The COMET Simulation: Signal and backgrounds

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Imperial College London

LPNHE, Paris, December 2014

Overview

- COMET signal + backgrounds
- ICEDUST: The comet software
- COMET simulation
- Alcap background measurements

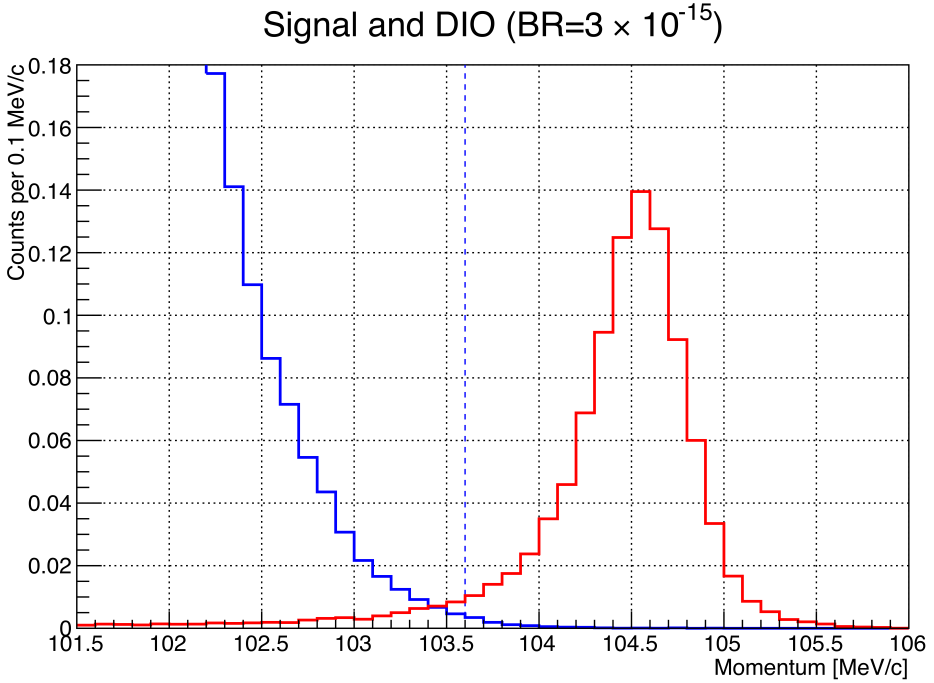
COMET: Signal

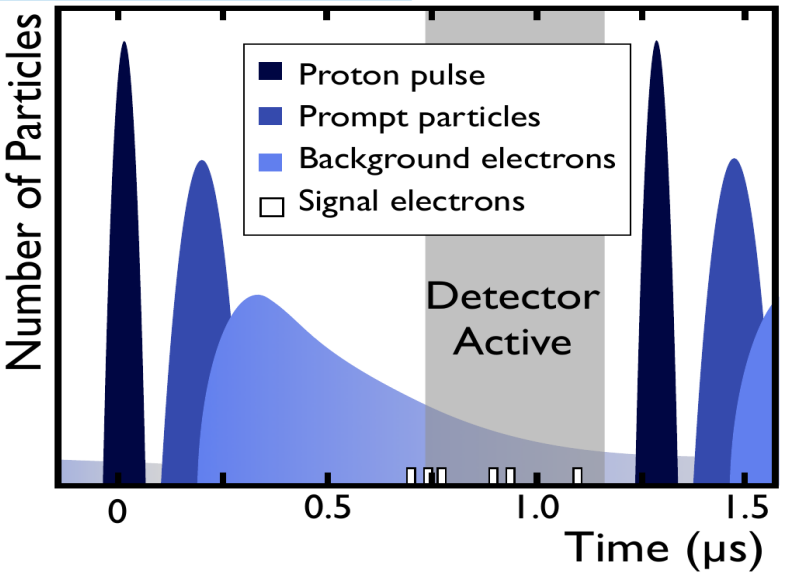
$$\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$$

$$E_e = M_\mu - B_\mu - E_{\mathrm{rec}} = 104.9\ \mathrm{MeV}$$

Target Material	Muonic Lifetime (ns)
Aluminium	846±6
Silicon	758±2

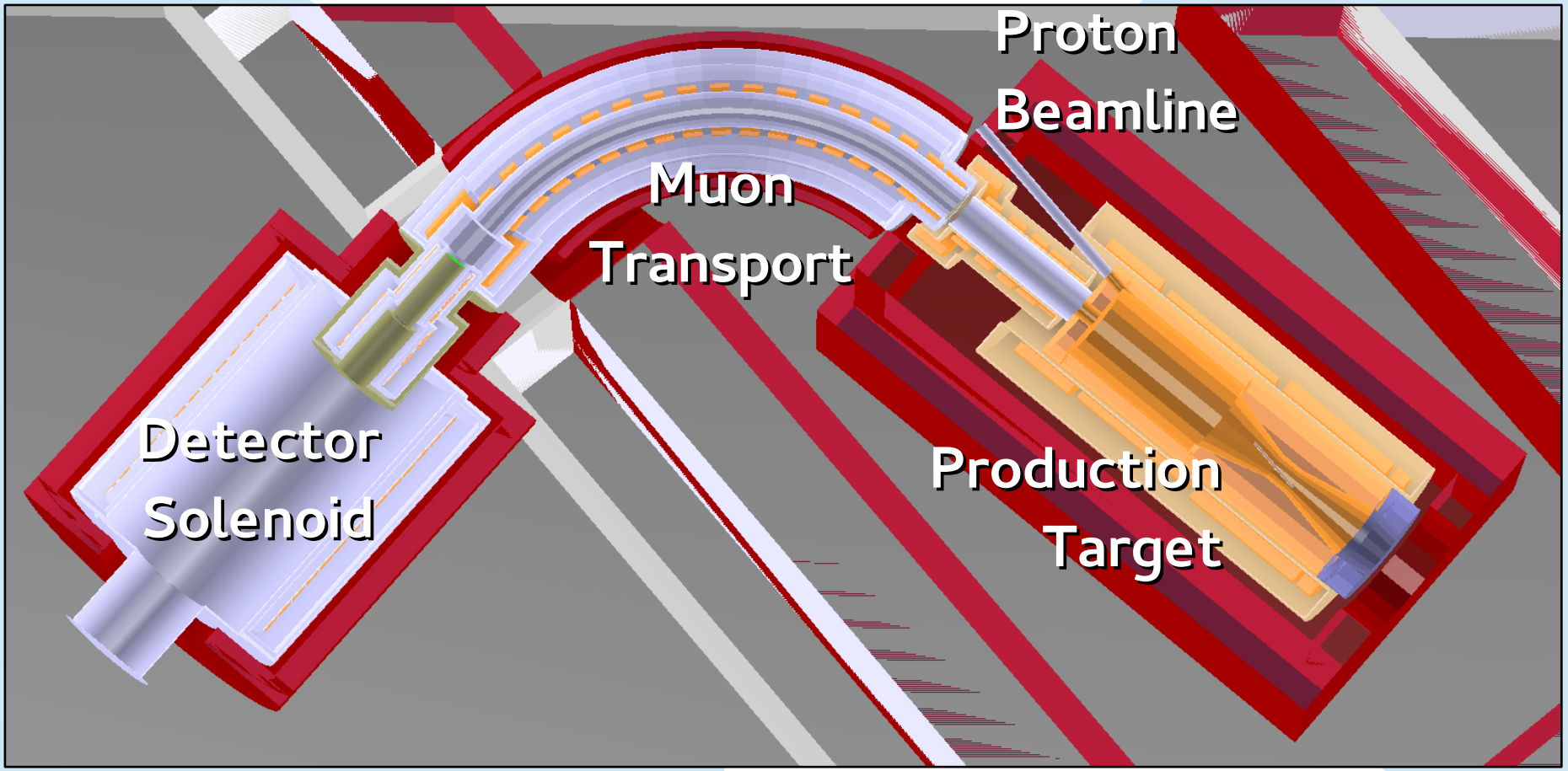
Measday et al., 2007





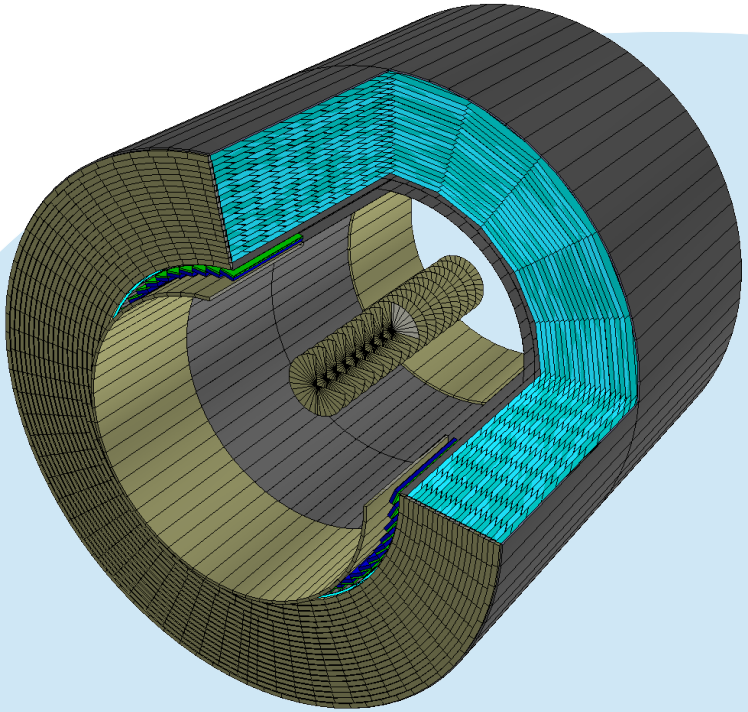
COMET

Overview

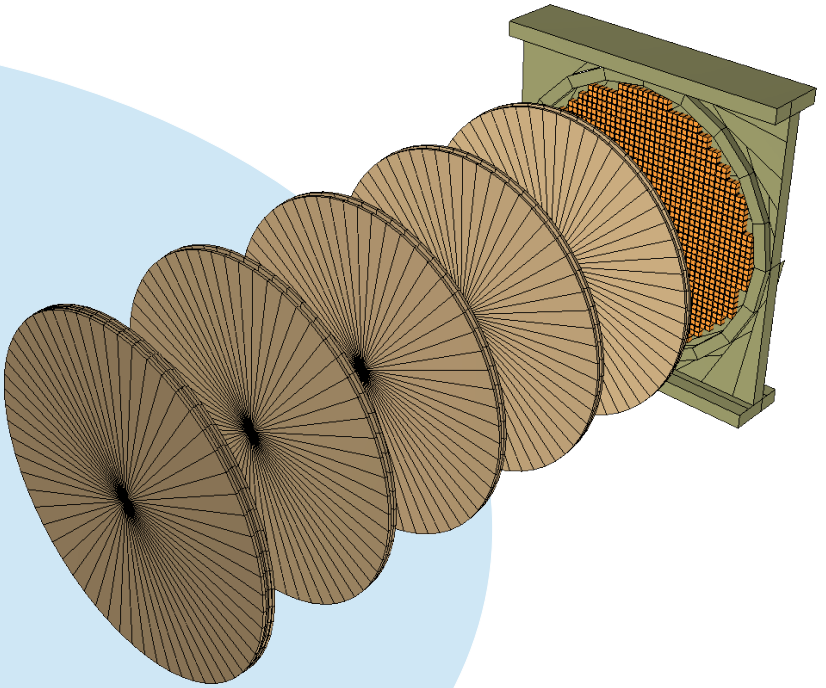


COMET

Detectors

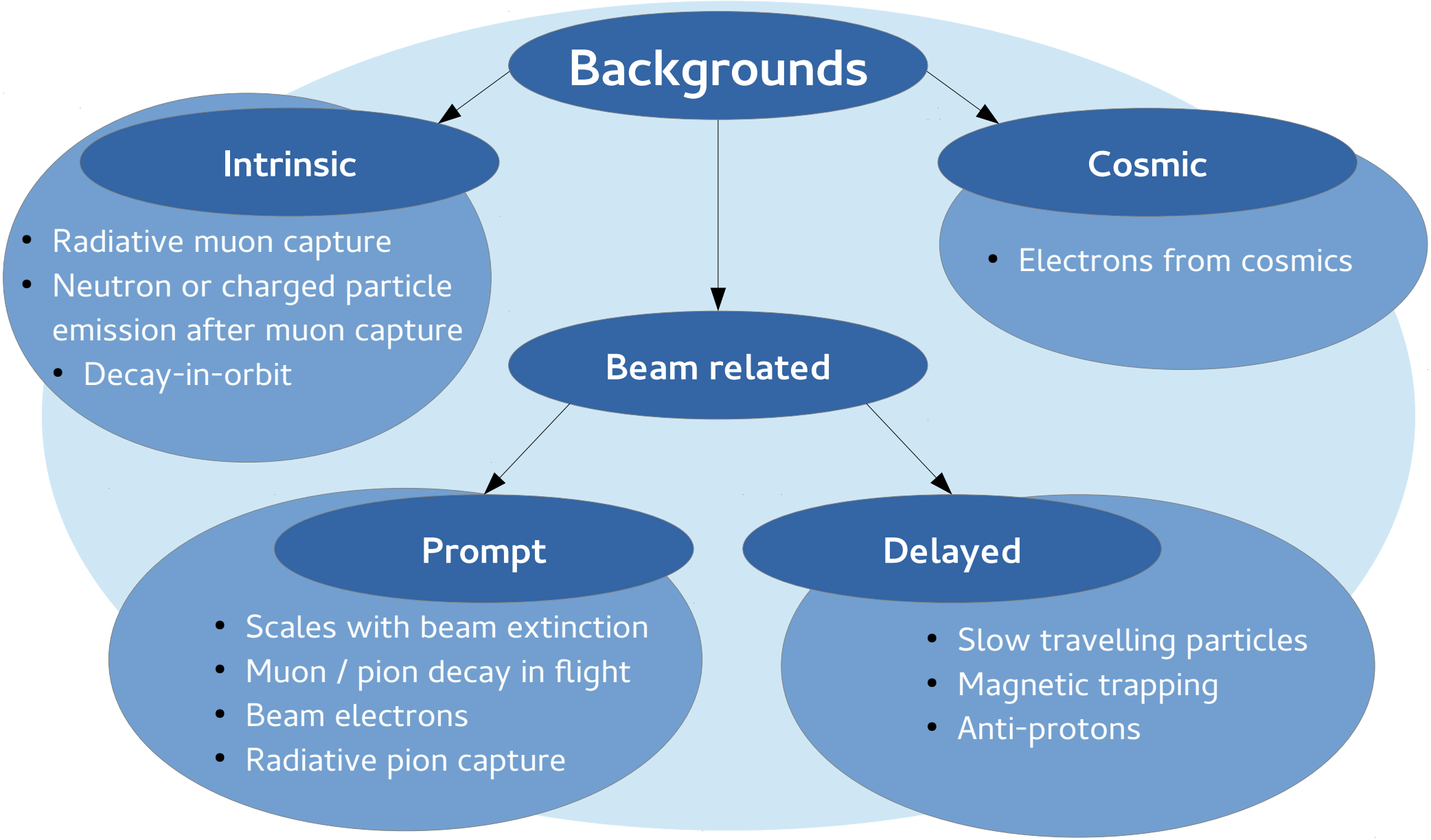


CyDet: Cylindrical Drift Chamber, centred on target, geometric acceptance ignores electrons with p<90 MeV



StrECAL: Phase-II proto-type, Straw Tracker (momentum) + ECAL (Energy) = PID + energy measurement

COMET: Background



COMET: Background

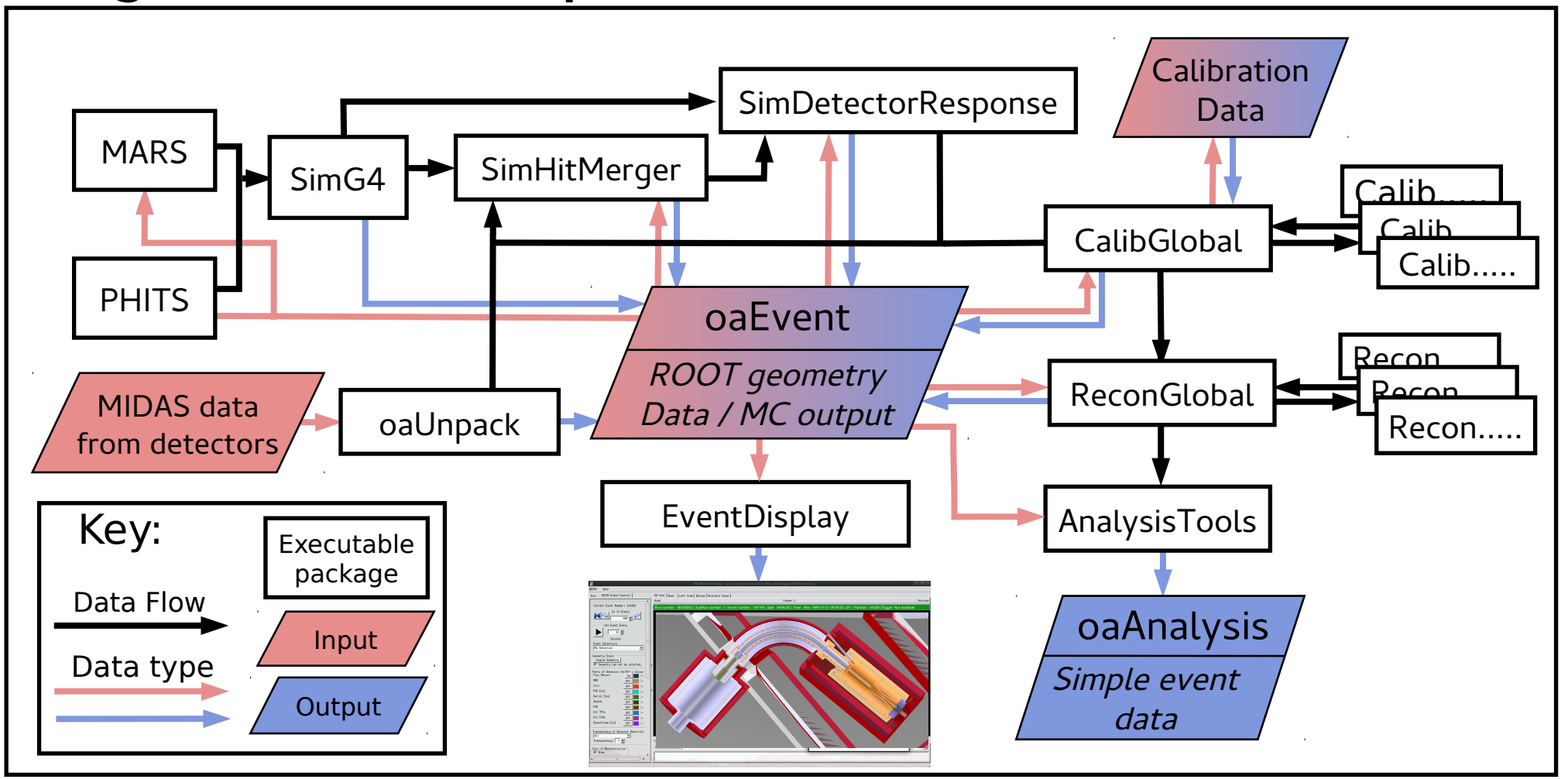
Table 30: *Summary of the estimated background events for a single-event sensitivity of* 3.1×10^{-15} *with a proton extinction factor of* 3×10^{-11}.

Type	Background	Estimated events
Physics	Muon decay in orbit	0.01
Physics	Radiative muon capture	5.6×10^{-4}
Physics	Neutron emission after muon capture	< 0.001
Physics	Charged particle emission after muon capture	< 0.001
Prompt Beam	Beam electrons (prompt)	8.3×10^{-4}
Prompt Beam	Muon decay in flight (prompt)	$\leq 2,0 \times 10^{-4}$
Prompt Beam	Pion decay in flight (prompt)	$\leq 2.3 \times 10^{-3}$
Prompt Beam	Other beam particles (prompt)	$\leq 2.8 \times 10^{-6}$
Prompt Beam	Radiative pion capture(prompt)	2.3×10^{-4}
Delayed Beam	Beam electrons (delayed)	~ 0
Delayed Beam	Muon decay in flight (delayed)	~ 0
Delayed Beam	Pion decay in flight (delayed)	~ 0
Delayed Beam	Radiative pion capture (delayed)	~ 0
Delayed Beam	Anti-proton induced backgrounds	0.007
Others	Electrons from cosmic ray muons	< 0.0001
Total		0.019

ICEDUST

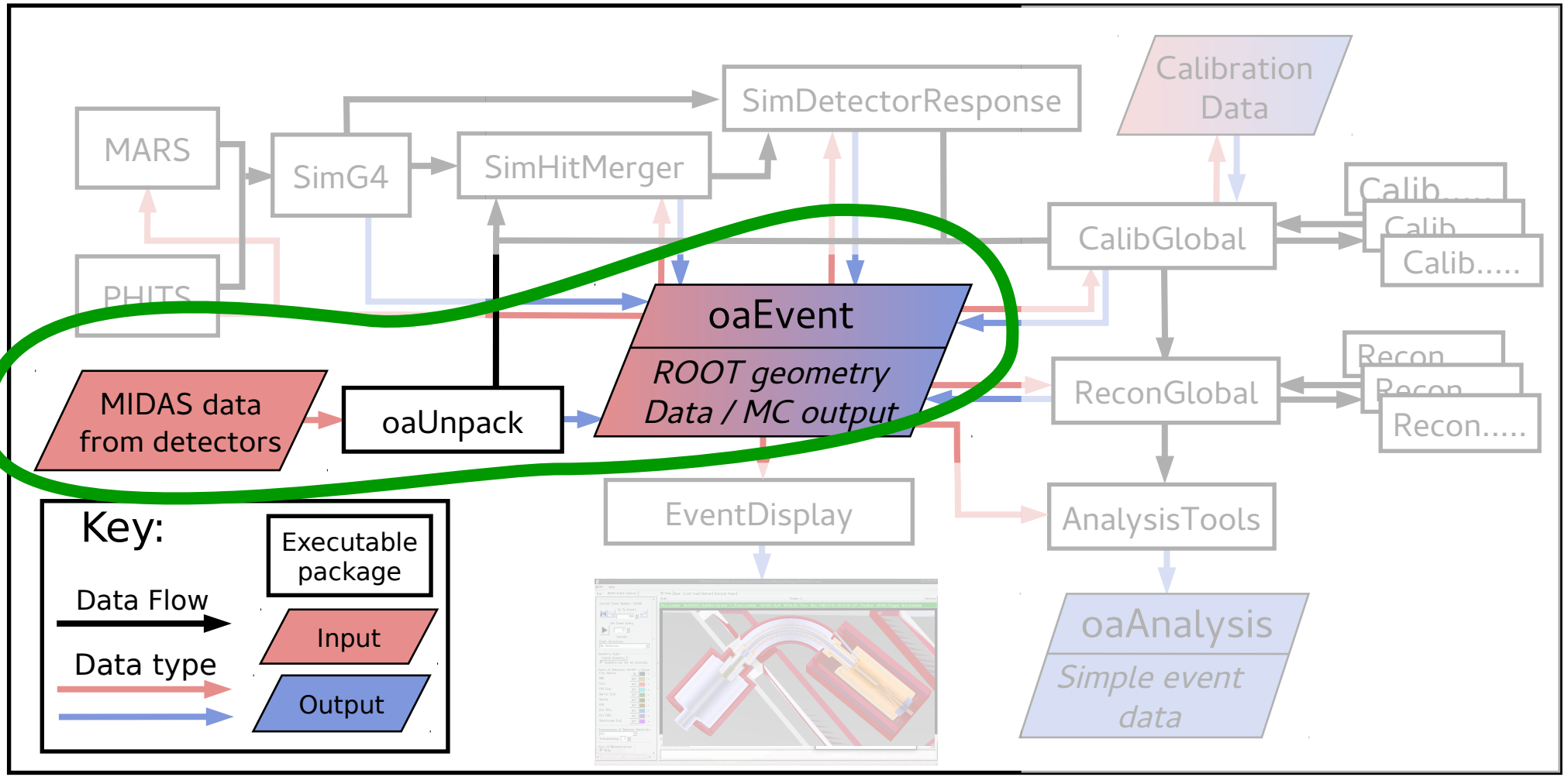
Overview

Integrated Comet Experiment Data User Software Toolkit

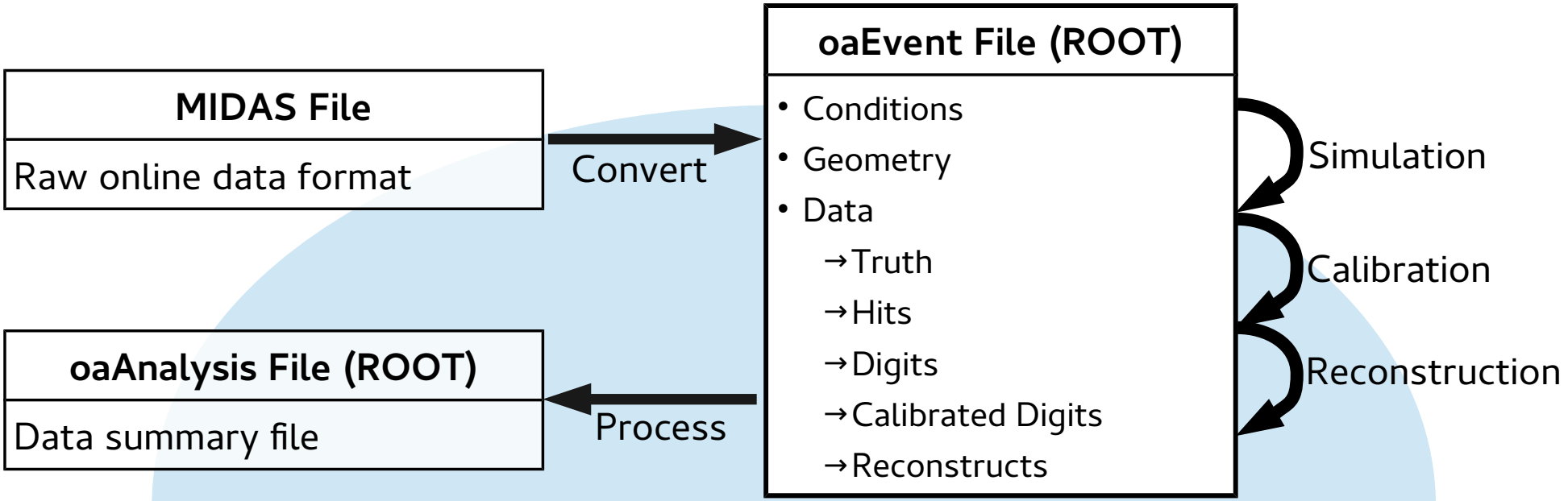


ICEDUST

Overview



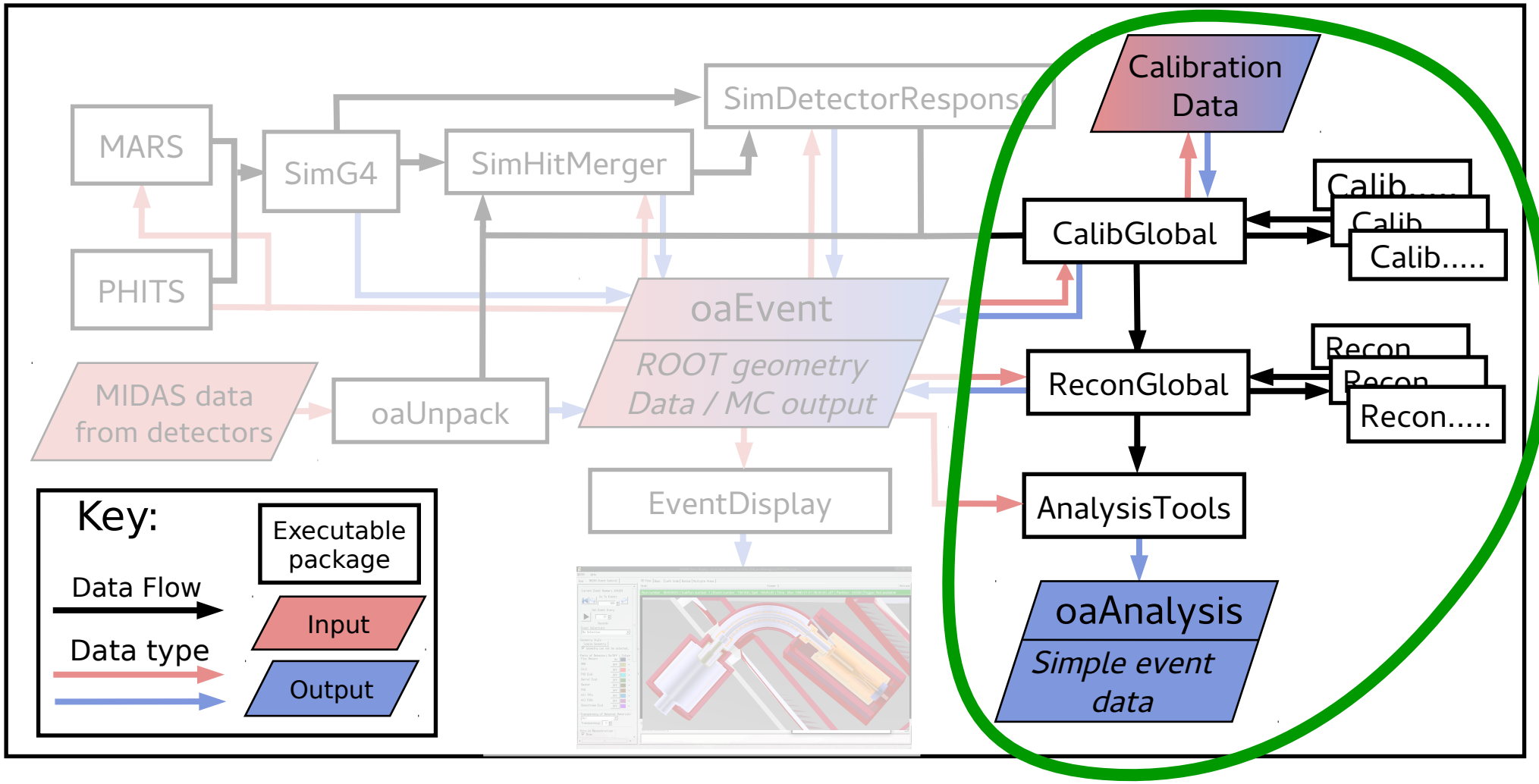
Data formats



- oaEvent used by all packages within the framework
  - Physically meaningful representation of data / objects
- Data and MC indistinguishable from an early point
- MIDAS output data conversion maintained by DAQ group
  - Elegant interface to offline software
- Tested on real data with ND280
  - Framework code left un-changed since forking

ICEDUST

Overview



Reconstruction

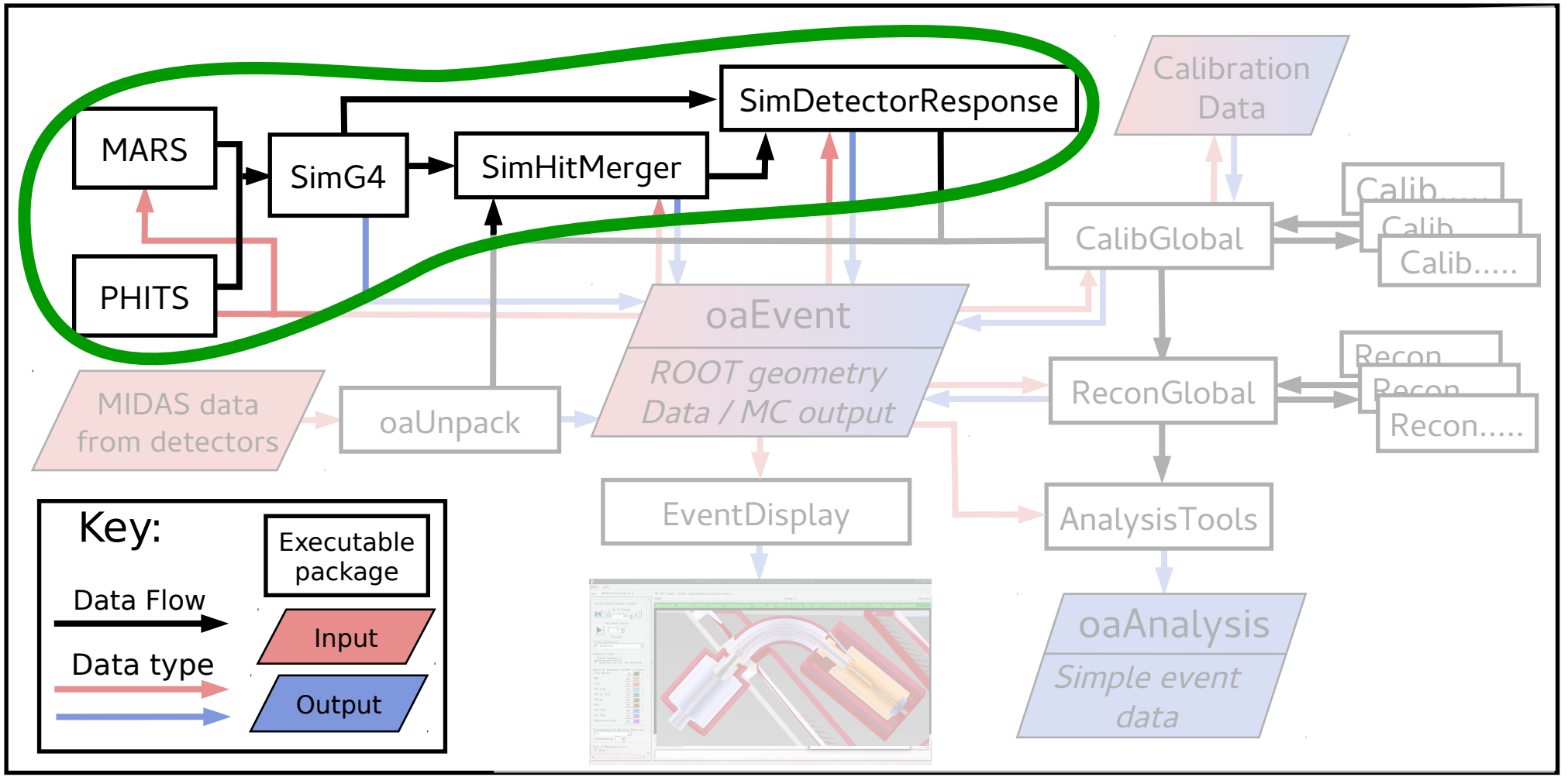
- Integrated GENFIT already
- Interface package being worked out
- Flexibility for other packages
  - ND280 uses RecPack
  - Persist physically meaningful quantities

Analysis

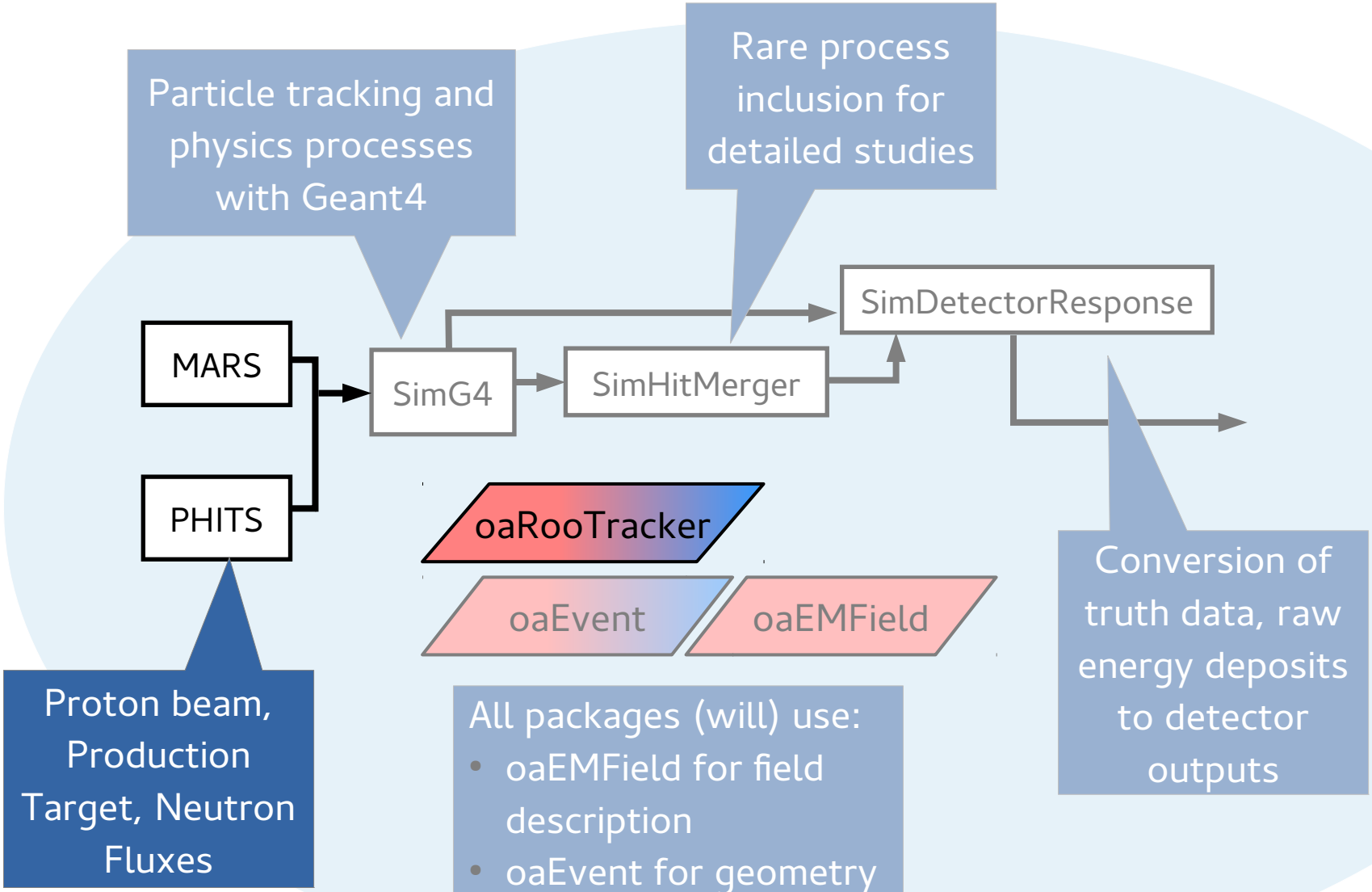
- Framework provides flexibility
- Well tested on real data
- Analysis stage uses paired down reconstruction data
- Considering un-biased analyses
  - Blind analysis
  - Different target runs
  - Different Detector Solenoid field strength

ICEDUST

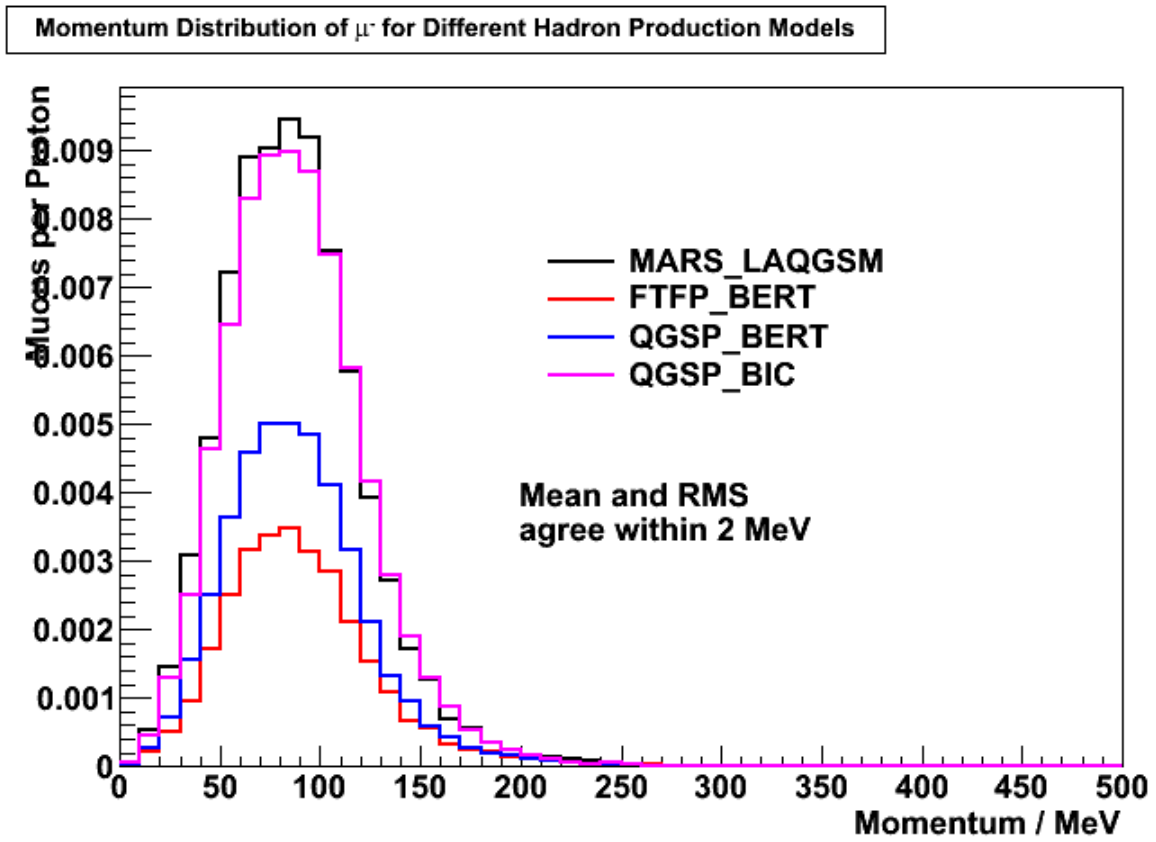
Overview



Simulation

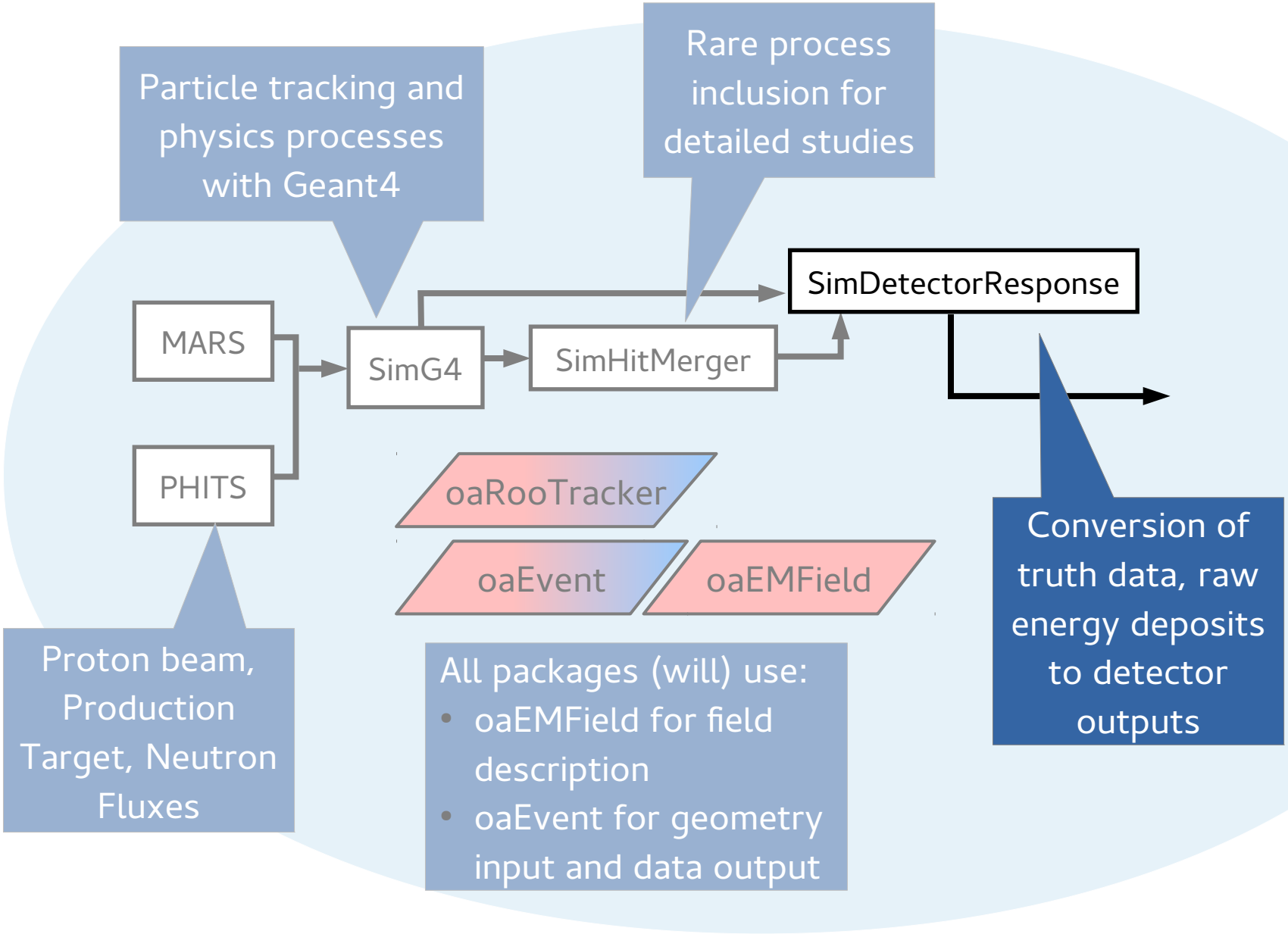

Particle tracking and physics processes with Geant4
Rare process inclusion for detailed studies
SimDetectorResponse
MARS
PHITS
SimG4
SimHitMerger
oaRooTracker
oaEvent
oaEMField
Proton beam, Production Target, Neutron Fluxes
All packages (will) use:
• oaEMField for field description
• oaEvent for geometry input and data output
Conversion of truth data, raw energy deposits to detector outputs

Simulation: Production Models



- Minimize uncertainty in pion yield
- PHITS, MARS, Geant4, (Fluka)
- See Andy's talk

Simulation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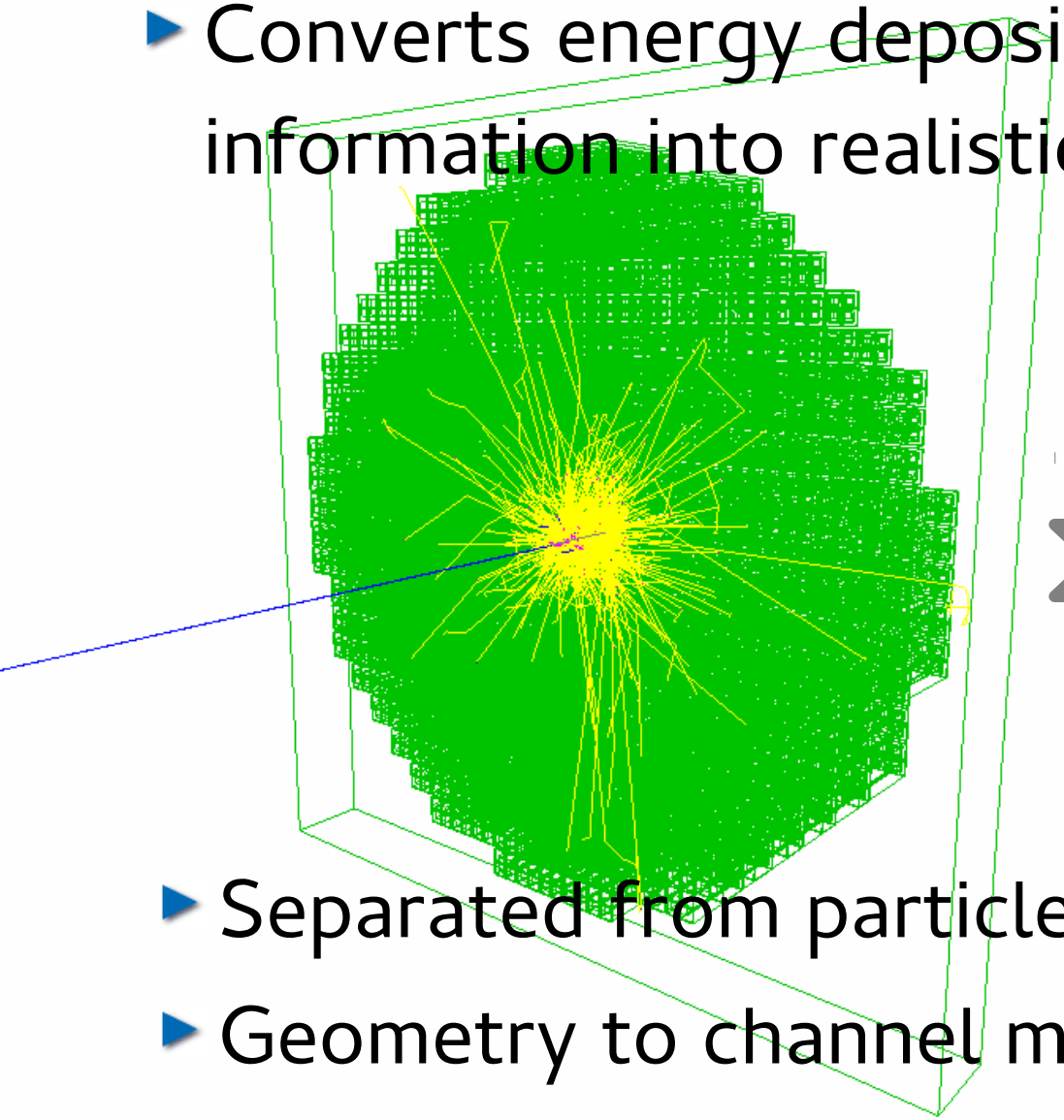
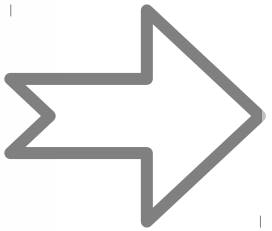
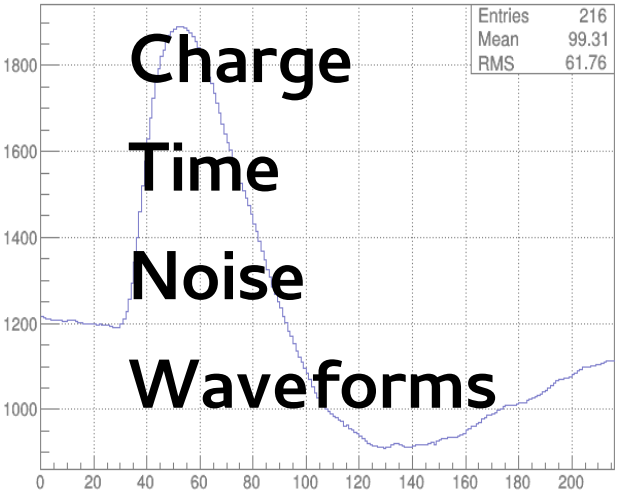
Simulation: Detector Response

- Converts energy deposits from truth information into realistic detector outputs

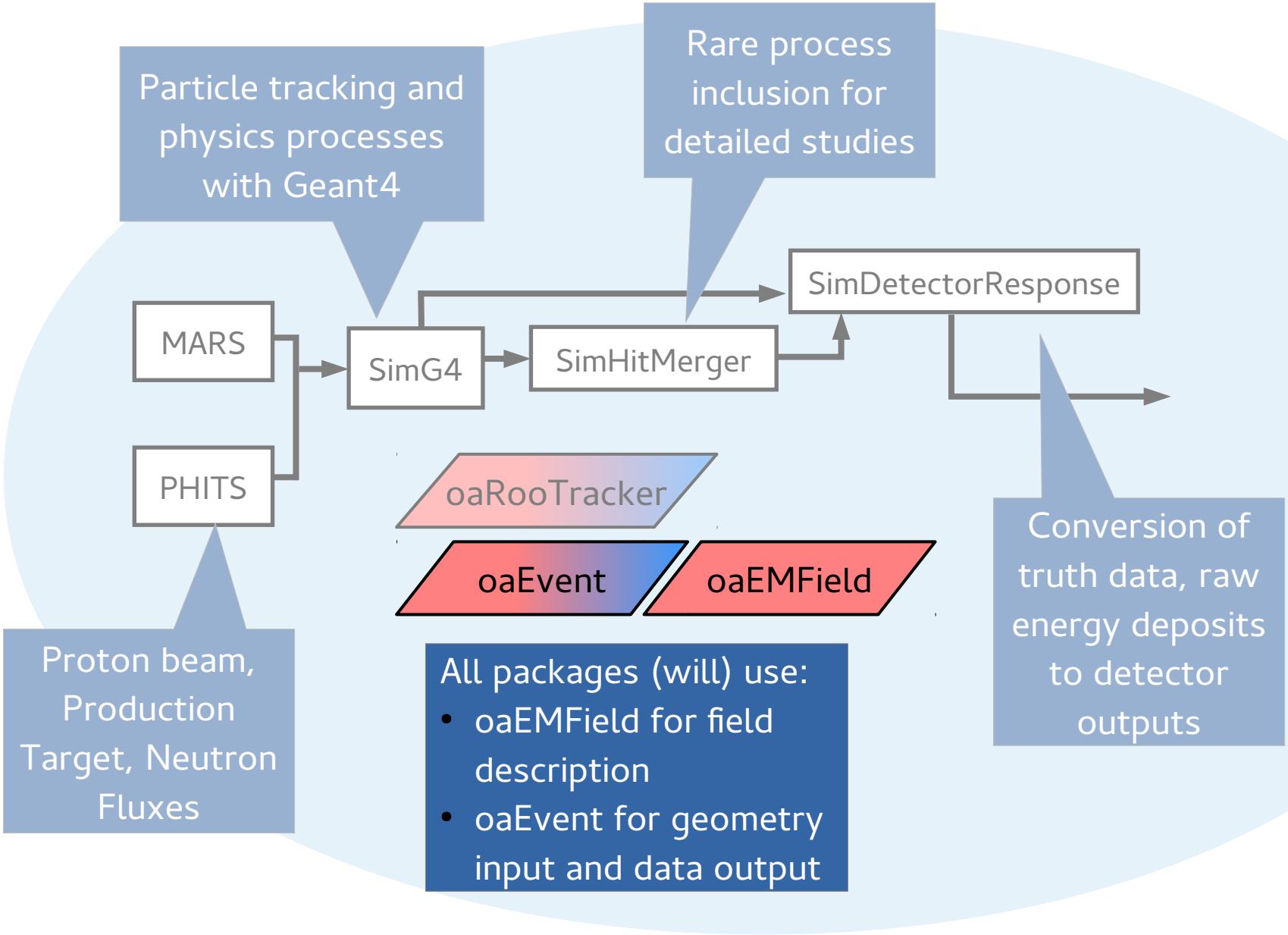






- Separated from particle tracking
- Geometry to channel mapping

Simulation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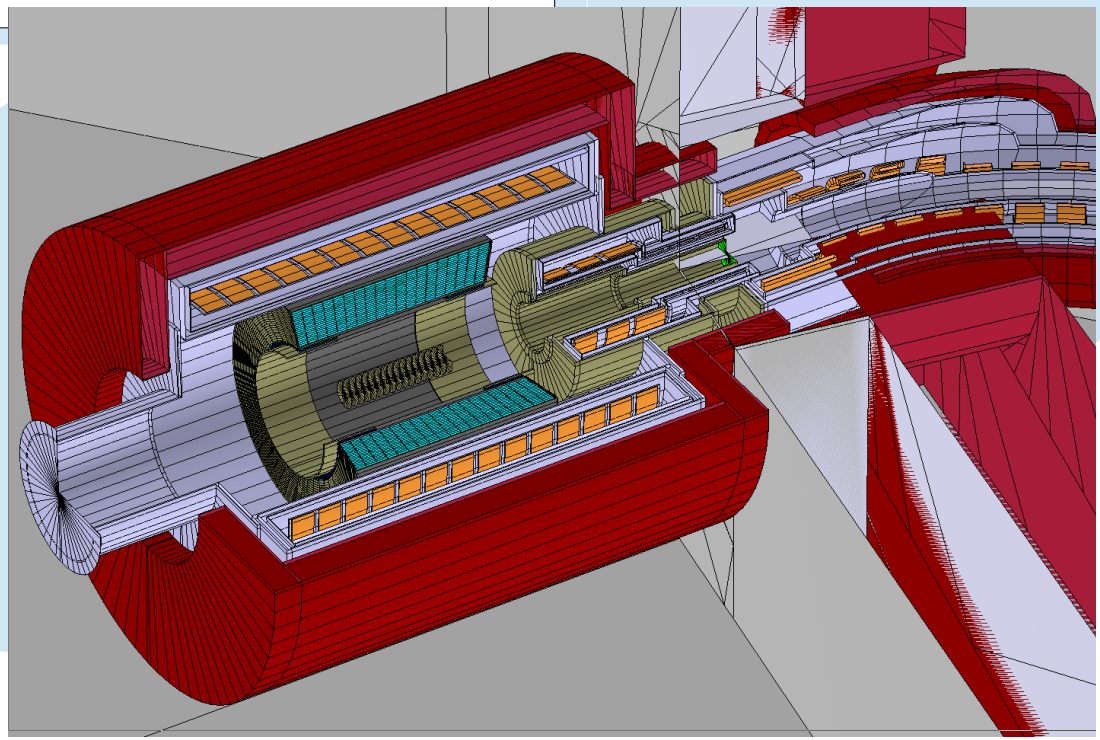
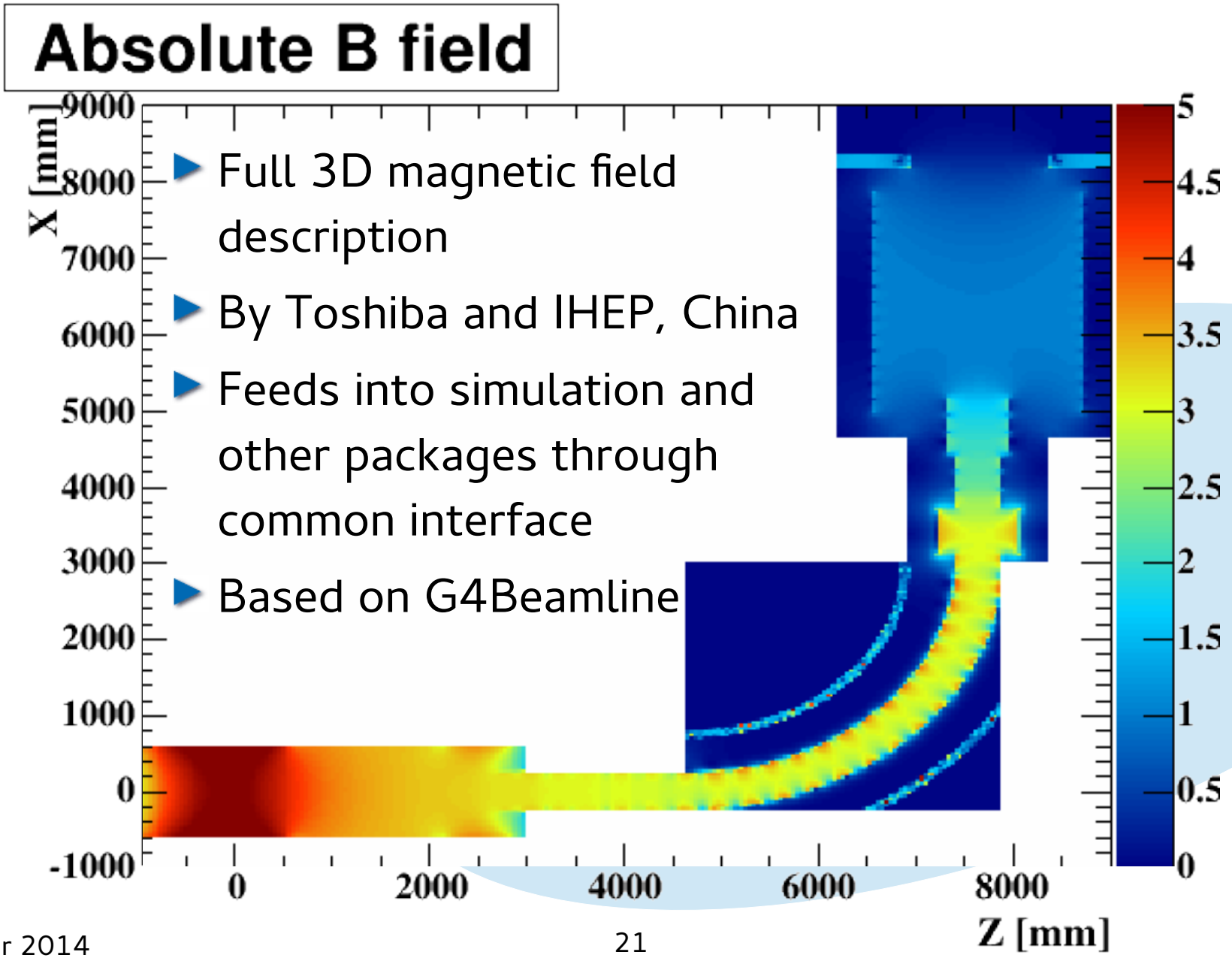
Simulation: Geometry

```
 6 # Container parameters
 7 {parent}/ProdTgtSec/Dimension Length   = 3.2*m
 8 {parent}/ProdTgtSec/Dimension Width    = 1.749*m
 9 {parent}/ProdTgtSec/Dimension Height   = 2.0225*m
10 {parent}/ProdTgtSec/Material  Material = Air
11
12 # Useful reference parameters for placement of sub-components
13 {parent}/ProdTgtSec/Dimension OriginZ = 1382*mm
14 {parent}/ProdTgtSec/Position  Origin  = (x=0, y=[Beamline:Height]- [Height], z=[OriginZ])
15 {parent}/ProdTgtSec/Position  End     = [BeamPipe:Position] + (0,0,[BeamPipe:Length])
16
17 # Key values for dimensions of sub-components
18 {parent}/ProdTgtSec/Dimension Shields:Length  = 0.5*([Length] + [Origin].Z)
19 {parent}/ProdTgtSec/Dimension Shields:OuterR  = 60*cm
20 {parent}/ProdTgtSec/Dimension Beamline:Height = 2.3*m
```

- Run-time configurable
- Input macro contains all dimensions, materials, positions
- Hierarchical components so we can work over many scales
- ROOT geometry output is used by all packages in ICEDUST

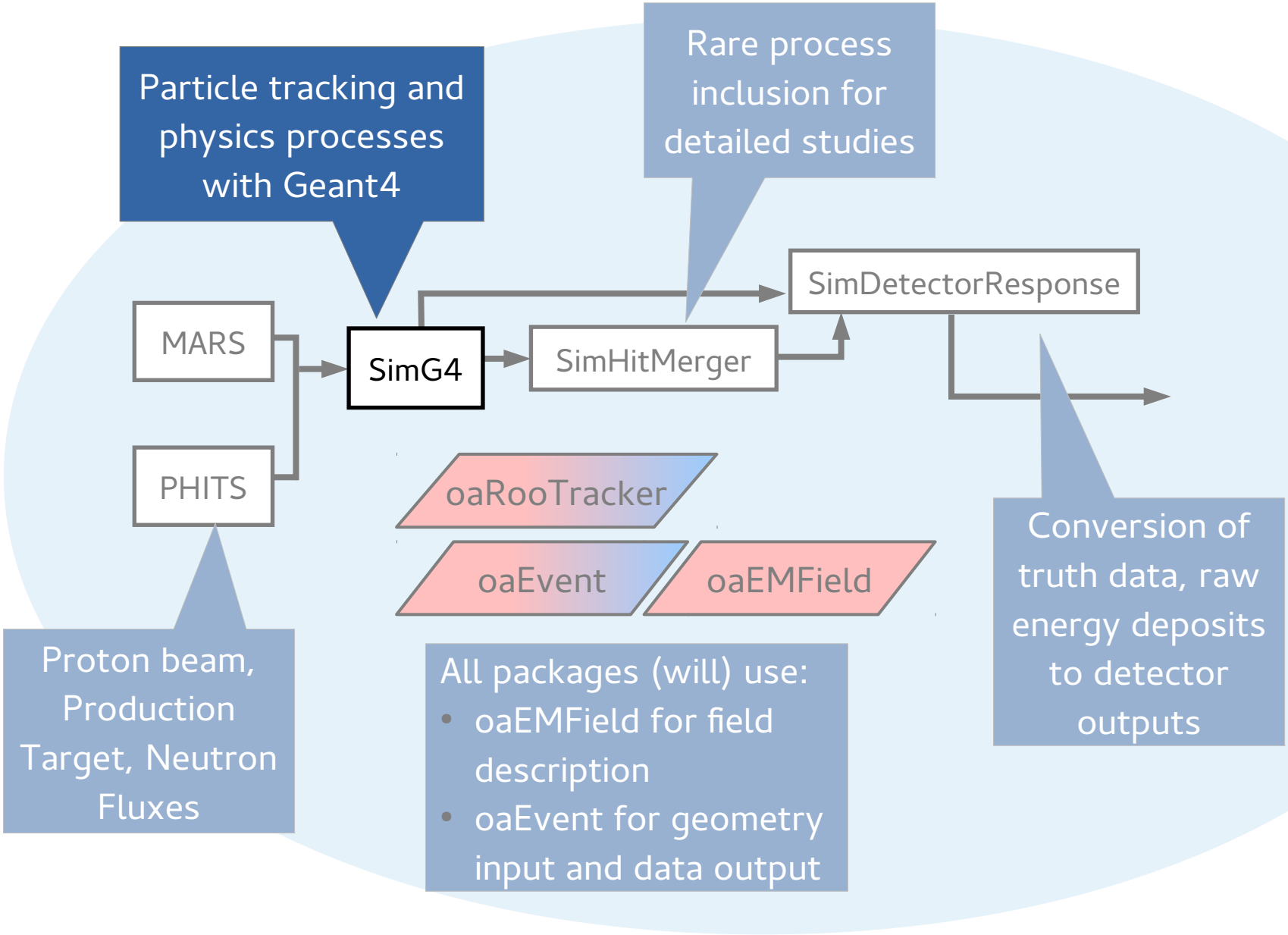


Simulation: EM Field



- Full 3D magnetic field description
- By Toshiba and IHEP, China
- Feeds into simulation and other packages through common interface
- Based on G4Beamline

Simulation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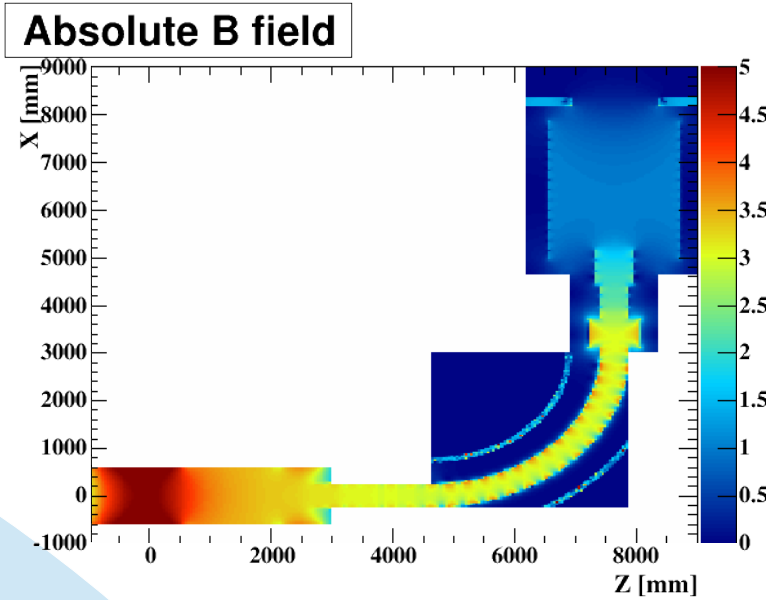
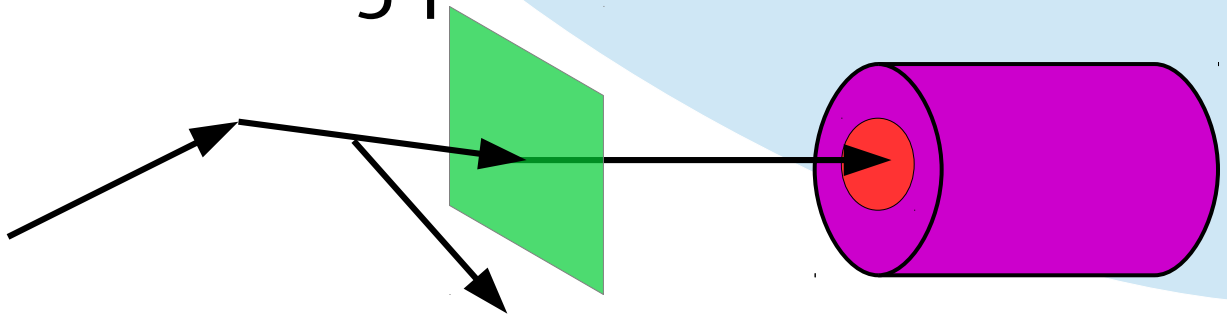
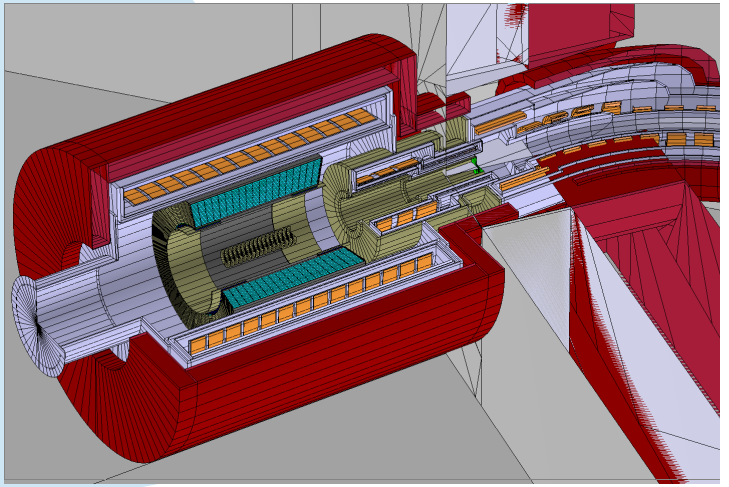
Simulation: SimG4

- Tracking
  - Full geometry
  - Magnetic field description
- Output truth information
  - Trajectories
  - Hits
  - Scoring planes

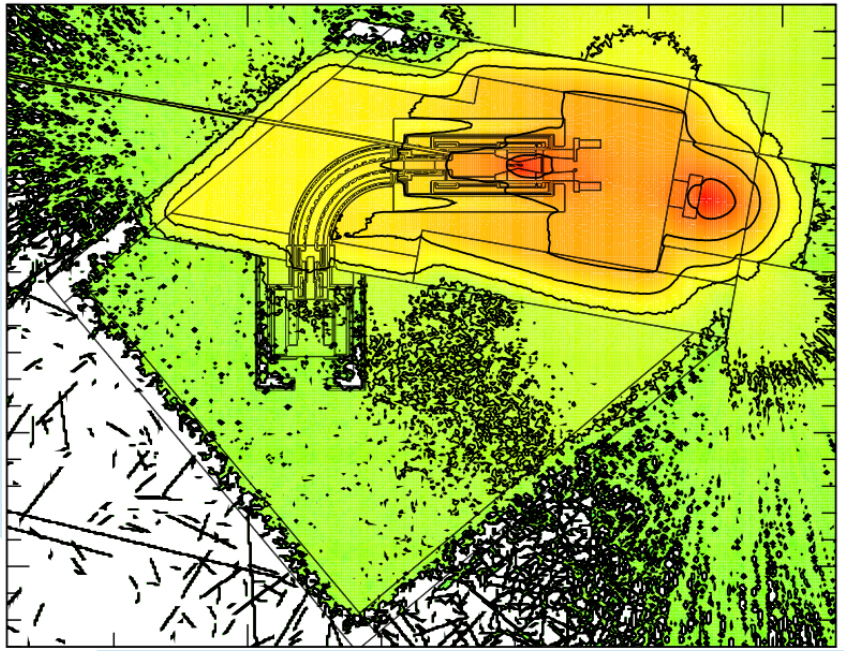




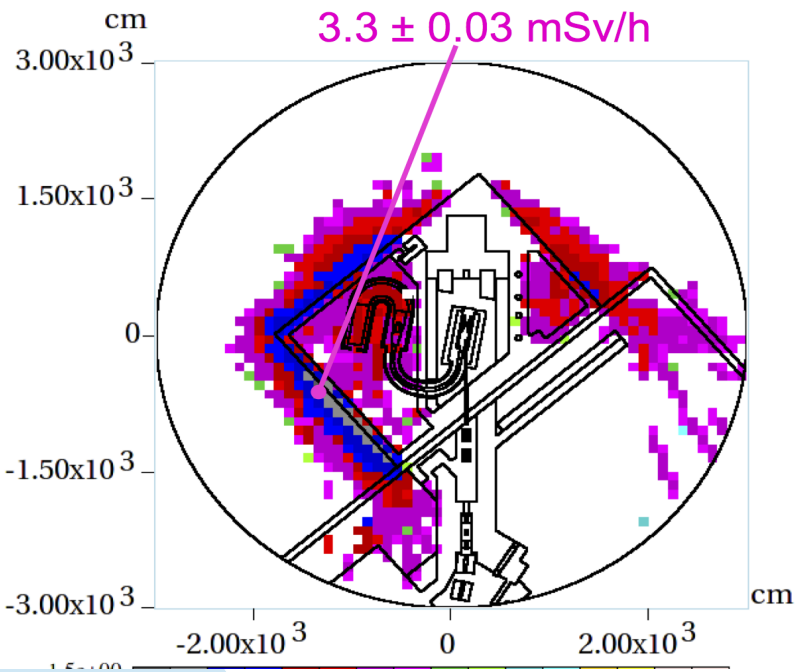


Simulation: Neutron Flux

PHITS

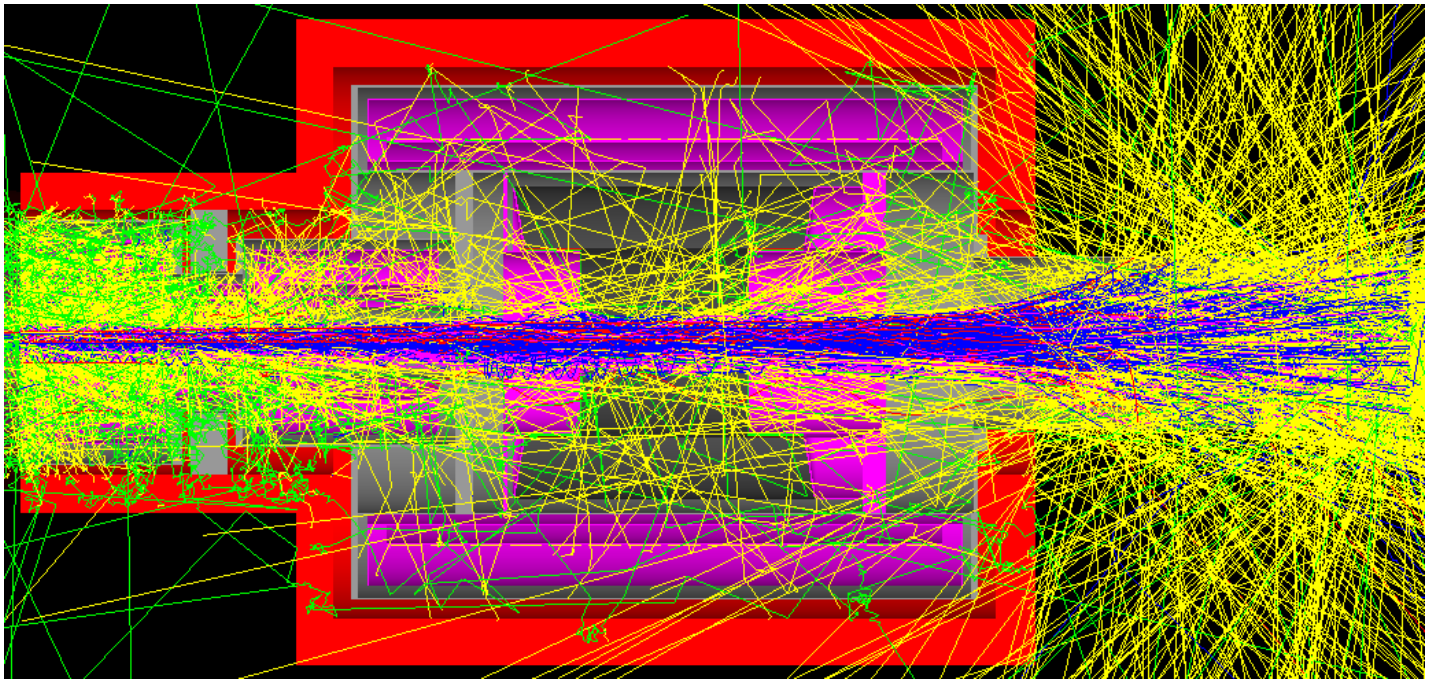


MARS



- Neutron modelling
  - PHITS
  - MARS
  - Geant4 with QGSP_BERT_HP

Simulation: Intrinsic BG

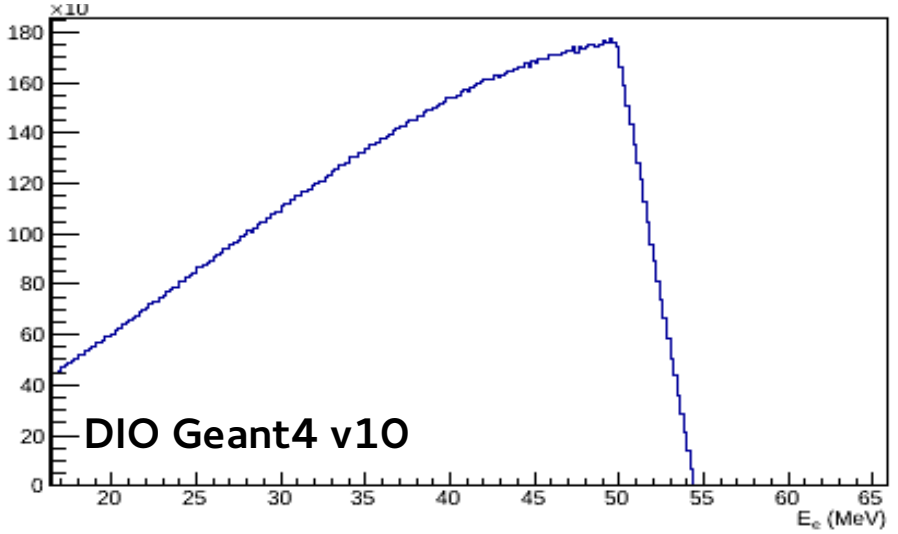


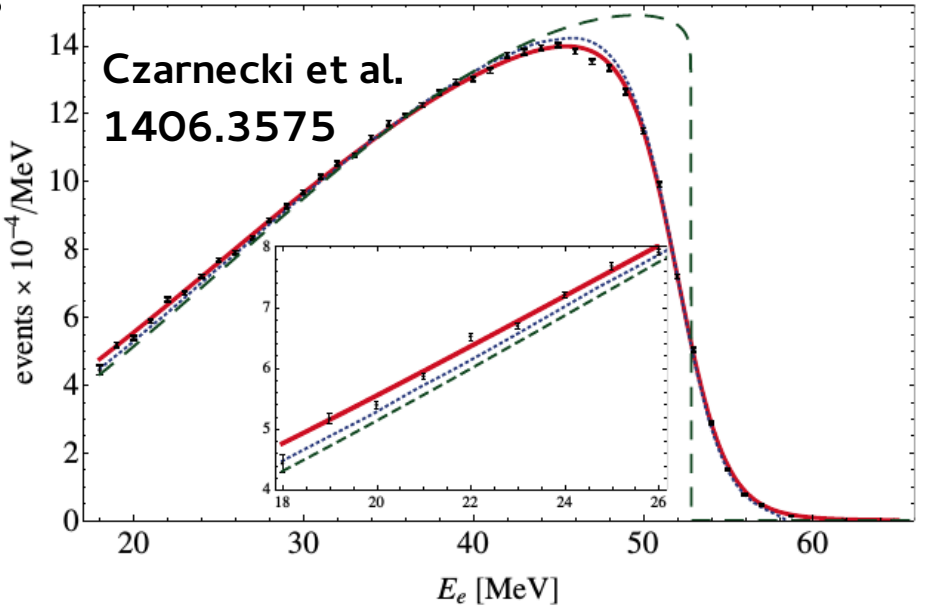
- Intrinsic backgrounds calculated:
  - Find muon stopping distribution in target
  - Generate background of interest with expected energy spectrum

Simulation: Intrinsic BG

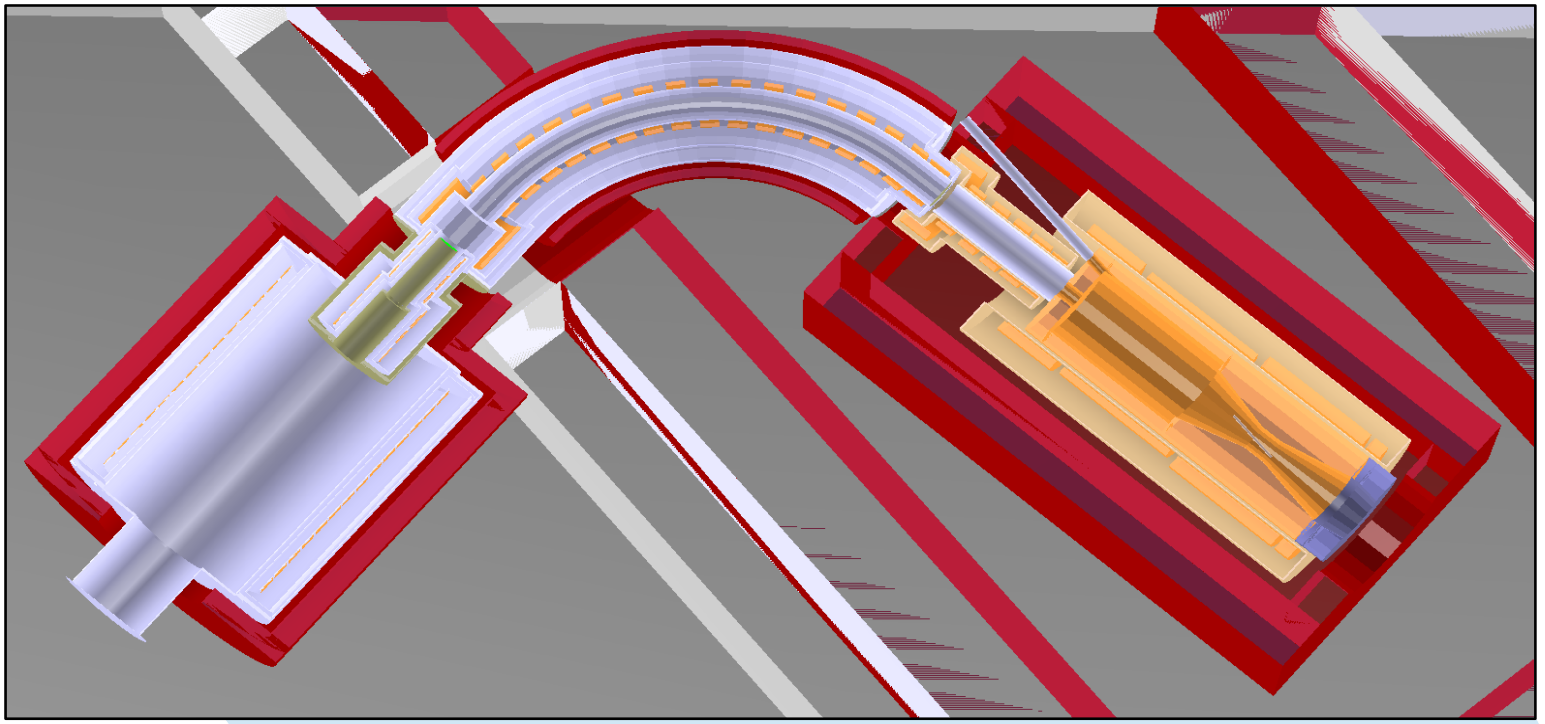
ICEDUST Simulation

- Switch to Geant4 v10
  - Muon stopping on all Z:
    - Capture rates: Suzuki, Measday, Roalsvig, Phys.Rev. C35 (1987)
    - Decay rates: Mukhopadhyay Phys. Rep. 30 (1977)
- Include muon and pion capture processes as extended physics models
  - Radiative μ and π capture
  - Charged particle emission after μ capture
  - Neutron emission after μ capture
  - μ decay in orbit using most recent calculations
    - Czarnacki et al. Phys. Rev. D 9 (2014)





Phase-I Validation



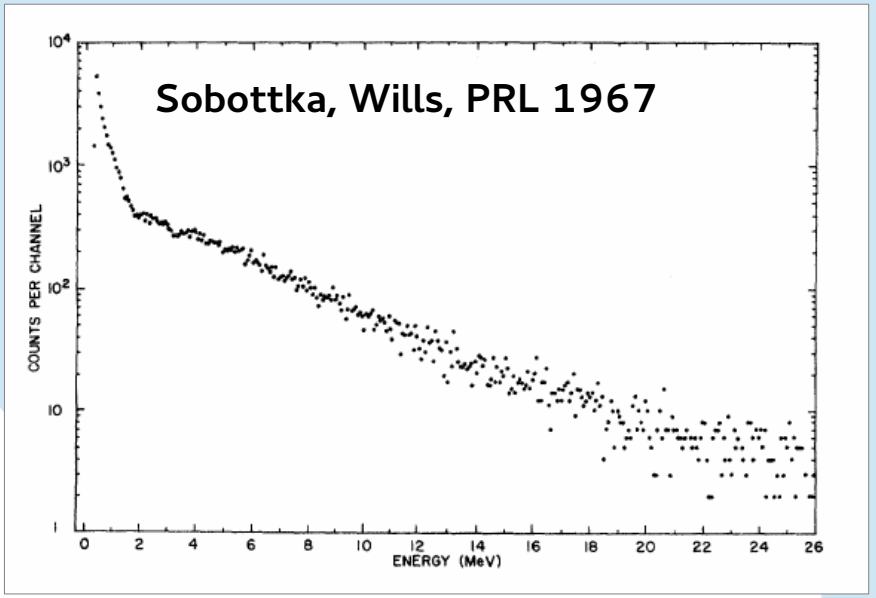
- Beam simulation validation using StrECAL detector
  - Rates, particle populations, momentum distributions
  - Insert absorbers, vary magnetic fields
- Analysis stage uses paired down reconstruction data
- Framework provides flexibility
- Well tested on real data

Existing Measurements

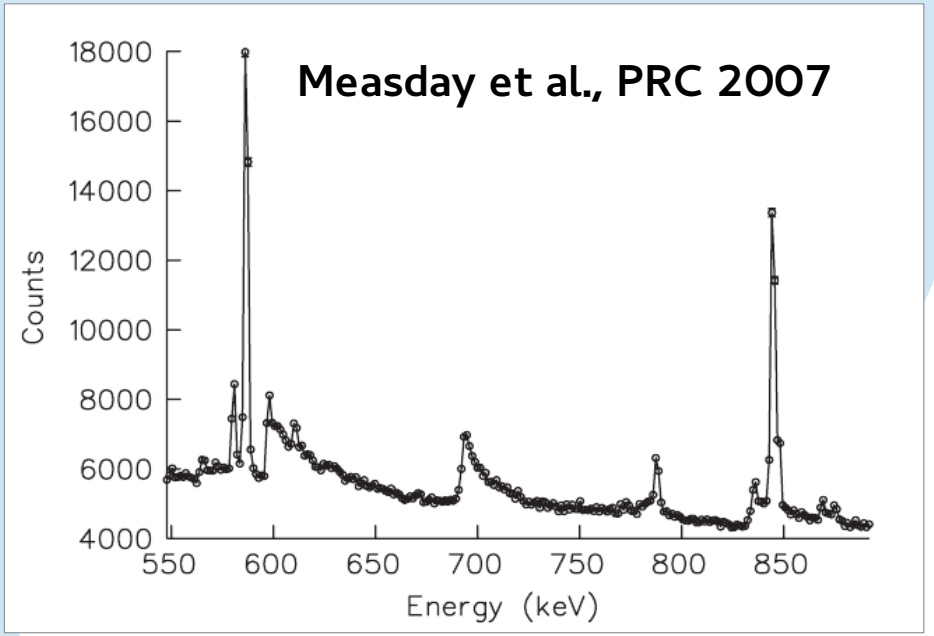
Target A, Z	$A-2, Z-2$ (μ^-, pn) (10^{-3})	$A-4, Z-3$ (μ^-, α) (10^{-3})
$^{27}_{13}Al$	28 ±4	7.6 ±1.1

Proton and alpha emission per muon capture
Wyttenbach et al. Nuc. Phys. 1978

- Proton rate
- Charged particle emission
- X-ray spectrum
- Neutron rate

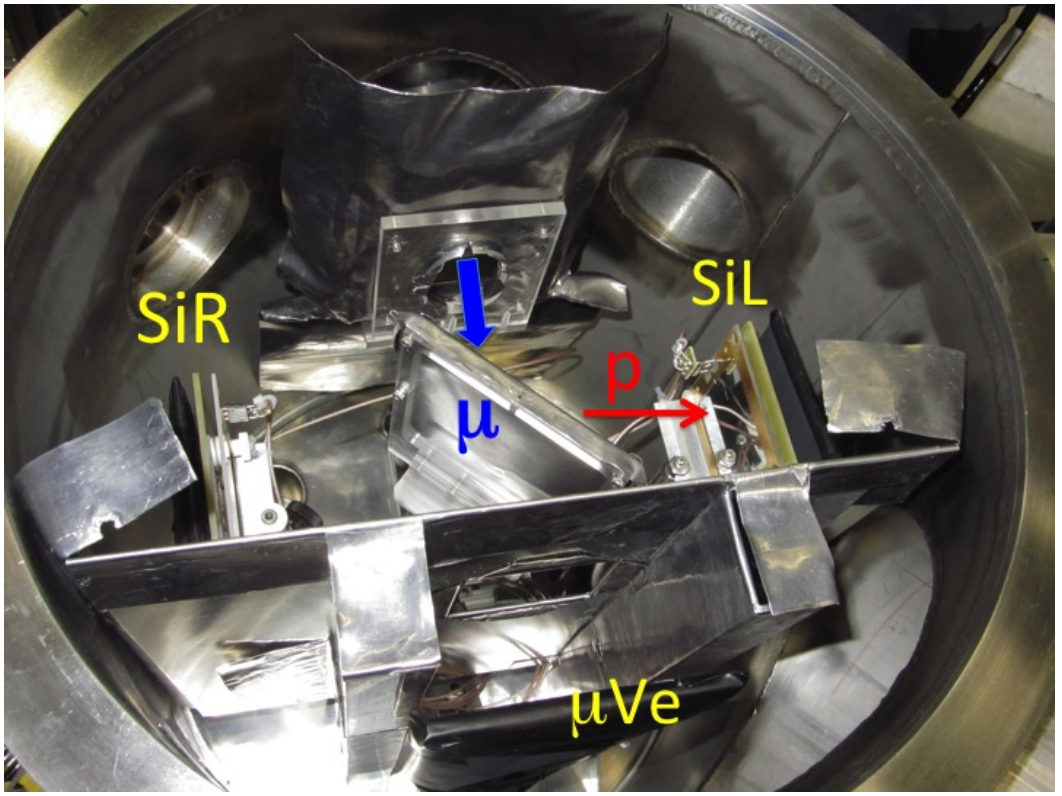


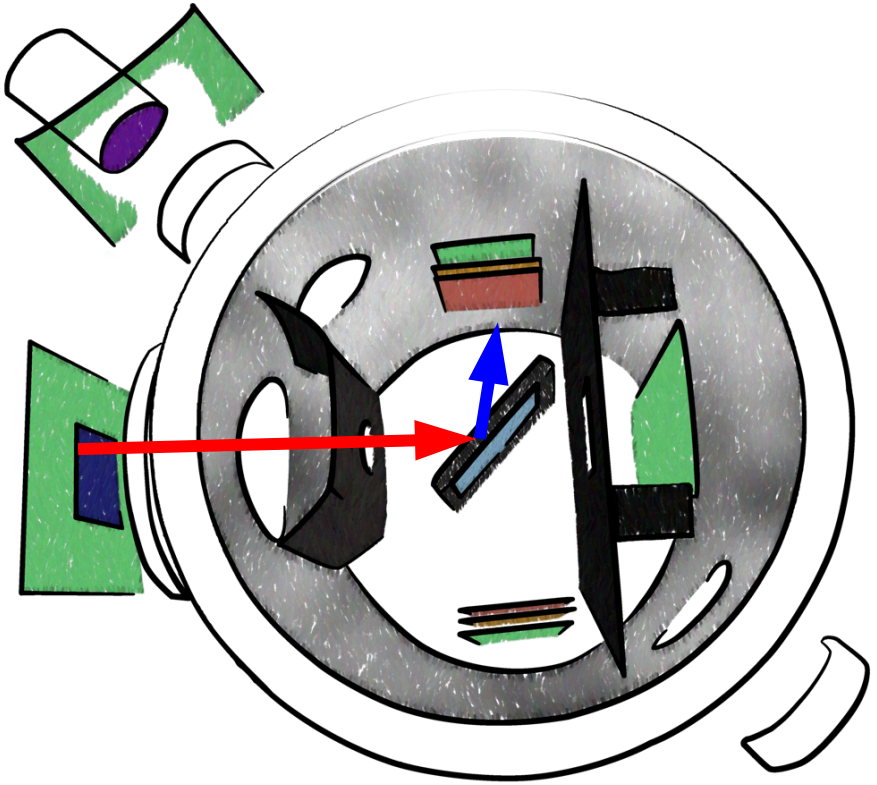
Emission of charged particles from capture on silicion



De-excitation gammas on Aluminium

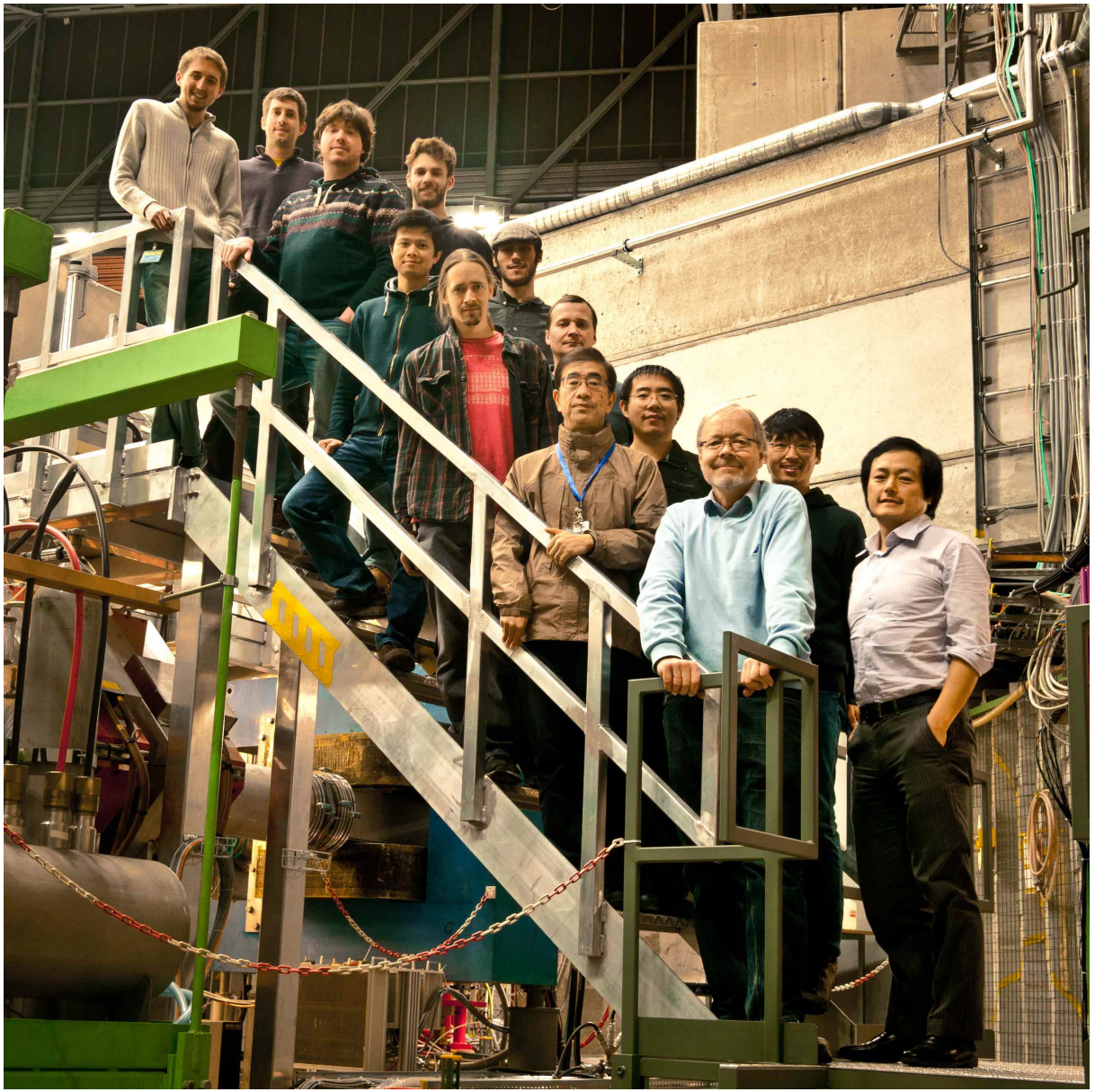
Alcap: COMET Backgrounds



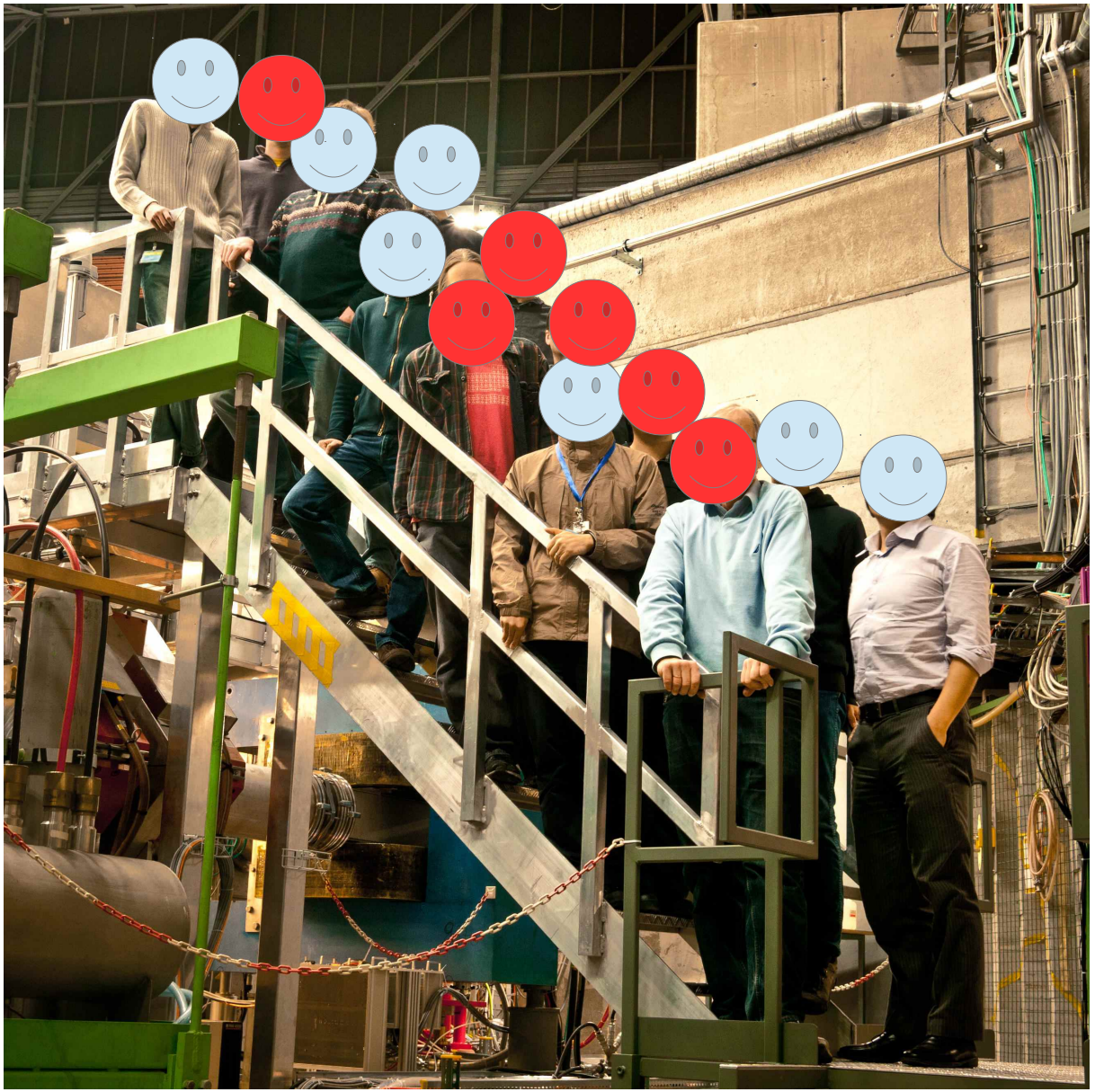


- Surface muon beam (about 30 MeV/c)
- Continuous mode at about 3-6 KHz
- Paul Scherrer Institute, Zurich, Switzerland

Alcap: mu-e Conversion Backgrounds



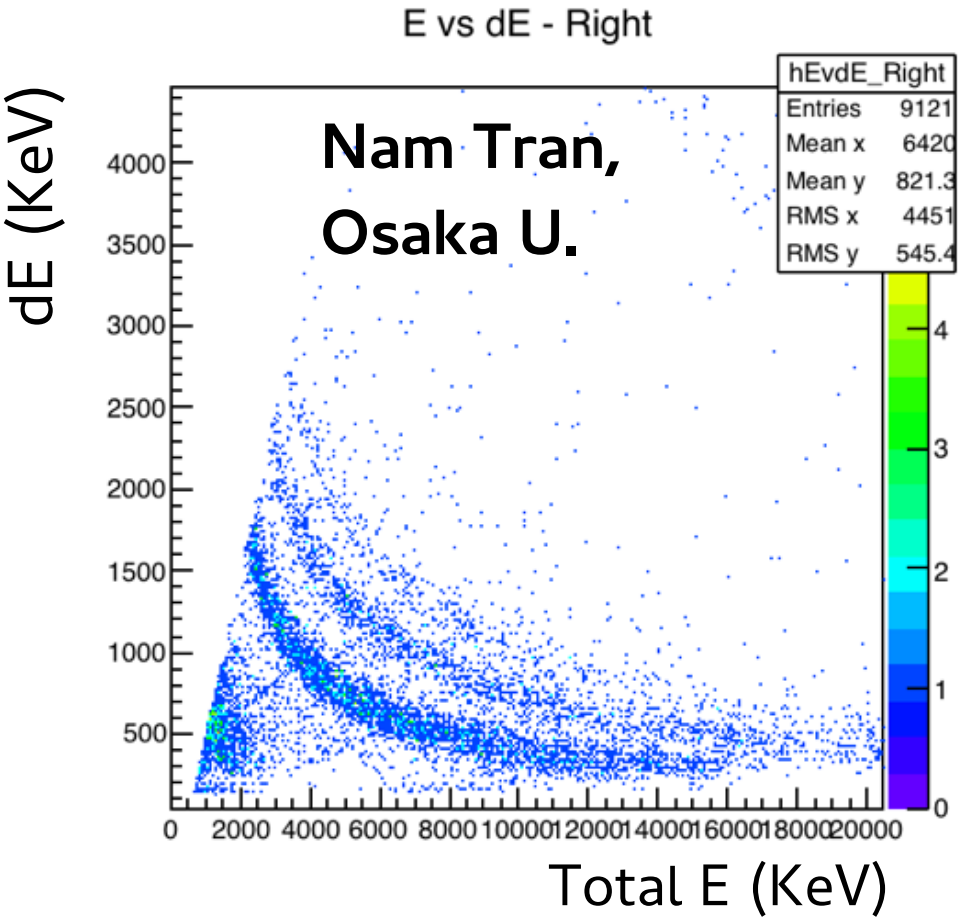
Alcap: mu-e Conversion Backgrounds

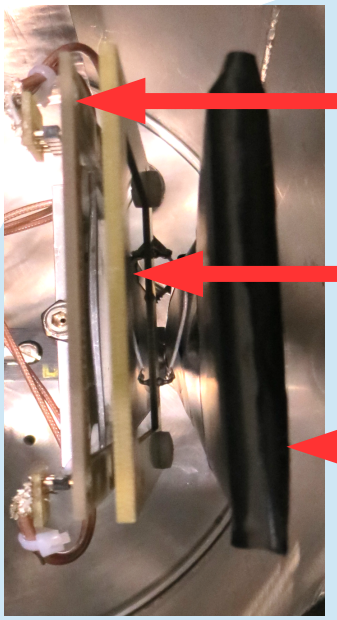


Mu2E

Comet

Alcap: Charged Particles

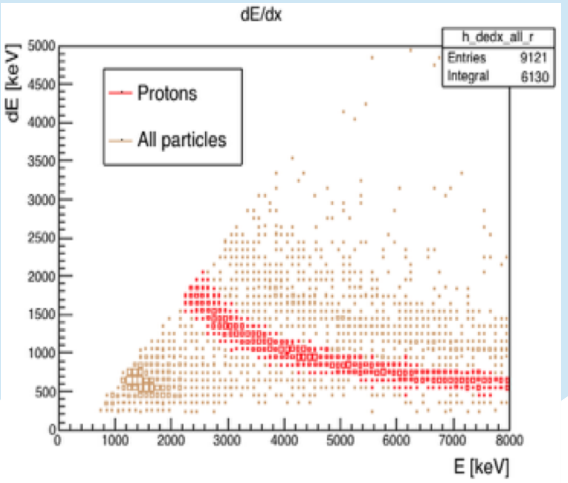




Thin Silicon (58 μm)

Thick Silicon (1.5 mm)

Punch-through
Scintillator veto



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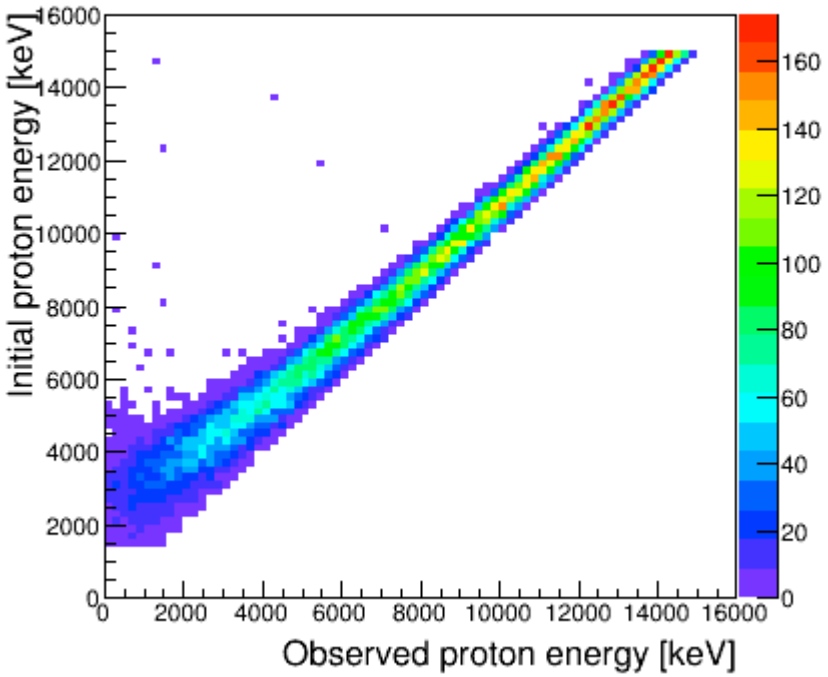
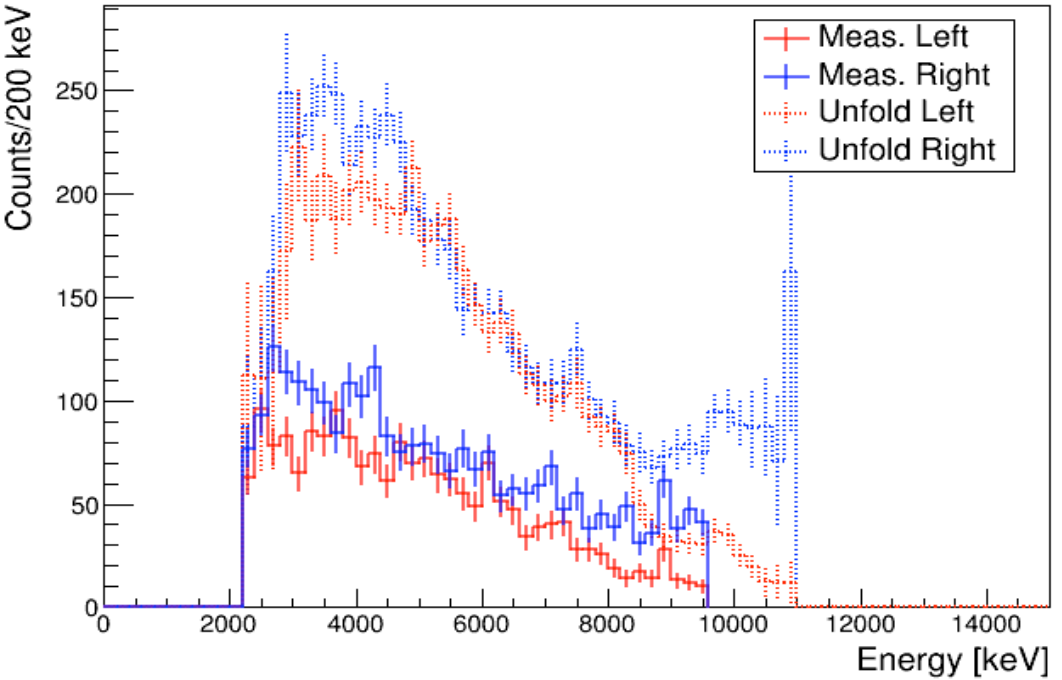
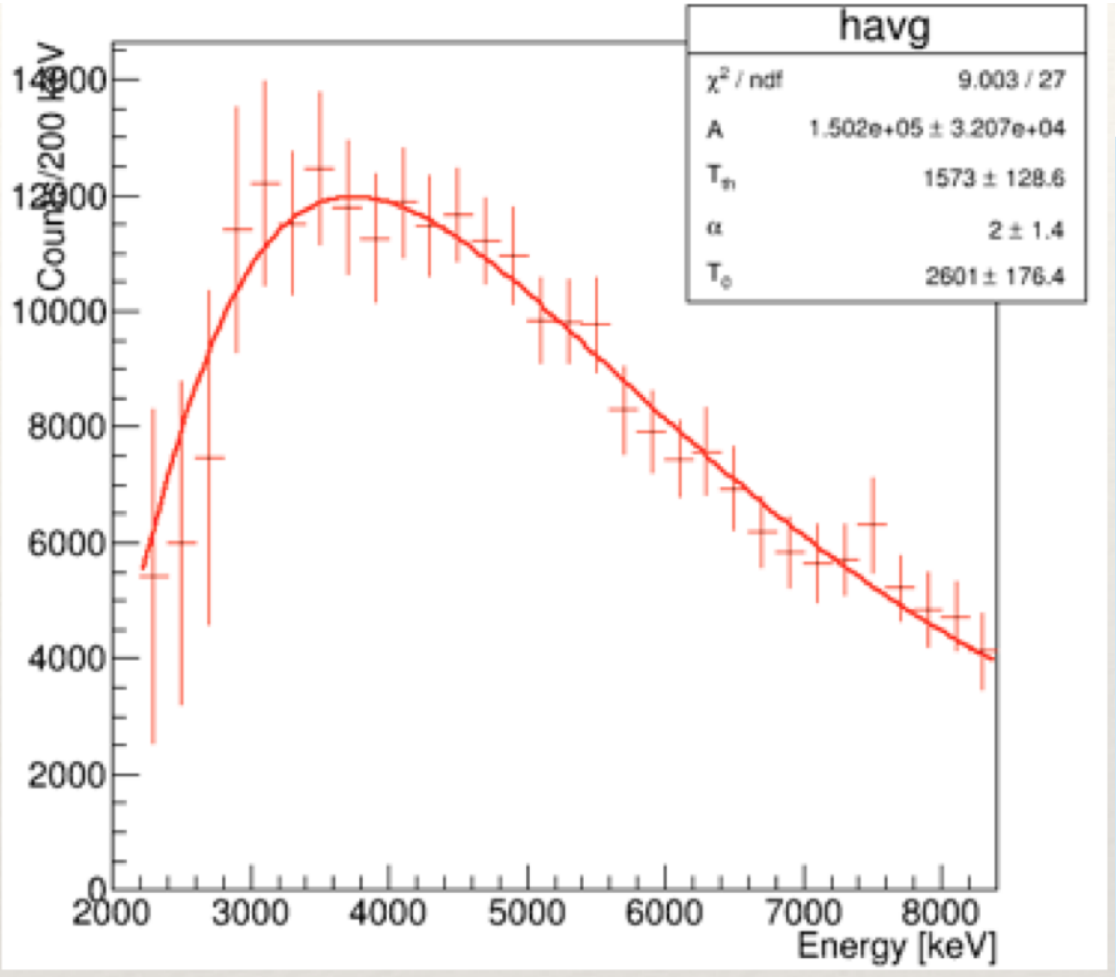




Unfold observed spectrum using response matrix found in Monte Carlo

Alcap: Charged Particles

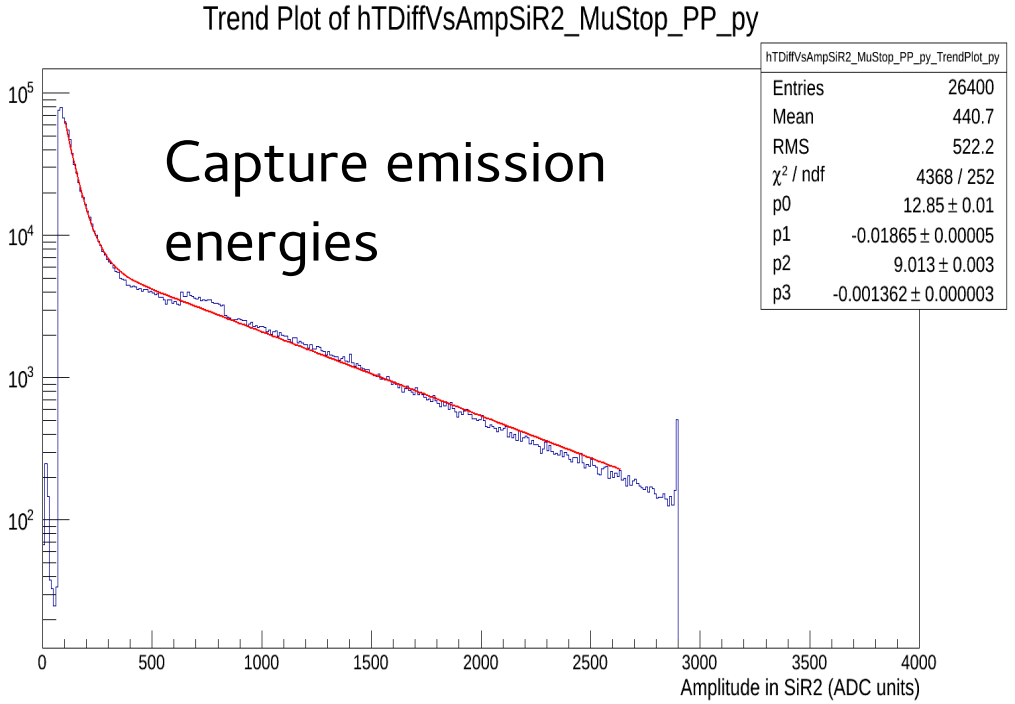


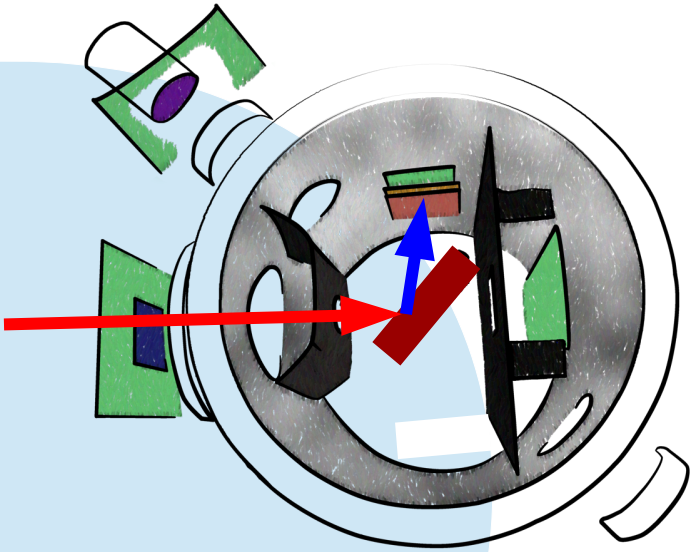
$$p(E) = A\left(1 - \frac{E_{th}}{E}\right)^{\alpha} \exp\left(-\frac{E}{E_0}\right)$$

- Protons per muon stop:
  - 1.7% (4-8 MeV)
  - 3.4% (Total)
- Previously:
  - > 2.8% Wyttenbach, 1978

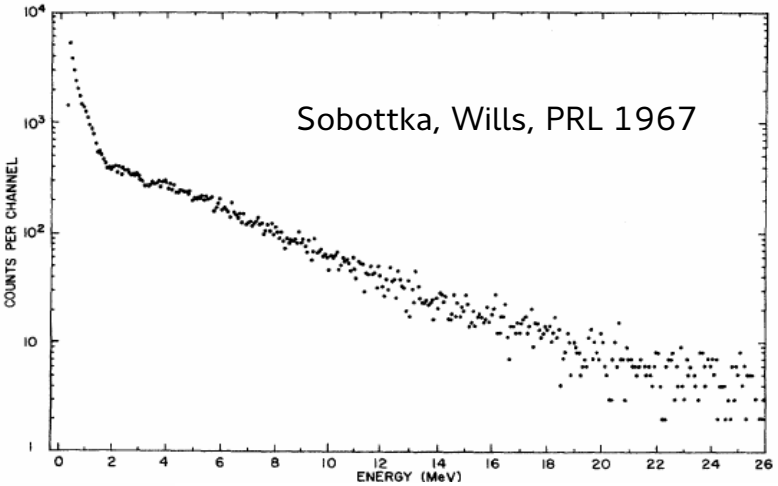
Background Measurements

Charged Particles



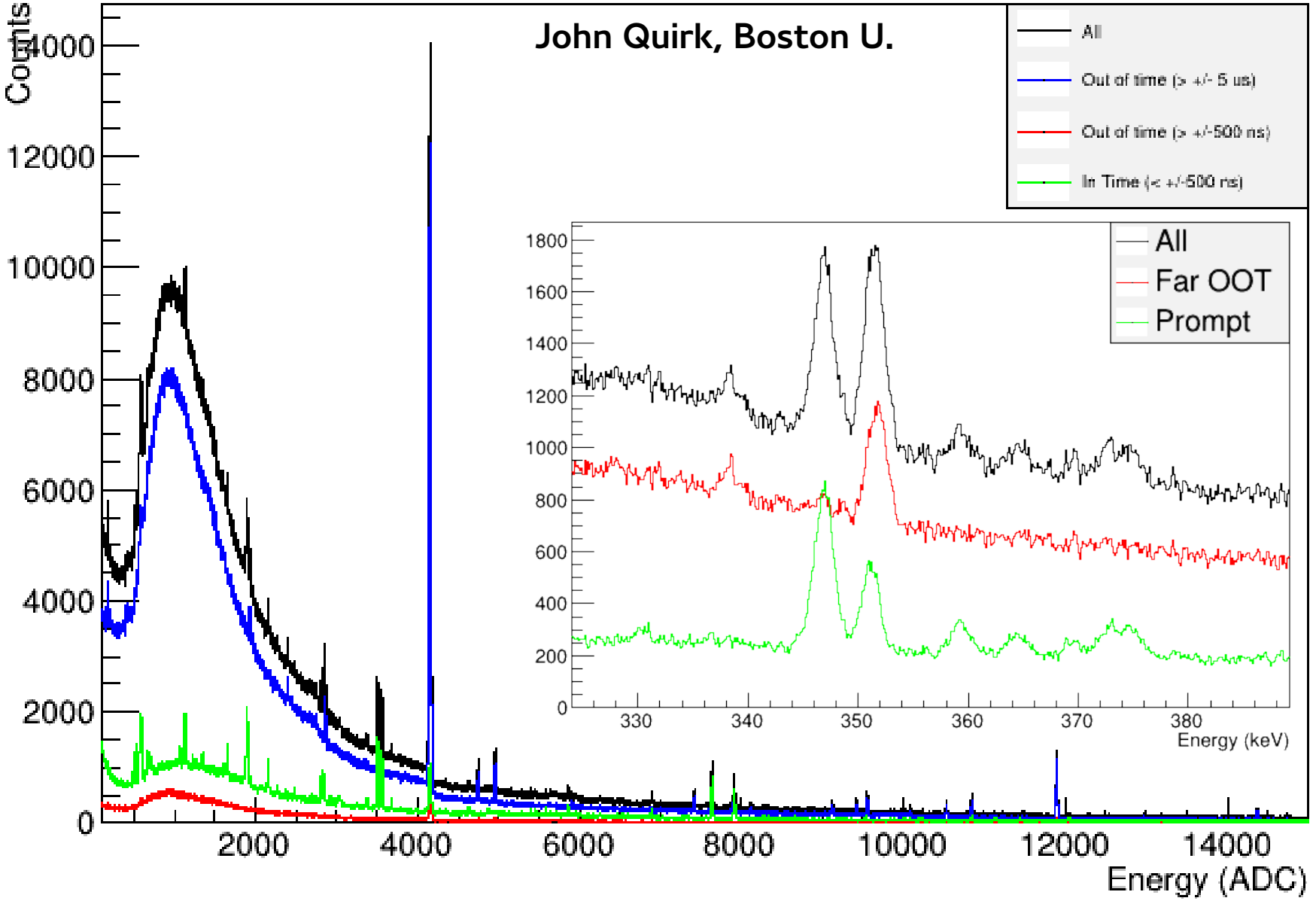


- Place one of the detectors as the target
  - Stop completely in thick silicon
- Require muon hit in active target
  - Muon at entrance scintillator
  - Muon at target



Emission of charged particles from capture on silicion

Alcap: X-ray spectrum



Alcap: Neutron spectrum

Table 4.7
Actual neutron multiplicity distribution (in %) obtained by unfolding the data of MacDonald et al. [328]. The higher multiplicities have been fixed, using the models as a guide. The average multiplicities are taken directly from the experiment and do not conform to the distribution because it has been adjusted at high multiplicity

	Average multiplicity	0	1	2	3	4
Al	1.262 (59)	9 (6)	75 (10)	5 (10)	9 (6)	0
Si	0.864 (72)	36 (6)	49 (10)	14 (6)	1 (1)	0
Ca	0.746 (32)	37 (3)	54 (5)	8 (3)	1 (1)	0
Fe	1.125 (41)	19 (4)	60 (6)	12 (5)	9 (3)	0
Ag	1.615 (60)	6 (9)	51 (18)	25 (18)	12 (11)	6 (6)
I	1.436 (56)	4 (10)	72 (19)	6 (18)	12 (11)	6 (6)
Au	1.662 (44)	10 (9)	43 (19)	27 (18)	12 (13)	8 (5)
Pb	1.709 (66)	0 (11)	59 (22)	23 (21)	5 (14)	13 (7)

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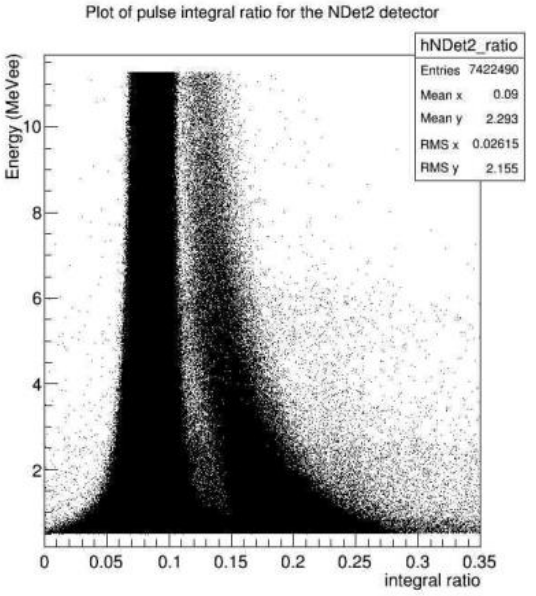

Alcap: Summary

- Measured:
  - Proton spectrum and rate
    - 3.4% protons per muon capture
  - X-ray spectrum
- Next steps:
  - Publish results
  - Future run proposal for next year
    - More targets and statistics
    - Neutron spectrum

Summary

- COMET Software: ICEDUST
  - Flexible and previously used
- Simulation
  - Considers magnetic field, geometry
  - Needs finer work on muon physics
- Alcap experiment
  - Effects of muon capture on Aluminium and Silicon
  - Publish results soon
  - Run again in 2015