Update on the 2016 Displaced Vertex Search

Matt Solt
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11/19/2019

Introduction

- 2016 vertexing resources: Confluence page and analysis note
- Initial look at recent MC
  - large MC production Data/MC comparison. Backgrounds appear to be as expected
  - Initial look at signal MC (A'-beam)
- Discussion on analysis procedure - optimization, validation, and blinded approach
- Longer-lived A's (L1L2 and L2L2)
- Machine learning approach
- Going after SIMPs (or generalized displaced vertices)
- Putting it all together, timeline, and future plans

Vertexing Analysis 2016 Resources

SLAC

https://confluence.slac.stanford.edu/display/hpsg/2016+Vertexing+Analysis+Page

- This page contains everything: data MC status, plots, etc.

- Vertexing meetings - Every other Thursday at 10am PST / 1pm EST
    - The core 2016 vertexing group (Matt S., Matt G., PF, and Tongtong) meets at the same time on the off Thursdays

Vertexing Analysis 2016 Resources

- We are starting an analysis note… lots of stuff to fill in!
- Ongoing Overleaf Document (You may have to request permission)

HPS-ANALYSIS-NOTE #XXX

Search for Displaced Dark Photons with the Heavy Photon Search Experiment at JLab

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MC Status

- **SLAC (Thanks Takashi!)**
  - tritrig-wab-beam 100% sample (Completed)
  - tritrig x10 sample (Currently in progress, about 50% done)
- **JLab (Thanks Tongtong!)**
  - Displaced A'
    - Mass points (MeV): 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100, 105, 110, 115, 120, 125, 130, 135, 140, 145, 150, 175
  - Displaced A' with beam (Completed)
    - Mass points (MeV): 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100, 105, 110, 115, 120, 125, 130, 135, 140, 145, 150, 175
  - Rad with beam (Completed)
  - Wab with beam (Completed)
  - Tritrig with beam (Completed)
  - Wab-beam-tri (Currently in progress)

More information here

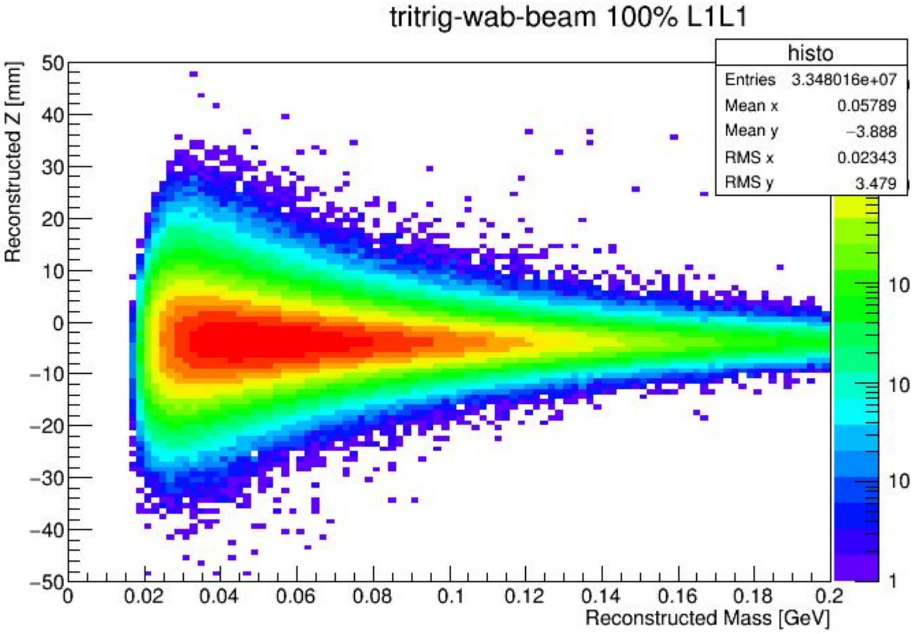
See Tongtong's collaboration meeting talk for more details

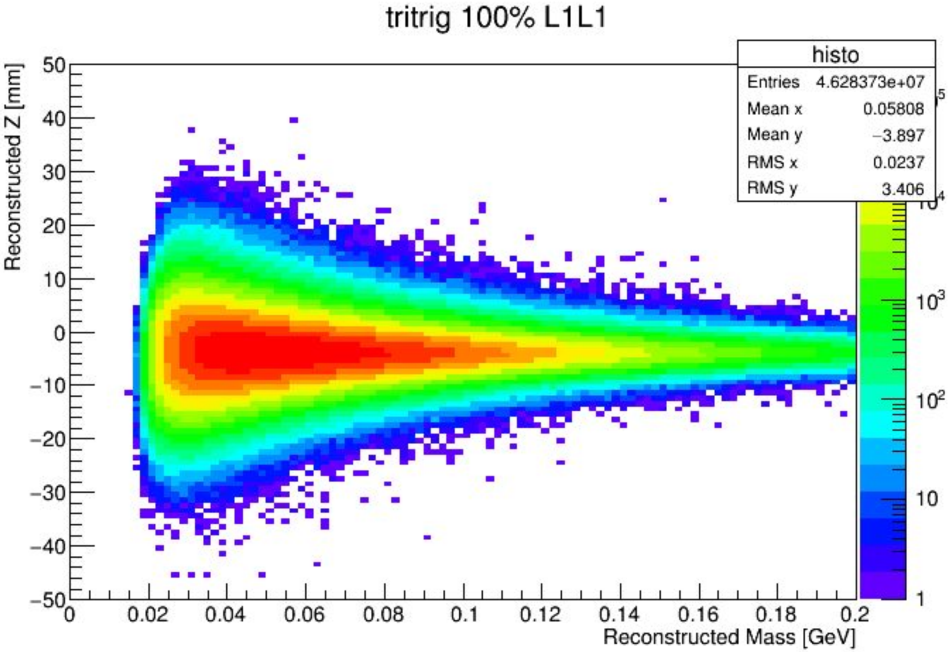
Large MC Samples First Look

- Preliminary look at the large MC sample
- The goal is to see the sources of high Z backgrounds
- “Tritrig” - pure tridents x10 sample
- “Tritrig-wab-beam” - enhanced tridents overlaid with simulated beam and wabs 100% sample
- Compare tritrig-wab-beam with equivalent sample of tritrig (2016 luminosity equivalent)
- These cuts are very loose (just to start)
- I plan on having a much more detailed look in the near future

Preselection Cuts
e+e- have L1 Hit (for L1L1), L2 Hit
Opposite volume e+e-
e+e- track/cluster match $X^2 < 10$
e+e- track - cluster time < 4 ns
e+e- cluster time difference < 2 ns
e+e- track X^2 / dof < 6
Beamspot constrained $X^2 < 15$
e- momentum < 2.15 GeV
Number of positrons in event = 1

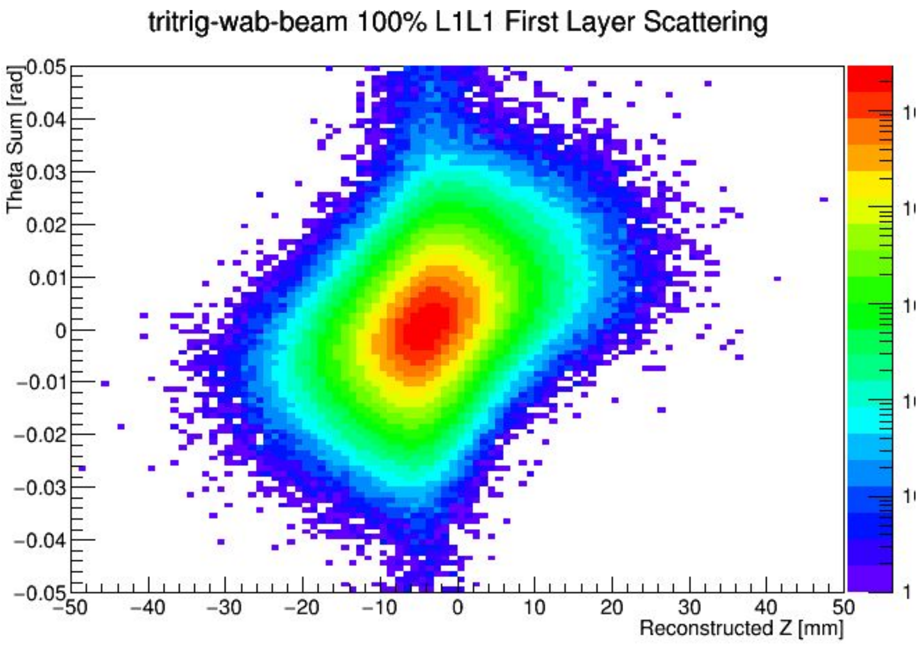
L1L1 MC Comparison

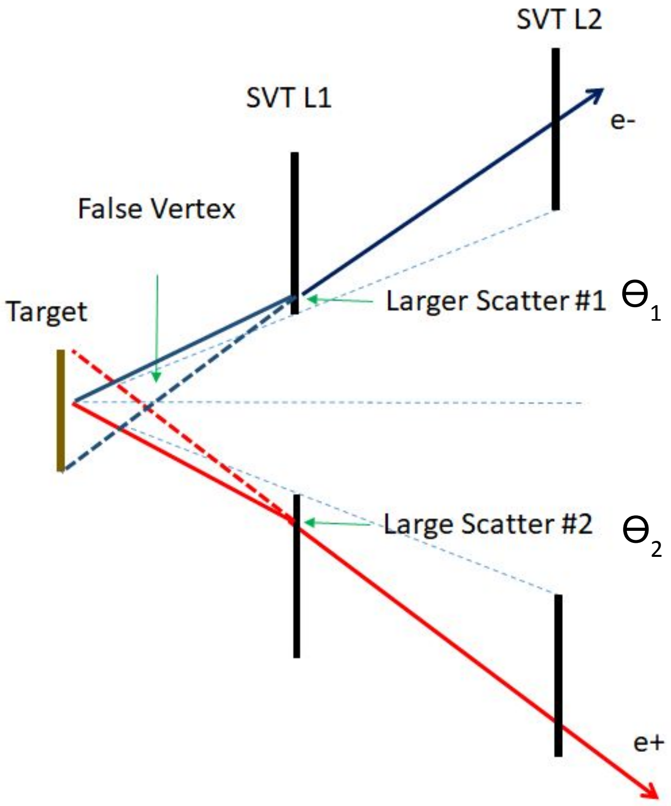




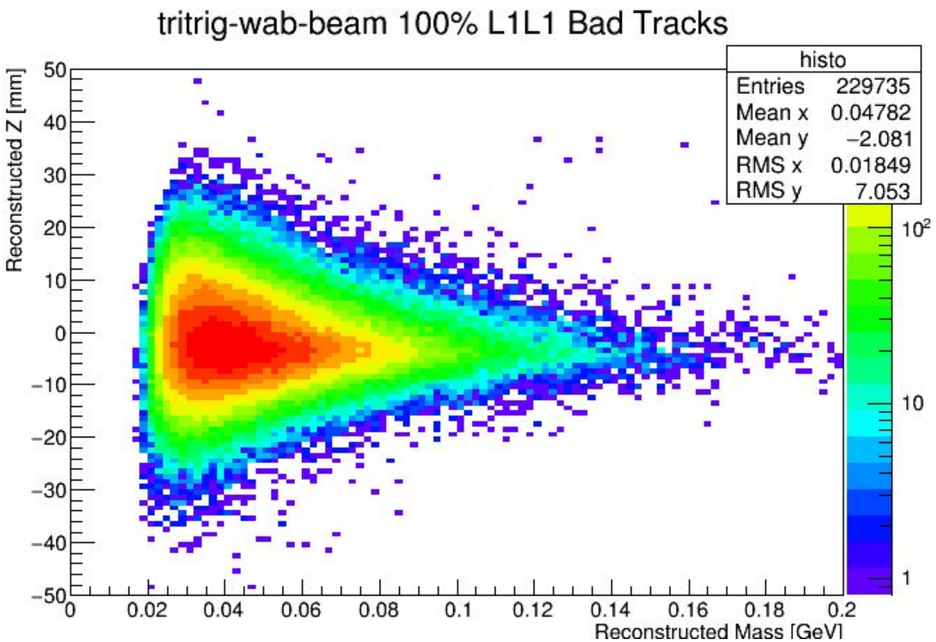
L1L1 MC High Z Backgrounds

$$\theta_{sum} = \theta_1 + \theta_2$$

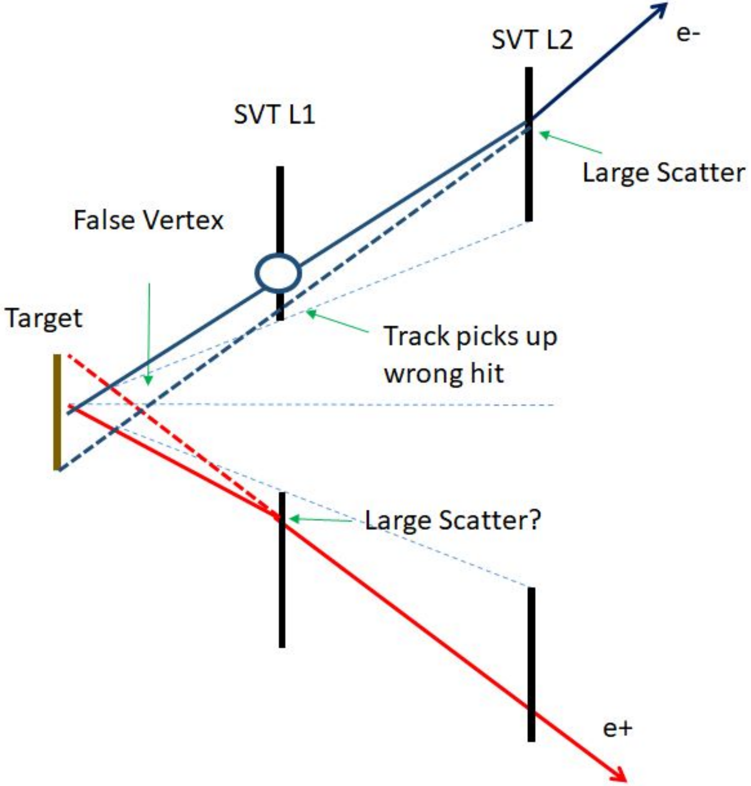




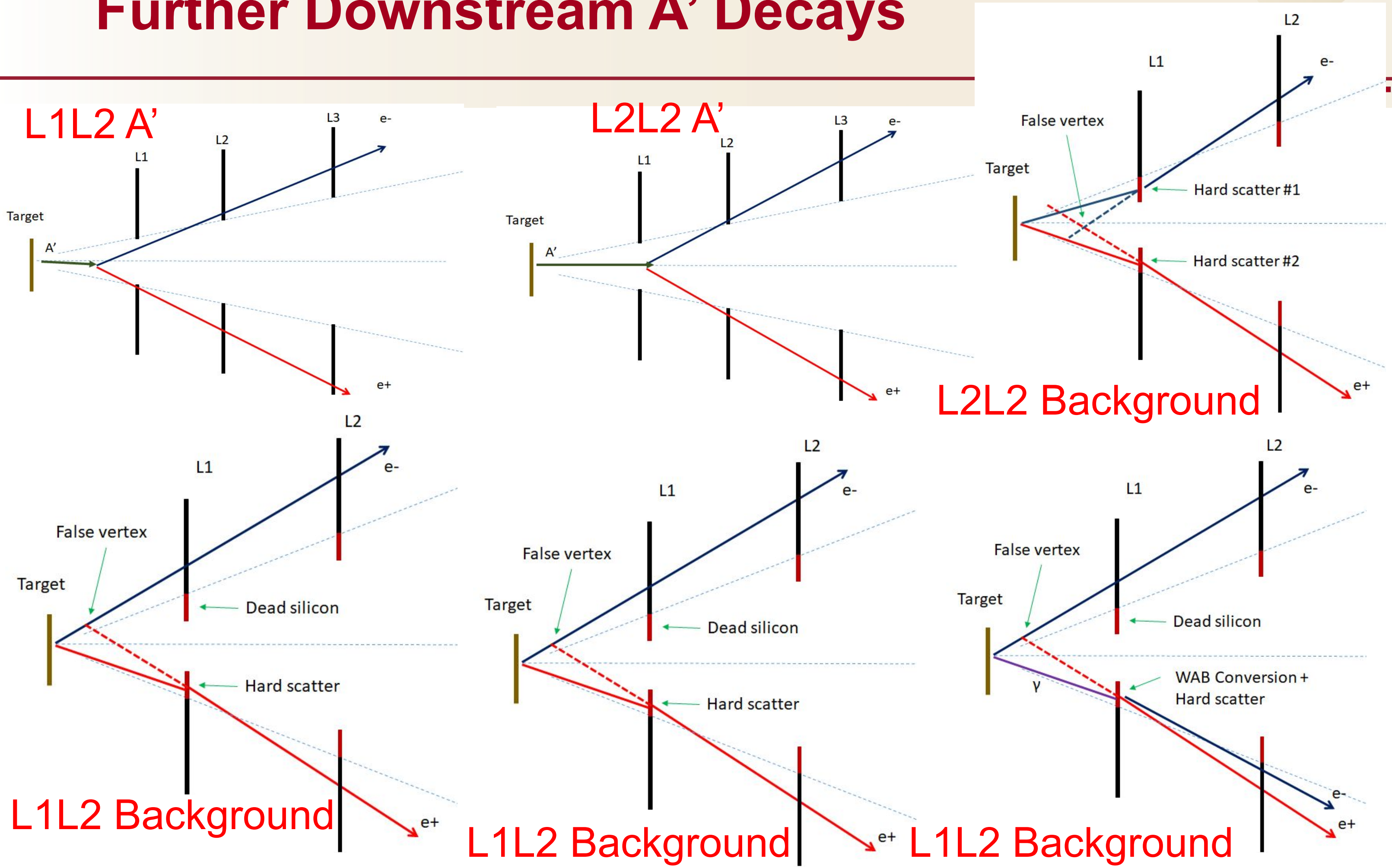
L1L1 MC High Z Backgrounds



Bad Tracks = at least one tracker hit on either e+ or e- track is not associated with the truth match MC particle

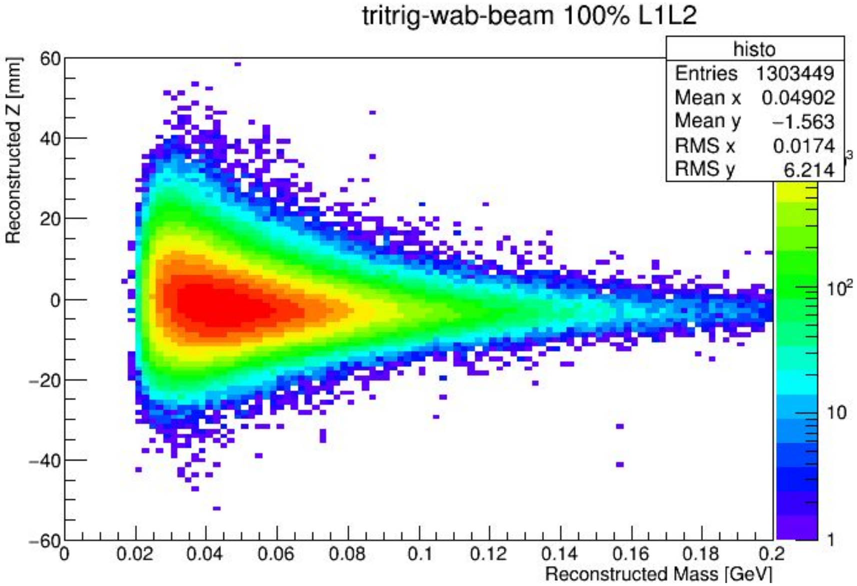


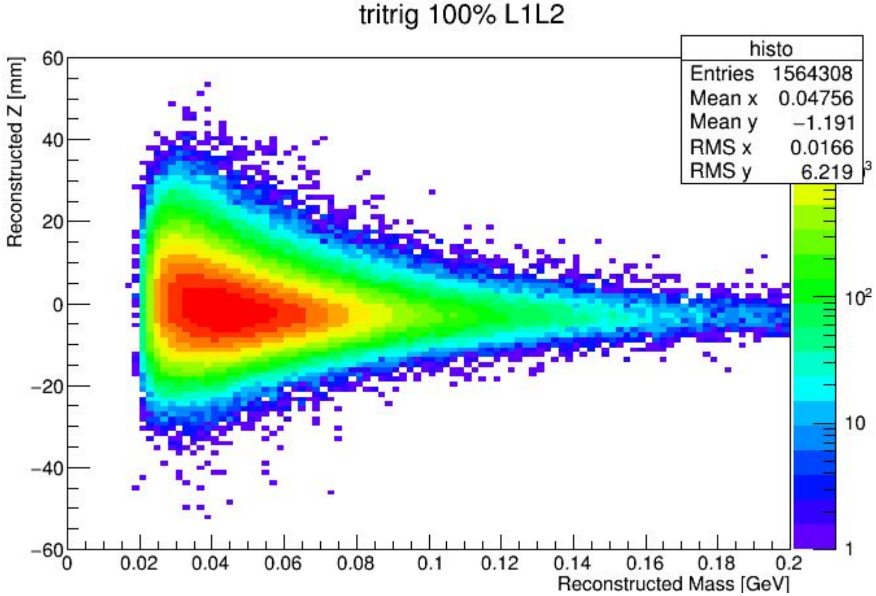
Further Downstream A' Decays



L1L2 MC Comparison

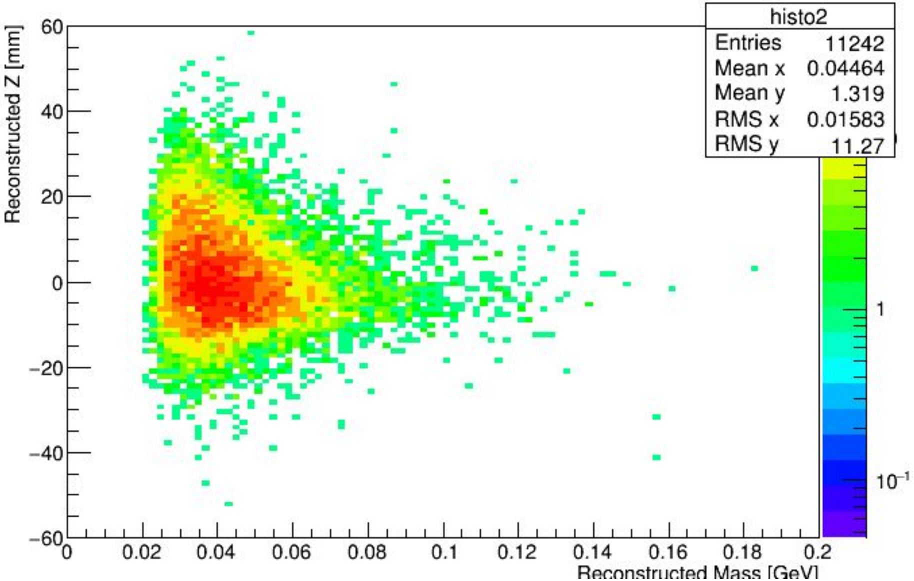
- L1L2 = Either the e+ or e- track has a missing layer 1 hit, the other track has a layer 1 hit

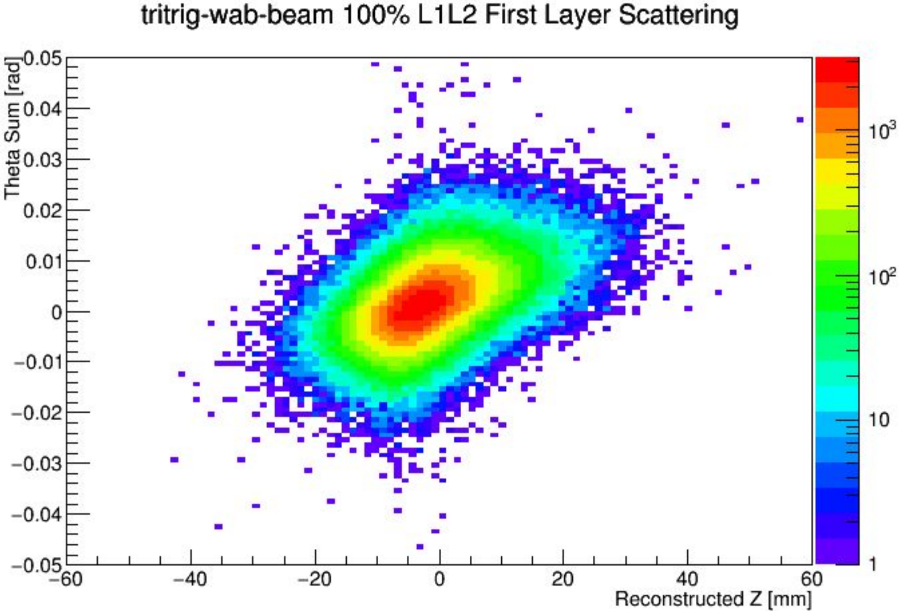




L1L2 MC High Z Backgrounds

$$\theta_{sum} = \theta_1 + \theta_2$$



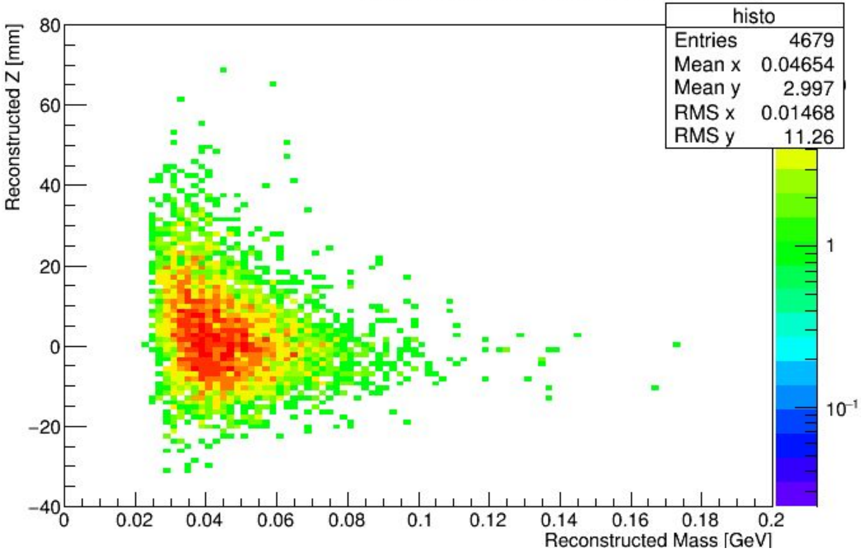


*Includes scattering in inactive silicon

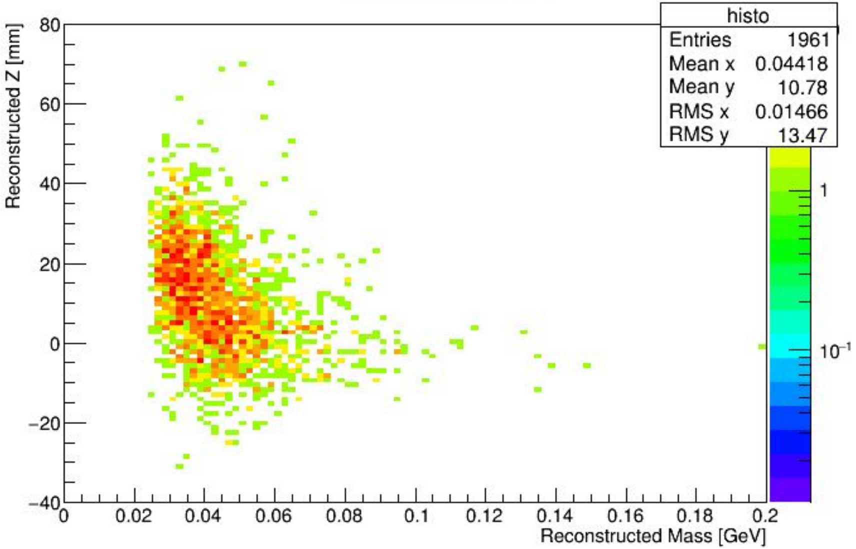
L2L2 MC Comparison

- L2L2 = neither e+ nor e- tracks have a layer 1 hit
- Trident production not included in MC, will need to be included in 2019
- L2L2 will most likely not be included in 2016 analysis (not much signal acceptance expected), still important to look at for 2019

tritrig-wab-beam 100% L2L2

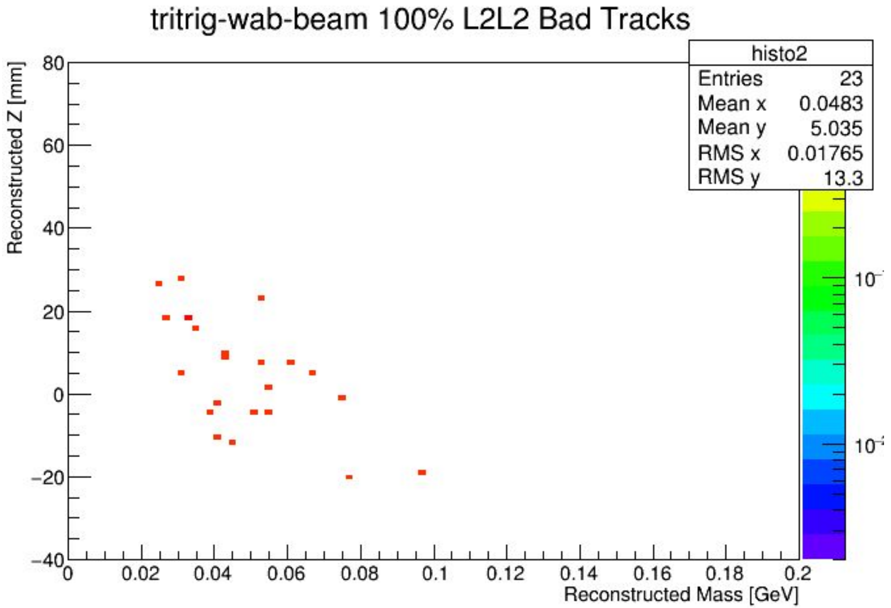


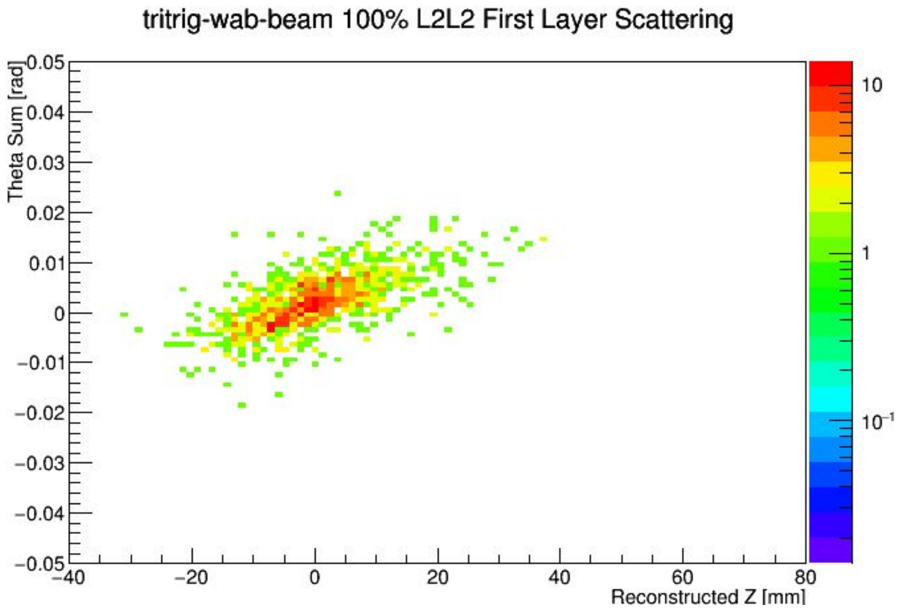
tritrig 100% L2L2



L2L2 MC High Z Backgrounds

$$\theta_{sum} = \theta_1 + \theta_2$$





*Includes scattering in inactive silicon

Data: Run-dependent Beam Parameters

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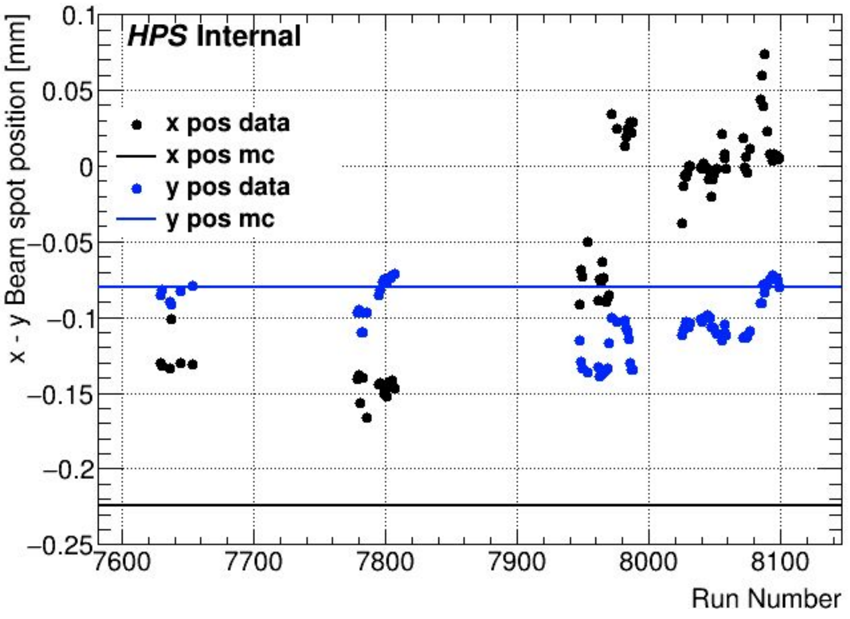
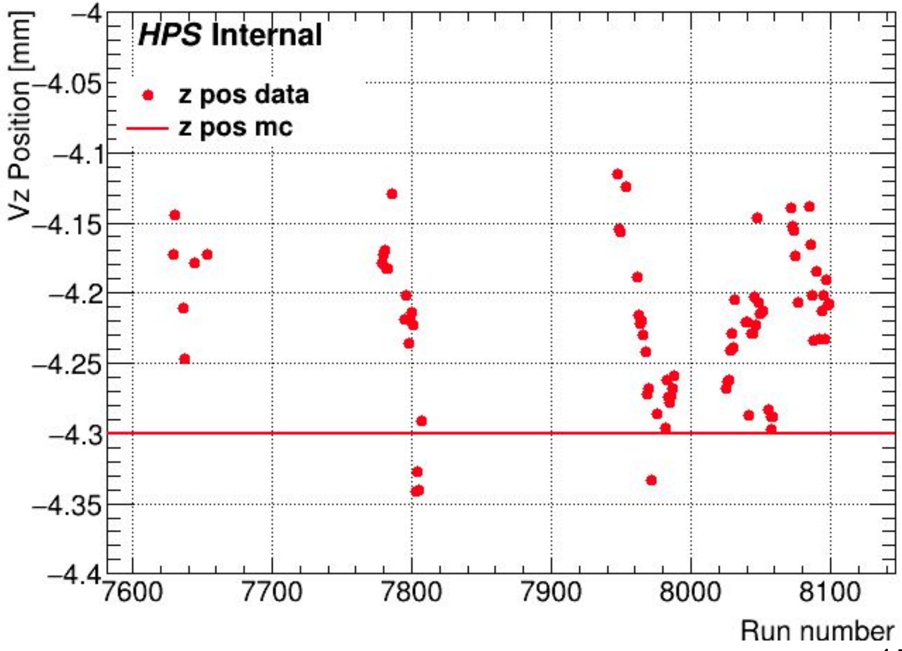
- Run-dependent beam parameters. Target at -4.3 mm is constant
- Beam parameters in MC are constant





Plots courtesy of PF Butti (SLAC)

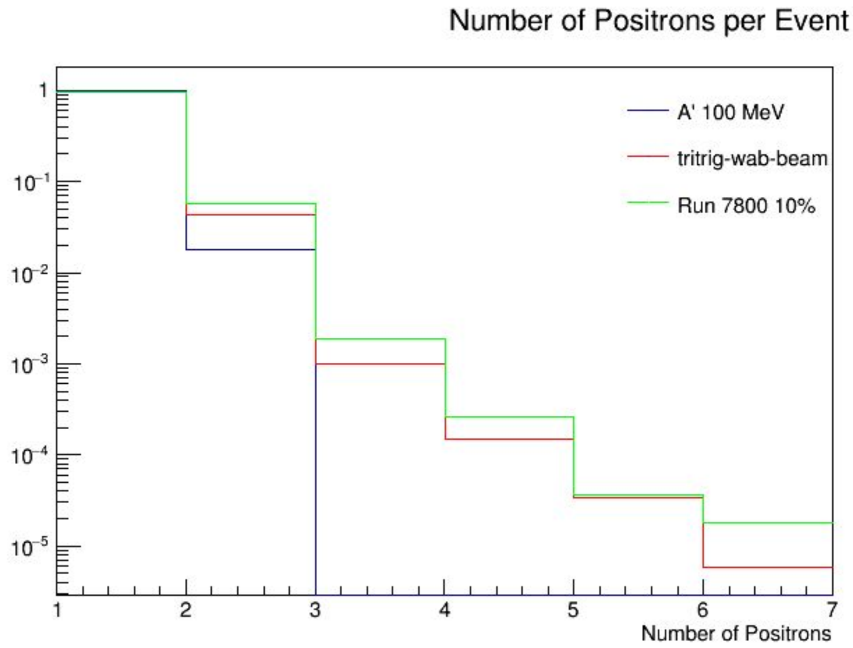
(Very Preliminary) Normalization

- Total Data is 10753 nb^{-1} and 10% sample is 1101 nb^{-1} according to golden runs spreadsheet. We need to agree on these numbers
- Tritrig-wab-beam
  - Number generated / x section = 10^9/359 microbarn = 2786 nb^{-1}
  - This needs to be double-checked. If correct, we may need more tritrig-wab-beam...
- Tritrig
  - Number generated / x section = 10^{10}/359 microbarn = 27860 nb^{-1}
- Radiative fraction
  - Need rad-beam, tritrig-beam, wab-beam MC (Tongtong has almost completed this)
  - Need cross sections of these MC samples (Tongtong)
- For now I normalize to unit area, but we should make normalization a priority

Initial Data/MC Comparisons

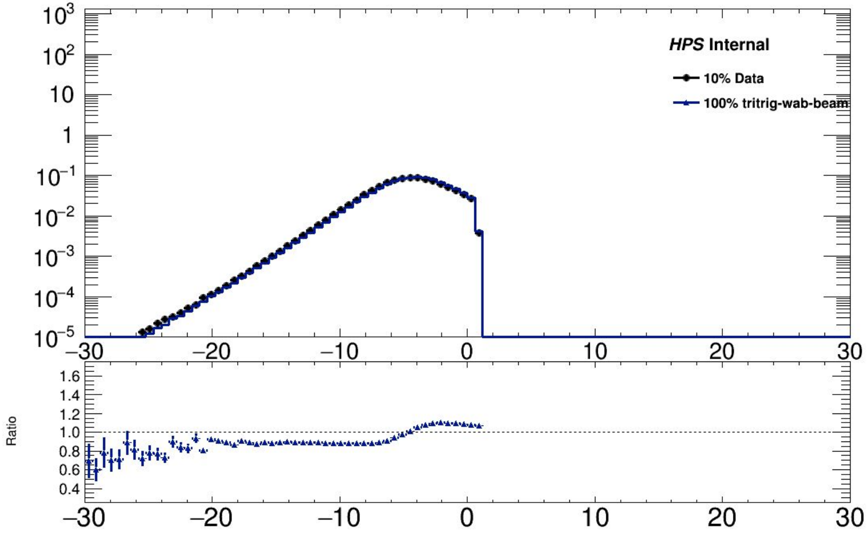
Preselection Cuts
e+e- have L1 Hit (for L1L1), L2 hit
Opposite volume e+e-
e+e- track/cluster match $X^2 < 10$
e+e- track - cluster time < 4 ns
e+e- cluster time difference < 2 ns
e+e- track X^2 / dof < 6
Beamspot constrained $X^2 < 15$
e- momentum < 2.15 GeV
Number of positrons in event = 1
Recon z - target z < 5 mm

- Start conservative - cut out data/MC for reco z 5 mm downstream of the target and compare
- Focus on single positron events (~5% effect)

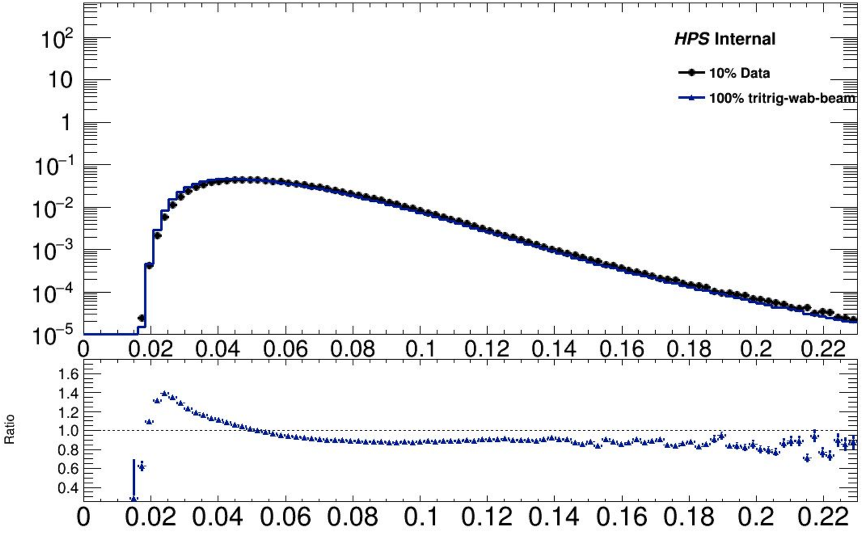


Initial Data/MC Comparisons

- Z is shifted between data/MC. Recon tends to shift mean ~0.5 mm upstream
- There is a shift in the mass scale between data/MC



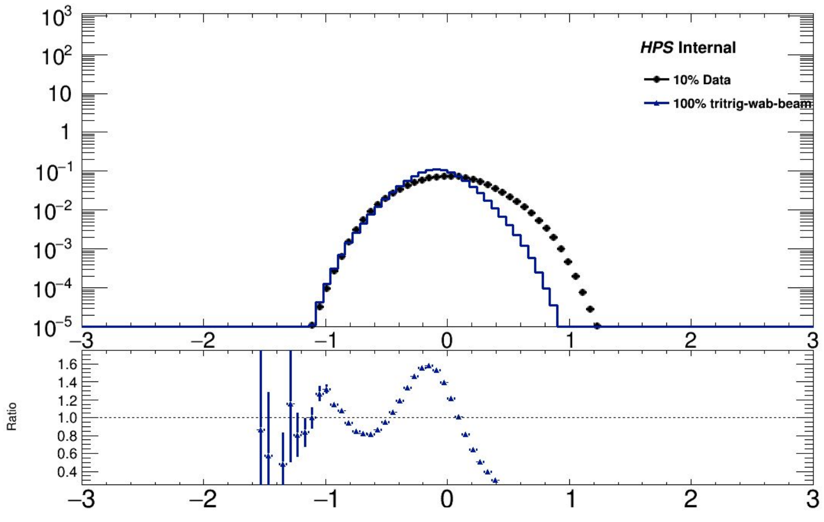
Reconstructed z[mm]



Reconstructed mass [GeV]

Initial Data/MC Comparisons

- X is in poor agreement (but we knew this, mostly due to mis-modeling of hits)
    - Both mean shifted and MC resolution is too good
- Y is shifted, apply proper shifts in data (as function of run) and it may clean up



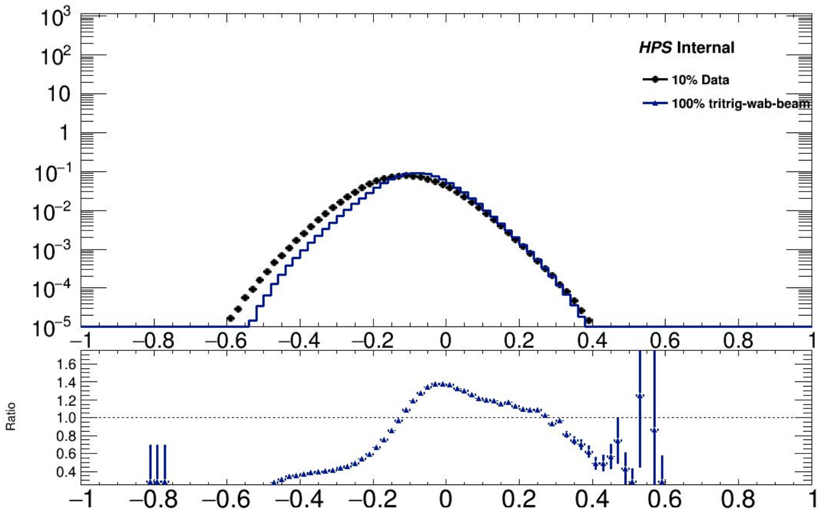


Table of Data/MC Agreement (L1L1)

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Agree Well	Agrees Ok	Poor Agreement
V0 momentum	e+e- track/cluster match X^2	Beamspot constrained X^2
e+e- total momentum	e+e- track X^2 / dof	V0 projection to target in x
V0 projection to target in y	Unconstrained X^2	V0 x
V0 y	V0 mass	Track D0
V0 z	Number of positrons in event	e+e- cluster time difference
e+e- Z0		e+e- track - cluster time

*Category of variables is somewhat subjective, need a better metric to quantify
**These are only variable shapes, we need to do proper normalizations

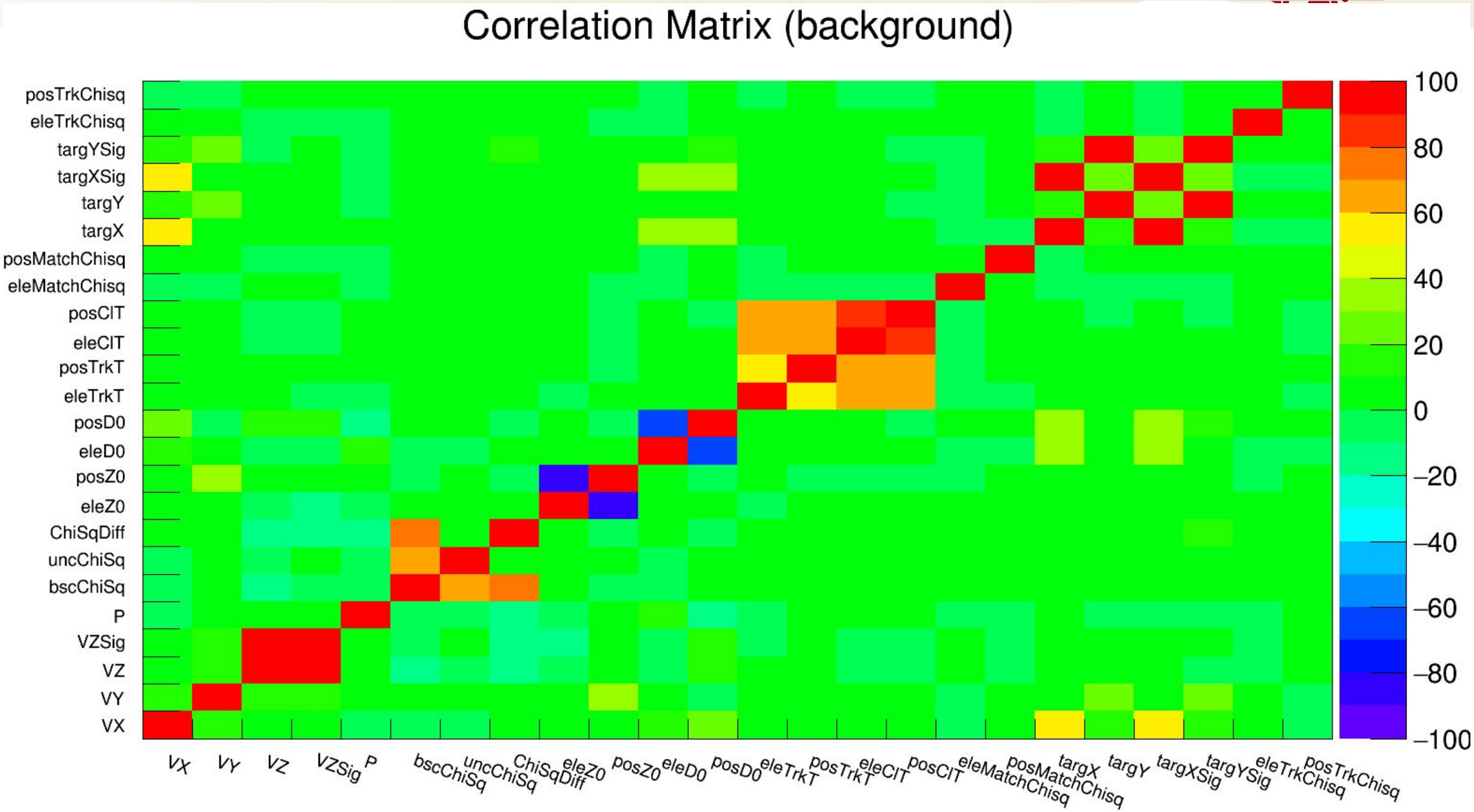
Tuning Cuts

- What cuts can be tuned on data? MC?
- How much data do we look at? 10%? Do we have to throw this data away?
    - We need to be confident that the we understand the tails of the distributions and that it matches MC
    - For now I don't look at Vz - target > 5 mm
- What criteria should we use to tune cuts? How much time/effort do we want to spend on this?
- Standard for justifying cuts
    - Correlations between potential cut variables
    - N-1 cut plots
    - Efficiency of each cut, cut flow plots in signal/background

Potential Cuts

- Ele/Pos have L1 Hit (for L1L1)
- Ele/Pos have L2 Hit
- Ele/Pos Track-Cluster Match Chisq
- Ele/Pos Track/Cluster Time offset
- abs(Ele - Pos Cluster Time)
- Beamspot Constrained Chisq
- Ele/Pos Track Chisq / DOF
- "Isolation" Cut
- Beamspot Constrained - Unconstrained Chisq
- Electron Momentum
- V0 Momentum (Radiative Cut)
- Ele/Pos Momentum Asymmetry Cut
- V0 Projection to Target (x and y)
- SVT Hits in L1

Correlation Matrix Tritrig-wab-beam



Correlation Matrix Tritrig-wab-beam (V0 Z > 5.3 mm)

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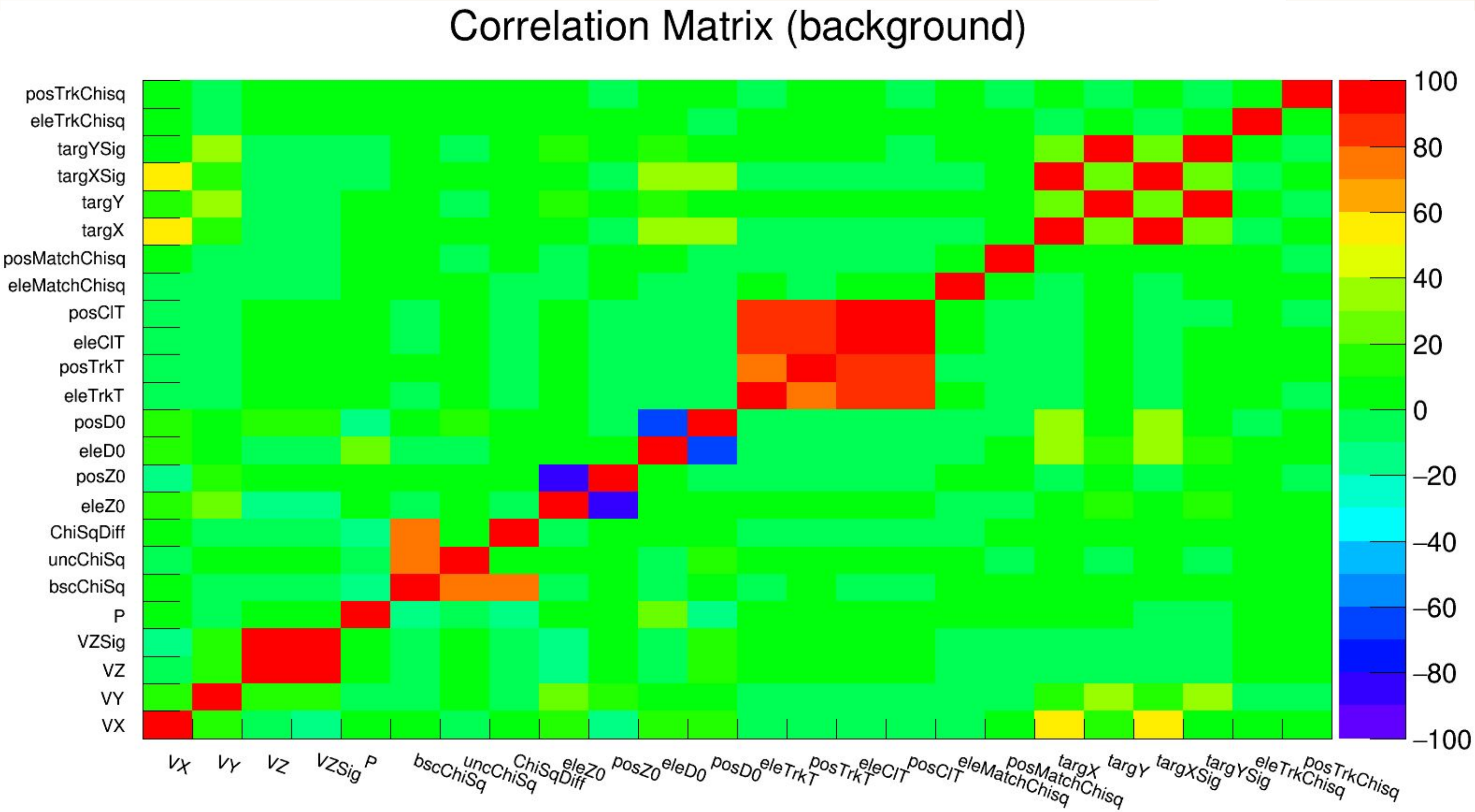
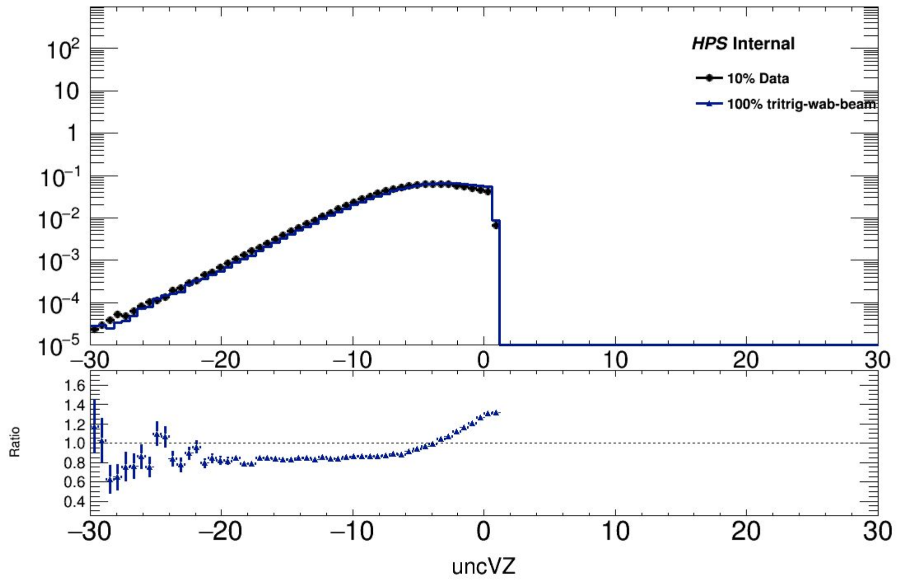
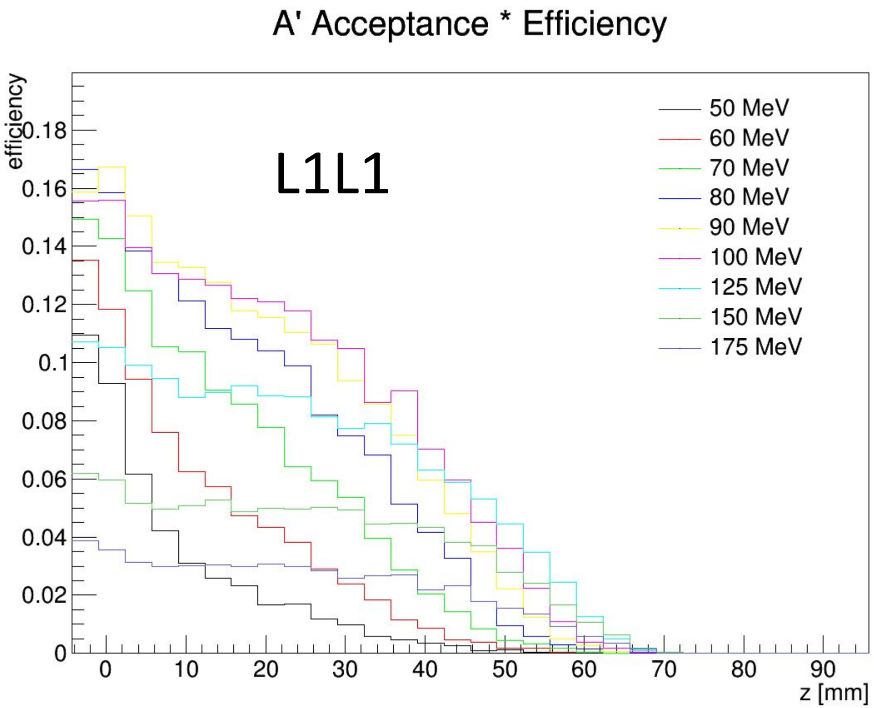


Data/MC Comparison L1L2

- How much can we trust out MC?
- We do not simulate hit efficiencies properly (which dominate L1L2)
- How do we predict a zcut or defined signal region? This is a black box
- Some of these questions may become clearer over time
- Should not be our focus, but we should include this in the dataset
- There is a shift in the mean of z similar to L1L1



A' Acceptance and Efficiency



- Plot shows A' acceptance times efficiency as a function of z for a range of A' masses

$$Acceptance(z) \times \epsilon_{trigger}(z) \times \epsilon_{recon}(z) \times \epsilon_{cuts}(z)$$

- Optimal mass is ~90-120 MeV (though we care about cross-sections too)
- Approximately scales from 1.05 GeV curves
- Needs to be updated with every new cut

A' Acceptance and Efficiency (Longer Decays)

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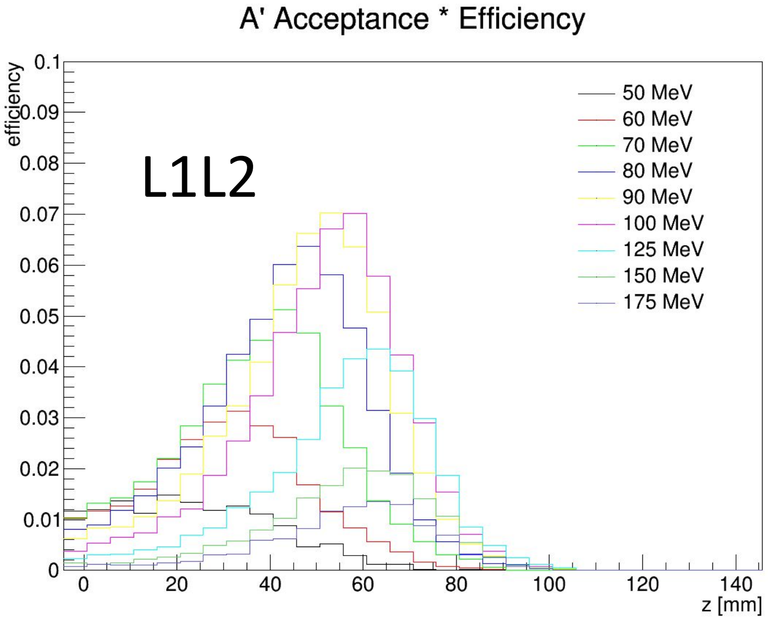
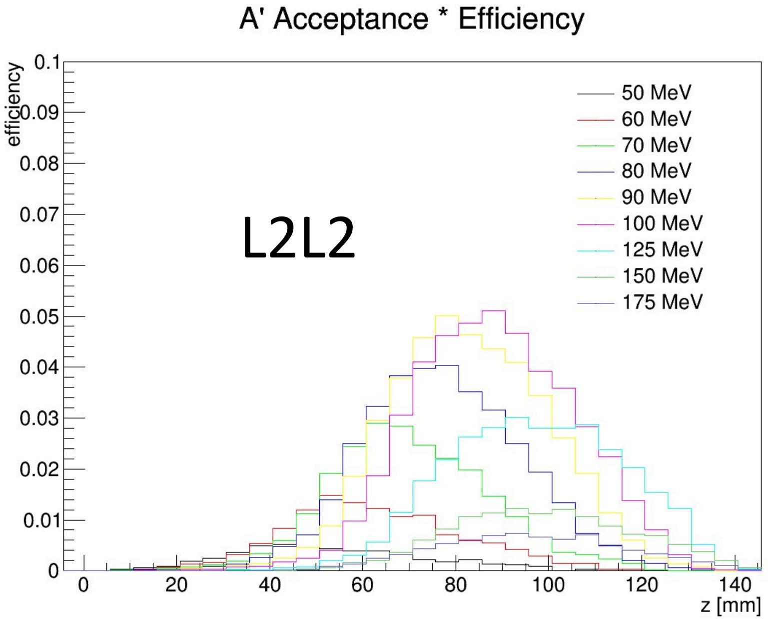
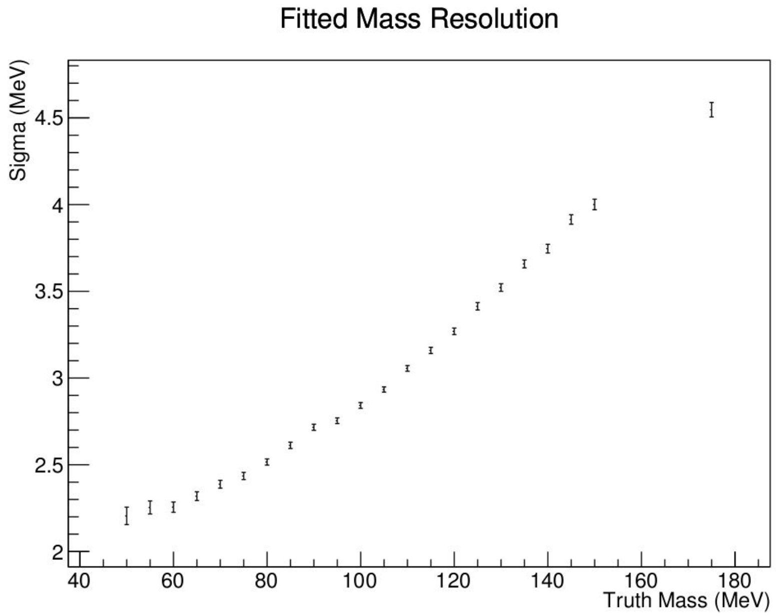


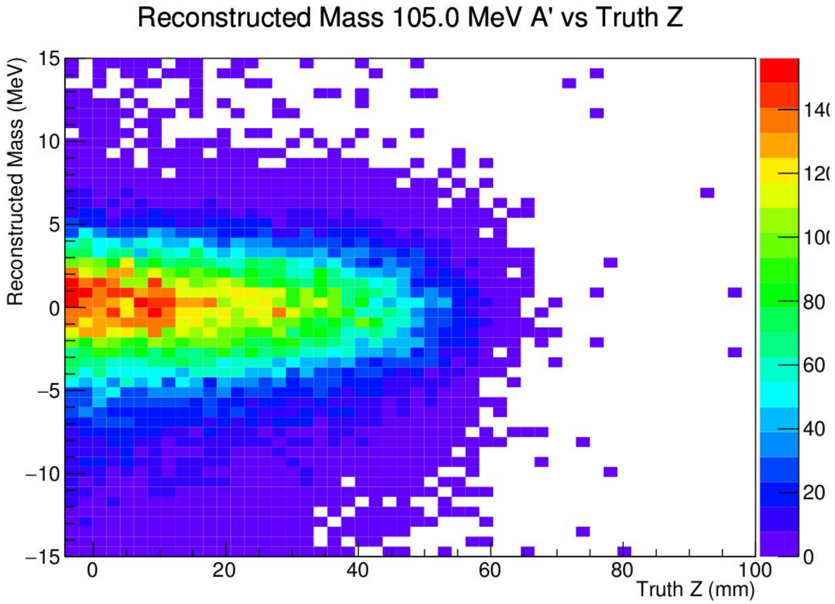


$$Acceptance(z) \times \epsilon_{trigger}(z) \times \epsilon_{recon}(z) \times \epsilon_{cuts}(z)$$

A’ Mass Resolution

- Needs to be updated with every new cut
- Make sure it agrees with bump hunt!

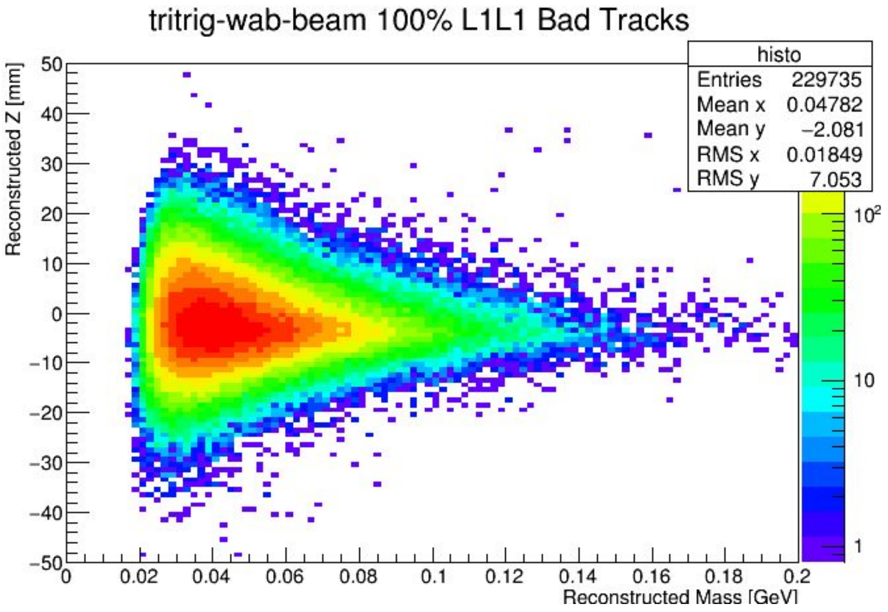




(need to fitted in z slices)

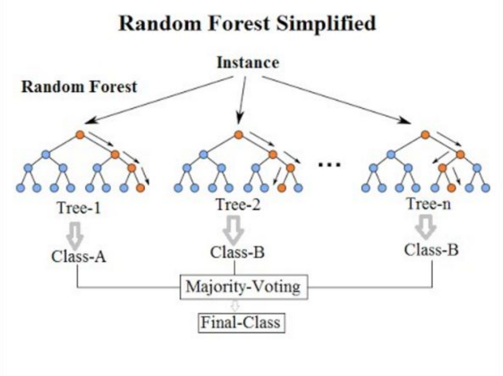
Mistracking

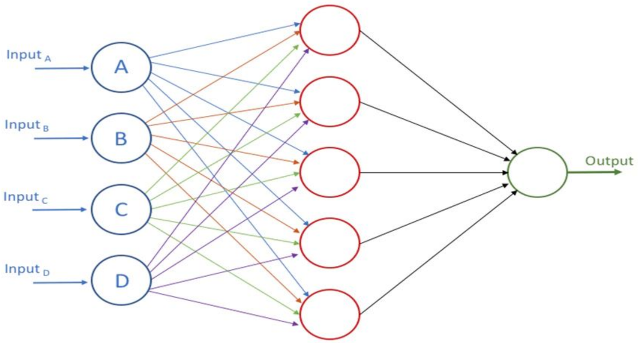
- According to MC, we have high z backgrounds due to mistracking
- Results from 2015 show isolation cut is effective, but not enough. I suspect the same from this dataset (though I will verify)
- Possible solutions to be explored (needs to be compared to signal MC)
    - Tighter isolation cut
    - Graph neural networks
- I have truth refitting tools in place to further explore these backgrounds

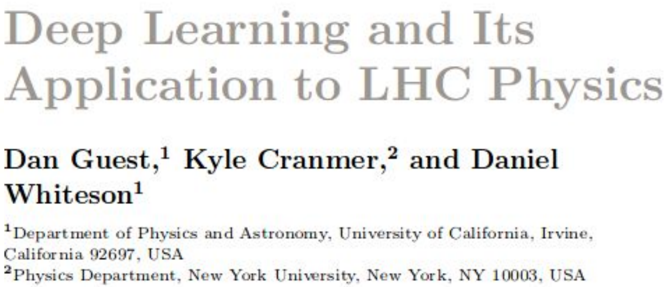


Machine Learning Approach

- Previous results showed improvement in signal yield and background rejection
- Binary Classification - Decision trees or neural networks (I am exploring both)
- Implement a simple method that is efficient and possibly transferable to 2019 data
- Machine learning approaches like this are common in HEP (particularly at the LHC). Very useful introduction to applications of machine learning to physics here






Deep Learning and Its Application to LHC Physics

Dan Guest,[1] Kyle Cranmer,[2] and Daniel Whiteson[1]

[1]Department of Physics and Astronomy, University of California, Irvine, California 92697, USA
[2]Physics Department, New York University, New York, NY 10003, USA

Potential Architectures

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- [Neural Network]
- [Focal Loss] from Facebook's AI
  - Penalizes poorly trained examples (large z backgrounds for us) disproportionately by modifying the loss (error) function
- Working on this for a project for CS230 with Pietro Caraguolo and Luke Pistol
- Start with random forest
  - Simple to implement
  - Feature importances!

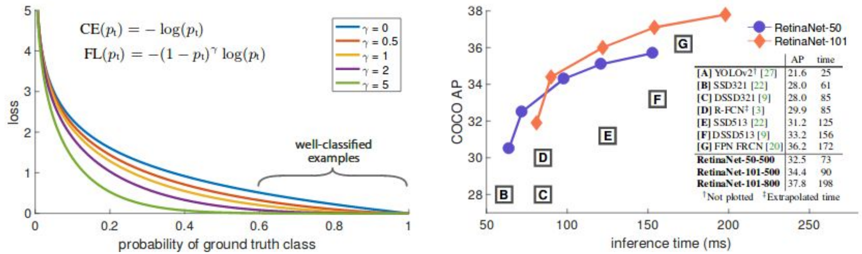
Searching for exotic particles in high-energy physics with deep learning

P. Baldi, P. Sadowski & D. Whiteson

Nature Communications **5**, Article number: 4308 (2014) | Download Citation

Focal Loss for Dense Object Detection

Tsung-Yi Lin   Priya Goyal   Ross Girshick   Kaiming He   Piotr Dollár
Facebook AI Research (FAIR)



Machine Learning Approach

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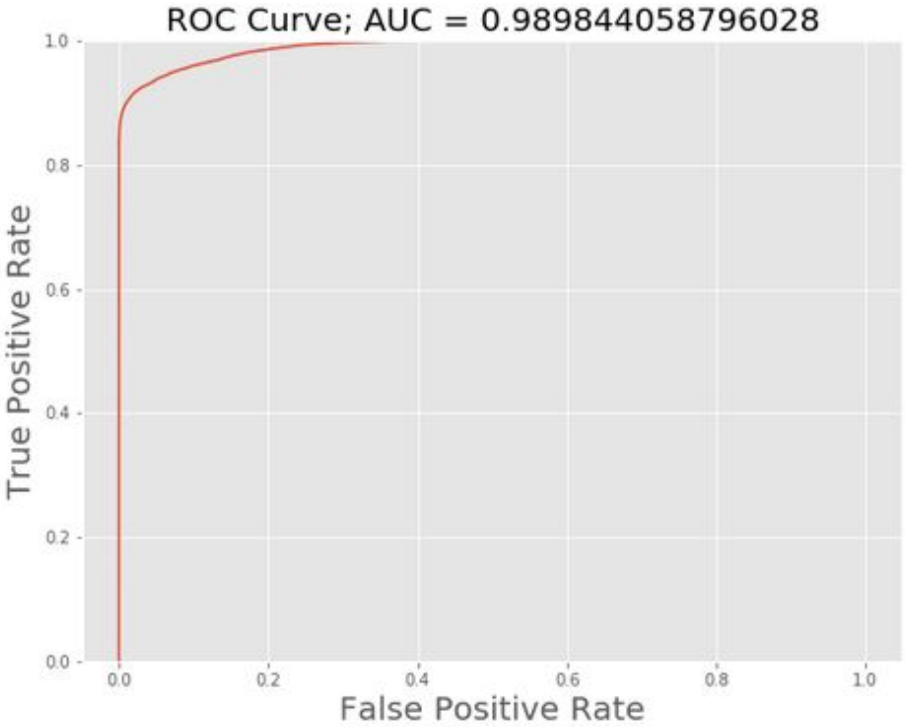
- What variables to use?
  - We must model them correctly in MC
  - Every variable added complicates systematics
  - Focus on tracking/vertexing variables in the measurement direction. Use input from random forest importances
- Train, validate, test
  - Train using ~75% of x10 tritrig sample
  - Validate (tune hyperparameters) using ~25% of x10 tritrig sample
  - Test using 100% tritrig-wab-beam (also test on some portion of data). We will use this test set to measure performance

Variables Used
VZ significance
VZ
VY
V0 y projection
Mass
ele/pos Z0

Signal/Background Comparison

- Example results from a random forest classifier

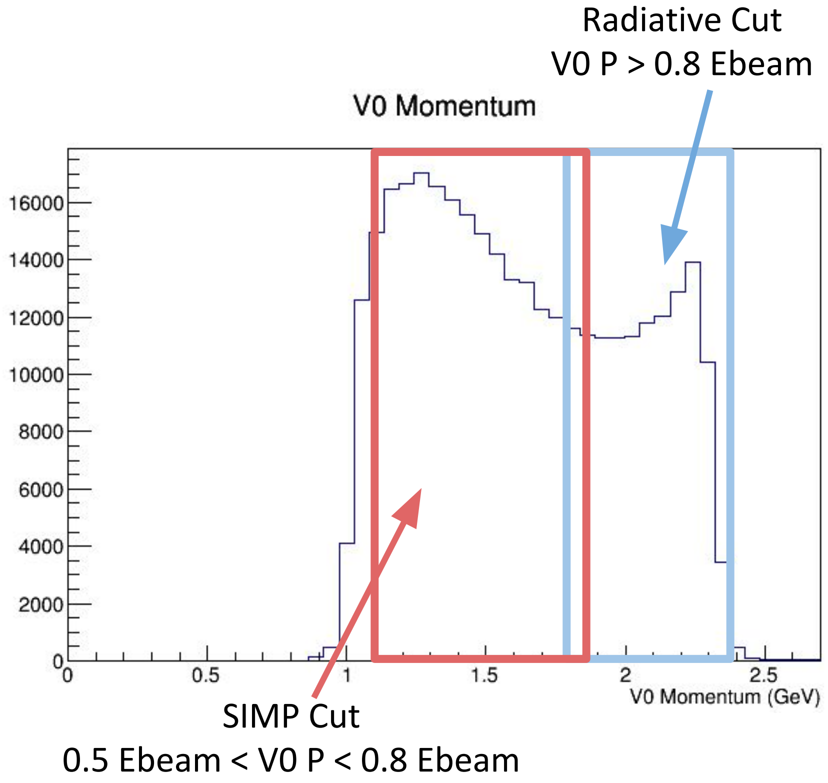


Machine Learning Approach

- Clean data (start with cut-based method) and train an algorithm
- Need to train on every mass point since signal shape changes as function of m
- Data augmentation (over/under sampling to get signal shapes for different ε)
- Setting a limit
    - Output of classifier is a variable that has a signal shape. Use OIM on that variable
- Possible options (assuming ML approach works)
    - Use this method over cut-based approach
    - Use this method as an improvement to cut-based approach
    - Use for background rejection only
    - Do it just for fun (hopefully not this option)

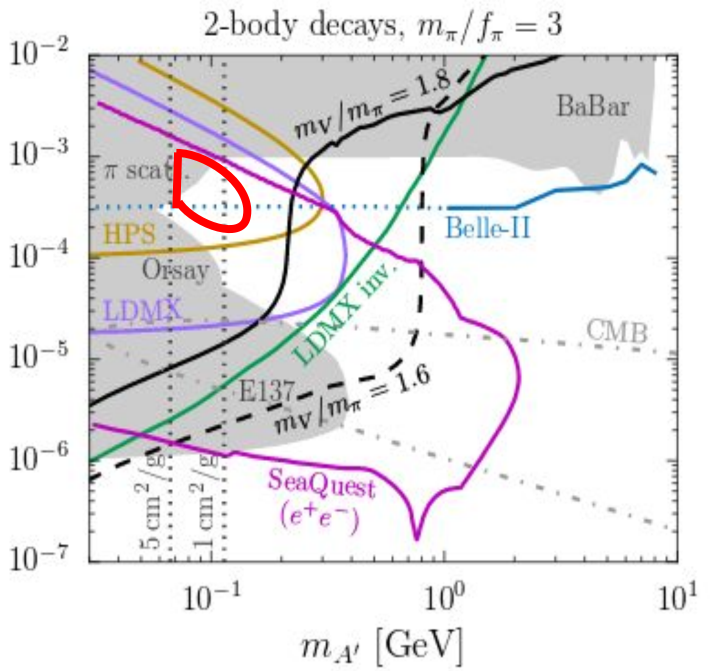
SIMPs for 2016 Analysis

- We can do SIMP searches in parallel with A's (in a different phase space)
  - Same or similar cuts
  - Except for PSum (mutually exclusive?)
- We should do this in a model independent way (loose kinematic cuts). We measure mass and livetimes
- Much of the analysis should be "turning the crank" on scripts for A' search
  - Good project for a rotation student!



SIMPs for 2016 Analysis

- Key differences and unanswered questions
  - Will similar cuts be effective?
  - Larger background rates and lower e+e- momentum (higher z backgrounds)
  - What MC is sufficient?
- MC needs (6 parameter model!)
  - We need to explore how A' and dark pion masses affect distributions
  - If not much, we just need displaced MC for different dark vector masses
  - If they do, we need to rethink this
  - Takashi knows how to do this MC, though it would be good for someone else to learn (Cameron?)



Reach plot is old, need updated MC!

Systematics

- We need a rigourous way to estimate systematics, 2015 was not
- Systematics included in 2015
  - Radiative Fraction
  - Target Position
  - Mass Resolution

Systematic Error	Value
Radiative Fraction	$\sim 7\%$
Target Position	$\sim 24\%$
Mass Resolution	$\sim 3\%$

- Target position systematic was large since we were >5 mm off in target position
- Additional systematics included in 2016
  - Beam position x and y
  - Target thickness
  - “Isolation” Cut
  - Other systematics?
- Systematics associated with ML approach

Putting It All Together

- We need to establish a robust validation and unblinding procedure
  - We should establish a review committee
- Method for setting limits? Probably optimal interval method (OIM)
- Method for determining signal significance
  - We probably don’t have enough for 5 sigma in this dataset, but it would be nice to establish such a method
- Combining datasets L1L1 and L1L2
  - Treat it as 2 different datasets and combine. Other suggestions?
- SIMPs and generalized displaced vertices
  - Attempting to do this in parallel with the A’ search
- Optimize for exclusion or discovery?
  - Suggestion - optimize for exclusion for A’s and discovery for SIMPs

2016 (Aggressive) Vertexing Schedule

SLAC

December 2019	January 2020	February 2020	March 2020
Finish 2016 MC Reconstruction	Moller Mass/Resolution	Tune Cuts for L1L2	Submit Unblinding Proposal
Complete Large MC Sample Analysis	Normalization and Radiative Fraction	Tune Cuts for SIMPs	Unblind Data (April 1)
Initial Analysis Procedure	Tune cuts for L1L1	Finalize Analysis Procedure	
Initial ML results	Finalize ML Approach		
	Finish SIMP MC		
	Prelim Document to Review Committee		

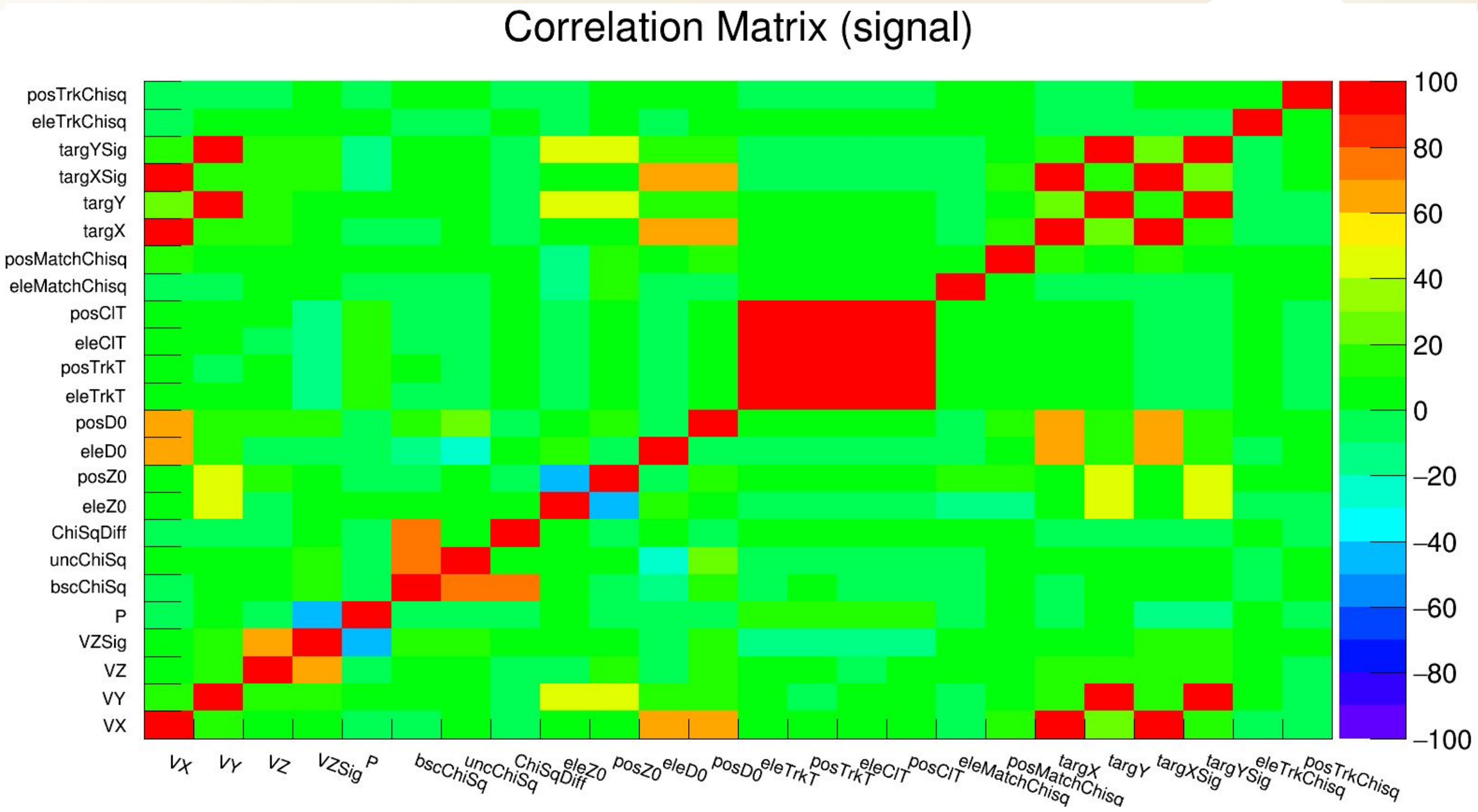
Making Reach Estimates

- What is needed for reach estimates? - All with the correct detector!
  - Displaced A' acceptance (needs A' MC for a wide mass range)
  - Zcut as a function of mass which comes from the fit of the tails (needs fairly large sample of tridents)
  - Basic cleanup cuts
  - Mass resolution
  - Normalization and radiative fraction (rad, tritrig, and wab MC with cross sections)
- We only know how to do this for L0L0, further downstream decays is more difficult to predict
- No update for reach estimate for 2016 from last collaboration meeting

Conclusion

- MC production is going well. Preliminary look is mostly as expected
  - Though there are still data/MC discrepancies
- We should discuss and agree upon an analysis procedure to move forward
- Next steps - closer MC look, normalization, and tune cuts
- Aggressive timeline proposed for this analysis, let’s see if we can stick to it!
- 2016 Analysis should be the priority, I want to finish sometime...

Correlation Matrix 100 MeV Displaced A'



Correlation Matrix Run 7800