Detector Design Aided By Machine Learning

A case study of the Charged Pion Polarizability Experiment at Jefferson Lab

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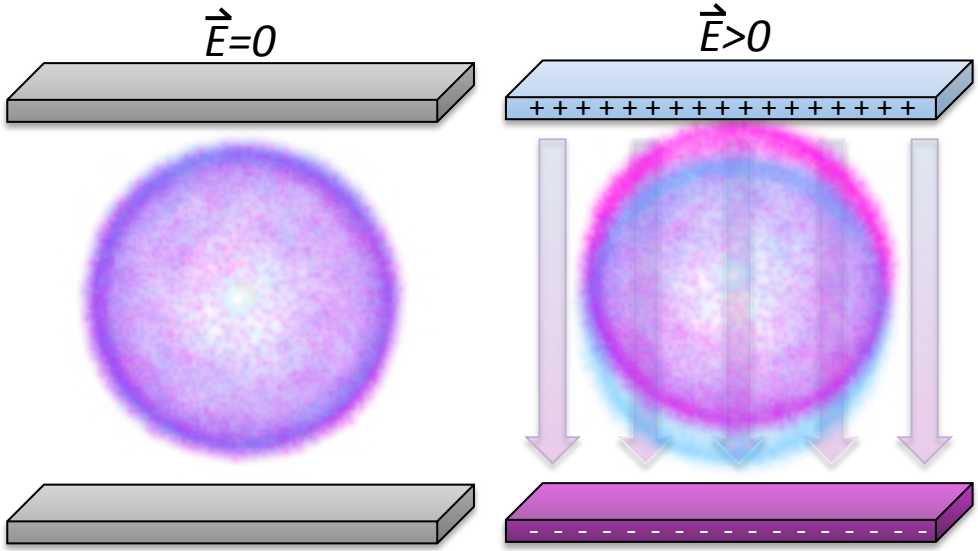
U.S. DEPARTMENT OF ENERGY | JSA | Jefferson Lab

Charged π Polarizability

- Polarizability: Ease in which an external field may induce a dipole moment in a particle
- Property which reflects nature of internal structure of particle



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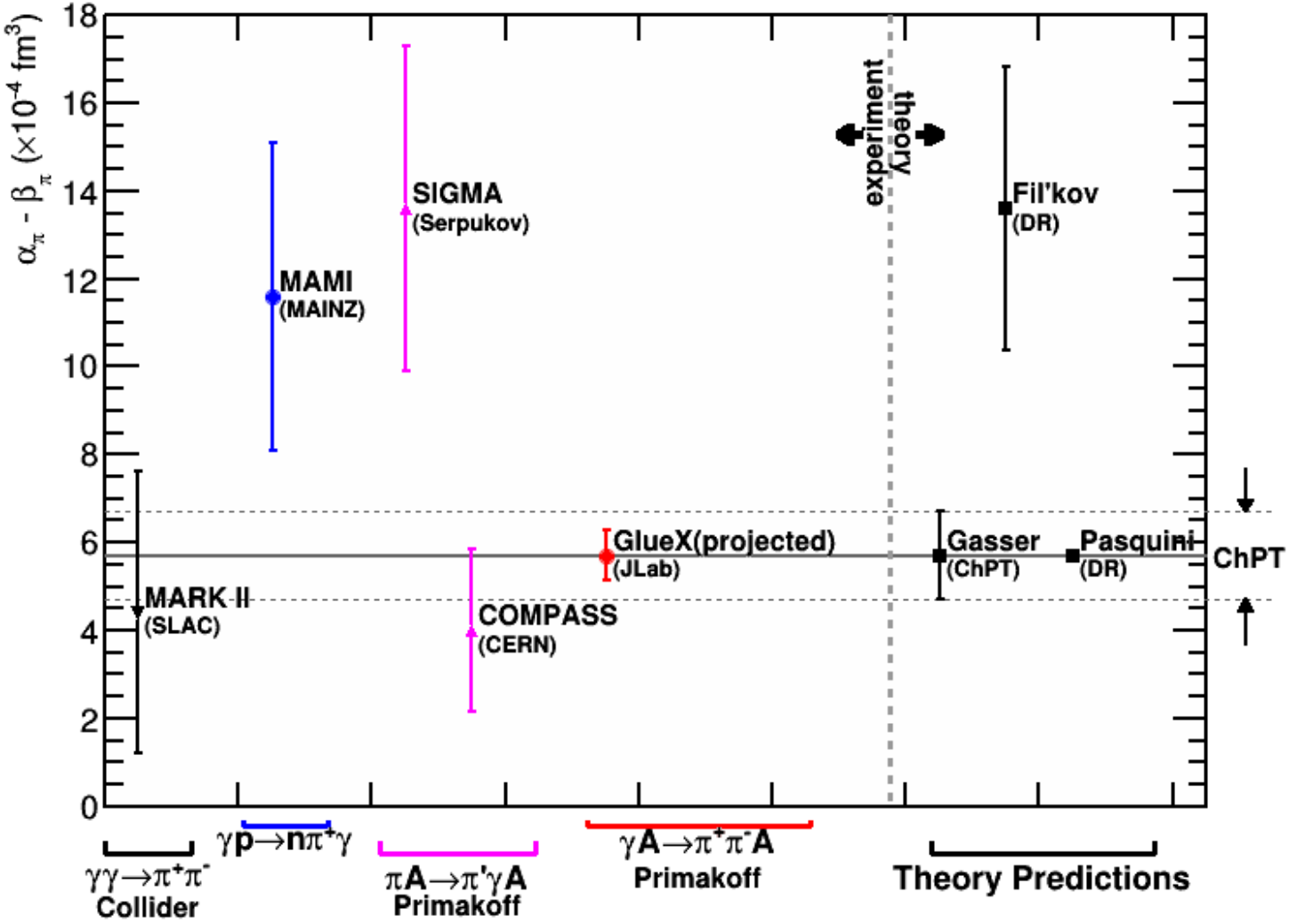
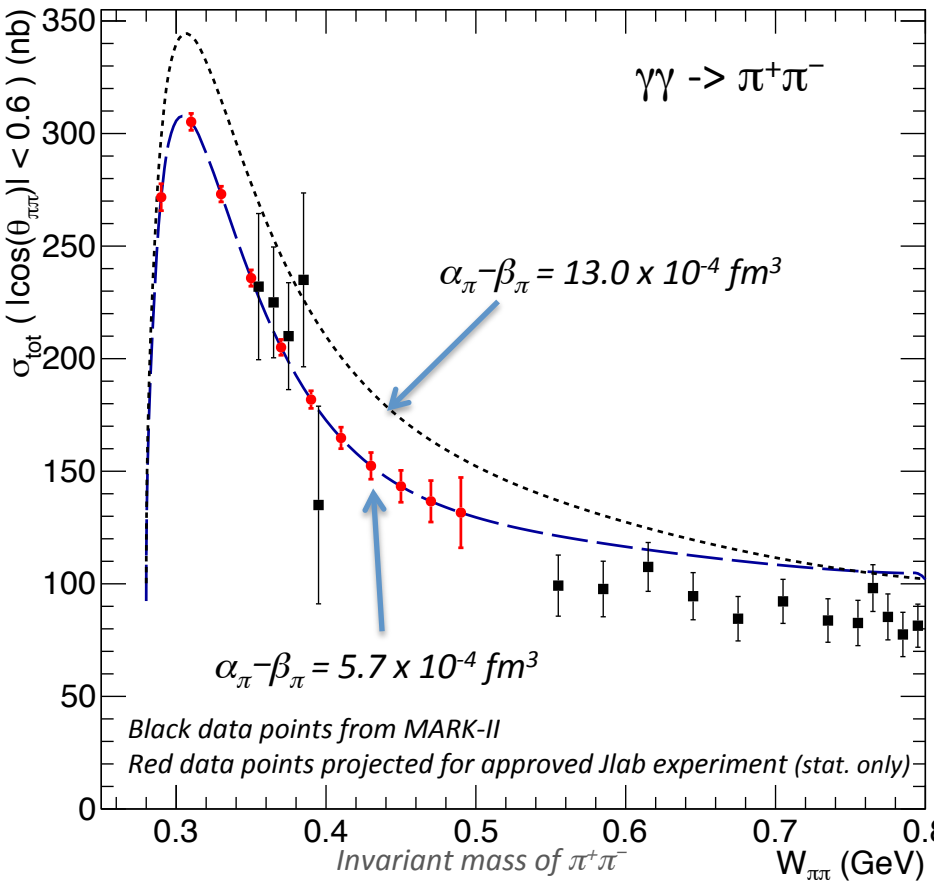
EXPERIMENTAL/THEORETICAL LANDSCAPE



RELATING CROSS-SECTION TO $\alpha_\pi - \beta_\pi$

Curves from figure 5. from Pasquini et al. Phys. Rev. C 77, 065211 (2008)



dotted: subtracted DR calculation with $\alpha_\pi-\beta_\pi$ = 13.0
dashed: subtracted DR calculation with $\alpha_\pi-\beta_\pi$ = 5.7

Cross-section for $\gamma\gamma \rightarrow \pi^+\pi^-$ calculated based on two values of $\alpha_\pi-\beta_\pi$:

$\alpha_\pi-\beta_\pi = 13.0 \times 10^{-4}$ fm^3 (top, dotted line)

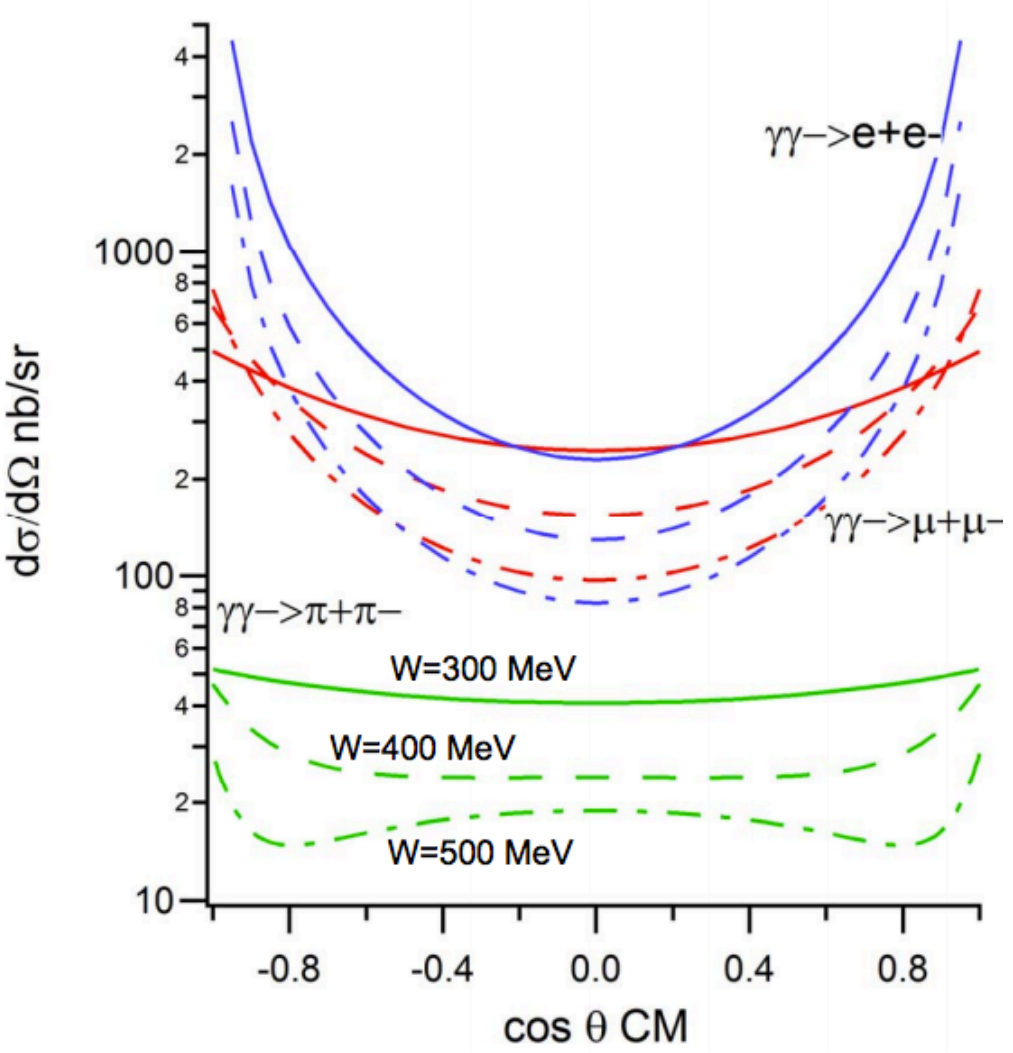
$\alpha_\pi-\beta_\pi = 5.7 \times 10^{-4}$ fm^3 (solid and dashed lines)

Cross-section varies by ~10% for factor of 2 variation in $\alpha_\pi-\beta_\pi$

Need measurement of $\sigma(\gamma\gamma \rightarrow \pi^+\pi^-)$ at few percent level

THE PROBLEM

- μ+μ- (background) are produced ~10x more often than π+π- (signal)
- To measure cross section to few percent means reducing a 10x bigger background to less than a few 1/10 of a percent
- GlueX detector has no way of distinguishing between μ+μ- and π+π- events at this level
- A new detector that works in tandem with GlueX is required



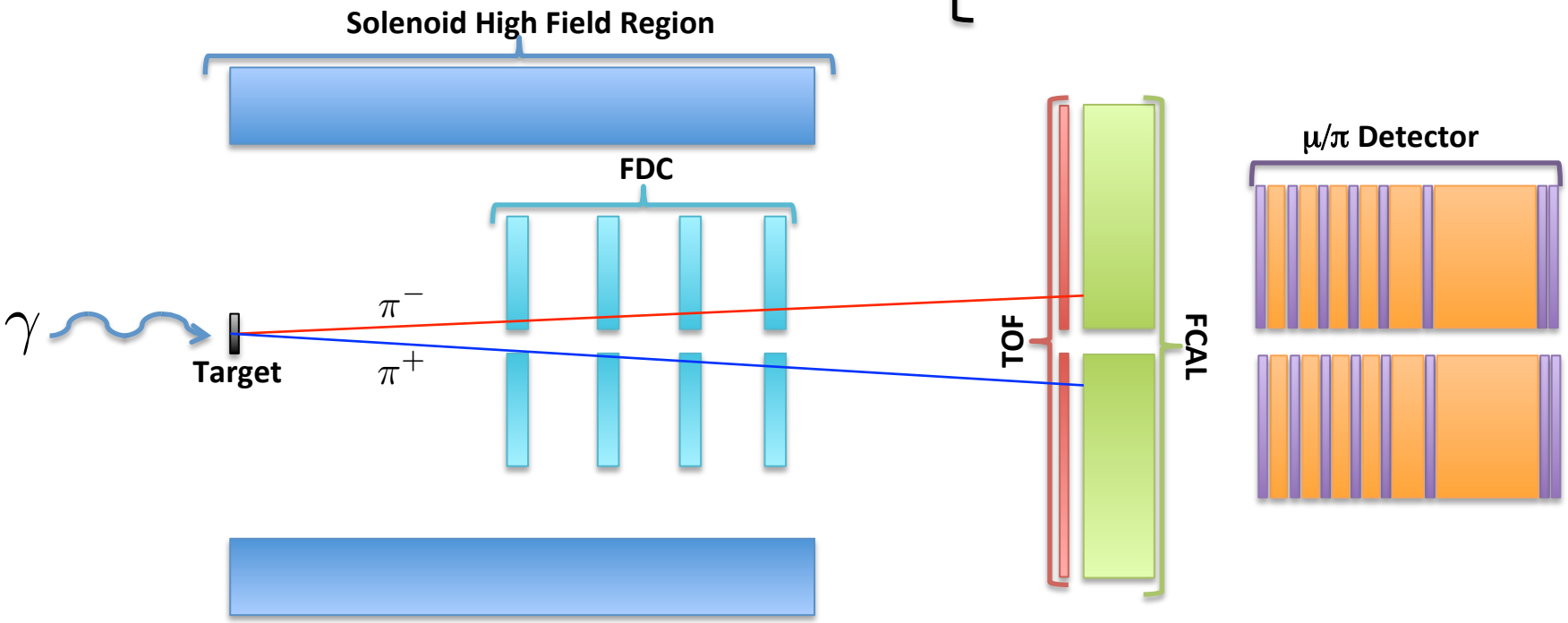
EXPERIMENTAL SETUP

$\gamma\gamma \underset{Z(\gamma,\pi^+\pi^-)Z}{\rightarrow} \pi^+\pi^-$ Signal reaction

$\gamma\gamma \underset{Z(\gamma,\mu^+\mu^-)Z}{\rightarrow} \mu^+\mu^-$ Normalization

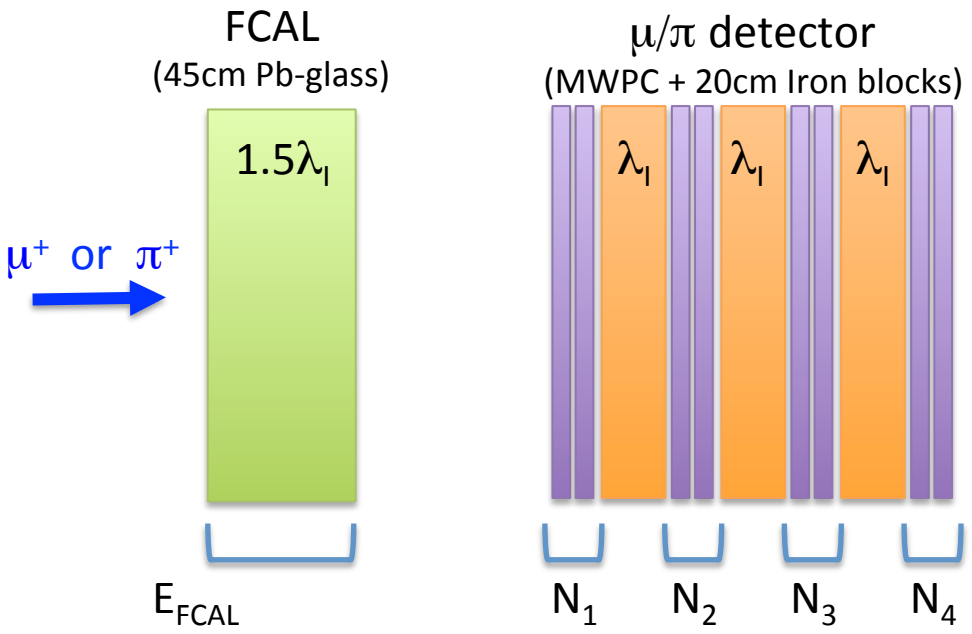
$\gamma\gamma \underset{Z(\gamma,\pi^\circ)Z}{\rightarrow} \pi^o$ Beam polarization

- All occur via the Primakoff effect (interaction with the Coulomb field of nucleus)
- All result in very forward going particles
- Low t ($-t < 0.005$ GeV^2)



First Attempt

- Simulate single 2GeV particles with simple geometry
- 4 nucl. Interaction lengths ➔ ~2% of πs make it through



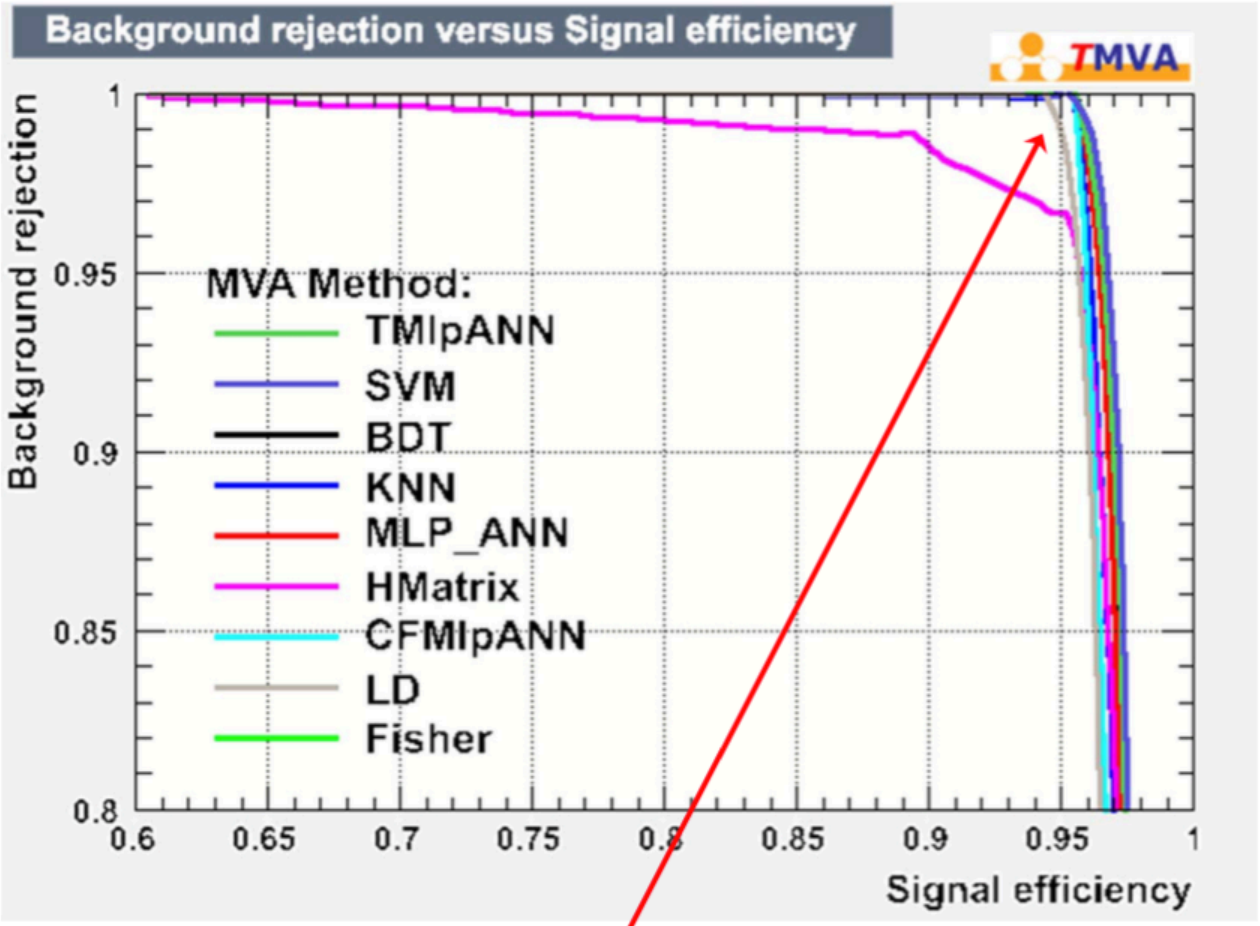
Tell TMVA what input variables to use

```
40      factory->AddVariable( "Nmwpc1", 'I' );
41      factory->AddVariable( "Nmwpc2", 'I' );
42      factory->AddVariable( "Nmwpc3", 'I' );
43      factory->AddVariable( "Nmwpc4", 'I' );
44      factory->AddVariable( "Efcal := Sum$(Edep)", 'F' );
```

Tell TMVA what methods to use

```
64      factory->BookMethod( TMVA::Types::kMLP,      "MLP_ANN", "H:!V" );
65      factory->BookMethod( TMVA::Types::kFisher,   "Fisher",  "H:!V" );
66      factory->BookMethod( TMVA::Types::kKNN,      "KNN",     "H:!V" );
67      factory->BookMethod( TMVA::Types::kHMatrix,  "HMatrix", "H:!V" );
68      factory->BookMethod( TMVA::Types::kCFMlpANN,"CFMlpANN","H:!V" );
69      factory->BookMethod( TMVA::Types::kTMlpANN,  "TMlpANN", "H:!V" );
70      factory->BookMethod( TMVA::Types::kSVM,      "SVM",     "H:!V" );
71      factory->BookMethod( TMVA::Types::kLD,       "LD",      "H:!V" );
```

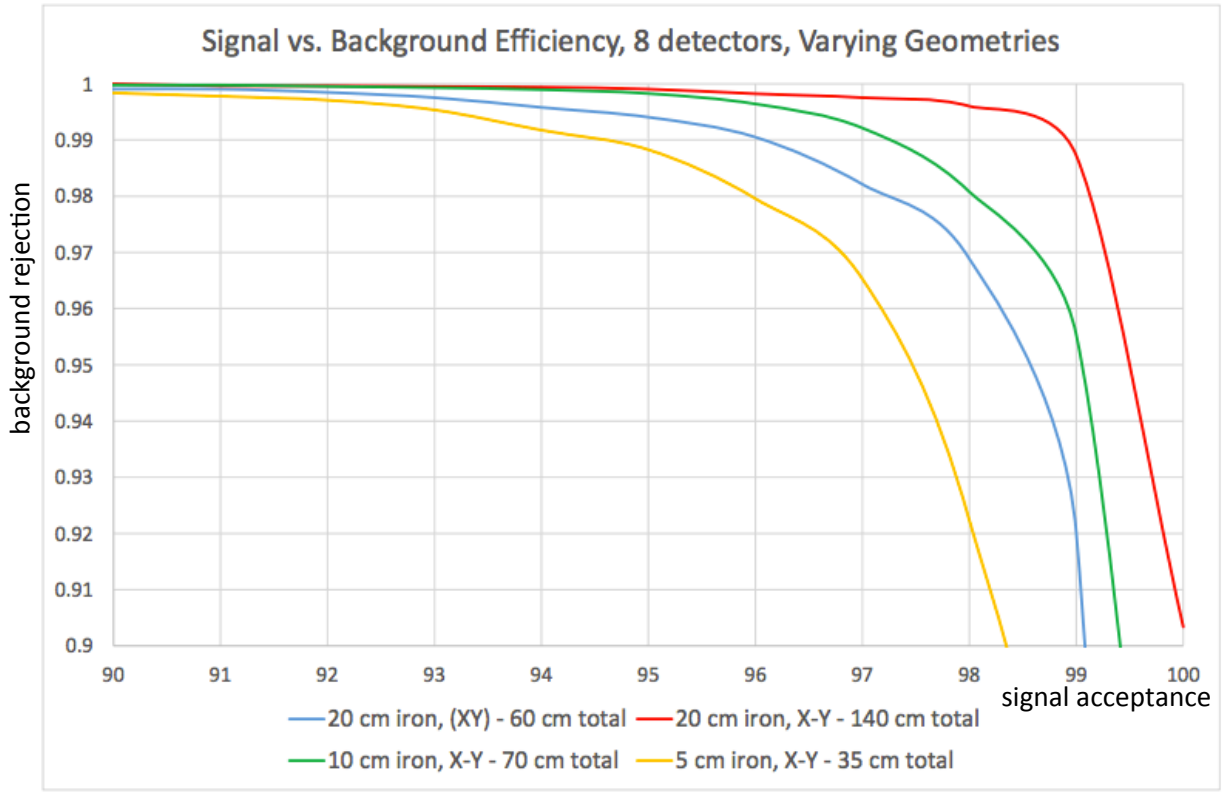
Multi-Variate Analysis for 2 GeV π+ and μ+



μ rejection at 0.998, π efficiency at 95%

More Iron Is Better

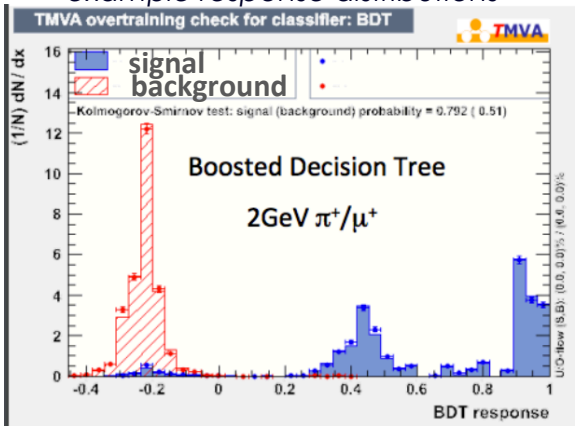
Question 1: Should we have 'xy-iron-xy-…', or 'x-iron-y-iron-x-iron-y- … ?



Compare blue (xy-iron-xy…) and green (x-iron-y-iron…) : Green is better.
To do: adjust so total amount of iron is identical.

- Realistic simulation with both particles present and distribution of incident photon energies
- An MVA can be biased by your choice of inputs, but not by your interpretation

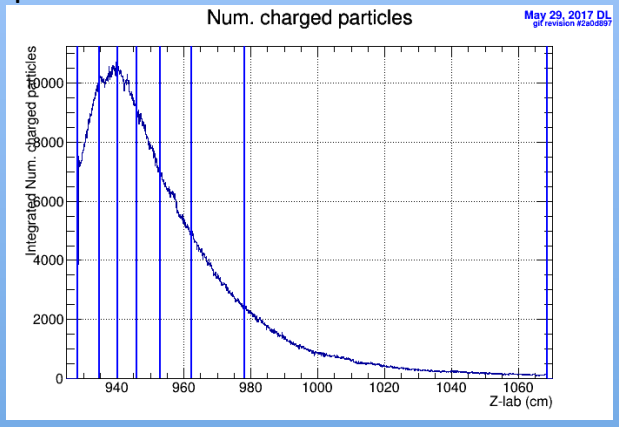
example response distributions

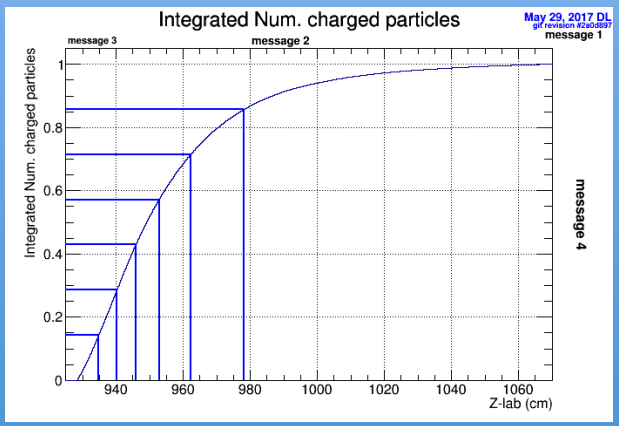


Study done by UMass undergrad. Bobby Johnston

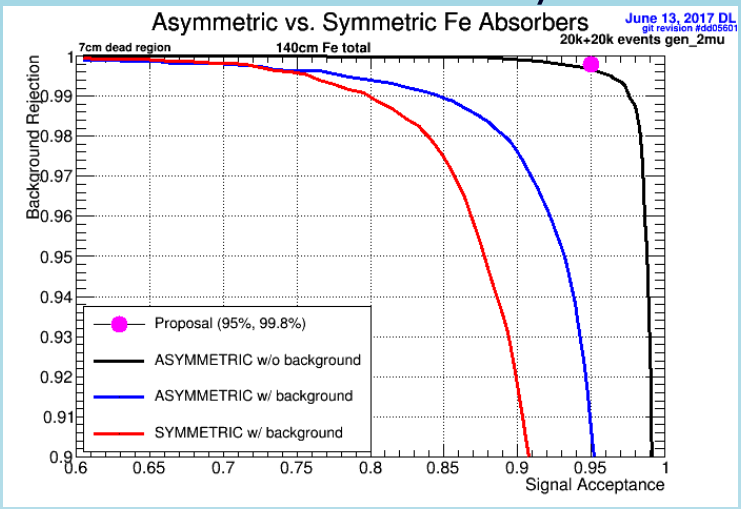
Symmetry of Iron Absorber Thickness

- Human Derived Concept
  - Integrate number of particles as function of depth in Iron for $\pi^{\pm}$ showers
  - Split Iron so sections contain equal number of particles



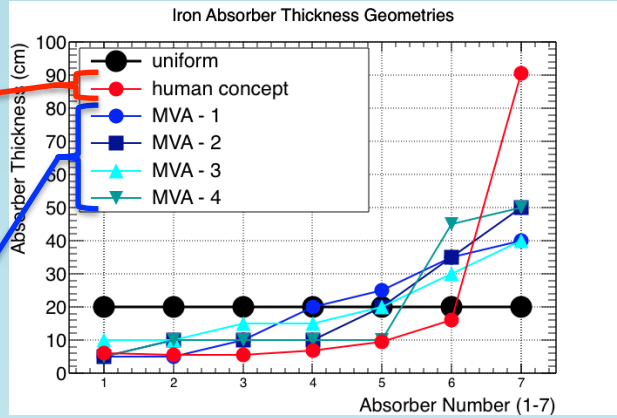


- Confirmation by MVA

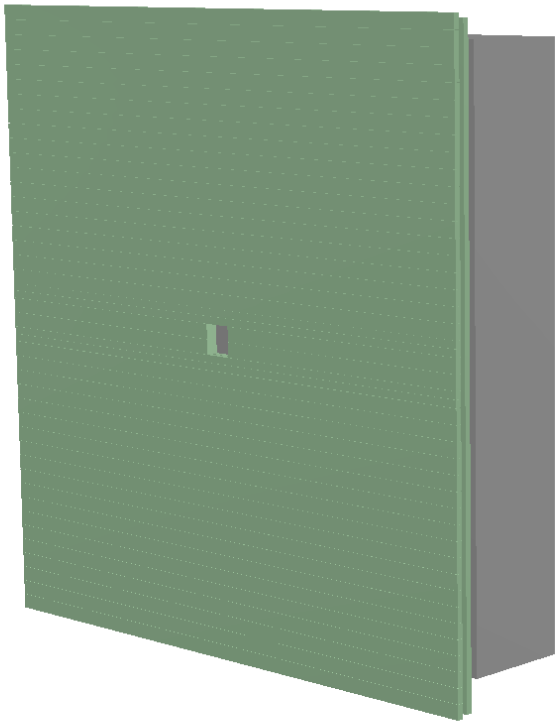


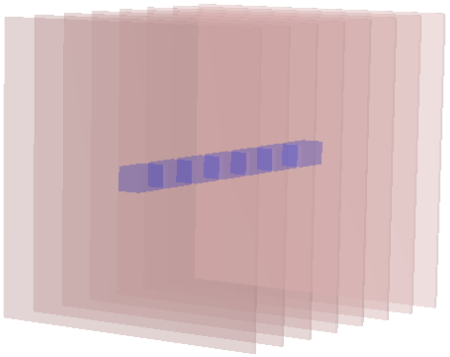
(human)

Top 4 MVA results of 741 geometries tested



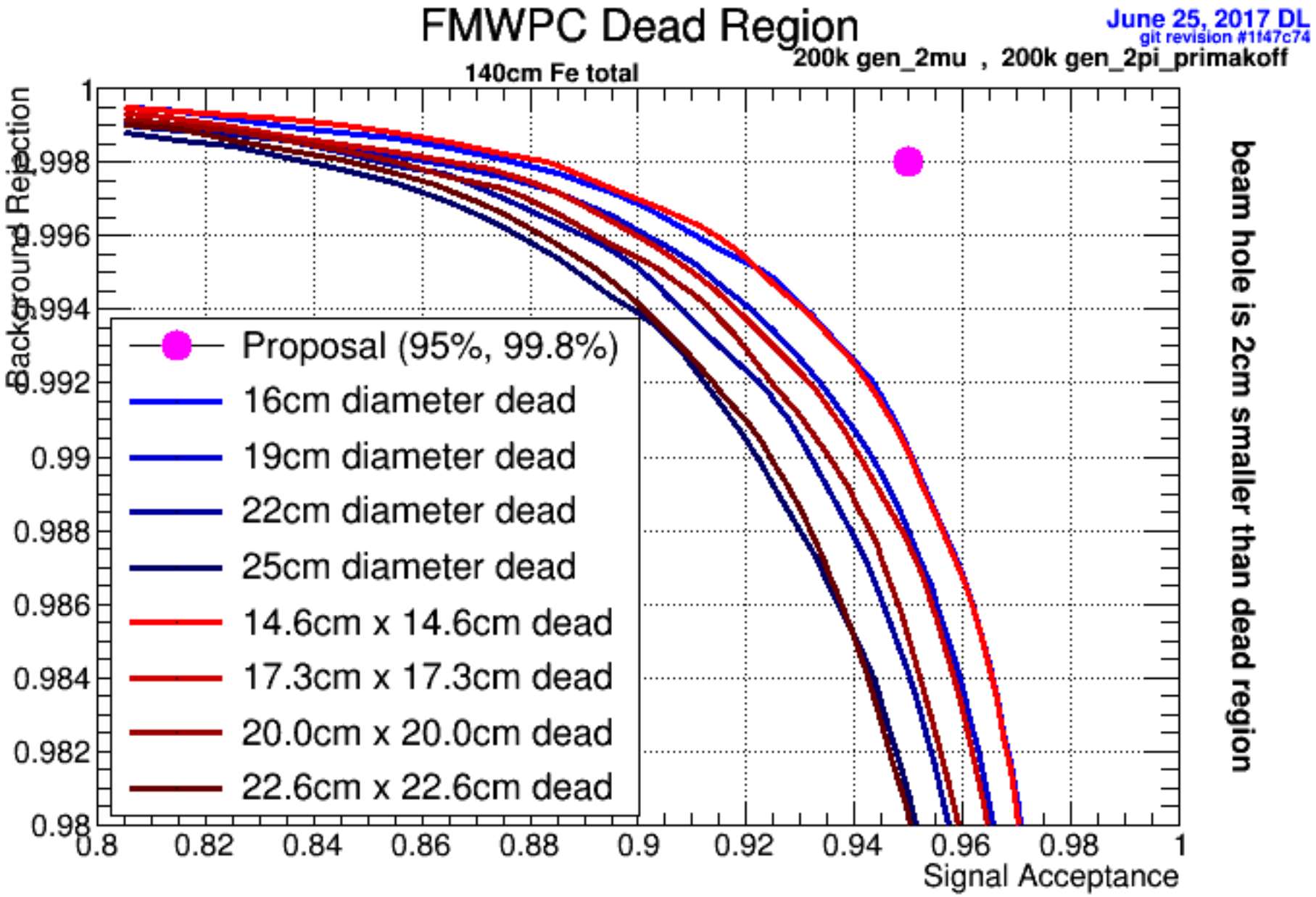
Beam Hole / Dead Region Geometry





- Primary photon beam passes through square holes in center of FCAL and TOF detectors
- Natural geometry of beam is round

- Should hole in Iron absorbers be square to match FCAL or round to match beam? Does it matter?
- What size should it be?
- What about dead region in chambers?


FMWPC Dead Region
June 25, 2017 DL
git revision #1f47c74
140cm Fe total
200k gen_2mu , 200k gen_2pi_primakoff
Background Rejection
Signal Acceptance
beam hole is 2cm smaller than dead region
Proposal (95%, 99.8%)
16cm diameter dead
19cm diameter dead
22cm diameter dead
25cm diameter dead
14.6cm x 14.6cm dead
17.3cm x 17.3cm dead
20.0cm x 20.0cm dead
22.6cm x 22.6cm dead
1
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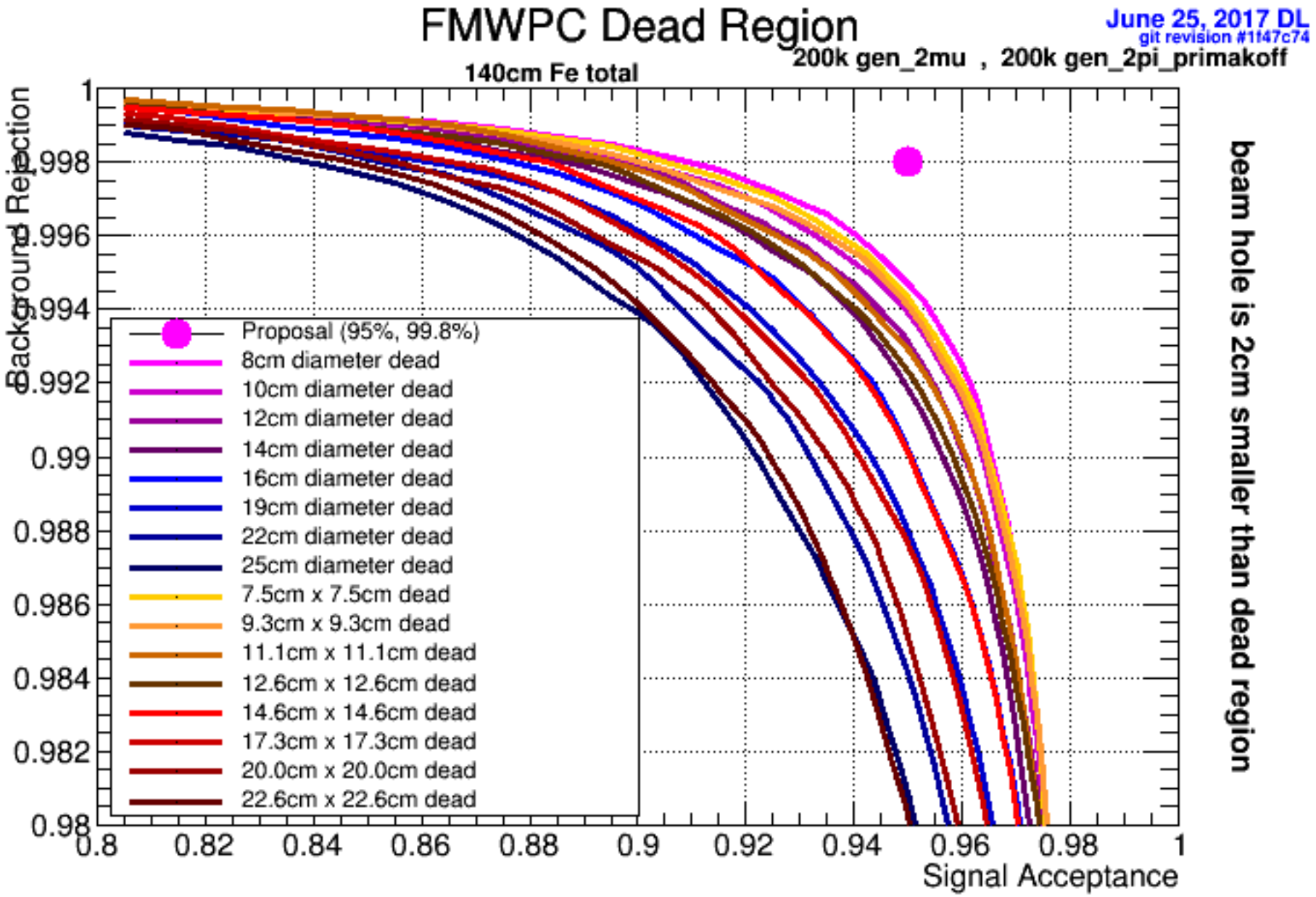
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140cm Fe total
200k gen_2mu , 200k gen_2pi_primakoff
Background Rejection
Signal Acceptance
beam hole is 2cm smaller than dead region
Proposal (95%, 99.8%)
8cm diameter dead
10cm diameter dead
12cm diameter dead
14cm diameter dead
16cm diameter dead
19cm diameter dead
22cm diameter dead
25cm diameter dead
7.5cm x 7.5cm dead
9.3cm x 9.3cm dead
11.1cm x 11.1cm dead
12.6cm x 12.6cm dead
14.6cm x 14.6cm dead
17.3cm x 17.3cm dead
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0.94
0.96
0.98
1

AN MVA SURPRISE

- In 2013 we had a software tutorial for GlueX
  - $\gamma p \rightarrow p\pi^+\pi^+\pi^-$
  - **Signal**: specialized generator with selected amplitudes
    - 5343 events
  - **Background**: pythia + selected reactions at low energy with uniform sampling in phase space
    - 8527 events

AN MVA SURPRISE

Original Exercise

: ---
: Rank : Variable : Variable Importance
: ---
: 1 : PV_r : 1.129e-01
: 2 : MissingNeutron_PT : 9.881e-02
: 3 : PiPlus1__Timing_FOM : 7.881e-02
: 4 : PiMinus__Timing_FOM : 7.325e-02
: 5 : Unused__Max_KPlus_FOM : 7.313e-02
: 6 : Unused__Max_Proton_FOM : 6.612e-02
: 7 : FOM_KinFit : 6.467e-02
: 8 : PiPlus2__Timing_FOM : 6.264e-02
: 9 : PiPlus1__NDF_Tracking : 5.885e-02
: 10 : PiPlus2__NDF_Tracking : 5.744e-02
: 11 : PiPlus2__DCdEdx_FOM : 5.722e-02
: 12 : Unused__Max_KMinus_FOM : 5.641e-02
: 13 : PiMinus__NDF_Tracking : 5.075e-02
: 14 : PiMinus__DCdEdx_FOM : 5.054e-02
: 15 : PiPlus1__DCdEdx_FOM : 3.848e-02
: ---

Added extra variable "just for fun"

: ---
: Rank : Variable : Variable Importance
: ---
: 1 : PV_r : 9.909e-02
: **2 : Entry$: 9.189e-02**
: 3 : MissingNeutron_PT : 9.053e-02
: 4 : PiPlus1__Timing_FOM : 8.114e-02
: 5 : PiMinus__Timing_FOM : 7.219e-02
: 6 : Unused__Max_KPlus_FOM : 6.512e-02
: 7 : Unused__Max_Proton_FOM : 6.133e-02
: 8 : PiPlus2__NDF_Tracking : 5.963e-02
: 9 : FOM_KinFit : 5.823e-02
: 10 : PiPlus2__Timing_FOM : 5.629e-02
: 11 : PiPlus1__NDF_Tracking : 5.361e-02
: 12 : Unused__Max_KMinus_FOM : 5.358e-02
: 13 : PiMinus__NDF_Tracking : 4.415e-02
: 14 : PiMinus__DCdEdx_FOM : 4.318e-02
: 15 : PiPlus2__DCdEdx_FOM : 3.784e-02
: 16 : PiPlus1__DCdEdx_FOM : 3.221e-02
: ---

SOME ADVICE

1. Any variable could be useful. Just give it to the MVA and let it decide
2. Avoid variables that are strongly correlated with a quantity you're trying to measure
   (e.g. inv. mass of a resonance you're trying to search for)
3. Make any obvious cuts before handing over to MVA so it doesn't have to waste discriminating power on the obvious

SUMMARY

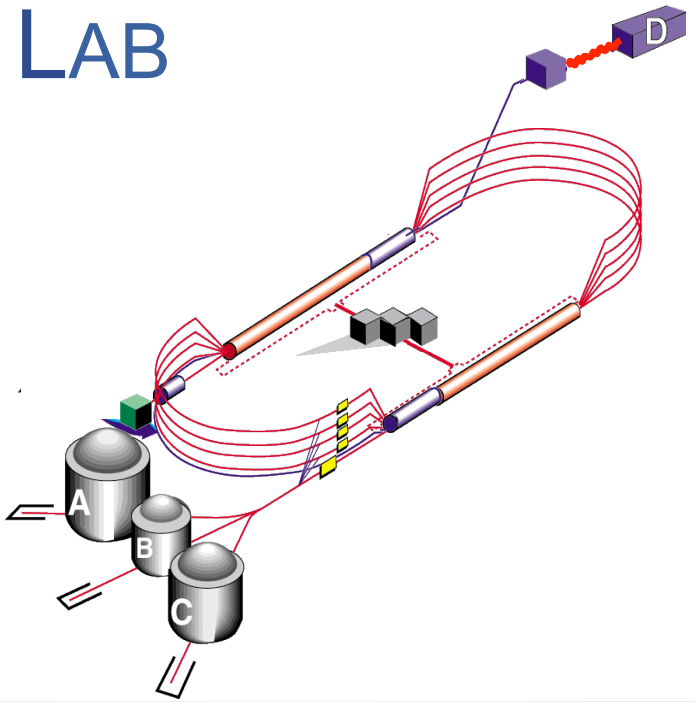
- Using multiple MVA algorithms can allow quick insight into design decisions without much expertise in machine learning
  - The TMVA package in ROOT is a great way to get started with machine learning and gives easy access to several algorithms using a single input format and API
- MVA is a great way to make relative comparisons between different detector designs
- The Charged Pion Polarizability experiment at Jefferson Lab Hall-D has used TMVA to refine several of the π/μ detector design aspects

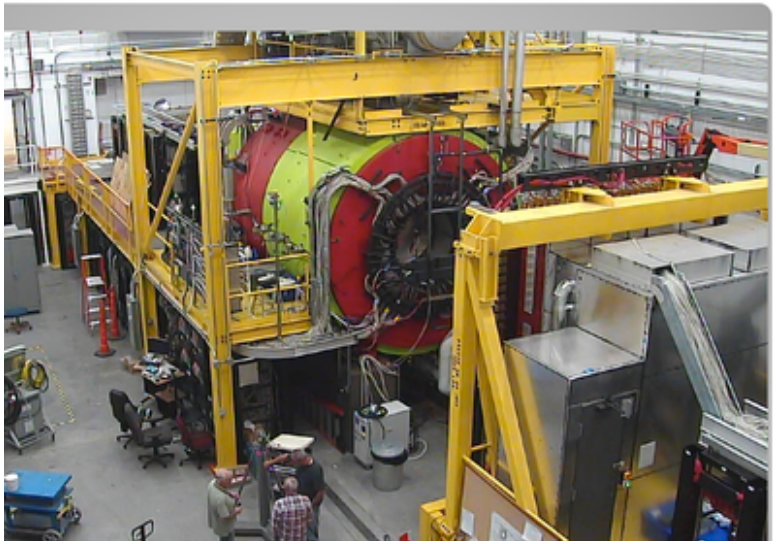
BACKUPS

HALL-D AT JEFFERSON LAB

(HOME OF GLUEX)

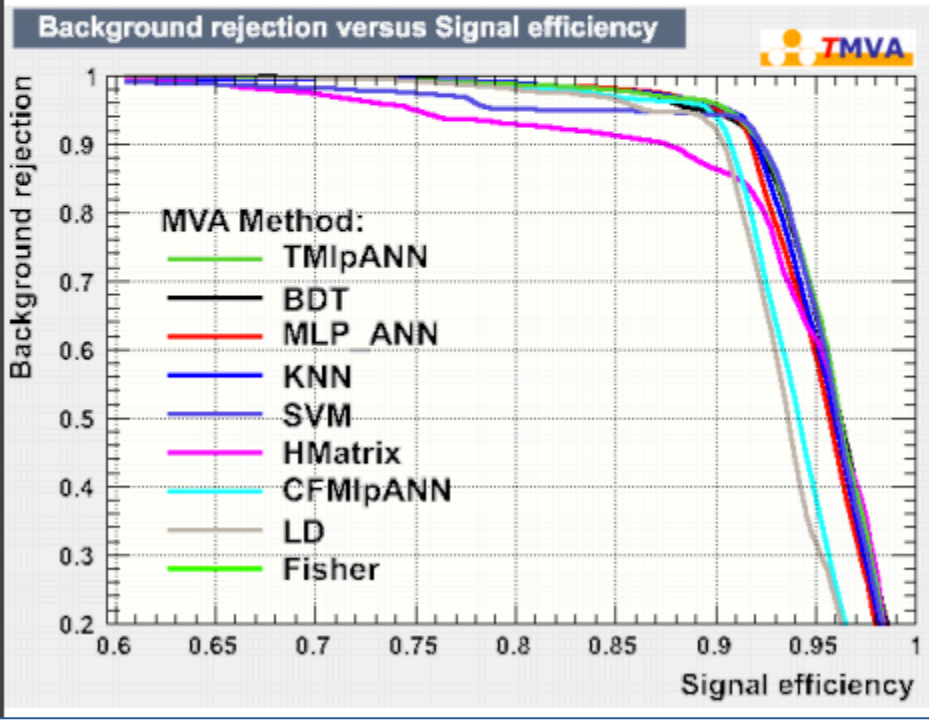
- 12GeV CW(2-4ns) electron beam
- Only high energy photons enter Hall-D

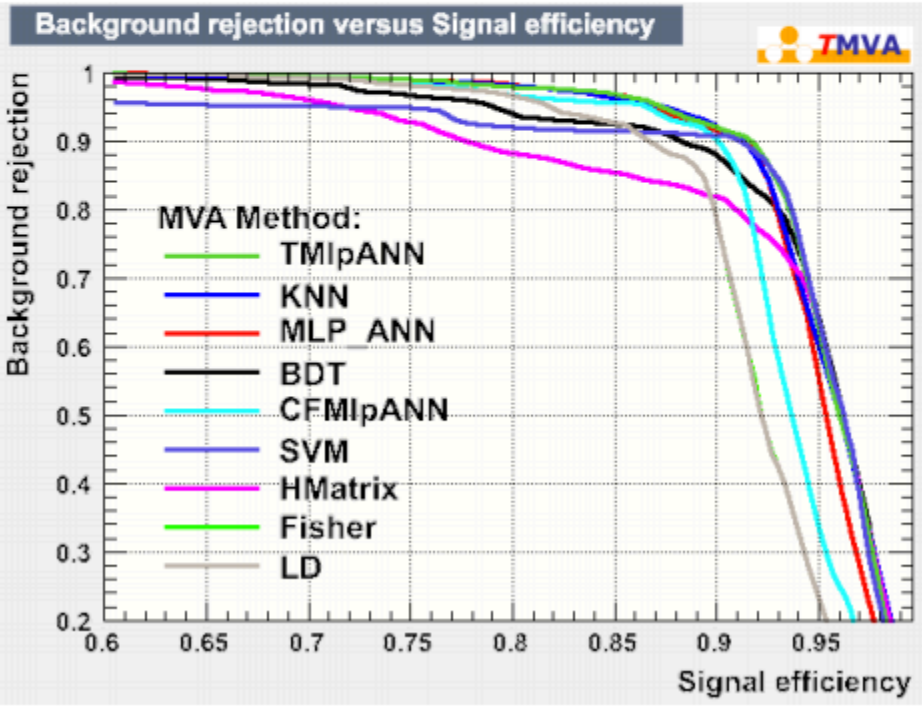




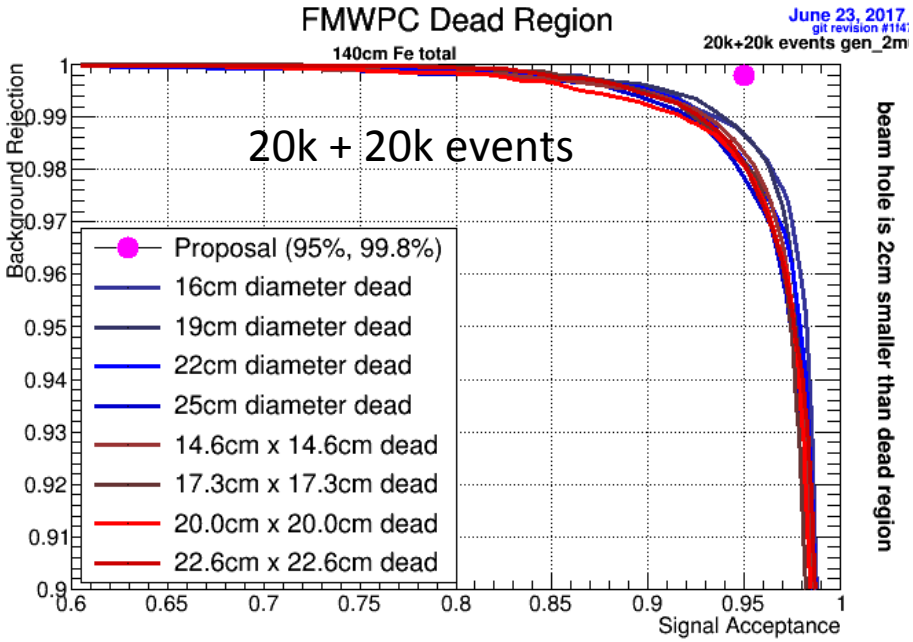
Realistic momentum Distribution

- *pb_pol70_10days: Primakoff + coherent ρ with 70% polarization*
- *10k events only (5k used for training, 5k used for testing)*





20k -> 200k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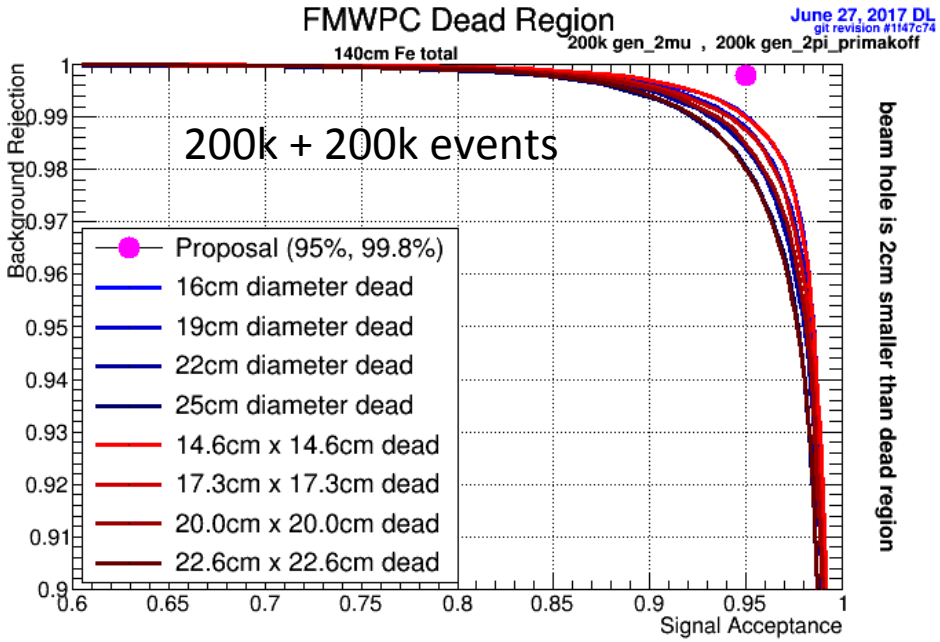
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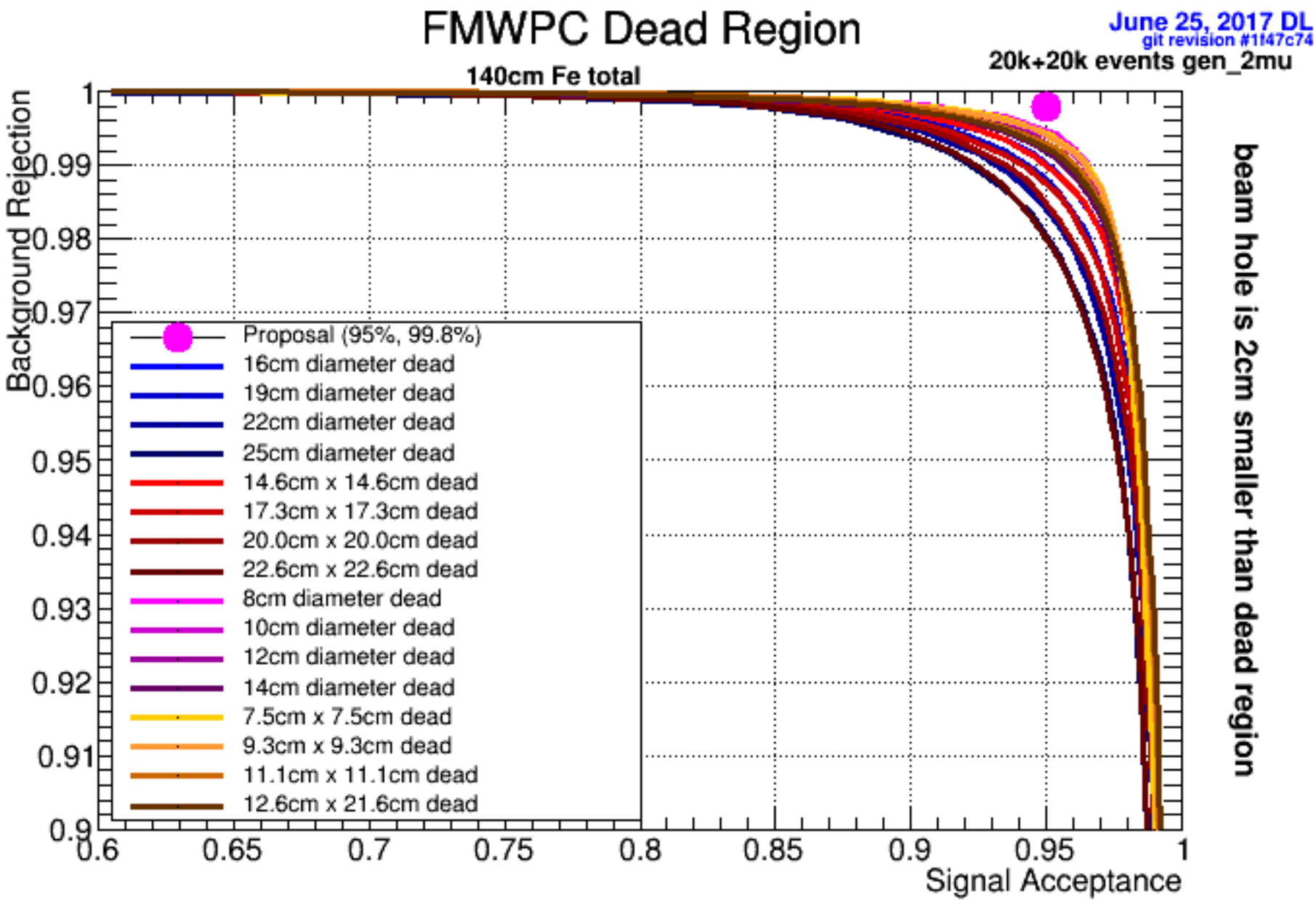
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