ND-LAr cryostat wall physics requirements

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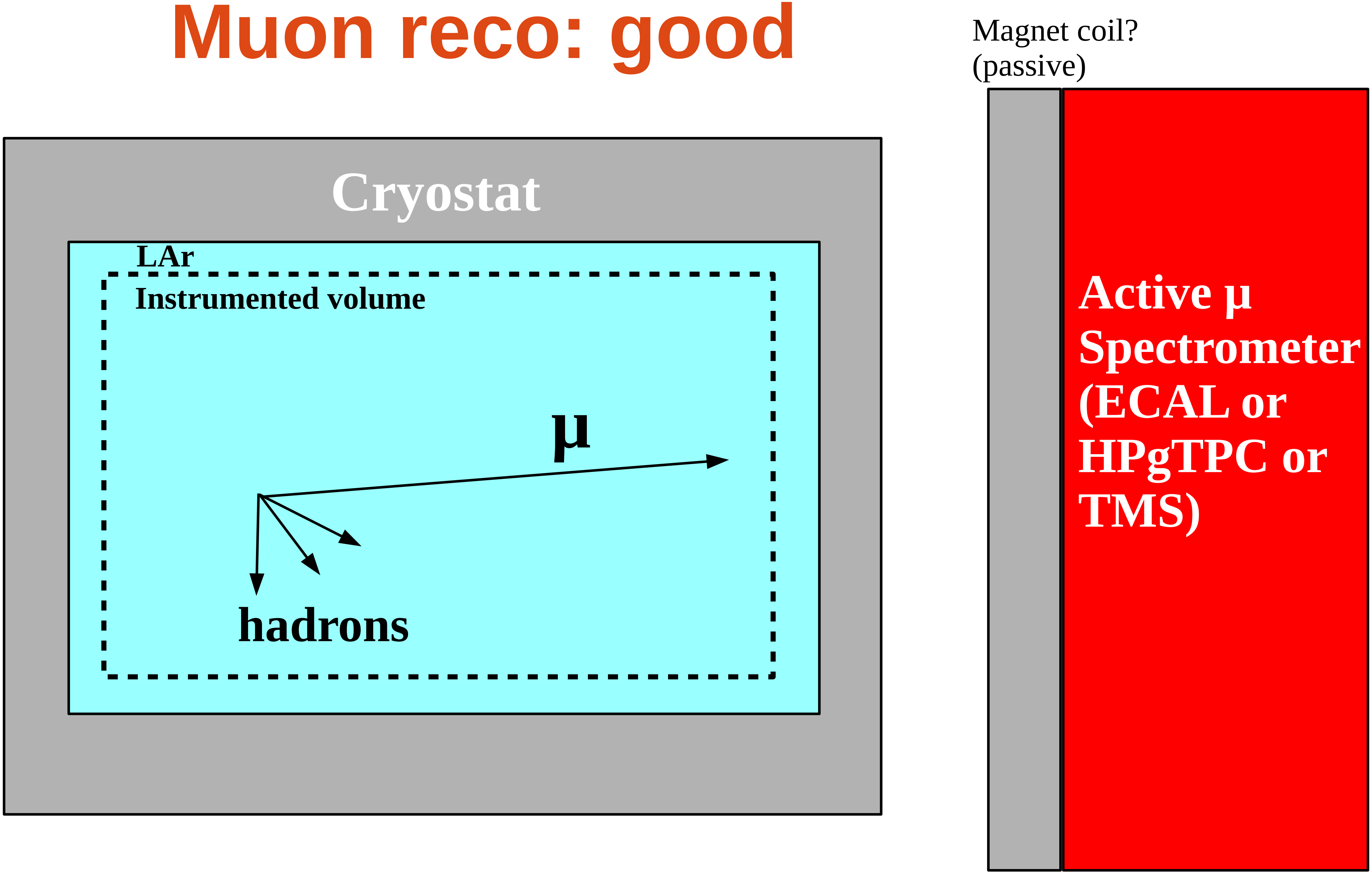
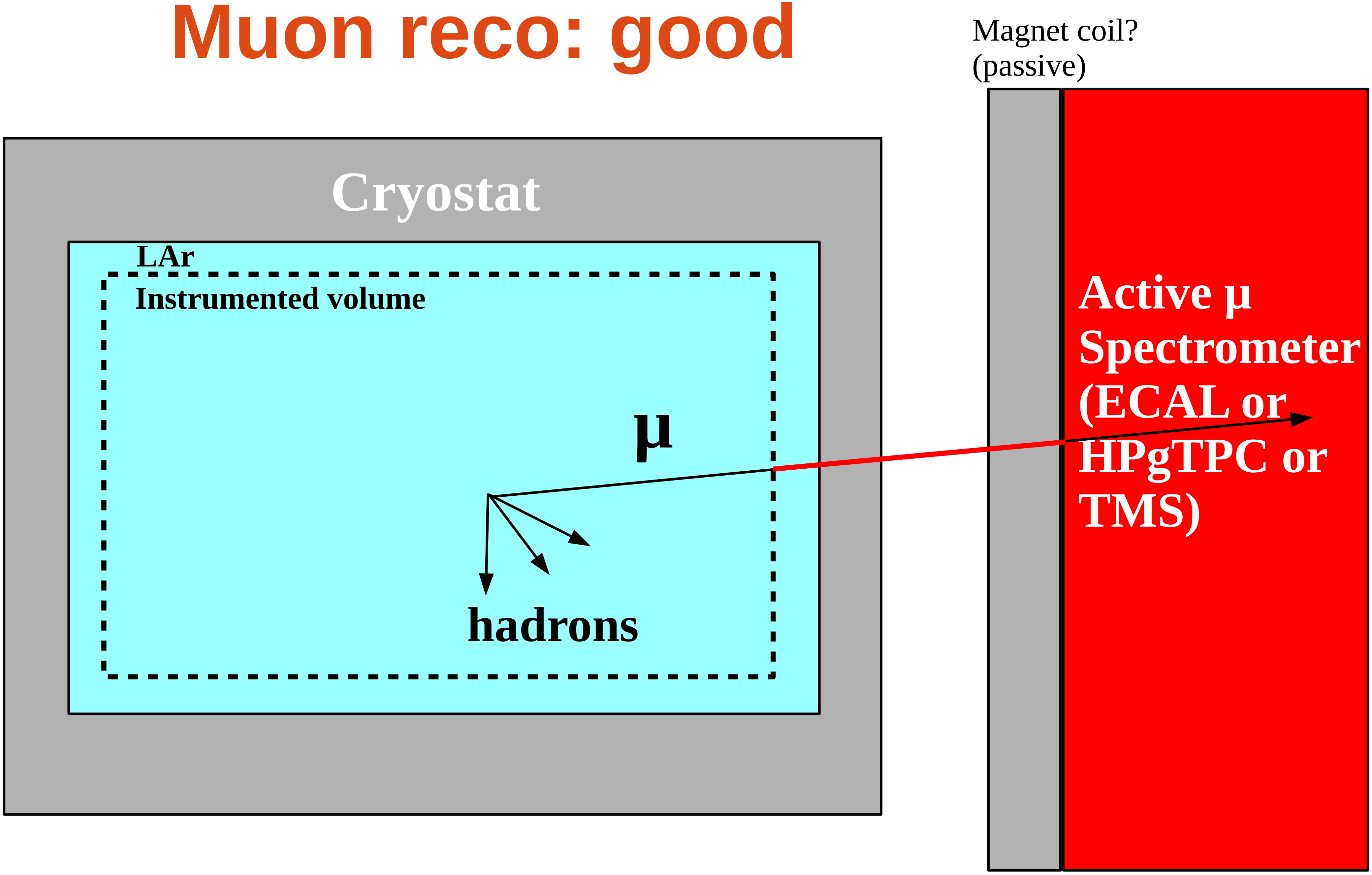
ND-LAr cryostat affects physics

- ND-LAr is functionally coupled to one of several possible muon spectrometers
  - ND-GAr + ECAL (aka MPD)
  - ND-GAr-lite
  - TMS/SSRI
- Muon momentum in LAr and in ECAL/TMS is measured by range → large gaps between active materials degrade energy resolution
- Only for downstream LAr face – sides, front, top/bottom have no requirement on thickness due to physics

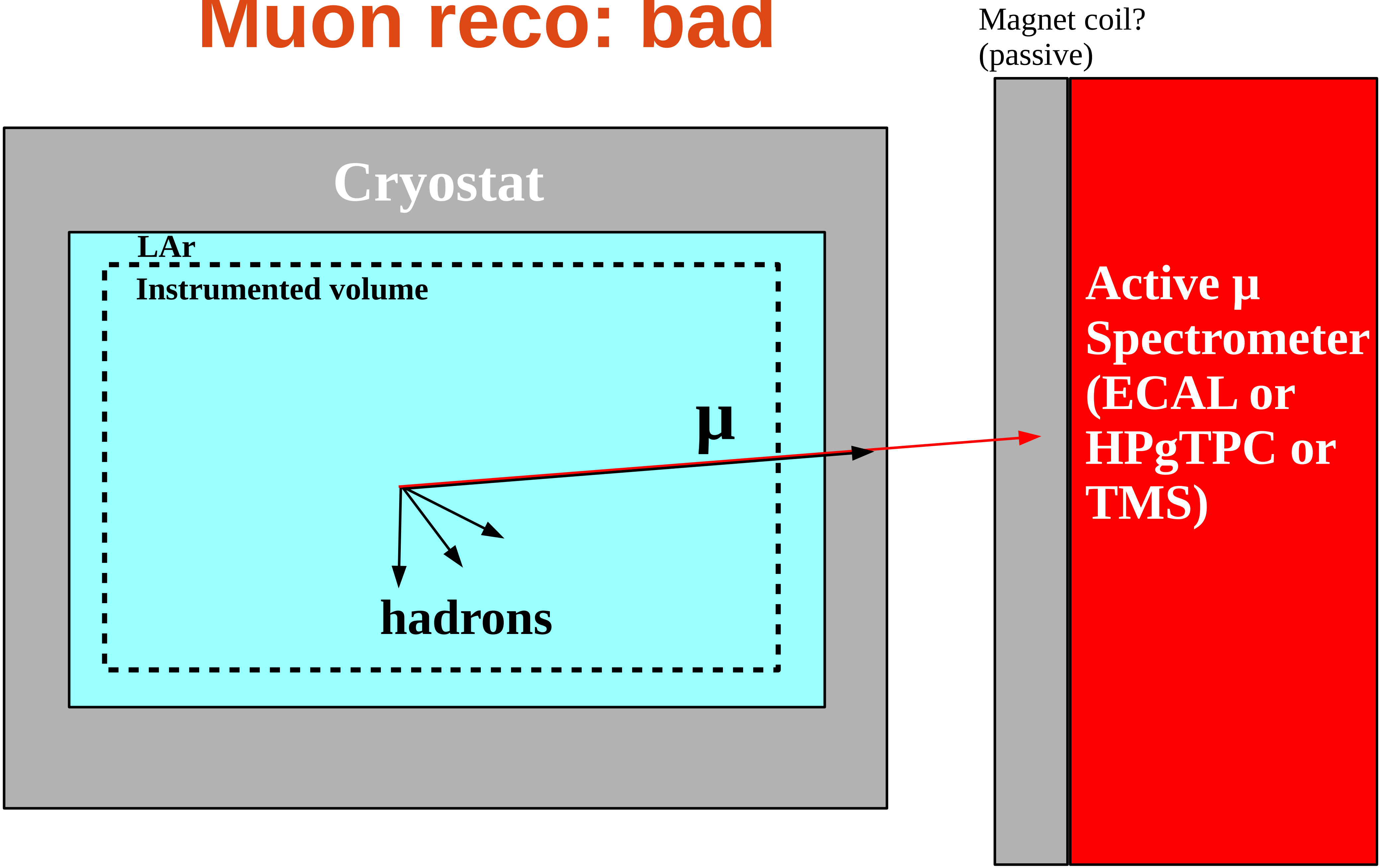
Muon reco: good



Muon reco: good



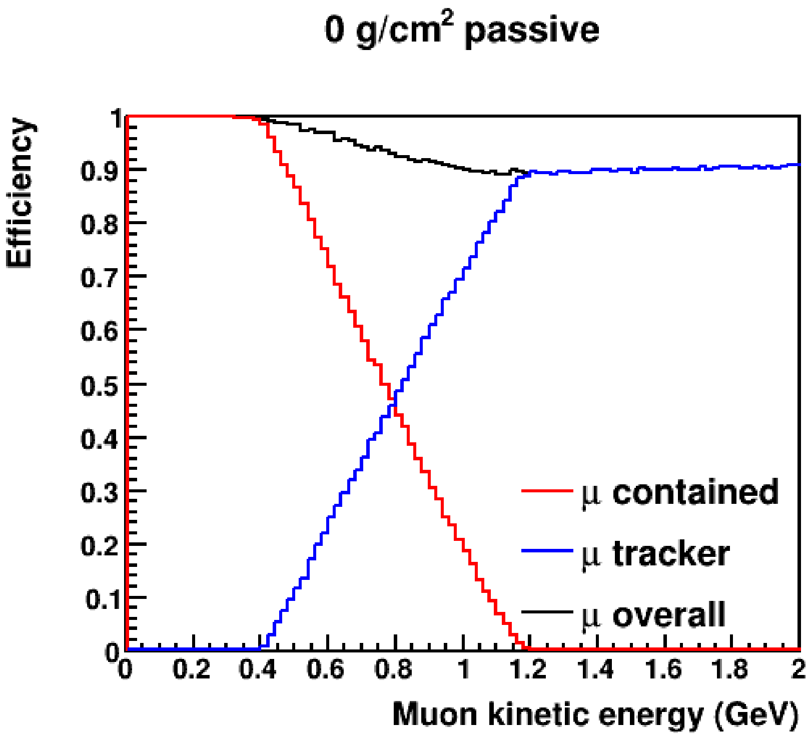
Muon reco: bad

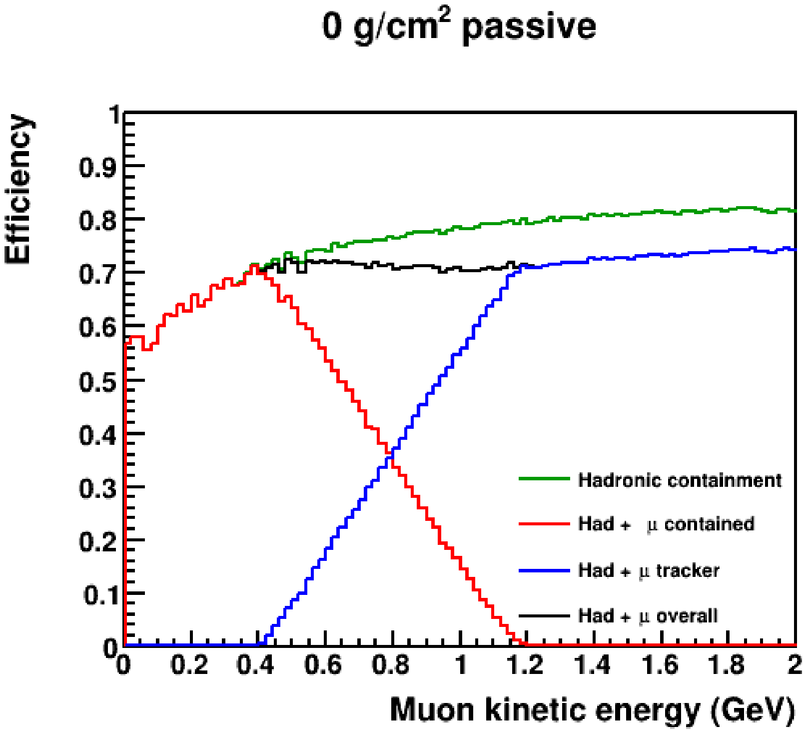


Resolution and acceptance

- We have two choices in analysis:
  - Analyze all events: muons that stop in the passive material have poor resolution → use a model to correct for the worsened momentum resolution
  - Reject passive stoppers: good resolution, but a dip in the acceptance → use a model to correct for the acceptance
- Resolution requirement is to match FD = 4%, which corresponds to <20 g/cm^2 on range 1 GeV, which cannot be achieved, so I focus on treating the passive stoppers as an acceptance effect

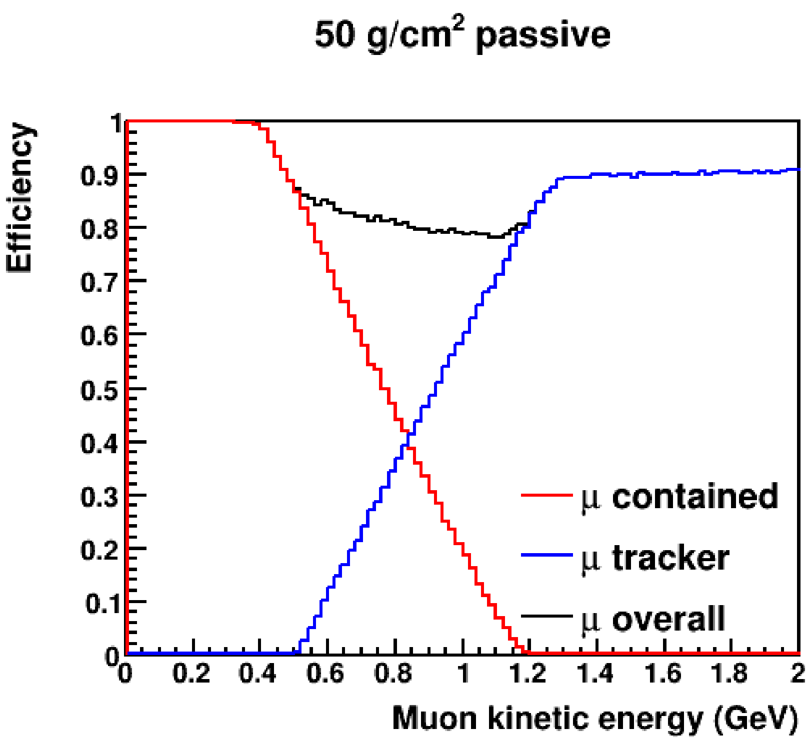
Acceptance effect due to rejecting muons that stop in passive material

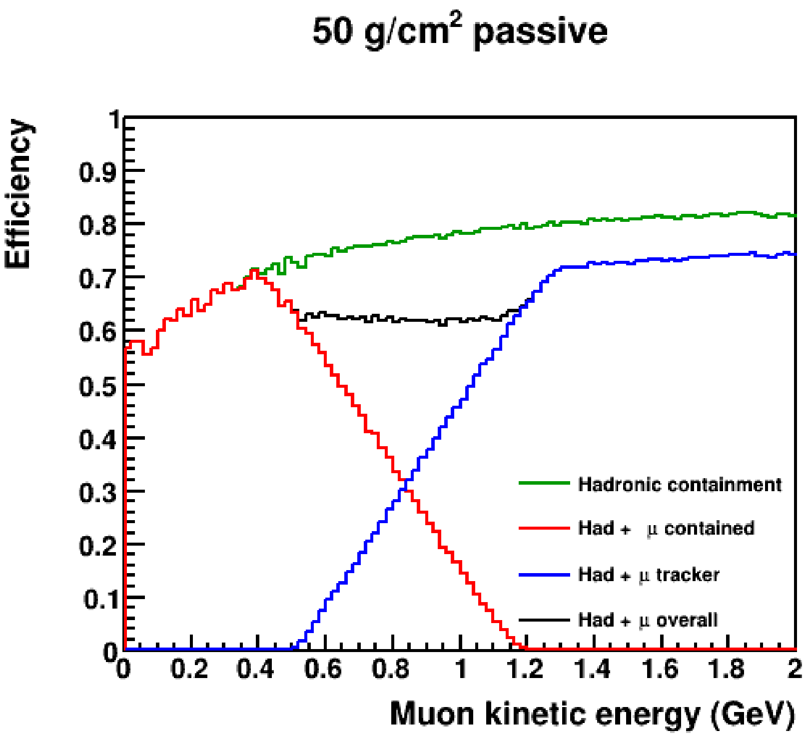




- Standard fiducial volume (50cm exclusion around edges, 150cm downstream) for good hadronic containment
- Left plot shows muon acceptance only, right plot shows muon + hadron
- Restricted to $\theta < 20$ degrees, forward muon direction (at wider angles, many more muons are contained, and passive material becomes less relevant)

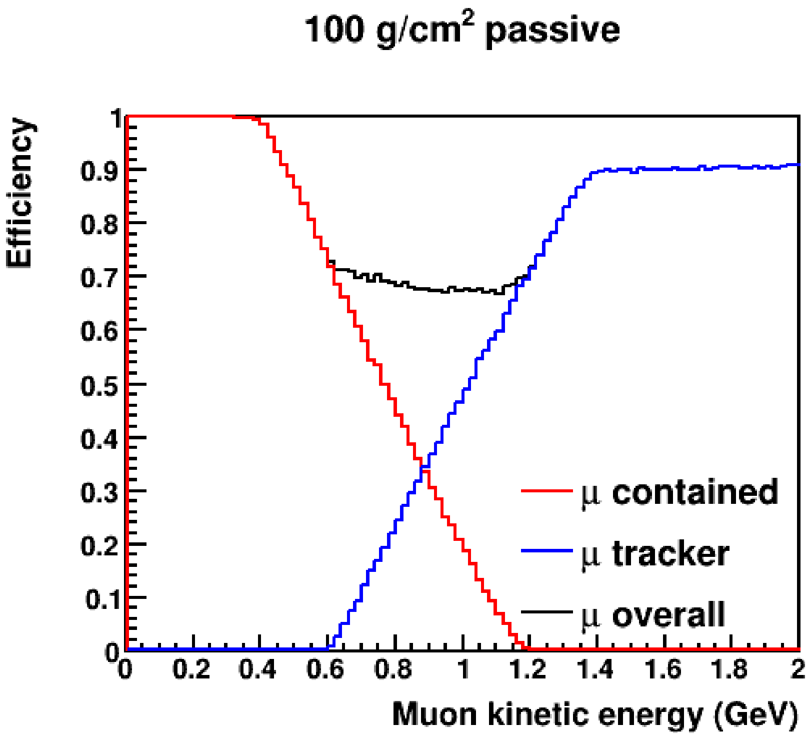
Adding 50g passive material

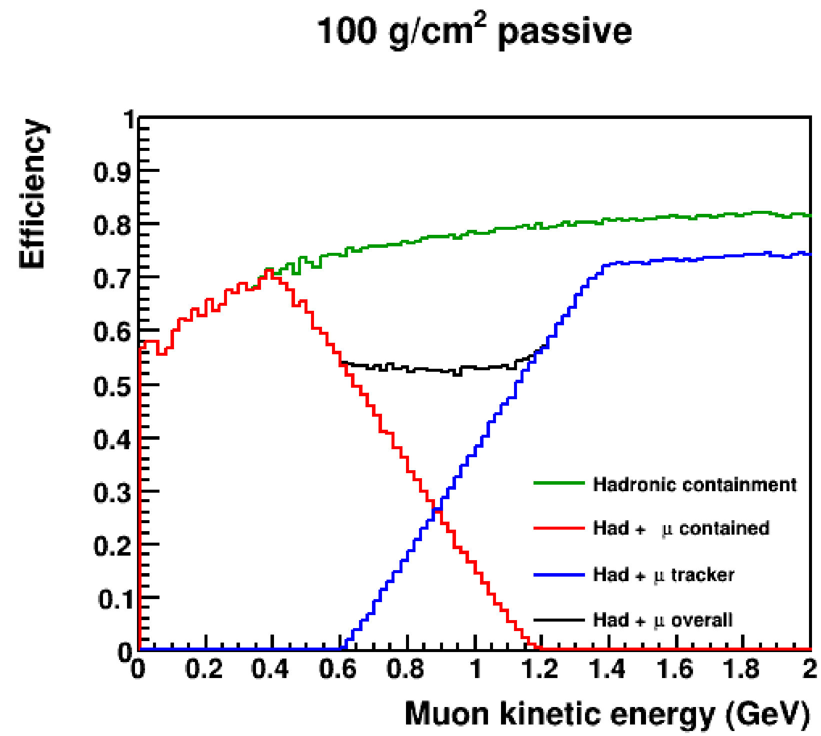




- Passive material adds a dip between ~0.5 GeV (the energy at which muons with downstream vertices start exiting) and ~1.2 GeV (energy at which muons with upstream vertices always exit)

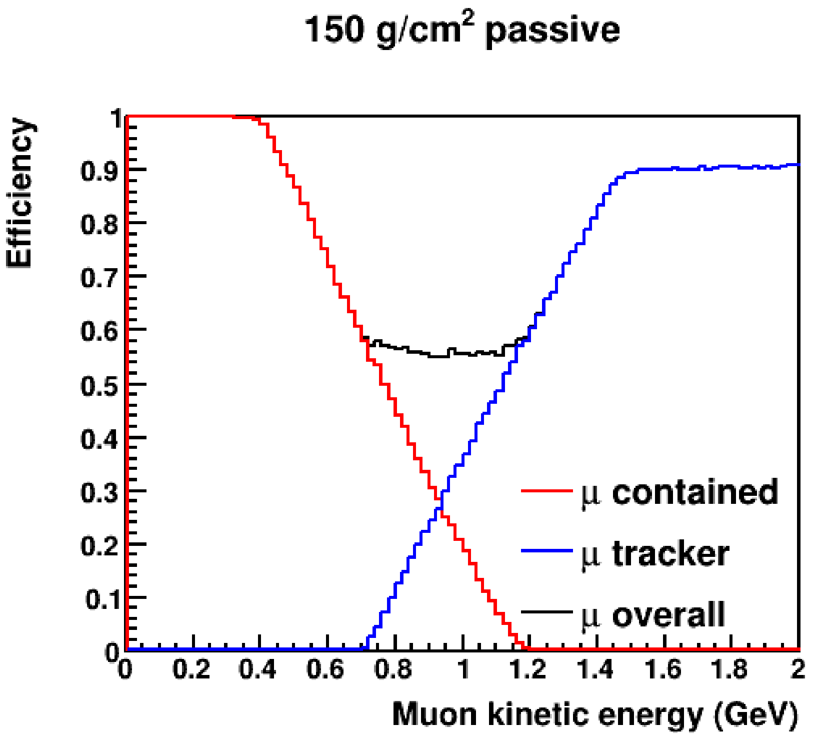
Adding 100g passive material

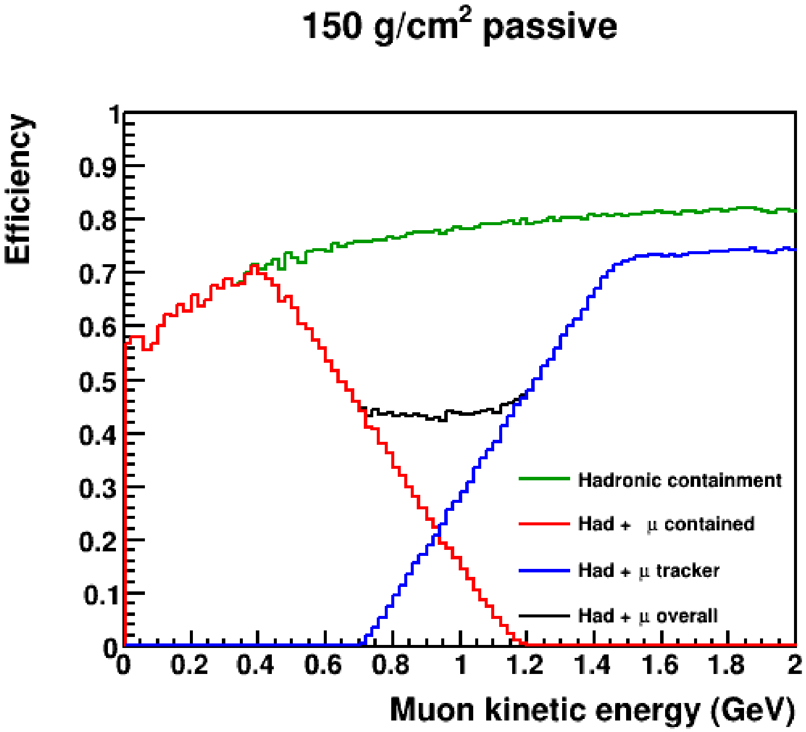




- Dip removes ~30% of muons with 100g material
- Generally the depth of the dip is roughly <passive material thickness> / <F.V. thickness>, and F.V. is 300cm LAr
- Not exact due to beam angle, muon angular distribution

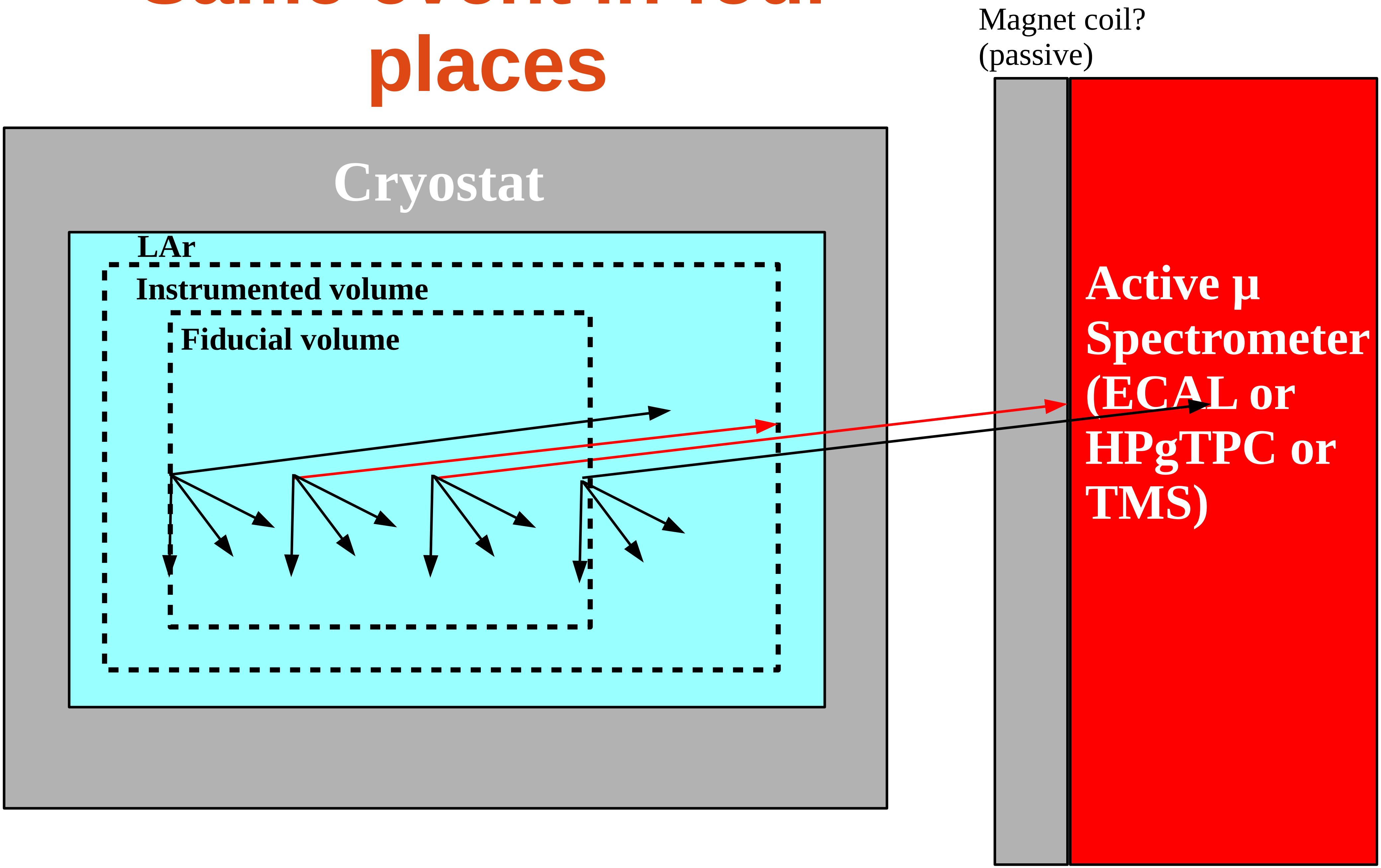
Adding 150g passive material



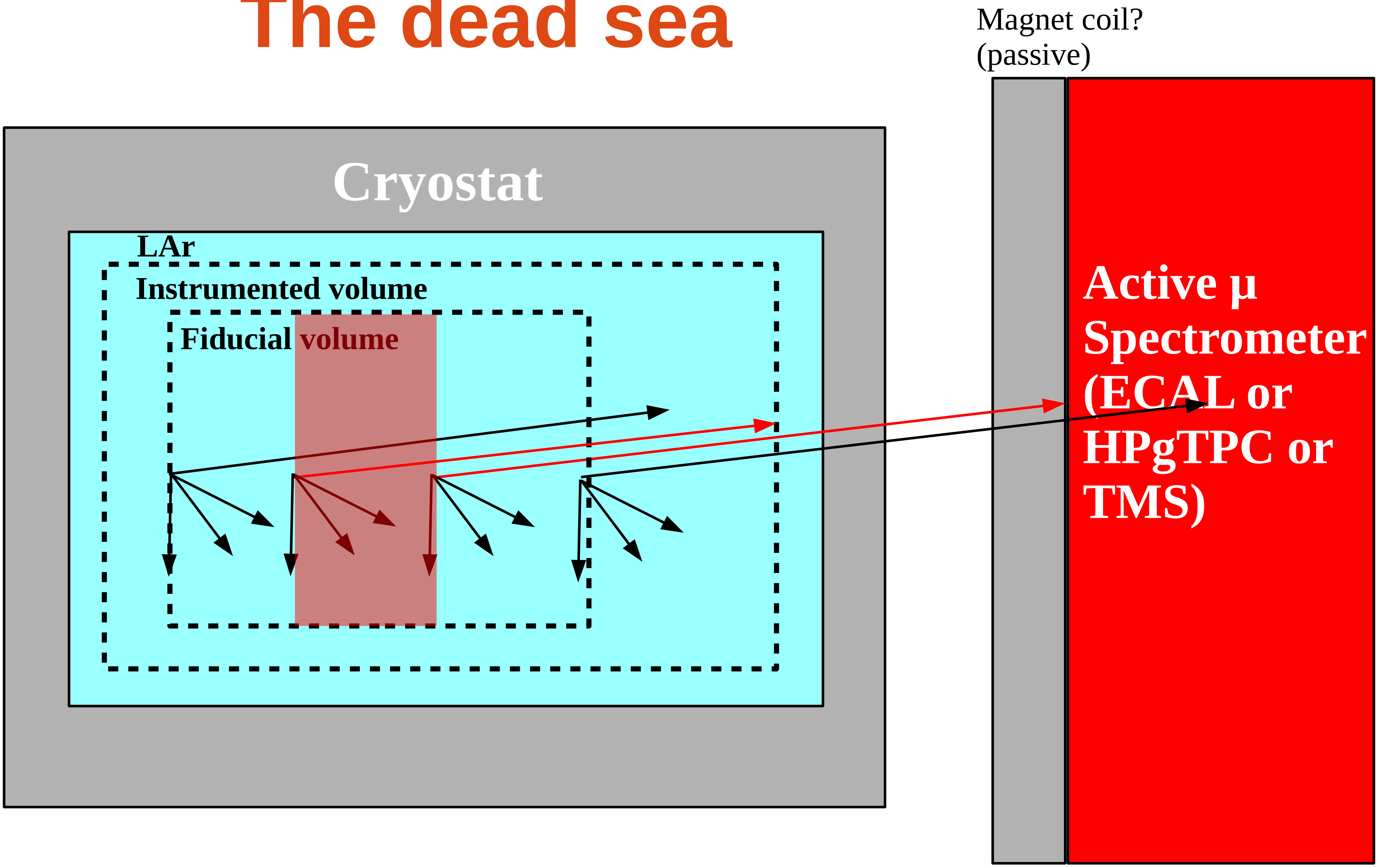


- ~45% of muons are lost in 150g passive material
- Need dip to be
  - Small, so that uncertainty in modeling dip leads to small uncertainty on overall distributions
  - Well understood as a function of other quantities, so that modeling uncertainties are not large

Same event in four places

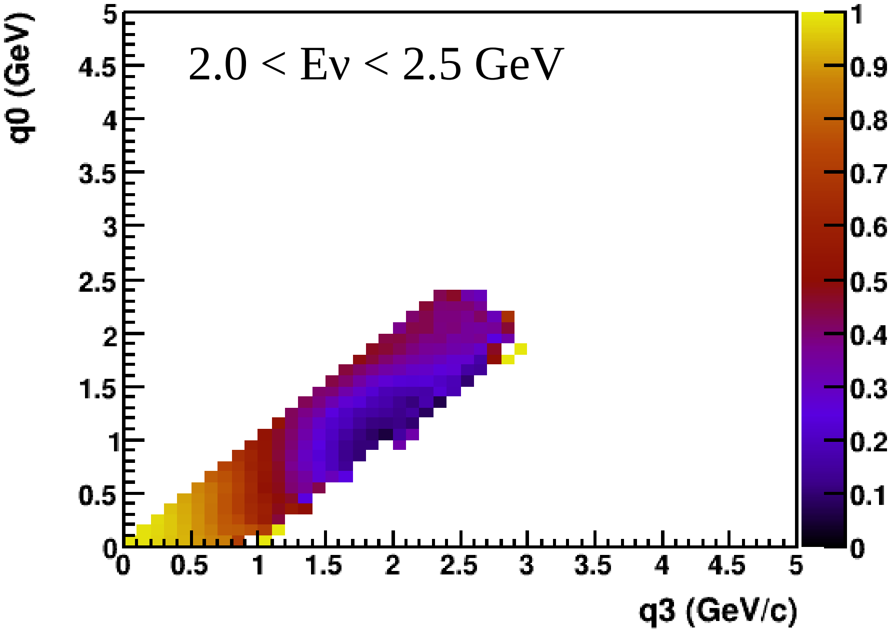


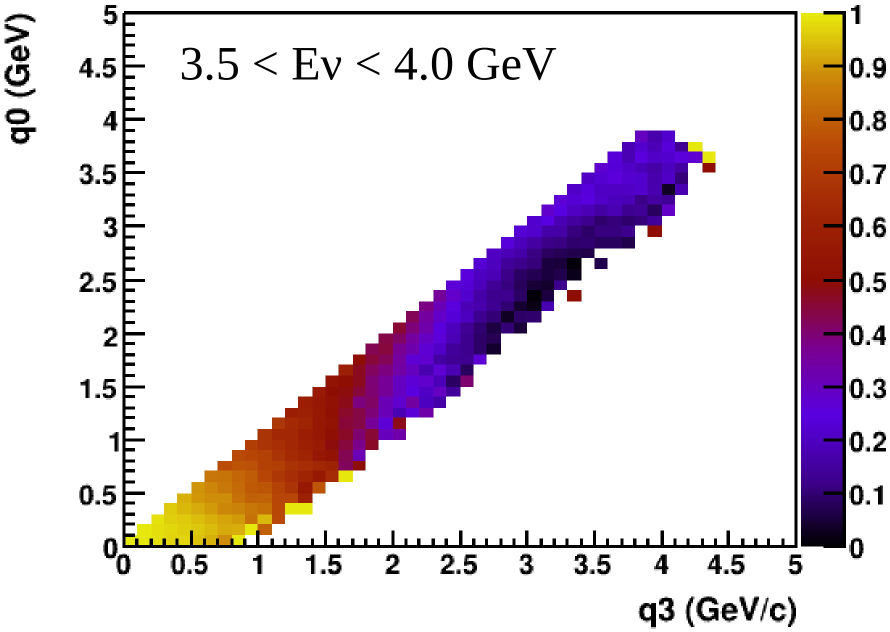
The dead sea



Magnet coil?
(passive)
Cryostat
LAr
Instrumented volume
Fiducial volume
Active μ
Spectrometer
(ECAL or
HPgTPC or
TMS)

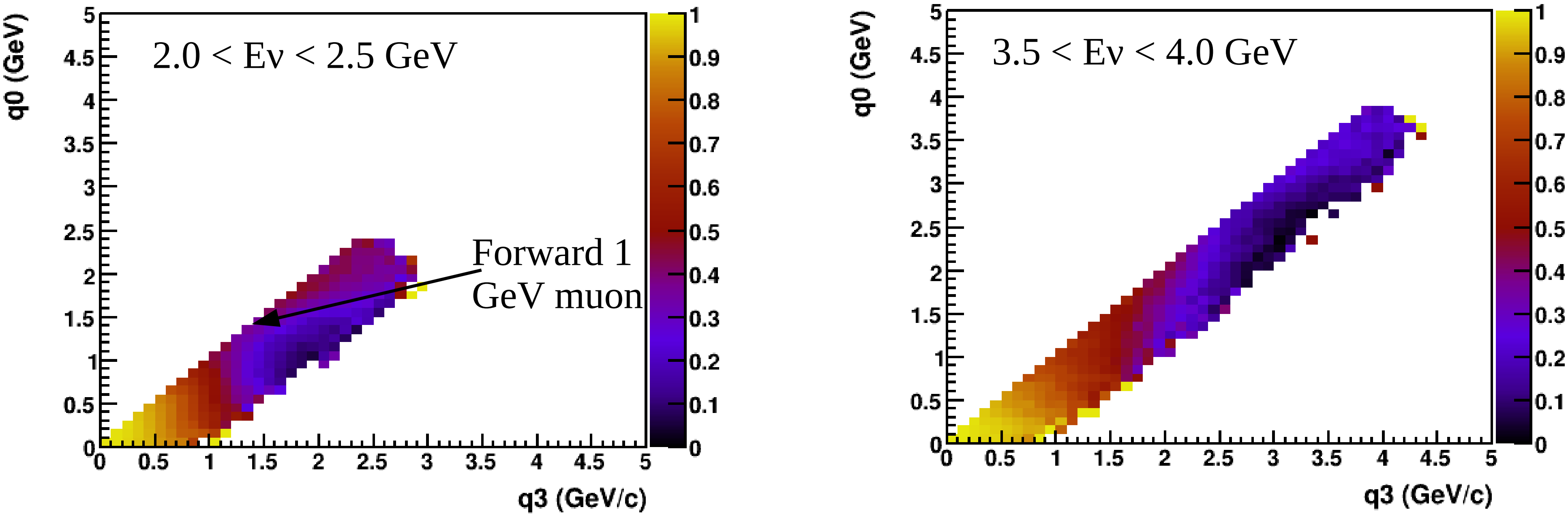
Acceptance vs 3-momentum and energy transfer, 100 g/cm2





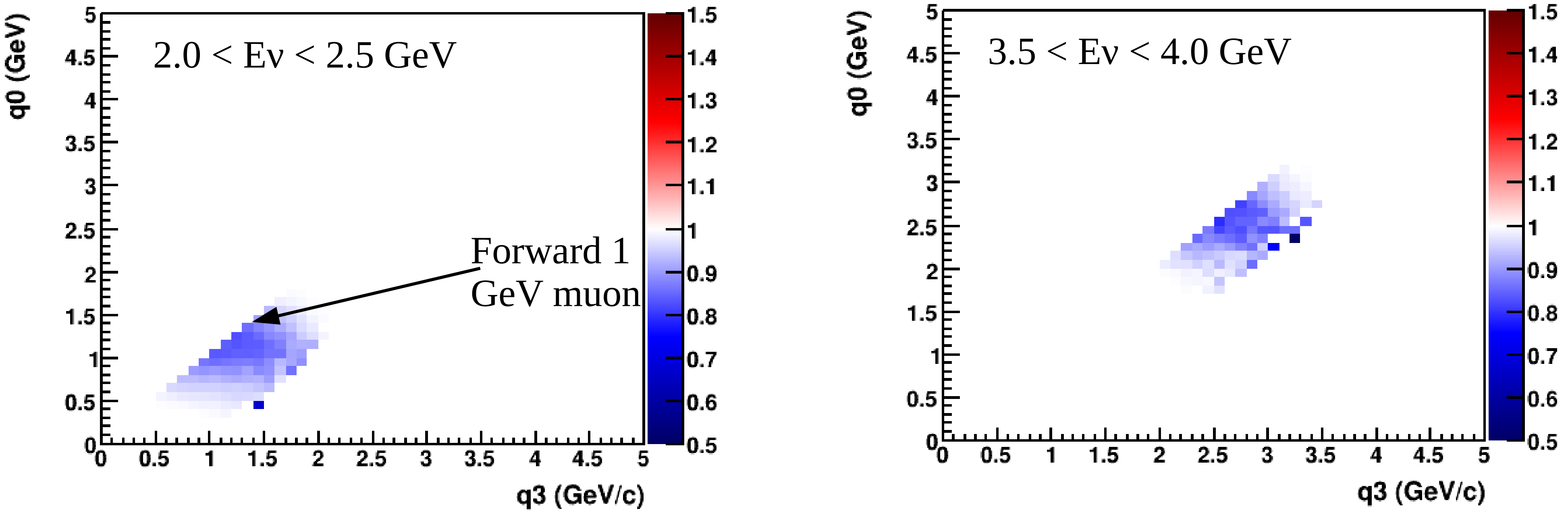
- q0 = hadronic energy, q3 = 3-momentum transfer ~ muon angle
- Generally, we can use data to measure this by shifting well-reconstructed events around within fiducial volume
- But region with very low acceptance is problematic, because the region where events is well reconstructed is too small

Acceptance vs 3-momentum and energy transfer, 150 g/cm2



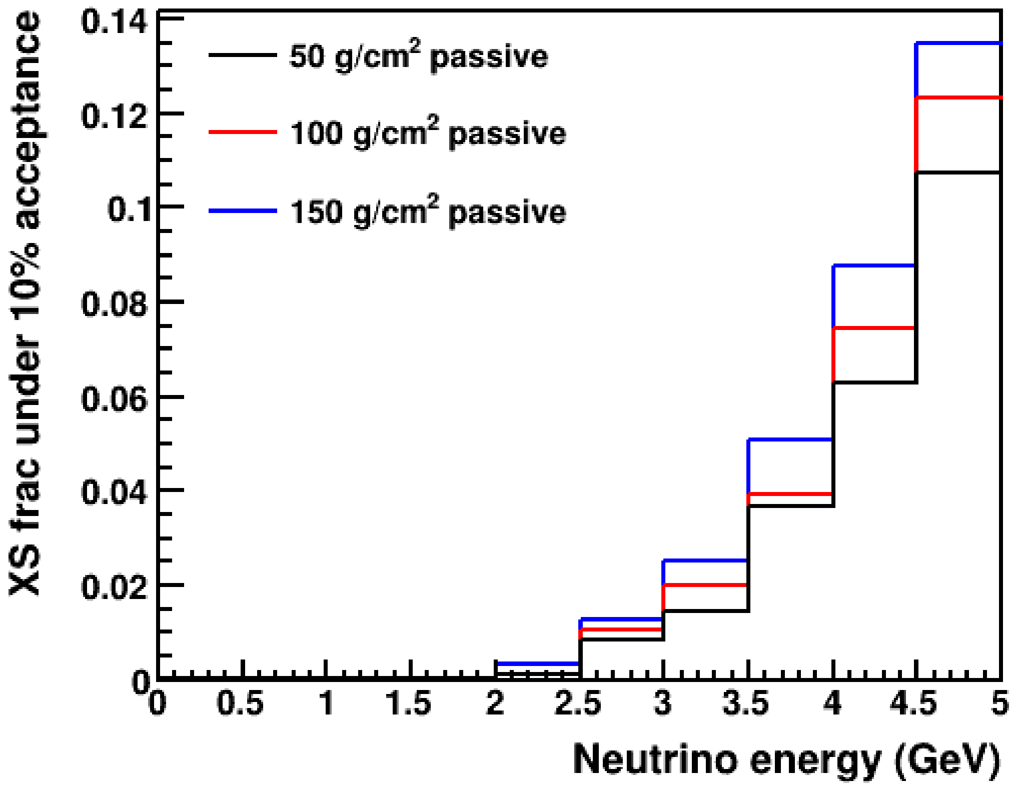
- "Bad region" grows, and creeps to low muon angle with more passive material
- Effect is gradual, so it's not as if there is a cliff at some areal density, but generally below 100g is not so bad

Ratio of 150g / 100g



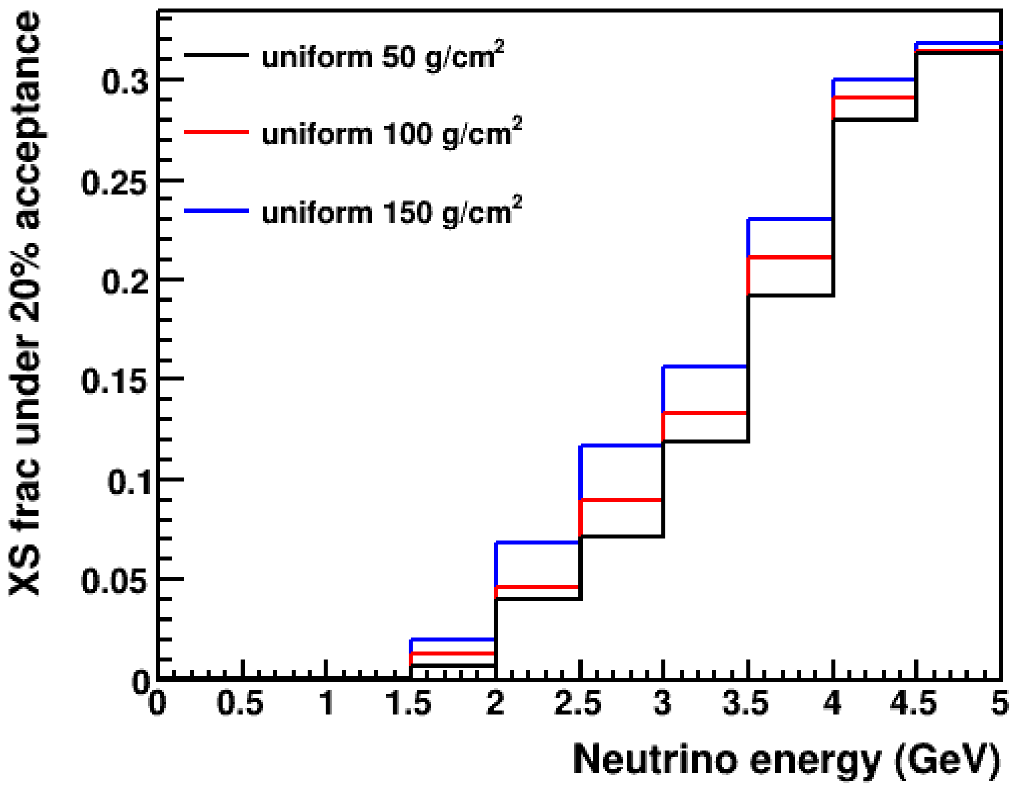
- 10-30% loss in already low acceptance region by increasing passive material by 50g = additional 100 MeV energy loss = additional 40cm to the dead sea

Fraction of total cross section with acceptance < 10%



- Essentially the size of the black region on q0-q3 plots, weighted by total cross section
- Above 3 GeV, we start to see regions of phase space with almost no ND coverage
- With 100g we are <4% up to 4 GeV

Fraction of total cross section with acceptance < 20%



- In the oscillation peak region, the fraction with acceptance under 20% is ~40% higher with 150g than 100g

100g split between LAr & spectrometer

- Physics is sensitive to the total passive material
- SPY magnet design has ~37 g/cm^2 passive material
- TMS has potentially zero (if scintillator before steel and track can be matched to single hit), or ~15g/cm^2 (if steel before scintillator)
- LAr cryostat must be compatible with all possible future muon spectrometer configurations
- Require LAr < 60 g/cm^2 in LAr, which allows for coupling to SPY+ND-GAr
- Goal of < 50 g/cm^2 to build in margin

G10 window design

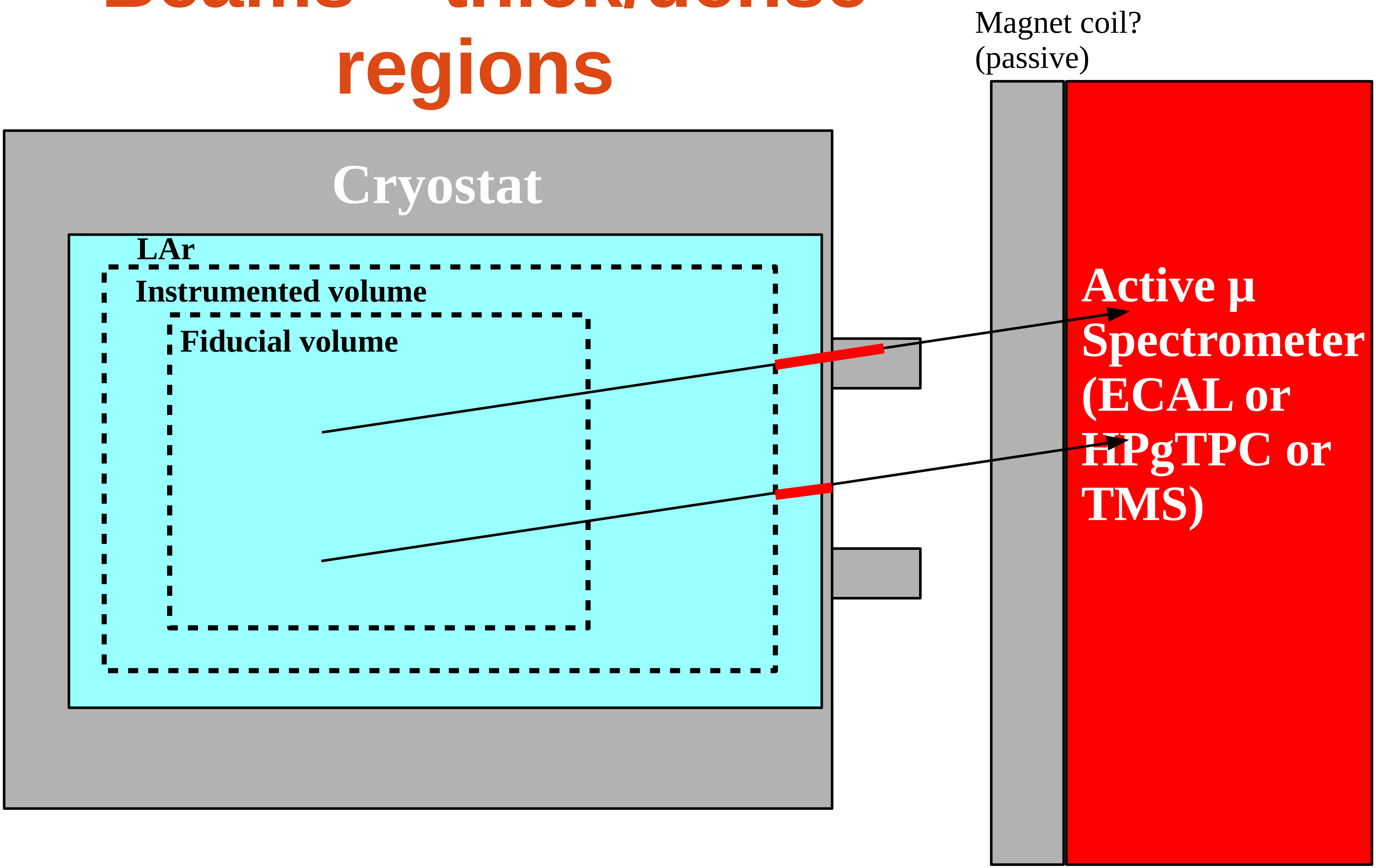
- This target can be achieved with a G10 window
- Most of the 1.4m thickness is low-density; most of the energy loss is in the passive LAr and G10

Element	Thickness (cm)	Density (g/cm3)	Areal density (g/cm2)
LAr	15	1.4	21
Inner Membrane: SS	0.2	7.9	1.6
Membrane: Poly insulation	80	0.1	7.2
Outer Membrane: SS	0.2	7.9	1.6
LD wall: Poly core	32.2	0.1	3.2
LD wall: G10 facing	5	1.7	8.5
Air	10	0	0
TOTAL	142.6		43.1

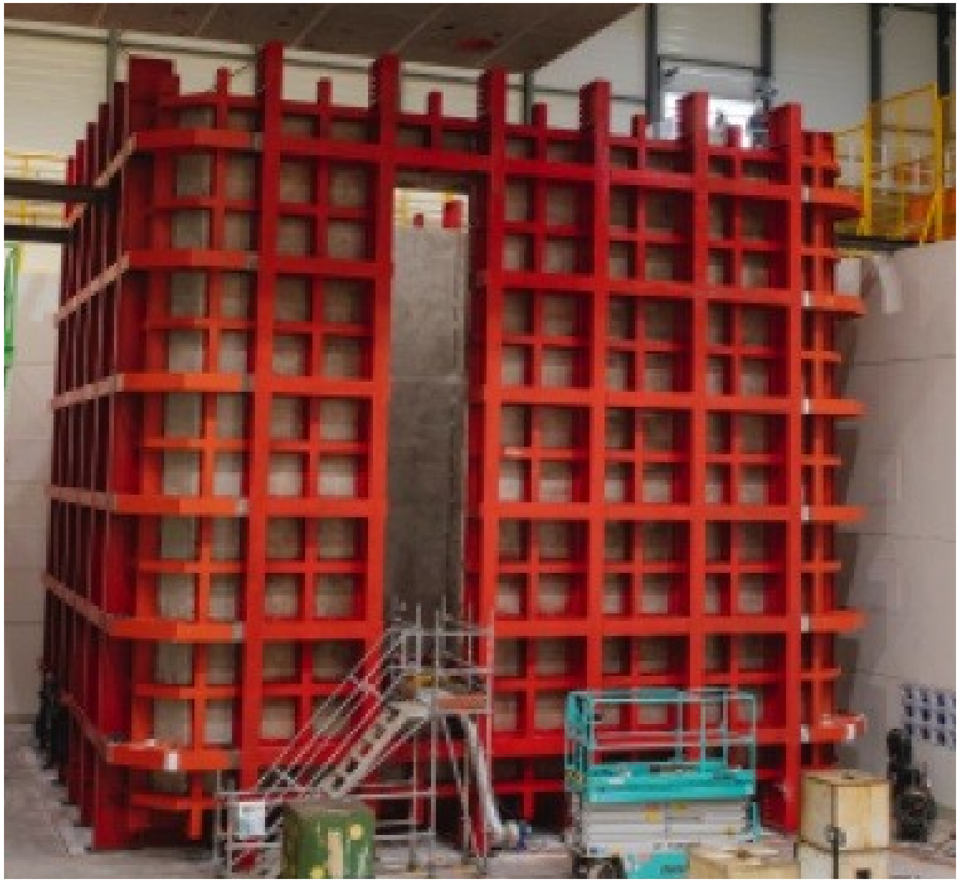
Material uniformity

- We must correct for energy loss in passive materials
- Uncertainty on this correction is due to ionization fluctuations, and non-uniformity of passive material
- Want: passive material uniformity should not dominate muon energy resolution
- 1 GeV muon loses 10% of its energy in 50 g/cm^2 passive material in cryostat
- If uniformity is better than 12% across downstream face, then this will be <4% on muon momentum

Beams – thick/dense regions

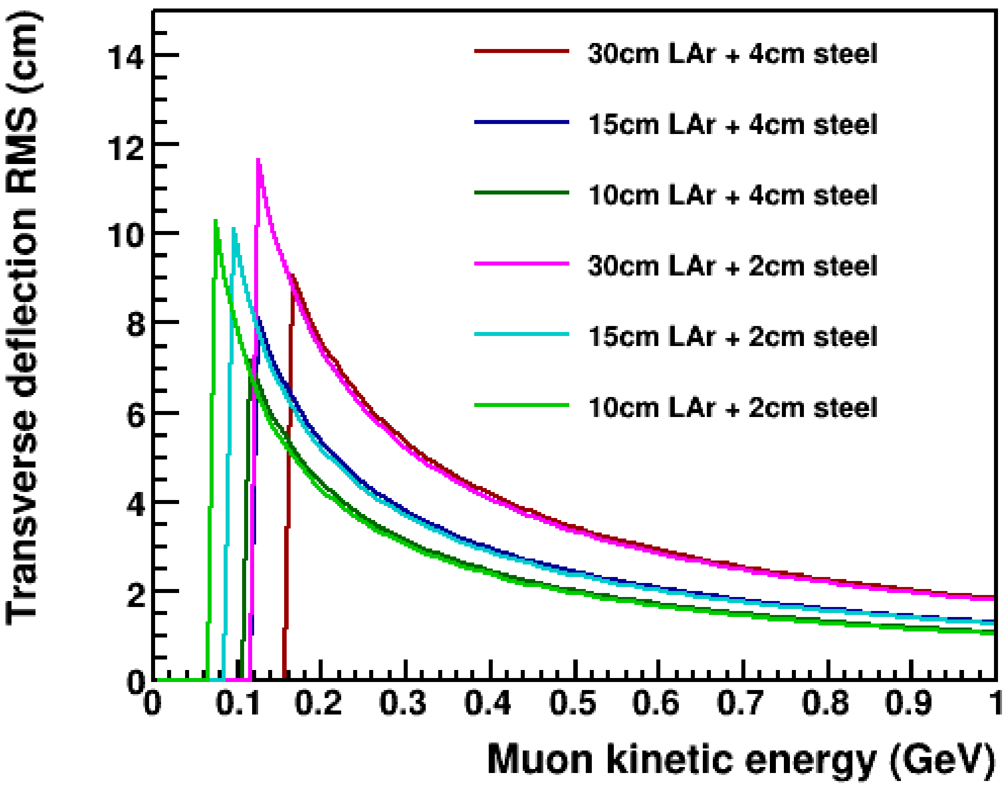


ProtoDUNE-like steel cryostat



- Few cm steel outer membrane, with large support beams spaced every ~1m and smaller beams every ~50cm
- In analysis, we need to know event by event how much passive material the muon went through, which would require cutting out the tracks near the beams, where a tiny change in position means a huge change in energy loss

Multiple scattering gives the size of the buffer region around the beams



- Reducing uninstrumented LAr downstream of active volume has a large effect because small angular deflections in LAr are amplified by large lever arm of insulating foam
- At low muon energy, transverse deflection between LAr and spectrometer reaches 10cm

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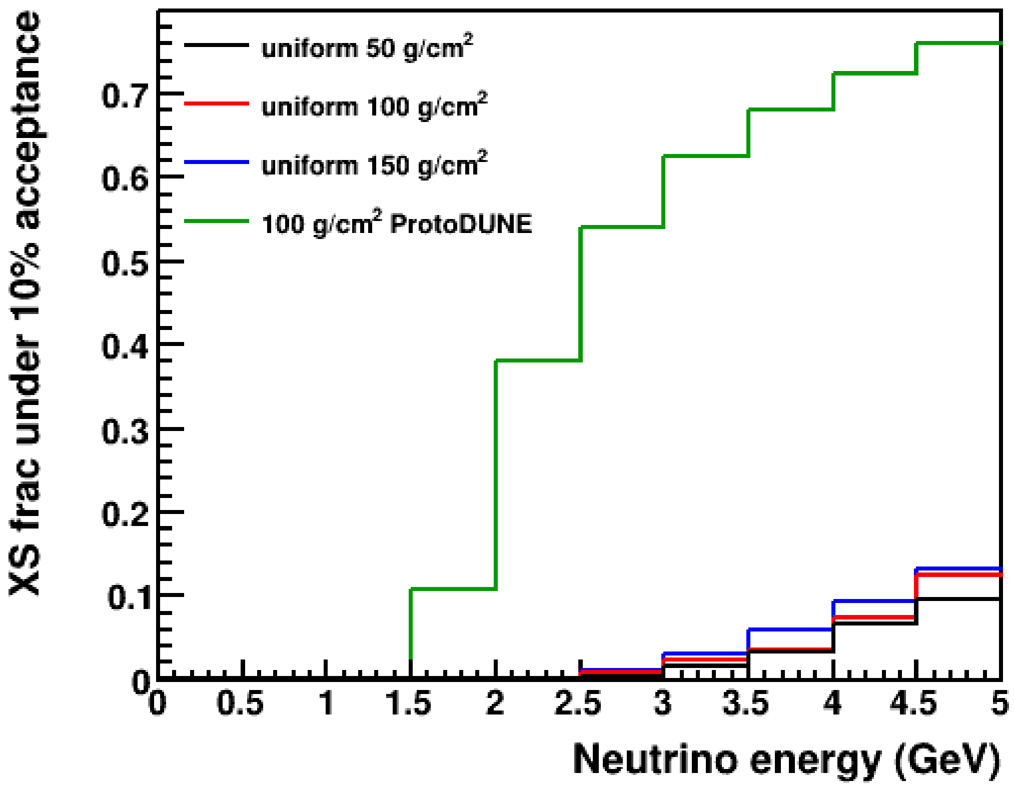
If you cut 10cm around the beams, it is devastating to acceptance



- Effectively reduces the "good region" by 84%
- Most of the cross section is now below 10% acceptance, though this is no longer concentrated in a narrow region of phase space

Ongoing optimization for fall-back cryostat

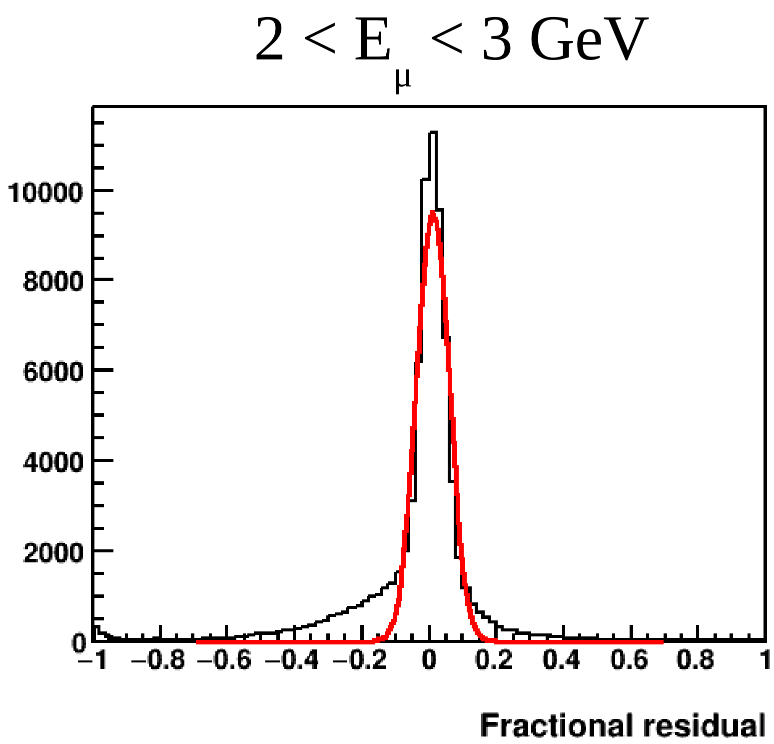
- Keep “thin region” passive material at ~50g with few cm steel outer membrane wall
- Maximize the space between beams, i.e. minimize the loss of acceptance due to a cut around beams
- Could be further mitigated by instrumenting region between beams immediately outside cryostat

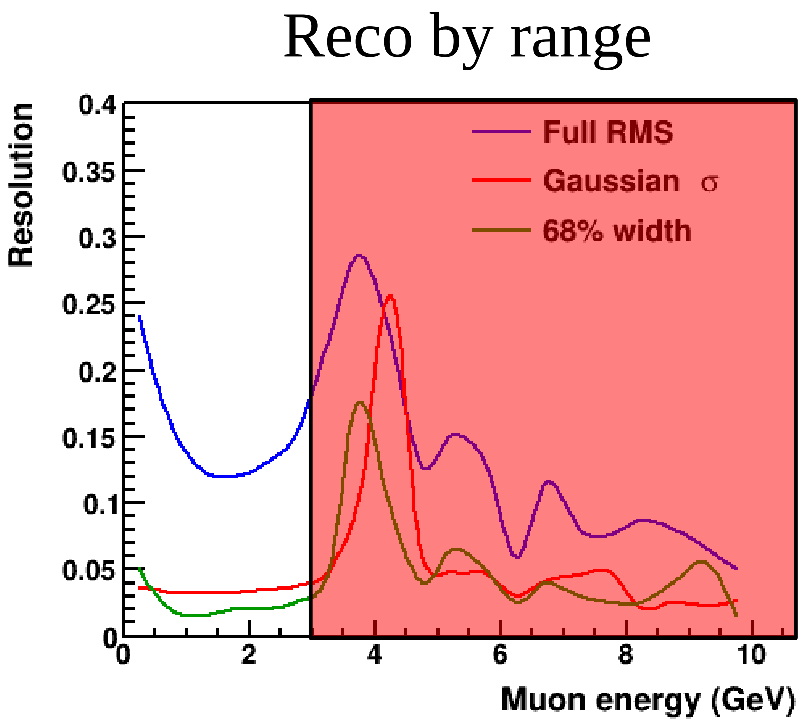
Summary

- Total passive material between downstream end of active LAr volume and outside surface of system < 60 g/cm^2, goal of < 50 g/cm^2 for margin in MPD design
- If uniform G10 window is not possible due to safety, fall-back design should keep minimize the area of support beams, and maximize their spacing
- Effort should be made to push the modules as far downstream in the LAr as possible

Backups

FD momentum resolution





- FD momentum resolution by range is σ ~ 4%, with full RMS (which includes reconstruction issues) ~ 12%
- This is true at high energy, but our FD simulation uses a reduced geometry where muons above 3 GeV are not typically contained
- ND resolution must at least match this 4% over oscillation region of 0.5-5 GeV

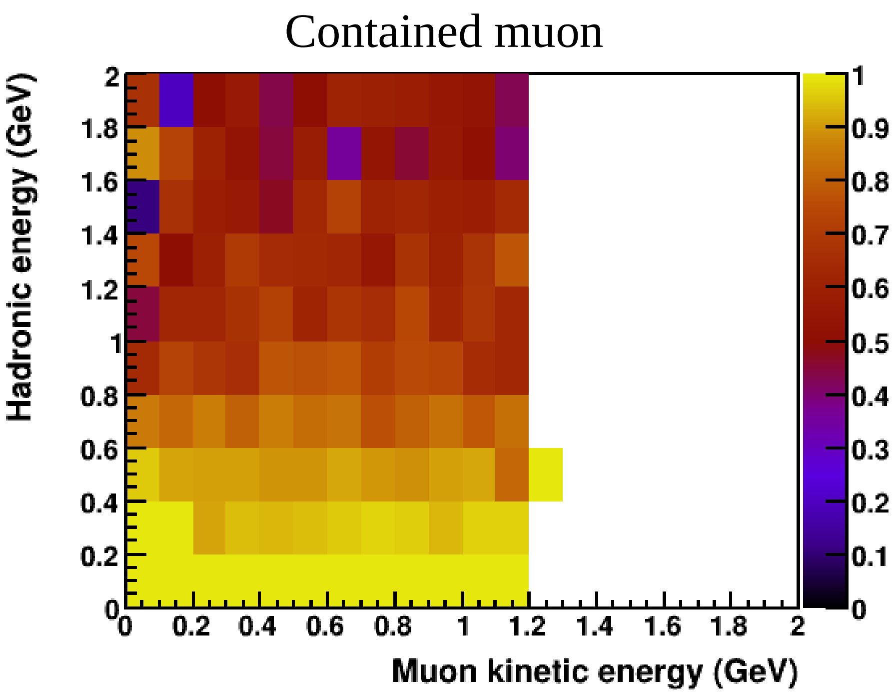
4% resolution by range → 20 g/cm^2

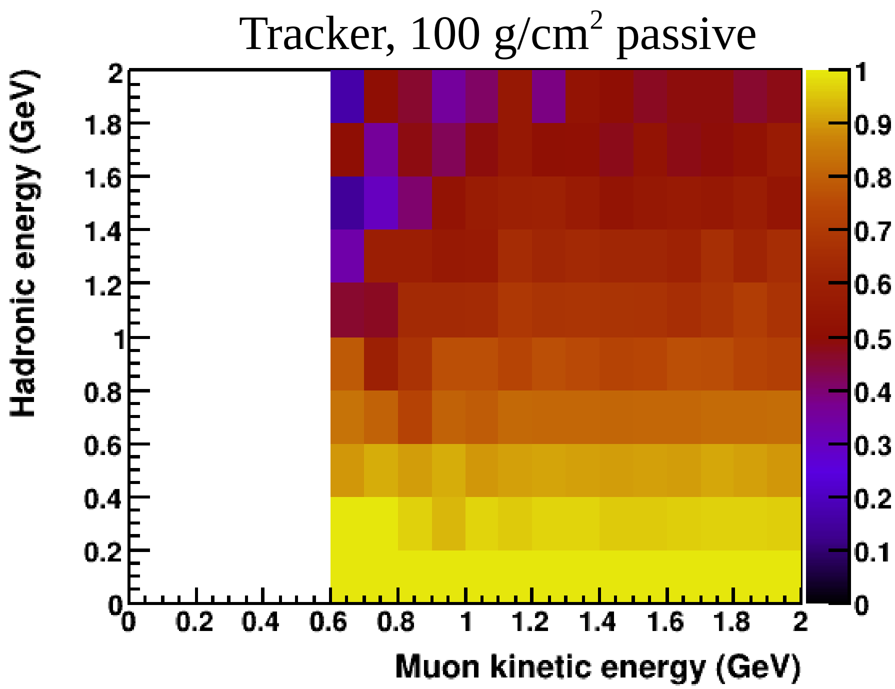
- At 1 GeV muon energy, events are reconstructed in the muon spectrometer
- Need uncertainty on range << 40 MeV, so that when combined with fluctuations, overall resolution is not worse than 4%
- This would imply that largest allowed gaps are ~20 g/cm^2
- This is not possible to achieve → we must exclude muons that stop in passive material from sample, so the selected events have resolution of ~4%
- We must model the acceptance effect that this creates

Why can't we just correct this effect with MC?

- Acceptance as a function of muon kinematics (energy & angle) is entirely geometric – you could map it out with muon gun simulation with zero dependence on interaction modeling
- But hadronic energy reconstruction is not constant across the detector volume, and this is not entirely geometric – it requires nuclear modeling
- Detector dimensions are basically minimum for hadronic containment – we can't afford to have muon reconstruction take a huge bite out of that
- Solution: Ensure muon reco in both upstream and downstream parts of F.V.

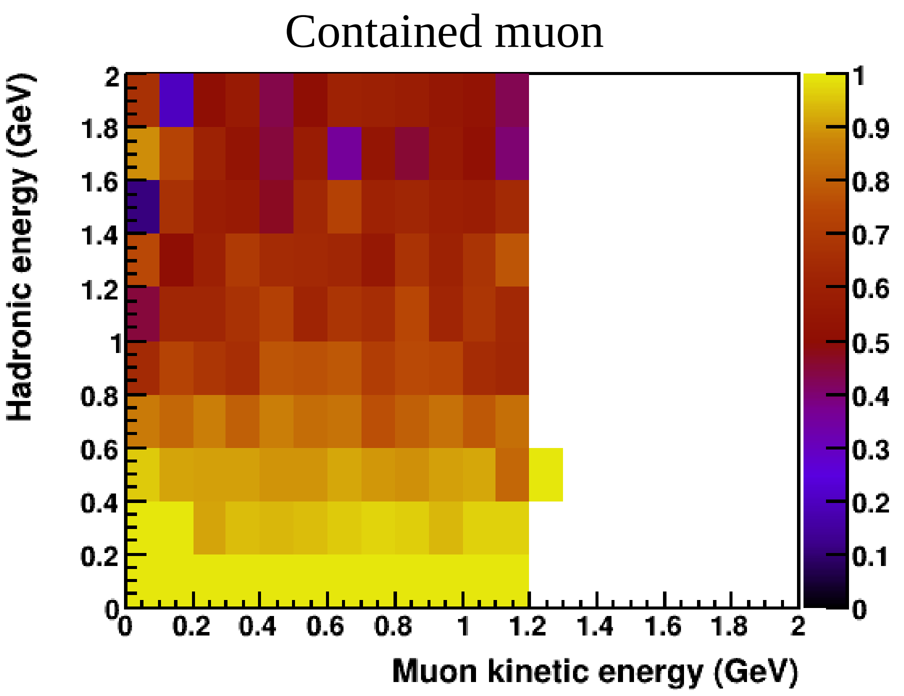
Hadron acceptance is different from contained vs. tracker muons

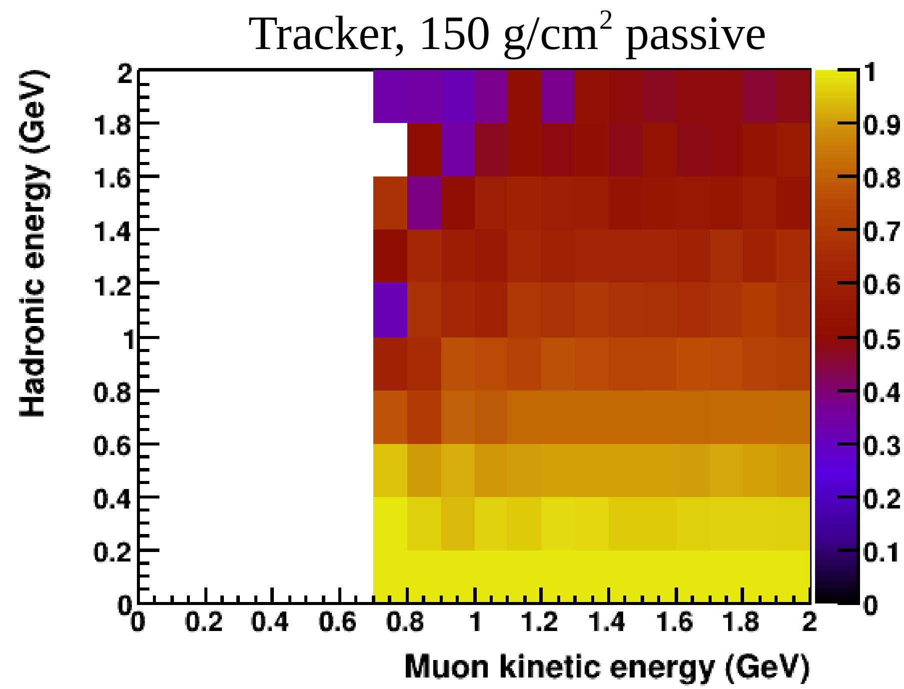




- In the overlap region, upstream events are contained, and downstream events are tracker-matched
- This is important, because it allows us to directly measure the hadronic energy over a broad range of detector positions
- Without upstream region, we would miss high-Ehad (q0) events; without downstream region, we would miss high-θ events (q3)

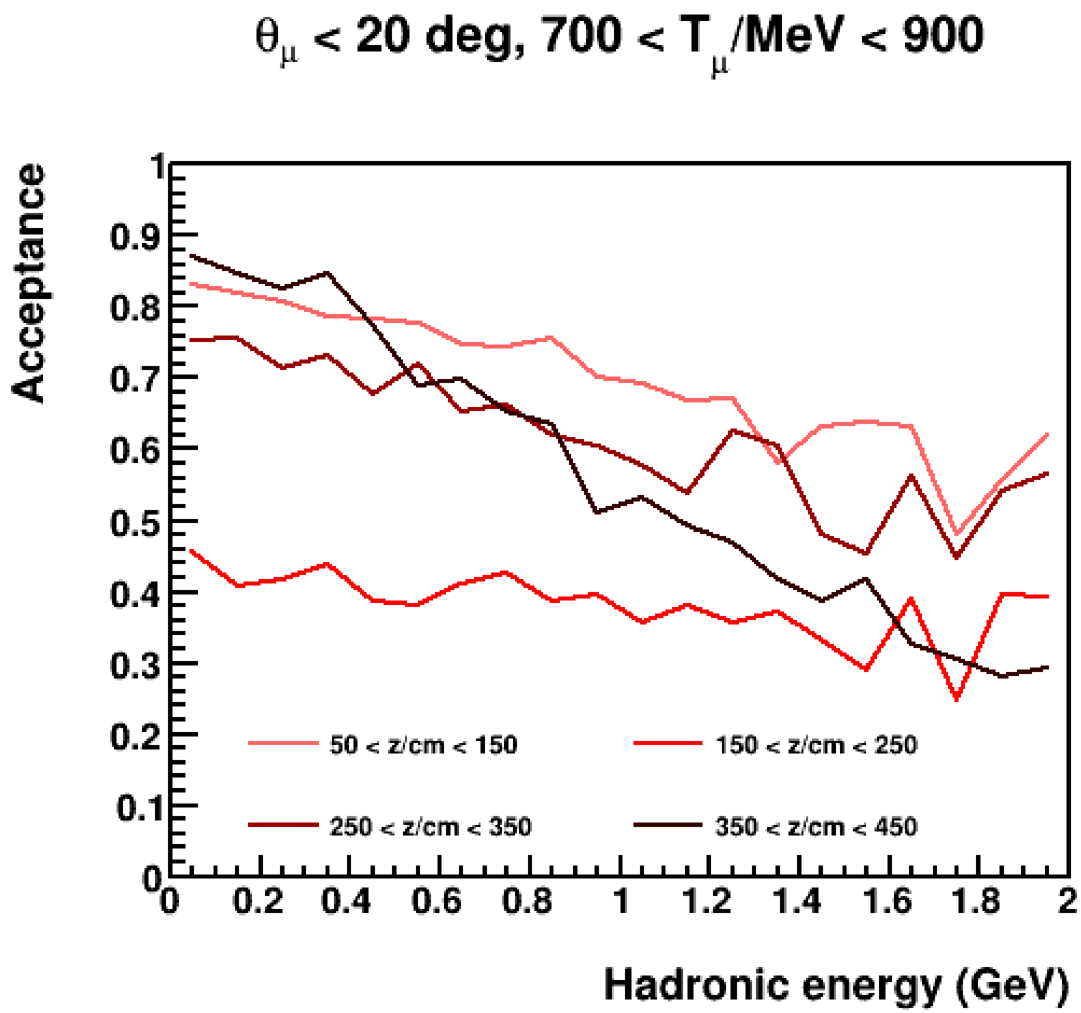
More passive material cuts into overlap region





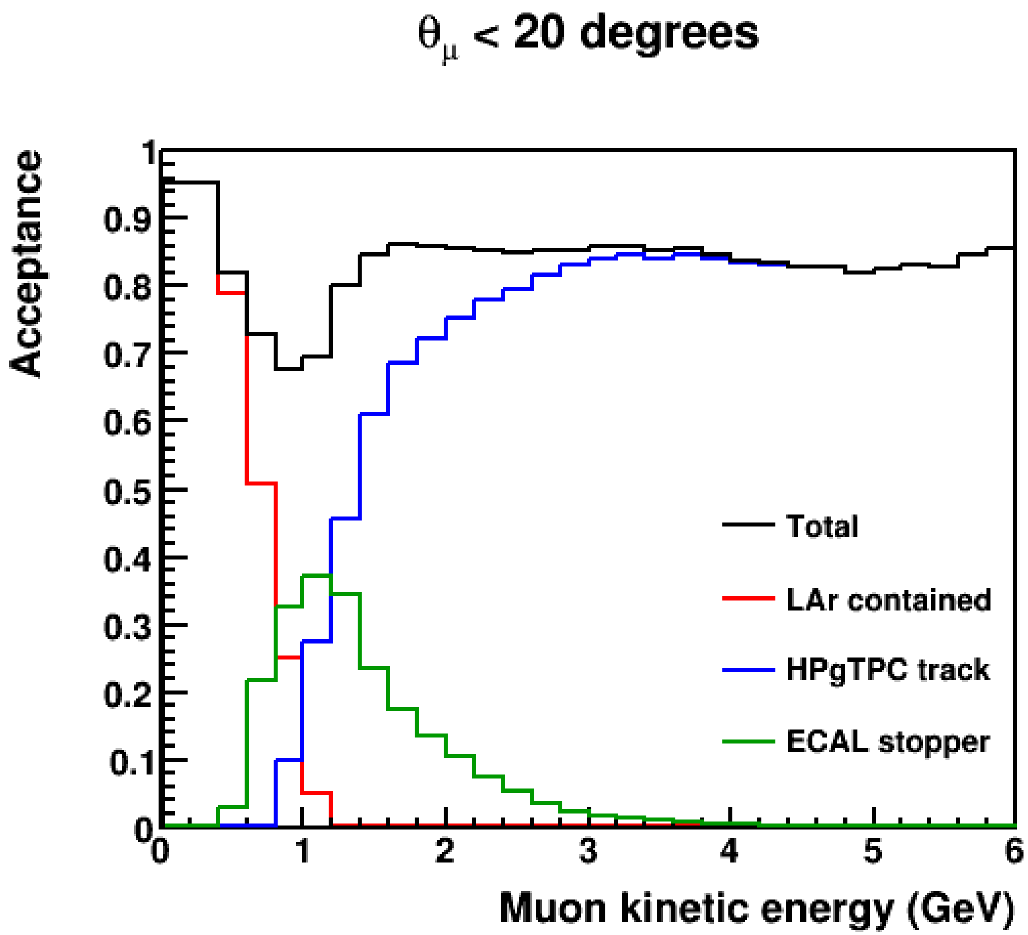
- At 1 GeV, for example, hadronic energy starts to fall off harder with 150g than with 100g

Acceptance in Z slices



- Low stats because this is binned in Ehad-Eμ-θ-Z
- 65 g/cm² passive material
- For forward muons from 700-900 MeV, the acceptance “dead sea” is the middle of the F.V., from 150-250 cm
- Acceptance vs. Ehad is different in the upstream (50-150) and downstream (250-350) regions
- Measuring this is valuable

An aggressive but plausible LAr+MPD geometry



- Thin G10 window (19g), polyethelyne (2.5g), steel (2.5g), $25 g/cm^2$ total on LAr side
- 10cm aluminum SPY magnet, $37 g/cm^2$ to ECAL, total of $62 g/cm^2$
- ECAL-stopping tracks are critical, but dip is <30% (slightly worse with MPD than TMS due to large x)