Gamma Polarimetry Using Conversion to e^+e^- Pairs With ASTROGAM

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The gamma-ray sky with astrogam
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Talk layout

1. In the best world possible
   (all events, no detector resolution, no multiple scattering)

2. Kinematic cuts

3. With multiple scattering

4. Important issues not covered in this talk

Astrogam converter / tracker

- Inputs
  - 70 layers of $60 \times 60\mathrm{cm}$, $400\mu\mathrm{m}$ Double-sided Silicon
  - RMS resolution $80\,\mu\mathrm{m}$
  - Strip pitch $240\,\mu\mathrm{m}$
  - Layer spacing $0.7\,\mathrm{cm}$

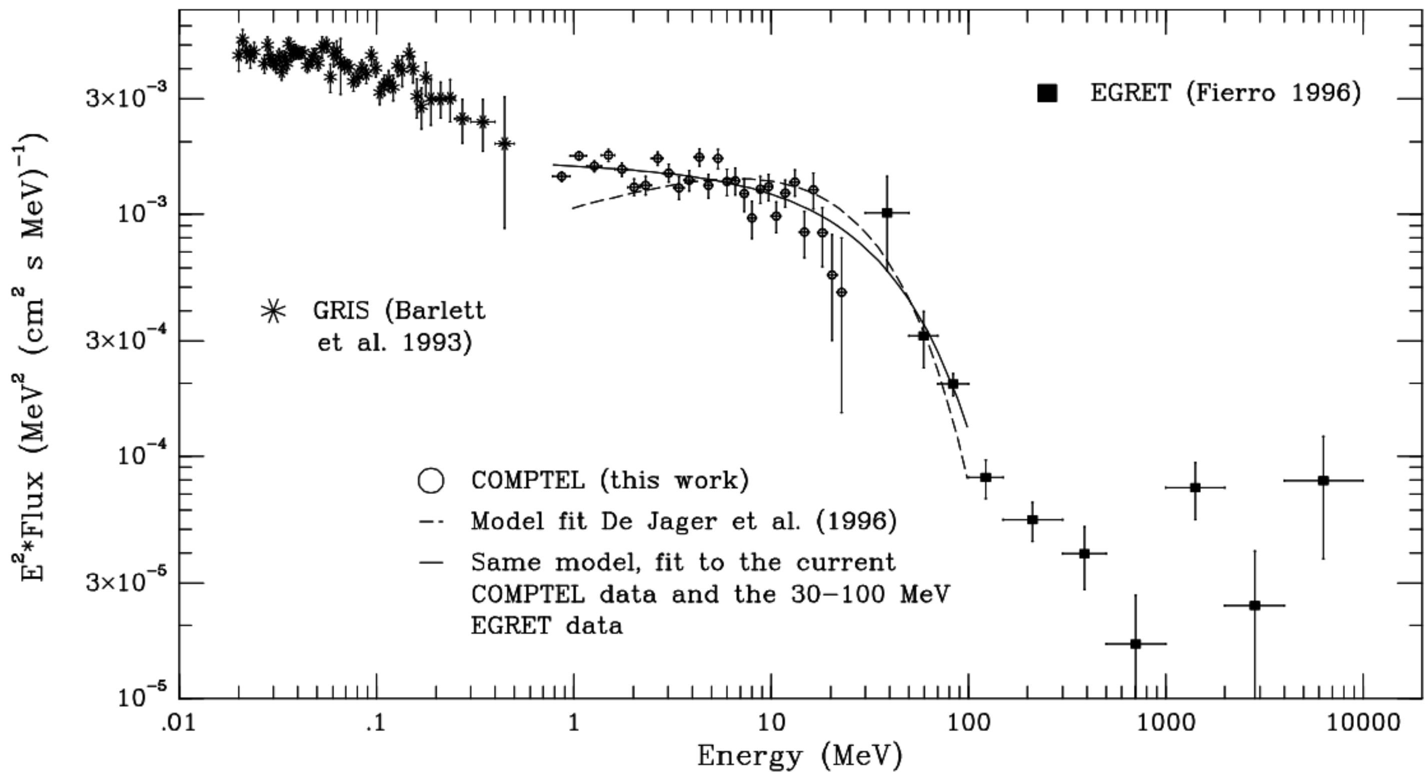
- Assumptions / approximations
  - Wafers sensitive on full thickness, no dead material between layers
  - Thin detector, i.e. no loss due to other processes (Compton, triplet ..)

- Thanks Vincent Tatischeff & Andrea Bulgarelli

Measurement

- Effective area $A = H \times M$, $392\,\mathrm{cm}^2$ @ 30 MeV
  - H $(\mathrm{cm}^2/\mathrm{g})$ nuclear pair conversion photon attenuation on Si, from NIST.
  - $M = 23.1\,\mathrm{kg}$ total silicon mass.
- Pointing mode,
  - exposure fraction $\eta = 1$,
  - trigger / reconstruction efficiency $\epsilon = 1$,
  - fiducial volume $\xi = 1$
- Duration $T = 10^6\mathrm{s}$
- Small background approximation :
  γ selection so that $S \gg B$, $S/\sqrt{S+B} \approx \sqrt{S}$
- Perfect azimutal angle measurement at the moment
  (no multiple scattering, no detector resolution)

Crab



- $\frac{dN}{dE} = K_s (E/3.5\,\mathrm{MeV})^{-\Gamma_s} \exp{(-E/E_0)}$
- yes .. its the nebula ..

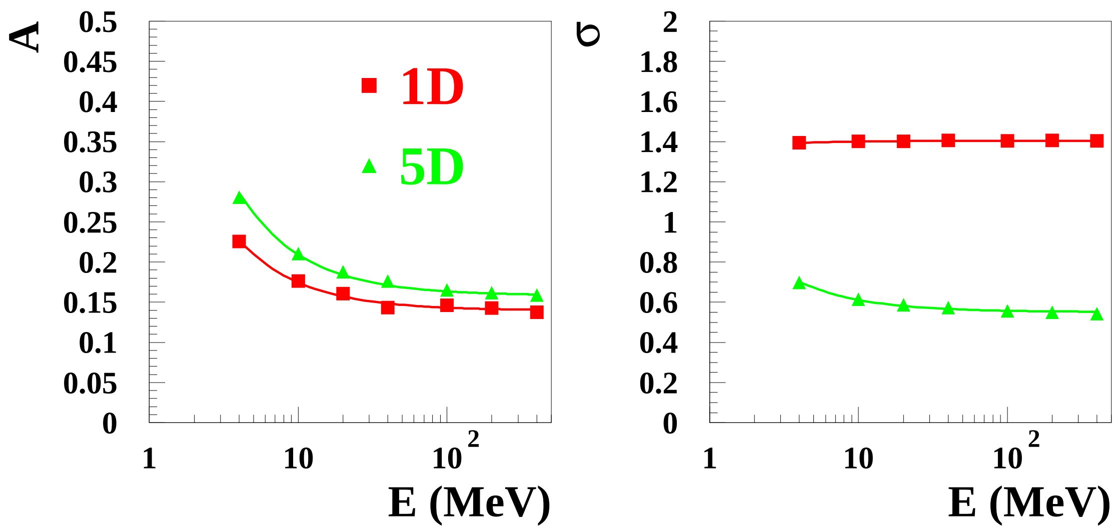
Comptel gamma-ray study of the crab nebula, Astron.Astrophys. 330 (1998) 321

γ *Polarimetry with Pair conversion*

- In this talk, use only the azimuthal angle information "1D"

$$\frac{d\Gamma}{d\phi} \propto (1 + \mathcal{A} P \cos[2(\phi - \phi_0)]), \qquad \sigma_P \approx \frac{1}{\mathcal{A}} \sqrt{\frac{2}{N}},$$

  - P cosmic source linear polarisation fraction
  - $\mathcal{A}$ photon conversion polarization asymmetry
  - ϕ event azimuthal angle



- $\mathcal{A} \approx 0.2$
- (How do better ? (use of optimal variable, 5D) : see D.B. NIM A 729 (2013) 765.)

Back-of the enveloppe calculation

$$N_{\rm evt} = T \int \frac{dN}{dE}(E) A(E) dE$$

- $\mathcal{A}$ asymmetry, A effective area
- Remember, no cut, no multiple scattering yet !
- $\mathcal{A} \approx 0.2$, $T = 10^6 \mathrm{s}$

E range (MeV)	1 – 100	10 – 100	(10 – 30	30 – 100)
N	66.2 k	21.2 k	17.8 k	3.4 k
σ_P	2.7 %	4.9 %	5.3 %	12 %

- Note that the uncertainty σ_P is independant of the value of P

2 - Kinematic cuts

- Still no detector resolution, no multiple scattering

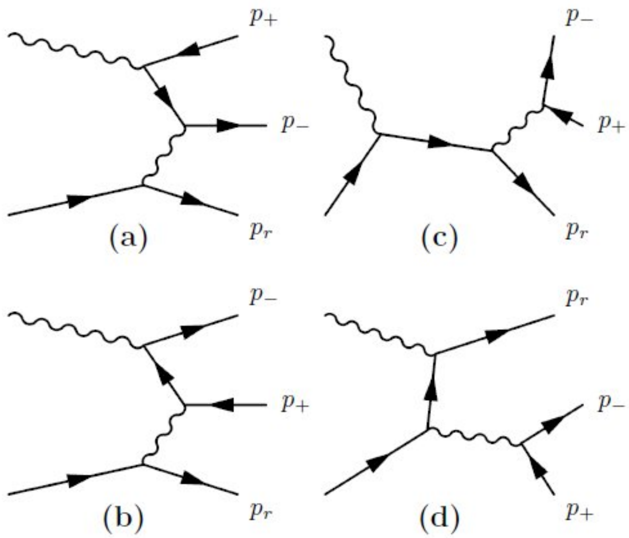
- Selection cuts
  - e^+e^- Opening angle cut : $\theta_{+-} > 2p_s/p_w = 0.069$ rad.
    - $p_s = 240\,\mu\mathrm{m}$ strip pitch
    - $p_w = 0.7\,\mathrm{cm}$ wafer spacing

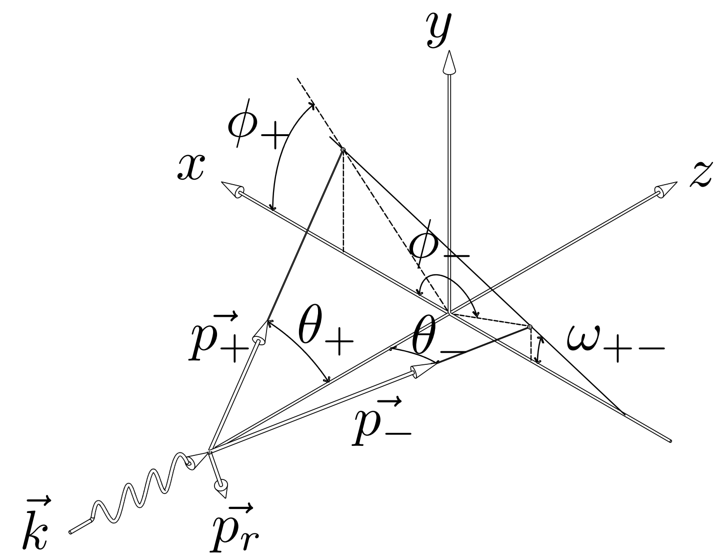
  - e^+ and e^- energy $>$ 5 MeV, $\propto 1.3\,\mathrm{cm}$ Si for a minion, $\propto$ 32 wafers

  - reco'ed photon direction within 10° with source direction (ion recoil not measured)

A full (5D) exact (down to threshold) polarized evt generator

- All graphs, either nuclear or triplet
- Bether-Heitler analytical differential cross section option
- Variables : azimuthal (ϕ_+, ϕ_-) and polar (θ_+, θ_-) angles of e^+ and e^-, and $x_+ \equiv E_+/E$





- Uses :
  - HELAS amplitude computation — H. Murayama, *et al.*, KEK-91-11.
  - SPRING event generator — S. Kawabata, Comput. Phys. Commun. 88, 309 (1995).
- Validation against published 1D distributions (nuclear and triplet conversions)

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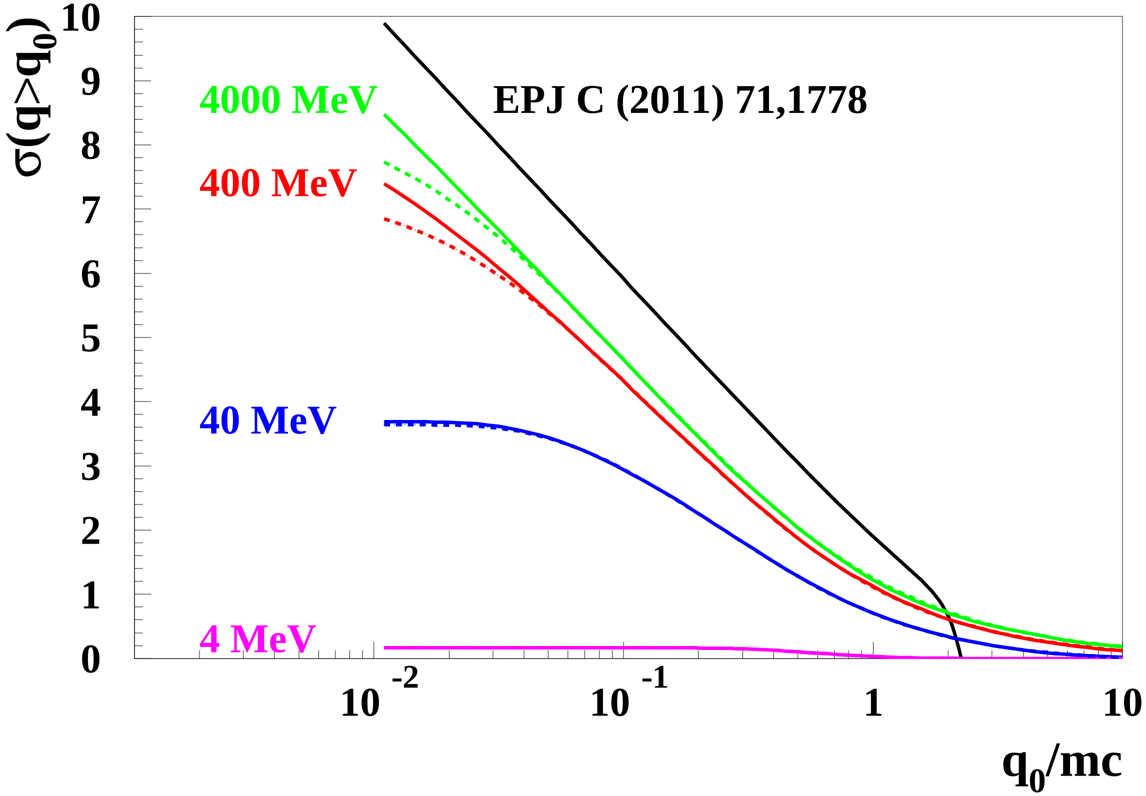
Evt Generator : One Example Comparison Benchmark

- Triplet conversion : cross section for recoil electron momentum larger than q_0, $\sigma(q > q_0)$, as a function of q_0/mc, for various photon energies E ; (Dashed is with form factor applied).
- High photon energy asymptotic expression by M. L. Iparraguirre and G. O. Depaola, Eur. Phys. J. C 71, 1778 (2011).



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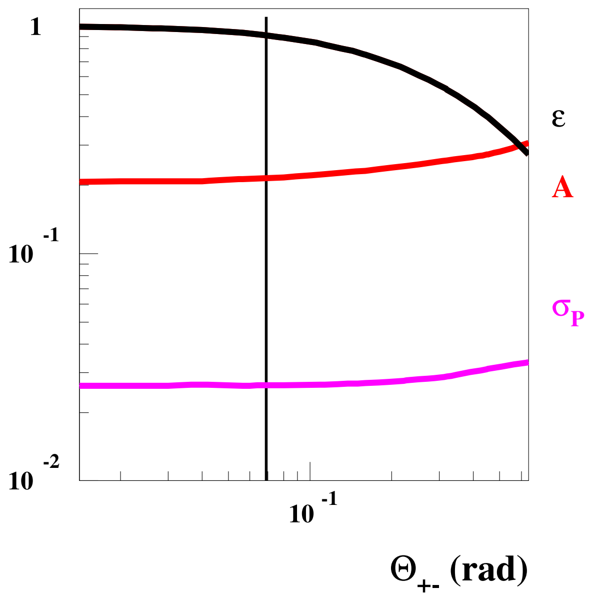
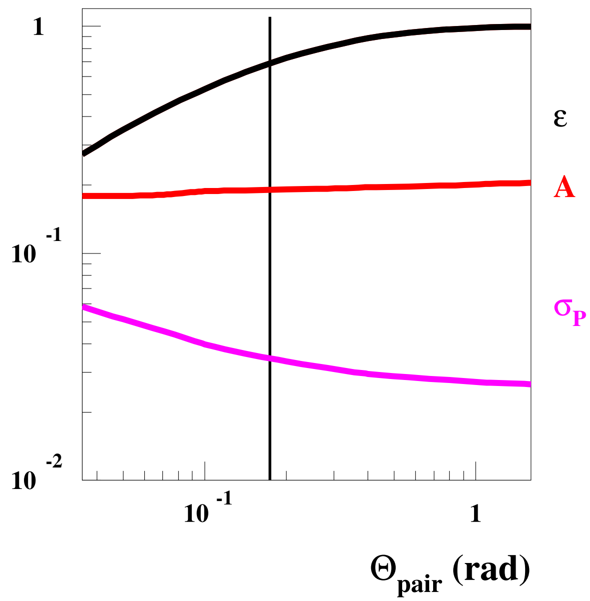
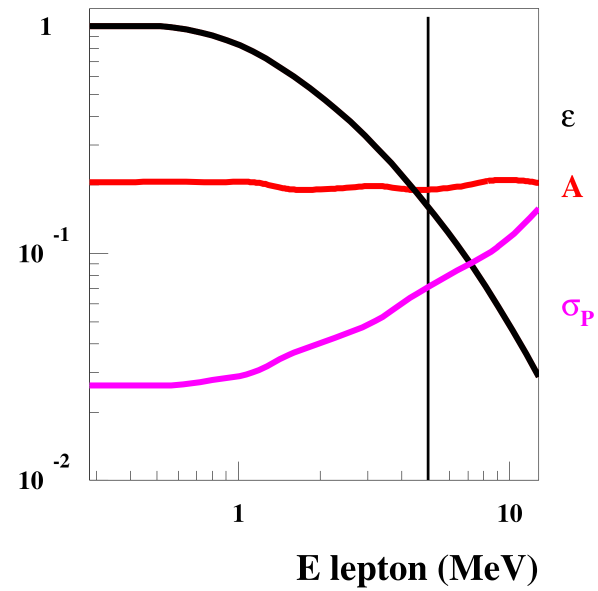
ASTROGAM : polarimetry : with kinematic cuts







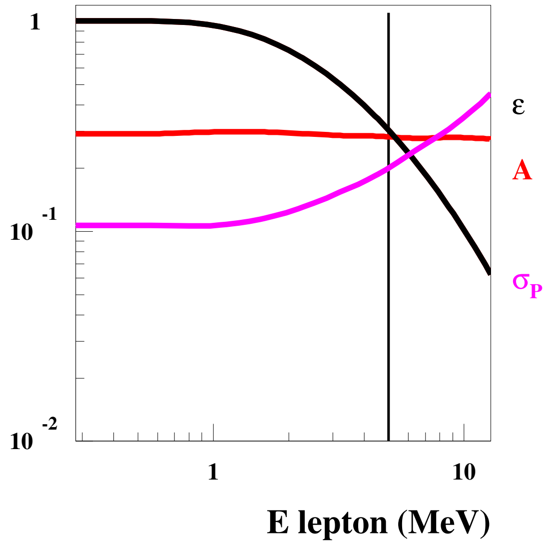
$\theta_{+-} > 0.069\,\mathrm{rad}$ $\quad$ $\theta_{pair} < 10^\circ$ $\quad$ $E_+ > 5\,\mathrm{MeV},\ E_- > 5\,\mathrm{MeV},$

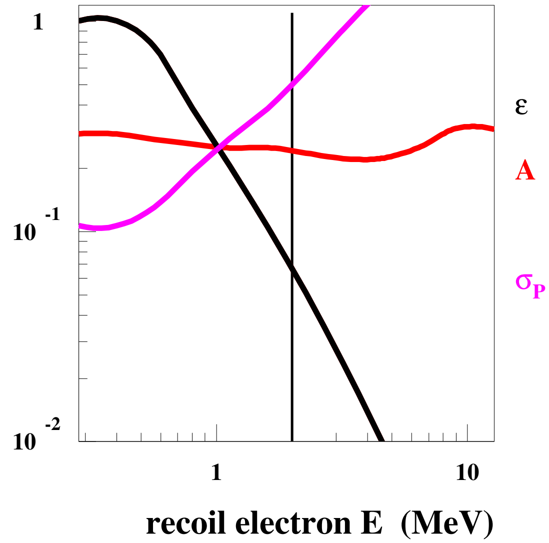
$\epsilon = 0.91$ $\quad$ $\epsilon = 0.69$ $\quad$ $\epsilon = 0.16$

- effective polarization asymmetry barely sensitive to cuts
- with all cuts applied, 6480 evts, ($\epsilon = 0.098$), $\mathcal{A} = 0.19$, $\sigma_P = 9.2\,\%$

What about triplets ?

- 1962 evts (no cut), $\sigma_P = 0.16$
- azimutal angle ϕ_{rec} of the recoil electron
- ability to reconstruct the recoil electron down to .. 2 MeV ?





$E_+ > 5\,\mathrm{MeV}$, $E_- > 5\,\mathrm{MeV}$, $\epsilon = 0.30$

$E_r > 2\,\mathrm{MeV}$, $\epsilon = 0.066$

- with all cuts applied, 43 evts, ($\epsilon = 0.022$), $\mathcal{A} = 0.22$, $\sigma_P = 98\,\%$

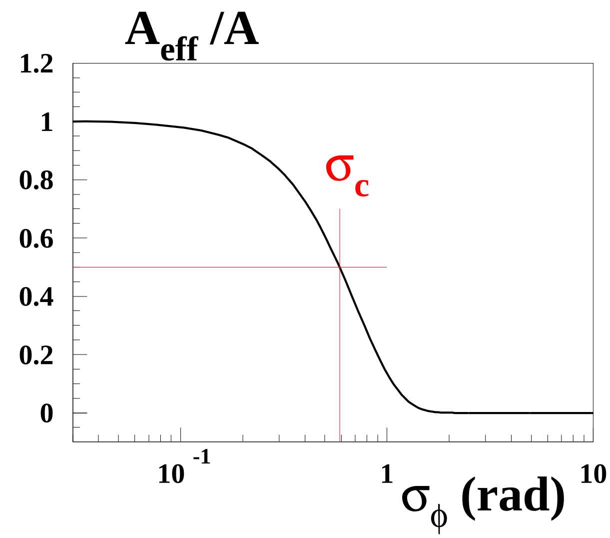
(not even applied multiple scattering on recoil e^- over its way out of the wafer)

Forget about triplets

3 - Multiple scattering : standard treatment : Dilution of the polarisation asymmetry

- γ conversion in a slab of thickness x. Assume pathlength = full thickness, for the moment
- $(1 + \mathcal{A}P\cos[2(\phi)]) \otimes e^{-\phi^2/2\sigma_\phi^2} = (1 + \mathcal{A}\, e^{-2\sigma_\phi^2}\, P\, \cos[2(\phi)])$

$\Rightarrow \mathcal{A}_{\text{eff}} = \mathcal{A}\, e^{-2\sigma_\phi^2}$



- azimuthal angle RMS $\sigma_\phi = \dfrac{\theta_{0,e^+} \oplus \theta_{0,e^-}}{\hat{\theta}_{+-}}$,
  - $\theta_0 \approx \dfrac{13.6\,\mathrm{MeV}/c}{\beta p}\sqrt{\dfrac{x}{X_0}}$,
  - most probable opening angle $\hat{\theta}_{+-} = 1.6\,\mathrm{MeV}/E$ Olsen, PR. 131, 406 (1963).

$\Rightarrow \sigma_\phi \approx 24\,\mathrm{rad}\sqrt{x/X_0}$ (e.g. $D \equiv \mathcal{A}_{\text{eff}}/\mathcal{A} = 1/2$ for $110\,\mu\mathrm{m}$ of Si, $4\,\mu\mathrm{m}$ of W)

- This dilution is energy-independent.

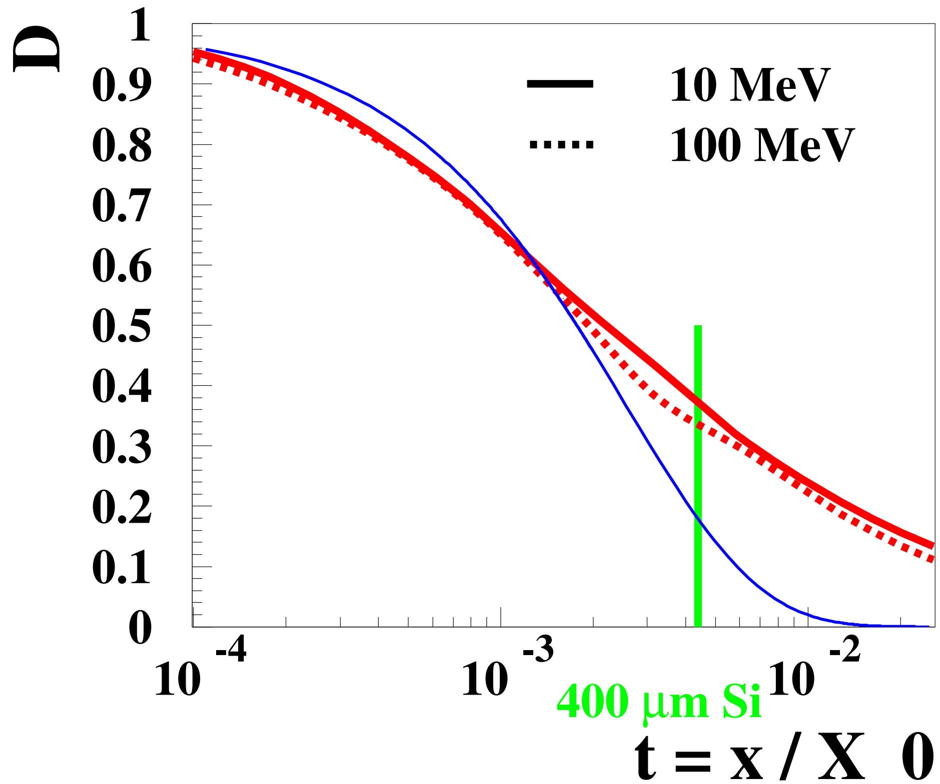
Conventional wisdom : γ polarimetry impossible with nuclear conversions $\gamma Z \rightarrow e^+e^-$

Yu. D. Kotov, Space Science Reviews 49 (1988) 185 J. R. Mattox *et al.*, Astrophys. J. 363 (1990) 270

(On how to do better with a continuous tracker (TPC) ?, see D.B. NIM A 729 (2013) 765)

Polarimetry with slab detector : with Evt Generator

- Full slab thickness $400\,\mu\mathrm{m}$ for all events
- Thin line is Kotov's E-independent, $\hat{\theta}_{+-}$-based approximation.



- Dilution improves somewhat with full generator, contribution of large opening angle evts.
- Typical $D \approx 0.35$ for $400\,\mu\mathrm{m}$ Si (full thickness), fairly E-independent

Crab with slab detector : full simulation

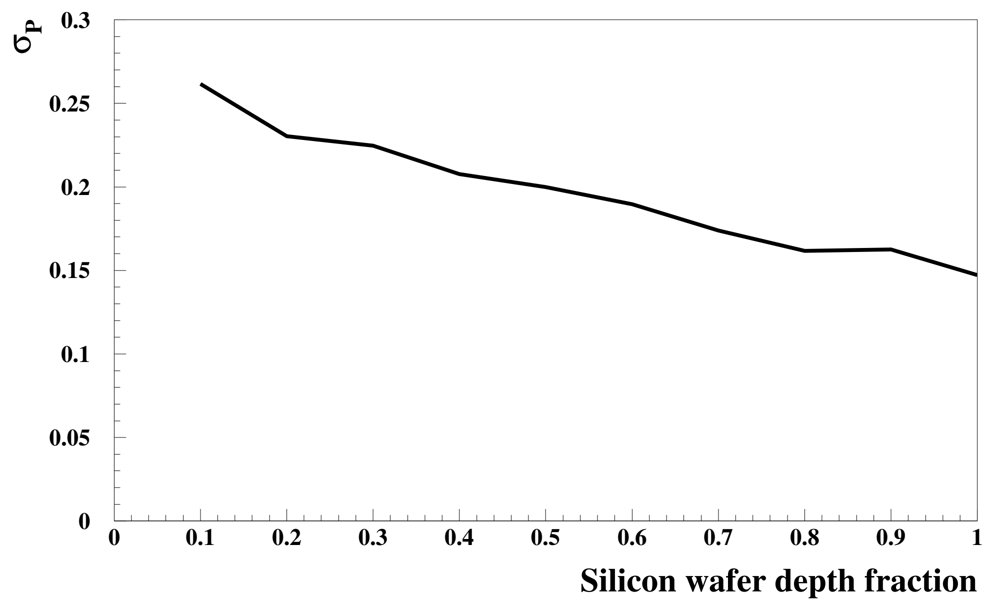
- uniform conversion probability per unit depth inside wafer
- with multiple scattering : kinematic cuts applied on the reco'ed angles.
- N_{evt}, $\mathcal{A}$, σ_P :

	no multiple scattering	with multiple scattering
no kinematic cuts	66211, 0.21, 0.026	66211, 0.11, 0.050
with kinematic cuts	6480, 0.19, 0.092	7473, 0.11, 0.149

- effective dilution on whole spectrum ≈ 0.5
- So, precision on the Crab, $10^6\,\mathrm{s}$ pointing mode, low background approximation $\sigma_P = 15\%$
- MDP (@ 3 σ) = 45%.

Multiple scattering : depth selection attempt

- assumes ((charge) energy deposition) depth in conversion wafer perfectly measured.



- Fails

4 : Important issues not covered in this talk

- $(1, 2) \leftrightarrow (x, y)$ point matching with strip'n slab detectors

- $\ldots$

Conclusion

- Despite the limitations of the case considered here ($T = 10^6\mathrm{s}$, $M = 23.1\,\mathrm{kg}$),
- and thanks to the double-sided reading of the Si wafers,
- ASTROGAM has some sensitivity to linear polarization
  Crab : ($\sigma_P = 15\%$, MDP (@ 3 σ) $=$ 45%)
  in the range 10 – 100 MeV, using γ conversions to e^+e^- pairs.
- The critical issue is the ability to perform trigger / reconstruction / selection of low energy photons.
- ($(1,2) \leftrightarrow (x,y)$ point matching : pending)

Je vous remercie de votre attention.

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