

Tenth International Fermi Symposium

9th-15th October 2022



Polarimetry of $\gamma \rightarrow e^+e^-$:

Performance of Silicon Strip Detectors-Based Telescopes;
A Case Study: the Fermi-LAT

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Nucl. Instrum. Meth. A **1042** (2022) 167462

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γ -Ray Polarimetry: Science Goals

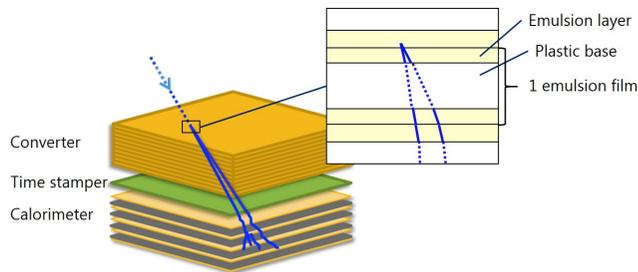
- Main targets: bright sources, deciphering emission mechanism
 - Blazars:
leptonic synchrotron self-Compton (SSC) or **hadronic** (proton-synchrotron) ?
Zhang and Böttcher, *Astrophys.J.* 774, 18 (2013)
 - Pulsars
J. Takata and H.-K. Chang, *Astrophys. J.* 670 (2007) 677
J. Pétri, *Mon. Not. Roy. Astron. Soc.* 434 (2013) 2636
B. Cerutti et al., *Mon. Not. Roy. Astron. Soc.* **463** (2016) L89-L93
Harding and Kalapotharakos, *Astrophys. J.* 840 73 (2017)
- Further away (pending on statistics)
 - LIV search (Lorentz-invariance violation), induced dilution of the GRB polarization signal
F. Kislak, arXiv:1907.06514 [astro-ph.HE],
 - Axion search, A. Rubbia and A. S. Sakharov, *Astropart. Phys.* **29** (2008) 20

MeV-GeV $\gamma \rightarrow e^+e^-$ -Pair Polarimeter: Homogeneous Active Targets

Emulsions (GRAINE)

sub- μm resolution, high density converter

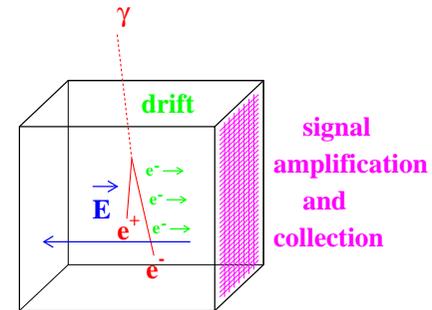
S. Takahashi *et al.*, PTEP **2015** (2015) 043H01



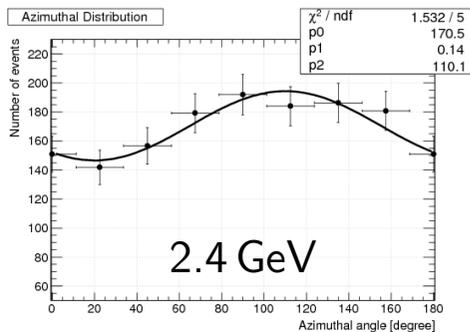
Gas time-projection chambers (TPC) (HARPO)

sub-mm resolution, low density converter

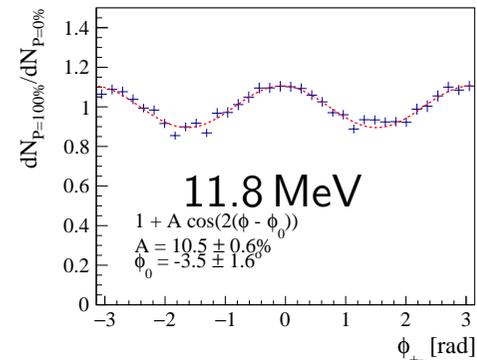
D. Bernard, NIM A 936 (2019) 405



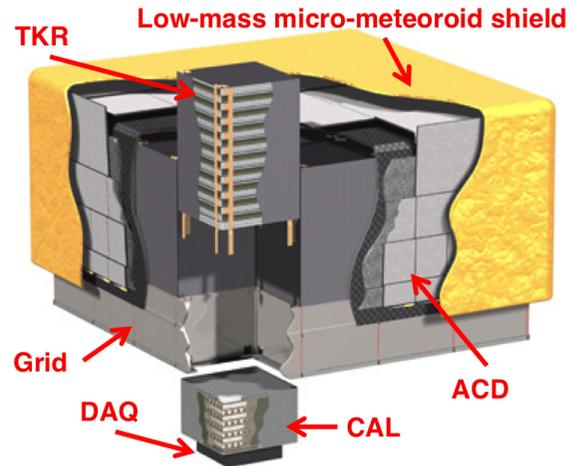
K. Ozaki *et al.*, NIM A **833** (2016)165



Ph. Gros *et al.*, Astroparticle Physics 97 (2018) 10



Silicon-Strip Detectors (SSD) Active Targets and Polarimetry



- *Fermi-LAT* (launched 2008)

“Estimate of the Fermi Large Area Telescope sensitivity to gamma-ray polarization,”

M. Gioni *et al.* [*Fermi-LAT*], *AIP Conf. Proc.* **1792** (2017) 070022

“For this study we will **assume** $A_{100} \approx 0.2$ ” A_{100} polarisation asymmetry

- Projects

- AMEGO (All-sky Medium-Energy Gamma-ray Observatory),

R. Caputo *et al.* [arXiv:1907.07558](https://arxiv.org/abs/1907.07558).

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

This work

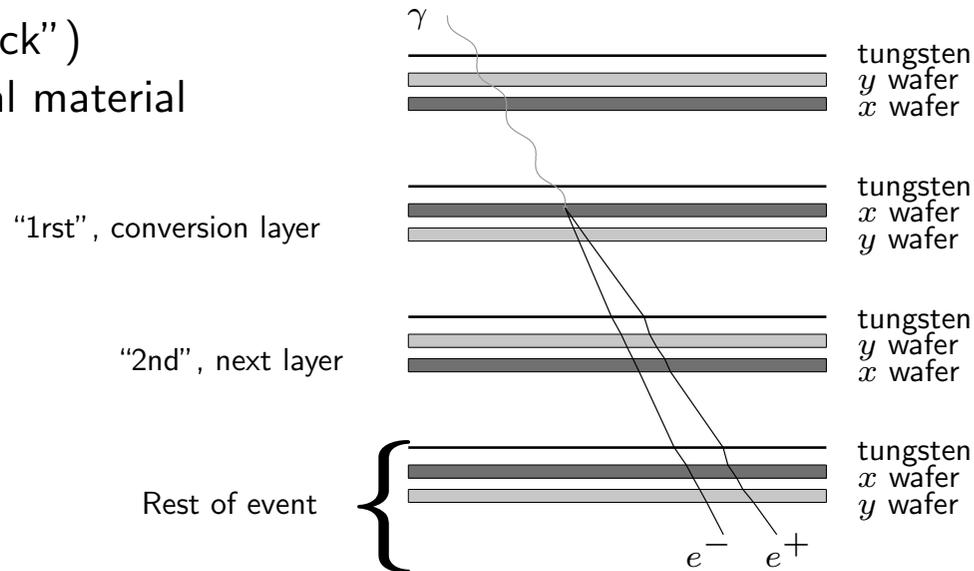
ASAP: As simple as possible

- Point-like source,
- Isotropic exposure map with $\cos \theta_{\text{LAT}} > 0.25$ cut (approx $\theta_{\text{LAT}} < 75^\circ$)
- Assume the *Fermi*-LAT provides γ sample associated with the source
 - γ direction (exactly) and
 - γ energy (approximately)known
- No background

Target

- **Transverse** infinite planes
- **Longitudinal** Simplified *Fermi*-LAT structure
 - Silicon
 - Tungsten (“Front”, “Back”)
 - Low-density Al structural material

1 layer \equiv pair of single-sided SSD + W foil



Information on event azimuthal angle blurred by multiple scattering through W foils:
Analysis based on 2 first layers.

Treatment

- **Event (pre)selection**

- Converts in LAT tracker

- Converts to e^+e^-

- Leaves signal in 3 layers in a row

(mimicks LAT trigger)

- **Signal treatment**

- Signal collected within $\pm 17.5\text{cm}$ from conversion point

(mimicks conversion at center of LAT tower)

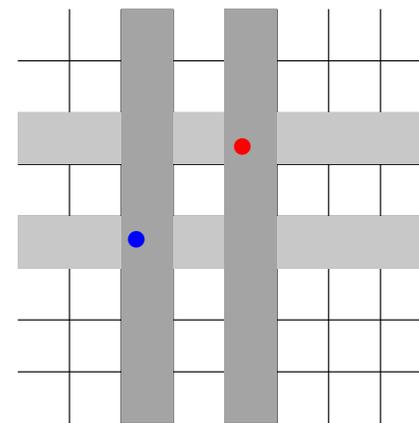
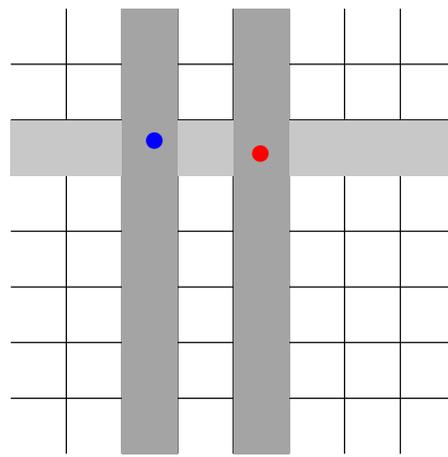
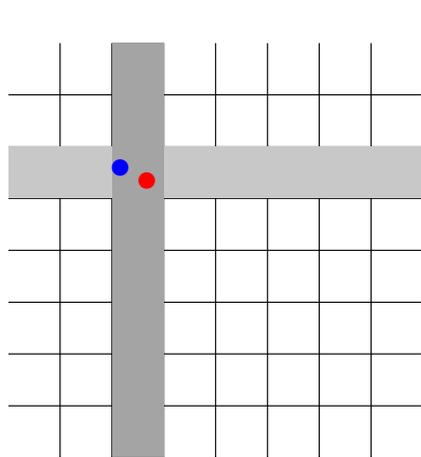
- Strip collected charge $> 35\text{ keV}$ -equivalent,

(mimicks LAT 1/4 MIP discrimination)

- Clusters formed from consecutive hit strips,

- Track position at wafer = geometrical cluster center

Event Configuration in Second Layer



Reconstructed track #
 Reco'ed γ candidate #
 Azimuthal information ?

$n_{\text{track}} = 1$
 1
 No

$n_{\text{track}} = 2$
 1
 Yes

$n_{\text{track}} = 4$
 2
 Yes
 Order-2 ambiguity

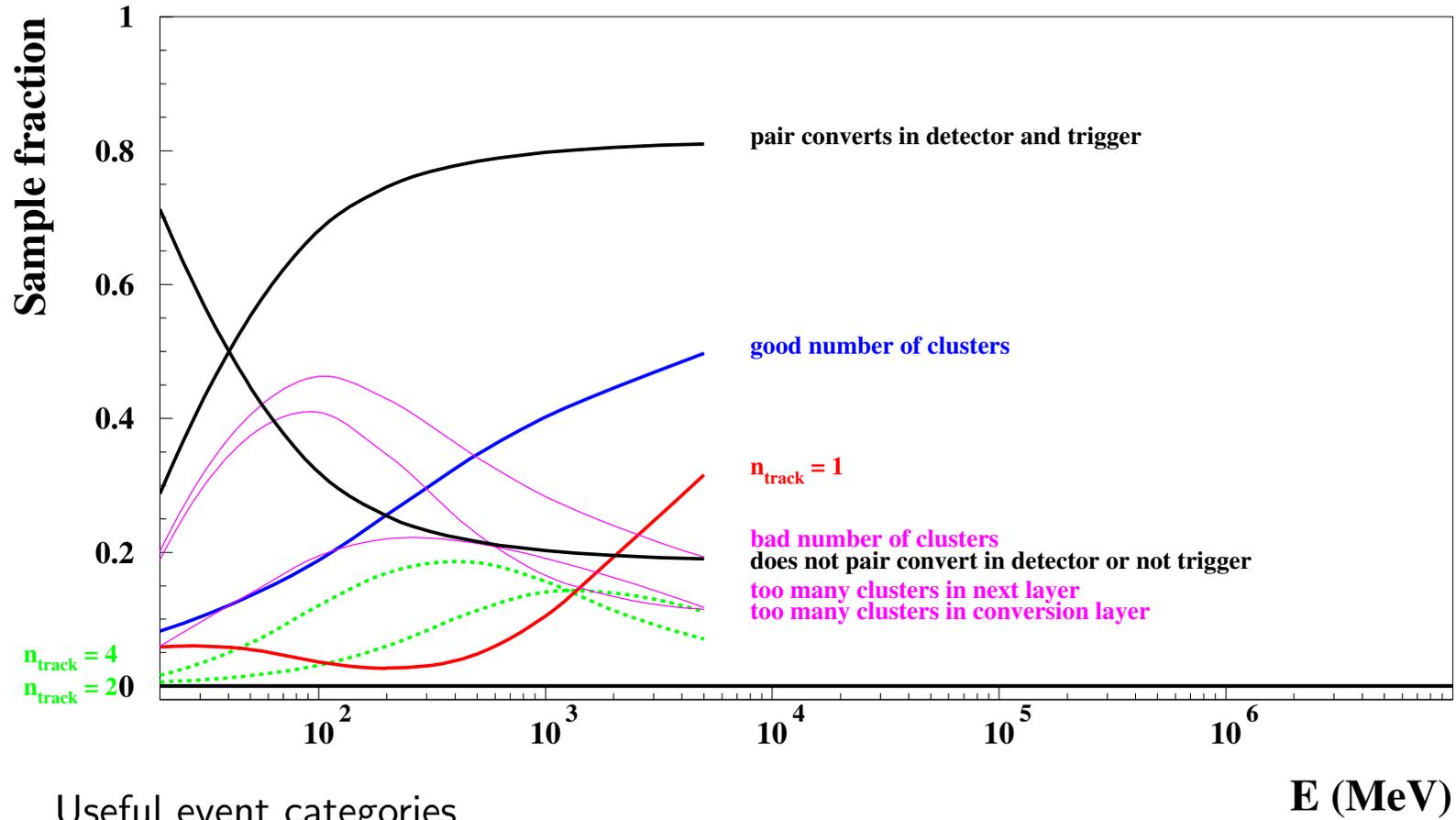
Gray: hit strip(s)

Use both γ candidates
 with weight 1/2

e^- track, e^+ track

(true track positions)

Event Fractions as a Function of Incident Photon Energy.

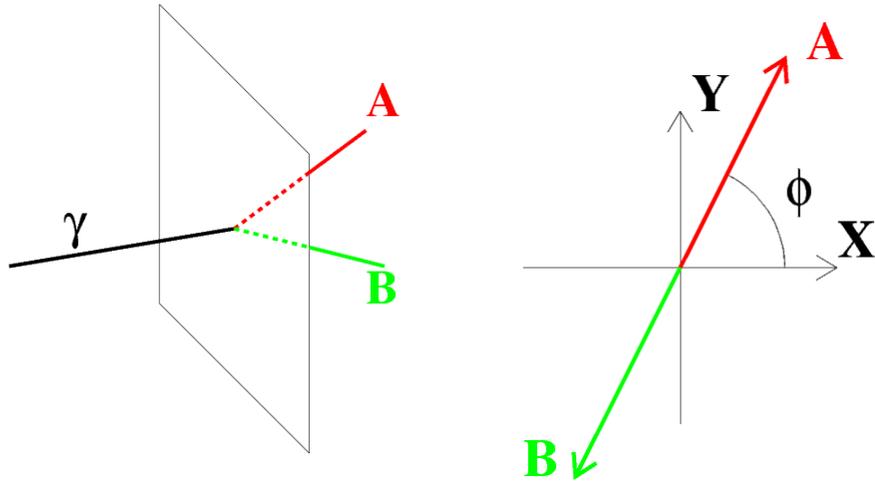


----- Useful event categories

----- Too many clusters in 1st and/or 2nd layer

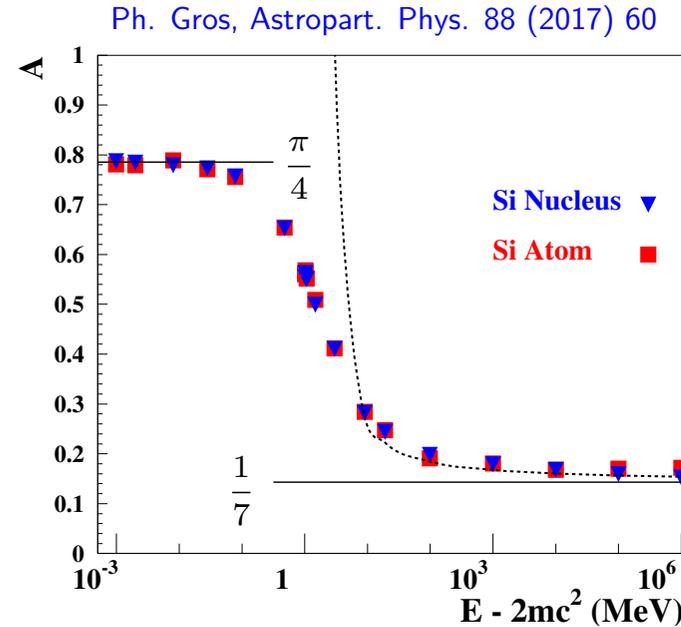
Polarimetry

$$\frac{d\Gamma}{d\varphi} \propto (1 + AP \cos [2(\varphi - \varphi_0)]),$$



- P source linear polarisation fraction
- A γ -ray conversion polarization asymmetry
- φ event azimuthal angle
- φ_0 source polarization angle.

$$\gamma \rightarrow e^+e^-, \quad A(E)$$



Dotted line: high-energy approximation

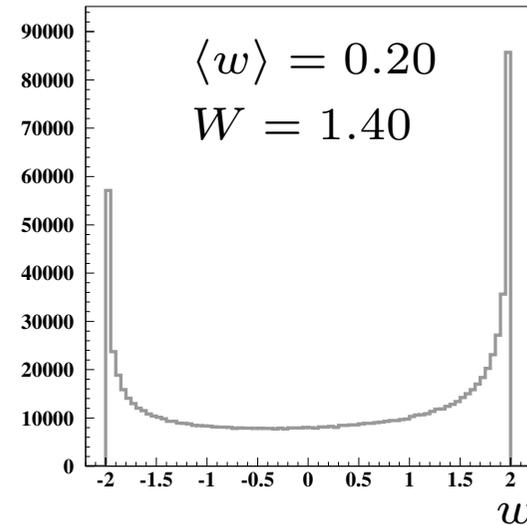
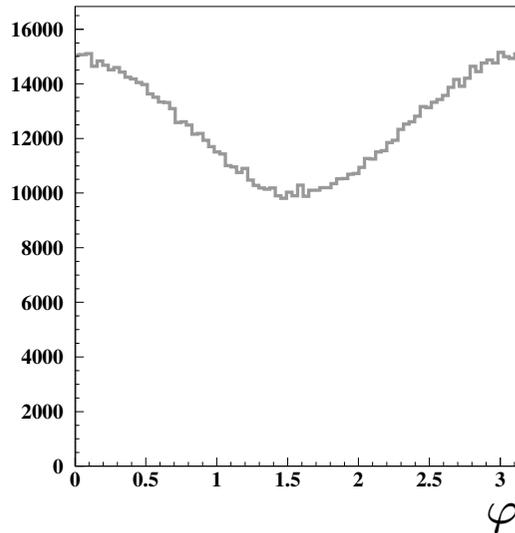
Boldyshev & Peresunko, Yad. Fiz. 14, 1027 (1971).

Polarimetry: Optimal Measurement with Moments

$$\frac{d\Gamma}{d\varphi} \propto (1 + AP \cos [2\varphi]), \quad \text{weight } w = 2 \cos [2\varphi], \quad (\text{here } \varphi_0 = 0).$$

$$E(w) = \int 2 \cos [2\varphi] (1 + AP \cos [2\varphi]) d\varphi = AP, \quad \text{that is, } AP = \sum_{i=1}^N w_i,$$

$$W \equiv \text{RMS}(w) = \sqrt{2 - (AP)^2}, \quad \sigma_P = \frac{1}{A\sqrt{N}} \sqrt{2 - (AP)^2},$$



Toy MC, $A = 0.2$ and $P = 1$.

*Polarimetry: Optimal Measurement with Moments
Unknown Polarization Angle φ_0*

$$A \times P = 2\sqrt{\langle \cos 2\varphi \rangle^2 + \langle \sin 2\varphi \rangle^2} \quad \sigma_{A \times P} \approx \sqrt{\frac{2 - (A \times P)^2}{N}}$$

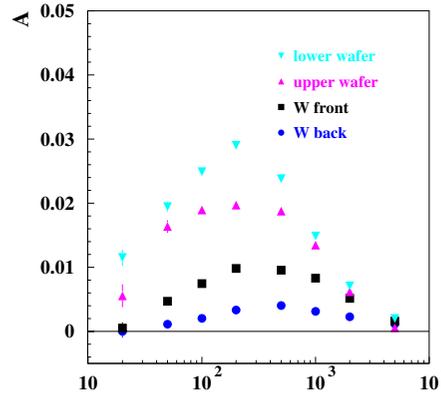
$$\varphi_0 = \frac{1}{2} \arctan \left(\frac{\langle \sin 2\varphi \rangle}{\langle \cos 2\varphi \rangle} \right) \quad \sigma_{\varphi_0} \approx \frac{1}{AP\sqrt{2N}}$$

F. Kislat et al., *Astropart. Phys.* **68** (2015) 45

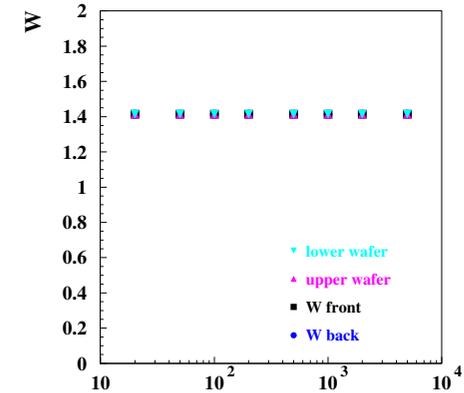
Full Simulation: Results

Weight average value
Effective polarisation asymmetry

$$n_{\text{track}} = 2$$



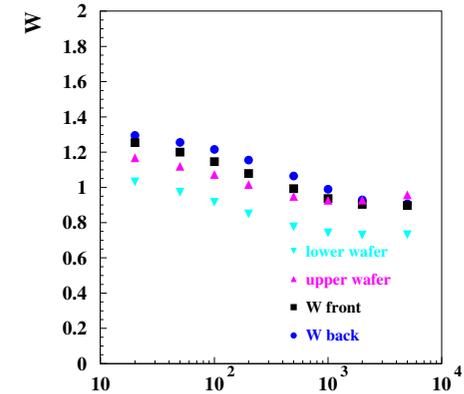
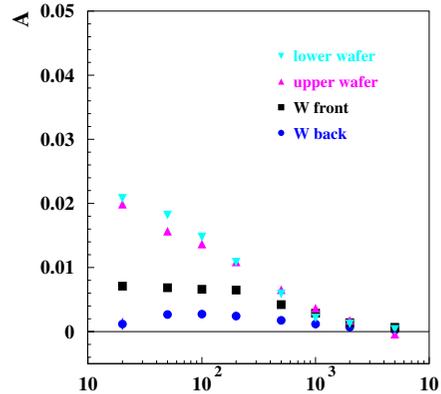
Weight RMS width



$$W \approx \sqrt{2}$$

$$n_{\text{track}} = 4$$

both γ candidates
used



E (MeV)

MC samples,

$$P = 1, \quad \varphi_0 = 0, \quad E = 20 \text{ MeV} - 5 \text{ GeV}$$

Conversion location information from MC

Moments Analysis: Optimal Sample Combination

- K samples. Weight each measurement with inverse variance

$$P = \left(\sum_k \frac{P_k}{V_k} \right) / \left(\sum_k \frac{1}{V_k} \right), \quad (\text{eg. D. J. Shahar Open J. Stat. 2017, 7, 216.})$$

$$\text{with } P_k = \frac{\sum_{i=1}^{N_k} w_{i,k}}{A_k} \quad \text{and} \quad \frac{1}{V_k} = \frac{N_k A_k^2}{W^2} \quad (\text{Assumes same width, } W_k = W)$$

A_k average effective polarisation asymmetry of sample k ,

- So, $P = \sum_k \sum_i^{N_k} w'_{i,k}$ with $w'_{i,k} = \frac{A_k w_{i,k}}{\sum_\ell N_\ell A_\ell^2}$

- If w optimal weight, $\lambda \neq 0$, $\lambda \times w$ optimal too. Forget denominator.

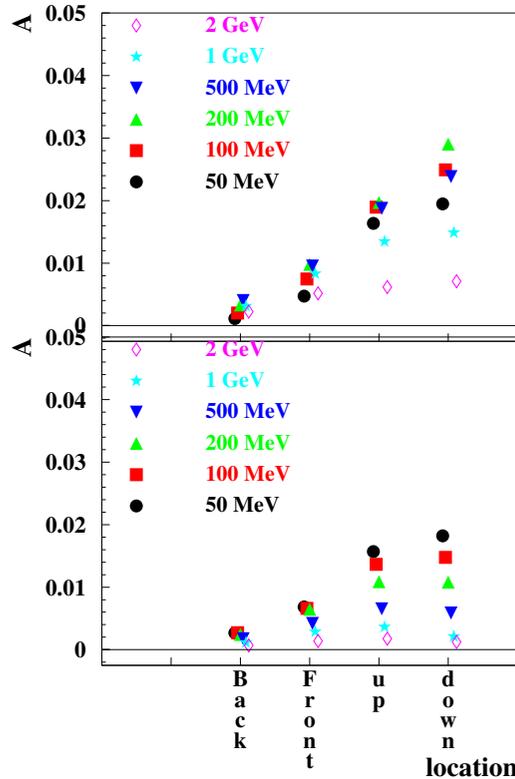
$$P = \sum_k \sum_i^{N_k} w'_{i,k}, \quad \text{with} \quad w''_{i,k} = A_k w_{i,k}$$

Weight each event by the average asymmetry of the sample to which it belongs.

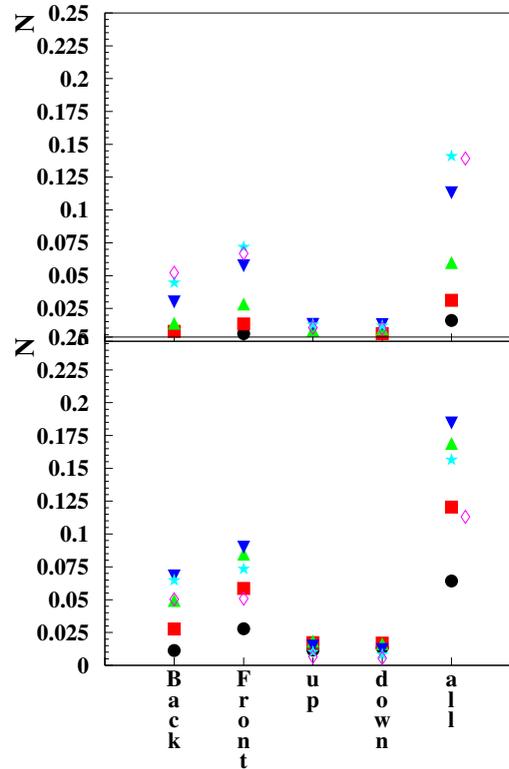
Combination of Several Samples

- Figure of merit: variance $\text{Var}(P) = \frac{W^2}{\sum_k N_k A_k^2}$
- Numbers of events normalized to 1 incident photon (i.e. “flat flux” equivalent)

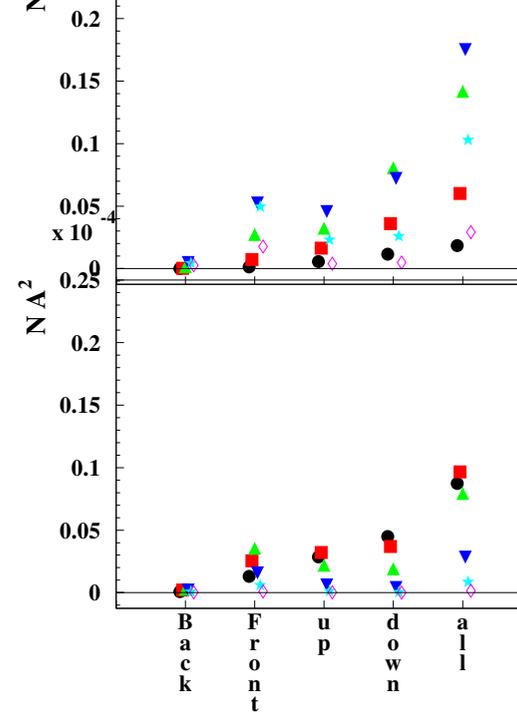
Polarization asymmetry



Number of events



Contribution to inverse variance



$n_{\text{track}} = 2$

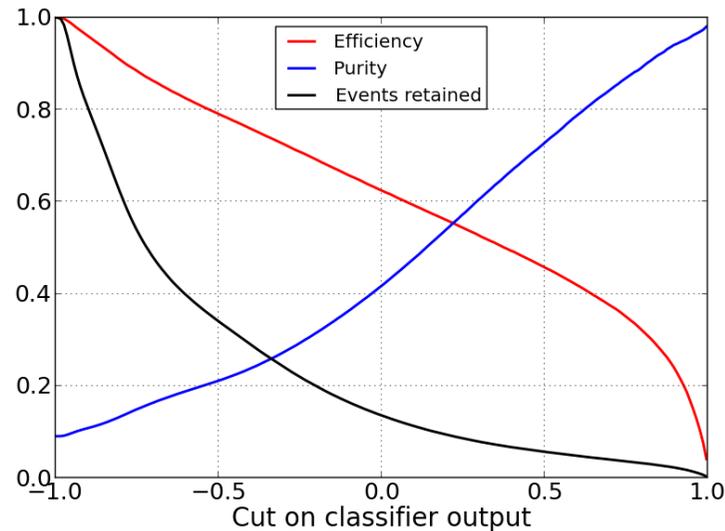
$n_{\text{track}} = 4$

Identification of Conversion Location

- I use MC information to apply weighting
 - Id of conversions in lower wafer easy – no signal in upper wafer
 - Id of conversions in upper wafer wrt W foils more difficult

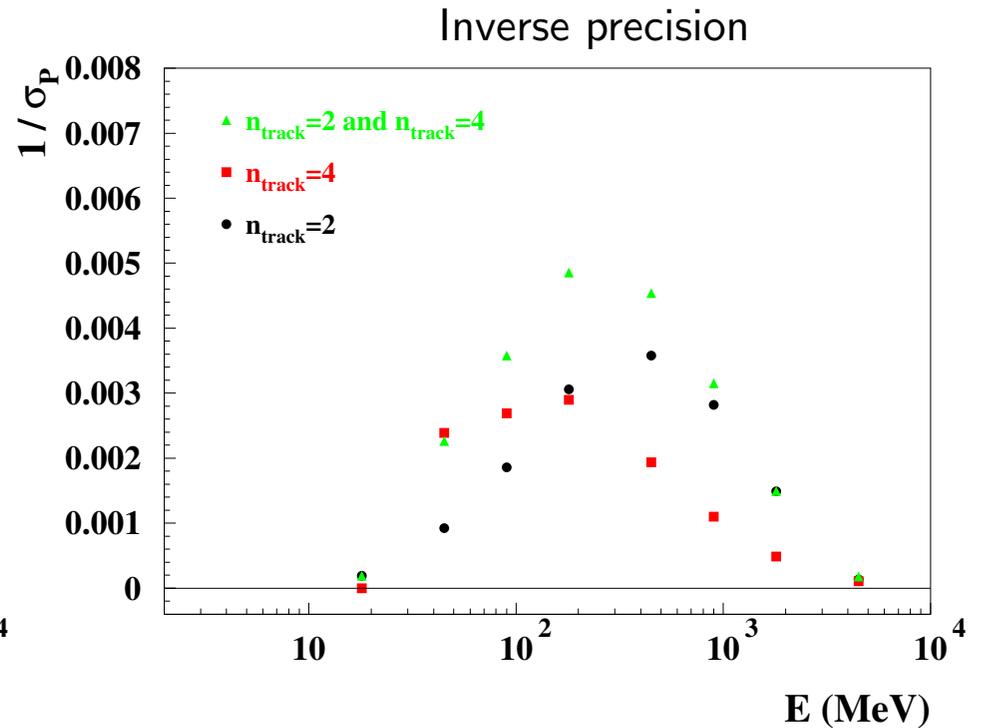
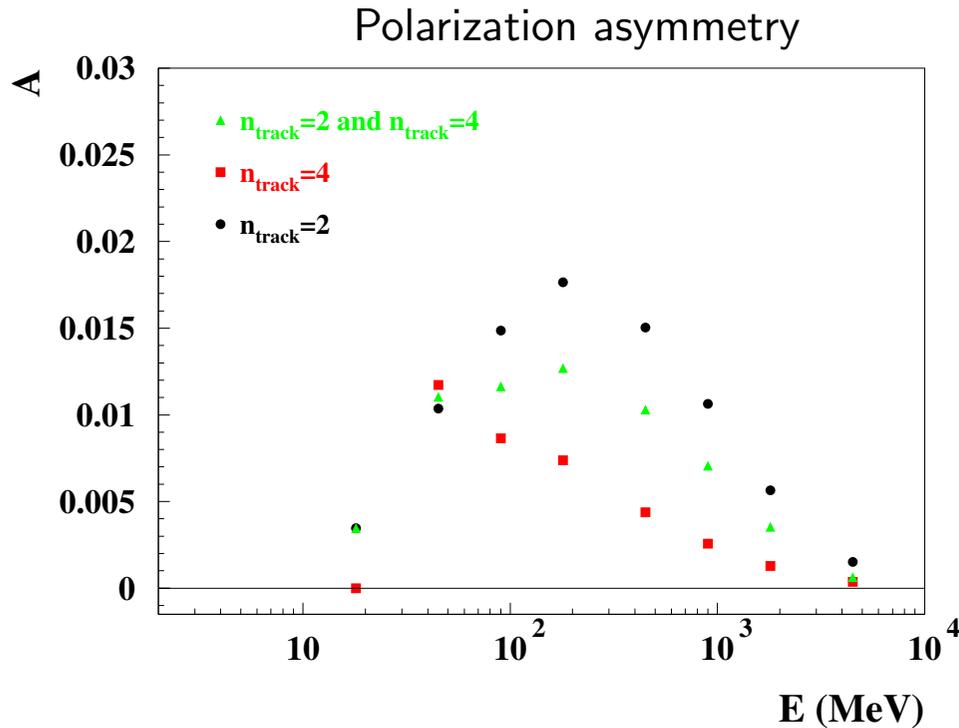
- Selection of silicon-converted events

in M. Giomi *et al.* [Fermi-LAT], AIP Conf. Proc. **1792** (2017) 070022



Boosted Decision Trees with gradient boosting (BDTG) TMVA

Wrap-up: Combination of $n_{\text{track}} = 2$ and $n_{\text{track}} = 4$ Samples



Inverse precision normalized to 1 incident photon

Full Spectrum: Back-of-the-Envelope Estimate

A bright source,

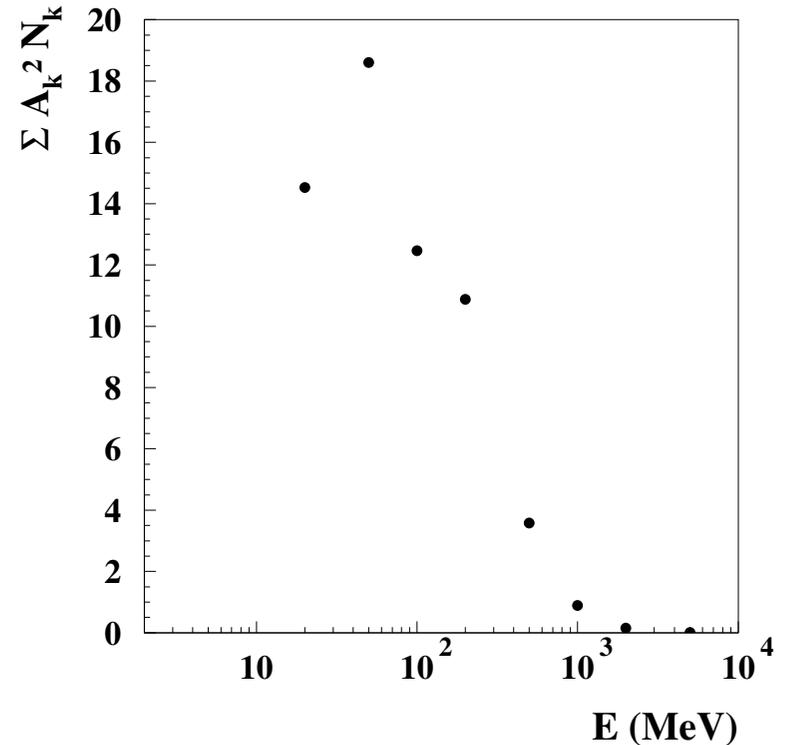
- Exposure $\epsilon \approx 2 \times 10^{11} \text{cm}^2 \text{s}$
- $\Gamma = 2, P = 1$
- $dN/dE = F_0/E^2, F_0 = 1.5 \times 10^{-3} \text{MeVcm}^{-2} \text{s}^{-1},$
- $E > 20 \text{MeV}.$

Pair-converted-and-triggered photons $N_d = 3 \times 10^6.$

- Segmentation (E , conversion location, n_{track})

$\sum_k A_k^2 N_k \approx 61,$ (assuming $W \approx 1.2$):

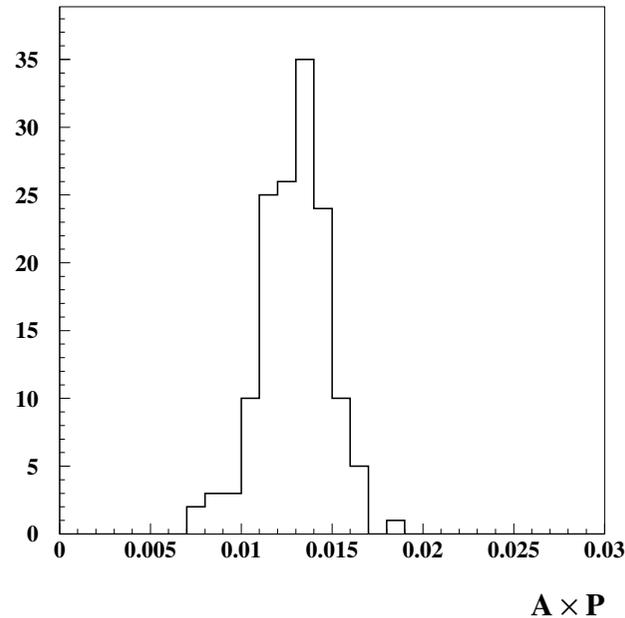
$$\sigma_P = 0.15$$



On the LAT's performance [20, 200] MeV, see [Lea's talk](#) on Tuesday

Full Spectrum: Full-Scale Exercise

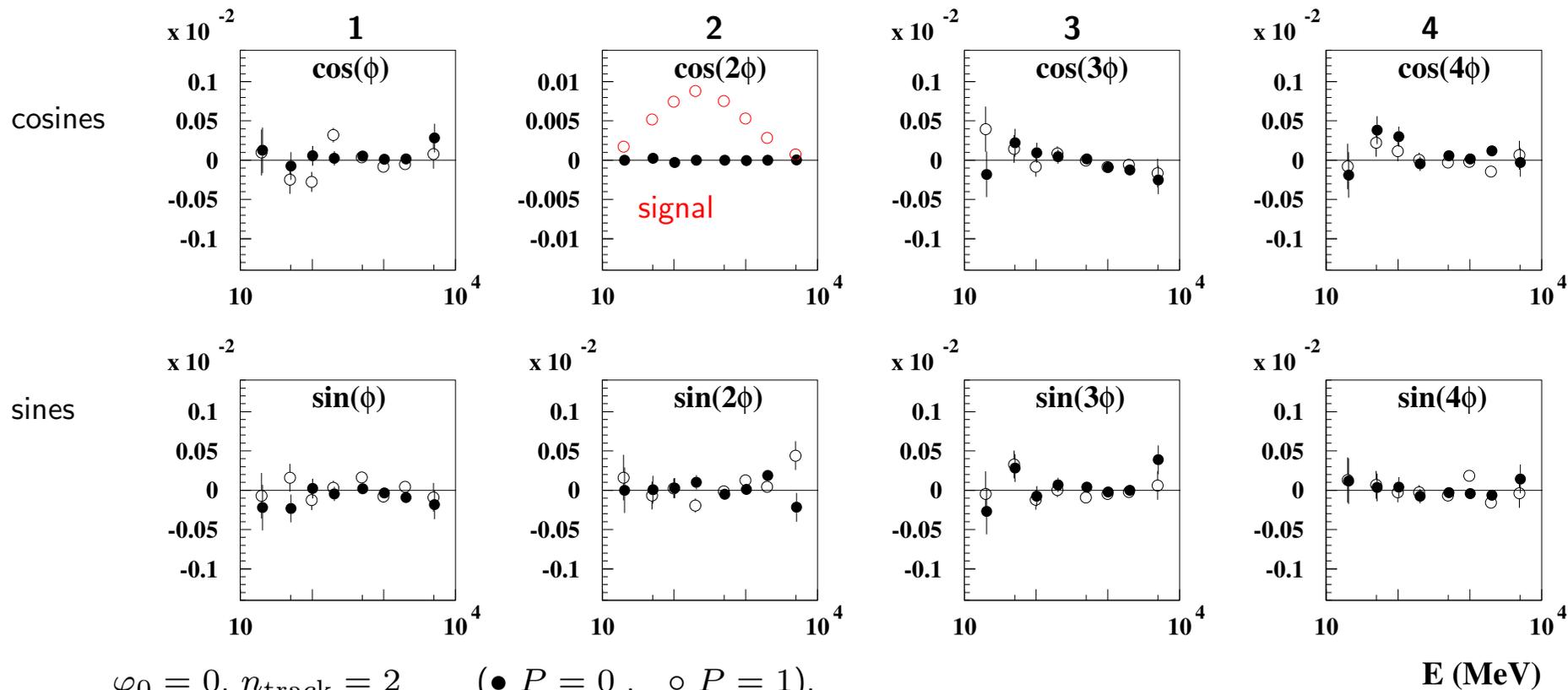
- 10^9 events generated, 20 MeV – 5 GeV, $\Gamma = 2$, $P = 1$
- Weighting (E , conversion location, n_{track}) $\Rightarrow A \times P = 0.013$ and $W = 1.18$.
- Sample split into $n = 144$ subsamples, ($N_d = 3 \times 10^6$ each) \Rightarrow



$$\sigma_P \approx 0.14$$

Systematics Control: Check Fourier Components

- (Azimuthal) angle resolution function **monstruous** but tracker moves wrt sky
- Isotropic exposure simulated: no systematic bias to be expected



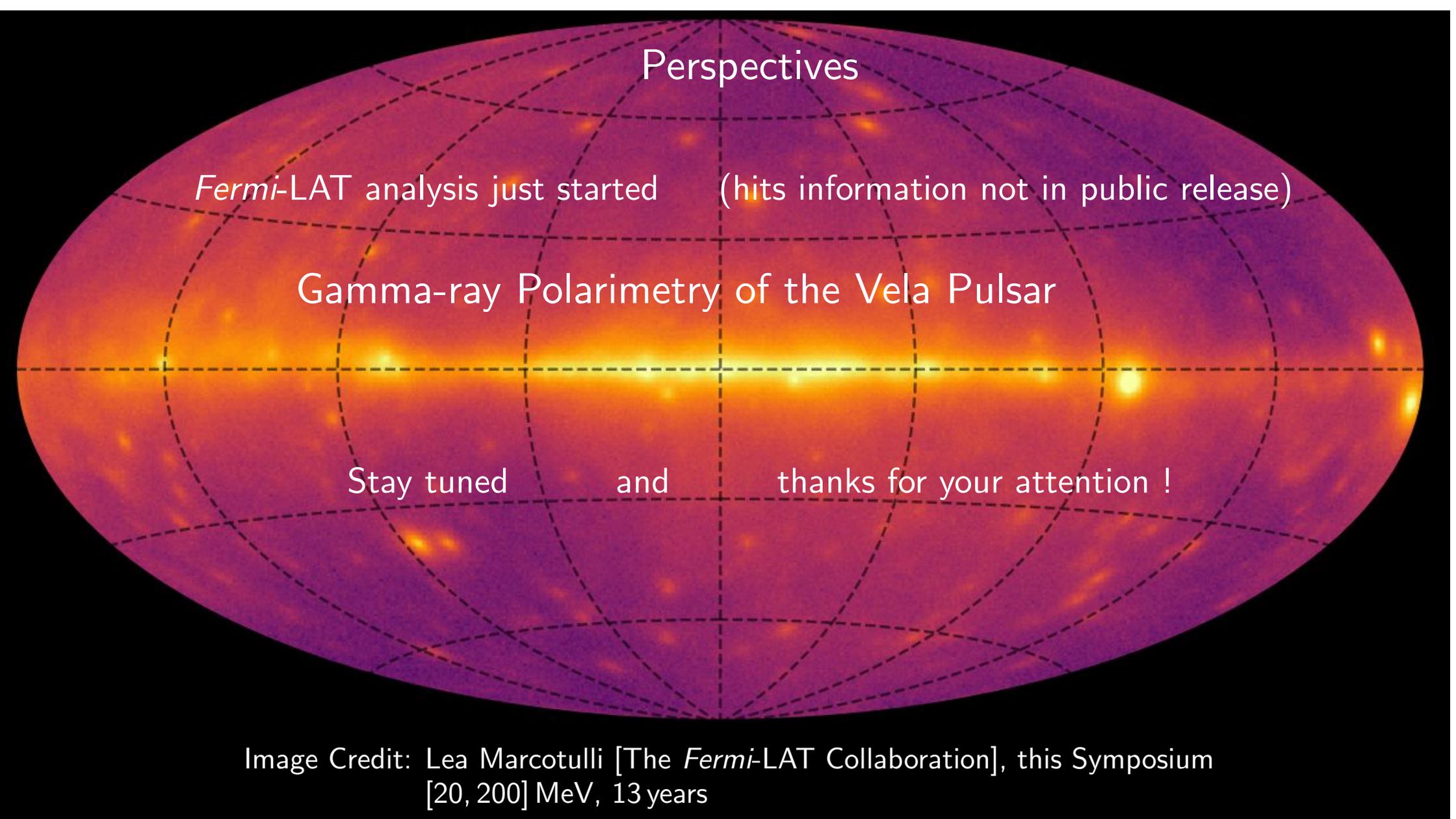
- No bias observed

Conclusion

- Strengths
 - Use simple, validated tools (eg., event generator)
⇒ enable 10^9 incident photon MC samples
 - Reject events without polarimetric information (eg., $n_{\text{track}} = 1$)
 - Combine separate samples optimally by weighting
- Weaknesses
 - No pattern recognition, no hit-to-track assignment
⇒ heavy statistics loss at low E from events with extra clusters
- Conclusions
 - Effective asymmetry small (0.013 on full spectrum),
 - $\sigma_P < 0.15$ to be expected on brightest sources

Nucl. Instrum. Meth. A **1042** (2022) 167462

There is hope !



Perspectives

Fermi-LAT analysis just started

(hits information not in public release)

Gamma-ray Polarimetry of the Vela Pulsar

Stay tuned

and

thanks for your attention !

Image Credit: Lea Marcotulli [The *Fermi*-LAT Collaboration], this Symposium
[20, 200] MeV, 13 years

Back-up Slides

Deciphering Emission Mechanism in Blazars with γ -Ray Polarimetry

- Blazars: active galactic nuclei (AGN) with one jet pointing (almost) to us

RX J0648.7+1516

leptonic synchrotron self-Compton (SSC)

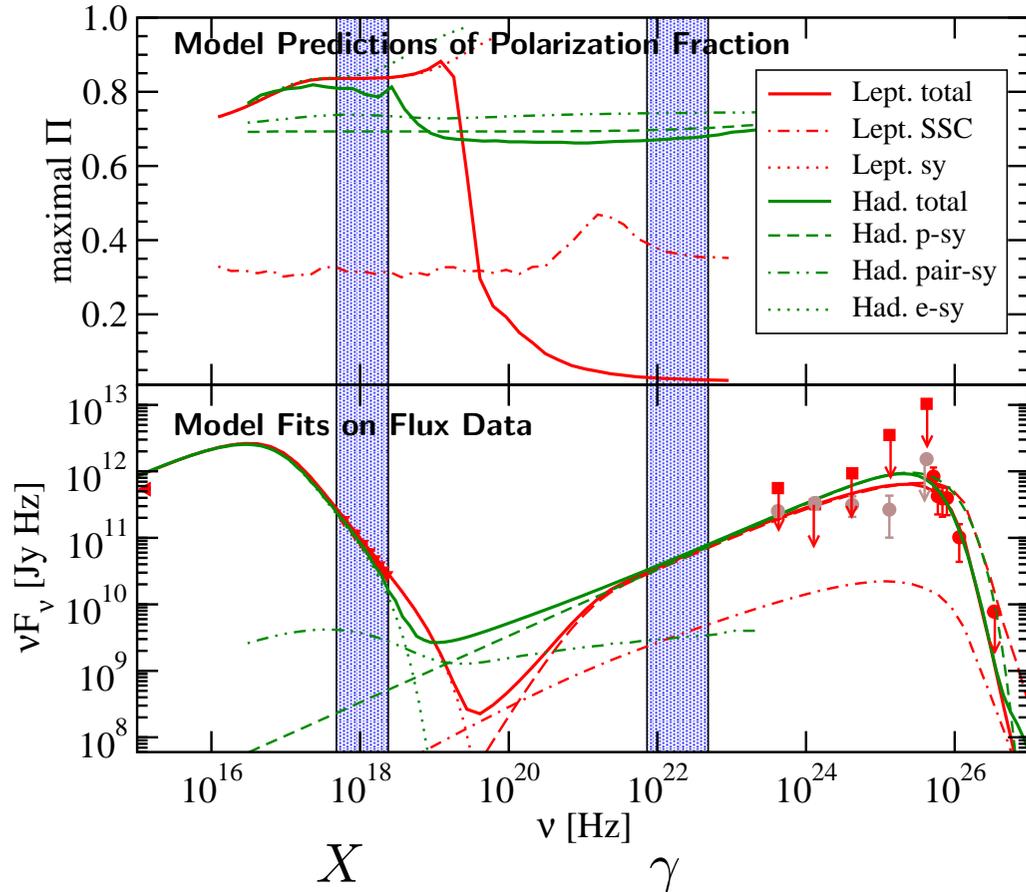
or

hadronic (proton-synchrotron) ?

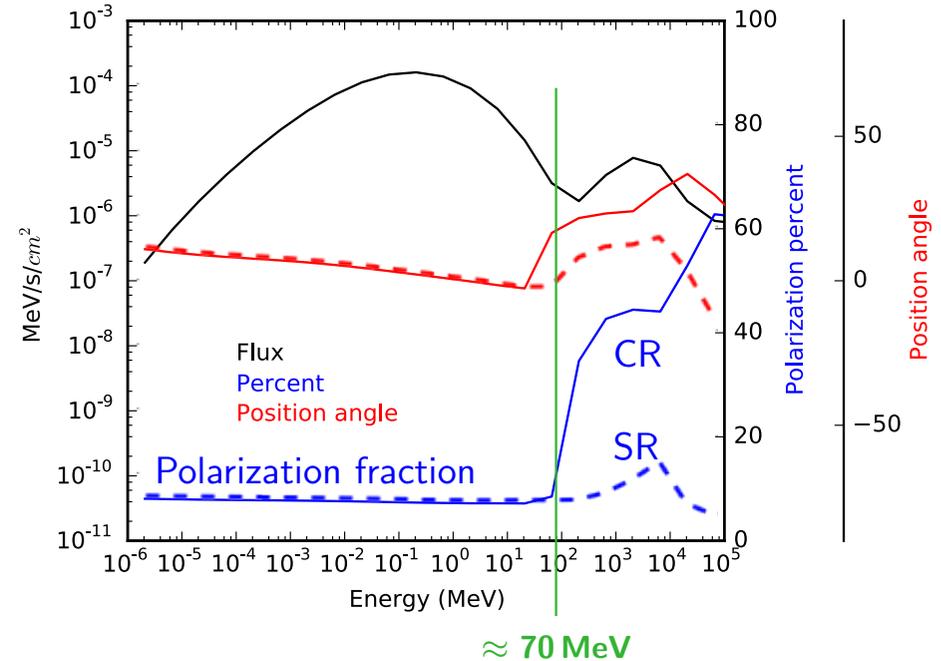
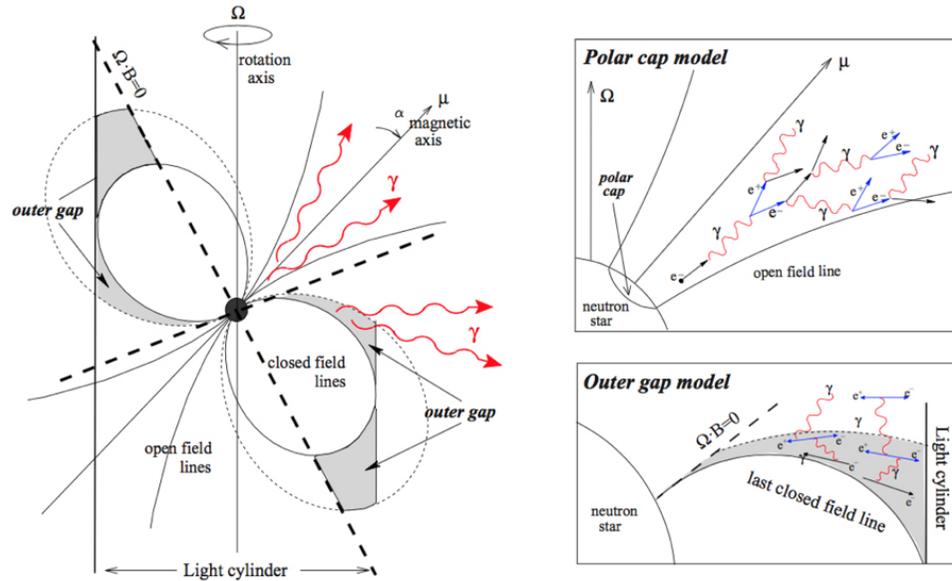
- high-frequency-peaked BL Lac
- X band: 2 -10 keV
- γ band: 30 - 200 MeV
- SED's indistinguishable, but
 - X-ray: $P_{\text{lept}} \approx P_{\text{hadr}}$
 - γ -ray: $P_{\text{lept}} \ll P_{\text{hadr}}$

Zhang and Böttcher, *Astrophys.J.* 774, 18 (2013)

“Maximal” Π : assumes no \vec{B} turbulence



Tagging the (Curvature Radiation CR – Synchrotron Radiation SR) Transition in Rotation-Powered Pulsars

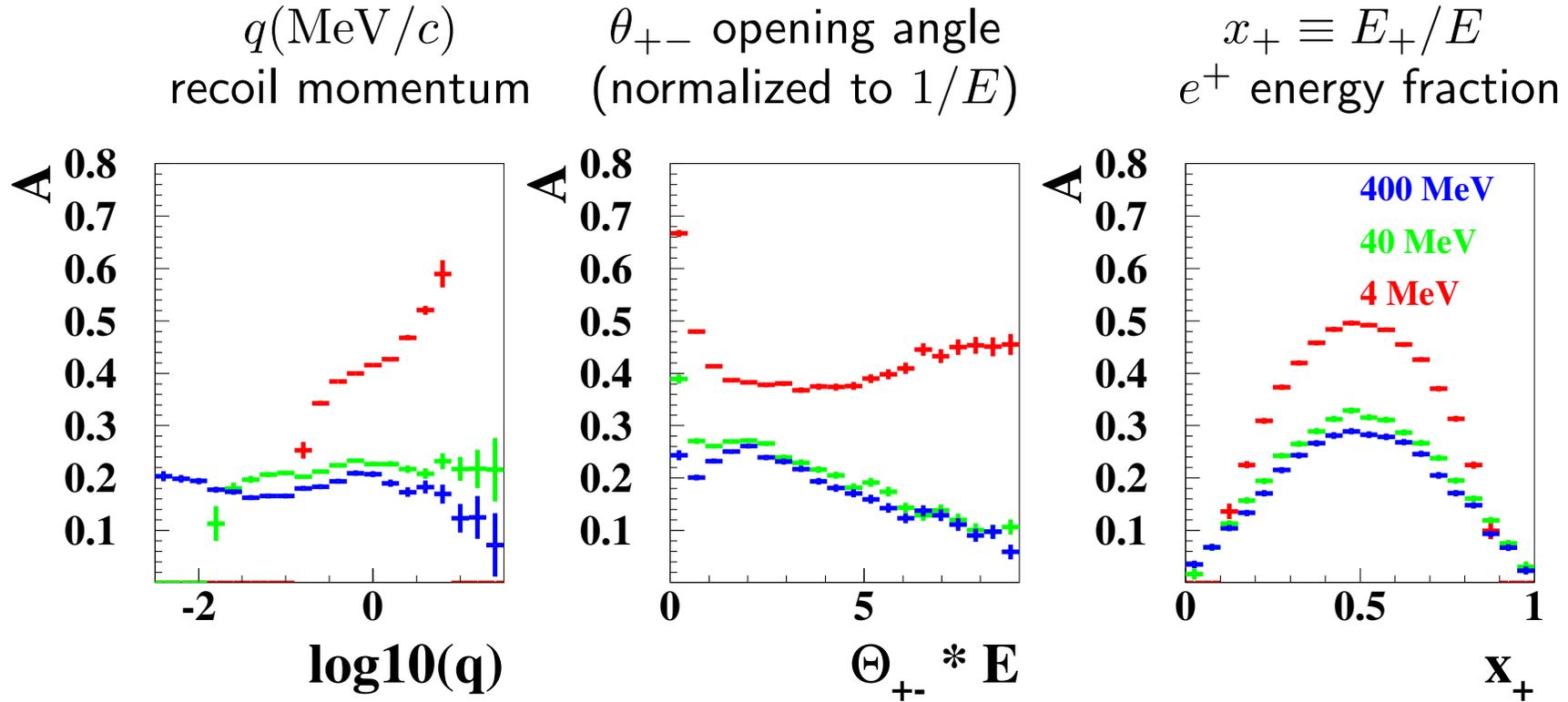


Polar-cap model of Crab-like pulsar

- MeV component is SR from pairs
- GeV component is either CR (solid line) or SR (dashed line)

Harding and Kalapotharakos, *Astrophys. J.* 840 73 (2017)

Variation of the QED Asymmetry with Event Kinematic Variables



Updated from [D. Bernard, NIM A 729 \(2013\) 765](#) with here A measured with $\varphi \equiv (\varphi_+ + \varphi_-)/2$

Optimal definition of azimuthal angle: [P. Gros et al. Astropart. Phys. 88 \(2017\) 30](#)

This work: Tools

- 5D $\gamma \rightarrow e^+e^-$ conversion event generator, [D.B., NIM A 899 \(2018\) 85](#)
 - Fortran prototype of G4BetheHeitler5DModel
- Electromagnetic physics EGS5, version 1.0.5, [H. Hirayama *et al.*, SLAC-R-730, 2005](#)

Sensitivity: Typical γ Energy

- Opening angle large enough to produce 2 clusters;

Most probable value, $\hat{\theta}_{+-} = \frac{1.6 \text{ MeV}}{E} \text{ rad}$,

H. Olsen, Phys. Rev. 131 (1963) 406.

$$\theta_c = p/\ell \Rightarrow E_c \equiv 1.6 \text{ MeV} \frac{\ell}{p} .$$

		ASTROGAM	AMEGO	LAT	AGILE	
Reading		DSSSD	DSSSD	SSSSD	SSSSD	
Wafer thickness	e	500.	500.	400.	410.	μm
Layer number	N	56	60	19	14	
Layer spacing	ℓ	1.	1.	3.	1.9	cm
Strip pitch	p	240	500	228	242	μm
Critical energy	E_c	67.	32.	211.	126.	MeV
W foil thickness	Δ			95	245	μm
				720		μm

Lower part of the LAT energy range.

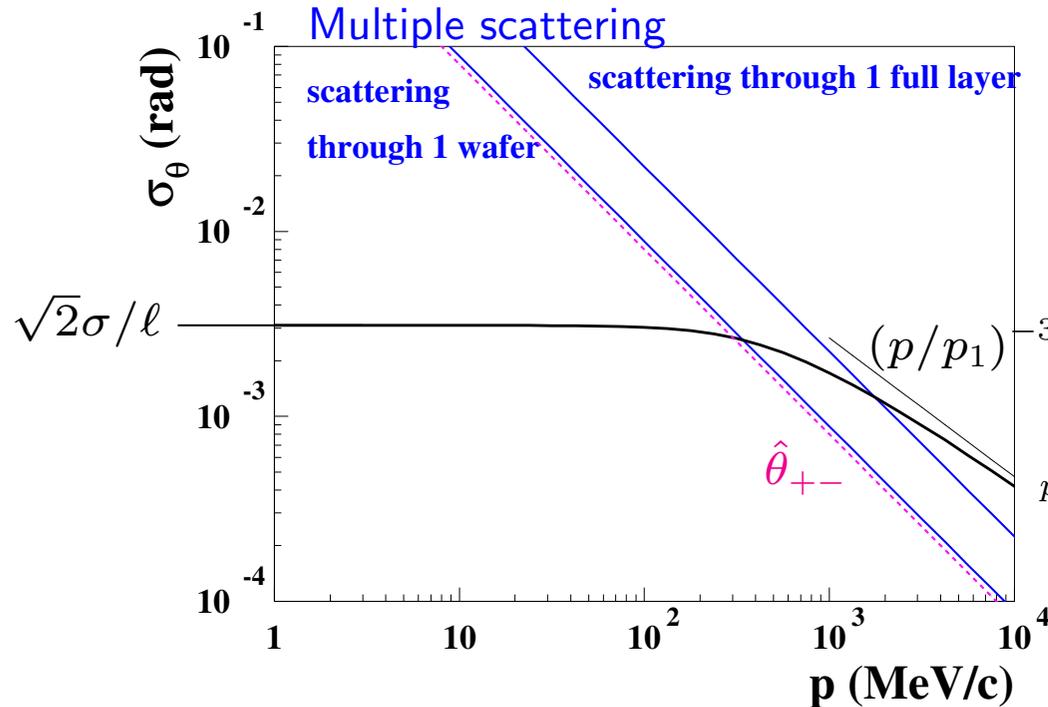
Single-Track (Polar) Angle Resolution

- **Black curve:** optimal tracking (à la Kalman),

eq. (1) of [D.B., arXiv:1902.07910](#)

Conversion point at bottom of layer

(No dE/dx here)



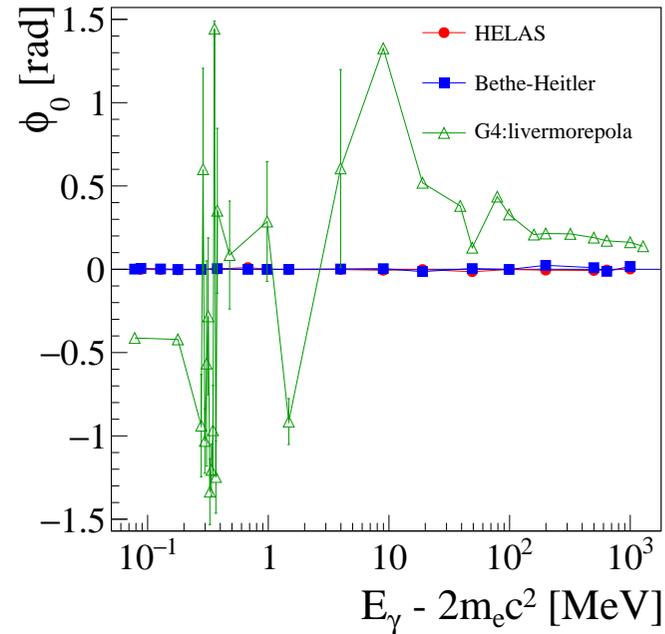
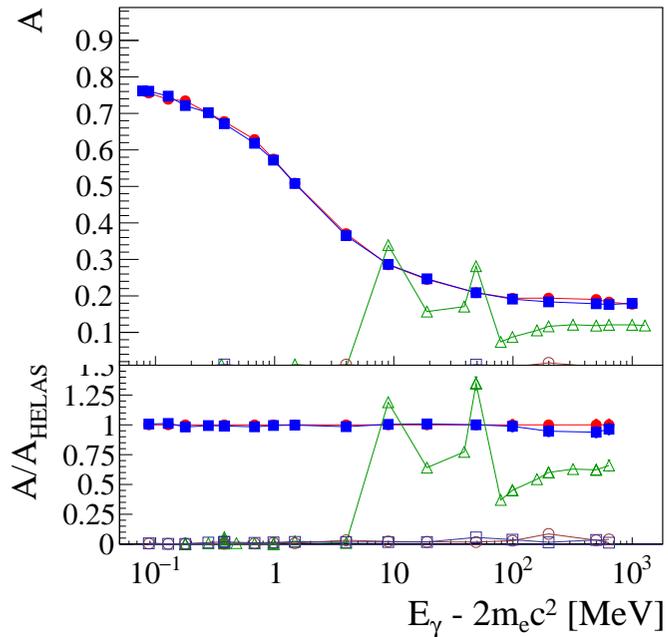
$$p_1 = 13.6 \text{ MeV}/c \left(\frac{2\sigma}{\ell} \right)^{1/3} \left(\frac{\Delta}{X_{0,W}} \right)^{1/2}$$

- Kalman filter tracking useless $< 100\text{s MeV}/c$

- Multiple scattering through full layer $>$ Most probable opening angle

\Rightarrow Simple event reconstruction, based on information from two first layers

Azimuthal Angle: On the Phase

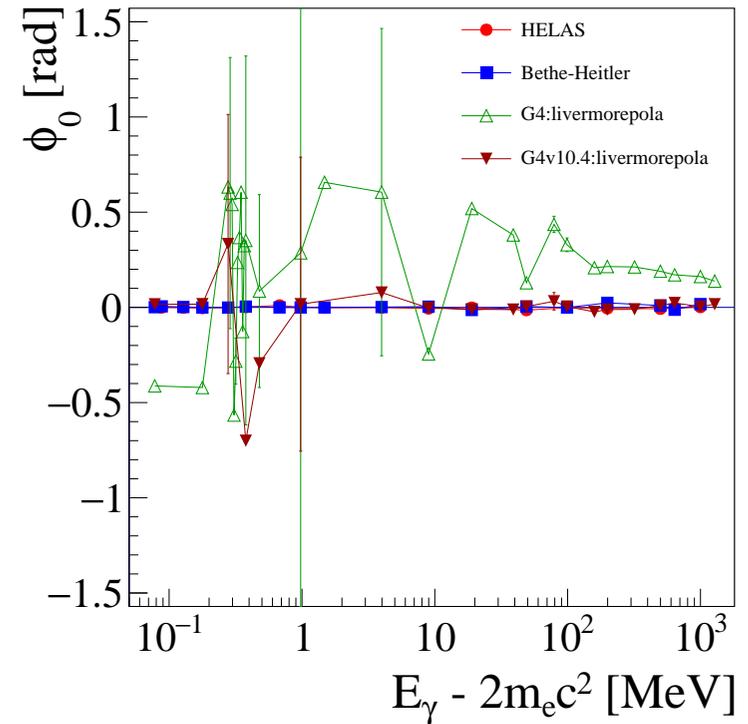
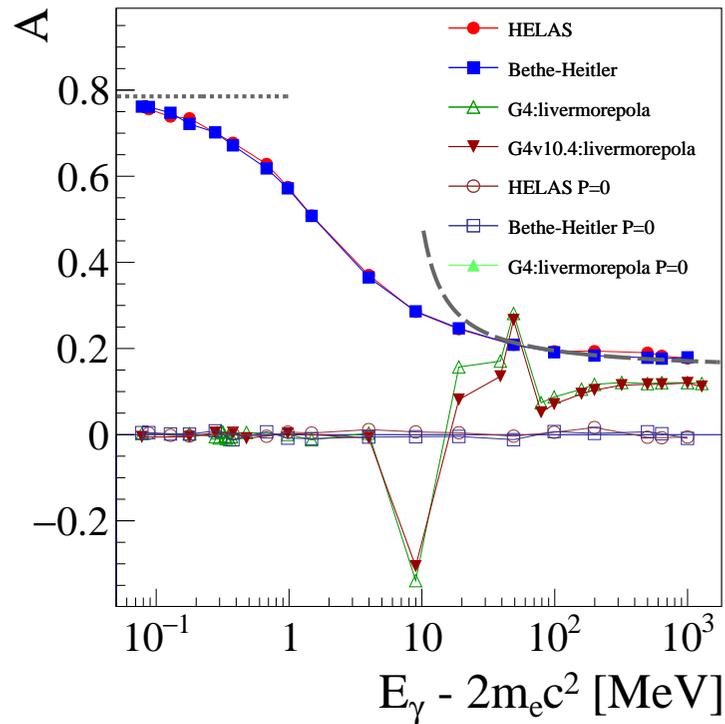


- Issues in simulation of polarized γ conversion to pairs by G4:livermorepola

- @ 100 MeV,
$$\frac{\mathcal{A}_{\text{BH}}}{\mathcal{A}_{\text{G4LivermorePolarizedGammaConversion}}} = \frac{(19.1 \pm 0.4)\%}{(8.7 \pm 0.6)\%} \approx 2.2$$

- Phase wrong

Phase Issue Fixed in G4LivermorePolarizedGammaConversion in Release 10.4beta



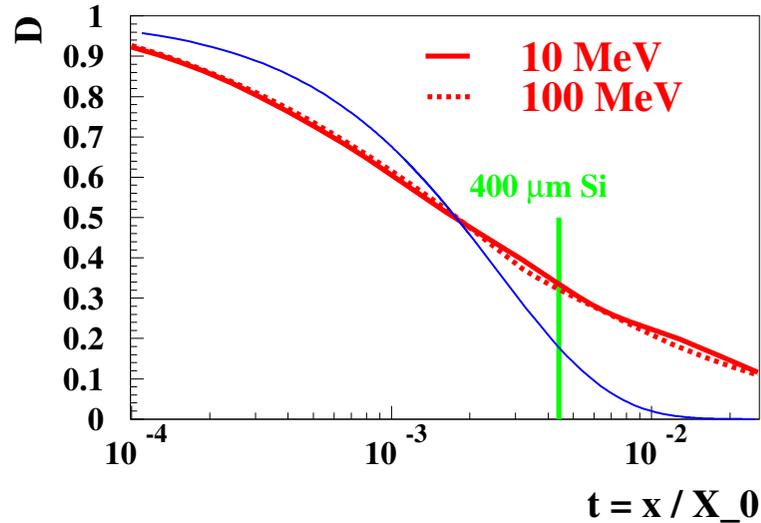
Ph. Gros [The HARPO Collaboration],

V. Ivantchenko [The Geant4 Collaboration],

Sept. 2017.

Multiple Scattering: Dilution of the Asymmetry in the Conversion Wafer

- Dilution, $D \equiv \frac{A_{\text{eff}}}{A_{\text{QED}}}$, x , full wafer thickness.



- Full (5D) simulation of the dilution of the polarization asymmetry as a function of wafer thickness normalized to radiation length
- Thin line is E -independent, $\hat{\theta}_{+-}$ -based approximation.

Kel'ner, *Yad. Fiz.* 21 (1975) 604, Kotov, *Space Science Reviews* 49 (1988) 185, Mattox, *Astrophys. J.* 363 (1990) 270

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

Polarimetry: Optimal Measurement with Moments

- $p(\Omega)$ the pdf of set of (here 5) variables Ω

- Search for weight $w(\Omega)$, $E(w)$ function of P , and variance σ_P^2 minimal;

- A solution is $w_{\text{opt}} = \frac{\partial \ln p(\Omega)}{\partial P}$

e.g.: Tkachov, Part. Nucl. Lett. 111 (2002) 28

- Polarimetry: $p(\Omega) \equiv f(\Omega) + P \times g(\Omega)$, $w_{\text{opt}} = \frac{g(\Omega)}{f(\Omega) + P \times g(\Omega)}$.

- If $AP \ll 1$, $w_0 \equiv 2 \frac{g(\Omega)}{f(\Omega)}$, and

for the 1D “projection” $p(\Omega) = (1 + AP \cos [2(\varphi)])$:

$$w_1 = 2 \cos 2\varphi, \quad E(w_1) = AP, \quad \sigma_P = \frac{1}{A\sqrt{N}} \sqrt{2 - (AP)^2},$$

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

- If $AP \ll 1$, Taylor series of w_{opt} , $\sigma_P = \frac{1}{A\sqrt{N}} \sqrt{2 - (3/2)(AP)^2}$,

D. Besset et al., Nucl. Instrum. Meth. **166** (1979) 515

$n_{track} = 4$: Ambiguity

Simple 1D model, photon impinging on detector from above, $\theta_{LAT} = 0$

- LAT frame, $\hat{\varphi}$,
- sky frame, φ ,
- δ , LAT azimuthal angle wrt sky, $\hat{\varphi} = \varphi + \delta$,

$$\hat{\varphi}' = \pi - \hat{\varphi}; \quad \text{so} \quad \varphi' = \hat{\varphi}' - \delta = \pi - \varphi - 2\delta.$$

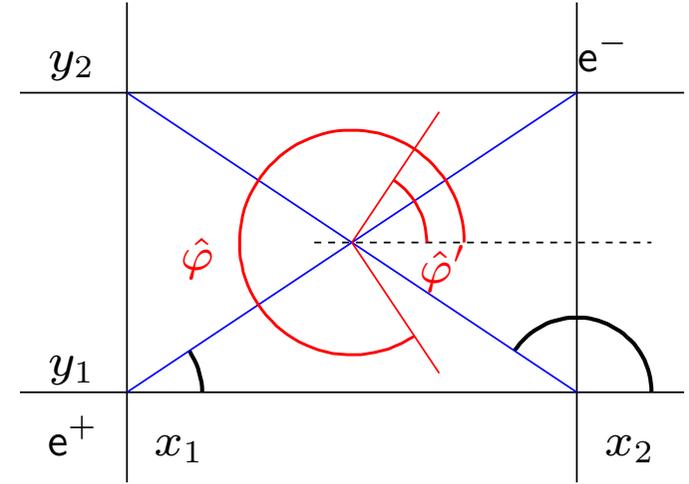
$$\frac{d\sigma}{d\varphi} \propto (1 + A \times P \cos[2(\varphi - \varphi_0)]) \quad \text{becomes}$$

$$\frac{d^2N}{d\varphi d\delta} \propto \frac{1}{2} [(1 + A \times P \cos[2(\varphi - \varphi_0)]) + (1 + A \times P \cos[2(\varphi + 2\delta + \varphi_0)])].$$

Integration on δ (isotropic exposure assumed) \Rightarrow

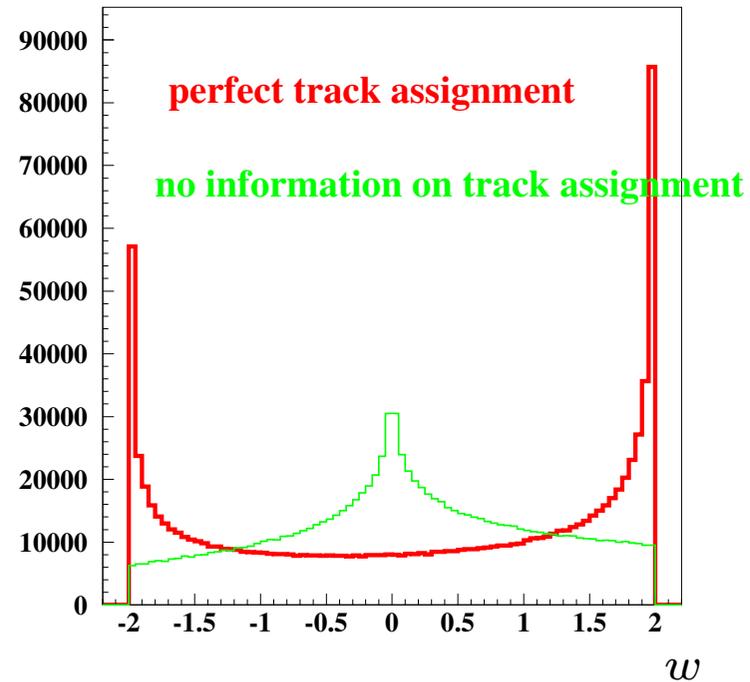
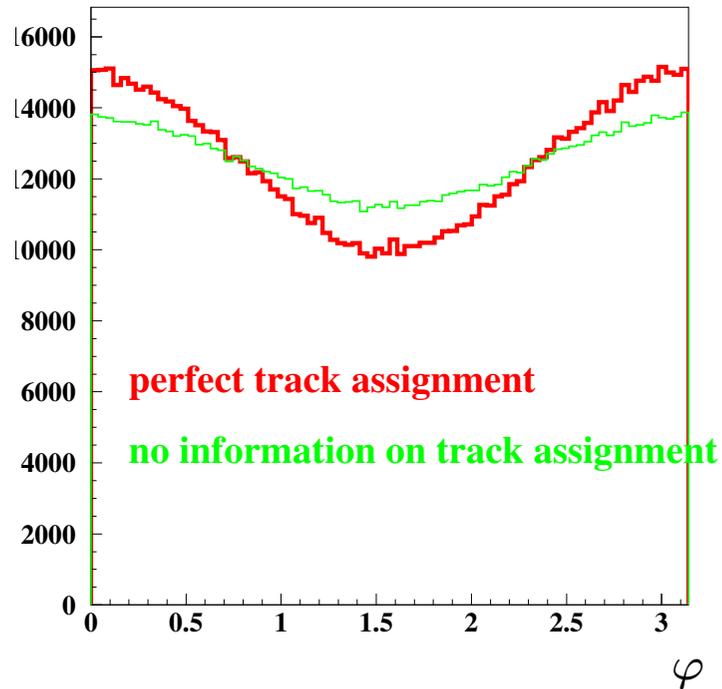
$$\frac{dN}{d\varphi} \propto \left(1 + \frac{A \times P}{2} [\cos(2(\varphi - \varphi_0))] \right) \Rightarrow$$

$$\text{Dilution factor } D = 1/2$$



$n_{track} = 4$: Ambiguity: Simple 1D model: Toy MC

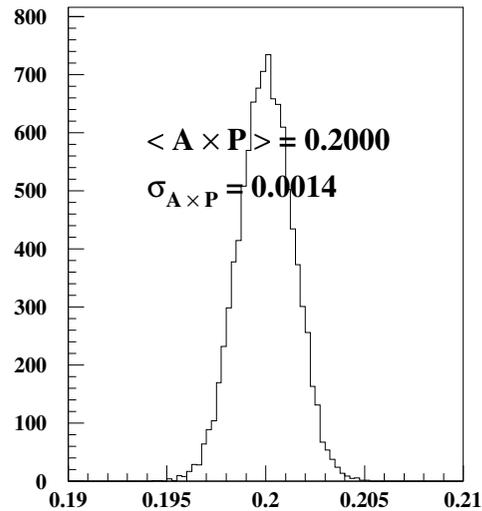
Toy MC expt, sampled from $\frac{d\sigma}{d\varphi} \propto (1 + AP \cos 2\varphi)$, $A = 0.2$ and $P = 1$.



Adapted from P. Gros, 2016

$n_{track} = 4$: Ambiguity: Simple 1D model: Toy MC

10^4 Toy expts, 10^6 events each, sampled from $\frac{d\sigma}{d\varphi} \propto (1 + AP \cos 2\varphi)$, $A = 0.2$ and $P = 1$.

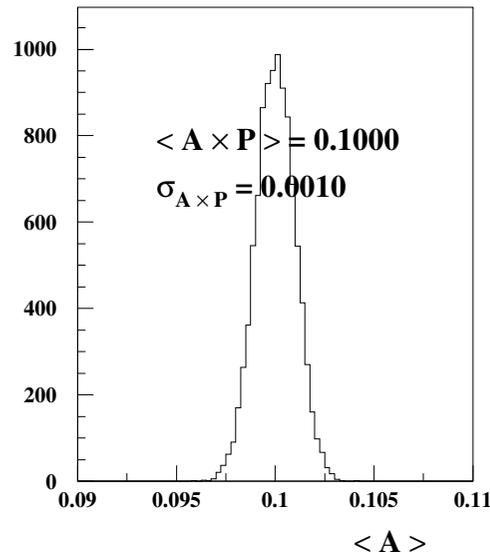


perfect assignment

$$D = 1$$

$$W \approx \sqrt{2}$$

$$W/D \approx \sqrt{2}$$



random LAT orientation
both track combinations used.

$$D = 0.5$$

$$W \approx 1$$

$$W/D \approx 2$$

Ambiguity: “only” a loss of a factor $\sqrt{2}$ on σ_P .

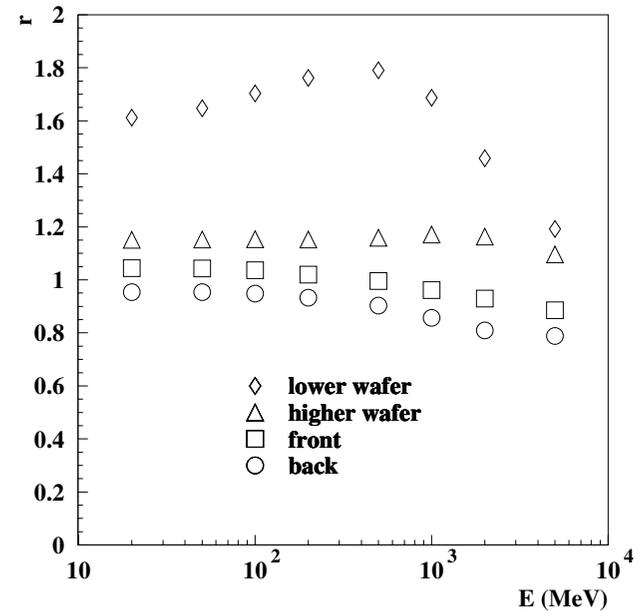
Full simulation: same result.

$n_{track} = 4$: Ambiguity: True Candidate Identification Attempt

Both candidates have same reco'ed photon direction. \Rightarrow no handle for discrimination.

Attempt to choose candidate with best acoplanarity angle

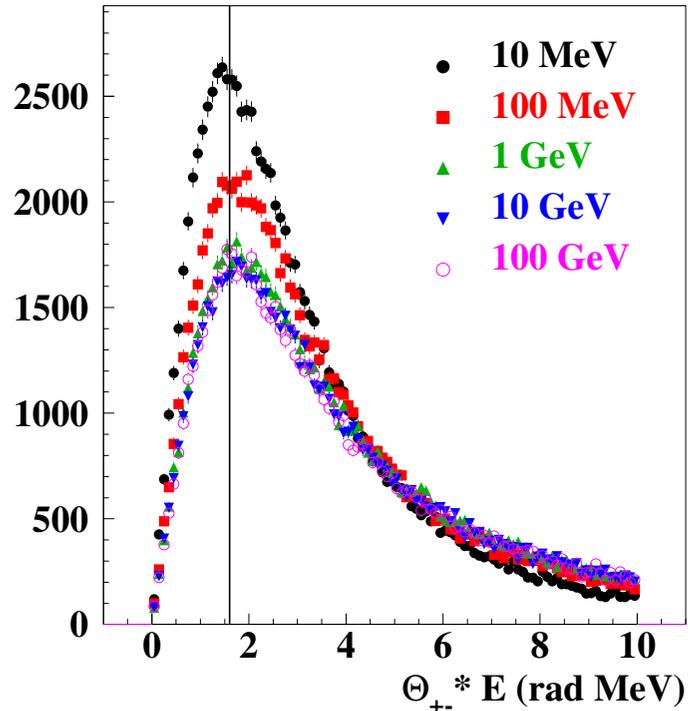
$$r = \frac{\text{number of correctly assigned candidates}}{\text{number of falsely assigned candidates}}$$



Nope ?

Pair Opening Angle: $1/E$ Scaling

(pair opening angle) \times (photon energy)



Vertical line: high-energy asymptotic most probable value

$$\frac{1.6 \text{ rad} \cdot \text{MeV}}{E}$$

H. Olsen, Phys. Rev. 131 (1963) 406

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

Geant4: (Linearly) Polarized γ -Ray Conversions Bethe-Heitler 5D Model

- 5D differential cross section

T. H. Berlin and L. Madansky, Phys. Rev. 78 (1950) 623.

M. M. May, Phys. Rev. 84 (1951) 265.

- G4BetheHeitler5DModel Physics Model from release [10.5](#)

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

I. Semeniouk et al., Nucl. Instrum. Meth. A **936** (2019) 290

- Available through G4EmStandardPhysics physics list option4, from release [10.6](#)

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

- Test module [TestEm15](#), see [histos 10 – 16](#).