Update on the UCSC/SCIPP BeamCal Simulation Effort

FCAL Simulation Group Meeting
March 28, 2018

FCAL Collaboration
High precision design

Bruce Schumm
UC Santa Cruz Institute for Particle Physics

Overview

Very little support for ILC work in US: progress depends on interest and availability of undergraduate students

Other than FLUKA simulation (paper under review by collaboration), not much progress made

I'll talk about FLUKA results on radiation levels and radiation damage, and then just lay out ideas and plans for other areas

Operation of the Prospective ILC Beamline Calorimeter in the High-Radiation Forward Environment of the International Linear Collider

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Work performed within the FCAL Collaboration

Draft sent by email to collaboration March 21

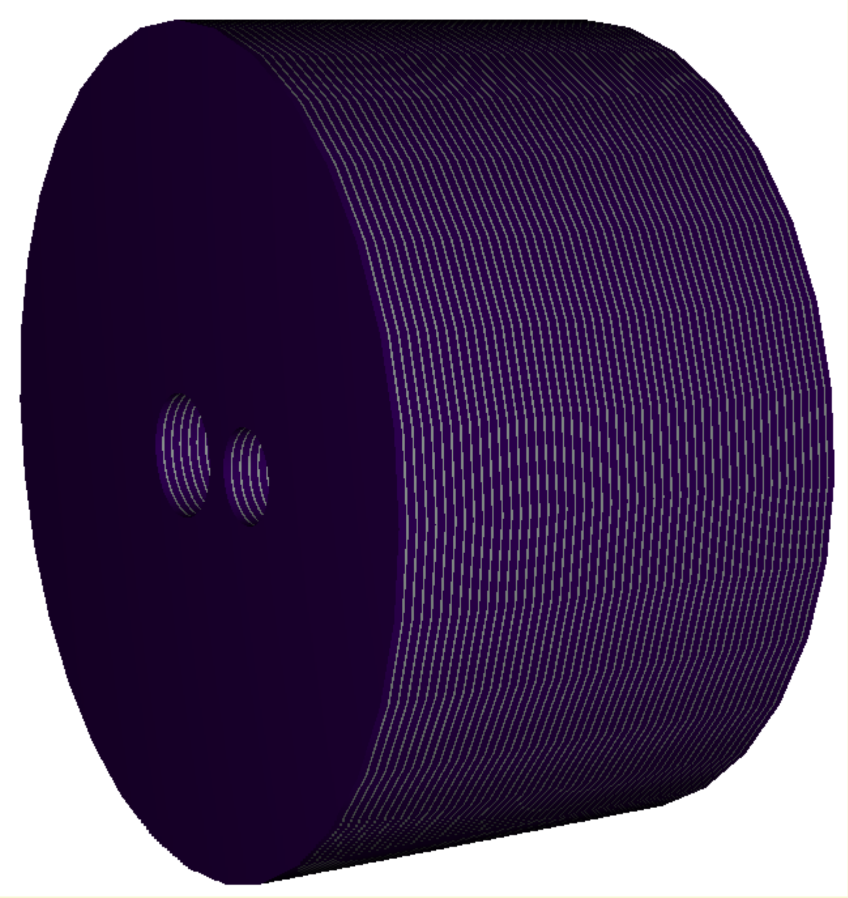
Comments due April 4

Review being organized by Veta

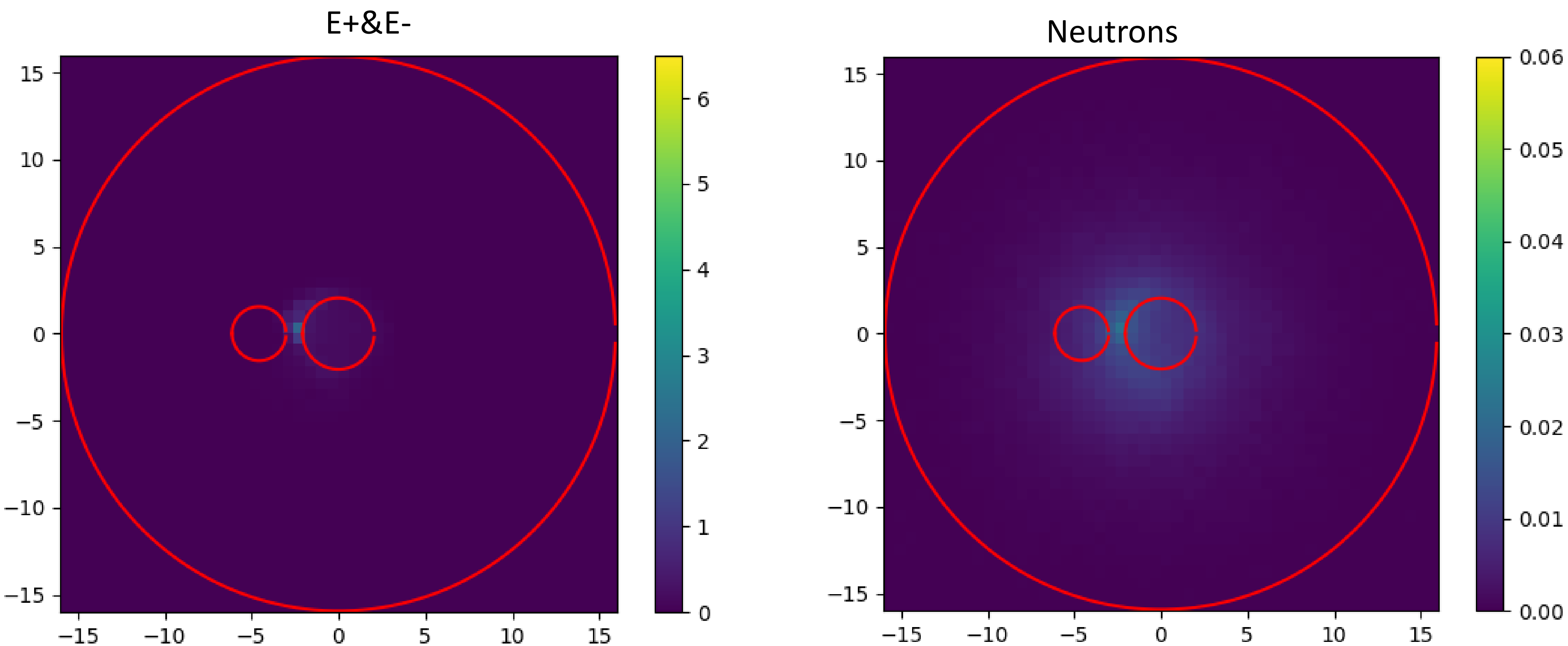
Intended for Nucl Instr & Meth

BeamCal Simulation in FLUKA
(Ben Smithers, SCIPP)

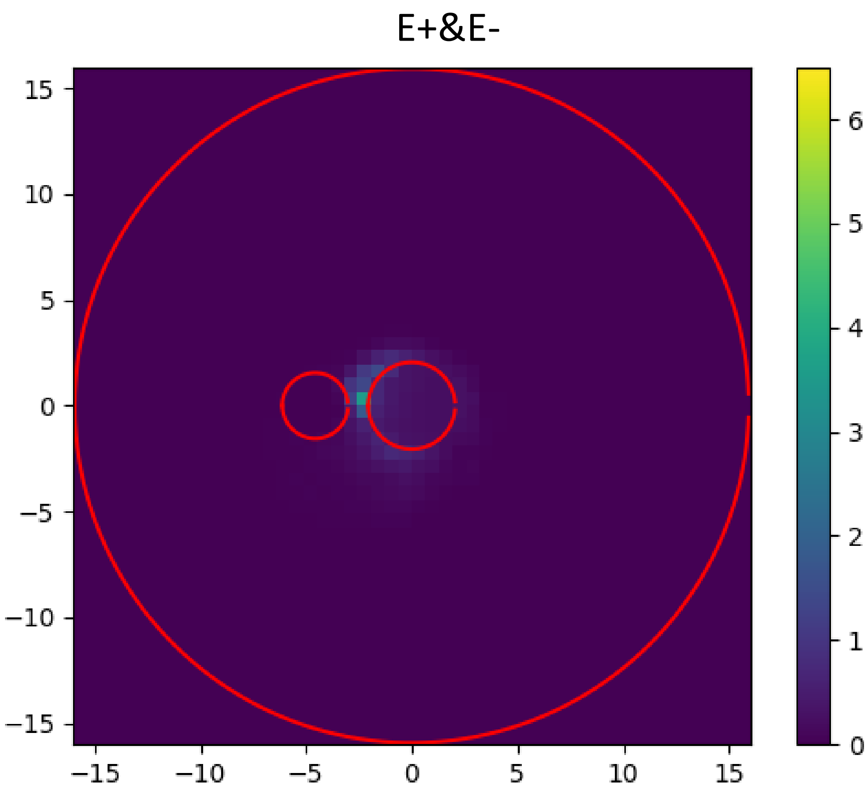
- BeamCal absorbs about 10 TeV per crossing, resulting in electromagnetic doses as high as **100 Mrad/year**
- Associated neutrons can damage sensors and generate backgrounds in the central detector
- GEANT not adequate for simulation of neutron field ➔ implement FLUKA simulation
- Design parameters from detailed baseline description (DBD)
- Primaries sourced from single Guinea Pig simulation of e^{+-} pairs associated with one bunch crossing

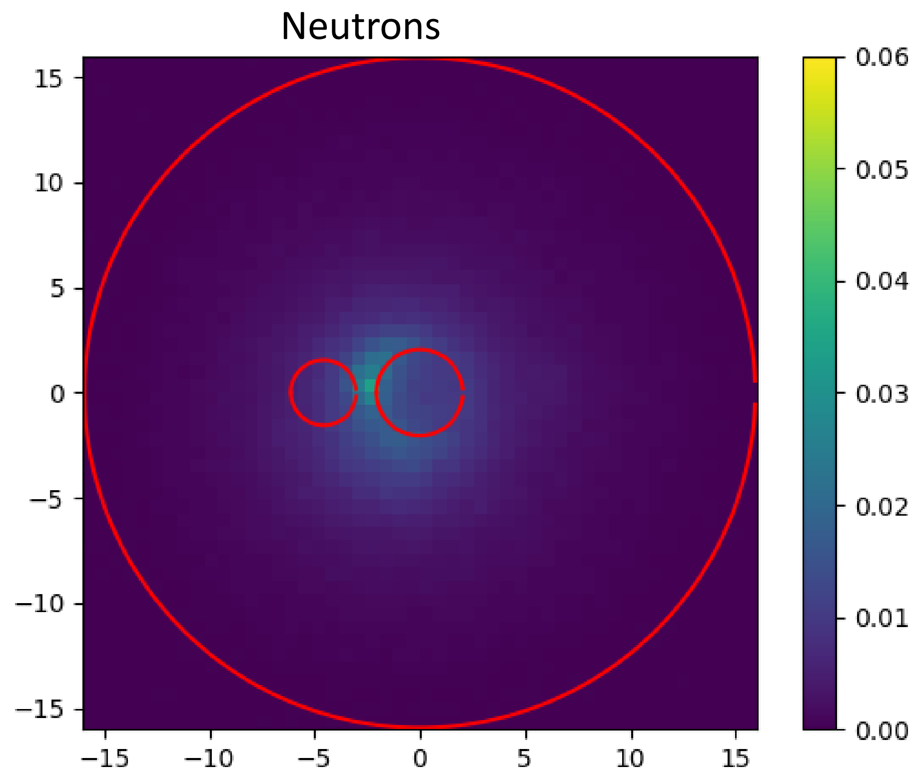


Layer 2 Detector - Fluence

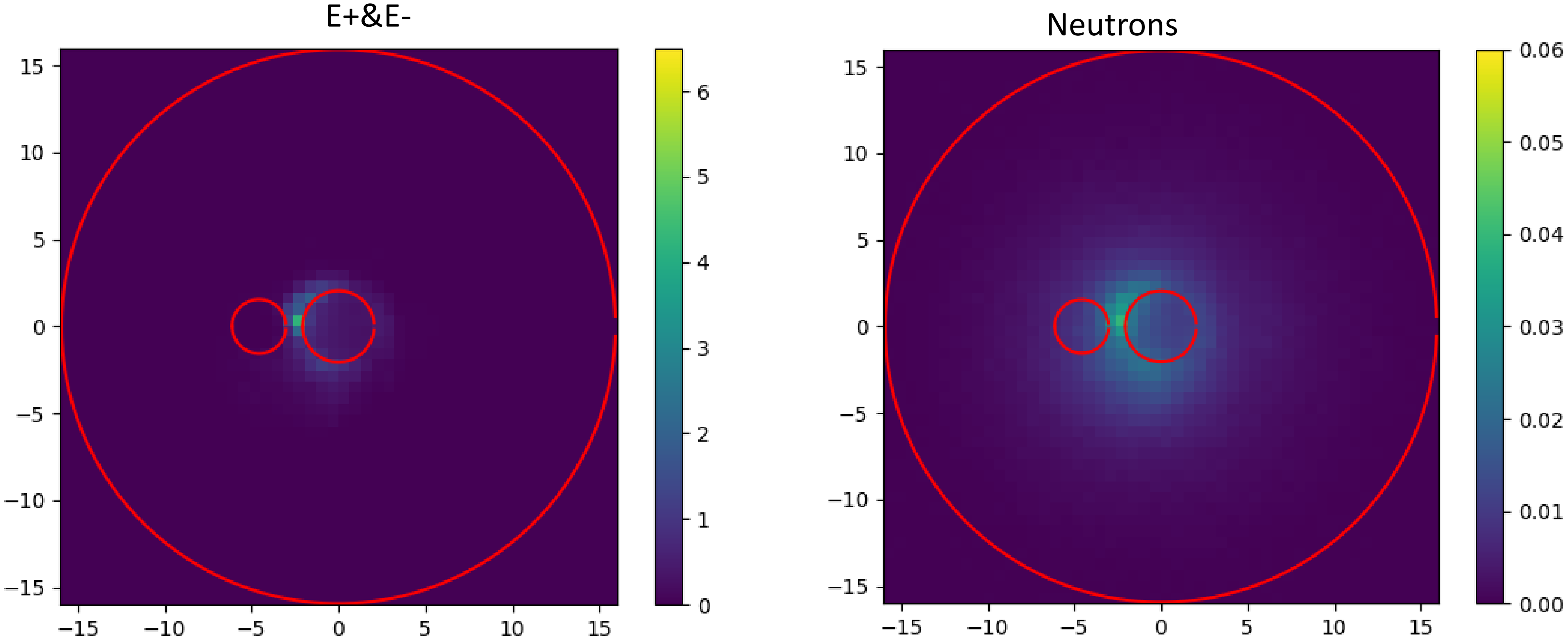


Layer 4 Detector - Fluence

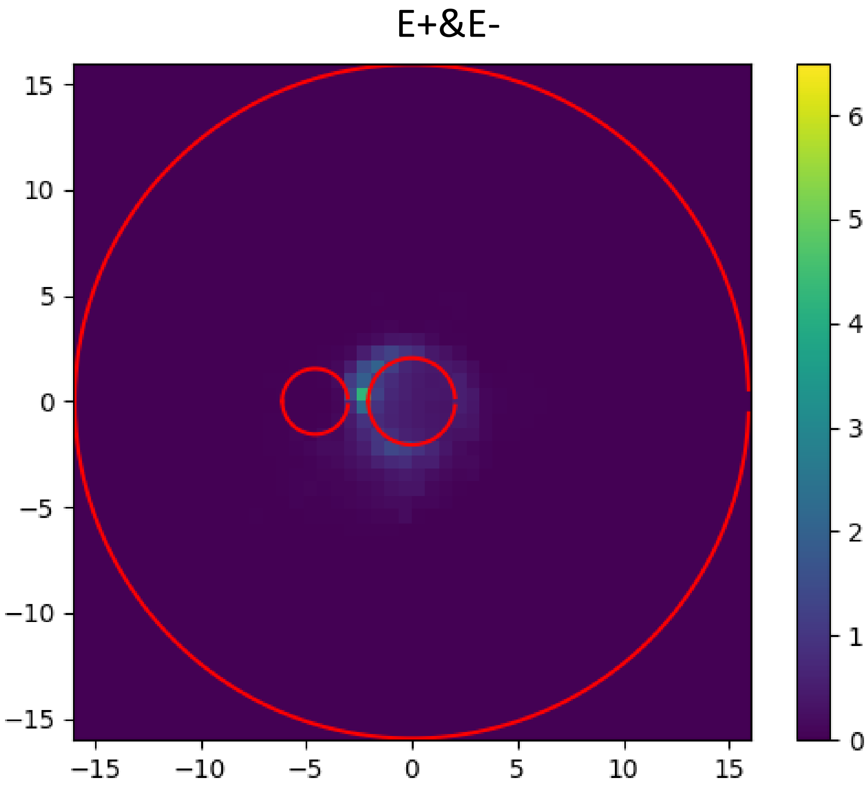


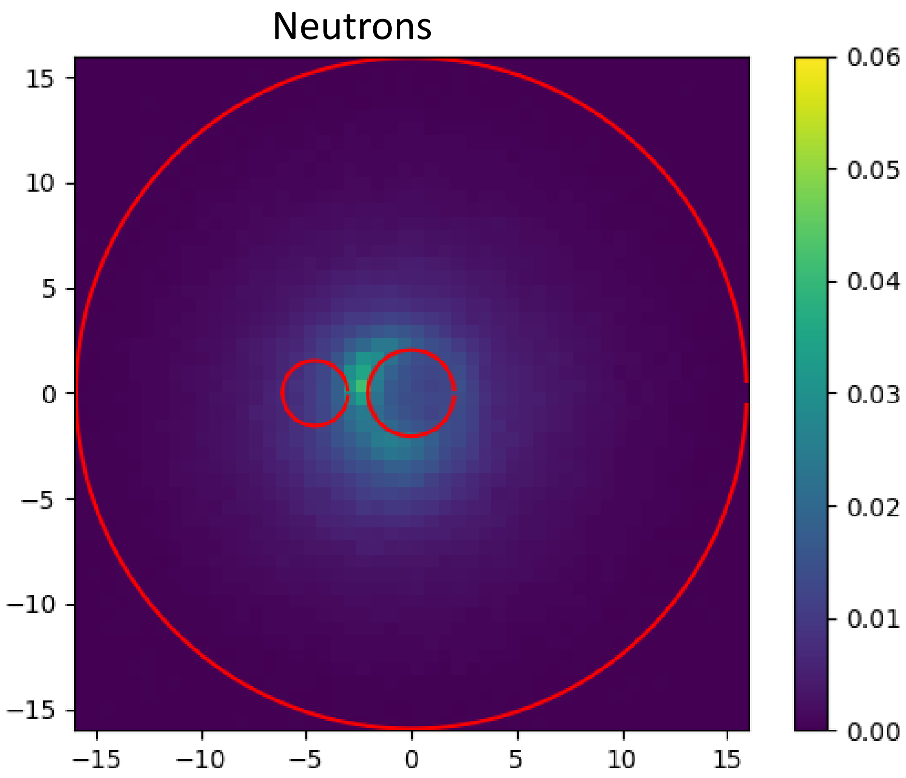


Layer 6 Detector - Fluence

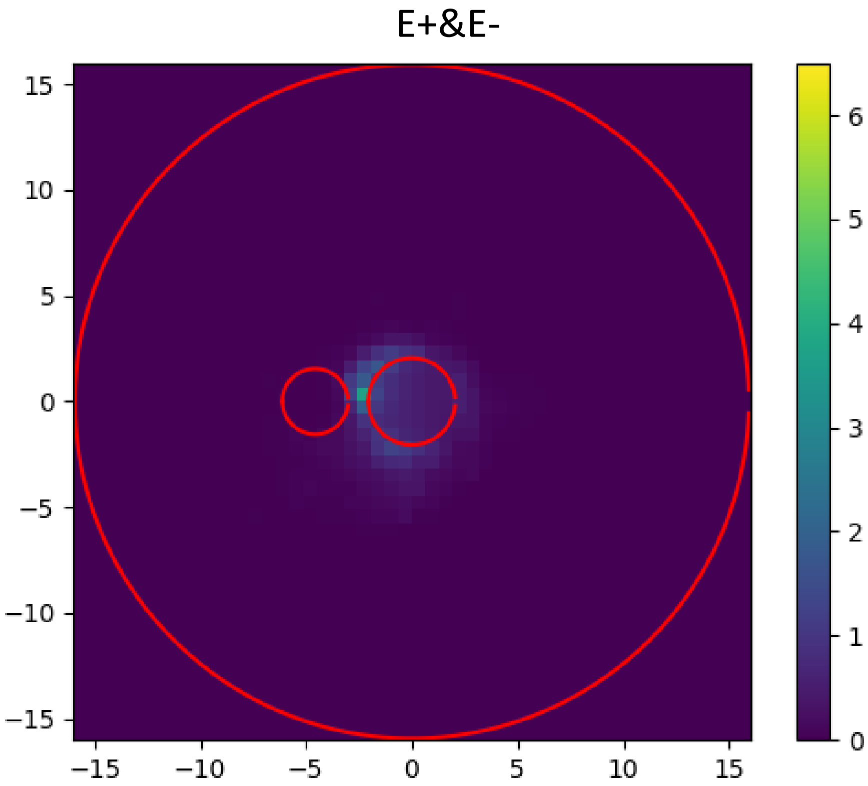


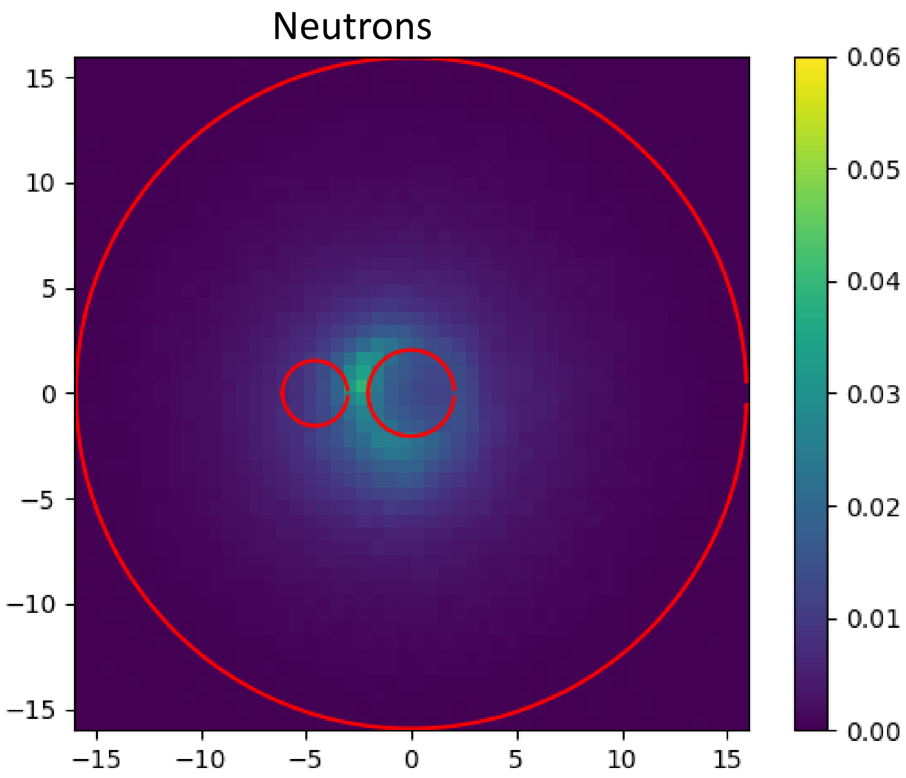
Layer 8 Detector - Fluence



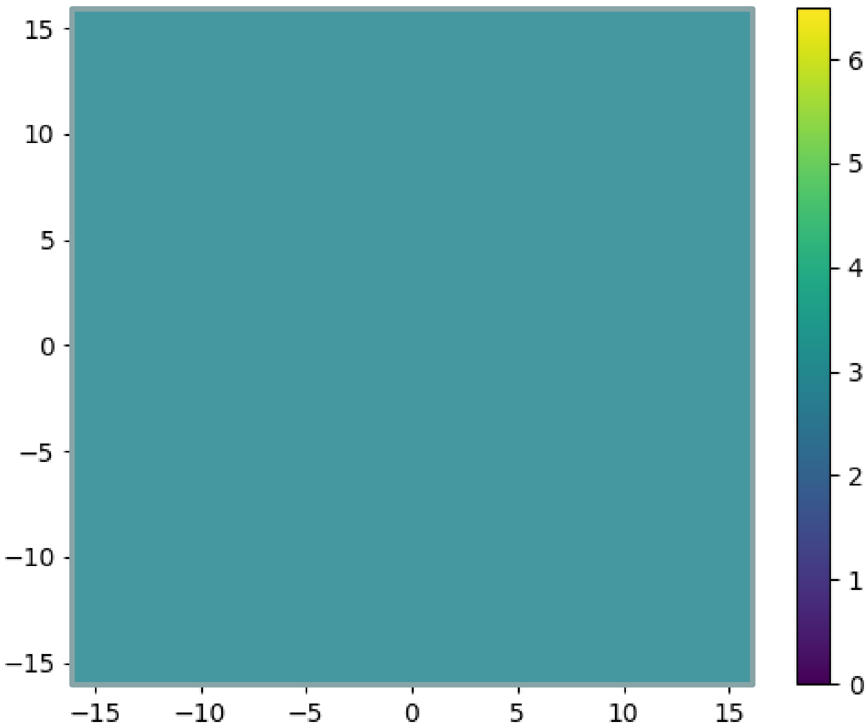


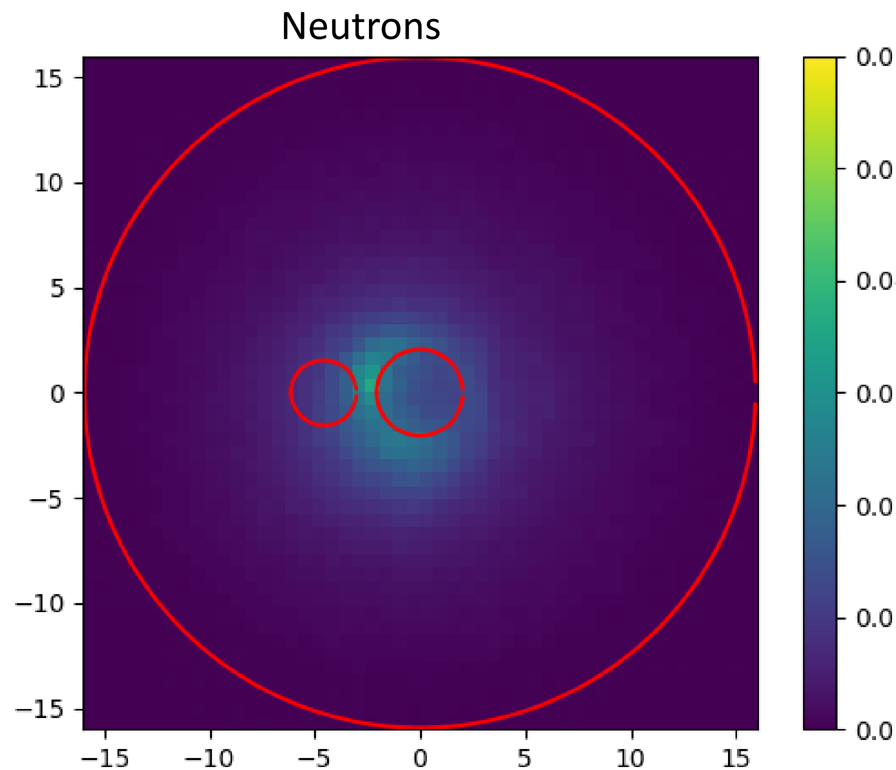
Layer 10 Detector - Fluence



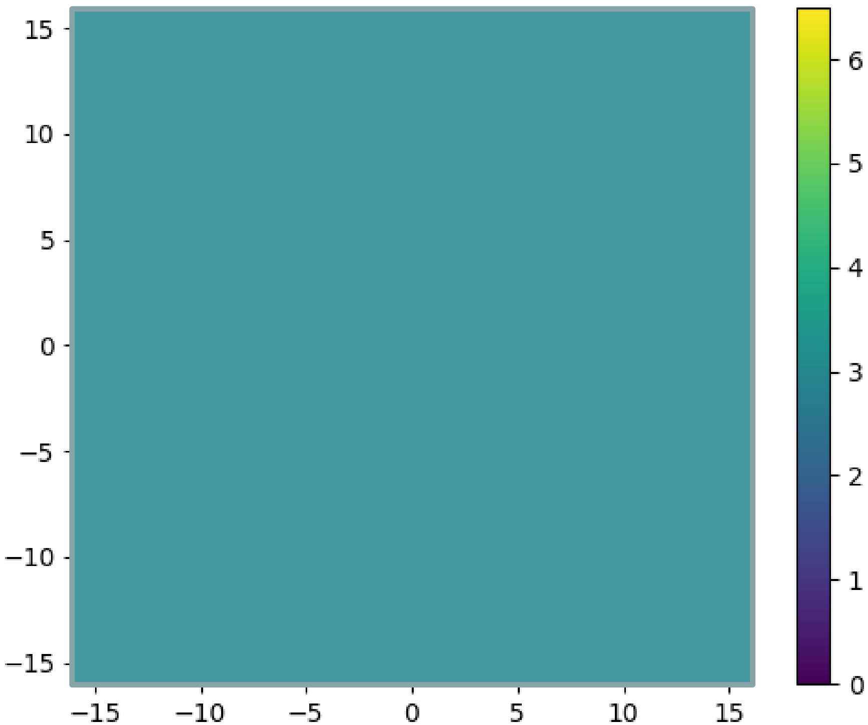


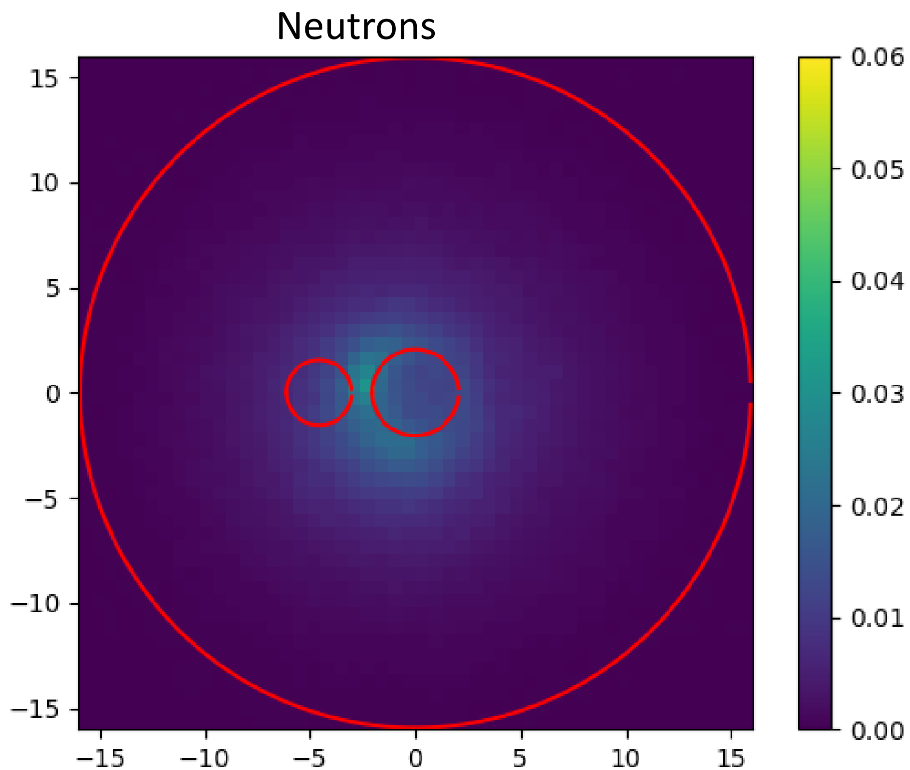
Layer 12 Detector - Fluence



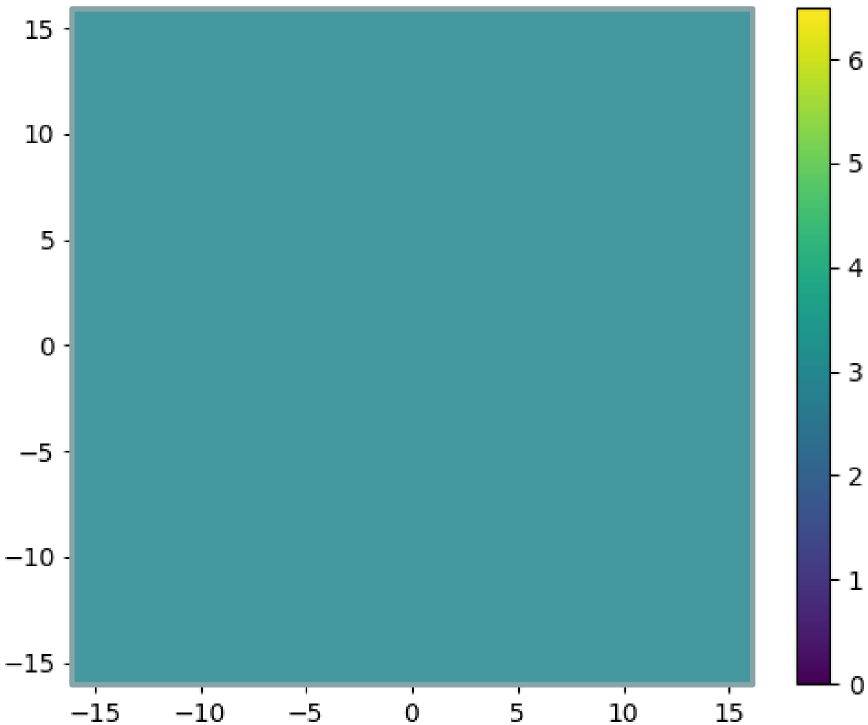


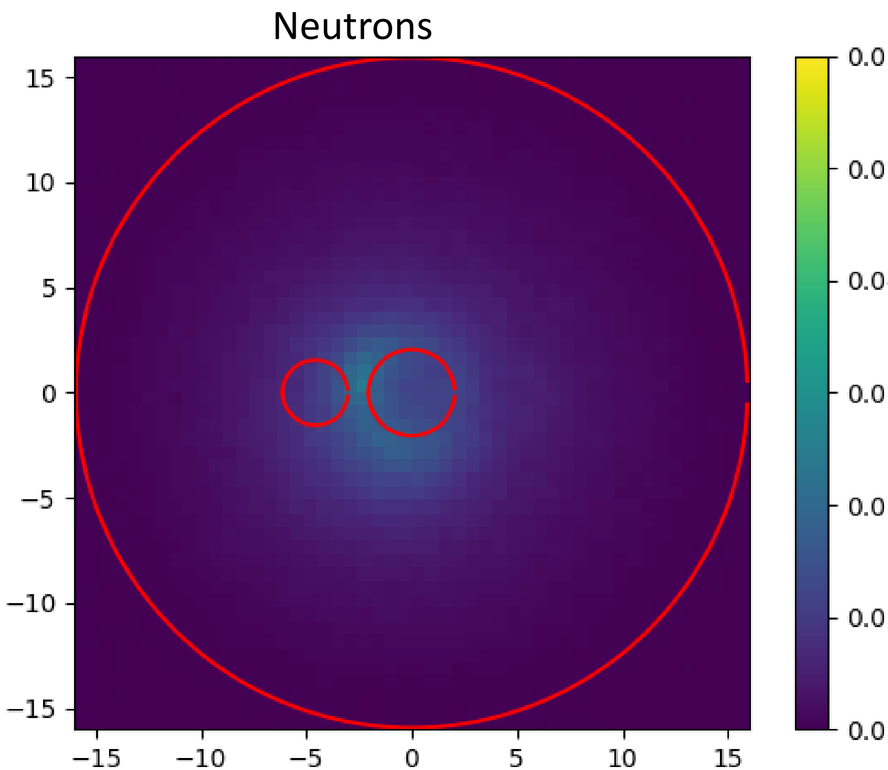
Layer 14 Detector - Fluence





Layer 16 Detector - Fluence





Idea: Use FLUKA to extrapolate from UCSC radiation-damage studies (T506)

Standard working assumption: bulk damage dominated by non-ionizing energy loss (NIEL)

➔ For silicon diode sensors, supported by T506 results (see below)

➔ Dominated by neutron component of EM shower (conservative assumption since neutrons are more widely distributed)

Define “fluence”

$$\Phi = \frac{l}{A dz},$$

Where *l* = total path length through sensor of area *A* and thickness *dz*.

FLUKA provides double-differential fluence distribution, from which we calculate the NIEL density Δλ, per bin in neutron energy and angle

$$\Delta\lambda = \frac{\Delta E_{\mathrm{NIEL}}}{A dz} = \rho N_n(E) \frac{d^2\Phi}{dE d\Omega}(E,\theta)\Delta E \Delta\Omega$$

in MeV/cm^3. ρ is the density of silicon, and N_n(E) is the silicon NIEL function, in MeV/(g/cm^2) of material traversed per through-going neutron (next page).

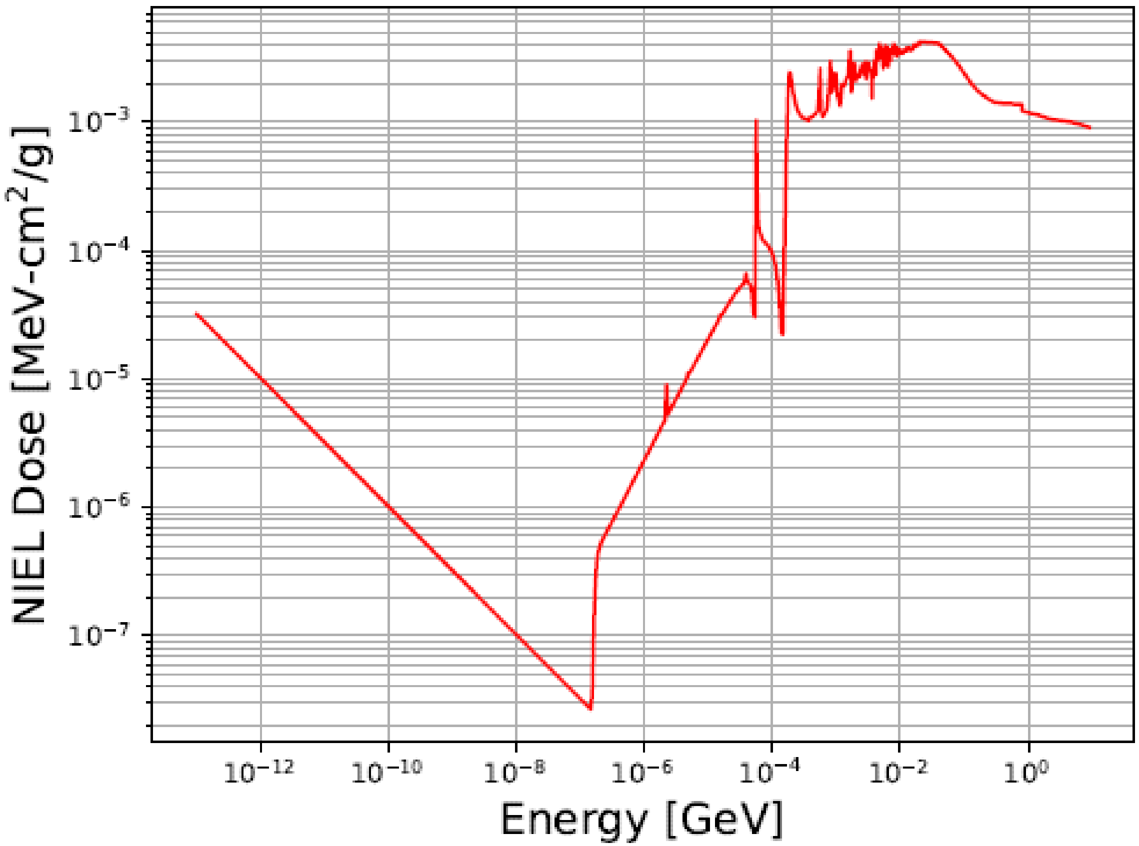
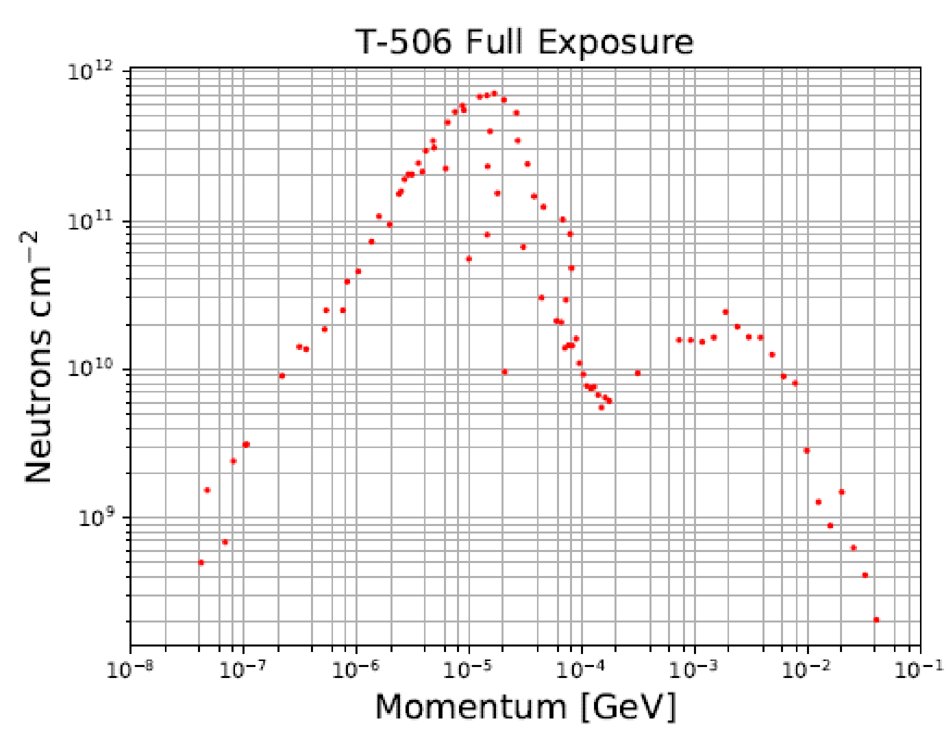
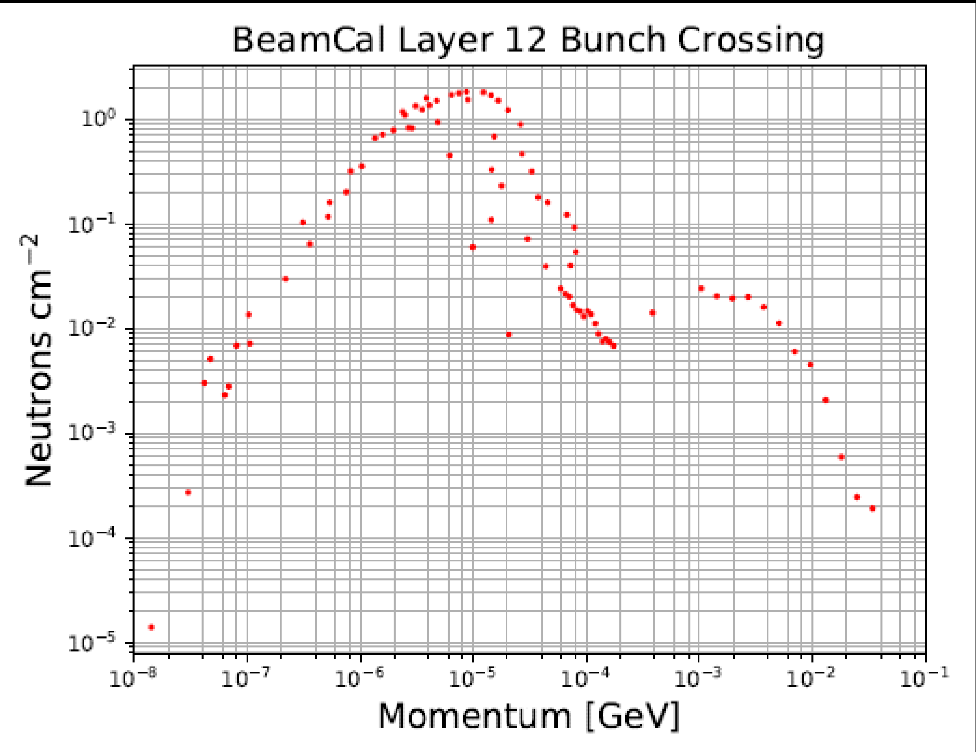


Figure 4: Energy dependence of neutron-induced NIEL in silicon, in MeV per g/cm^2 of silicon traversed per through-going neutron. This plot displays the data tabulated in [9].

[9] A. Vasilescu and G. Lindstroem, *Displacement damage in silicon, on-line compilation*, 2006, http://rd50.web.cern.ch/RD50/NIEL/default.html.

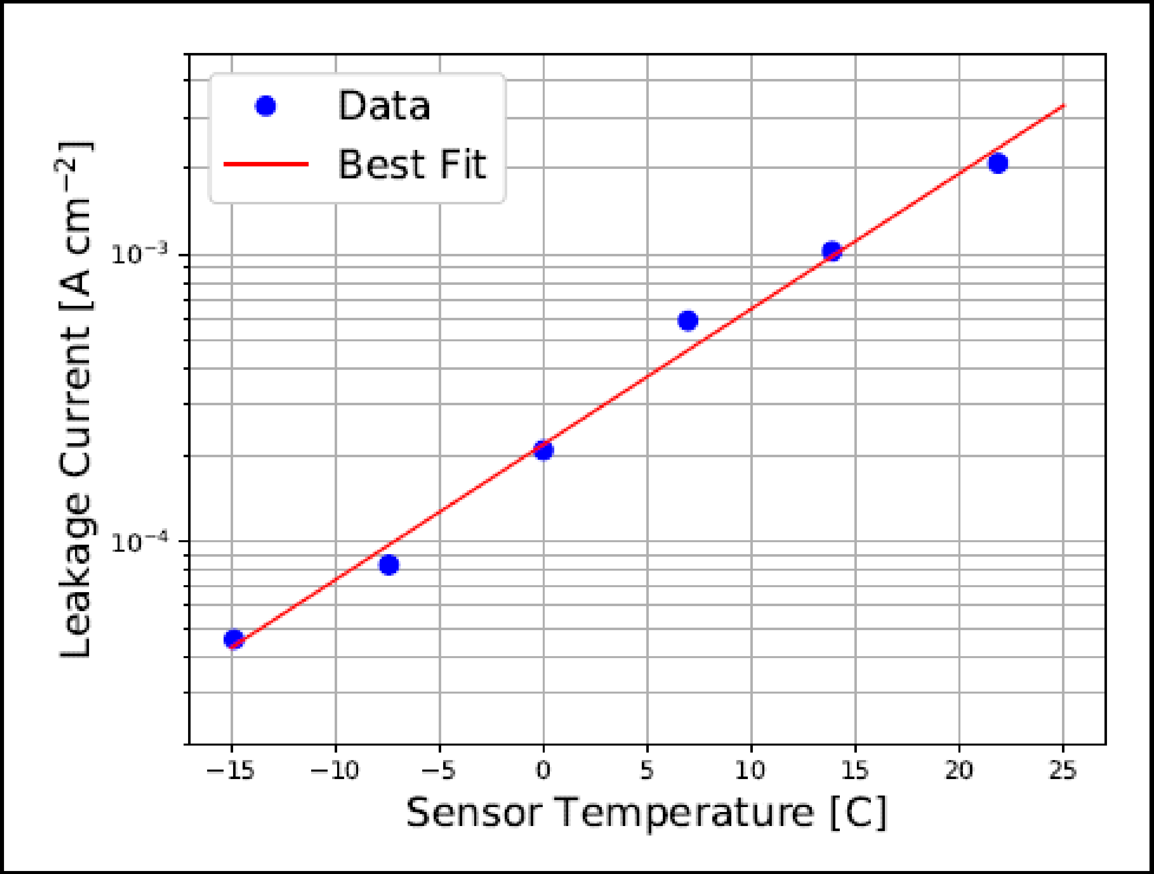




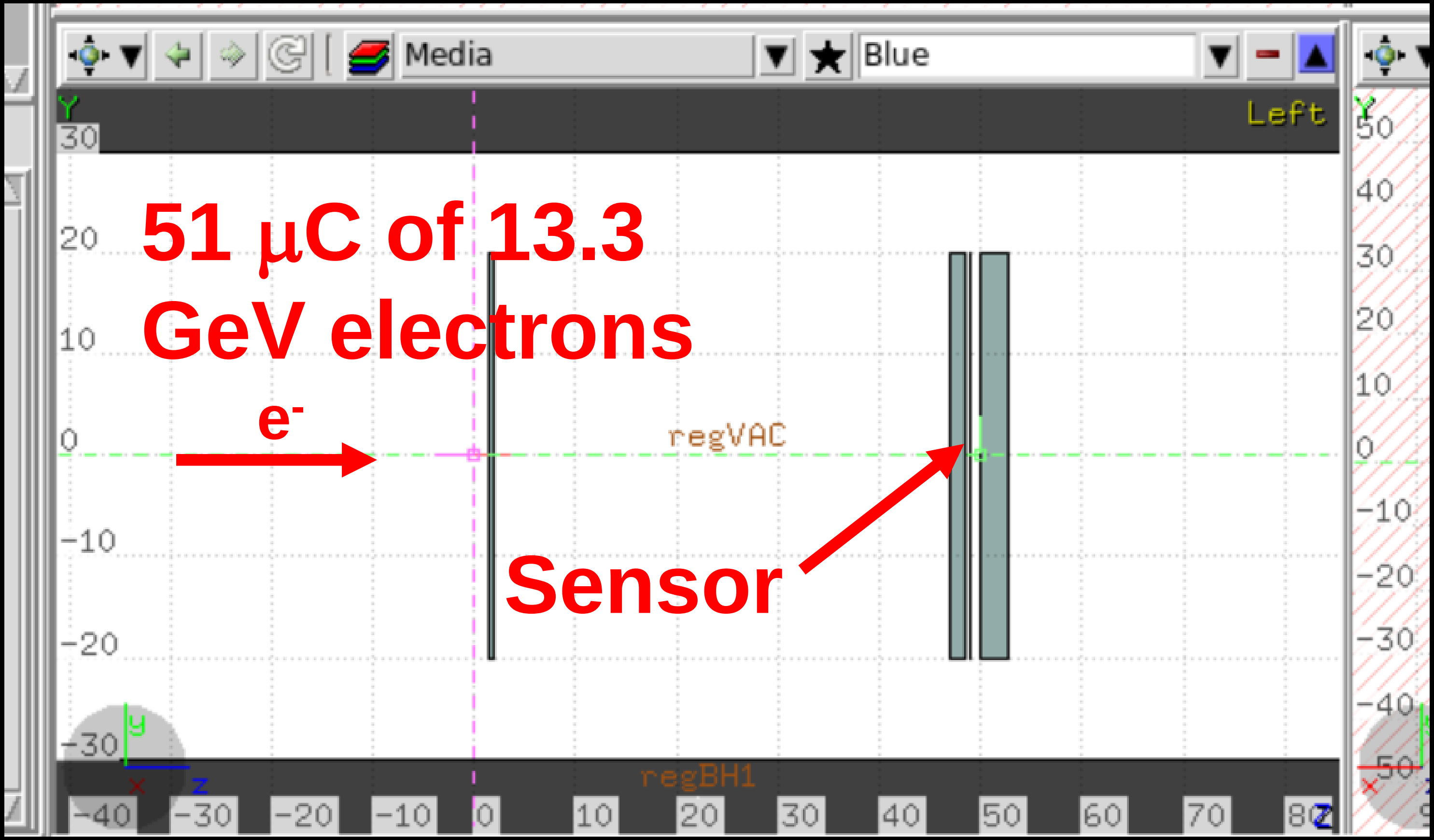
N.B.: Energy distribution of neutrons for T506 and for BeamCal very similar, so damage estimates not particularly dependent upon details of NIEL scaling specific to silicon

T506 experiment

- 270 Mrad exposure of p-bulk Si diode
- 80% charge-collection at V_B = 600 V
- Current draw vs. temperature as shown below



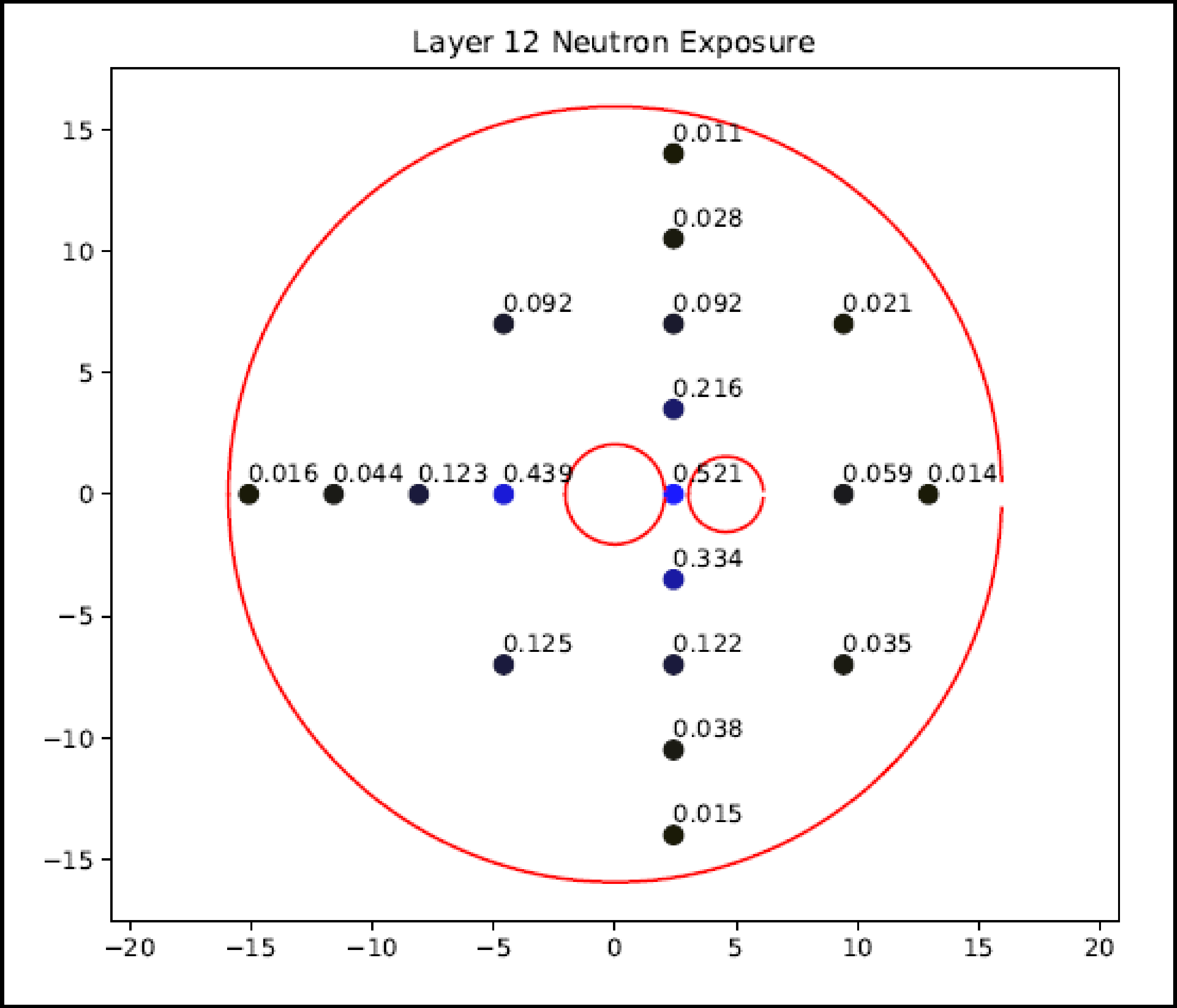
T506 simulation



Total neutron NIEL dose of

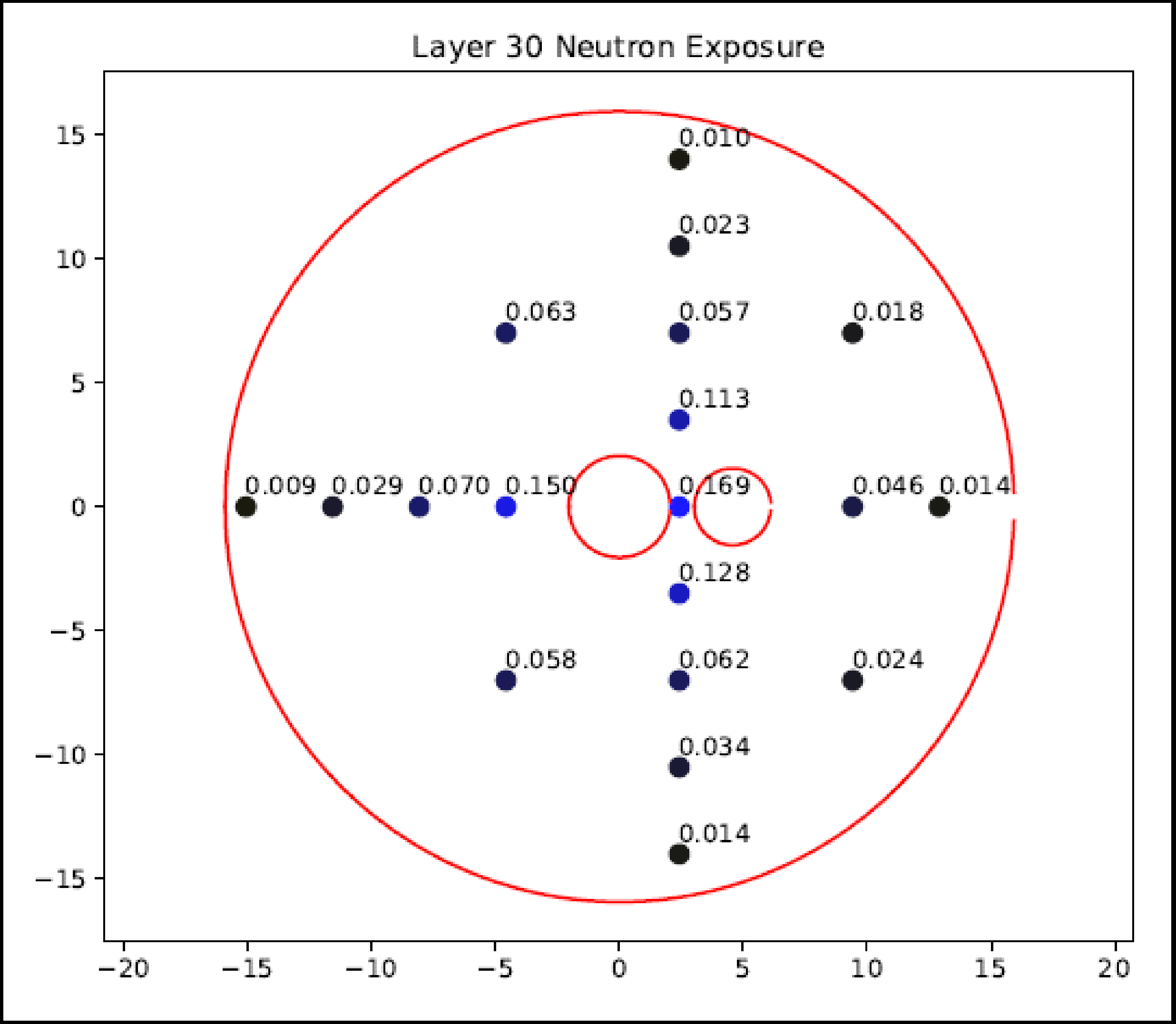
$$\lambda_{T506} = 2.7 \times 10^{11}\ \mathrm{MeV/cm^3}$$

Simulated BeamCal NIEL Dose – Layer 12



- Per year (10^7 seconds) of ILC operation
- In T506 dose unit λ_{T506}

Simulated BeamCal NIEL Dose – Layer 30



- Per year (10^7 seconds) of ILC operation
- In T506 dose unit λ_{T506}

Estimated Power Draw per Layer

- Based on average neutron NIEL λ_L in given layer
- One year (10^7 seconds) of ILC operation
- Operation at V_B = 600 V

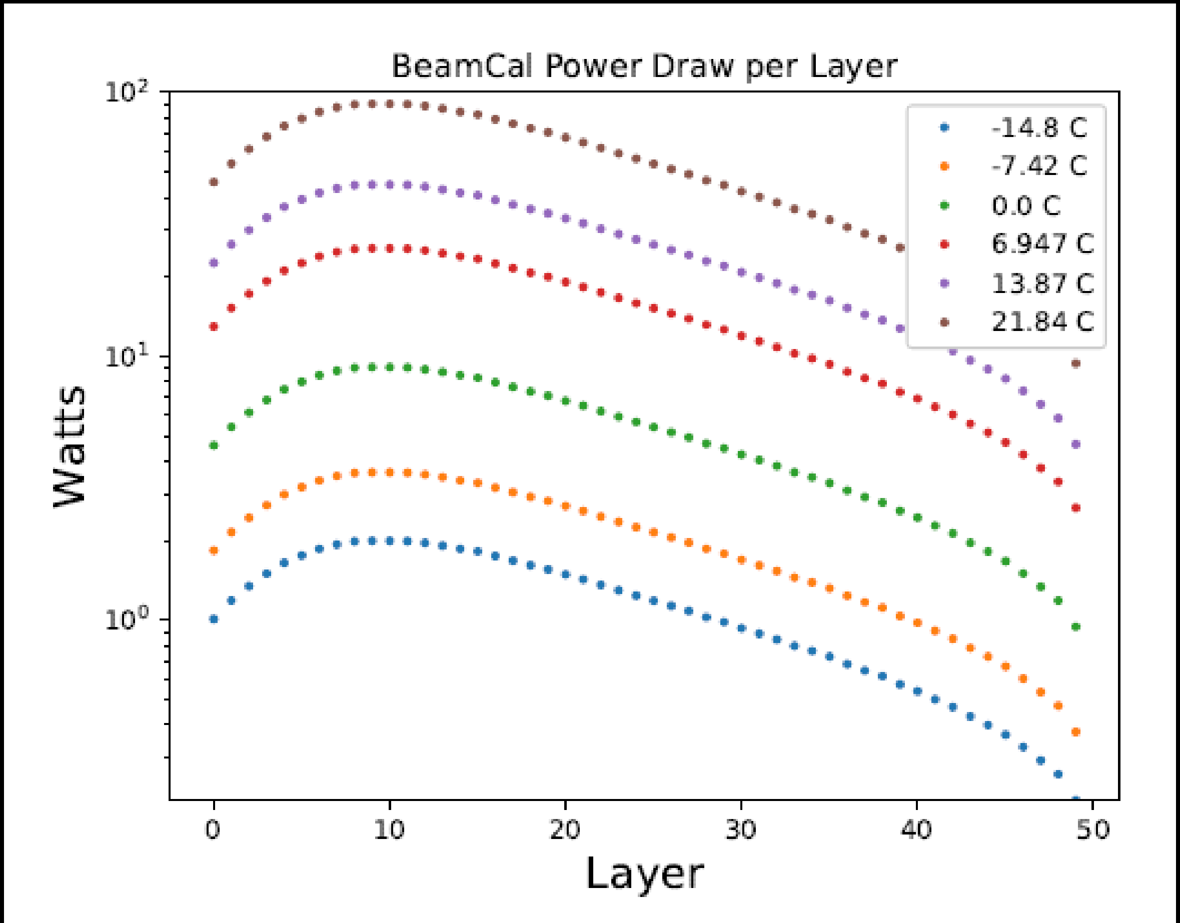
$$P_L(T) = V_B I_L(T) = V_B \frac{\lambda_L}{\lambda_{T506}} A\sigma(T)$$

- Leakage current density σ(T) from T506 results

$$\sigma(T) = ae^{T/T_s}$$

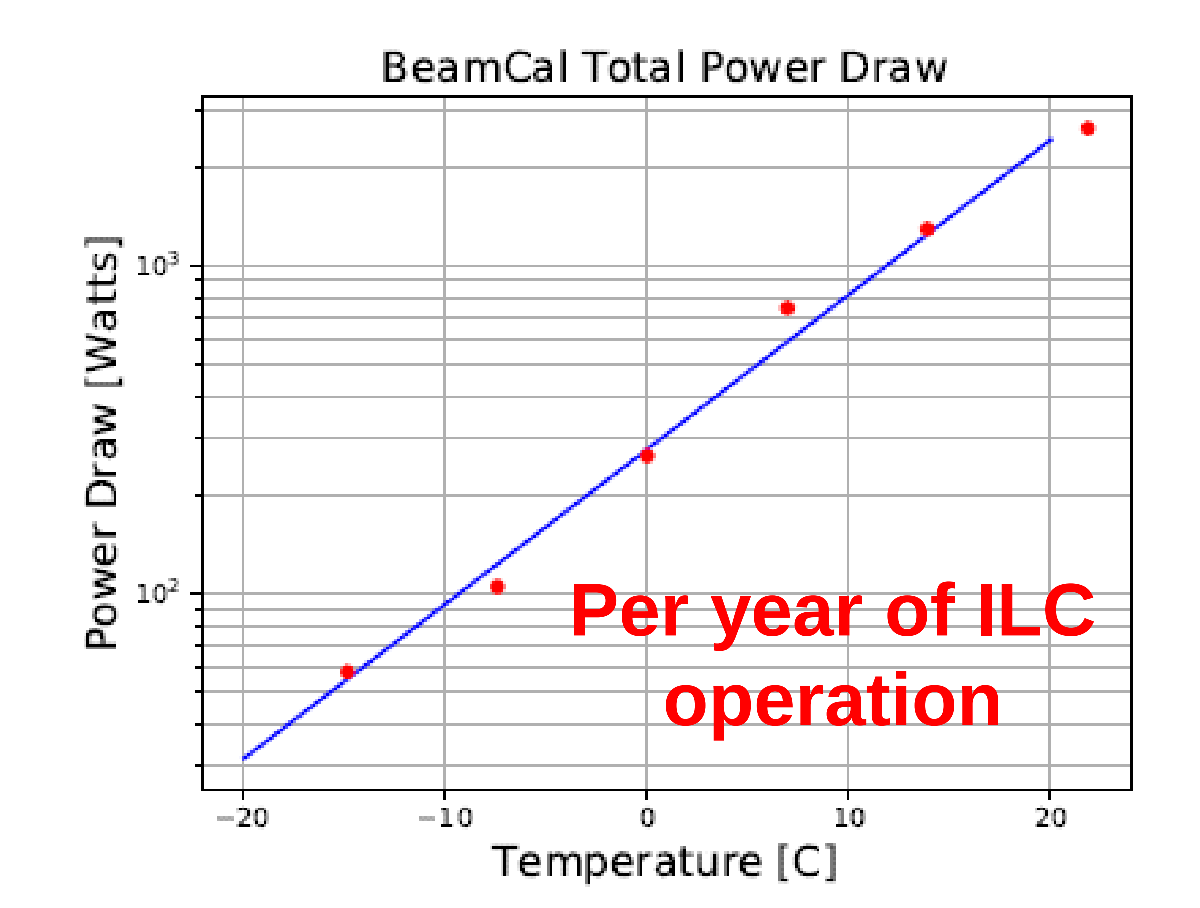
$T_S = 9.2^o$ C   a = 220 μA/cm^2

Layer-by-Layer Power Draw vs Temperature



- Accumulation per year (10^7 s) of ILC operation
- Maximum power-draw density is ~25 mW/cm^2 at V_B = 600 V and T = -10^o C (< 5 mW/cm^2 at -30^{o}C)

Overall Power Draw vs Temperature



- **Can limit accumulation to less than 100W per year by operating below -10º C**
- **At -30º C (standard for LHC sensor operation), accumulation would be of order 15 W per year**

Peripheral Fluence Estimates

- **Front-end electronics will likely be mounted just outside BeamCal instrument**

Table 2: Neutron fluences at various positions 1 cm outside the BeamCal instrument, for 10^7 seconds of ILC operation, in cm^{-2}. The angle is measured relative to the axis defined by the center of the BeamCal and the centerline of the smaller circular cutout.

Angular position	0	$\pi/2$	π	$3\pi/2$
Layer 12 fluence (cm^{-2})	4.9×10^{11}	5.9×10^{11}	7.3×10^{11}	8.0×10^{11}
Layer 30 fluence (cm^{-2})	4.8×10^{11}	4.6×10^{11}	5.7×10^{11}	5.4×10^{11}

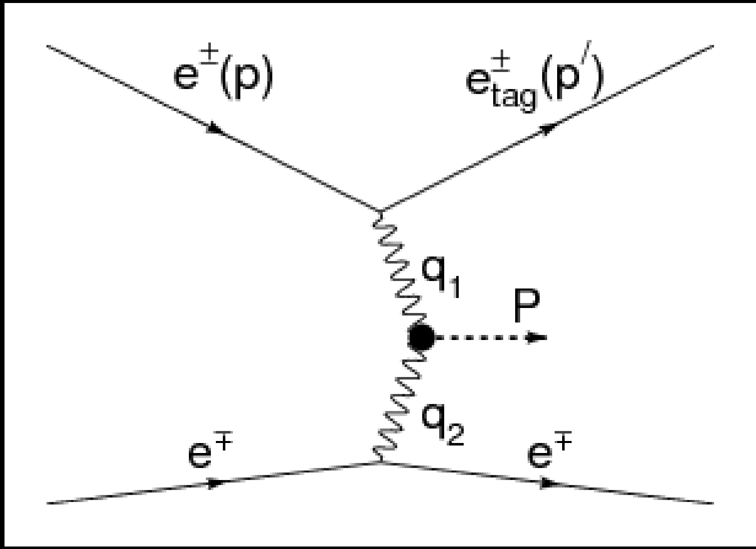
- **Electromagnetic fluence less than $10^{11}/cm^2$ at any position**
- **These levels far below conventional levels of concern**

Next Step with FLUKA Simulation: Backscatter into Central Detector

- In addition to radiation field with the BeamCal, FLUKA also yields the albedo emanating from the face of the BeamCal back towards the central detector
- In hand, we have 4-vector files representing the albedo from ~10 beam crossings (for the electron side only).
- Working to translate them into SLCIO format so that they can be put into the SiD simulation (note that inner layers very similar for SiD and ILD)
- Can study backscatter as a function of BeamCal geometry, and perhaps also presence of AntiDiD

Two-Photon Event Facts

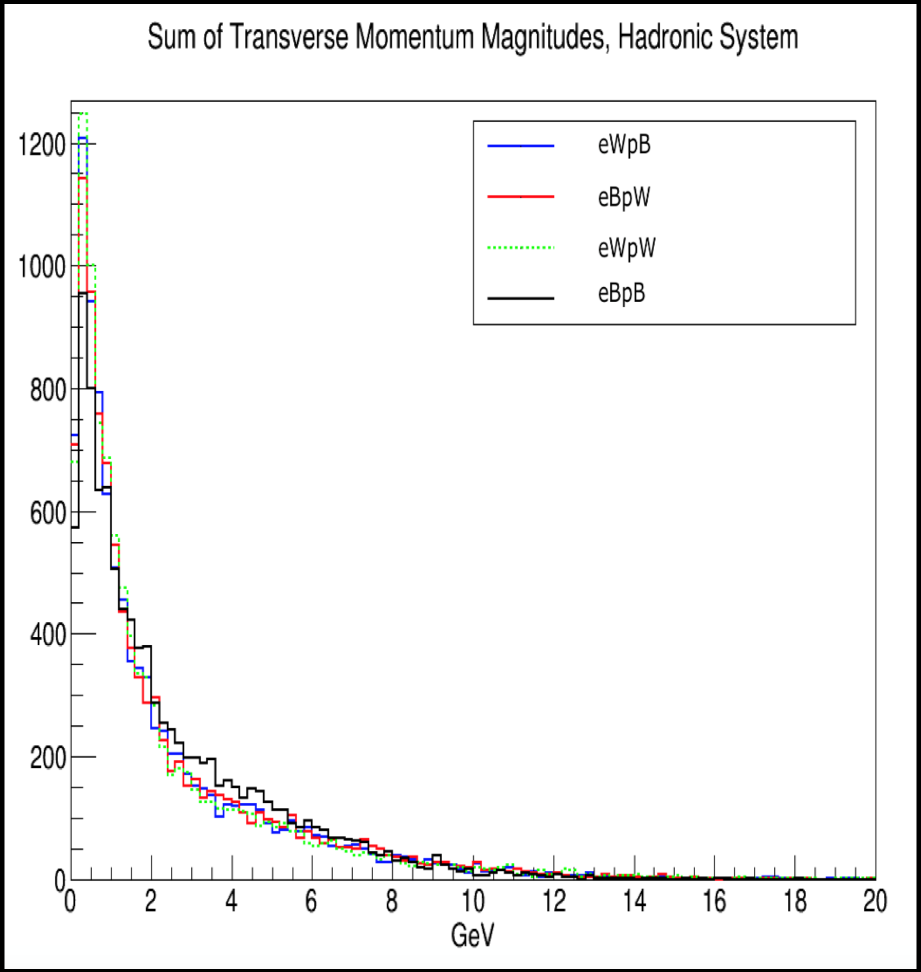
Tim Barklow has simulated $\gamma\gamma \to$ hadrons down to the $\pi\pi$ threshold

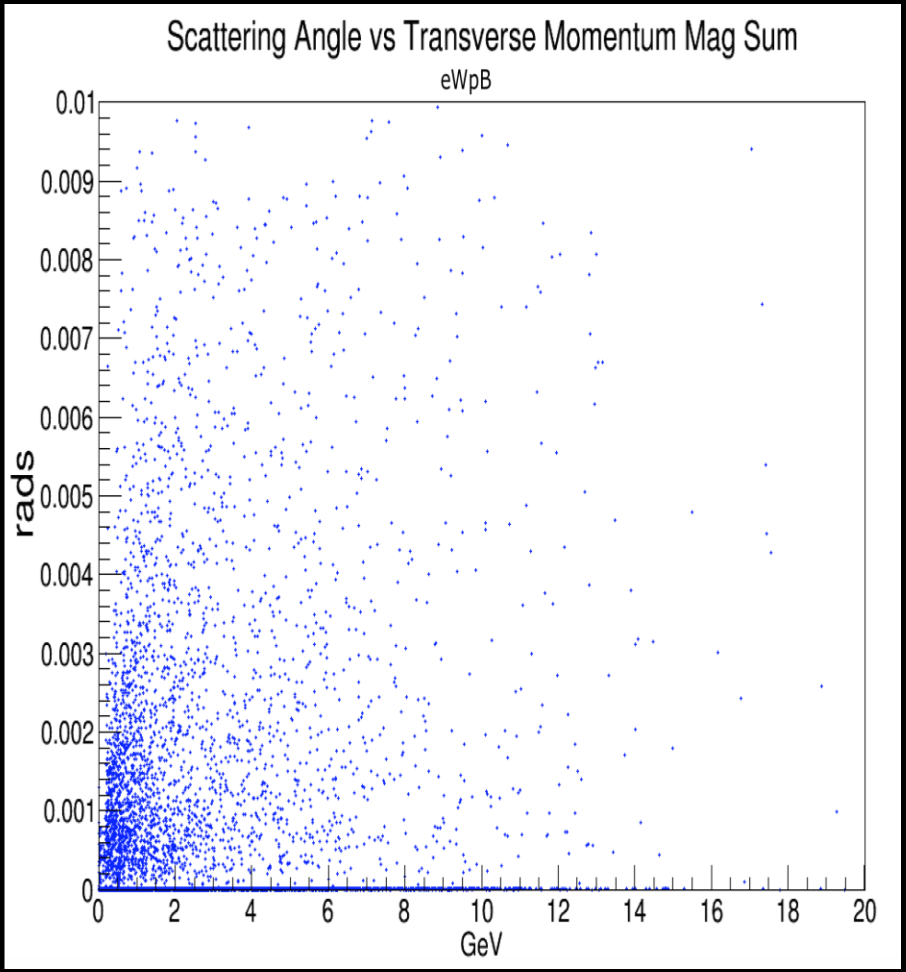


Photon flux from

- Beamstrahlung (B) ➔ no p_T kick for $e^{\pm}$
- Weiszacker-Williams (W) ➔ $e^{\pm}$ sometimes get p_T kick

In this simulation, **for only about 15% of $\gamma\gamma$ events does an $e^{\pm}$ get a p_T kick**



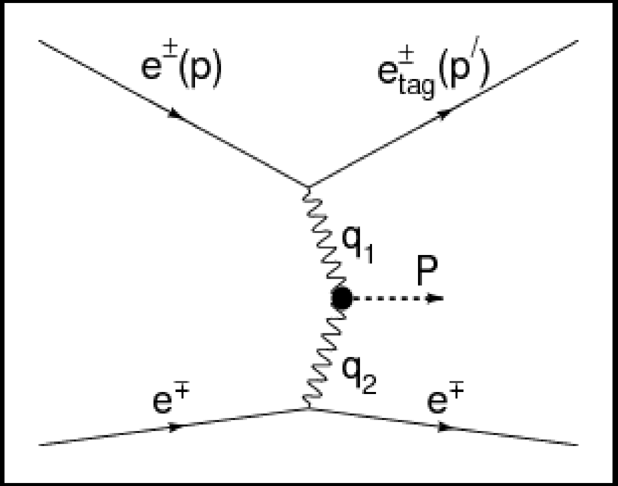


Most γγ events leave very little p_T in the detector, but for those that do, we'll need to know they were γγ events by finding the scattered $e^{\pm}$ if there is one.

The "Prediction Algorithm"

Jane Shtalenkova, William Wyatt

Based on the properties of the hadronic ($\gamma\gamma$) system, can predict trajectory of deflected $e^{\pm}$ up to two-fold ambiguity (don't know if e^+ or e^- scattered)



Set transverse momentum e_T (p_T) of scattered e^- (e^+) to inverse of $\gamma\gamma$ system transverse momentum

Longitudinal momentum e_z (p_z) given by

Either electron…

$$e_z = -\frac{e_T^2 - \alpha^2}{2\alpha} \qquad p_z = \frac{p_T^2 - \beta^2}{2\beta}$$

Or positron.

$$\alpha = 500 - H - h_z \qquad \beta = 500 - H + h_z$$

H = $\gamma\gamma$ system energy; h_z = $\gamma\gamma$ system longitudinal momentum

Prediction Algorithm cont'd

Thus, each event gives us a prediction of where the e^- (e^+) would have gone if the e^- (e^+) got the entire p_T kick.

If this assumption is true, and the hadronic system is perfectly reconstructed, one of these is exactly correct and the other is wrong (the "wrong" particle in fact goes straight down the exhaust beam pipe).

Assumed veto strategy:

Case 1): If an e^+ or e^- is seen in either BeamCal (and is/are inconsistent with Bhabha event), veto event.

Case 2): If neither e^+ nor e^- inconsistent with Bhabha event are seen, veto if neither is "predicted" to hit the BeamCal.

Peril: If e^+ and/or e^- is "predicted" to hit the BeamCal, but none does ("hit/miss event"), may be mistaken for SUSY.

Why would prediction algorithm fail in this way?

- Both e^+ and e^- get p_T kick ("WW" events)
- One of incoming e^+ or e^- is significantly below E_{beam}
- Incomplete/inaccurate reconstruction of $\gamma\gamma$ system

Avoid first of these for now by looking at "WB" events: only electron deflects (require $\Sigma\ |p_T| > 1$ GeV for hadronic system)

```
#e-e+
#PTPT                [Quantity]
-0000: 94.9535%      [5513]
-0001: 0.0000%       [0]
!0010: 0.2584%       [15]
-0011: 0.0000%       [0]
-0100: 0.2928%       [17]
-0101: 0.0000%       [0]
-0110: 0.0344%       [2]
-0111: 0.0000%       [0]
!1000: 0.0172%       [1]
-1001: 0.0000%       [0]
!1010: 0.0172%       [1]
-1011: 0.0000%       [0]
-1100: 0.8784%       [51]
-1101: 0.0000%       [0]
-1110: 3.5481%       [206]
-1111: 0.0000%       [0]
total: 5806
bad events(!): 0.2928%
```

"1O" configuration in either electron (positions 1&2) or positron (positions 3&4) BeamCal leads to false positive for SUSY signal.

Many false predictions on positron side, but most of these are associated with a true electron deflection that would be observed!

➔ 0.3% of events are problematic (cases marked by "!" in table)

Prediction Algorithm: Next Step

- **Explore performance as a function of coverage of the hadronic system (here, we assume that we reconstruct everything perfectly)**

- **Perhaps resolution as well?**

- **Realistic beam crossings: background events are not pure BW, WB, BB, WW, but an admixture, that also includes Bhabha events**

- **Event overlays to produce realistic beam crossings already in hand (at four-vector level only)**

➔ **See next slides**

Realistic ILC Beam Crossing Samples

- An ILC beam crossing is not a single $\gamma\gamma$ of Bhabha event:

Event Type	BB	BW	WB	WW
Crossing (fb)	134427168.3	93474234.88	94353013.33	81276125.5867
Events/Crossing	0.368855	0.256484181	0.2588954634	0.2230137589

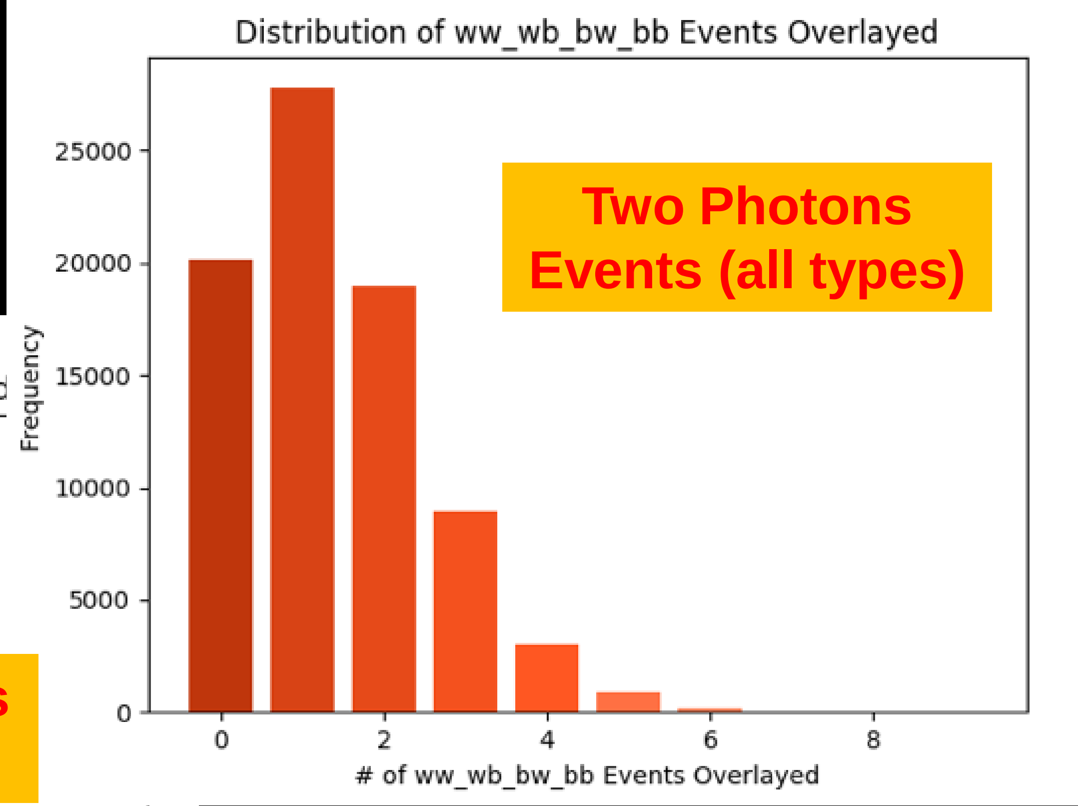
Secondary Radiation	e^+e^-	$e^+e^-\gamma$	$e^+e^-\gamma\gamma$
Crossing (fb)	278555100.0	853356.41.88	15389.98.33
Events/Crossing	0.764327339	0.002341525	0.000042229

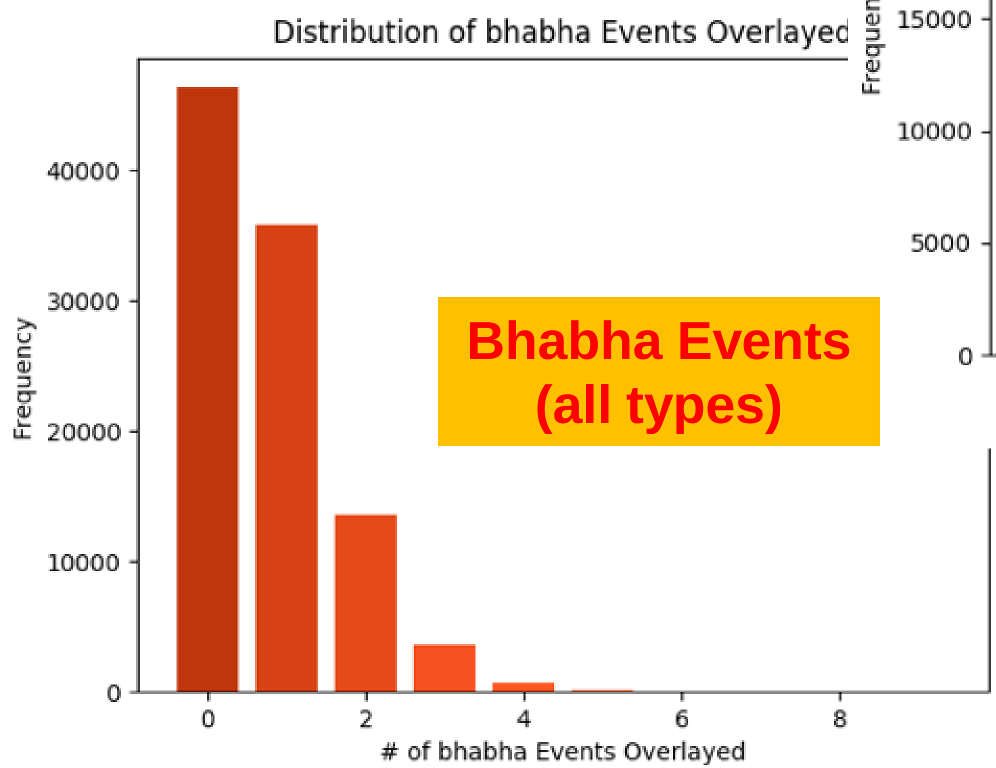
Events rates from cross sections for

- $\gamma\gamma$ down to di-pion mass threshold
- Bhabhas down to virtuality of $\sqrt{Q^2} > 1$

Nominal Event Number Distributions

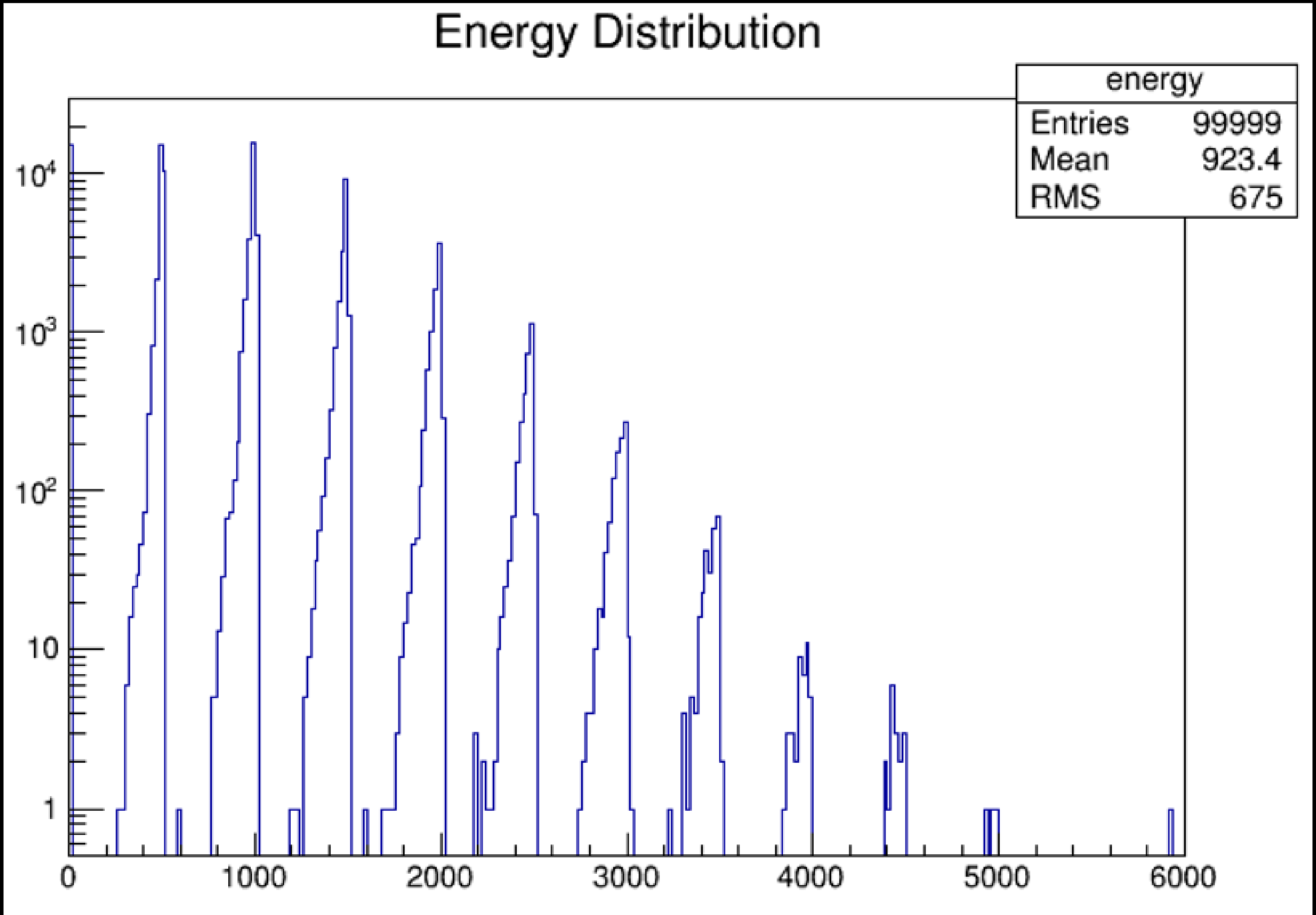
These are input to event generation





Realistic Beam Crossing Simulation

Total energy (visible & invisible) for 100,000 nominal ILC beam crossings



Summary and Outlook

- FLUKA simulation in place
  - Used for radiation-field calculations and power-draw estimates for a Si-diode based BeamCal
  - Planning to use for exploring potential problems with BeamCal albedo
- "Prediction algorithm" developed
  - False positive rate of 0.3% could be problematic; need to do "offline" study with SUSY signal
  - Preparing to explore effects of limiting hadronic coverage
- Other studies underway, (no recent progress)
  - Offline SUSY analysis; razor variables under exploration
  - BeamCal reconstruction fast simulation algorithm

BackUp…

Simulation Hurdle: Two-Photon Event Rate

For baseline pulse luminosity, approximately 1.1 $\gamma\gamma$ events per pulse

(10^7 seconds/year) x (10^4 pulse/second) ➔ 10^{11} $\gamma\gamma$/yr

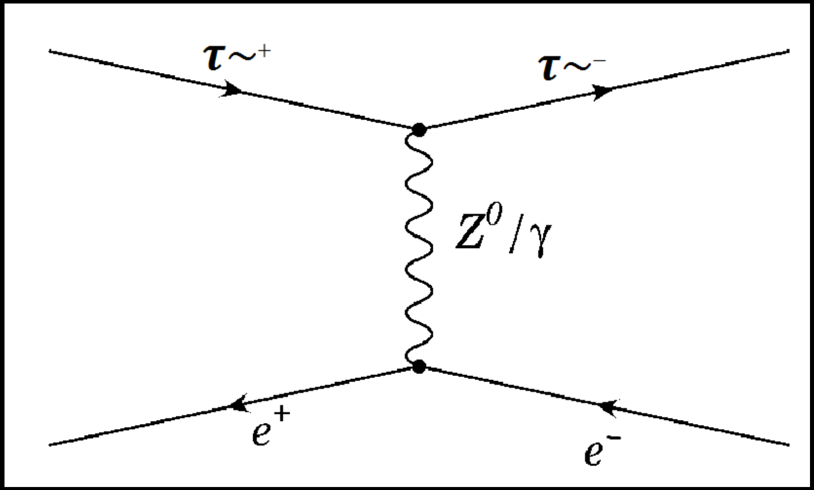
Simulation/storage capacity: 10^9 events is realistic.

➔ Helpful to develop "generator level" cut to reduce $\gamma\gamma$ rate by 10^{-2}.

But must be efficient for whatever signal you seek.
Use degenerate SUSY as study guide.

SUSY Signal Selection

At SCIPP, have simulated $e^+e^- \rightarrow \sim\tau^+\sim\tau^-$; $\sim\tau \rightarrow \tau\chi^0$ over a range of $\sim\tau$ mass and $\sim\tau/\chi^0$ degeneracy



$m_{\sim\tau}$ = 100, 150, 250 GeV

$\Delta_m = m_{\sim\tau} - m_\chi$ = 20.0, 12.7, 8.0, 5.0, 3.2, 2.0 GeV

Exploring discriminating observables and the impact of limited detector coverage

Summer Zuber

Event Observables

Have explored the following observables so far (“S” is just the scalar sum of transverse momenta mentioned above)

$$S_{(\gamma\gamma)} = \sum_{(\gamma\gamma)} \sqrt{p_x^2 + p_y^2}$$

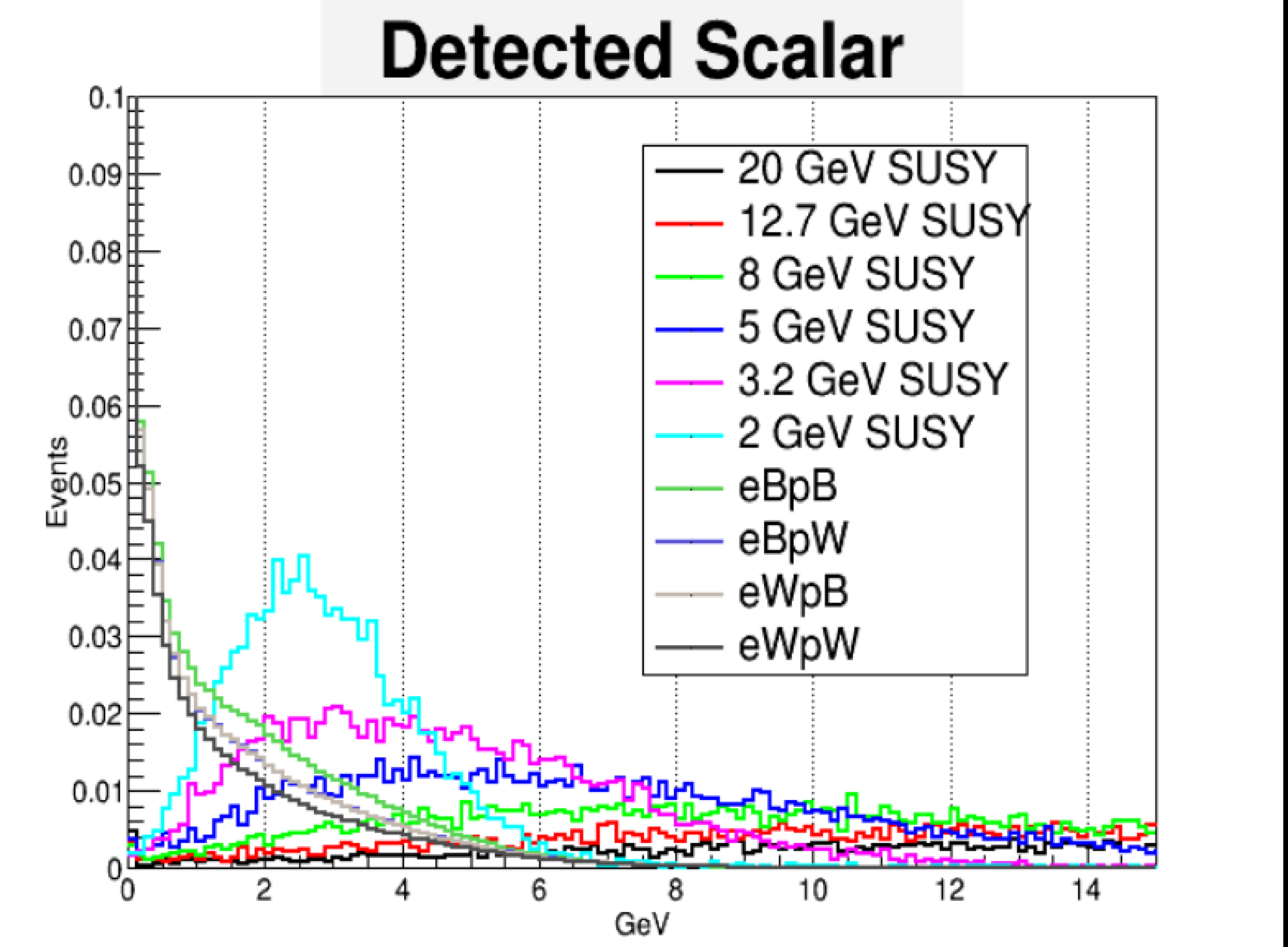
$$V_{(\gamma\gamma)} = \sqrt{(\sum_{(\gamma\gamma)} p_x)^2 + (\sum_{(\gamma\gamma)} p_y)^2}$$

$$M_{(\gamma\gamma)} = \sqrt{(\sum_{(\gamma\gamma)} E)^2 - \| \sum_{(\gamma\gamma)} \vec{p} \, \|^2}$$

The Effects of Detectability

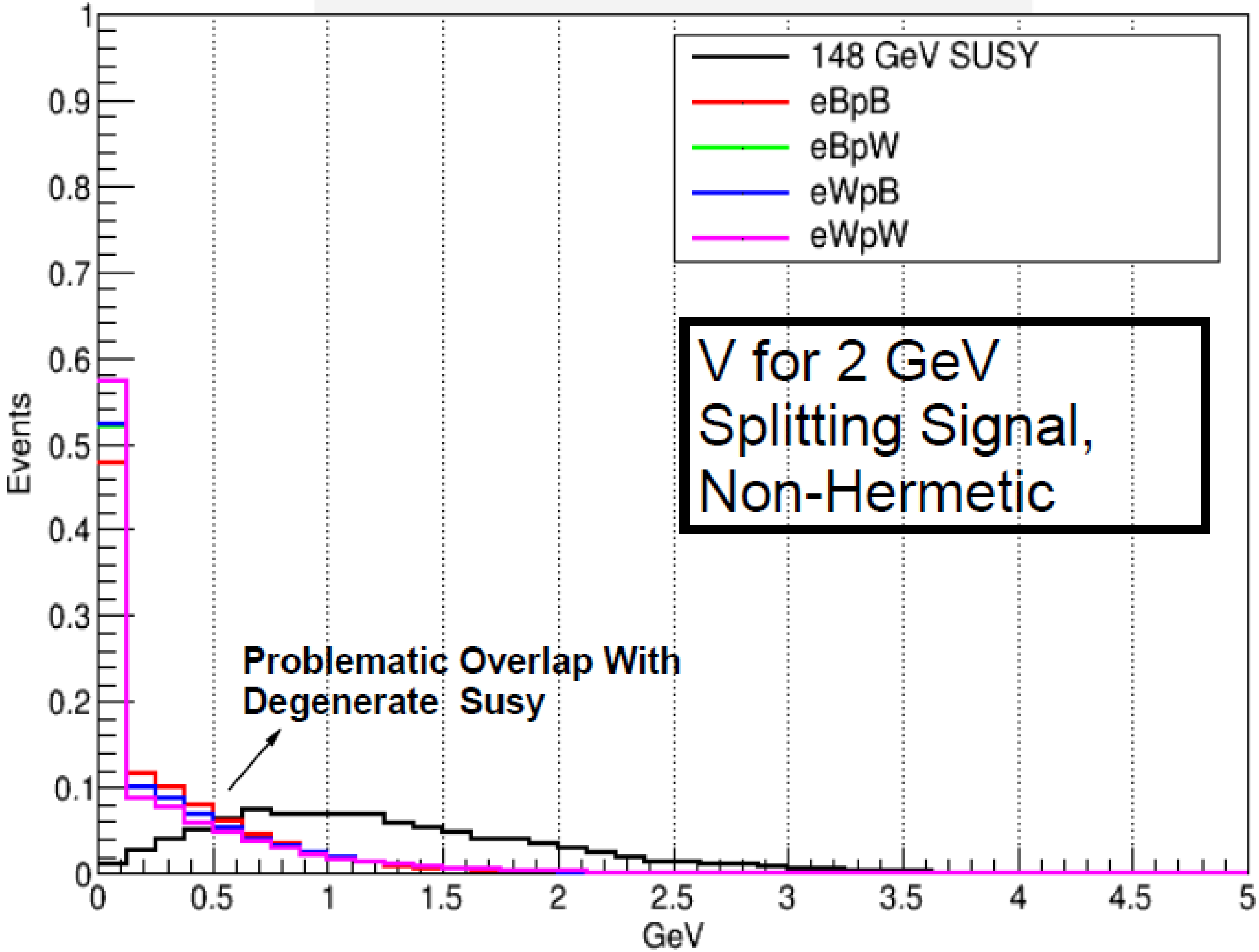
The Discriminating Power of Event Observables Can Depend on Coverage of the Detector

- Truth Level: All “final state” particles
- Detectable Level: excludes neutrinos/neutralinos (i.e. completely hermetic detector)
- Detected Level: excludes neutrinos/neutralinos and forward particles with $|\cos(\theta)|>\alpha$; we have initially chosen a conservative value of $\alpha = 0.9$

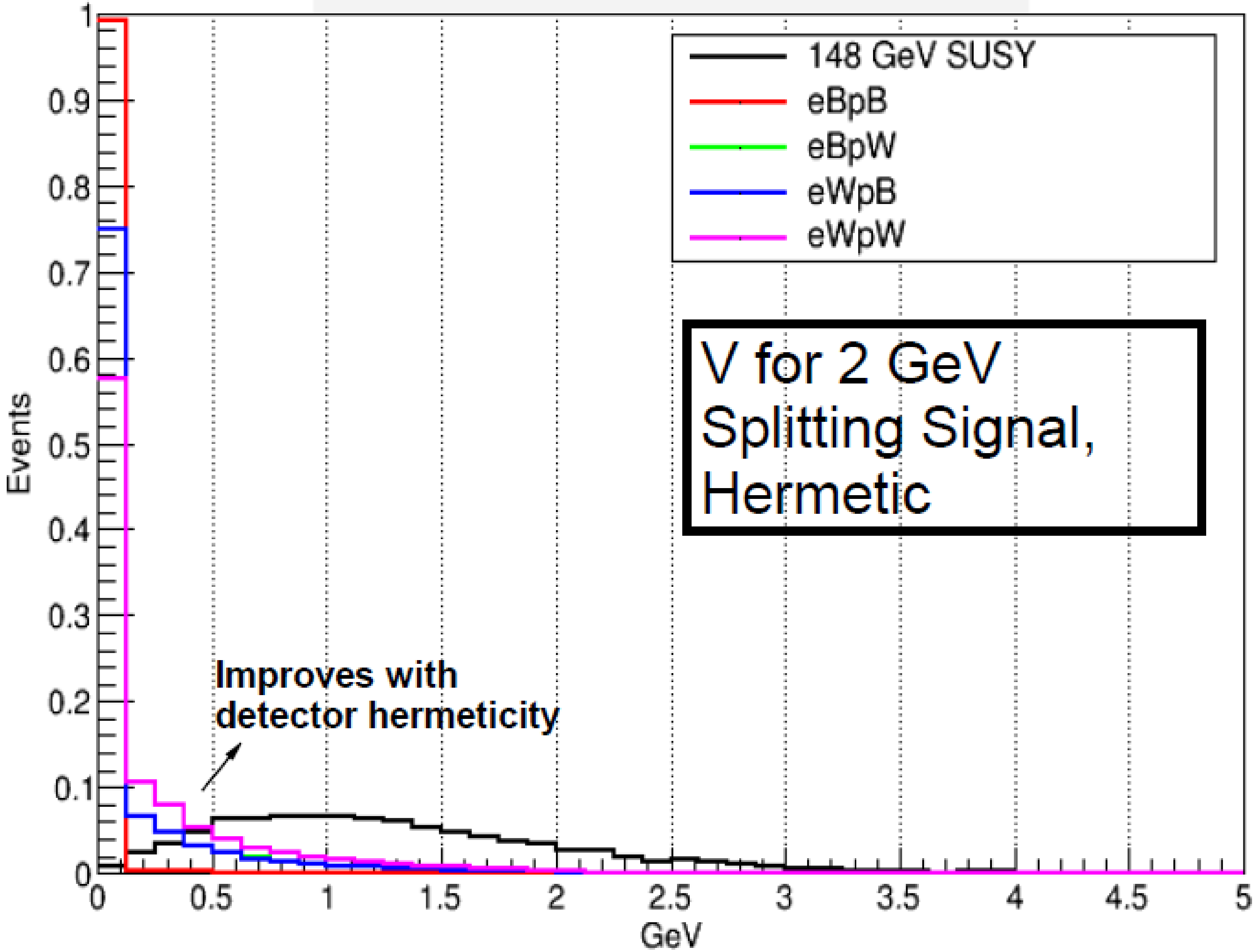


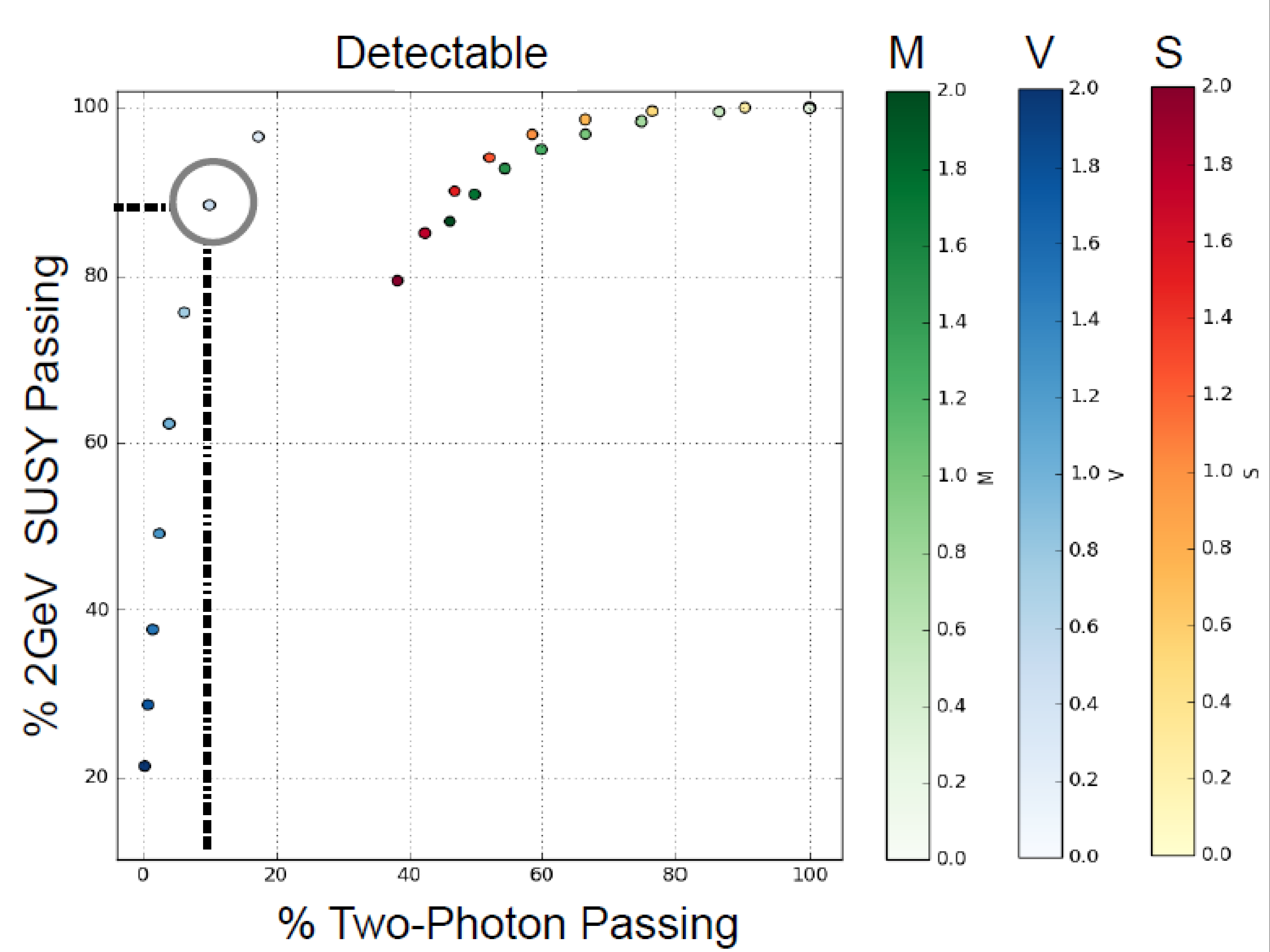
Detected Scalar
Events
GeV
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
2
4
6
8
10
12
14
20 GeV SUSY
12.7 GeV SUSY
8 GeV SUSY
5 GeV SUSY
3.2 GeV SUSY
2 GeV SUSY
eBpB
eBpW
eWpB
eWpW

Detected Vector

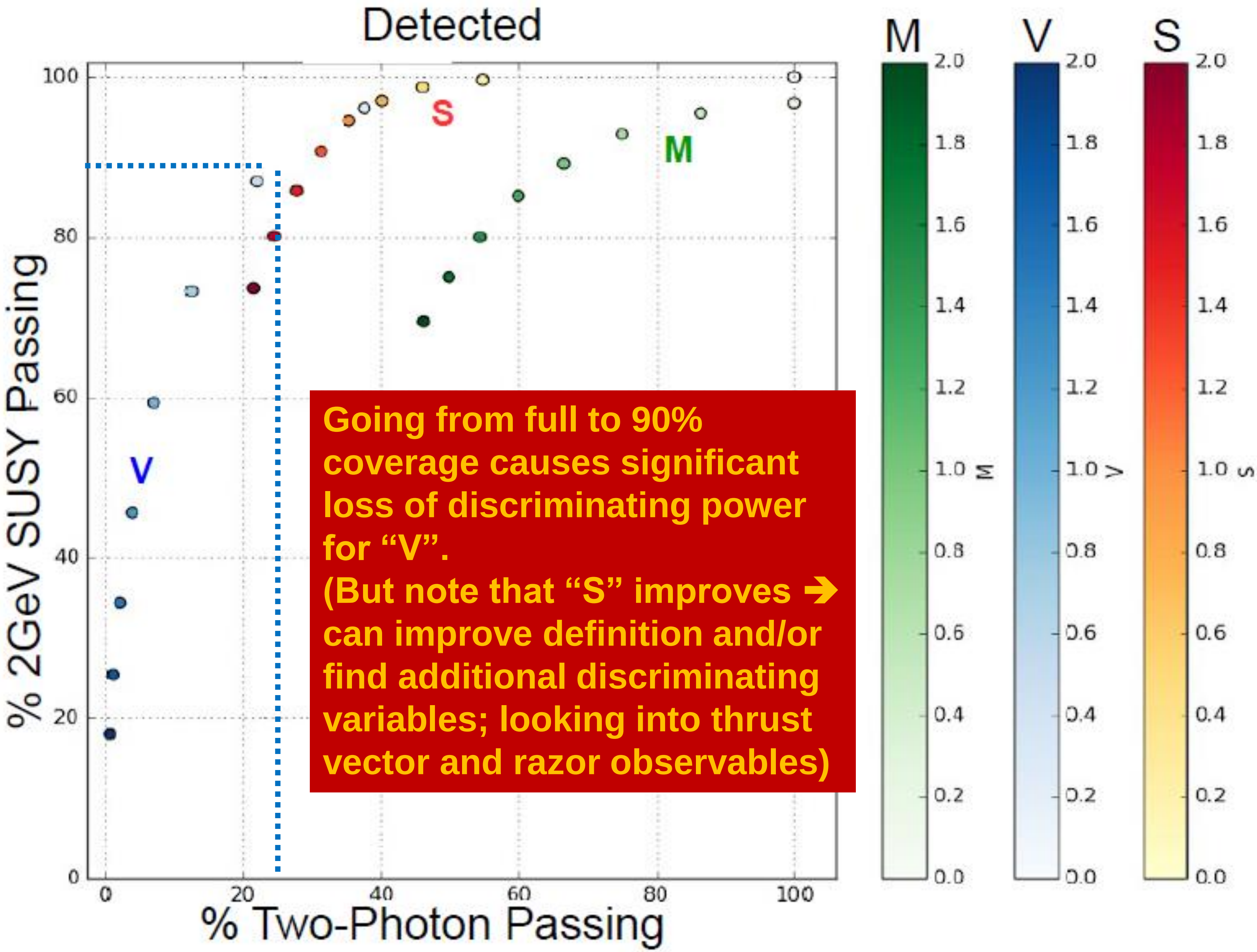


Detectable Vector





Detectable
M
V
S
% 2GeV SUSY Passing
% Two-Photon Passing
100
80
60
40
20
0
20
40
60
80
100
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0



Going from full to 90% coverage causes significant loss of discriminating power for "V". (But note that "S" improves → can improve definition and/or find additional discriminating variables; looking into thrust vector and razor observables)