A Bethe-Heitler 5D Polarized Photon-to-e^+e^- Pair Conversion Event Generator,

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e-ASTROGAM: The extreme Universe workshop,
28 Feb. - 02 Mar. 2017, Padova

`http://llr.in2p3.fr/~dbernard/polar/harpo-t-p.html`

Talk Layout

- The context: HARPO: high-performance γ-ray astronomy and linear polarimetry with conversion to e^+e^- pairs with a gas TPC

telescope performance studies	NIM A 701 (2013) 225
polarimeter performance studies	NIM A 729 (2013) 765
cosmic-rays TPC tracker characterization	NIM A 718 (2013) 395
polarized γ-ray beam data-taking campaign	PoS (ICRC2015) 1016
high dilution factor polarimetry on beam demonstrated	SPIE (2016) 99052R
Recent Summary	SciNeGHE2016 arXiv:1702.08429

- Event generator:
  - Past achievements: a VEGAS based generator

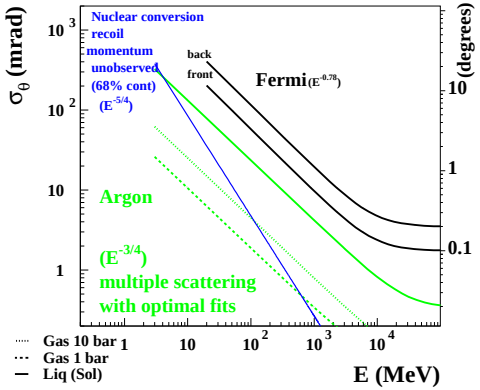
Exact, 5D, polarized, Event generator	NIM A 729 (2013) 765
Polarimetry again (azimutal angle definition)	Astropart. Phys. 88 (2017) 30
Event generator comparison	Astropart. Phys. 88 (2017) 60

  - Present activities: towards VEGAS free generation
  - Perspectives for the future: a Geant4 Physics Model.

The Context: HARPO

single photon angular resolution

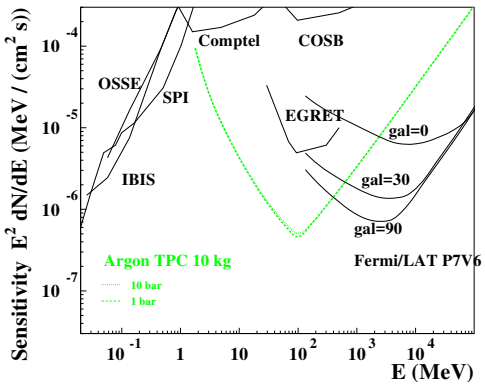
$0.27 \oplus 0.27 = 0.38^\circ$ @ 100 MeV



Nucl. Instrum. Meth. A 701 (2013) 225

point-like source sensitivity

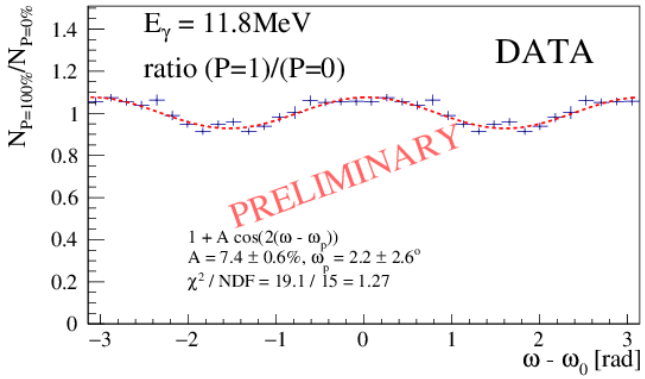
(à la Fermi, 3 year, 5σ, $> 10\gamma$ ..)



Nucl. Instrum. Meth. A 701 (2013) 225

(x, t) and (y, t) signal maps

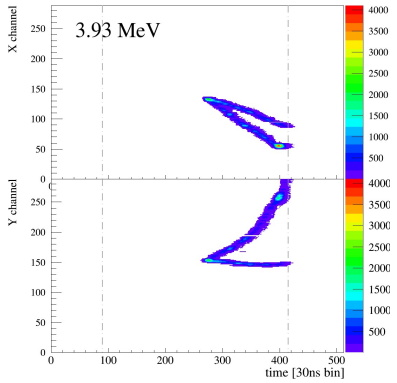
11.8 MeV γ in 2.1 bar Ar-iC4H10 95-5%



SPIE (2016) 99052R

azimuthal angle distribution

4 MeV γ in 2.1 bar Ar-iC4H10 95-5%



SciNeGHE (2016) arXiv:1702.08429

VEGAS-Based Generator

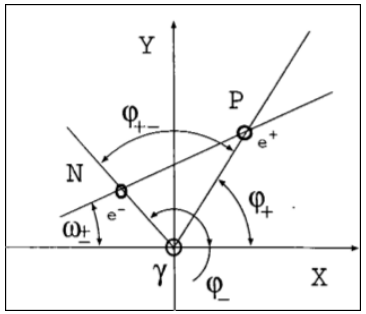
- Final state: $\varphi_+, \theta_+, \varphi_-, \theta_-, x_+ \equiv E_+/E_\gamma$
- BASES / SPRING version of the VEGAS method, S. Kawabata, Comp. Phys. Comm. 88, 309 (1995).
- differential cross section either from:
  - Feyman diagrams (important for low energy triplet) HELAS, H. Murayama, KEK-91-11.
  - Bethe-Heitler approximation (2 dominant diagrams only)
- exact:
  - no low energy approximation
  - no small angle approximation
  - 5D differential Xsection sampled, no product of 1D differential Xsections
  - strict energy-momentum conservation
- polarized:
  - linearly polarized photons
  - unpolarized photons
  - partially polarized photons
- target: nucleus or electron (triplet conversion)
- atomic electron field screening: form factor $F(q^2)$, coherent (nuclear), incoherent (triplet)
- extensive validations for high-energy photons, $E \geq 4\,\mathrm{MeV}$

NIM A 729 (2013) 765

γ Polarimetry with Pair Conversion

$$\frac{d\Gamma}{d\varphi} \propto (1 + \mathcal{A} \times P \cos[2(\varphi - \varphi_0)]), \qquad \sigma_P = \frac{1}{\mathcal{A}} \sqrt{\frac{2 - (\mathcal{A} \times P)^2}{N}} \approx \frac{1}{\mathcal{A}} \sqrt{\frac{2}{N}},$$

- P cosmic source linear polarisation fraction
- $\mathcal{A}$ photon conversion polarization asymmetry, $\mathcal{A} \approx 0.2$ for conversion to pairs
- φ event azimuthal angle, How define φ ? $\varphi \equiv \omega$ used up to now
- φ_0 source polarization angle
- N number of signal events
- $D \equiv \dfrac{\mathcal{A}_{\rm eff}}{\mathcal{A}_{\rm QED}}$ polarization asymmetry dilution factor

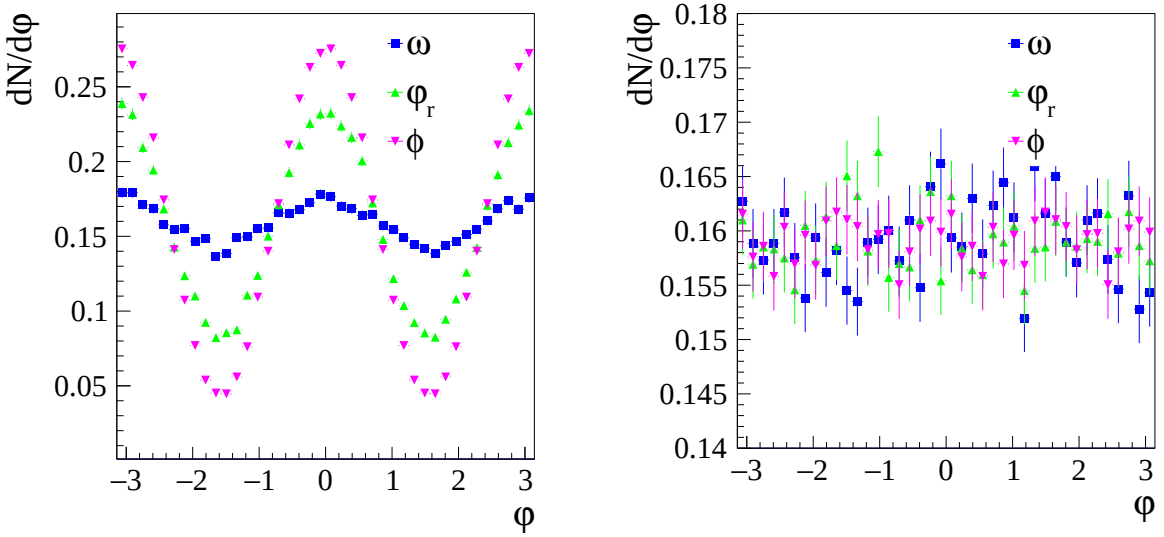


"polarized beams and polarimeters"

B. Wojtsekhowski (2000)

Polarimetry: Defining the Azimuthal Angle ?

$P = 1$ $\qquad$ $P = 0$

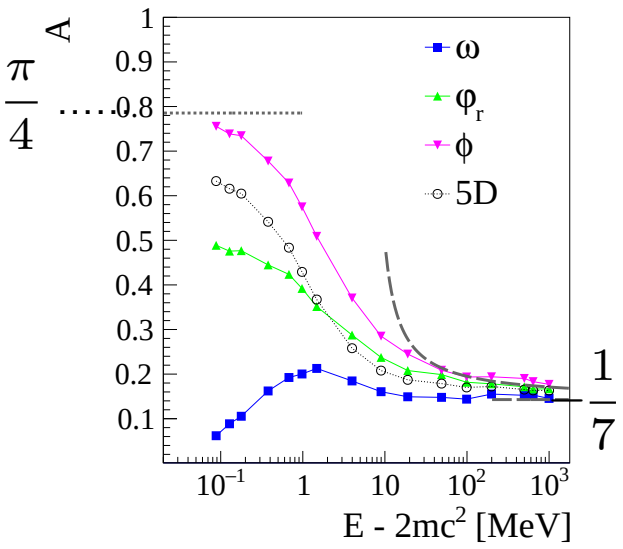


azimutal angle distributions of 1.2 MeV photon conversions to pairs

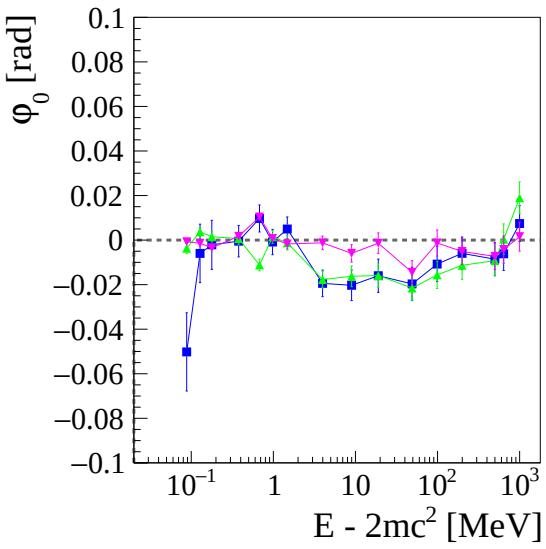
- ω already defined
- φ_r recoil angle, $\varphi_r = \varphi_{\rm pair} \pm \pi$
- $\phi = (\varphi_+ + \varphi_-)/2$, bisector of e^+ and e^- direction

Polarimetry: Defining the Azimuthal Angle ?

polarization asymmetry



polarization angle



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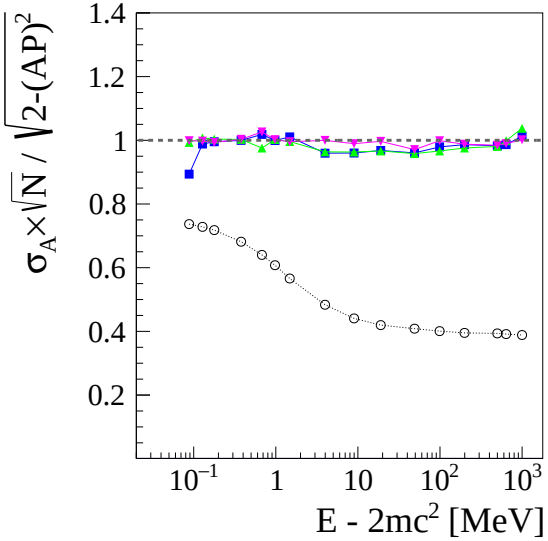

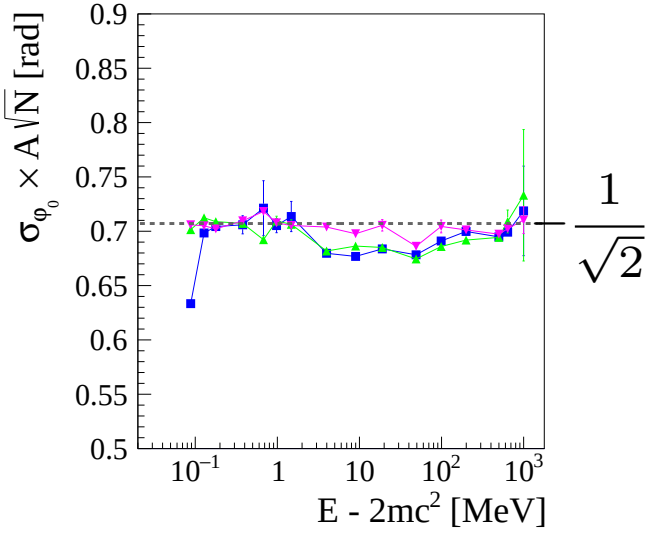

loss factor wrt ϕ

E (MeV)	ω	φ_r or $\varphi_{\rm pair}$
10	0.56	0.67
100	0.74	0.94

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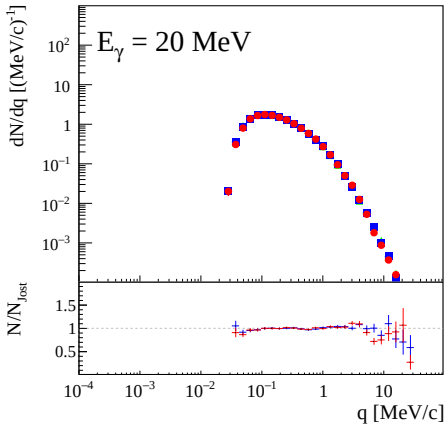
We checked that on a $P = 0$ MC sample, the measured value is found to be $\mathcal{A} \times P \approx 0$

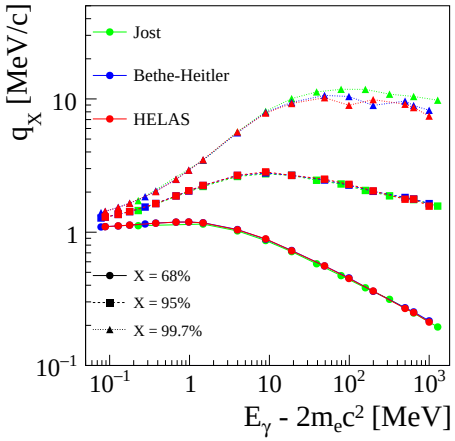
We checked that form factors do not affect the polarization asymmetry

VEGAS-based generator: more on validations

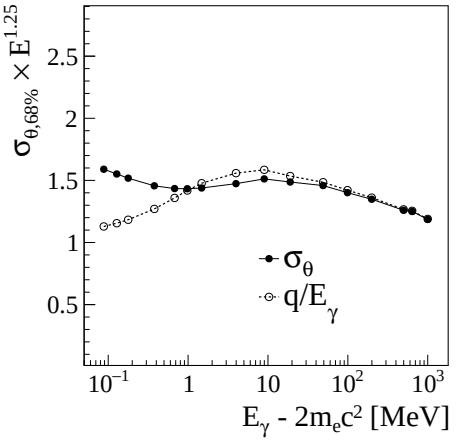
recoil momentum q



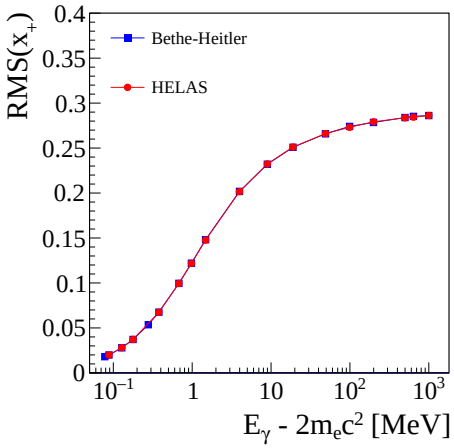
recoil momentum q containment



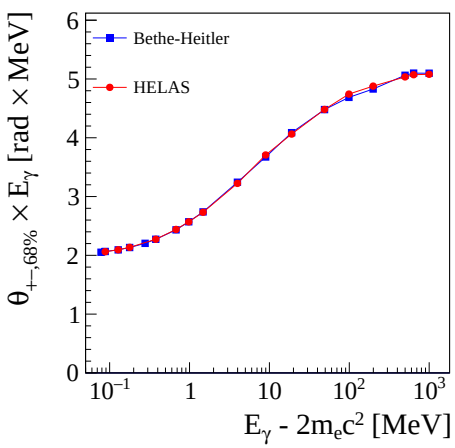
angular resolution containment



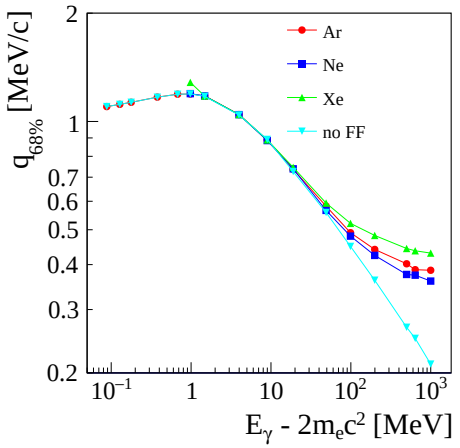
R.M.S. of $x_+ \equiv E_+/E$



opening angle containment



recoil momentum containment



R. Jost, "Distribution of Recoil Nucleus in Pair Production by Photons," Phys. Rev. 80, 189 (1950).

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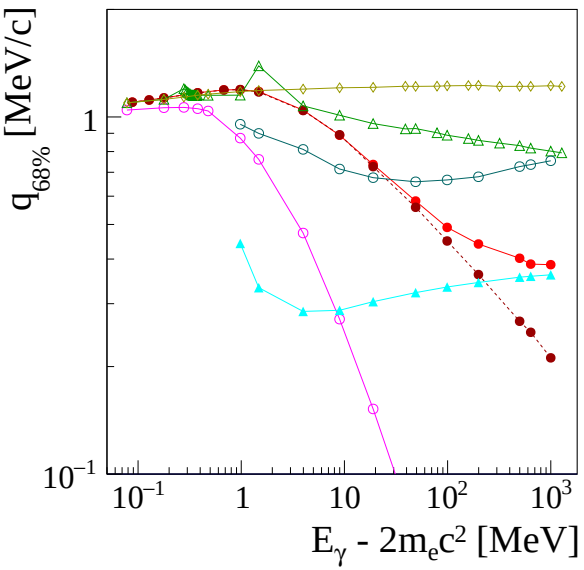
Conversion Event Generators: A Comparison

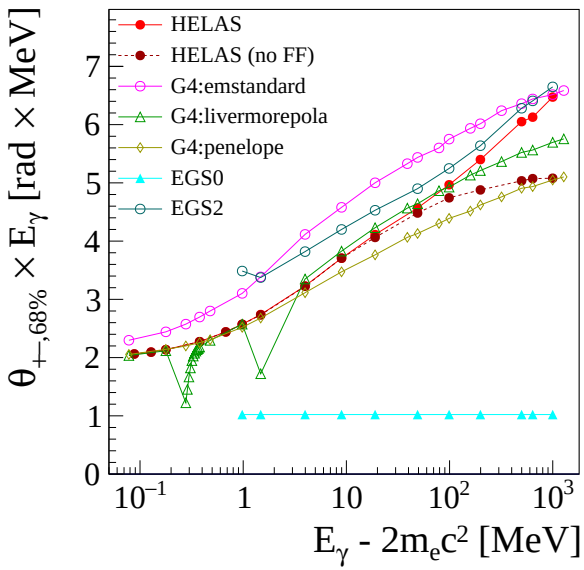
Name	Model	Generator
HELAS	HELAS Feynman amplitudes	BASES/SPRING
Bethe-Heitler	Bethe-Heitler	BASES/SPRING
G4:emstandard	G4BetheHeitler	Geant4 10.02.01
G4:livermorepola	G4LivermorePolarizedGammaConversion	Geant4 10.02.01
G4:penelope	G4PenelopeGammaConversion	Geant4 10.02.01
EGS0	egs5, IPRDST$= 0$	egs5 1.0.6
EGS2	egs5, IPRDST$= 2$	egs5 1.0.6

Event Generator Comparison: Kinetic Variables

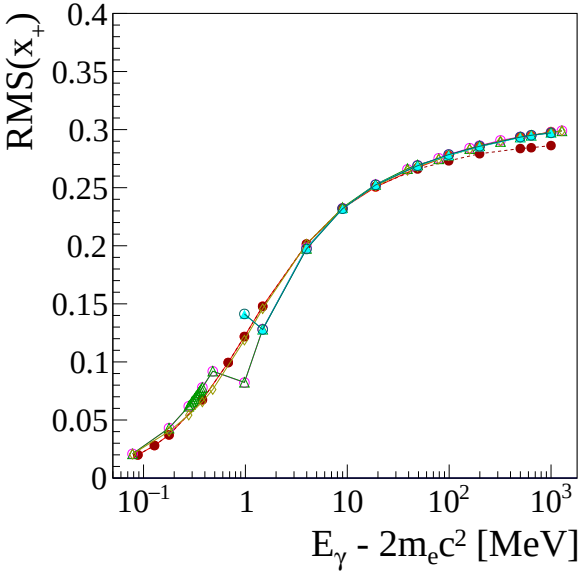
recoil momentum containment



opening angle containment



R.M.S. of $x_+ \equiv E_+/E$



- recoil momentum incorrectly simulated by G4 and EGS5 physics models
- inspection of code and/or documentation shows that they (most often) don't even conserve energy-momentum.

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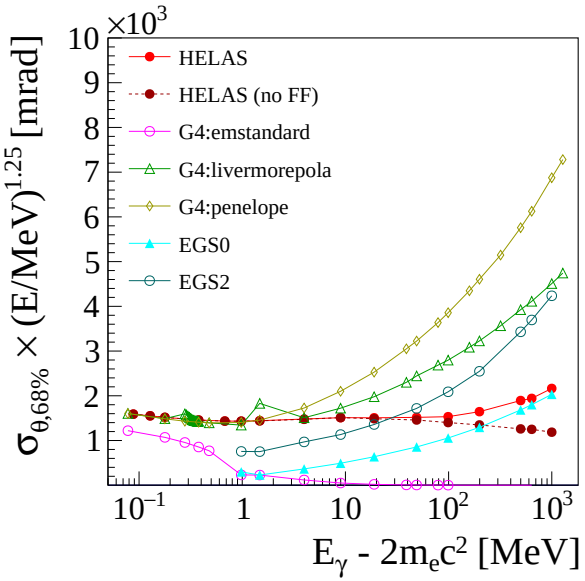
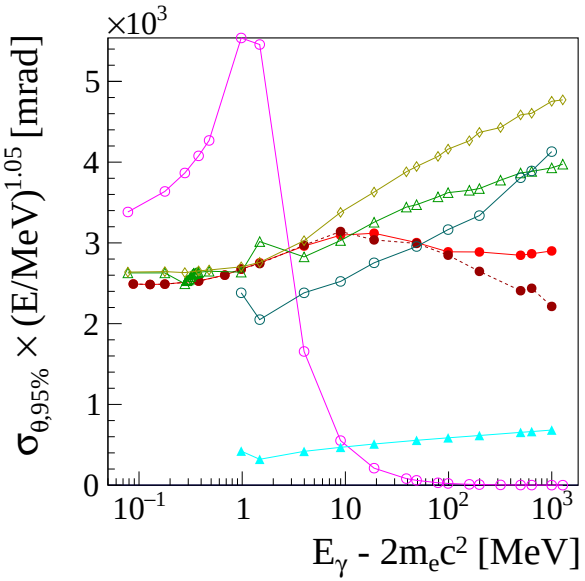
Event Generator Comparison: Angular Resolution

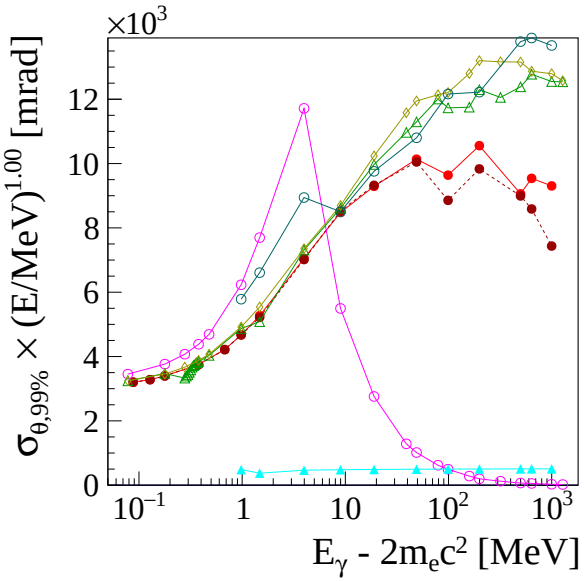
68%



95%



99.7%



- HELAS: Form Factor (argon): an effect for $E > 100\mathrm{MeV}$
- HELAS: parametrization of σ_θ:

68%	$1.5\,\mathrm{rad}\,(E/\mathrm{MeV})^{1.25}$
95%	$2.9\,\mathrm{rad}\,(E/\mathrm{MeV})^{1.05}$
99.7%	$4-9\,\mathrm{rad}\,(E/\mathrm{MeV})^{1.00}$

- G4 and EGS5 models have 68% angular resolution crazy.

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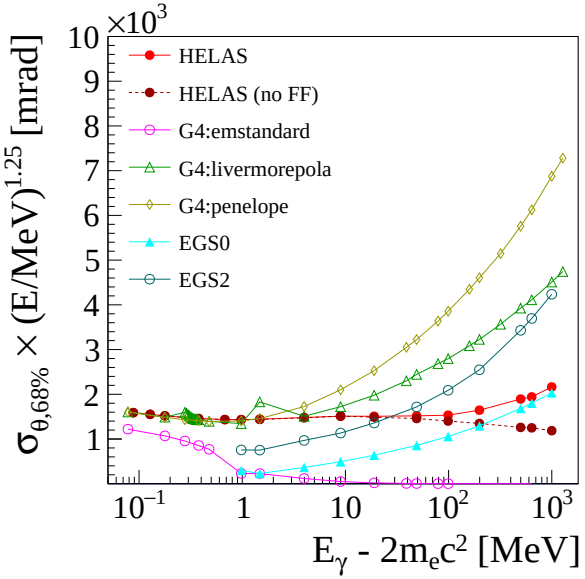
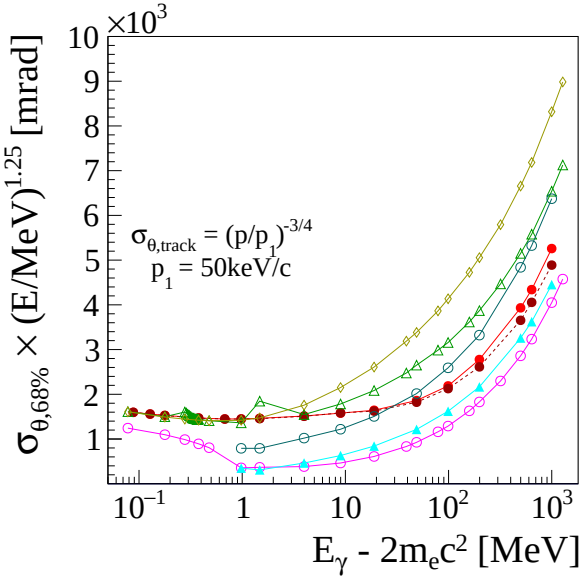
Event Generators and Telescopes

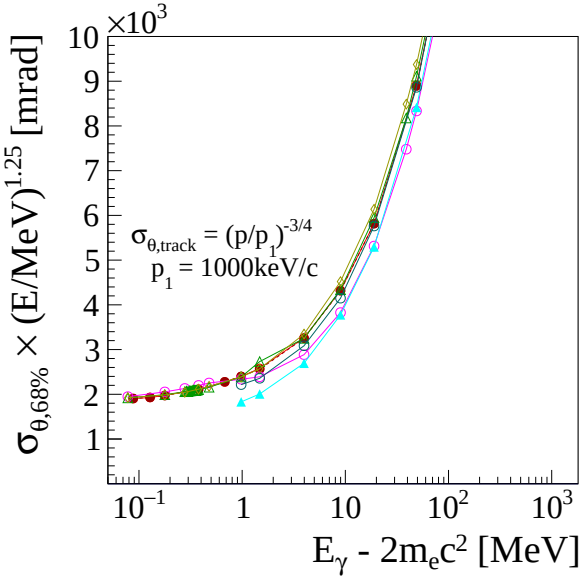
no detector effect



gas detector



Fermi



- For dense, high-Z telescopes, the multiple scattering washes out the event generator differences

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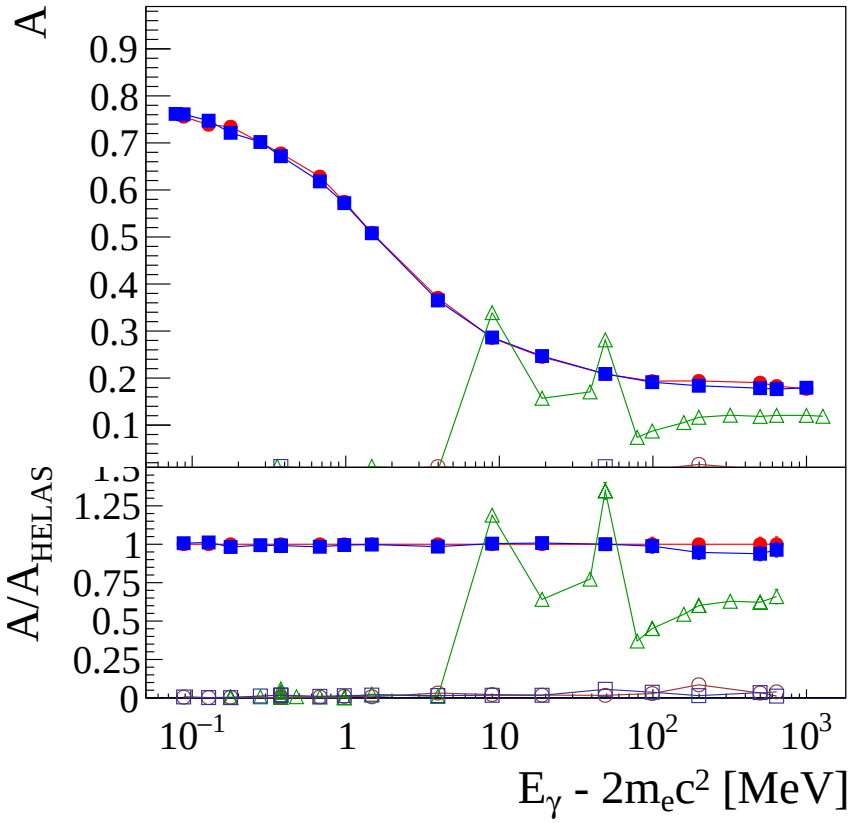
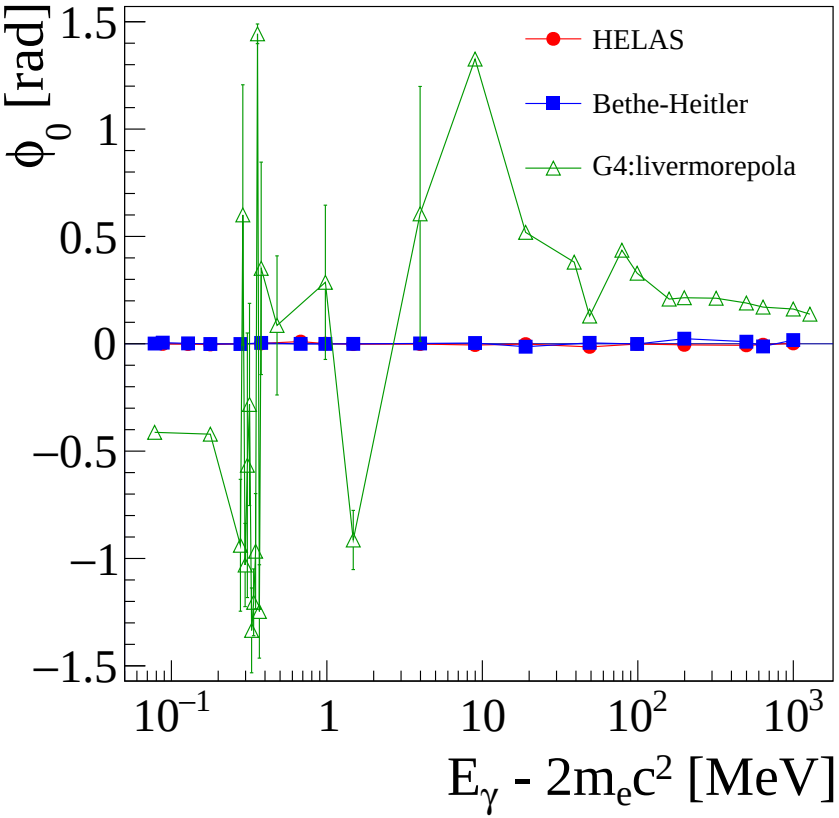
Event Generators and Photon Linear Polarization





- Simulation of polarized γ conversion to pairs by G4:livermorepola surprising (polarisation asymmetry and polarisation angle)

@ 100 MeV, $\dfrac{\mathcal{A}_{(\mathrm{HELAS\ or\ BH})}}{\mathcal{A}_{\mathrm{G4:livermorepola}}} = \dfrac{(19.1 \pm 0.4)\%}{(8.7 \pm 0.6)\%} \approx 2.2$

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Present Activity: Change to a VEGAS-free generator

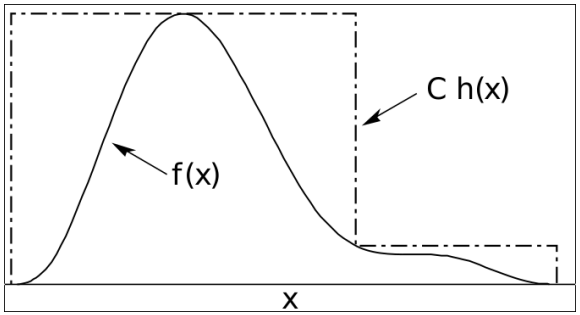
- VEGAS: An Adaptive Multidimensional Integration Program

  Finds an optimal tabulation of the differential Xsection based on a product of 1D Xsections (at a given photon energy E)

  G.Peter Lepage, CLNS-80/447 and J.Comput.Phys. 27 (1978) 192

- This is named "integration" and takes several seconds

- Then the exact nD differential Xsection is generated by the Acceptance-rejection method



plot from PDG

- Zillions of events generated rapidly (at given E), 4-vectors passed to (HARPO) Geant4 (silicon samples given to Valentina)

- Presently moving to a parametrized(E) version for each variable.

  No sign of (Bethe-Heitler)-HELAS difference: HELAS dropped

Perspectives for the future: a Geant4 Physics Model

- Fortran $\rightarrow$ C++
- Contact with Geant4 Collaboration taken
- Abstract submitted to the April Geant4 Space Users' Workshop

Conclusion

- Presently available physical models on the market inapropriate
  - for simulation of high-resolution γ telescopes with pairs
  - for simulation of γ polarimeters with pairs
- VEGAS-based exact, 5D, polarized event photon conversion event generator built, validated, published.
- Polarimetrists with pairs, beware the azimuthal angle definition
- MC samples available to the Community at given (E, Z):
  $(e^+, e^-$, recoil) 4-vectors, on request
- de-VEGAS-ification in progress $\rightarrow$ (several)-μs single-photon generation

  validation extended to $E = 1\,\mathrm{PeV}$
- Geant4 Physics Model later this year.