The Ultimate Goal

Claim discovery with one event

- ID, p-vector and E of all annihilation and nuclear products
- Statistical corrections not possible
- No combinatorial mistakes allowed

Of course we will have to compromise

Annihilation in a nucleus makes a big difference

Time to include in the design
As well as backfround

Evidences 1

Topology

- common vertex with at least two charged pion tracks
- 3D tracking by TPC pointing in and out
- safe combinatorics by 3D pointing
- 2D track inside vacuum.
- no vertex in 2nd foil

Evidences 2

Particle identification (PID)

- Identify charged particles as pions or protons
- Identify pairs of gammas as neutral pions.
- TPC for dE/dx sometimes combined with E or range from calorimeter

Evidences 3

Energy and momentum

- needs PID. At least 280MeV in charged pion rest masses.
- large Energy fraction carried by nuclear fragments
- Energy by neutrons lost
- cuts on energy and momentum have to be generous
- Toyal energy still high compared to anything else
- resolution in kinetic energy less important

Evidences 4

Direction

- All particles must move outwards
- charged particles – DOF
- neutral EM showers DOF calorimeter and/or Cherenkov.
- Vetoing chaged Cosmics

Two important facts for the design:

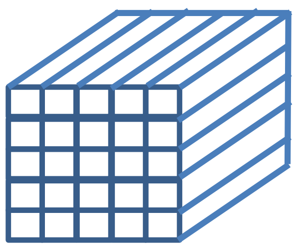
Signal events is only a few particles

Coarse granularity is OK

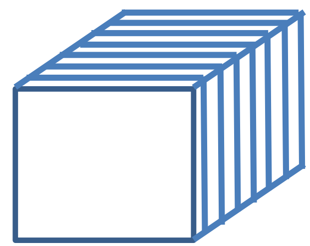
Background may be high rate but completely uncorrelated to signal events

short signals is the best – less pileup

high granularity needed



Granularity for signal



Granularity for neutron induced backgnd can be like this

And some more:

Compton electron from nuclear gammas deposit < 1MeV

A MIP deposits 2MeV/cm in plastics.
With 2cm plastic scint a threshold can discriminate charged pions from backgnd

In a gas or in a Si detector
the compton electrons give higher energy deposit than MIPs.

Consequence.

Detectors should be thick to discriminate between signal from nucl phys backgnd.
Make thicker to discriminate better

(Particularly Important for DOF/track trigger detector)

It is time to take the nucleus into account

Annihilation in a Carbon nucleus gives quite different final sate compared to a a free n-nbar annihilation

We implant strongly interacting particles in a strongly interacting medium
(but color neutral not colored as in Quark Gluon Plasma).

Very important simulations by Golubeva, Barrow, Ladd GBL
Benchmarked to p-pbar
DOI: 10.1103/PhysRevD.99.035002

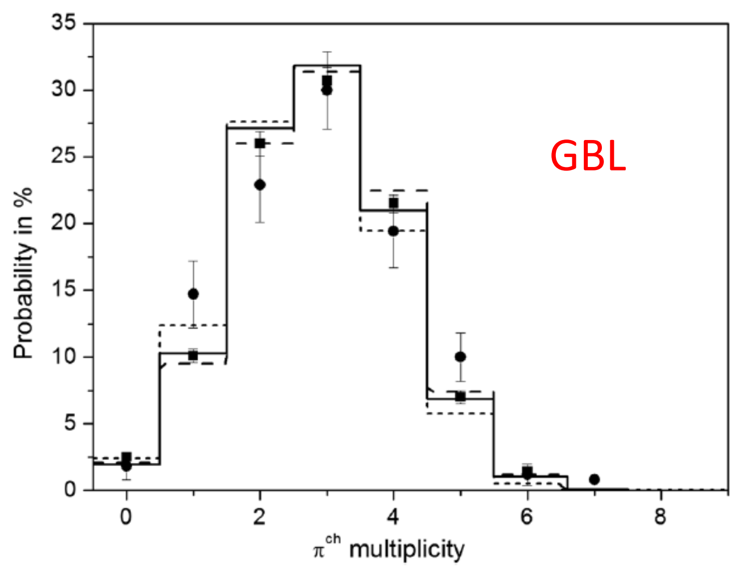
Topology-tracking

- common vertex with at least two charged pion tracks
- 3D tracking by TPC pointing in and out
- safe combinatorics by 3D pointing
- 2D track inside vacuum.
- no vertex in 2nd foil

Charged pion multiplicity in C

88% 2 or more charged pions
Ok to reconstruct vertex

10% only one charged pion
verify vertex hypothesis with
Pi-sero or protons



Topology-tracking TPC

TPC is the backbone in tracking

Safe 3D tracks with **no combinatorial ambiguity**

Pointing reilably inwards

- selects which foil (hopefully TPC only)
- 2 coordinates in 2D inside give high resolution vertex

Pointing reliably outwards

hit position in TOF detector improves time resolution

links safely energy and tof measurement to

charged particles and vertex.

Extremely high granularity but still a gas detector

So, compton electrons from gammas can give long tracks track

Operation in neutron and gamma envirenonment needs

studies

Topology-tracking inner detectors

The vacuum vessel wall (nominally 2cm Al)

- deteriorates pointing resolution from outside
- increases detection threshold for dE/dx and E measurement

But shields outer detectors from neutron induced backgnd from the foils (maybe high Z material instead???)

Stops electrons from beta decaying neutrons

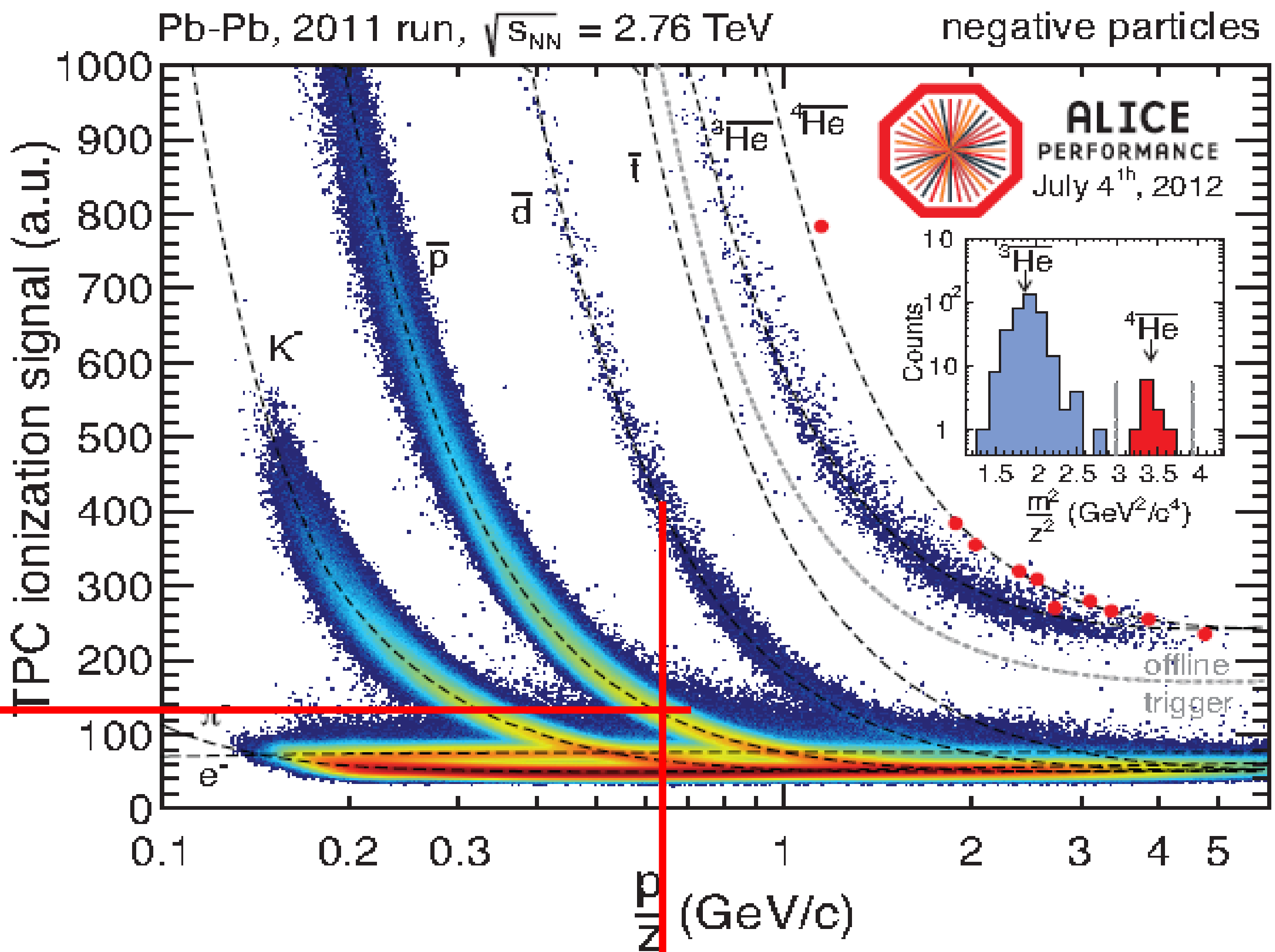
- Inner tracking needed since vertex cut is crucial
- Much background – very high granularity
- 2stations with 1D - high resolution position
  (Provided that TPC gives pattern recognition)
- dE/dx would be good for particles stopping in wall
- Gas is difficult due to pressure difference
- A simple Si detector (one strip layer per station)
  may be adequate and affordable).

Particle identification (PID), charged

- Identify charged particles as pions or protons
- Identify pairs of gammas as neutral pions.
- TPC for dE/dx sometimes combined with E or range from calorimeter
- Narrow inv mass peak in Emcal needs good energy resolution

A TPC is great for dE/dx in spite of thin medium

- many measurements – remove Landau tail
- no combinatorial mistakes between track and dE/dx (it is the same information)



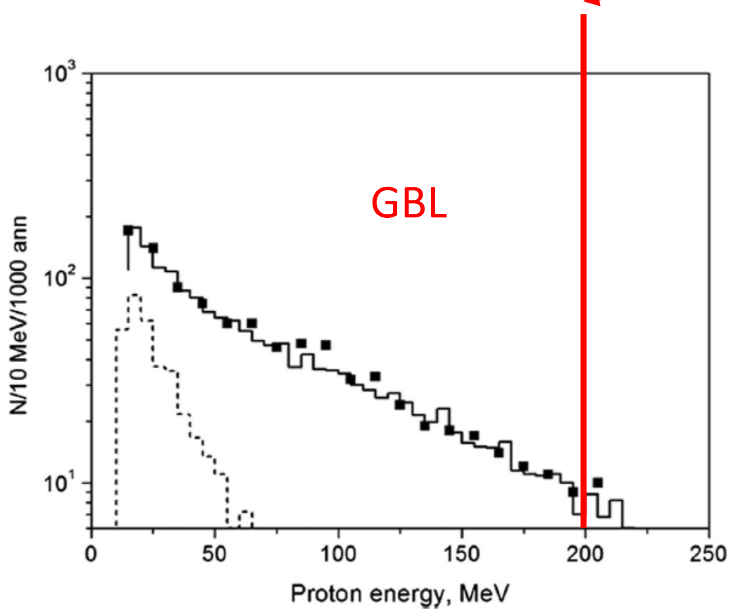
But we do not measure momentun

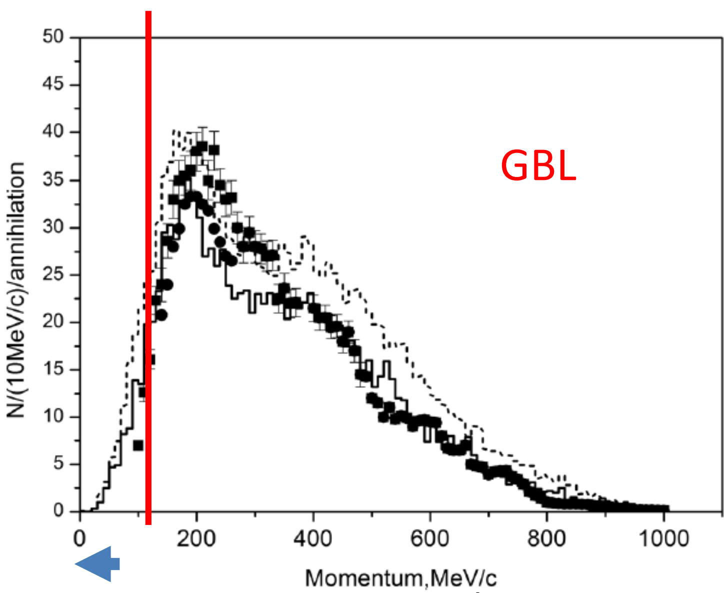
Top end of proton spectrum
200MeV kinetic Energy

Particle identification (PID), charged

Equal dE/dx. Also Cherenkov threshold

So physics helps us a lot





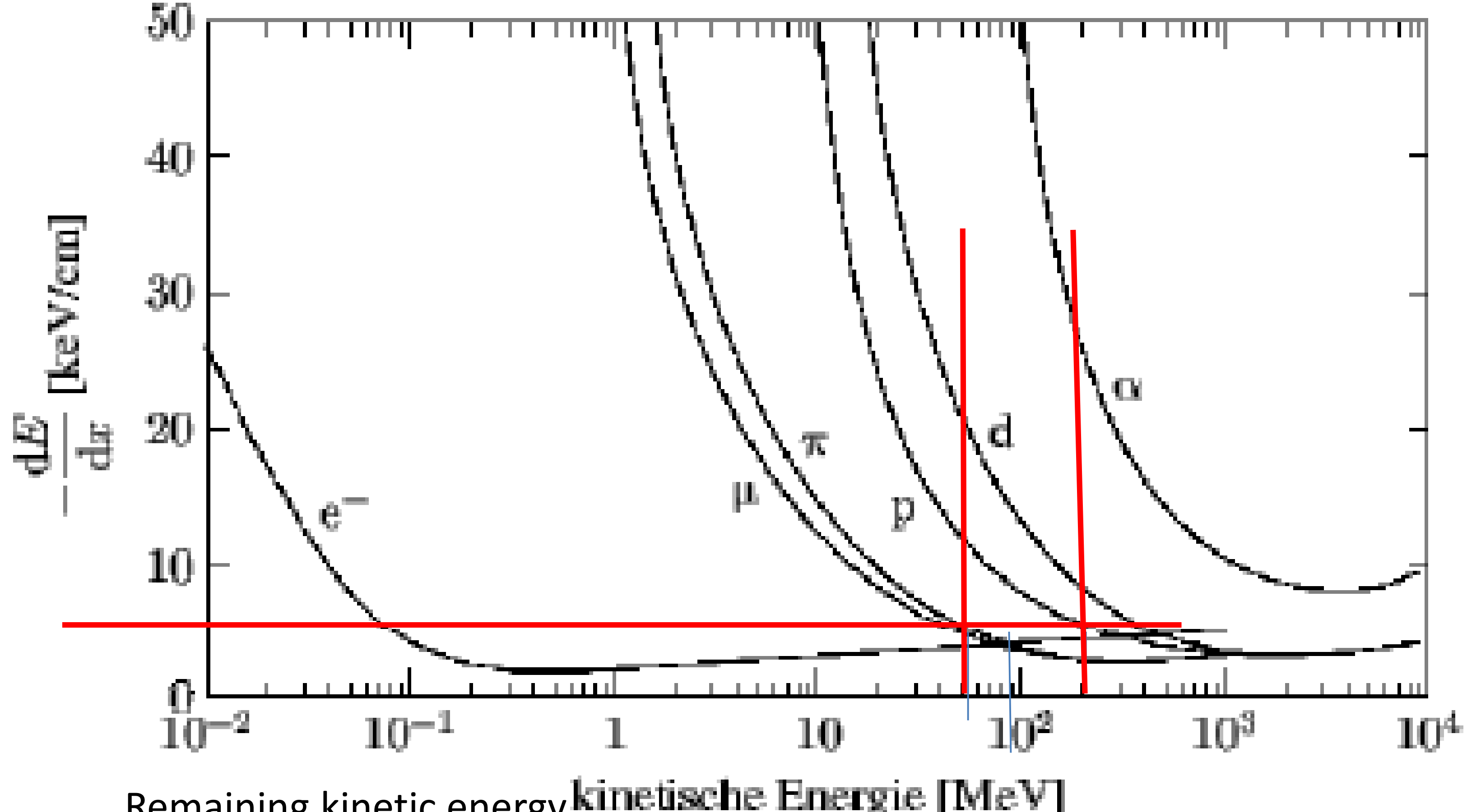
Pions up to 80MeV/c stop in 2 cm Al

For dE/dx in TPC it will be remaining Energy after Al wall

TPC for charged pion and protons id

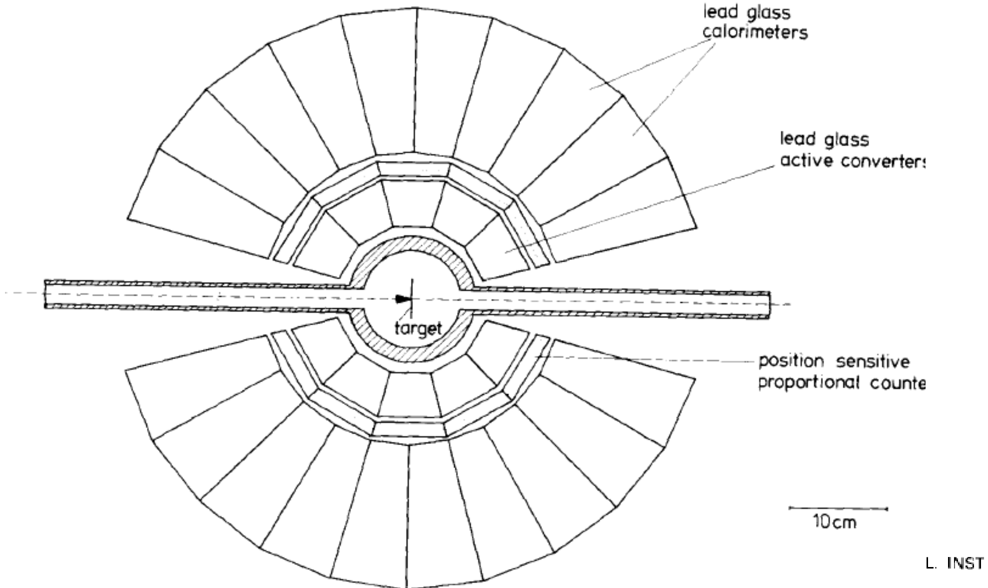
de/dx 5-10%

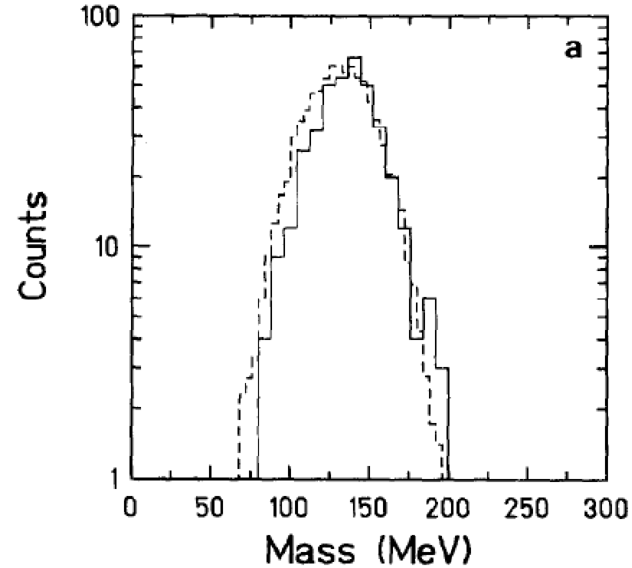
Cherenkov threshold in lead glass



Remaining kinetic energy

Particle identification (PID), pizeroes





From when I was young.

Lead glass. We had poor angular resolution (very close)

Invariant mass resolution thus not great due

But if there is no background this does not matter so much

This was nuclear collisions at 100 MeV/nucleon and very few gammas with E>65MeV

.

Will be the same for nnbar but

when we have an event there may be more than 2 gammas and

then inv mass resolution helps to find the right combination

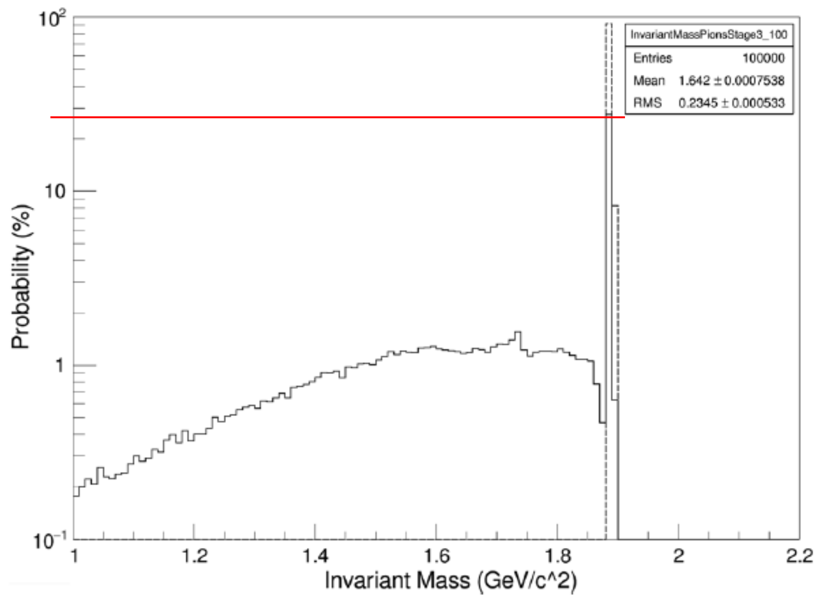
Energy and momentum

- needs PID. At least 280MeV in charged pion rest masses.
- large Energy fraction carried by nuclear fragments
- Energy by neutrons lost (50% of the nucl fragment?)
- cuts on energy and momentum have to be generous
- energy still high compared to anything else
- **resolution in kinetic energy is not that important**

Total energy, annihilation i C

GBL

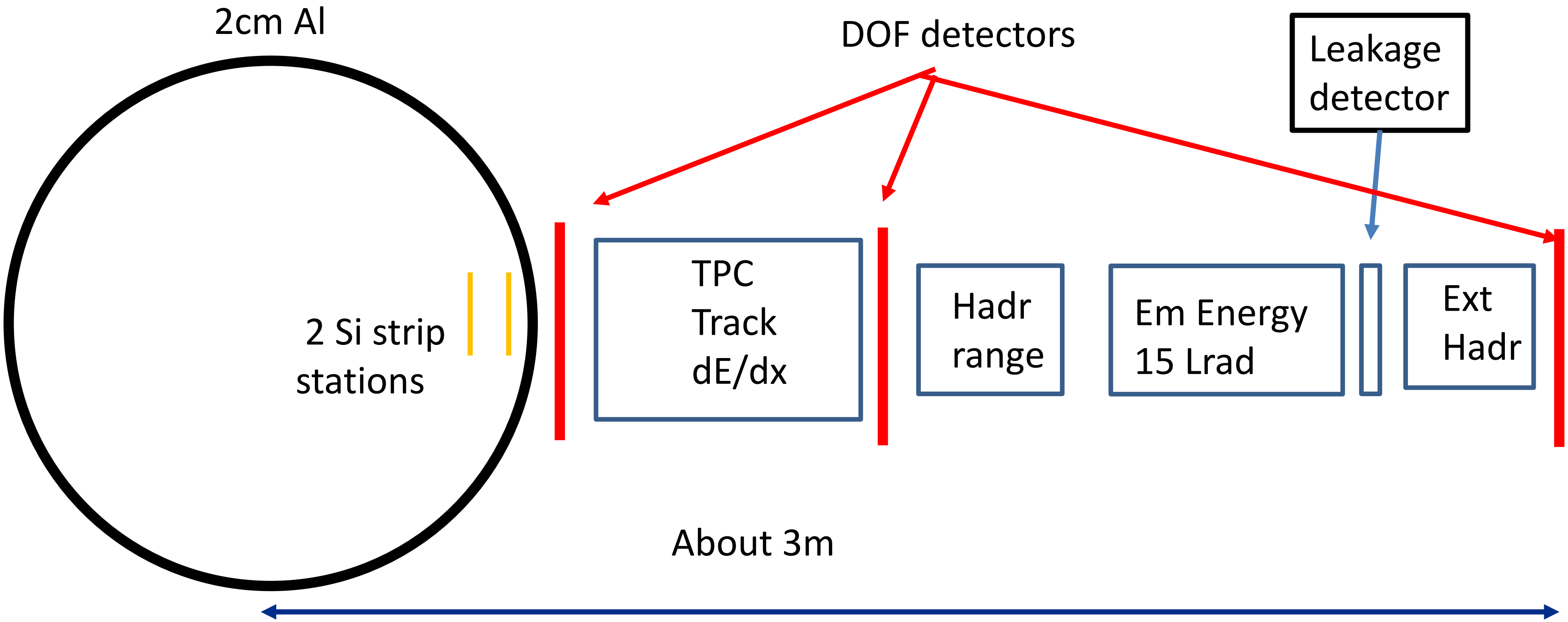
Only 30



So momenta can not be required to add up to zero

but if we have a promising event but if the missing momentum points into uninstrumented directions we will be happy to take shifts for another year.

The full chain



Energy and momentum, Photons and pizero

No viable arguments for high resolution crystals

EM-calorimetry has poor shower statistics – large fluctuations

- Sampling calorimetry poor energy resolution
- Full absorption calorimeter - no energy fluctuations
- Sampling and full absorption - position resolution is affected

Much talks for full absorption lead glass

Energy and momentum, Photons and pizero

Lead glass

Full absorption

Cherenkov threshold 200MeV for protons

- blind to nuclear fragments
- Sensitive most charged pions
- Sensitive to nucl physics gammas, but low signal
- Fast response, reduced background pileup
- Direction sensitive

Arguments for sampling EMCal

maybe cheaper

maybe less sensitive to backgnd

(gammas converting in dead absorber do not matter)

Range measurement of charged pions possible

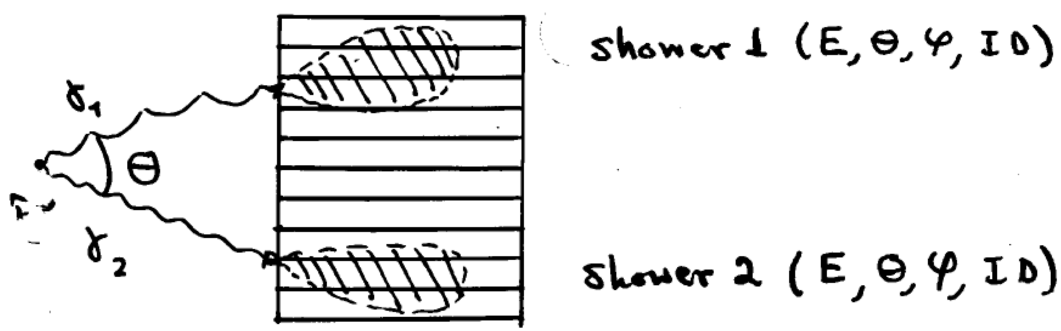
Does EM resolution matter?

For pizero identification – Not so much since cominatorial backgnd is zero

For vertex association of gammas, yes

shower energy

shower position matters



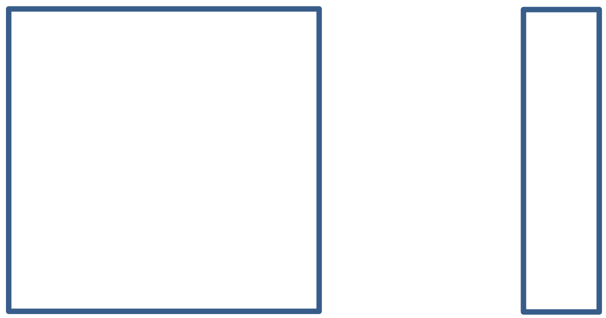
The invariant mass is given by

$$m_0^2 = 2 \cdot E_1 \cdot E_2 \cdot (1 - \cos\Theta)$$

EM Cal interesting solution to try

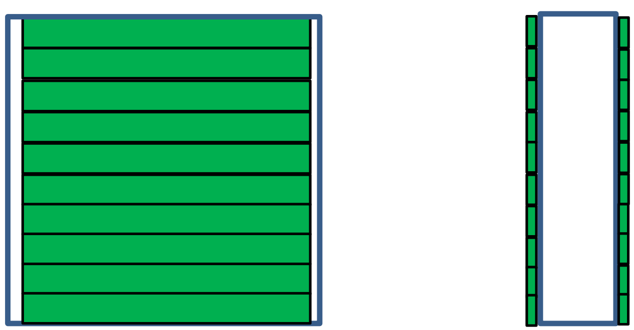
Make use of fact that our signal does not need high granularity

1*1m, 25 cm thick. Single block, (yes it is heavy but EMCal will be)



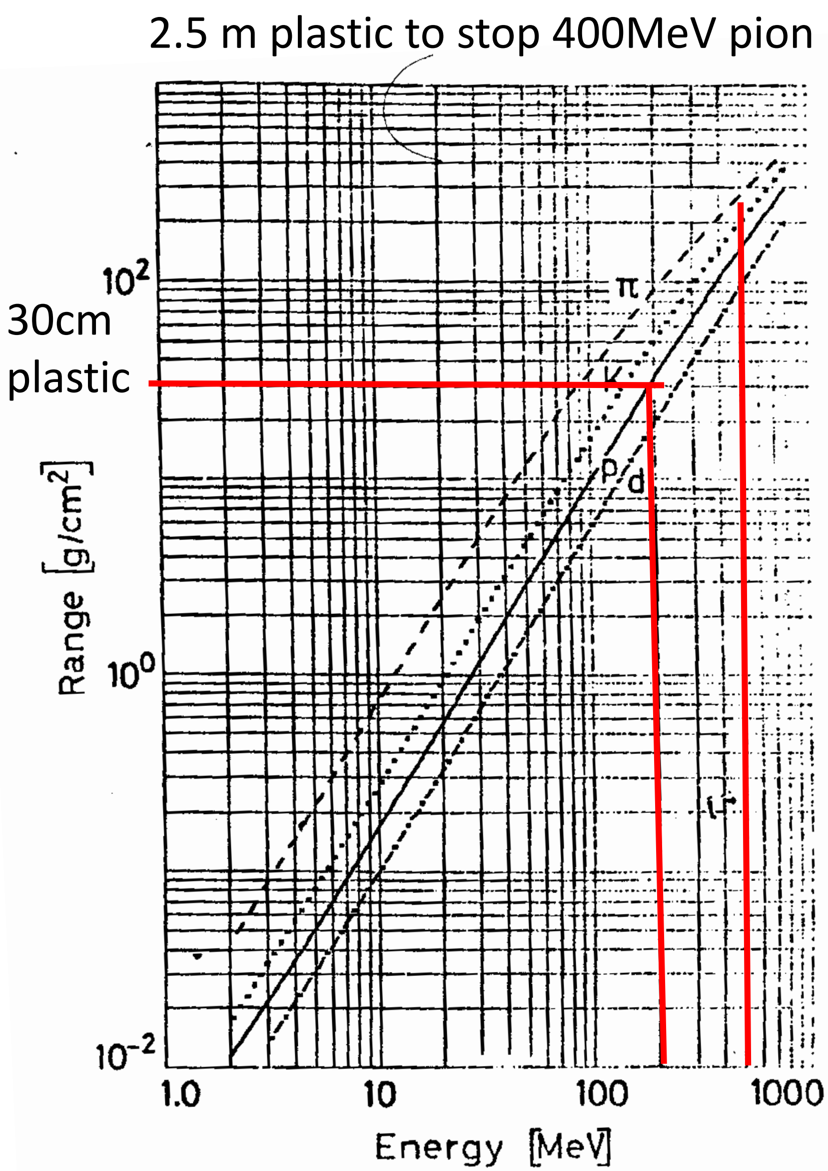
20 Lrad

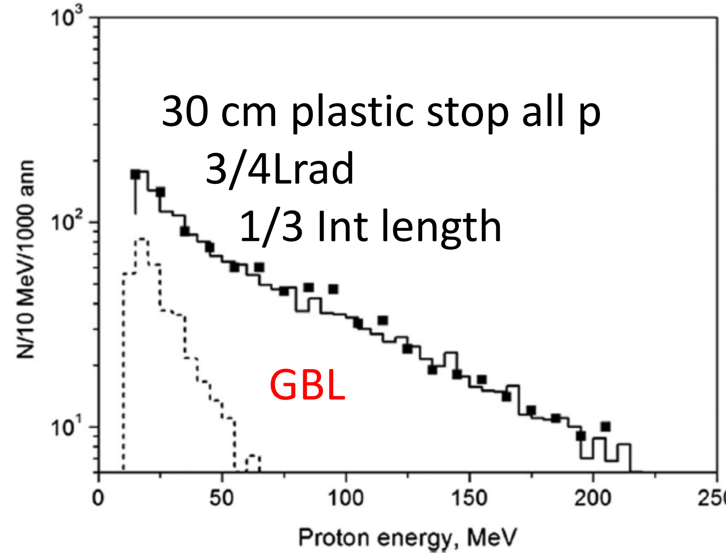
WLS shifter readout on both ends for position
And both sides for shower and particle direction

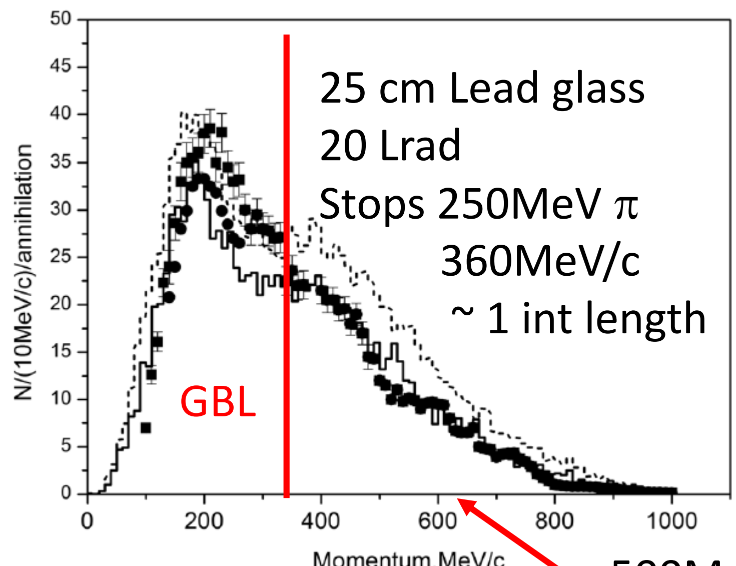


Avalanche Photodiodes
1-2 cm^2 size

Hadron energy







500MeV kinetic

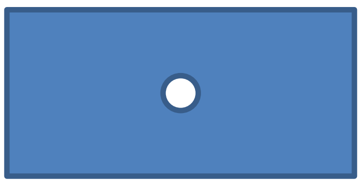
- Hadron calorimetry is lousy at these energies
- Range more reliable than measured energy
- We know identity from dE/dx

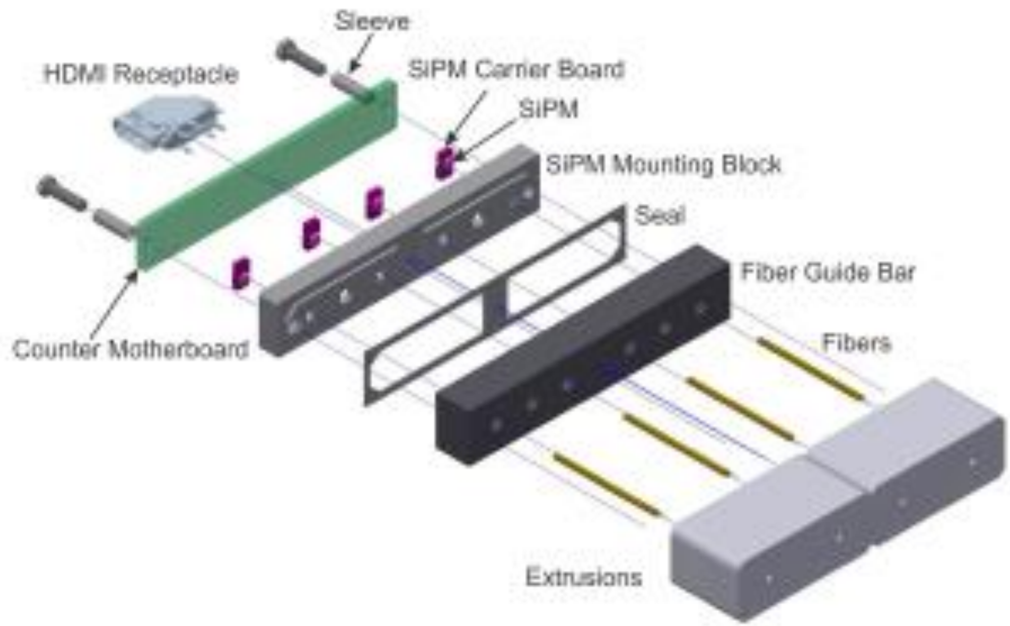
  or we improve it by dE/dx vs range
- Split up 30cm depth in 10 range bins
- 3cm per scintillator-6MeV for MIP.
- Threshold sufficient to discriminate to Nuclear gammas
- Granularity in depth
- TPC points track in 3D for pattern recognition

Elegant and cheap solution

Scintillator bar
1m long

5*3cm^2 cross-sectiom



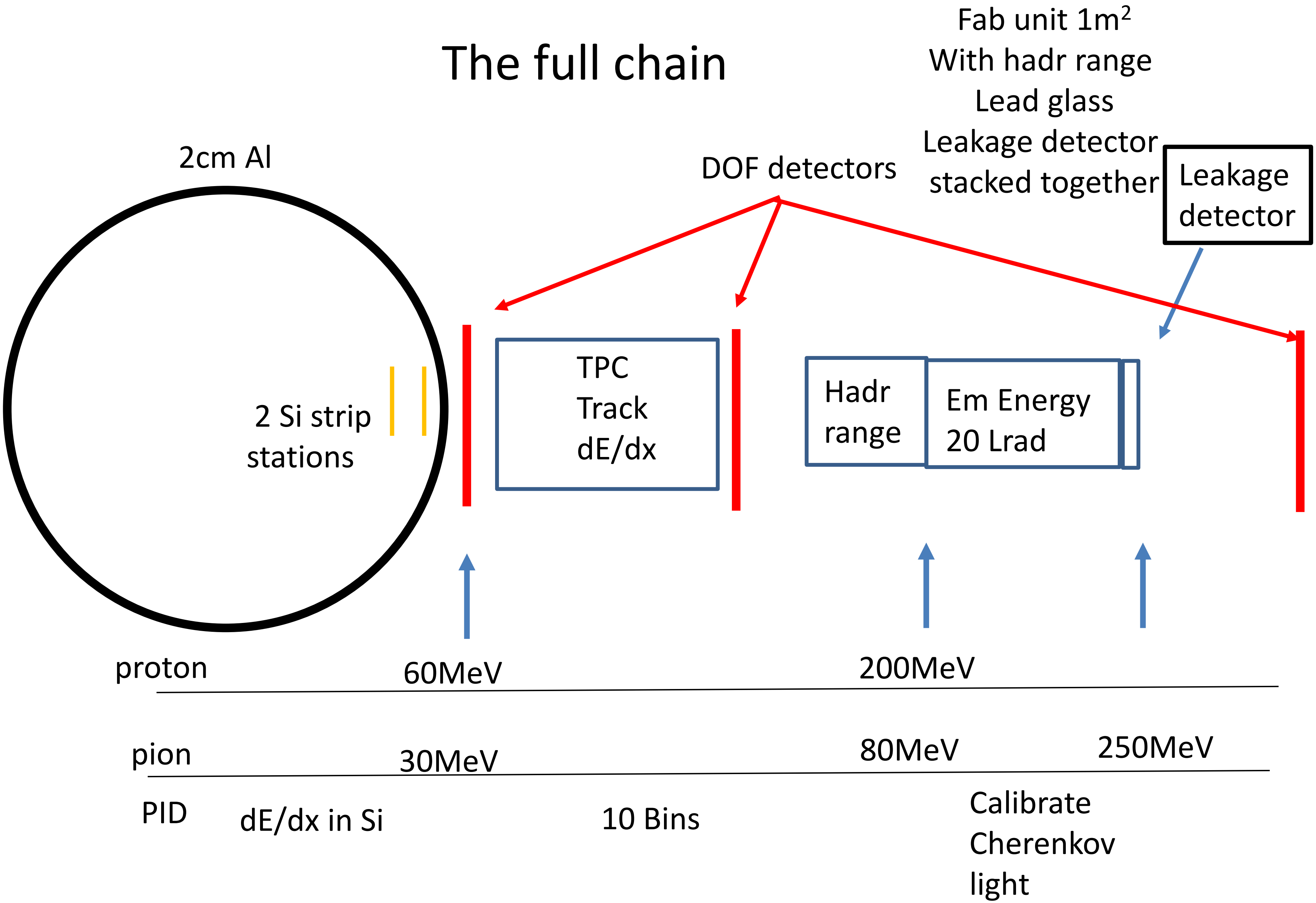


Surfaces diffuse reflection
WLS shifting fiber in the hole
Read out small SiPM 1mm2 both ends
Threshold between MIP and gamma
Time difference for position
Or crossed planes and one sided readout

https://arxiv.org/pdf/1709.06587.pdf

Mu2E collab
Also LDMX

The full chain



DOF detectors and cosmic charged particle veto .

Plastic scintillators thick enough to separate MIP from gamma.

Charged particle trigger

Same argument about discriminating between gammas and pion/protons

DOF scintillators fairly thick

Pizero and/or gamma trigger.

Straightforward by tower threshold

If Cherenkov one can avoid showers in wrong direction in trigger

Many interesting and unusual detector options to try out
But
Background is crucial

For the detector studies one is not so much helped by backgrounds quantified in Sivert

A first effort could be a simplified detector with some materials included.

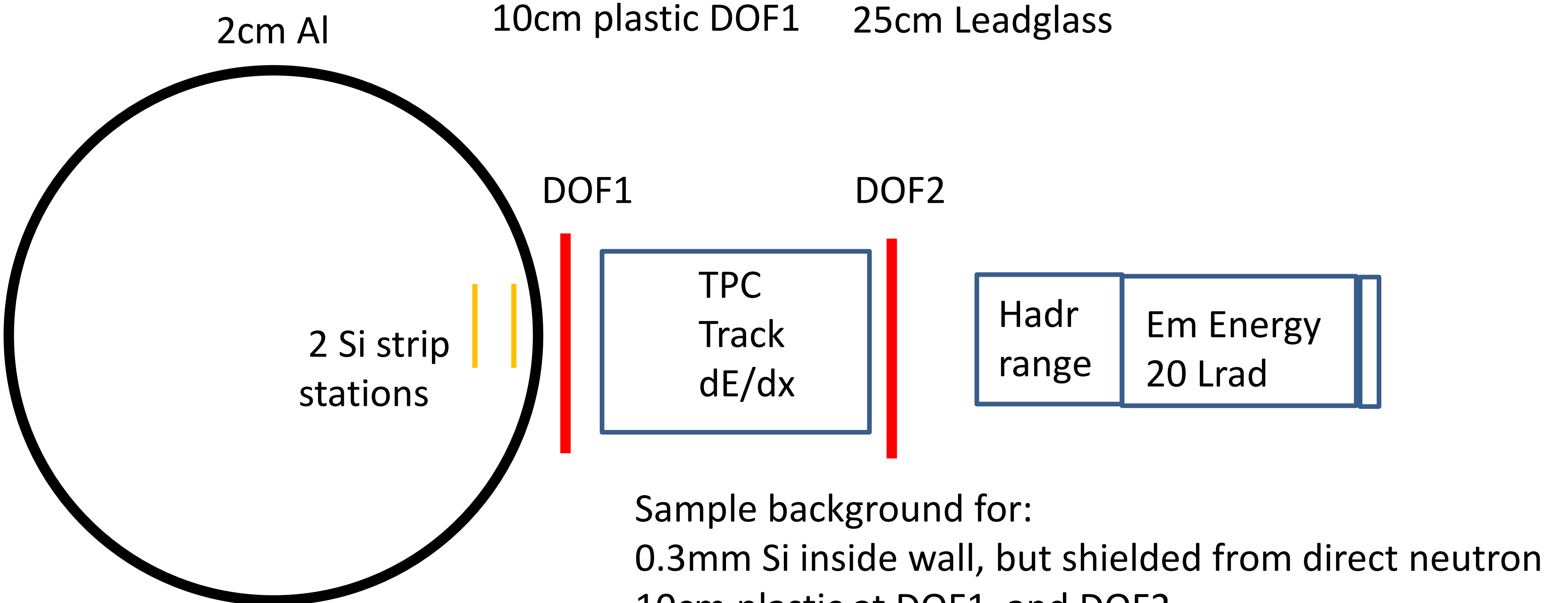
materials

2 target foils

Starting at 1m

0.6mm Si
2 cm Al
10cm plastic DOF1

1m Ar at 1atm for TPC
10cm plastic DOF2
30cm plastic for hadr range
25cm Leadglass



Sample background for:
0.3mm Si inside wall, but shielded from direct neutron
10cm plastic at DOF1 and DOF2
100 cm Ar at TPC
3cm plastic at 0,15,22 cm in hadr range
total deposit at 0 and 10cm and 20cm on EMCal

Want to know
Rate per cm^2
energy spectrum of different particles responsible for the rate
(presumably only electrons from gamma conversions and beta decay)