Searches for SLOwly moving Particles (SLOPs) with IceCube

M.L. Benabderrahmane[1] and S. Schoenen[2]

for the IceCube Collaboration

[1] DESY-Zeuthen
[2] RWTH Aachen

HELMHOLTZ ASSOCIATION

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DESY

Outline

- Introduction

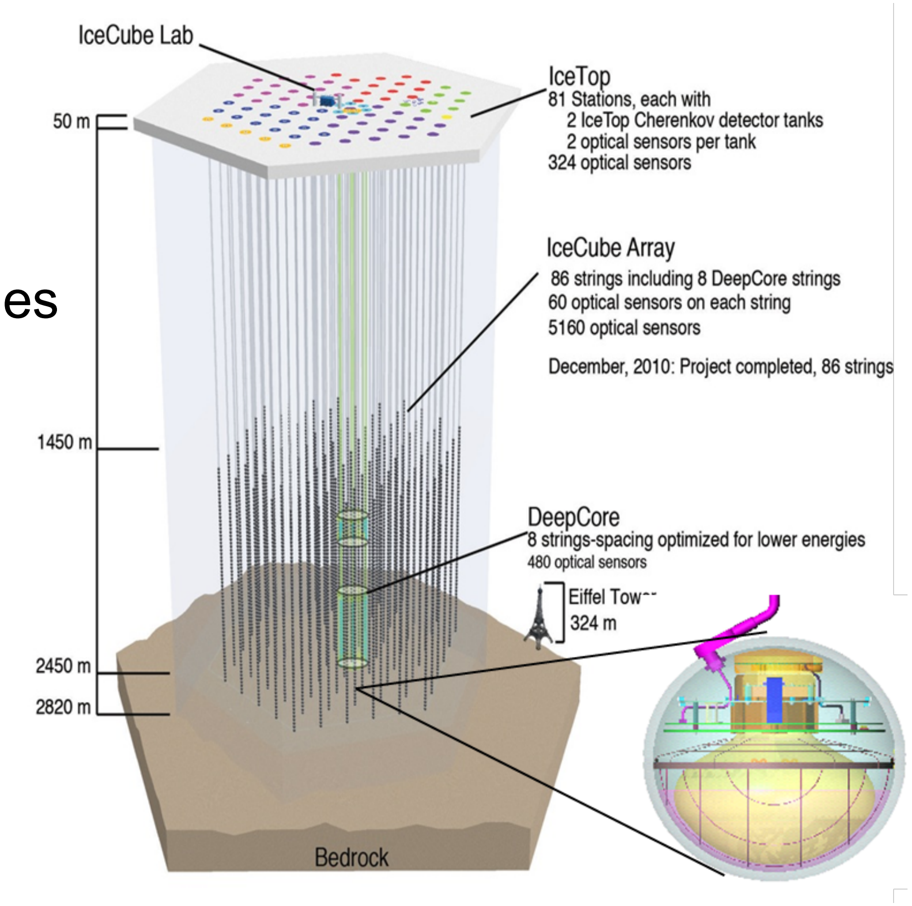
- Searches for SLOPs with IceCube:
  - Standard IceCube triggers
  - With SlowMonople trigger

- Data analysis

- Outlook

The IceCube Detector

- IceCube completed in Dec. 2010
- 86 strings with 5160 Optical Modules
- 1 km^3 instrumented volume
- 162 Ice-Cherenkov tanks (IceTop)



Primary goal:
Neutrino detection via the
Cherenkov light of secondary leptons

In addition:
Search for exotic particles, like
Monopoles, Q-balls, Nuclearites ...

SLOPs: GUT Monopoles, Q-Balls and Nuclearites

> GUT Monopoles

- Predicted by GUT theories
- More details next slide !

> Q-balls

- Heaviest Dark Matter Candidates of SUSY theories
- Aggregates of squarks, sleptons and Higgs field
- 10^5 GeV < MQ < 10^{22} GeV

> Nuclearites (Strange Quark Matter)

- Almost equal proportion of u, d and s quarks + electrons
- Should be stable for baryon number $300 < A < 10^{57}$

Magnetic Monopoles

- Dirac (in 1931): Existence of magnetic monopoles could explain quantification of electric charge
  - Elementary magnetic charge **g** and electric charge **e** are related by:

$$g_D = 68.5e$$

- GUT: Masses of magnetic monopoles ~ masses of X,Y GUT bosons: $m_M \sim 10^{16}$ GeV cannot be accelerated to relativistic velocities

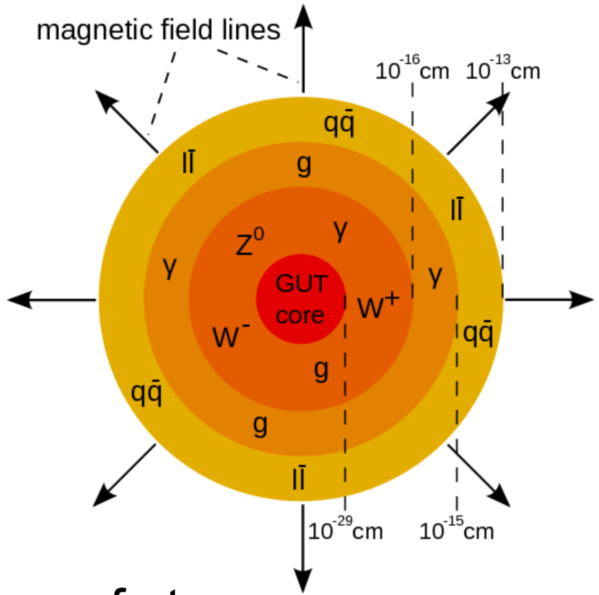
- Magnetic Monopoles are produced during phase transitions in the early universe

- Intermediate-mass Monopoles with $m_M = 10^7 - 10^{13}$ GeV may have been produced in later phase transitions

  → Can be accelerated to relativistic velocities by galactic magnetic fields

Searches for SLOPs (Q-balls & Monopoles) via the Rubakov-Callan effect

- Interaction of GUT monopole core (X,Y bosons) with a nucleon leads to reaction where nucleon decays: monopole catalysis of nucleon decays, i.e. Rubakov-Callan effect



$$M + p \rightarrow M + e^{+} + \pi^{0}$$

- The catalysis cross section is comparable to the one of strong interactions:

$$\sigma_{catalysis} = 0.17 \times \sigma_0/\beta^2 \quad (\; 10^{-32} < \sigma_0 < 10^{-24} \text{ cm}^2 \;)$$

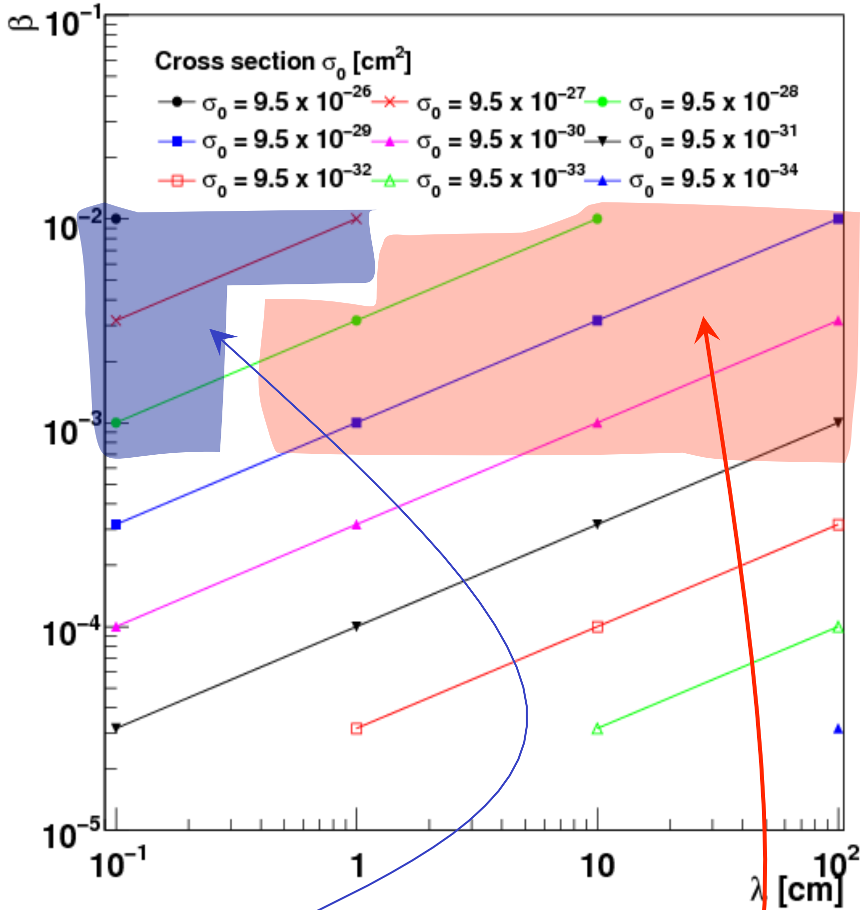
- Neutral Q-balls would also interact via p(n)-decay catalysis

Phase space parameters

Catalysis cross section:

$$\sigma_0 = \frac{\beta^2}{0.0175 \cdot N_A \cdot \lambda}$$

λ: distance between two catalysis acts



Depending on β,

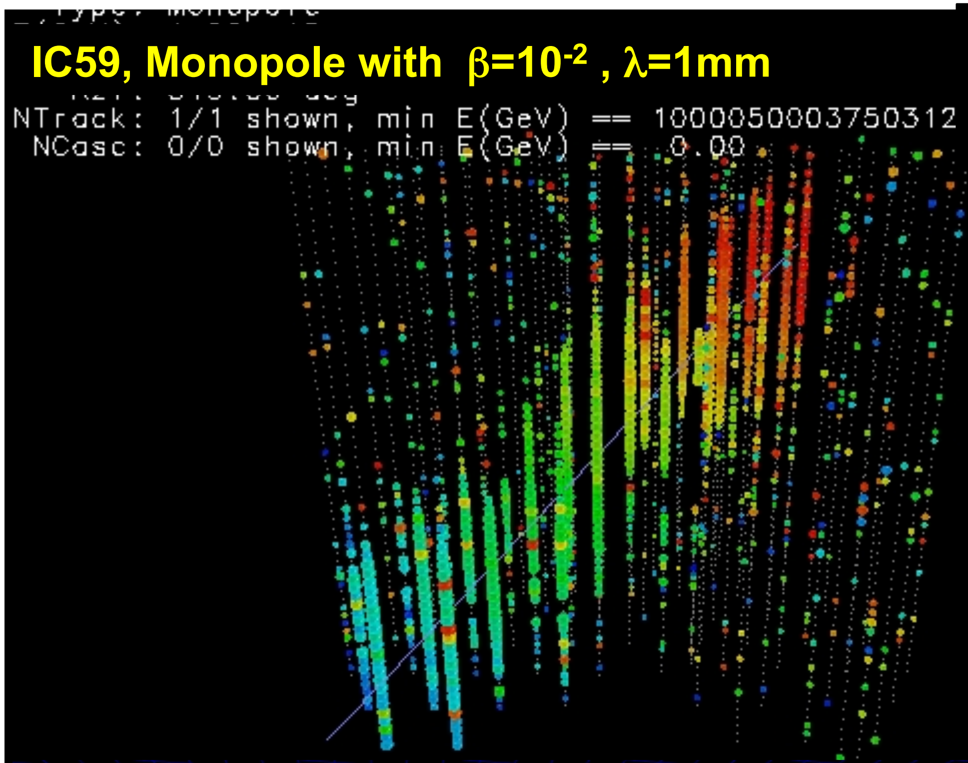
- Monopoles with high σ_0 ($\sigma_0 > 10^{-28}$) tend to keep the trigger fulfilled during all their passage

→ IC59 analysis, based on standard IceCube triggers

- Monopoles with low σ_0 ($\sigma_0 < 10^{-28}$) split up in several subsequent events → Solution dedicated trigger

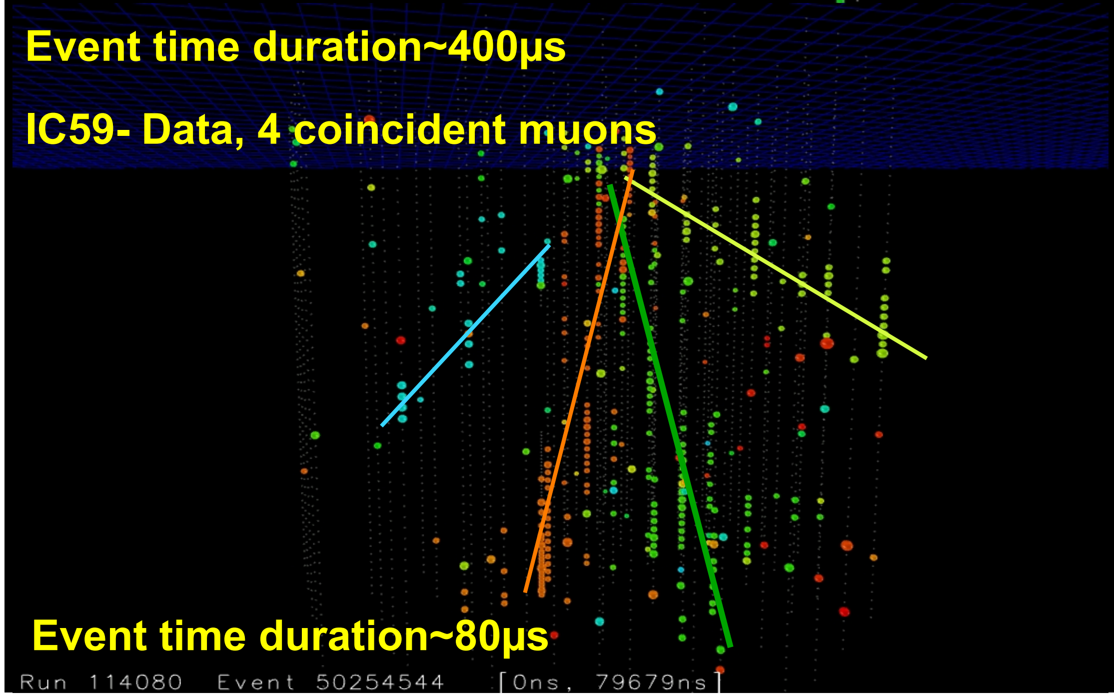
→ IC86/DeepCore analysis using a dedicated trigger

IC59, Monopole with $\beta=10^{-2}$, λ=1mm

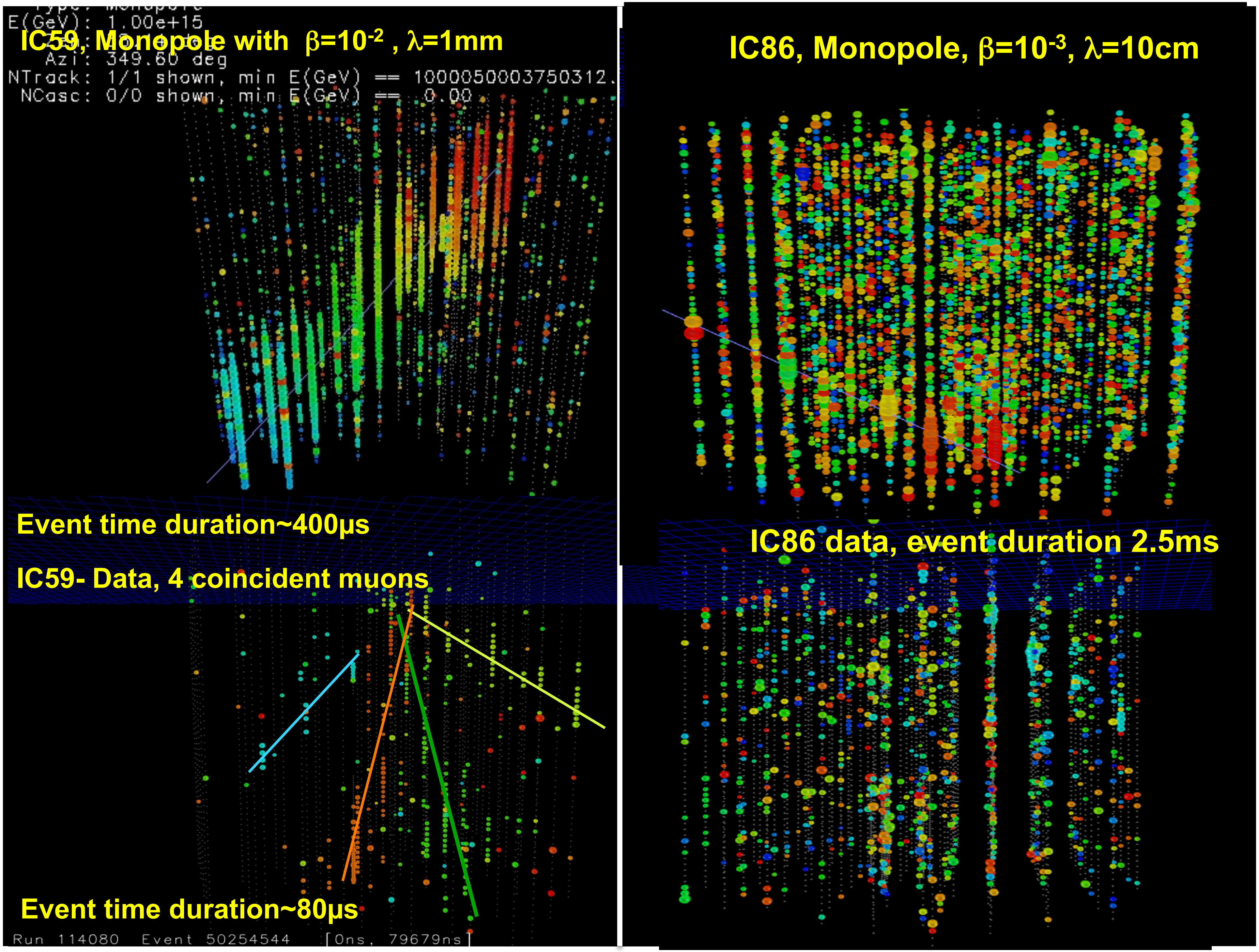


Event time duration~400μs

IC59- Data, 4 coincident muons



Event time duration~80μs


E(GeV): 1.00e+15
IC59, Monopole with β=10^-2 , λ=1mm
Azi: 349.60 deg
NTrack: 1/1 shown, min E(GeV) == 1000050003750312.
NCasc: 0/0 shown, min E(GeV) == 0.00
Event time duration~400μs
IC59- Data, 4 coincident muons
Event time duration~80μs
Run 114080 Event 50254544 [0ns, 79679ns]
IC86, Monopole, β=10^-3, λ=10cm
IC86 data, event duration 2.5ms

Search for bright Monopoles: using standard IceCube triggers

- 2009 season (IC59): no dedicated filter was deployed for SLOPs

  → use events from all available filters (muons, cascades ...)

  Rate ~ 85Hz

- Divide the data into two sets:

  1) λ_{cat} for σ =1.7•10^{-22} =1mm

  2) λ_{cat} for σ= 1.7•10^{-23} =10mm

- Look for events with:
  - long event time duration, t >28μs
  - low reconstructed velocity, $\beta<5 \cdot 10^{-2}$ (v < 0.015m/ns)

  } Rate ~4mHz

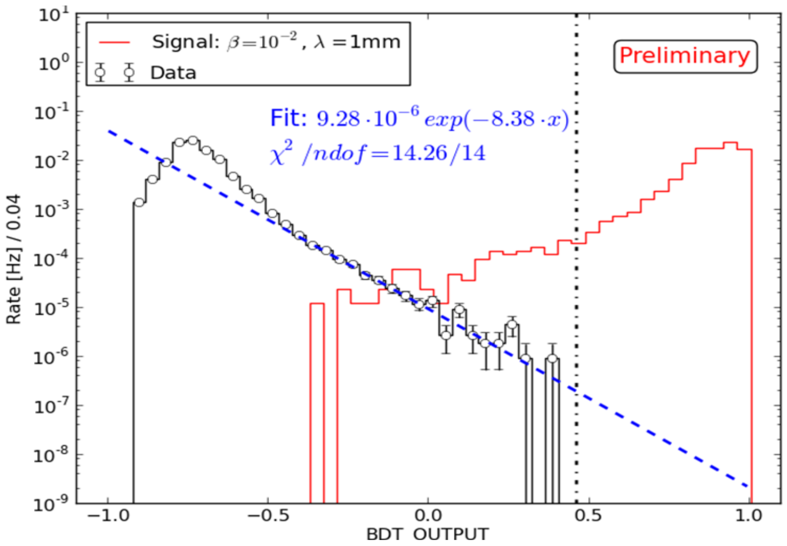
- Use Boosted Decision Trees (BDT) for final cut
- Analysis is performed blindly

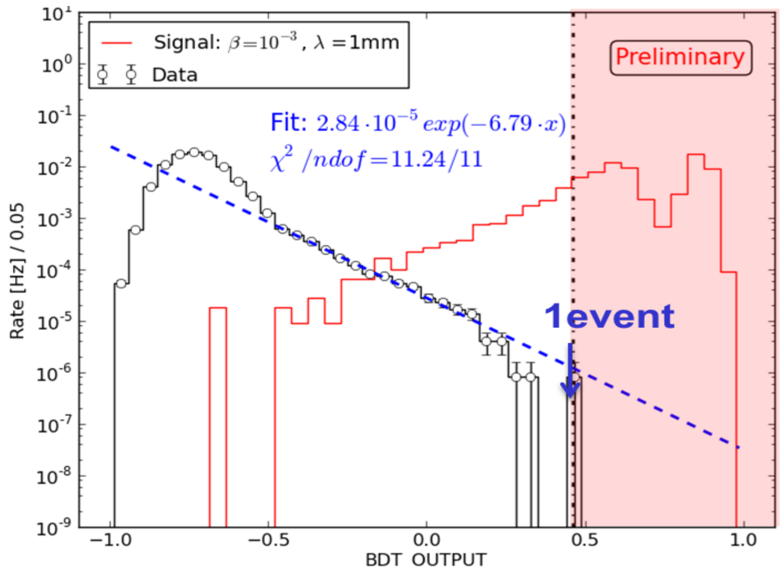
Results of the IC59 analysis

- Train BDT for each (β,λ), fit tails with an exponential

  (β,λ) = (10^{-2},1mm/10mm) & ($10^{-2.5}$,1mm/10mm), (10^{-3},1mm)

- Sensitivity for (10^{-3},10mm) drops after extrapolation to 1year
- Optimize final cut on BDT scores using the burn sample

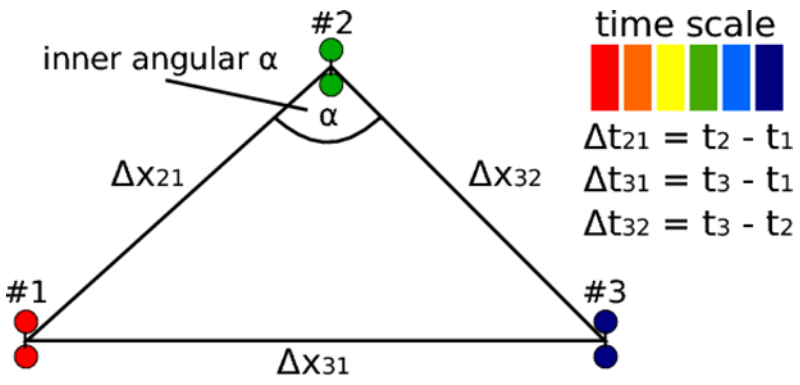




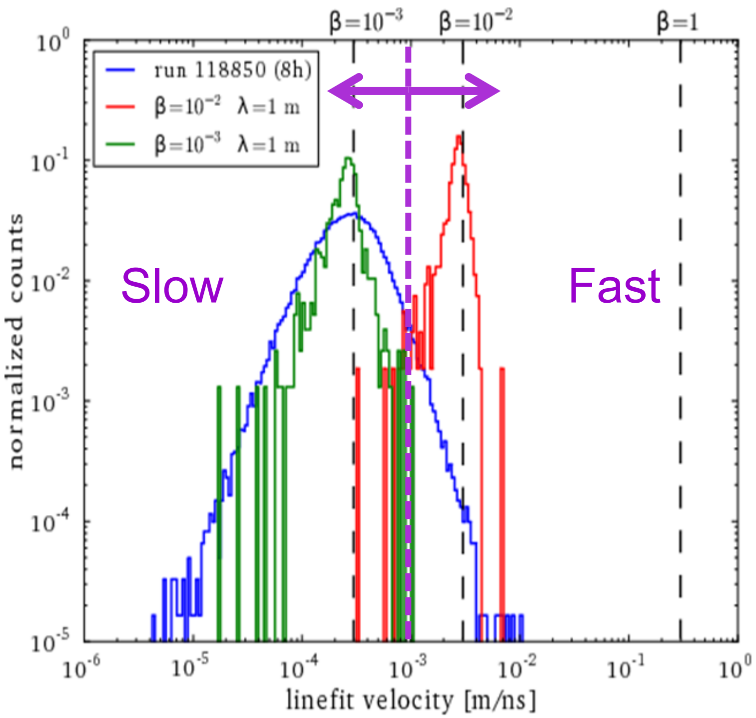
- One event survived the five (β,λ) → compatible with background

Search for faint monopoles: SlowParticle trigger

- Topological trigger sensitive to low σ_{cat} running in DeepCore
- Trigger basics:
  - Uses temporally isolated local coincident hit (HLC pairs)
  - 3 HLC pairs form a triplet



Trigger rate ~2Hz

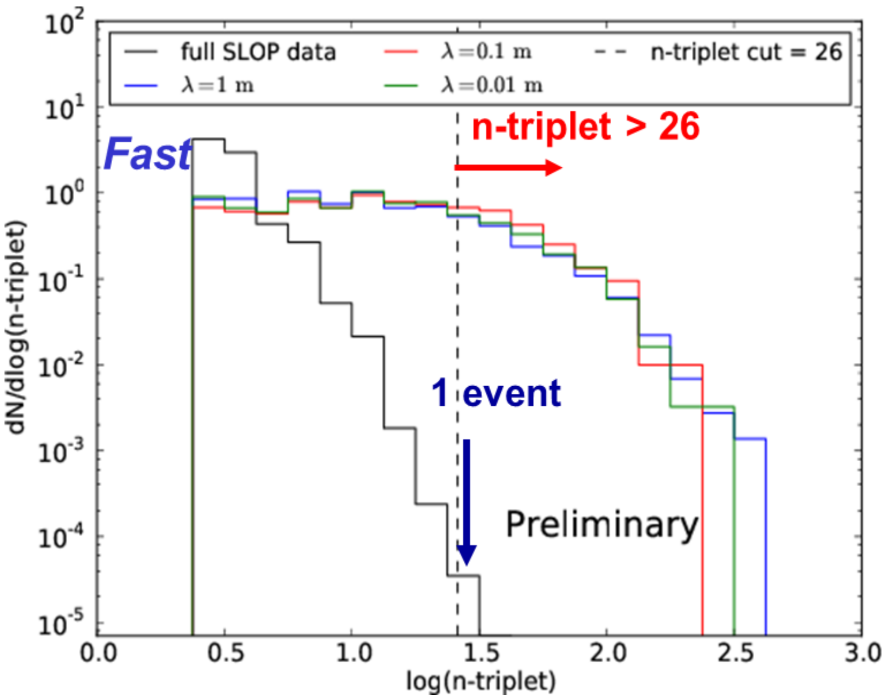


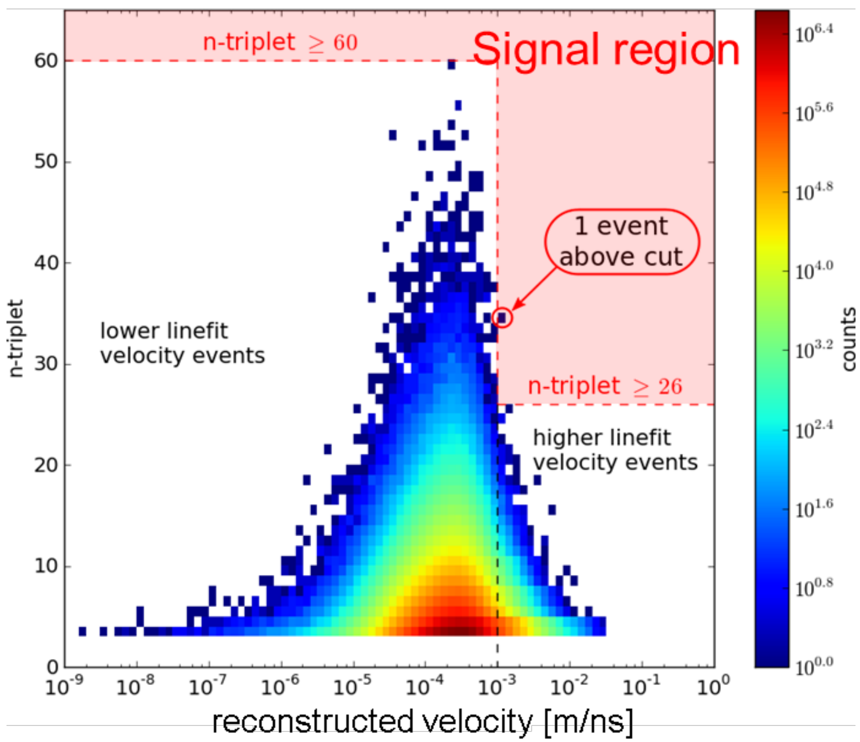
- Quality criteria for a tuple:
  - Track-like
  - Velocity consistency between HLCs
- Form n-triplets overlapping in time

Results of the IC86 analysis

- Fit n-triplets with an exponential (trigger mostly on dark-noise)
- Final cuts were defined blindly
- One event survives, compatible with background

S. Schoenen

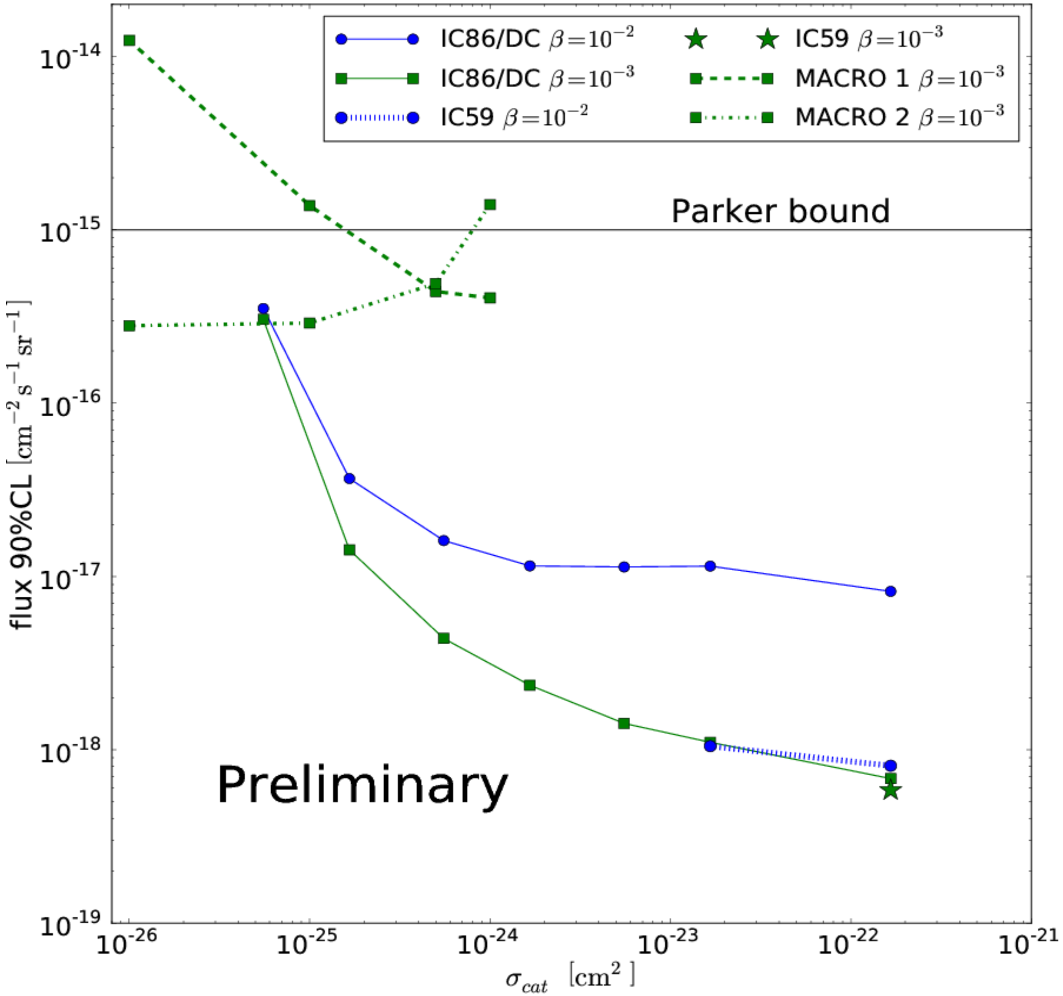




The remaining event has β close to the separation line

Monopole Flux Limits

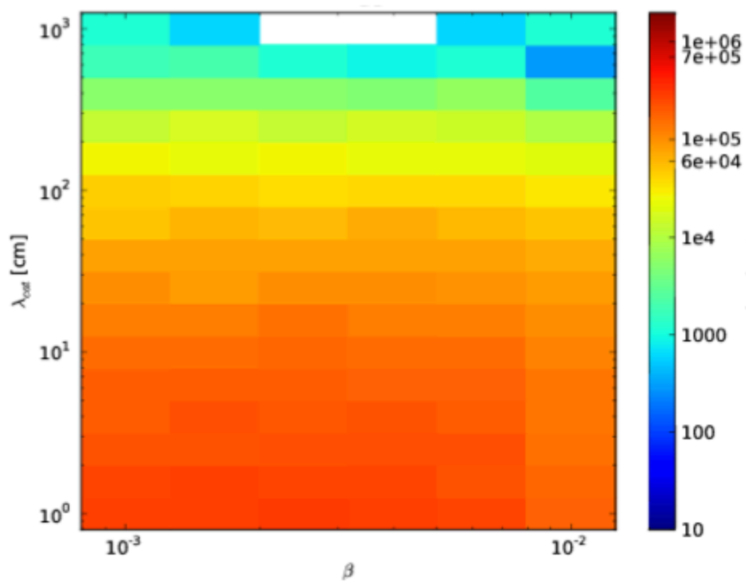
- Observations of the IC59 and IC86/DC analysis consistent with background
  - Calculate limits (90%C.L.)



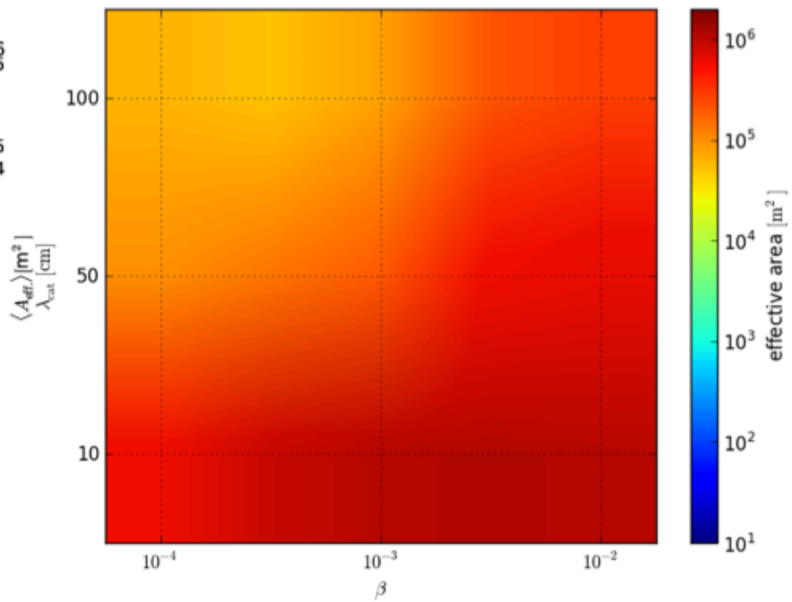
- Improvement of the best flux limits of MACRO
- IC86/DC analysis sensitive:
  - to $\sigma_{cat} < 10^{-23} \mathrm{cm}^2$
- IC59 analysis sensitive:
  - to $\sigma_{cat} > 10^{-23} \mathrm{cm}^2$

Summary and Outlook

- Improvement of the best upper limits for slow monopoles by a factor 100
- Results will be published soon
- The trigger is running on the whole detector:
  - sensitive to bright and dim tracks
  - gain in the total effective area up to a factor ~10



2011 DeepCore only



2012 full detector

Backup Slides

Event Selection

Divide data into two sets:

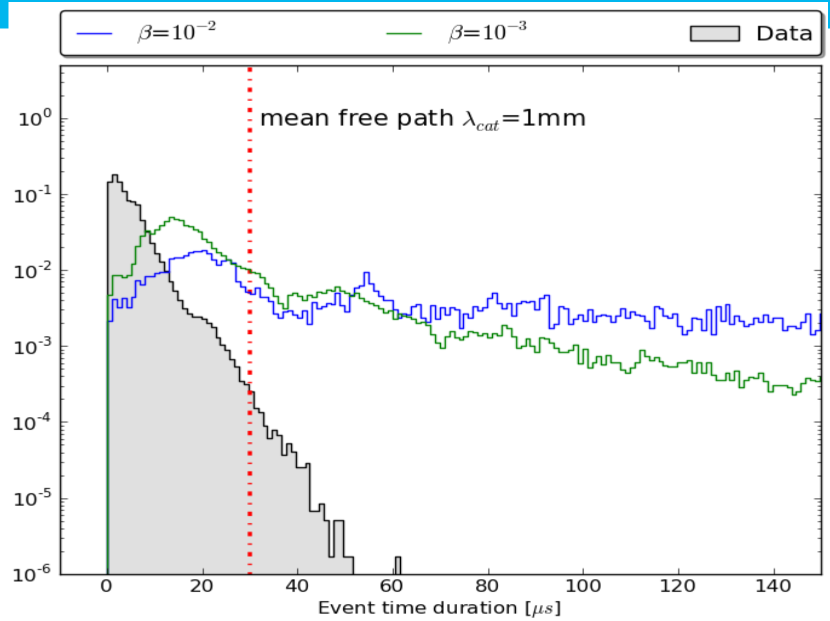
$\lambda_{cat}(\sigma = 1.7 \cdot 10^{-22}) = 1mm$

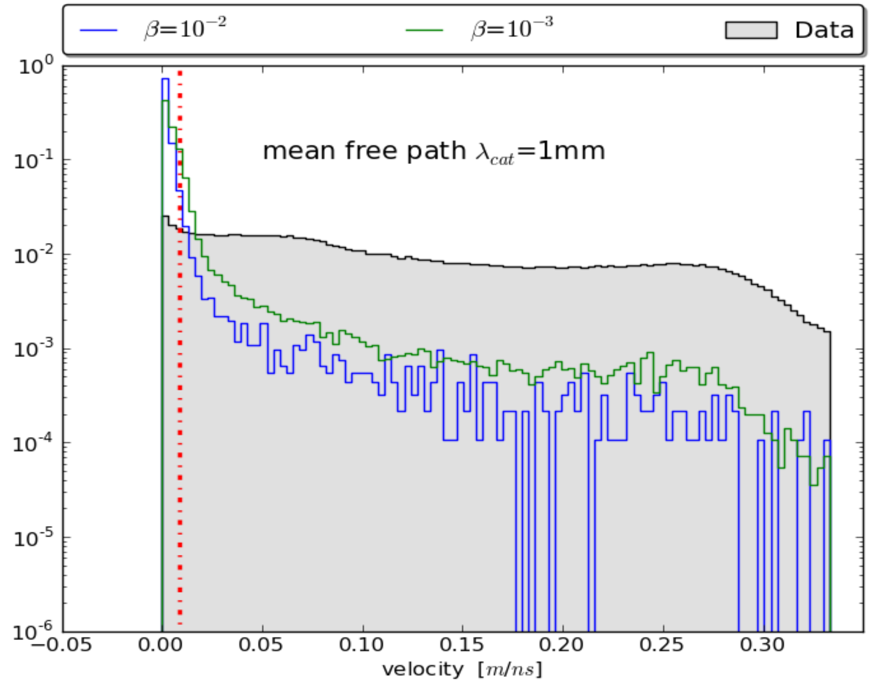
Look for events with:

- long event time duration, $t > 30\mu s$
- low reconstructed velocity, $\beta < 3 \cdot 10^{-2}$ ($v < 0.009 m/ns$)

$\lambda_{cat}(\sigma = 1.7 \cdot 10^{-23}) = 10mm$

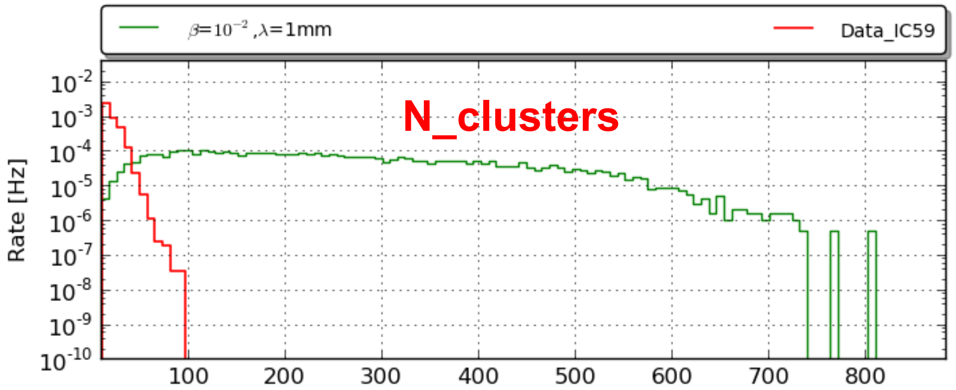
- long event time duration, $t > 28\mu s$
- low reconstructed velocity, $\beta < 5 \cdot 10^{-2}$ ($v < 0.015 m/ns$)

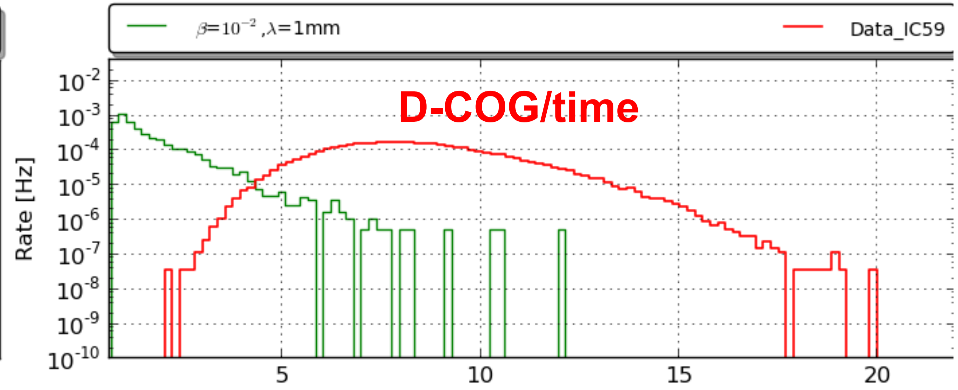


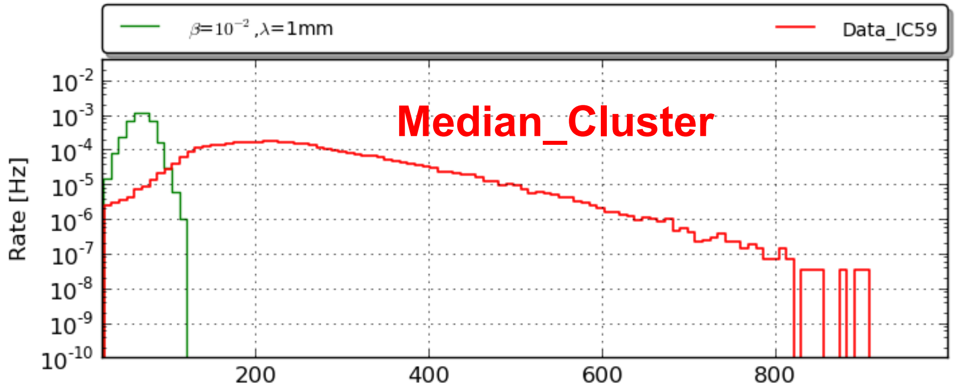


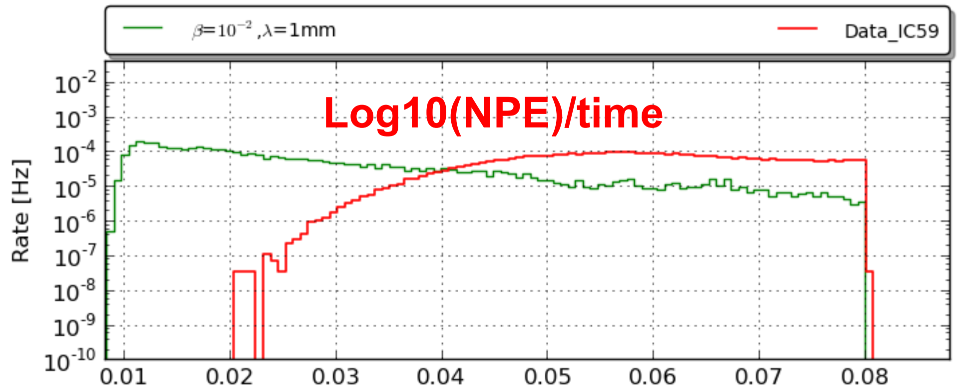
<u>**Data rate reduced by a factor 10^5**</u>

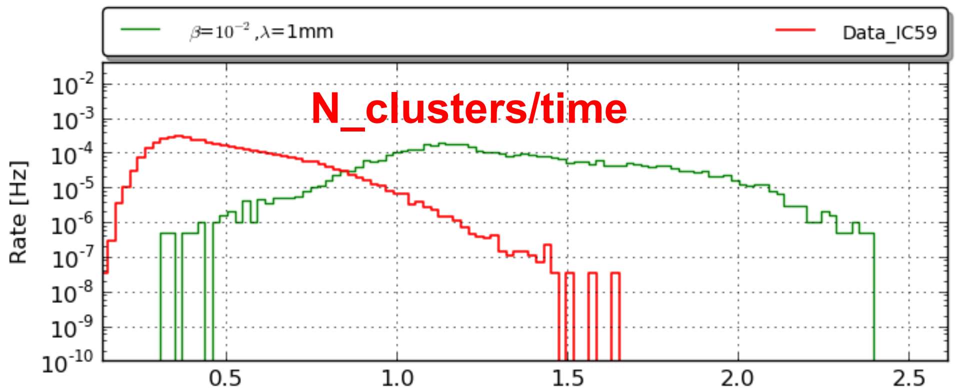
Variables used for BDT training

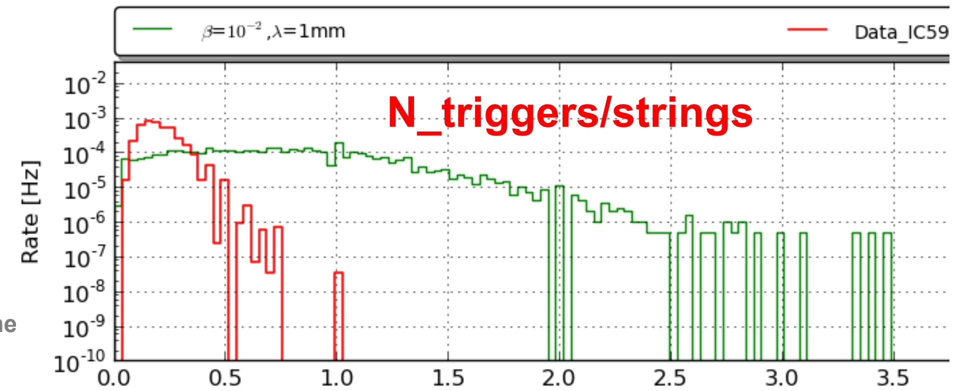




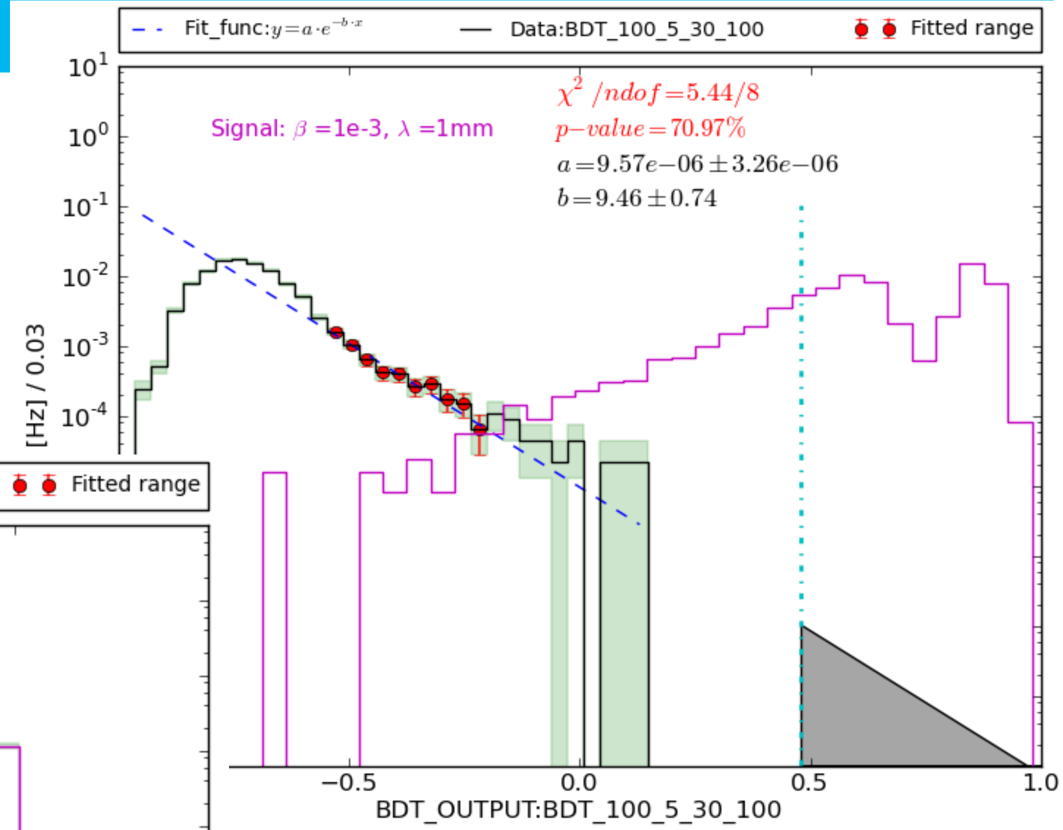




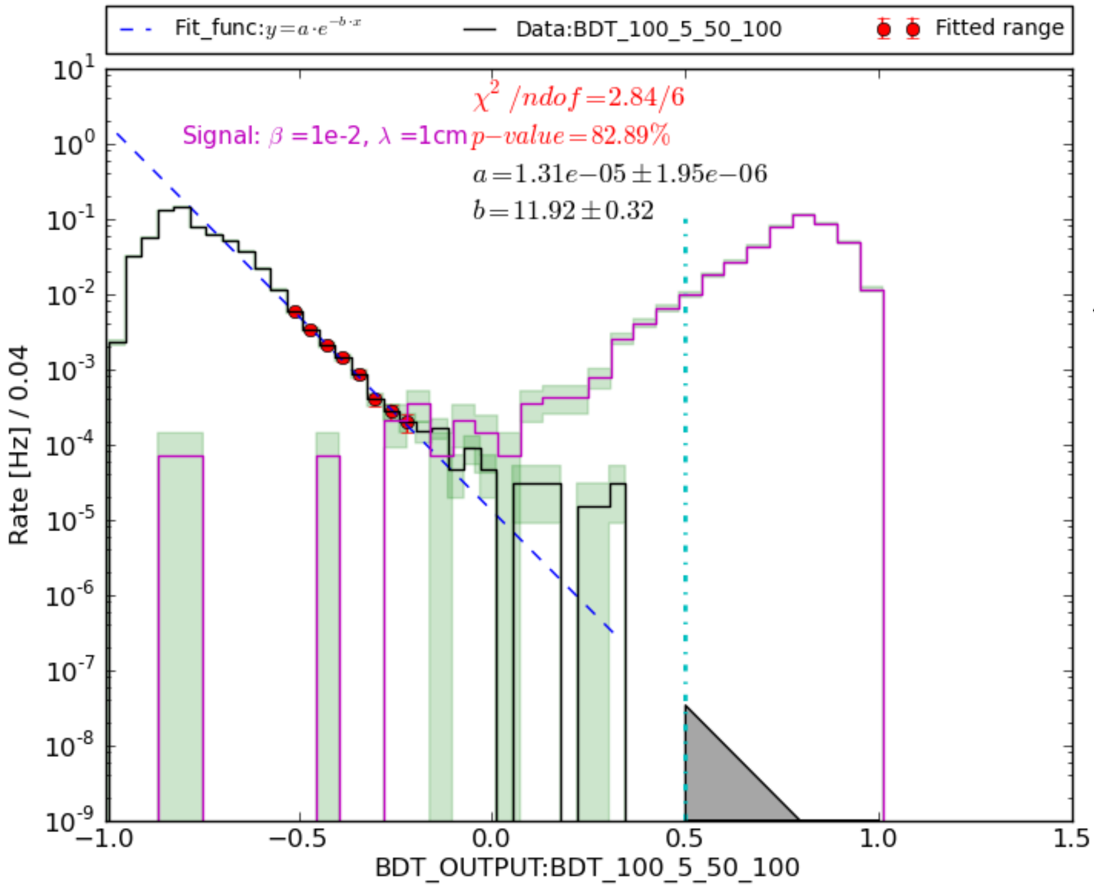




BDTs scores



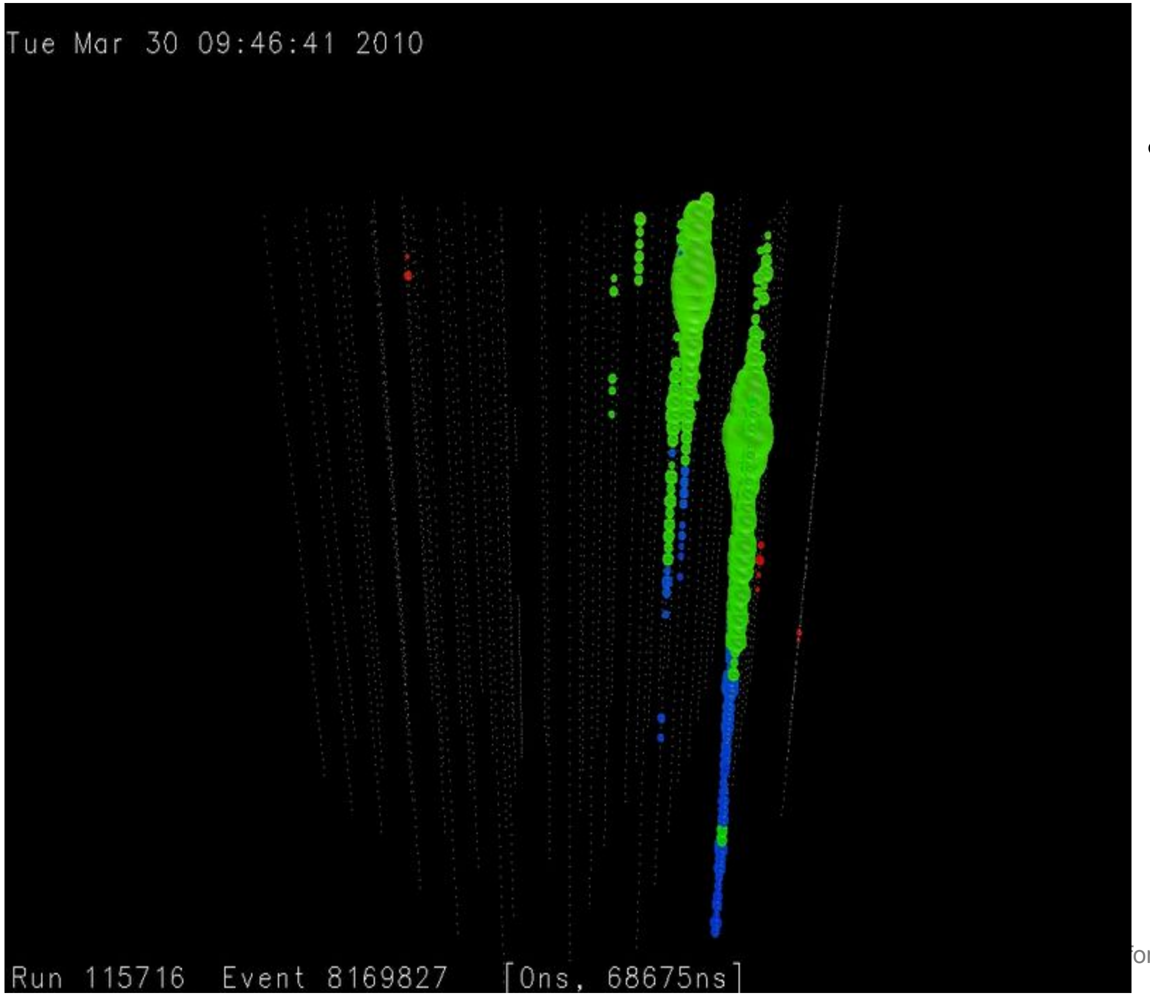
Fit_func: $y=a\cdot e^{-b\cdot x}$
Data:BDT_100_5_30_100
Fitted range
Signal: β =1e-3, λ =1mm
χ^2 /ndof=5.44/8
p-value=70.97%
a=9.57e-06±3.26e-06
b=9.46±0.74
[Hz] / 0.03
BDT_OUTPUT:BDT_100_5_30_100



Fit_func: $y=a\cdot e^{-b\cdot x}$
Data:BDT_100_5_50_100
Fitted range
Signal: β =1e-2, λ =1cm
χ^2 /ndof=2.84/6
p-value=82.89%
a=1.31e-05±1.95e-06
b=11.92±0.32
Rate [Hz] / 0.04
BDT_OUTPUT:BDT_100_5_50_100

IC59 analysis: remaining event

- Remaining event of BDT trained with paramter λ_{cat}=1mm and $\beta=10^{-3}$:



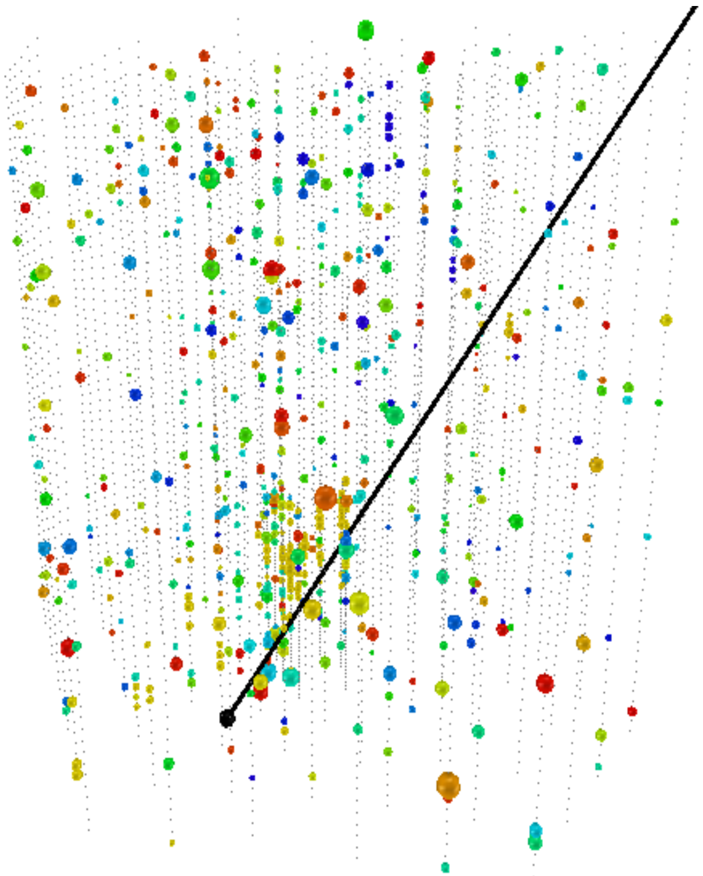
- Two muons coming vertically consecutively and hitting same strings (+ hitting IceTop)

Background expectation:

$\beta=10^{-3}$, λ=1mm	$\beta=10^{-2.5}$, λ=1mm	$\beta=10^{-2}$, λ=1mm
Background expectation: $\langle N_{BG} \rangle = 4.18$ **Observed events:** $N_{obs} = 1$	**Background expectation:** $\langle N_{BG} \rangle = 2.19$ **Observed events:** $N_{obs} = 0$	**Background expectation:** $\langle N_{BG} \rangle = 0.63$ **Observed events:** $N_{obs} = 0$
$\beta=10^{-3}$, λ=1cm	$\beta=10^{-2.5}$, λ=1cm	$\beta=10^{-2}$, λ=1cm
No sensitivity	**Background expectation:** $\langle N_{BG} \rangle = 2.81$ **Observed events:** $N_{obs} = 0$	**Background expectation:** $\langle N_{BG} \rangle = 2.99$ **Observed events:** $N_{obs} = 0$

IC86 analysis: remaining event

- Event before hit cleaning:



- Event after hit cleaning: