Search for a Long-Lived $\mu\mu$ Resonance at ICARUS in SBN

NuFact 2024

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September 16th, 2024

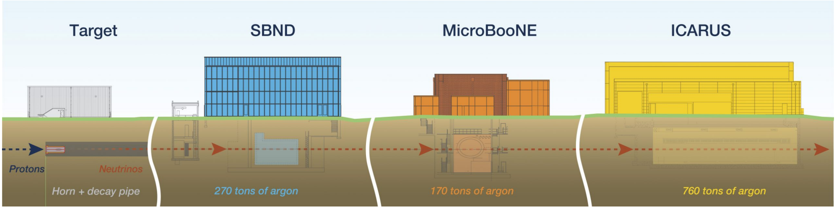
Imaging Cosmic And Rare Underground Signals

THE UNIVERSITY OF CHICAGO

SBN Program

- **ICARUS and SBN**
- Dimuon Signal Model
- Coh Pion Prod Background
- Unboxing Fake Data Demonstration
- Results
- Interpreting Results as Limits
- Conclusion

Short Baseline Neutrino Program

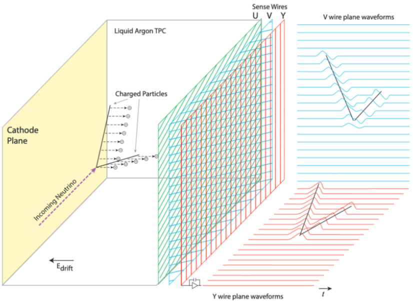


- Multi detector oscillation analysis program will leverage near detector to constrain systematics
- Diverse set of analysis opportunities for cross-section and BSM analyses as well
- All detectors have reached data taking stage as of July!

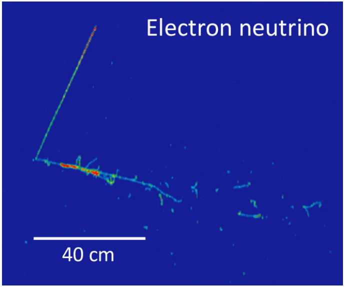
The ICARUS Detector

- ICARUS TPC previously operated at Gran Sasso Laboratory. Moved to Fermilab in 2018.
- Completed Comissioning Phase in Summer 2022
- Initial detector operation detailed in: Eur.Phys.J.C 83 (2023) 6, 467

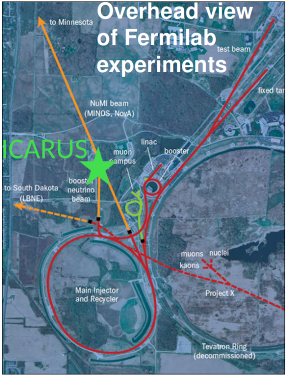
LArTPC Operating Principles

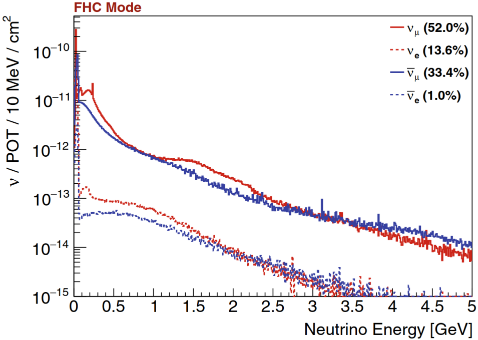


- Incoming neutrinos interact with liquid argon in detector
- Charged products produce scintillation light and ionization electrons which drift to wire planes



NuMI Beamline

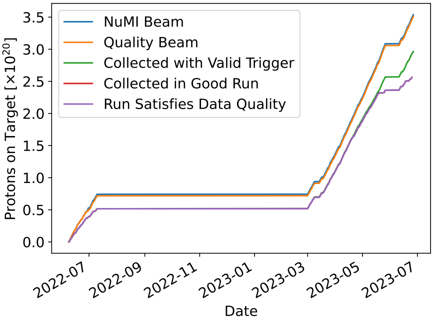




Source: Mistry, K.V.J., The NuMI Beam and Neutrino Flux Prediction at MicroBooNE

- NuMI beam has higher beam energy relative to BNB which allows for production of Kaons at a greater rate
- Can leverage this high Kaon production rate for signs of BSM physics

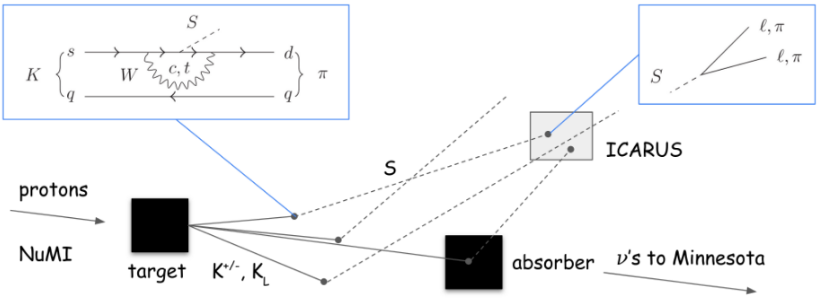
Data Collection



Final POT: 2.41×10^{20}

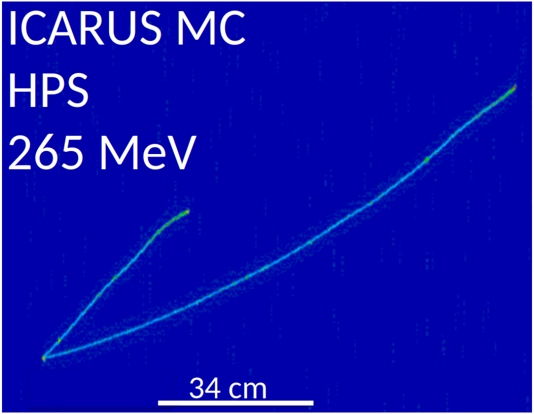
- ICARUS data collected from Runs 1 & 2
- Quality Beam Cuts: Beam operating at ideal conditions
- Valid Trigger: Trigger and beam agree
- Good Run: Detector operating at ideal conditions
- Data Quality: Software for data processing behaves as expected

Dimuon Signal Model



S = Higgs Portal Scalar, Heavy QCD Axion

Dimuon Signal Model



- Neutrinos don't produce two muons $\rightarrow$ no irreducible backgrounds
- Reducible backgrounds should have products which are easily misinterpreted as muons or missed protons.

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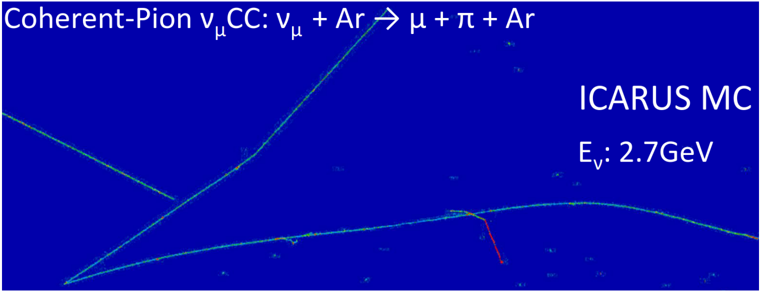
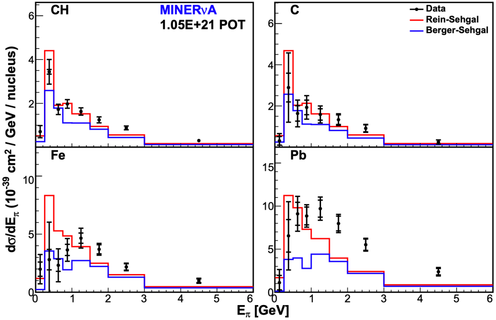
Coh Pion Prod Background

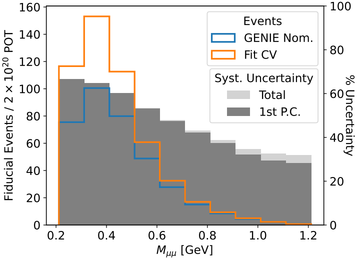


- After event selection (Muon/proton ID, kinematic cuts) we have primarily Coherent-Pion production.
- This interaction is poorly understood, especially for argon nuclei.
- Can leverage previous measurements from MINERvA data to better inform our MC.

- Tune to MINERvA data gives us valuable information about the shape uncertainty
- In the invariant mass distribution, majority of systematic uncertainty manifests as normalization uncertainty
- Want to utilize the invariant mass distribution, search for "bumps".

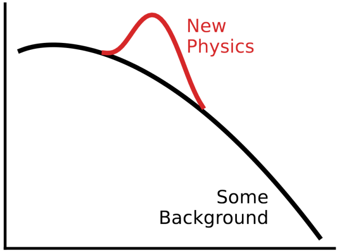
Source: The MINERvA Collaboration, Phys. Rev. Lett. 131, 051801





Unboxing Fake Data Demonstration

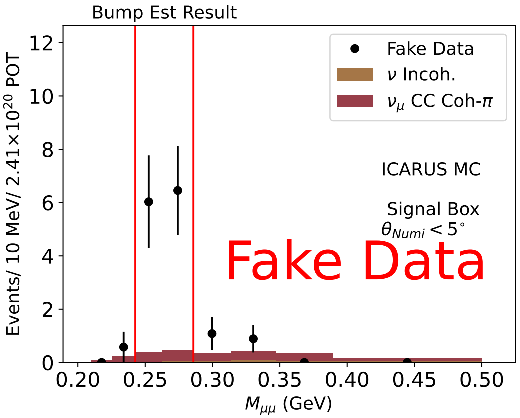
Utilize ATLAS collaboration's BumpHunter test statistic (Georgios Choudalakis, arXiv:1101.0390) which takes data and background as input and outputs test statistic describing deviation.

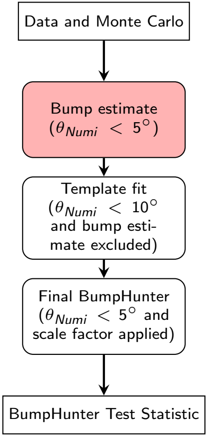


Want to be robust against imperfections in the Coh MC background component, so muct perform several additional steps including a template fit to obtain data driven MC correction. Following demo uses HPS MC ($\theta = 7.2 \times 10^{-5}, M_s = 260$ MeV).

Bump Estimate

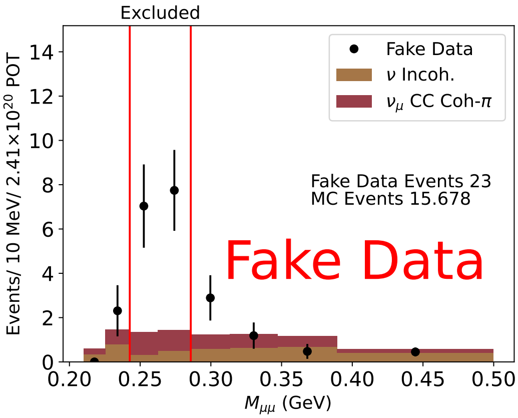
Using BumpHunter, can estimate region of largest deviation from the background for $\theta_{Numi} < 5^\circ$ before template fit. This is our "Bump Estimate" region, which we block out for the template fit.

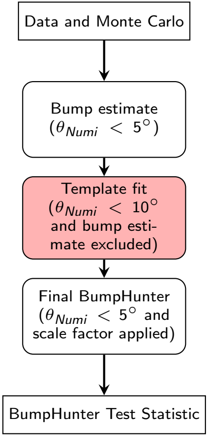




Template Fit

Allow for variations of Coherent MC normalization via template fit based method. After removing "Bump Estimate" region, perform a template fit using data with $\theta_{Numi} < 10^\circ$.





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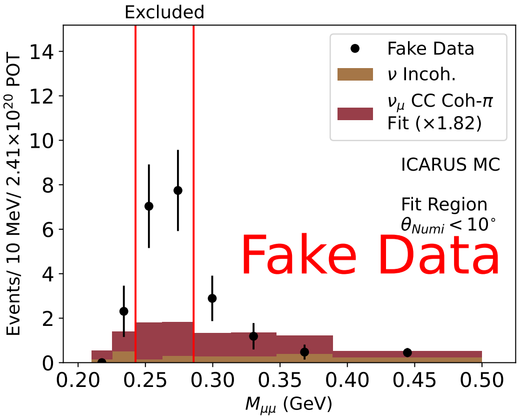
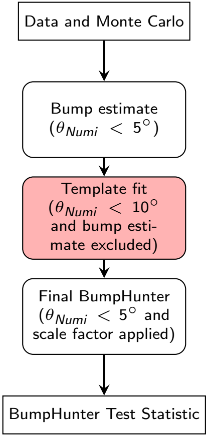
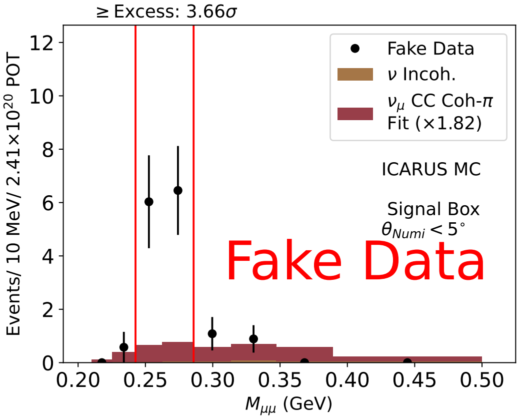
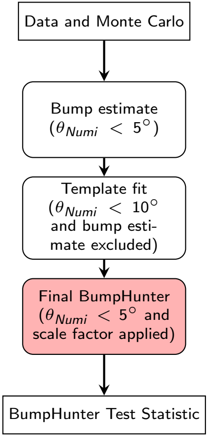




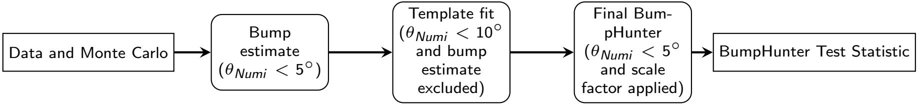
Final BumpHunter

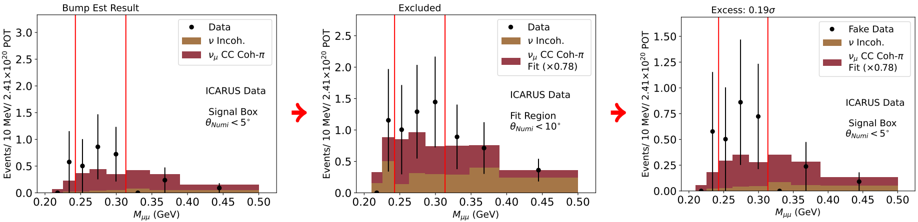
Apply the scale factor obtained from template fit to $\theta_{Numi} < 5^\circ$ region to get data driven correction to MC. We can then obtain a final BumpHunter test statistic.



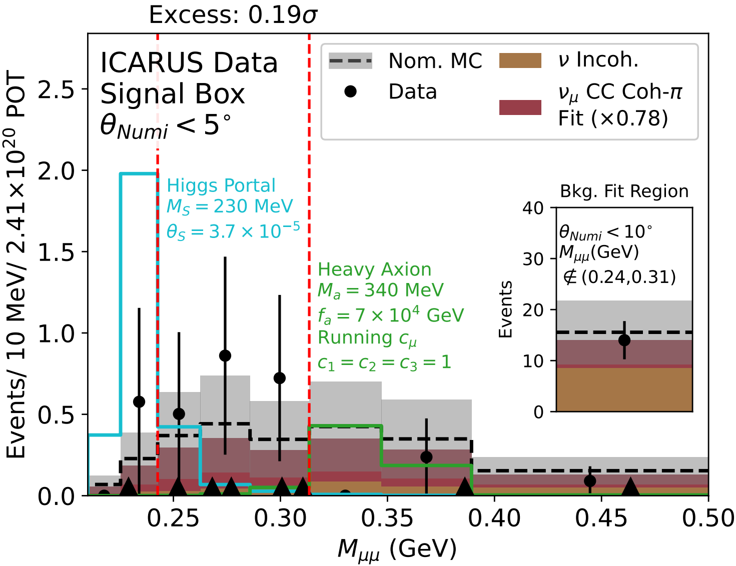


Results


Data and Monte Carlo
Bump estimate ($\theta_{Numi} < 5^\circ$)
Template fit ($\theta_{Numi} < 10^\circ$ and bump estimate excluded)
Final BumpHunter ($\theta_{Numi} < 5^\circ$ and scale factor applied)
BumpHunter Test Statistic


Bump Est Result
Data
ν Incoh.
ν_μ CC Coh-π
ICARUS Data
Signal Box
$\theta_{Numi} < 5^\circ$
Events/ 10 MeV/ 2.41×10^20 POT
$M_{\mu\mu}$ (GeV)
Excluded
Data
ν Incoh.
ν_μ CC Coh-π Fit (×0.78)
ICARUS Data
Fit Region
$\theta_{Numi} < 10^\circ$
Events/ 10 MeV/ 2.41×10^20 POT
$M_{\mu\mu}$ (GeV)
Excess: 0.19σ
Fake Data
ν Incoh.
ν_μ CC Coh-π Fit (×0.78)
ICARUS Data
Signal Box
$\theta_{Numi} < 5^\circ$
Events/ 10 MeV/ 2.41×10^20 POT
$M_{\mu\mu}$ (GeV)

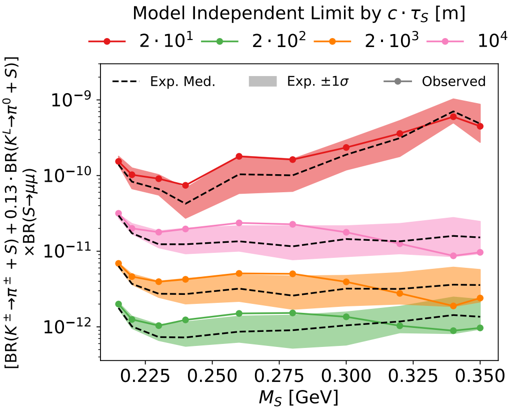
Results



Excess: 0.19σ
ICARUS Data
Signal Box
$\theta_{Numi} < 5^\circ$
Nom. MC
Data
ν Incoh.
ν_μ CC Coh-π
Fit (×0.78)
Higgs Portal
$M_S = 230$ MeV
$\theta_S = 3.7 \times 10^{-5}$
Heavy Axion
$M_a = 340$ MeV
$f_a = 7 \times 10^4$ GeV
Running c_μ
$c_1 = c_2 = c_3 = 1$
Bkg. Fit Region
$\theta_{Numi} < 10^\circ$
$M_{\mu\mu}$(GeV)
$\notin (0.24,0.31)$
Events
40
30
20
10
0
Events/ 10 MeV/ 2.41×10^{20} POT
2.5
2.0
1.5
1.0
0.5
0.0
0.25
0.30
0.35
0.40
0.45
0.50
$M_{\mu\mu}$ (GeV)

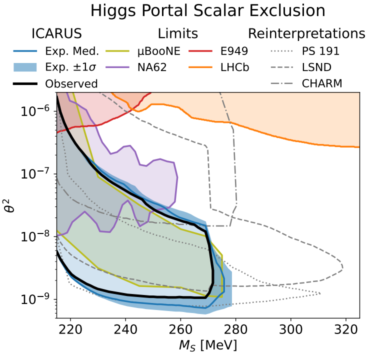
Model Independent Limit

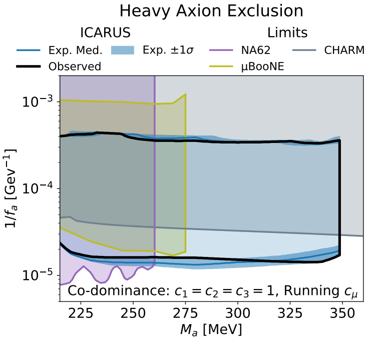
Dimuon processes are more general than individual BSM models. Can see what this analysis method looks like just in terms of the branching ratios (which control the rate) and the lifetime (which determine the mean distance traveled). Can calculate the 90% CL in this phase space.



Model Dependent Limit

Can reweigh the model independent limit to match those of the two particular models we are interested in: Higgs Portal Scalar and Heavy QCD Axion.





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Conclusion

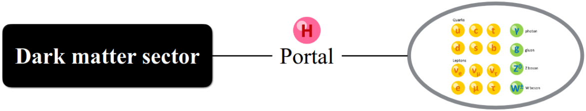
- Using ICARUS data from the NuMI beam, we conducted a search for dimuon signal processes which could yield evidence of BSM phenomena.
- An unboxing procedure was developed which was resilient against normalization uncertainty in the coherent pion production background.
- No significant excess was found, leading limits on the Higgs Portal Scalar and Heavy QCD Axion models were set.
- Current extensions of the analysis are in development which leverage timing information from PMTs to exploit the timing structure of the beam and to include exiting muons in the search.
- Paper currently under review!

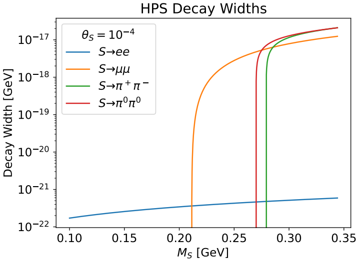
Many thanks to the ICARUS collaboration for making this analysis possible!

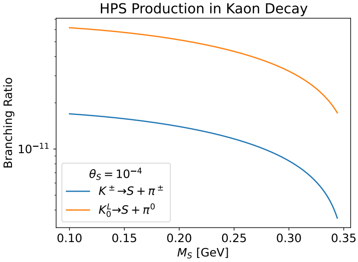
Back-Up

Higgs Portal Scalars

Some models of BSM physics suggest the possibility of a new scalar particle which could mediate interactions between dark and ordinary sectors.





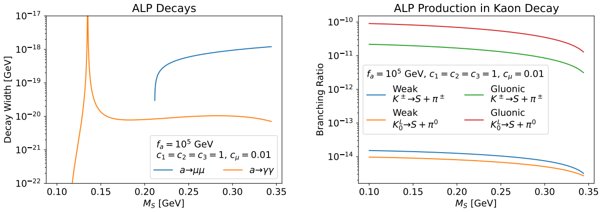


In cases where $210 MeV < m_S < 270 MeV$, the $\mu^+\mu^-$ channel is the most sensitive.

Heavy QCD Axions

"Strong CP Problem": CP violation in strong interactions experimentally found to be $O(10^{-10})$, in contrast to theoretical predictions of $O(1)$

Solution: "QCD axion" has potential with CP-conserving minimum.

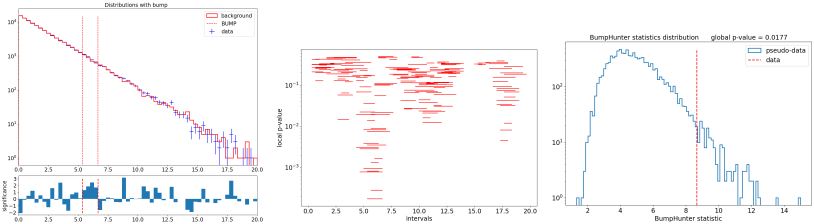


"Axion quality problem" arises: Planck scale suppressed terms in the Lagrangian can cause drive the axion away from the minimum

Solution: "Heavy QCD Axion" gives strengthened stable, CP conserving potential.

BumpHunter Test Statistic

Method for locating bumps in invariant mass plots and determining their significance from ATLAS collaboration Georgios Choudalakis: arXiv:1101.0390.



Given a background and a set of recorded data (signal+background), we can determine local p-values in a bunch of windows. Using the smallest local p-value, calculate “bump hunter hyper test statistic”. Use this to obtain a global p-value.

- Included in Scikit-HEP Project
- Minimal dependencies: numpy, scipy, matplotlib
- Developed by members of the ATLAS collaboration

pyBumpHunter

launch binder | automated_testing passing | pypi v0.4.2 | DOI 10.5281/zenodo.7684558

This is a python version of the BumpHunter algorithm, see arXiv:1101.0390, G. Choudalakis, designed to find localized excess (or deficit) of events in a 1D or 2D distribution.

The main BumpHunter function will scan a data distribution using variable-width window sizes and calculate the p-value of data with respect to a given background distribution in each window. The minimum p-value obtained from all windows is the local p-value. To cope with the "look-elsewhere effect" a global p-value is calculated by performing background-only pseudo-experiments.

The BumpHunter algorithm can also perform signal injection tests where more and more signal is injected in toy data until a given signal significance (global) is reached (*signal injection not available in 2D yet*).

Content

- pyBumpHunter : The pyBumpHunter package
- example : Folder containing a set of example scripts and notebooks
- example/results : Folder containing the outputs of example scripts
- test : Folder containing the testing scripts (based on pytest)
- data/data.root : Toy data used in the examples and tests
- data/gen_data.C : Code used to generate the toy data with ROOT

For the invariant mass distribution, we can count the data, d, and background, b, (given by the template fitted MC) in some window of the distribution. In each window, we define the local test statistic in terms of some arbitrary positive monotonically increasing function, f, to be

$$t = \begin{cases} 0 & d \leq b \\ f(d-b) & otherwise \end{cases}$$

If $t_0 = 0$ then $t \geq t_0$ so we have a pvalue of 1. If $t_0 > 0$, then $t \geq t_0$ implies $d - b \geq d_0 - b \iff d \geq d_0$. The pvalue $P(d \geq d_0 | H_0)$ is then essentially the probability of getting a Poisson fluctuation greater than d_0 given a Poisson distribution with mean b.

This probability corresponds to adding the contributions from Poisson distribution at higher integers. and is equal to $\sum_{n=d_0}^{\infty} \frac{b^n}{n!} e^{-b}$. This expression is just the series expansion of the CDF of a Gamma distribution. In integral form, this is equal to

$$\Gamma(d, b) = \frac{1}{\Gamma(d)} \int_0^b t^{d-1} e^{-t} dt$$

This means that we can calculate a p value analytically to be

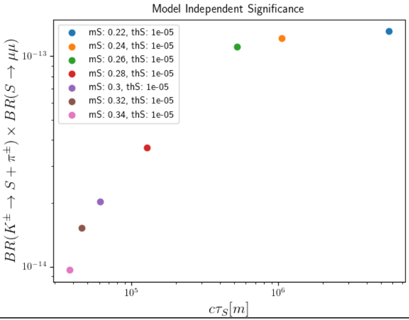
$$p = \begin{cases} 1 & d \leq b \\ \Gamma(d, b) & otherwise \end{cases}$$

from the data and background counts in the window. This is particularly helpful because it means we do not need to produce pseudodata for each window we look at. Calculating a local pvalue for some user defined set of windows, we can then calculate the global test statistic as $-\log(p_{min})$

“Model Independent” interpretation of results

Dimuon processes are more general that just the HPS model. Can see what this analysis method looks like just in terms of the branching ratios (which control the rate) and the lifetime (which determine the mean distance traveled).

Each (m_S, θ_S) point also corresponds to a specific point in the $(c\tau, BR)$ parameter space. One can reweigh events to move a specific point around the $(c\tau, BR)$ parameter space.



Efficiencies for PID, Kinematic cuts

Efficiency is model dependent. Some examples: