm RMS,0} \approx \frac{p_0}{p}\sqrt{\frac{\Delta}{X_0}}\left(1+\epsilon\log(\Delta/X_0)\right) \qquad , \qquad p_0 = 13.6\,{\rm MeV}/c$$

(PDG) Prog. Theor. Exp. Phys. 2022, 083C01 (2022) (pdf)

- Tracking: fit track model ((position, direction) at track origin)

Problem of correlation induced by multiple scattering

Tracking with multiple scattering: optimality: Kalman filter

- Assumes Gaussian statistics (detector PSF & multiple scattering deflection)
- Assumes linearity
  state (position, direction) at plane i, depends linearly on states at planes j ($j < i$)
- Proceeds by induction:
  - Assuming that we have an optimal **estimate** of the model for planes $i = 1 \cdots n$, (and covariance matrices) and
  - That we know the statistics of the process noise (the RMS of the deflection angle) from plane n to plane $n+1$, and
  - Given the value of the position **measured** at plane $n+1$ (and covariance matrix)

  $\Rightarrow$ the Kalman filter mechanism provides an **optimal estimate** of the model at plane $n+1$ (a "simple" weighting by the inverse variance)
- Optimality requires two "passes",
  - 1rst, forward "filtering"
  - 2nd, backward "smoothing"

R. Frühwirth Nucl. Instrum. Meth. A **262**, 444 (1987).

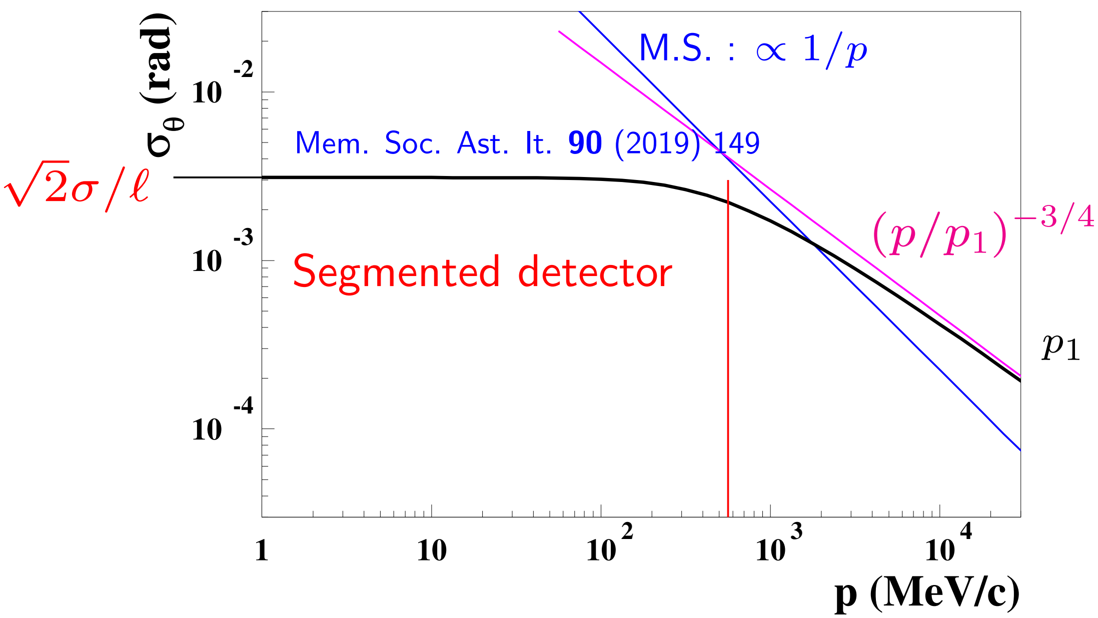
If the system is not linear (e.g. tracking with $\vec{B} \neq 0$), linearize it ! $\Rightarrow$ "Extended" Kalman filter

Single-Track (Polar) Angle Resolution

– Optimal tracking (à la Kalman), M. Frosini et al., Nucl. Instrum. Meth. A 867 (2017) 182

Conversion point at bottom of layer (No dE/dx here)

– Kalman filter tracking useless < few 100s MeV/c



homogeneous detector

$$p_1 = 13.6\,\mathrm{MeV}/c \left(\frac{2\sigma}{\ell}\right)^{1/3} \left(\frac{\Delta}{X_{0,W}}\right)^{1/2}.$$

D. Bernard, Nucl. Instrum. Meth. A 729 (2013) 765

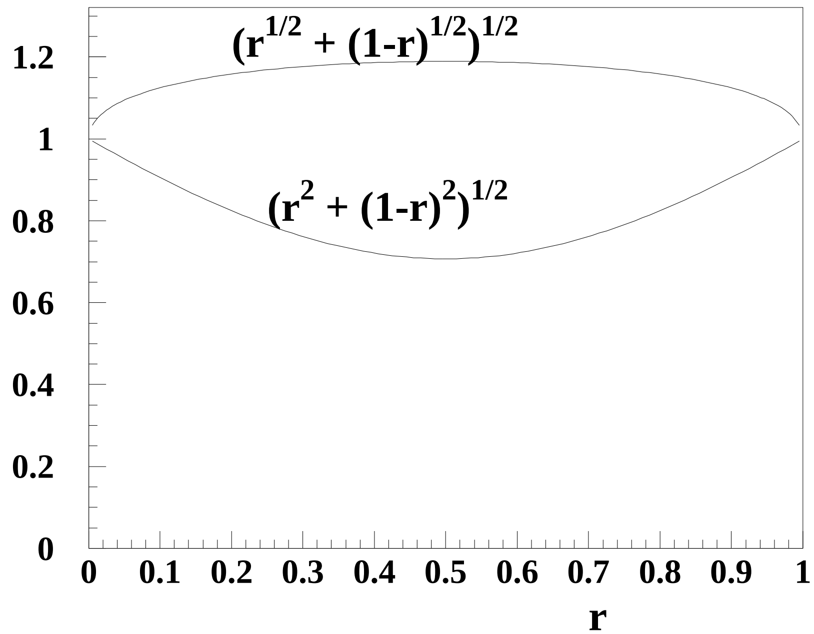
– M.S.: Multiple scattering through (full) conversion layer ; dominates at low energy anyway

Fermi LAT

$l = 3\,\mathrm{cm}$, layer spacing
$\sigma = 228\,\mu\mathrm{m}/\sqrt{12}$, single measurement space precision
$\Delta = 95\,\mu\mathrm{m}$, W foil thickness (front)
$p_1 \approx 0.37\,\mathrm{MeV}/c$,

Polar Angle Resolution: from Single-Track to Single-Photon

$\sigma_{\theta t}(p)$ scaling translate to $\sigma_{\theta\gamma}(E)$ scaling, p, track momentum, E, photon energy.



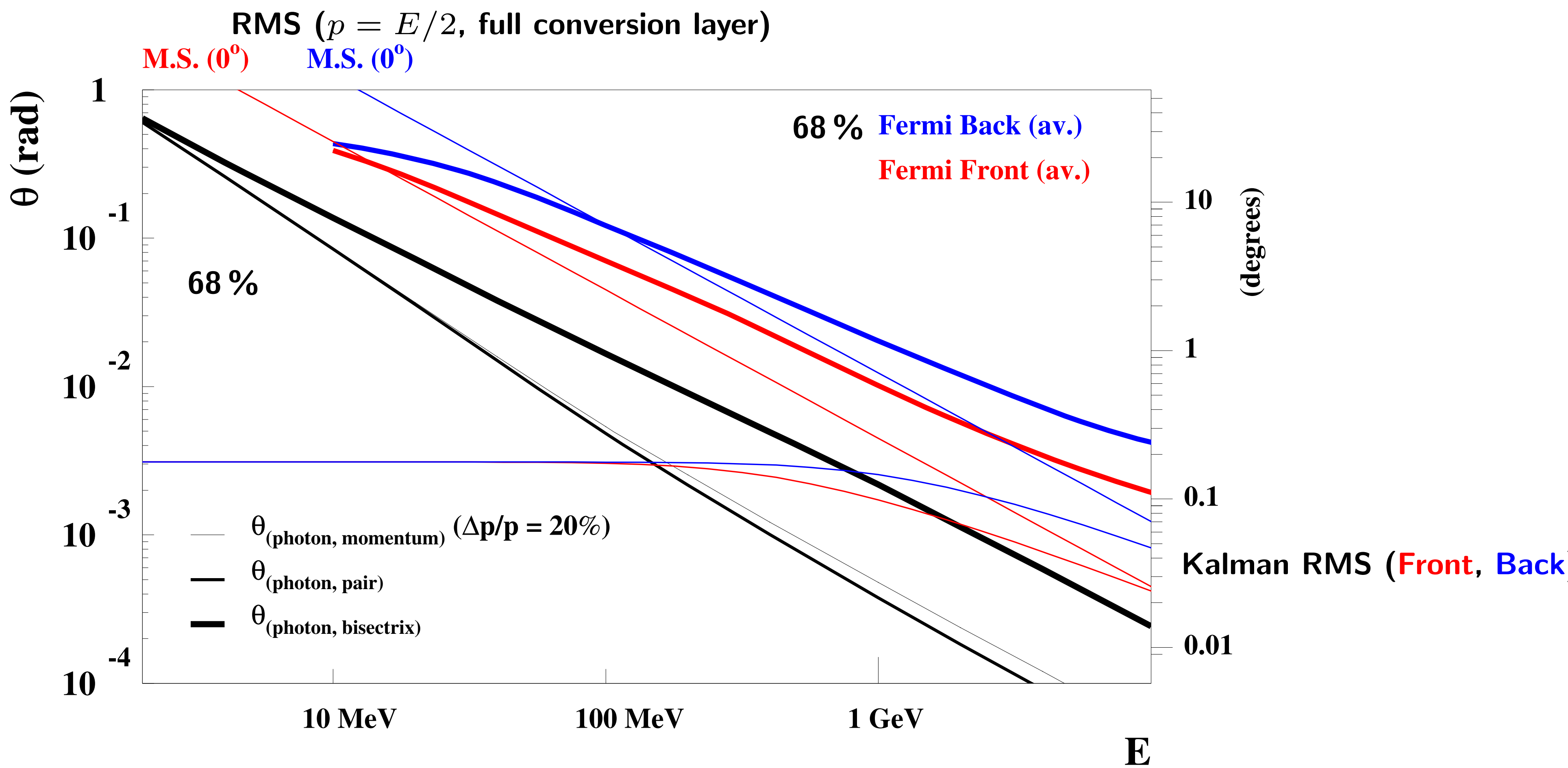
Track-to-photon angular resolution factors as a function of $r = E_+/E_\gamma$

- $\sigma_{\theta\gamma} = \sigma_{\theta t}\sqrt{\sqrt{r} + \sqrt{1-r}}$, multiple scattering dominated regime, $\sigma_{\theta t} \propto (p/p_1)^{-3/4}$
- $\sigma_{\theta\gamma} = \sigma_{\theta t}\sqrt{r^2 + (1-r)^2}$, ultra-high energy regime, $\sigma_{\theta t} = \frac{2\sigma}{L}\sqrt{3/(N+3)}$

D. Bernard , Nucl. Instrum. Meth. A **701** (2013) 225 [err: Nucl. Instrum. Meth. A **713** (2013) 76]

I will neglect this factor

Fermi LAT



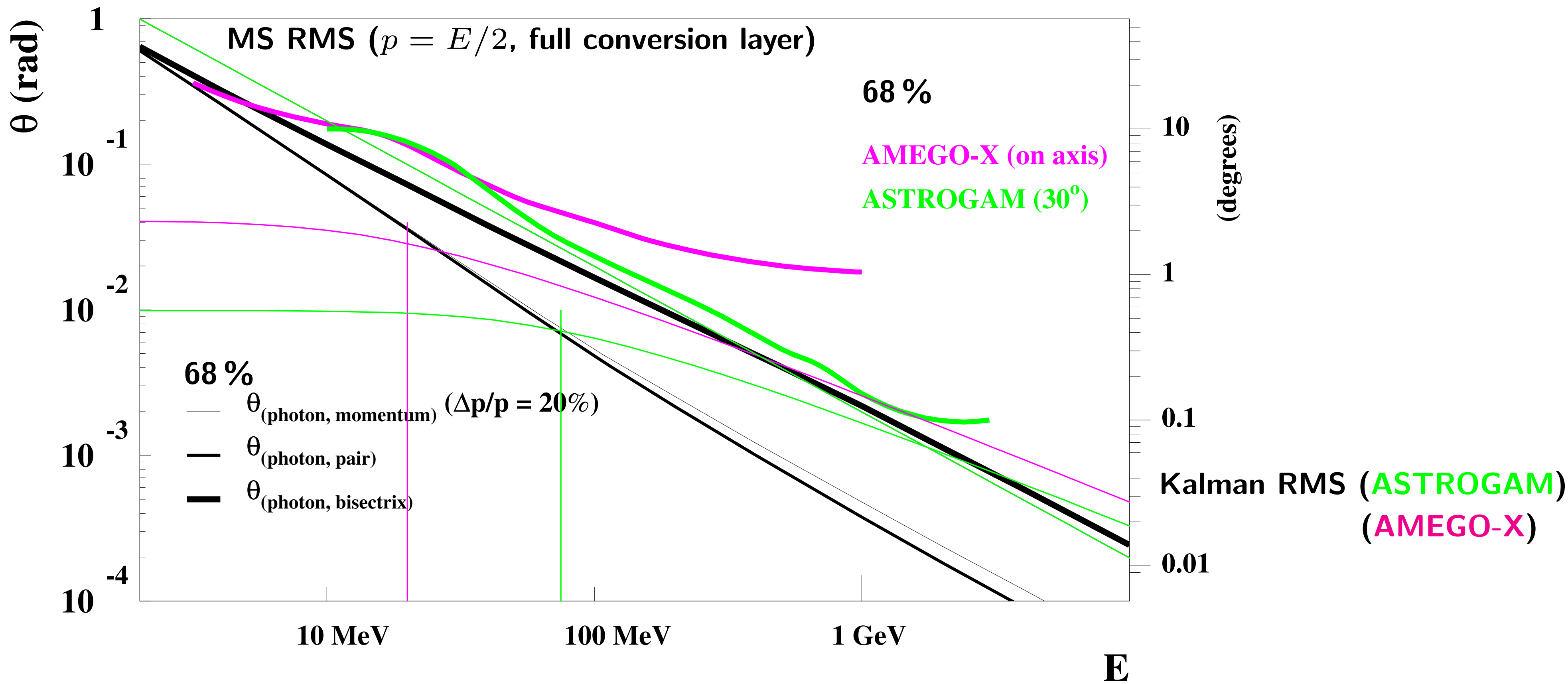
– Angular resolution heavily dominated by multiple scattering in conversion layer

– Slope not understood

– Pass8 based on one "main" track though

W. Atwood *et al.* [Fermi-LAT], 2013, eConf C121028, 8, in Proc. 4th Fermi Symposium, Monterey

AMEGO-X / ASTROGAM



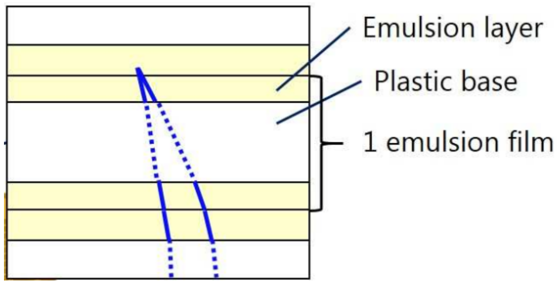
Both dominated by multiple scattering; Bisectrix ?

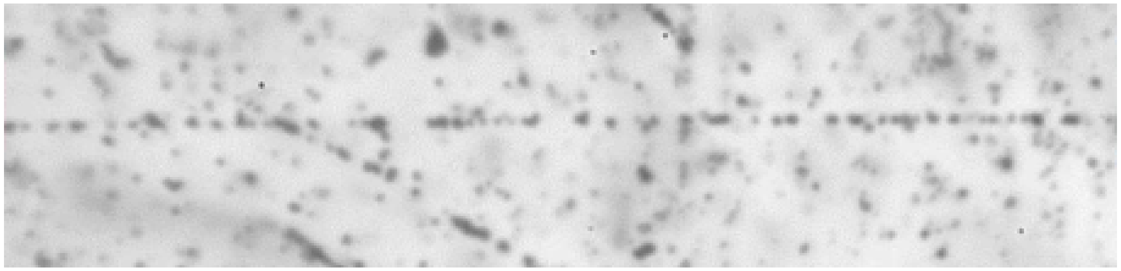
	AMEGO-X	ASTROGAM	
Segmentation	pixels	strips	
N, layer number	60	56	
Δ, Layer thickness	500	500	µm
l, layer spacing	1	1	cm
p, read-out pitch	240	1000	µm

GRAINE; Two measurement methods

- **Machine scan** track angle from position difference between top and bottom emulsions of same film

  (Absolute position of film in scanning machine (RMS $0.42\,\mu\mathrm{m}$) limiting factor of multi-film analysis)



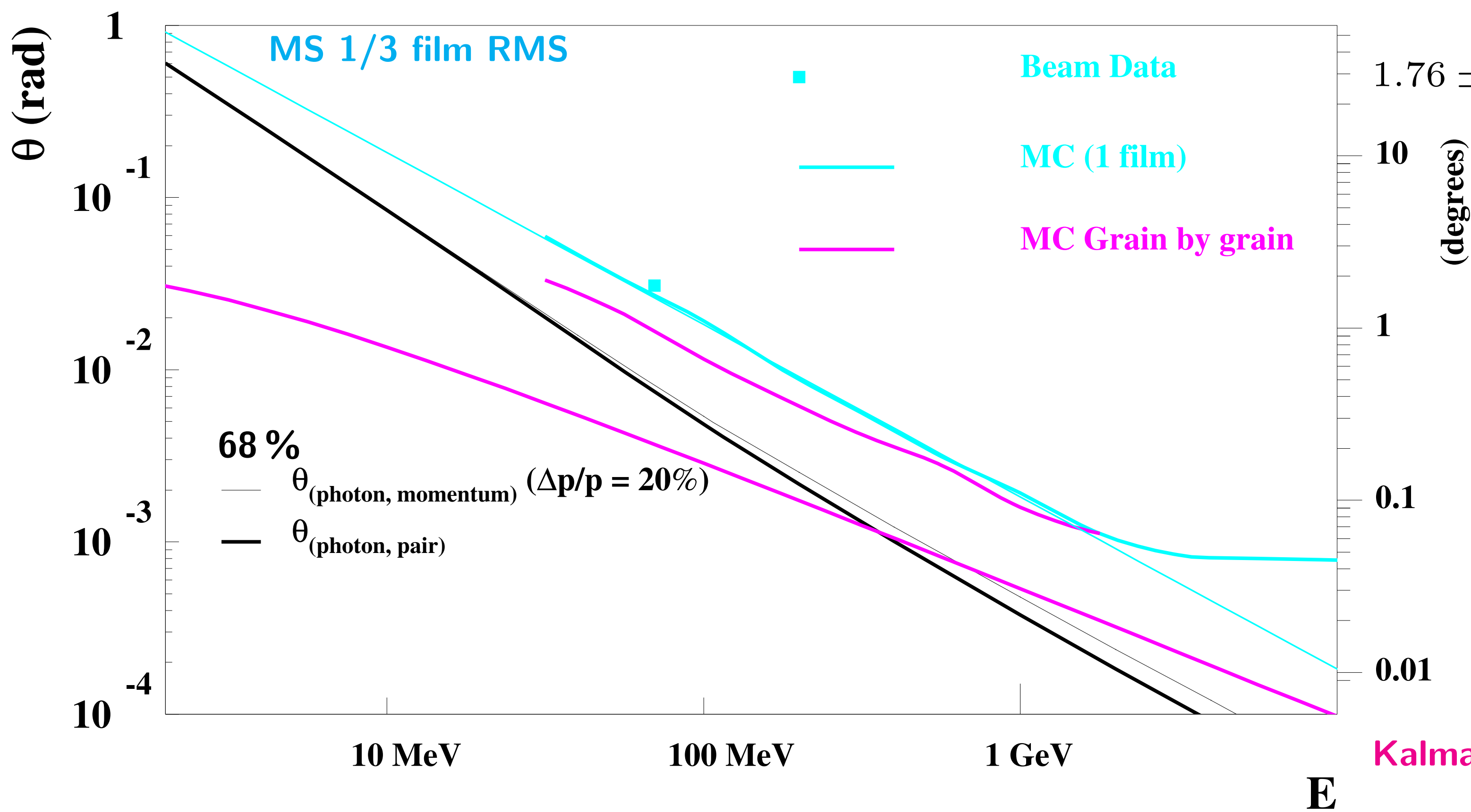


- **Human scan (microscope)** grain by grain

  High-density emulsions: Grain density (50 counts / 100 microns)
  single grain position measurement 60 nm.

  K. Ozaki, Ph. D. 2016, Kobe University

  Momenta measured, see slide 15.



$1.76 \pm 0.12^\circ$ @ $70.8\,\mathrm{MeV}$

K. Ozaki, Ph. D. 2016

Kalman RMS (Grain à grain)

Machine measurement dominated by multiple scattering in film

Grain-by-grain measurement would benefit a Kalman filter fit

$N = 70\,\mu\mathrm{m}/2\,\mu\mathrm{m} = 35$, layer number
$X_0 = 2.84\,\mathrm{cm}$
$l = \Delta = 2\,\mu\mathrm{m}$, longitudinal sampling
$\sigma = 0.060\,\mu\mathrm{m}$
$\sigma_p/p = 20\,\%$, momentum relative precision

Conclusion; perspectives

– Examined various contributions to the telescope angular resolution

Angular resolution (68 %) scaling

- $E^{-5/4}$ Unmeasured nucleus recoil momentum
- E^{-1} Multiple scattering in conversion layer
- $E^{-0.95}$ Track momentum measurement with ifxed relative precision
- $E^{-0.91}$ Bisectrix
- $E^{-3/4}$ Tracking in homogeneous detector

– Fermi-LAT, AMEGO-X / ASTROGAM, GRAINE (Machine scan): Multiple Scattering in the conversion layer.

- AMEGO-X / ASTROGAM: bisectrix ?
- GRAINE (grain by grain): improvement to be expected with Kalman filter tracking ?

How do better ? Gas TPC (time projection chamber) Talks at this conference:

- SMILE – ETCC: Atsushi Takada
- HARPO: Shaobo Wang
- MeGaT: Zhiyong Zhang

– Not in this talk: Pair telescopes poor line sensitivity in the MeV energy range.

Acknowledgements

Fermi LAT	Simone Maldera
AMEGO-X	Regina Caputo
GRAINE	Satoru Takahashi

Errors, misconceptions, outrageous approximations and harzardous assumptions ... mine.