Status of milliQan simulation

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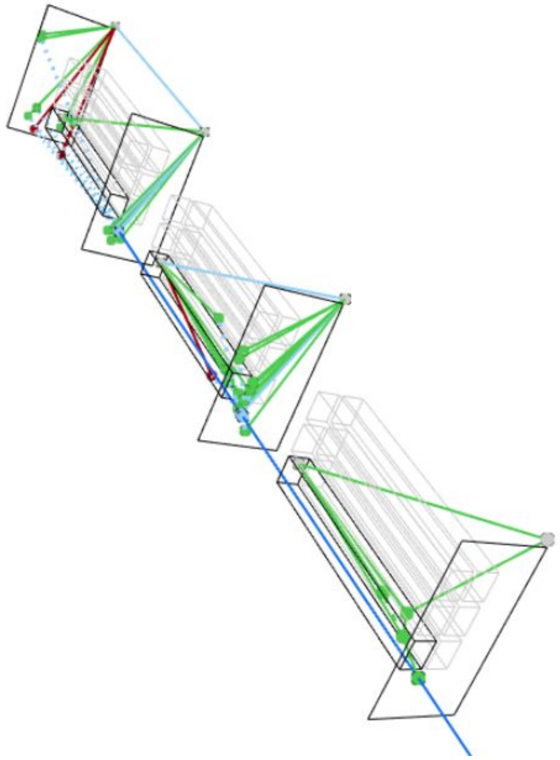
milliQan monthly meeting
December 5, 2019

Overview of simulation pipeline

1. **Generation of initial four-vectors**
   - Compute cross sections/p_T distributions for all possible production modes of mCPs and muons
   - For signal, decay mother particles to get mCP pairs
2. **Propagate from IP to detector face**
   - Through map of CMS material/magnetic field, including multiple scattering and energy loss
3. **Feed list of positions/momenta into Geant model of demonstrator**
   - Full geant model, including all bars/slabs/panels, individual PMTs, hodoscopes, lead bricks, support structure, cavern
4. **Ntuple-ize raw Geant output into simple PE counts and times**
5. **Inject PE pulses into zero bias data for realistic output**
   - SPE pulse templates and area distributions measured on the bench with LEDs, separately for each PMT type
   - Randomly sample over large number of zero bias runs to avoid bias



mCP production

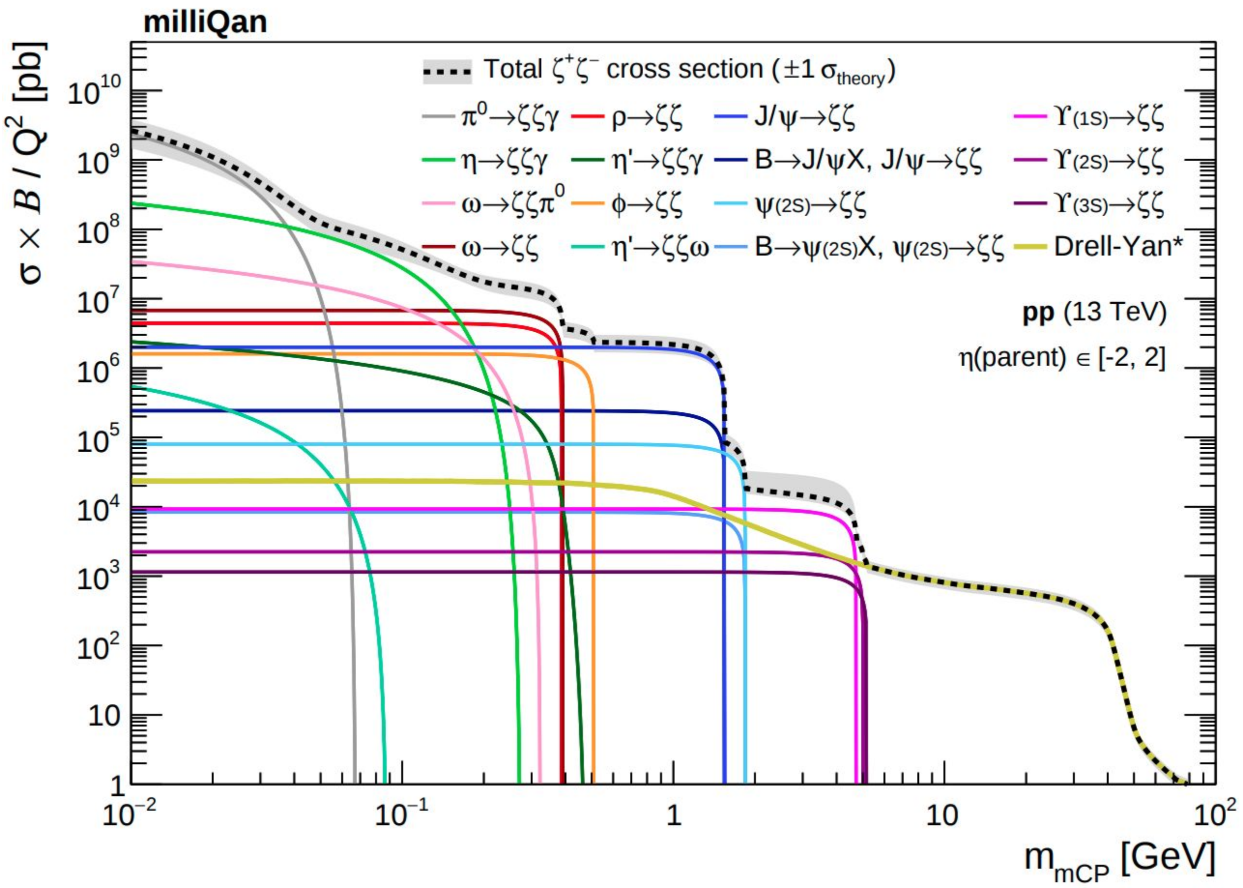
Many possible modes of mCP production. Anything that produces an e^+e^- pair via a virtual photon can also produce an mCP pair

1. Two-body and Dalitz decays of **π^0, η, η’, ρ, ω, ϕ**
   - Rates of light meson production taken from Pythia MinBias/QCD
   - Using the standard CMS tune as a default, but will assign a systematic based on variation from choice of tune
2. Decays of **J/ψ** and **ψ’**, either directly produced or from B decay
   - Rate from B decay taken from FONLL web tool
   - Cross sections and p_T spectra of direct production taken from theorists
3. Decays of **Υ(1,2,3S)**
   - For $p_T > 20$ GeV, taken from 13 TeV CMS data
   - For $p_T < 20$ GeV, taken from 7 TeV ATLAS data rescaled to 13 TeV (13/7 TeV ratio taken from CMS/LHCb measurements)
4. **Drell-Yan**
   - Sub-dominant until upsilons die out at $m_{mCP} = 5$ GeV

Mother particles are produced randomly, flat in eta [-2,2] (or [-3,3] for upsilons), and decayed with proper 2-body or Dalitz kinematics

All documented in more detail here: https://github.com/bjmarsh/milliq_mcgen/blob/master/docs/milliqanGeneration.pdf

mCP production

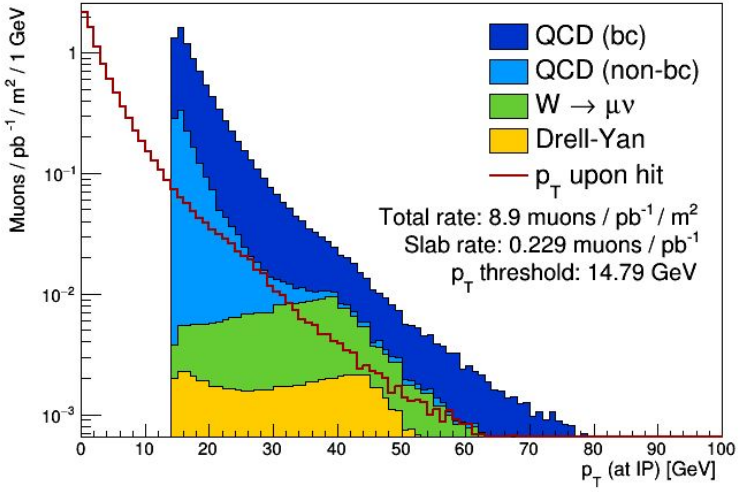


Muon production

Need muon simulation so that we can compare with data and validate

Four separate muon production processes to generate. Need both cross sections and p_T distributions

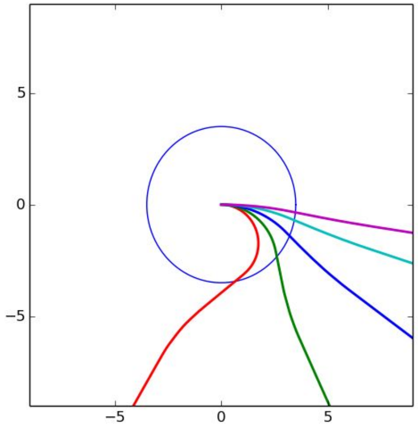
1. from **b- or c-hadron decays**
   - $d\sigma/dp_T$ from theorists (FONLL)
   - This is known to be low so we scale up by a constant factor of 1.25, based on a CMS measurement
2. from **light-flavor meson decays** in flight
   - Taken from pythia MinBias/QCD, like signal
   - Mostly from $\pi^{\pm}$ and $K^{\pm}$, some from $\tau^{\pm}$, ω, ρ, ϕ, K^0_L
3. **W → μν**
4. **Drell-Yan**
   - Taken from MadGraph

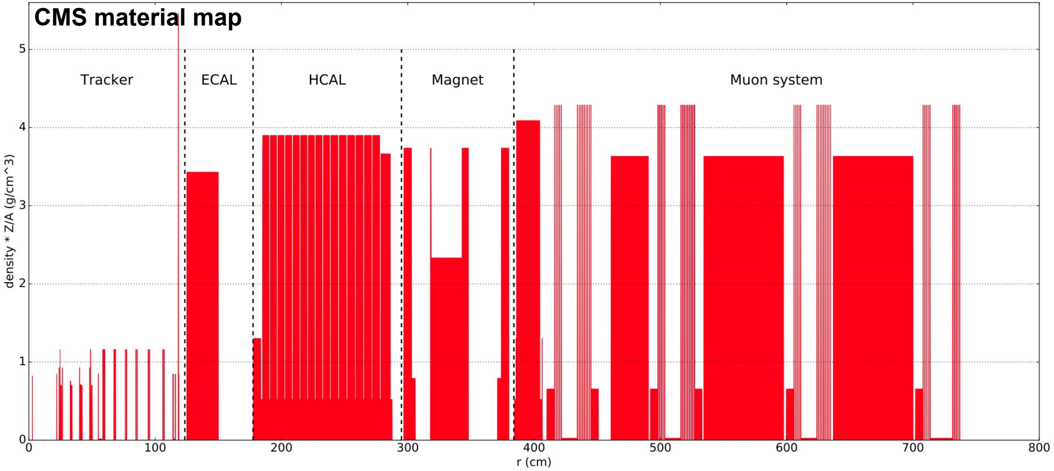


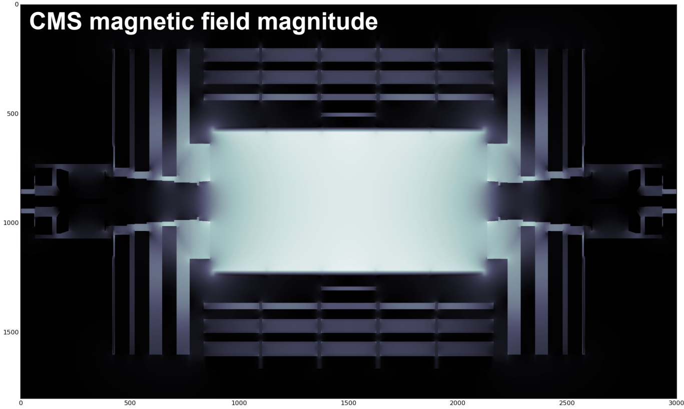
Composition at detector face is **53%** from b-hadrons, **29%** from c-hadrons, **14%** from light-flavor mesons or taus, **3%** from W, and **1%** from DY

Propagation

- mCPs and muons are propagated to milliQan detector face with a python simulation, including B-field, multiple scattering, and energy loss effects
- Realistic models of CMS magnetic field and material
- Documented in detail here: https://github.com/bjmarsh/milliq_mcgen/blob/master/docs/milliqanPropagation.pdf

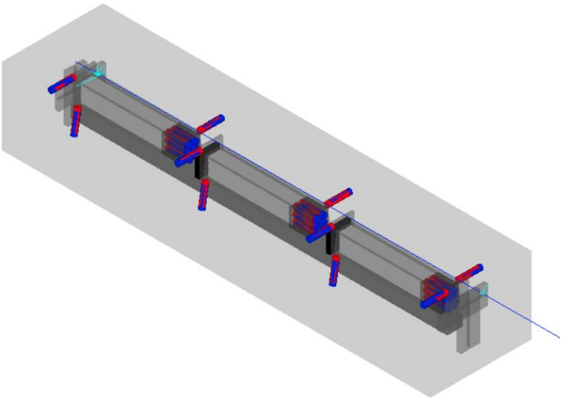


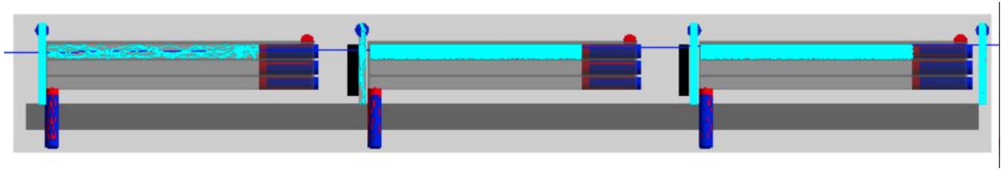


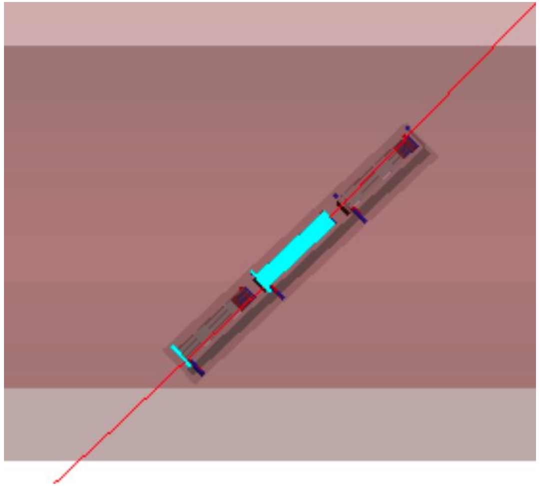


Geant4 simulation

- Thanks to much work from Ryan @ UCSB and Michael @ OSU, have a working full Geant4 model of the demonstrator
- Includes bars, slabs, panels, type-specific PMTs, hodoscopes, lead bricks, aluminum support structure, arch-shaped cavern
- Can handle mCPs and both beam and cosmic muons
- Scintillator response calibrated with a variety of bench tests
- Individual PMT calibrations done with in-situ methods (work in progress)
- Recently updated cavern geometry with latest measurements
- Working on improving cosmic angular distribution (with inputs from both underground measurements and simulation from Mukesh)

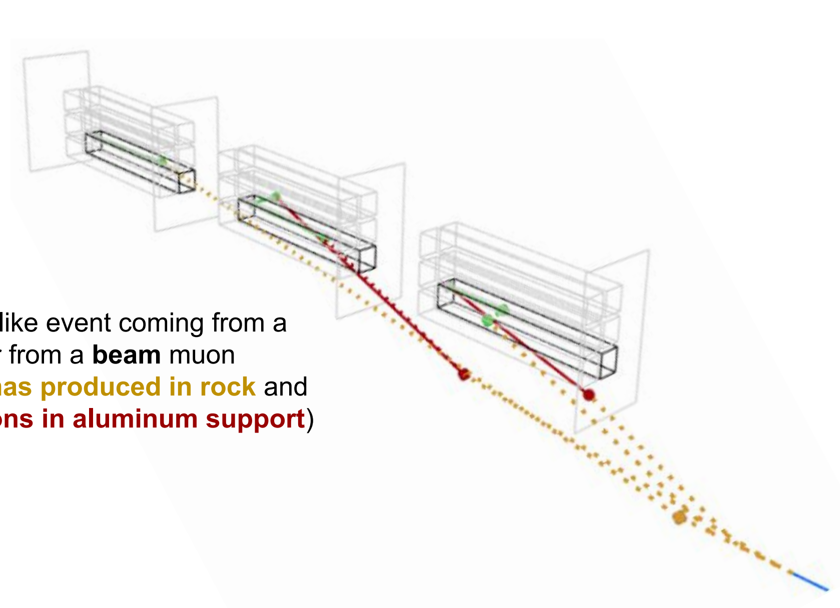




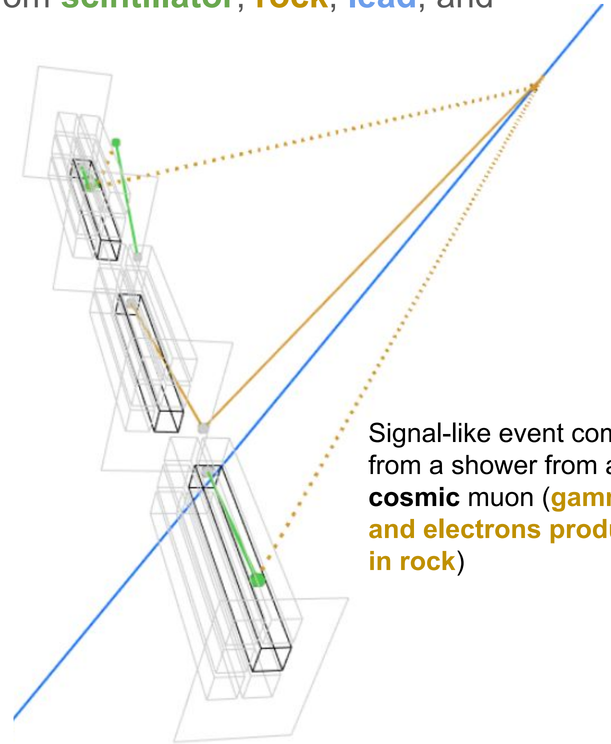


Geant4 simulation

- Geant outputs a highly detailed event record, that allows one to trace the specific chain of processes that led to each individual PE detection
- Very useful e.g. for determining contributions of secondary particles from **scintillator**, **rock**, **lead**, and **aluminum support**



Signal-like event coming from a shower from a **beam** muon (**gammas produced in rock** and **electrons in aluminum support**)



Signal-like event coming from a shower from a **cosmic** muon (**gammas and electrons produced in rock**)

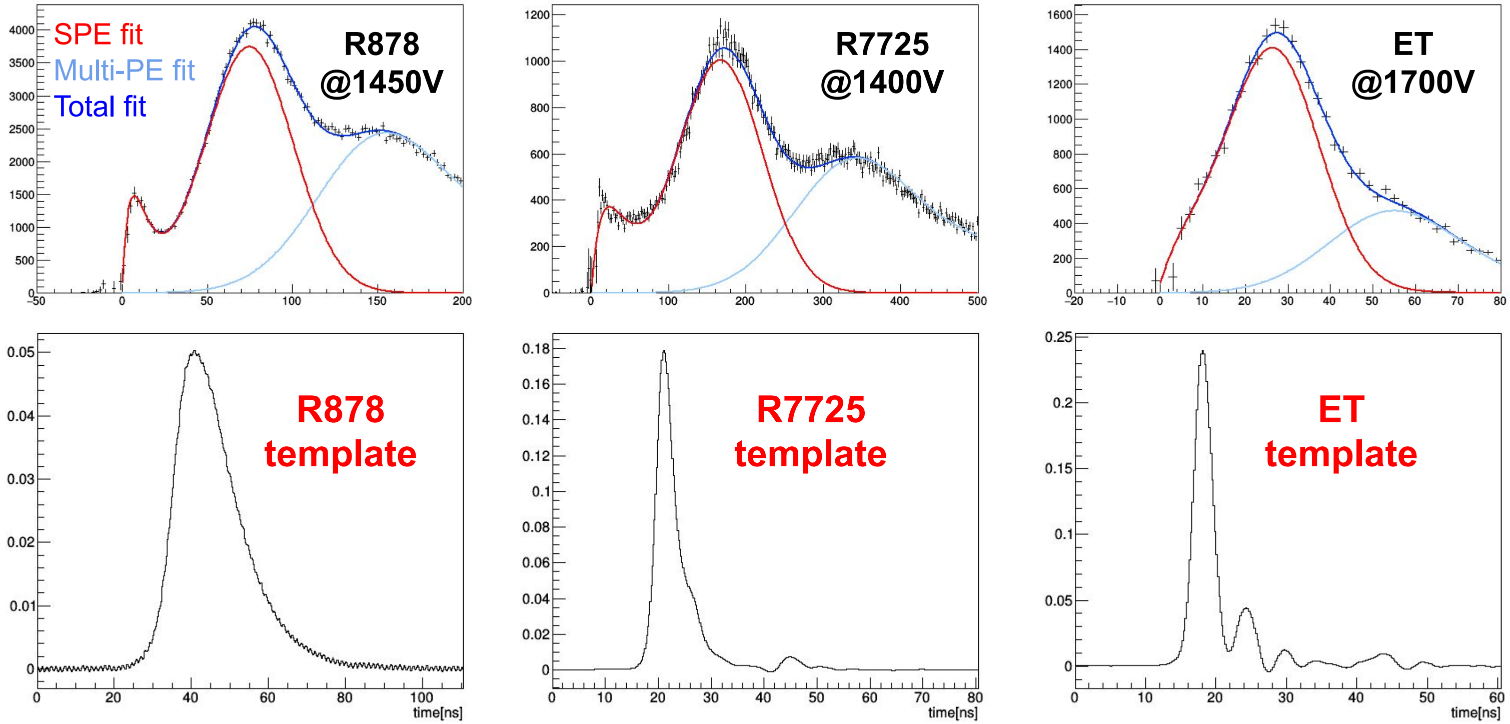
Link to interactive visualizations of many types of events:
http://uaf-10.t2.ucsd.edu/~bemarsh/dump/jsroot/index.htm?file=inputs/mq_events.root

Pulse injection

- Geant sim outputs the exact time of every PE detection
- Can use this to inject simulated PE pulses in zero bias data to get realistic output
- Measure SPE pulse shape and area distribution with LED bench tests for each PMT type

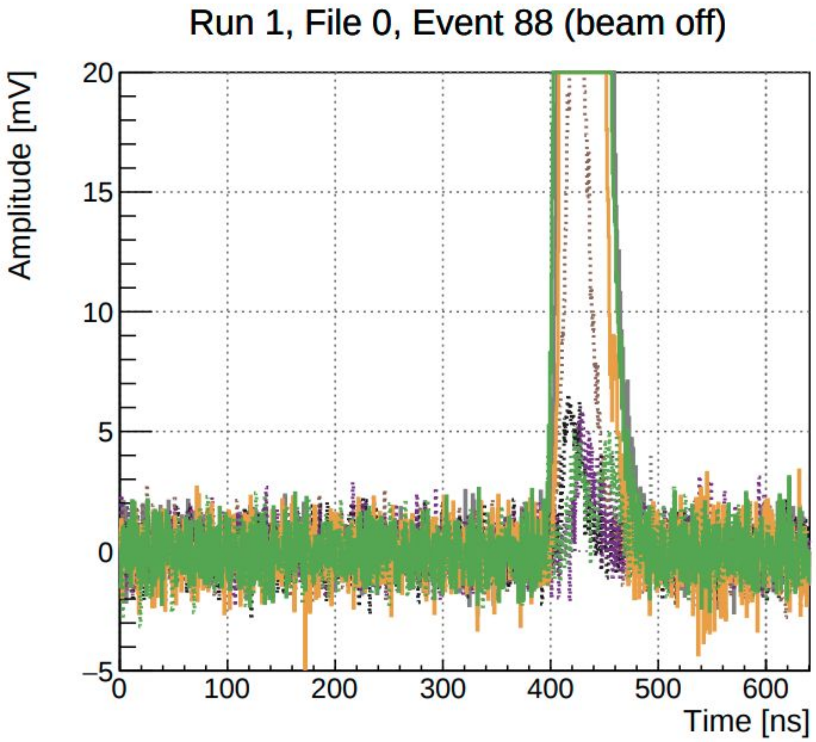
Area distributions

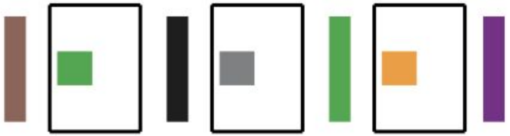
Pulse shape templates



Pulse injection

- Simulated event with a through-going mCP of **m = 1 GeV** and **q = 0.03**
- Charge is high enough that we register a small hit in all 4 slabs





Channel 16, V_{max} = 556, N_{pulses} = 1

400 ns: 556 mV, 21197 pVs, 93 ns

Channel 18, V_{max} = 28, N_{pulses} = 1

403 ns: 28 mV, 1054 pVs, 61 ns

Channel 20, V_{max} = 7, N_{pulses} = 1

410 ns: 6.6 mV, 187 pVs, 37 ns

Channel 21, V_{max} = 6, N_{pulses} = 1

422 ns: 5.9 mV, 148 pVs, 35 ns

Channel 22, V_{max} = 1250, N_{pulses} = 1

404 ns: 1250 mV, 33403 pVs, 63 ns

Channel 24, V_{max} = 563, N_{pulses} = 1

398 ns: 563 mV, 21869 pVs, 79 ns

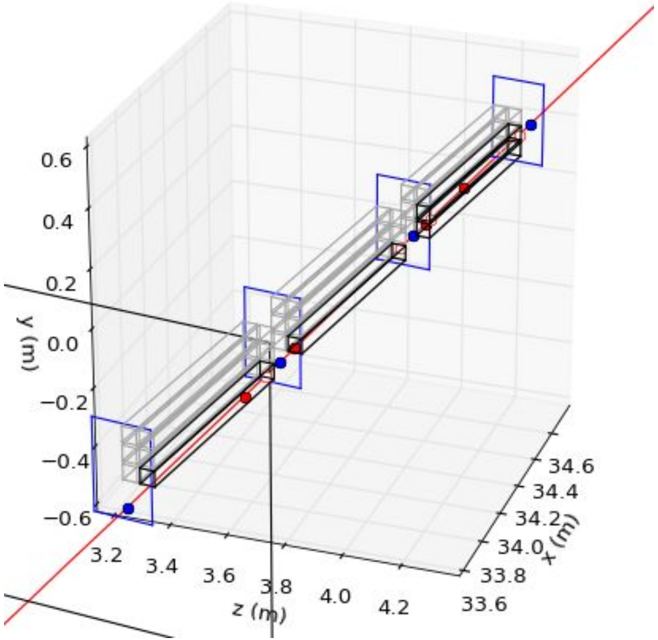
Channel 28, V_{max} = 5, N_{pulses} = 1

Muon rate

- Four-slab rate measured in data: **0.18 / pb^{-1}**
  (using nPE>150 as a slab hit)
- From “fast” sim (pure geometric):

(0.256 × (1.25*0.8+0.2)) ± 20% (bc xsec) ± 10% (non-bc xsec) ± 25% (acc.)
Total: 0.31 ± 0.10 (33%)

- Now from full sim: **0.28 ± 0.09 / pb^{-1}** (reduces rate by ~9%, from stoppage/scattering in lead or other material)
- Fancier multiple scattering algorithm (larger tails) is not propagated to full sim, but using the ratio from fast sim this would lower rate to **0.25 ± 0.08 / pb^{-1}**
- So the (sim/data) ratio is either **1.56 ± 0.52** or **1.39 ± 0.47**, depending on multiple scattering algorithm used. Close to 1σ deviation in either case.



Muon angles

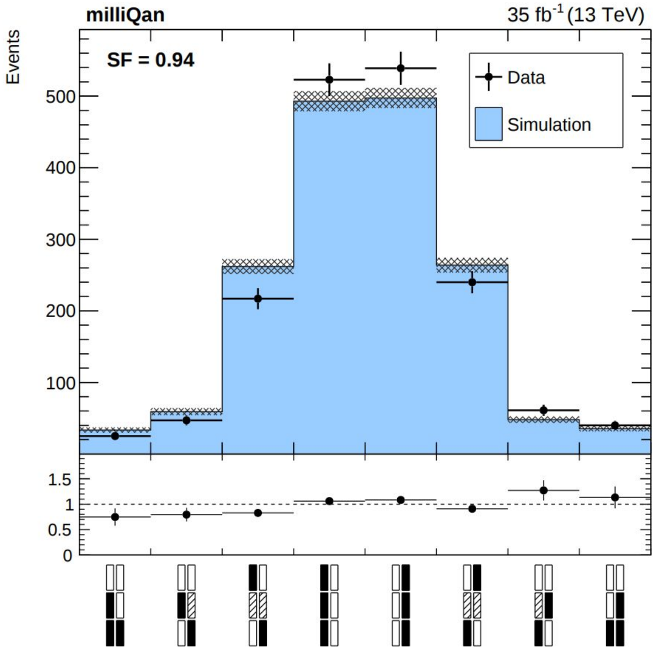
- Defined a set of patterns in the bars to compare the muon angular distribution in sim/data
- Reasonable agreement, after a bit of fudging for “fake rate” modeling in simulation

Black means require a muon hit

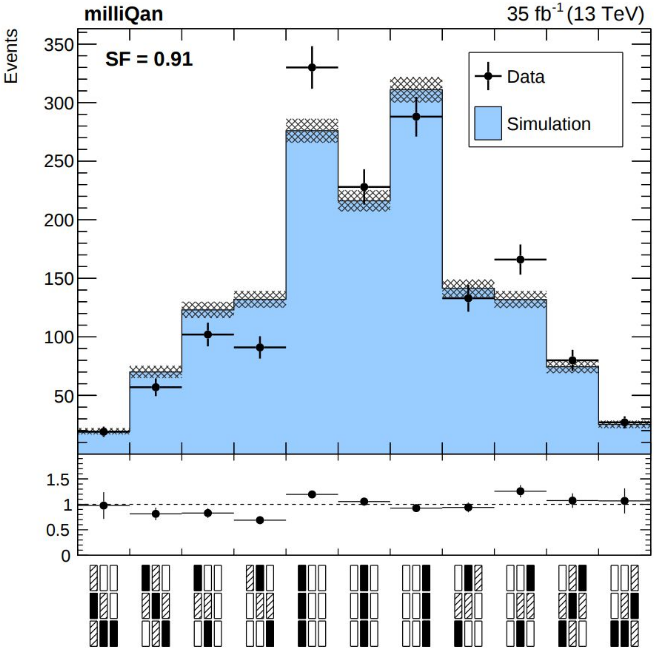
White means require no muon hit

Hashed means no requirement either way

Bar hits are **OR’d** in orthogonal direction



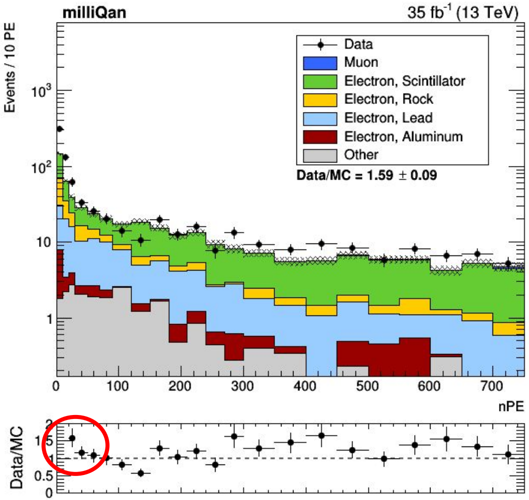
Top view



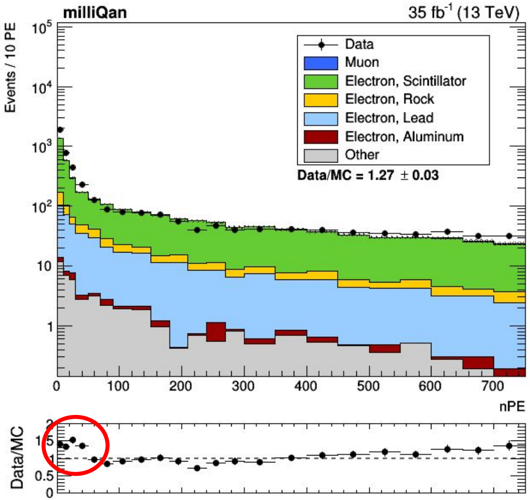
Side view

Secondary hits - beam muons

- Modeling of nPE distribution from secondary hits is pretty good, except at very low nPE (<30)
- Factor of ~1.5-2 underprediction
- Process that produces these is generally: muon knocks off a low-energy delta ray (electron) in a scintillator, which then brems into a low-energy gamma ray that travels into another scintillator and deposits energy via photoelectric effect or compton scattering
- May be due to geant modeling of these lower-energy processes; still under investigation



nPE in bars when muon goes through 4 slabs but no bars

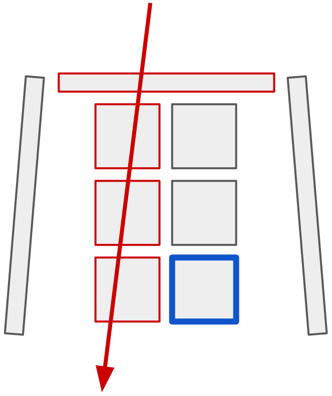


nPE in bars that neighbor a bar that got hit by muon

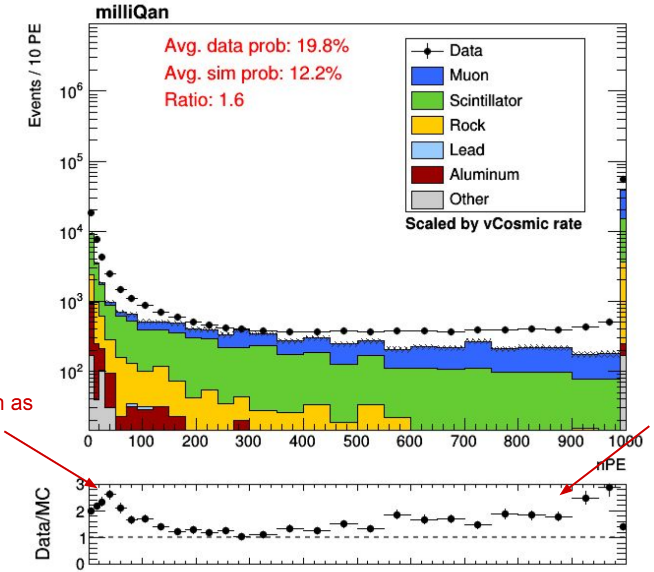
Secondary hits - cosmics

- Can also look at nPE in events with a tagged vertical cosmic, in channels not hit by the cosmic

- First: bars **neighboring** the vertical cosmic(probe mostly e's/gammas from scint)



same low-nPE underprediction as seen before?



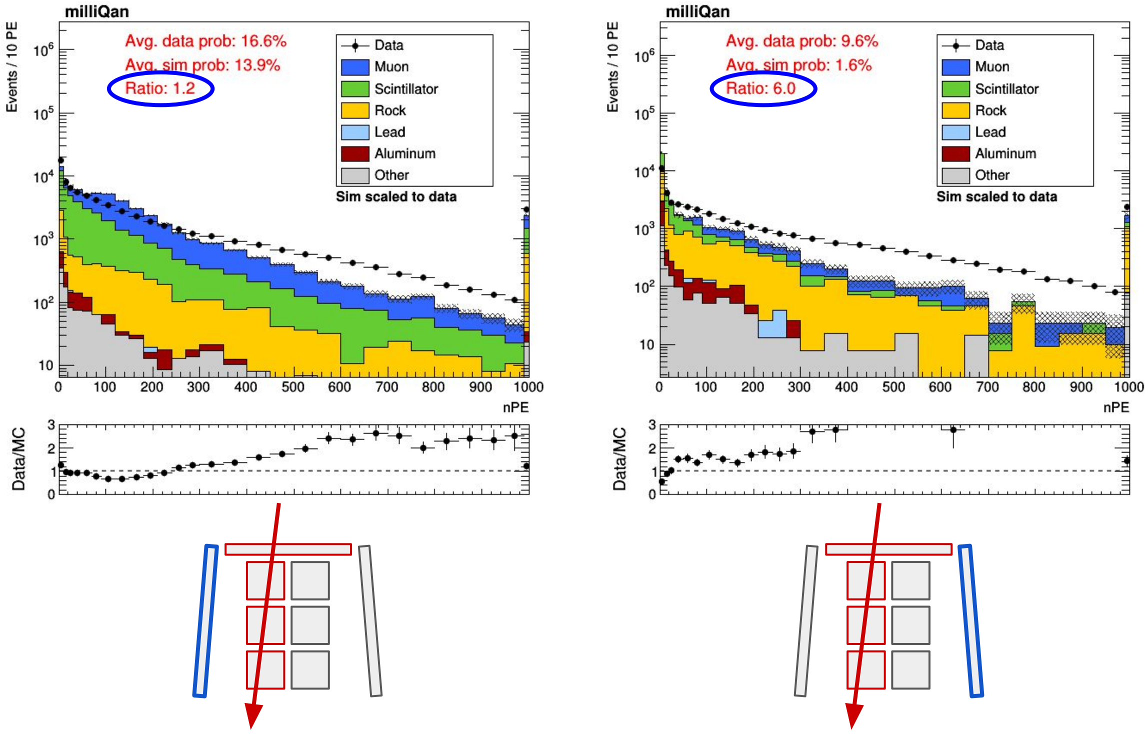
Rise at high-nPE from PMT saturation in data?

- OK shape agreement
- Pulse activity higher in data by factor of 1.6

Secondary hits - cosmics

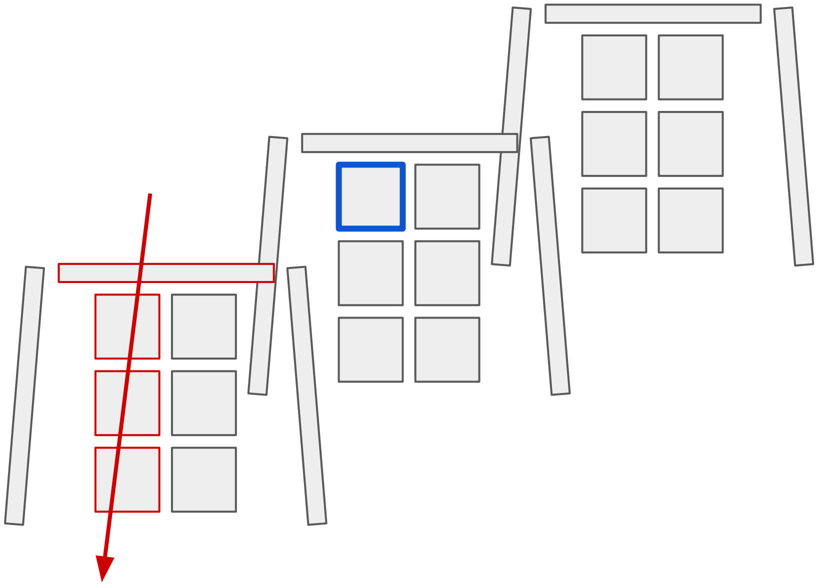
- Next, look at panels **near** and **far** from vertical cosmic

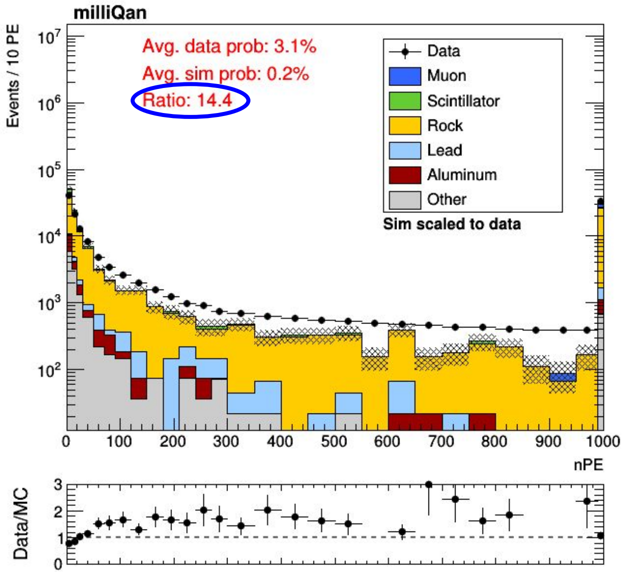
- Near is OK, but far (which is more dominated by showers from rock) is under-predicted by a factor of 6



Secondary hits - cosmics

- Next, look at **bars 1 layer away** from vertical cosmic
- Almost entirely due to showers from rock

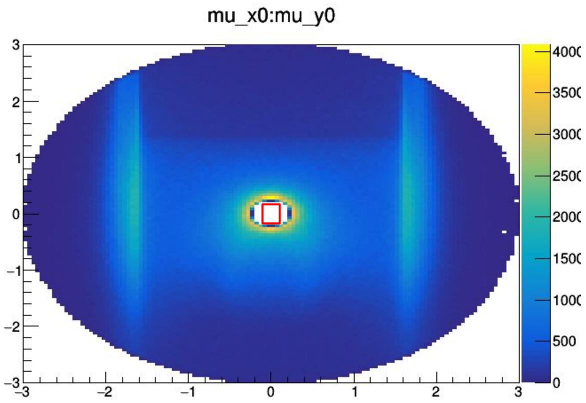




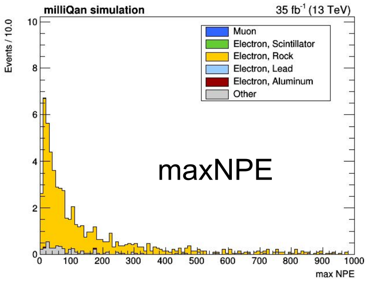
- Shape is ~OK, but probability of activity is **14x higher in data**
- Seem to be underestimating contribution from rock showers by quite a bit

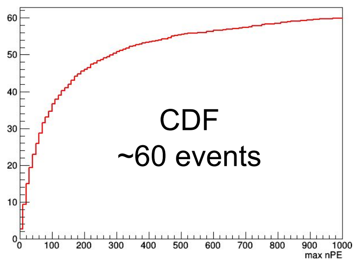
Signal-like events

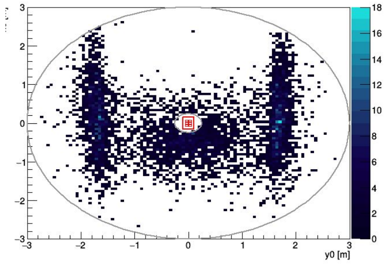
- Study signal-like events from beam muons (three bars in a straight line, no other pulses in bars or panels)
- Almost all rate comes from rock showers from muons **far from detector**
- Sim says expect ~1 event in 37 fb^{-1}, but we know that rock showers may be under-modeled



Location of muon for all events with a PE in at least one channel







One pulse per layer: **60 events** in 35 fb^{-1}
Add panel veto: **31 events**
Add straight line requirement: **1.2 events**

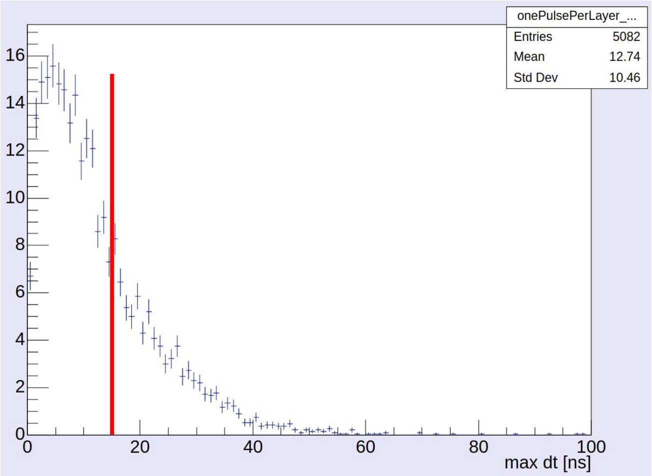
Signal-like events

- Will backgrounds still satisfy ABCD method when this is added to beam-off backgrounds? Scale-independent way to check is to make sure (1) beam-based backgrounds alone satisfy ABCD, and (2) transfer factor (pointing/non-pointing) is the same for both beam-based and beam-off backgrounds

- Do these satisfy ABCD method alone? **AC/BD = 1.03 ± 0.17**, consistent with 1.0

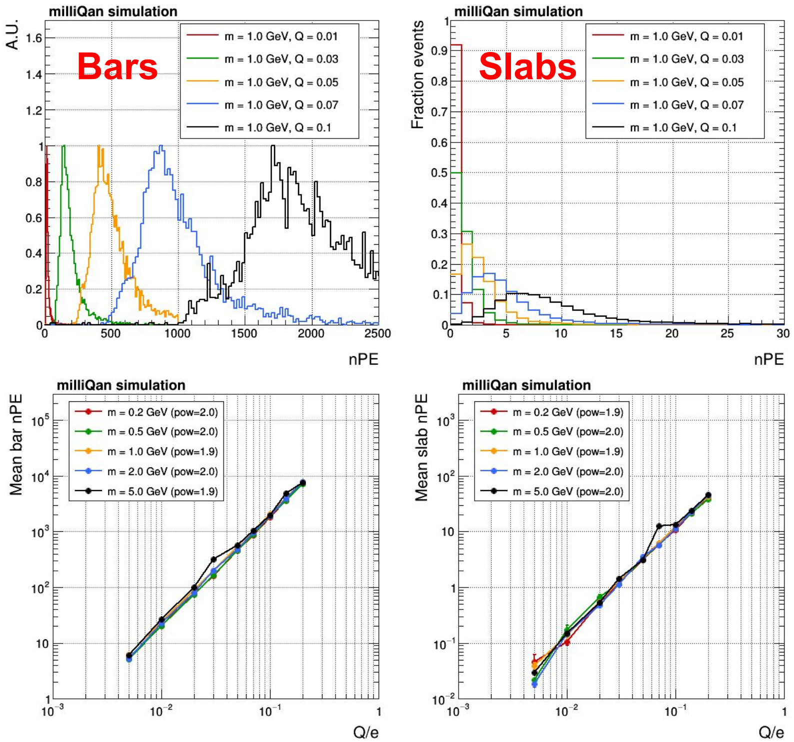
- Non-pointing/pointing ratio should be 11 if bar position in each layer is completely independent. Measure **10.1 ± 0.8**, so if any correlation it is small

	pointing	non-pointing
$\max\Delta t$ < 15 ns	A: 126	D: 1254
$\max\Delta t$ > 15 ns	B: 60	C: 616



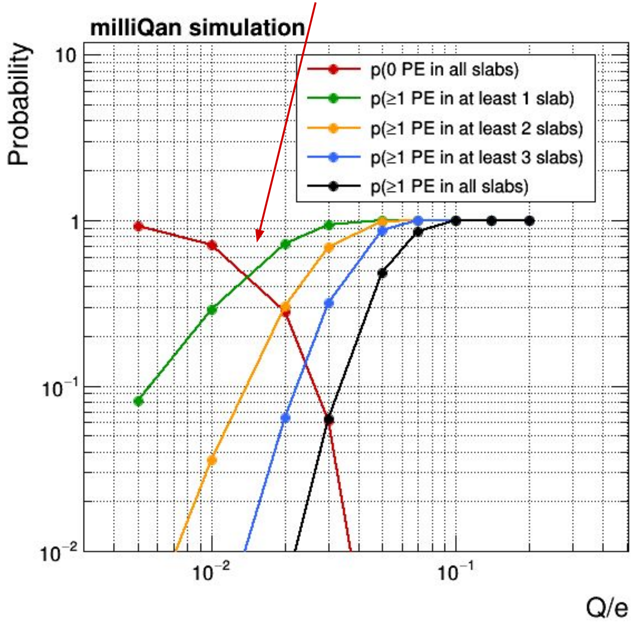
Signal simulation

- Have validated signal simulation, and using this to inform signal region design (see Matthew's talk)



Mean nPE follows Q^2 dependence

Q~0.015 is threshold between zero slab and ≥1 slab regions



Simulation-related systematics

- What uncertainties do we need to apply to signal predictions, and how to assign values?
  - **Theory cross section**
    - For psi and upsilon production, we have these directly (some are very asymmetric)
    - For all other modes of production, rates are taken from pythia. Claudio has found some measurements of these processes in data. Plan to use these comparisons and tune variations to inform choice of systematic (probably O(30%))
  - **Material model**
    - Can vary density of materials uniformly up/down and re-do propagation, as for muons
    - Not done yet, but effect should be small and probably a minor systematic
  - **PMT calibration**
    - Calibration measurements in progress (see Matthew's talk)
    - Once a model of calibrations and uncertainties is finalized, tools in place to translate these into systematics, taking into account correlations between channels and between signal regions

Summary & to-do

- Full simulation pipeline, from event generation and propagation to Geant simulation and pulse injection, is in place
- Much analysis has been performed to validate and understand simulation and compare to measurements from data
- Full grid of 276 (m,Q) signal points from 16 different production modes have been processed through the pipeline, and are being used to inform signal region design
- **What is left to do?**
  - Re-run Geant simulation with updated geometry and higher PMT efficiencies (to allow for proper calibrations)
  - Finalize calibrations and propagate to simulation output
  - Better understand mis-modeling of low-nPE sources and showers from rock, though these have no direct effect on background or signal predictions

Many people contributed to the work shown here! Thanks to Ryan, Franny, Brunel at UCSB, Michael at OSU, and Gregory and Mukesh at NYU