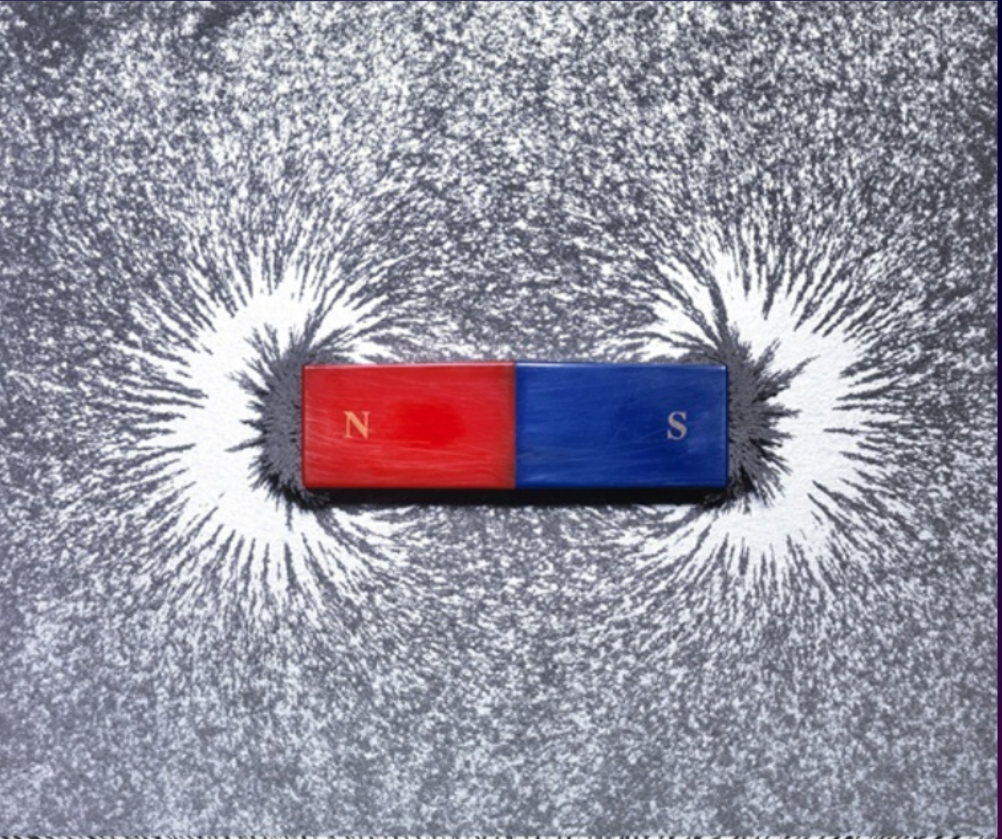


MoEDAL

Monopole and **E**xotics **D**etector at the **LHC**

Lewis Millward
l.millward@qmul.ac.uk
Queen Mary University of London

- MoEDAL Physics
- MoEDAL Detector
- Machine learning for MoEDAL

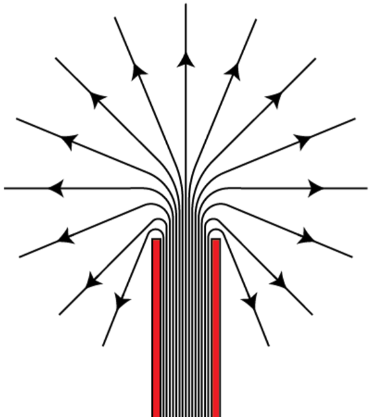
l.millward@qmul.ac.uk

Magnetic Monopoles

Many different predictions;

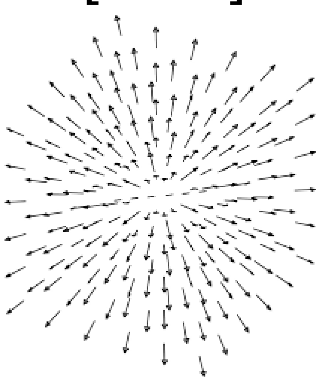
- Dirac monopole [1931]

pointlike singularity modelled as infinitely long solenoid 'dirac string'



- T'Hooft-Polyakov [1973] GUT

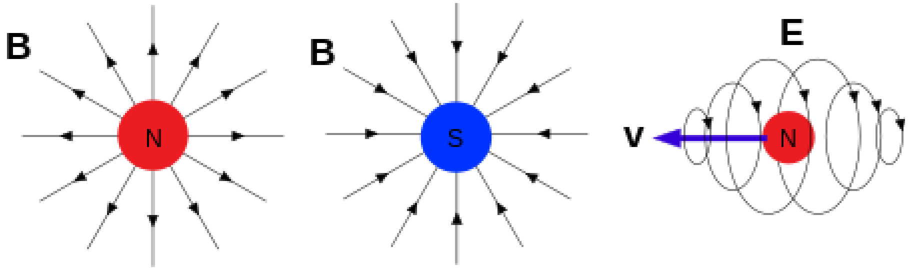
Topological soliton in fundamental gauge fields in theories with broken symmetries.



- Cho, Maison [1996] EW
  modifications to SU(2) x U(1) electro-weak theory possibly allows TeV monopoles hybrid of Dirac / T'Hooft
- Dyons, magnetic and electric

Common properties;

- Acts like particle with magnetic charge. EM interaction with much stronger coupling! $g_D \sim 68.5e$



- Mass ~ varies by theory, uncertain Unconstrained for Dirac monopoles EW 4~10TeV, Tevatron > 600GeV
- Explains charge Quantisation, possibly baryon asymmetry, early cosmos
- Stable if topological solitons

= Heavy, Stable, Highly Ionising

l.millward@qmul.ac.uk

Exotics and HIPs

Monopole signal = Heavy, Stable, Highly Ionising

Similar exotics;

- Stable Massive particles
  SUSY; stops, staus, gluinos
  (esp. if parity conserved)
- Multi-Charged particles
  eg, double charged Higgs
  Bilepton
- High momentum + low velocity,
  high ionisation, indicates
  heavy charged BSM object

at higher energies are from Ref. 5. Vertical bands indicate boundaries
different approximations discussed in the text. The short dotted line
"μ^-" illustrate the "Barkas effect," the dependence of stopping power o
charge at very low energies [6].

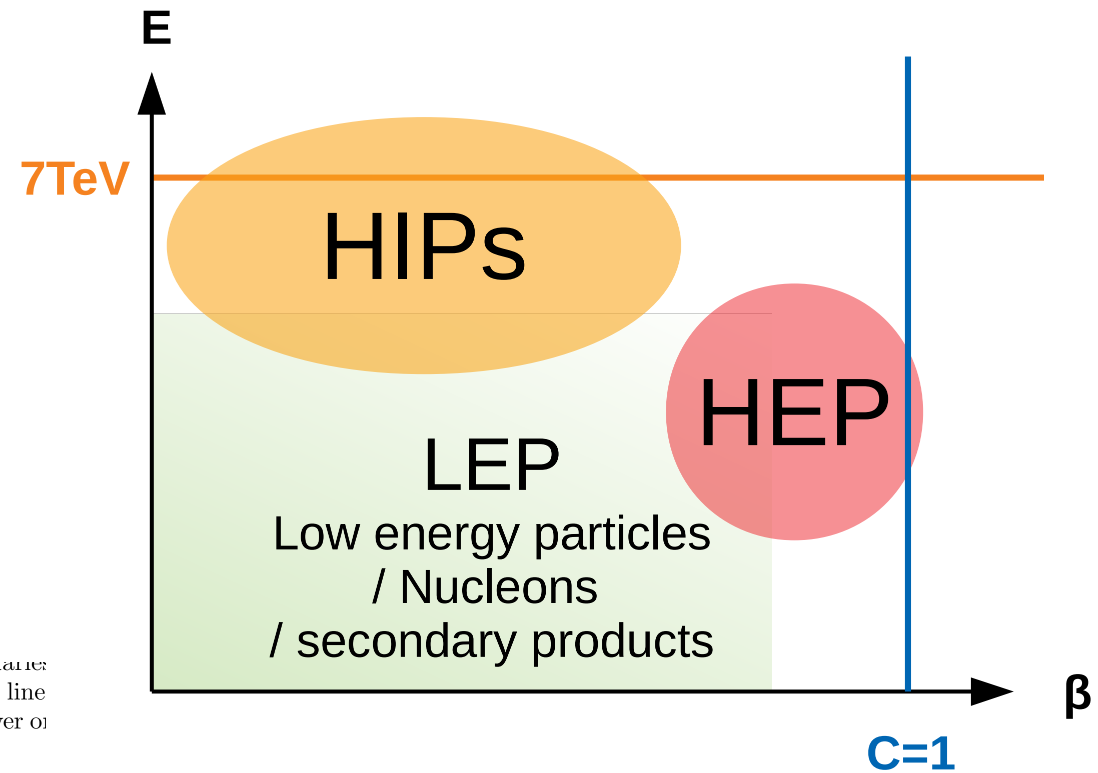
27.2.2. ***Stopping power at intermediate energies*** :
The mean rate of energy loss by moderately relativistic charged heav
$M_1/\delta x$, is well-described by the "Bethe-Bloch" equation,

Lep Hep

$$\left\langle \frac{dE}{dx} \right\rangle = -Kz^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right] .$$

It describes the mean rate of energy loss in the region $0.1 \lesssim \beta\gamma \lesssim$
intermediate-Z materials with an accuracy of a few %. At the lower
projectile velocity becomes comparable to atomic electron "velocities" (S

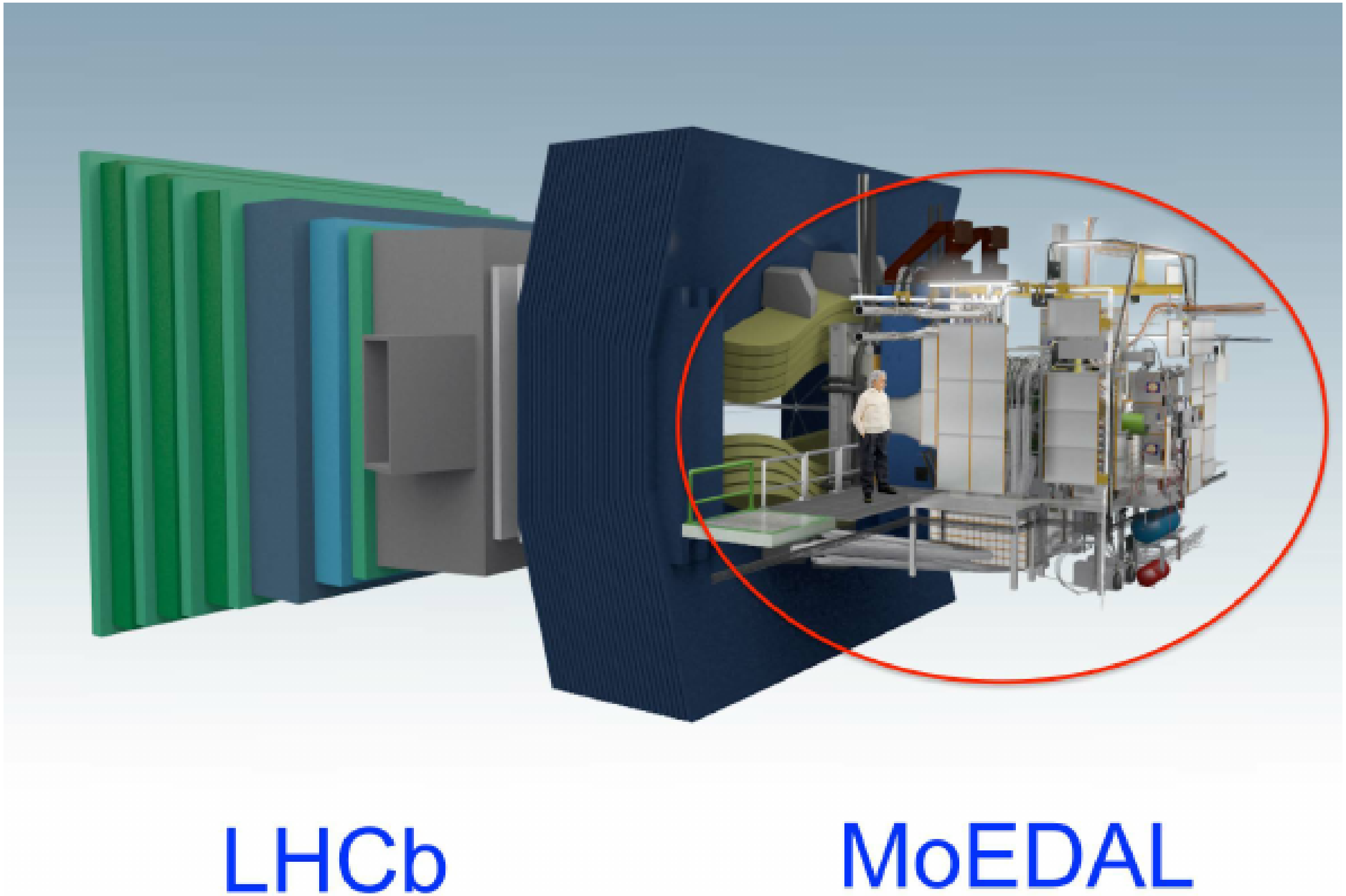
February 2, 2010 15:55



- Detectors optimised
  triggering on ~ light speed particles, minimally ionising / penetrating
- High bunch crossing rate, most events discarded
- Rare HIP signal, can look like v. common backgrounds

MoEDAL detector

LHC
IP:8



MMTs
Aluminium ferromagnetic monopole trappers

NTD array + VHCC
Ionisation detectors
(rest of this talk)

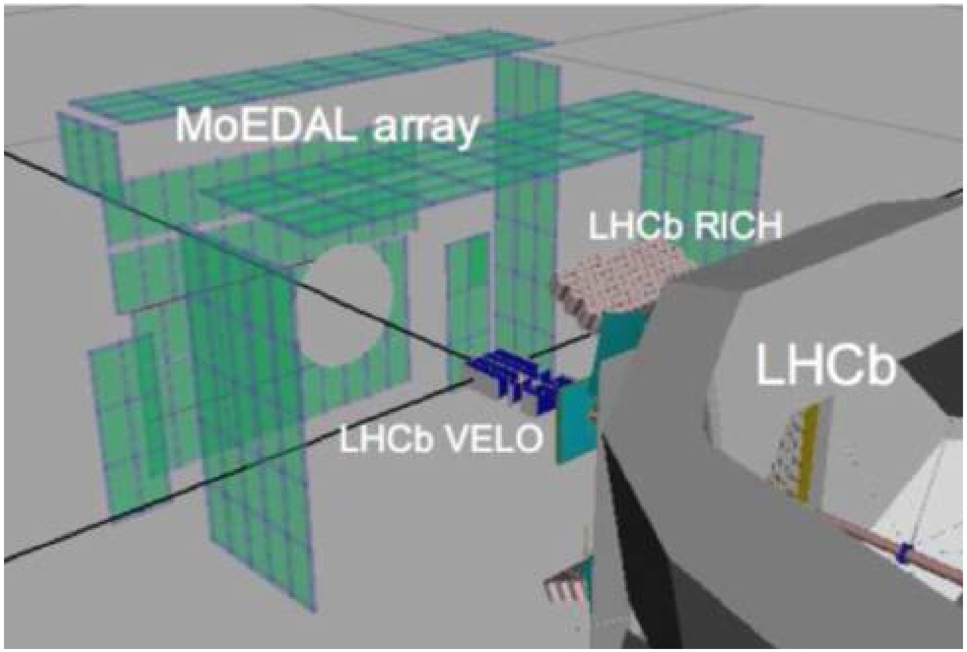
Timepix
Radiation environment monitoring

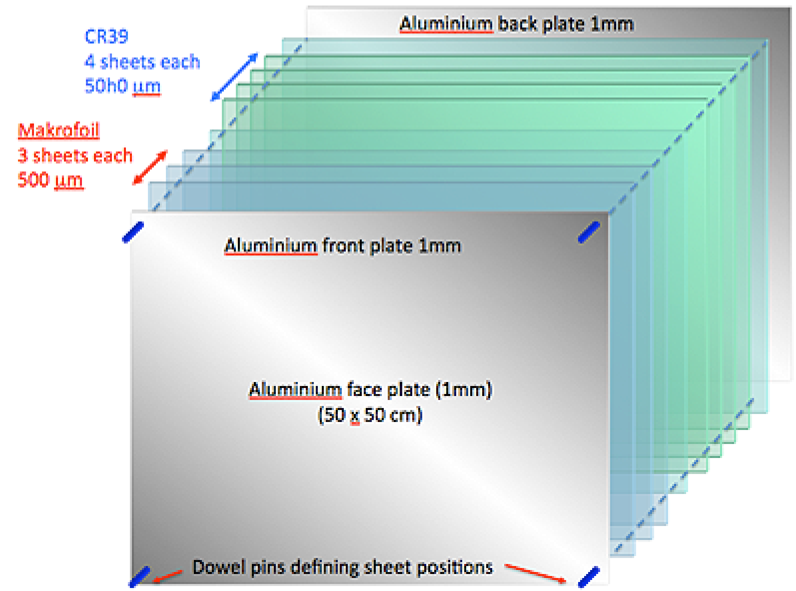
MAPP
Millicharged particle detector

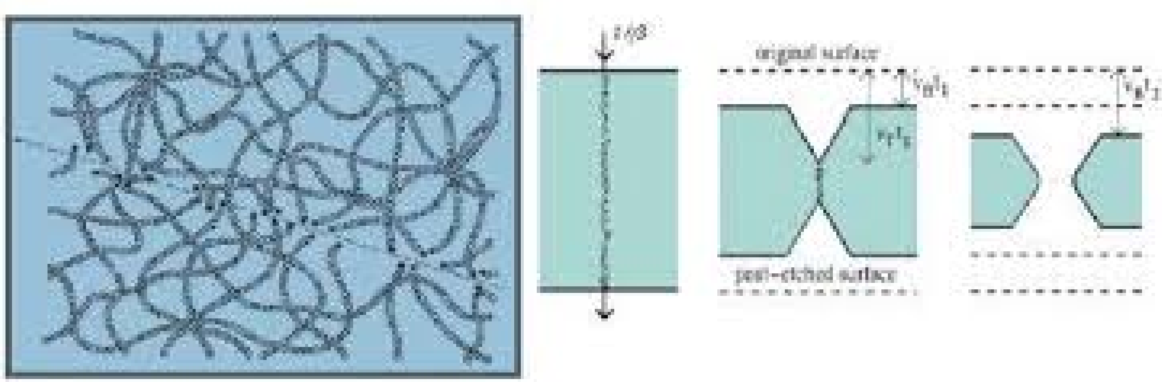
l.millward@qmul.ac.uk

Moedal: NTD arrays

Stacked Arrays of ionisation sensitive polymer solid state nuclear track detectors (NTDs)
Sensitive to Heavily Ionising Particles, low sensitivity to standard model particles





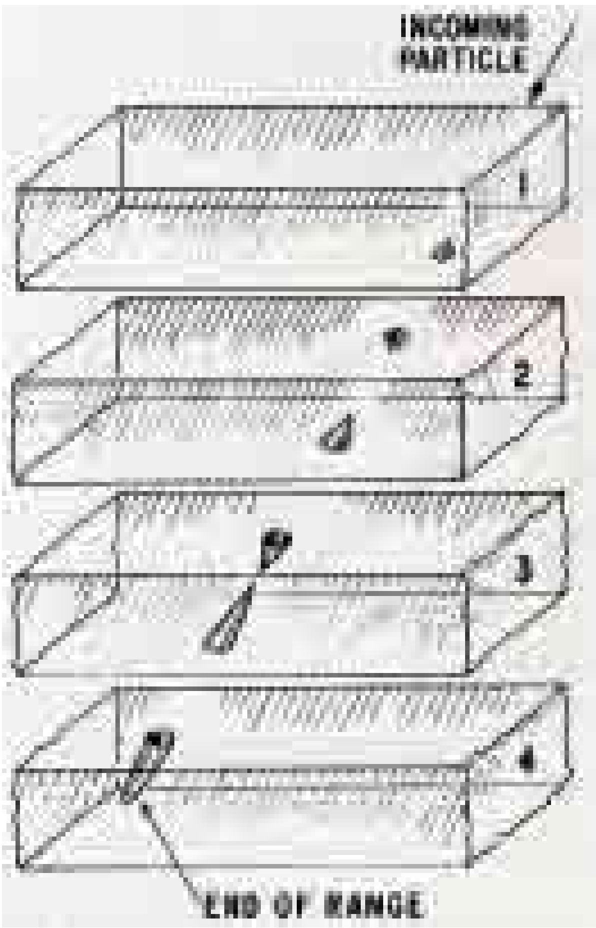


NANOSCOPIC ⟶ **MICROSCOPIC**

- Ionising particles break polymer chains in NTD foil in localised region
- Leaves latent 'Ion track'
- Chemical etching process occurs faster along ion tracks than bulk medium
- Forms 'etch-pits' where ionising particles entered and exited the foil

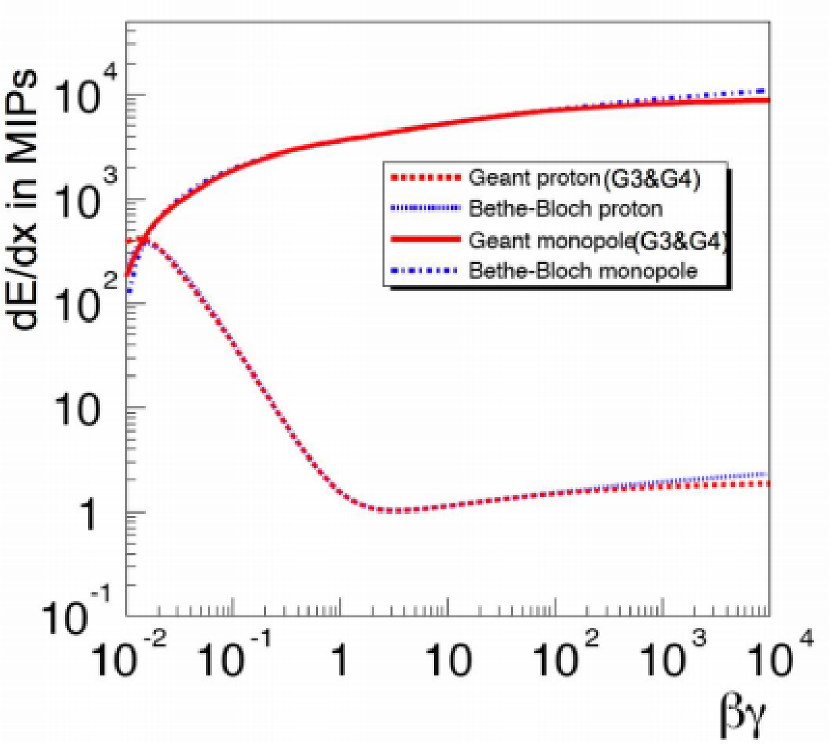
l.millward@qmul.ac.uk

Standard Model Ionisation Behavior



Courtesy INF Bologna

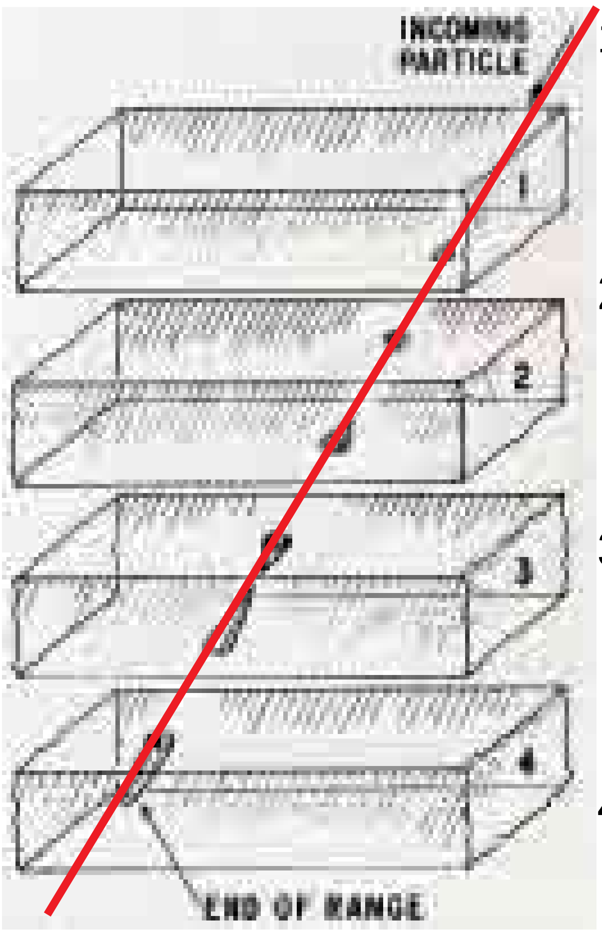
1. Initial High energy causes minimal ionisation. Doesn't show up as etch pit
2. Particle loses energy, lower velocity, efficient ‘electronic’ ionisation. ‘Ranging in’
3. Reaches peak energy loss
   larger etch-pits form at point of entry and exit
4. Energy loss, ‘electronic’ ionisation ceases, etch-pit formation stops. ‘Ranging out’



Particles in NTD stack

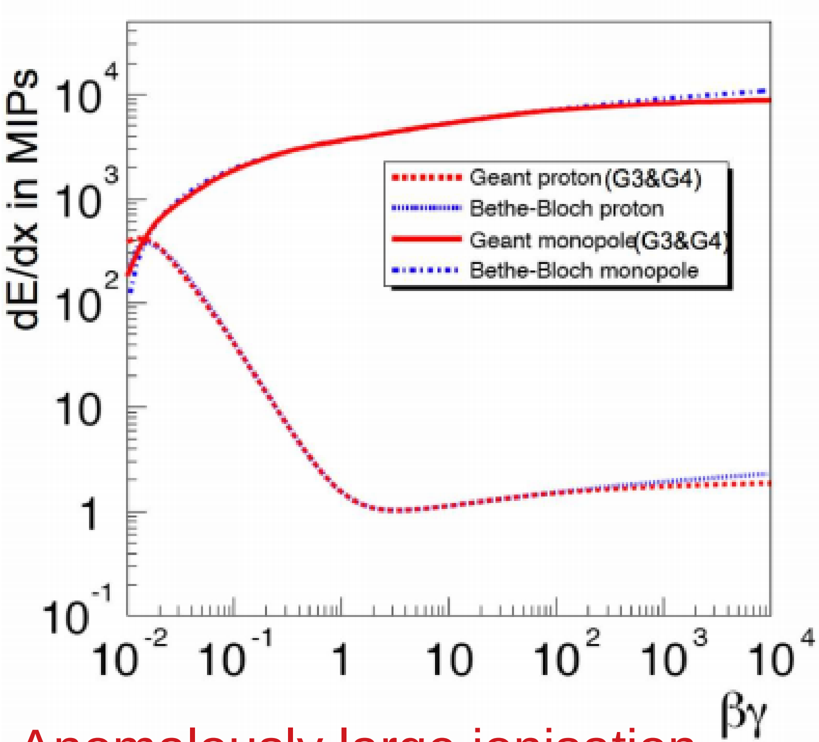
l.millward@qmul.ac.uk

BEYOND ~~Standard Model~~ Ionisation Behavior



Courtesy INF Bologna

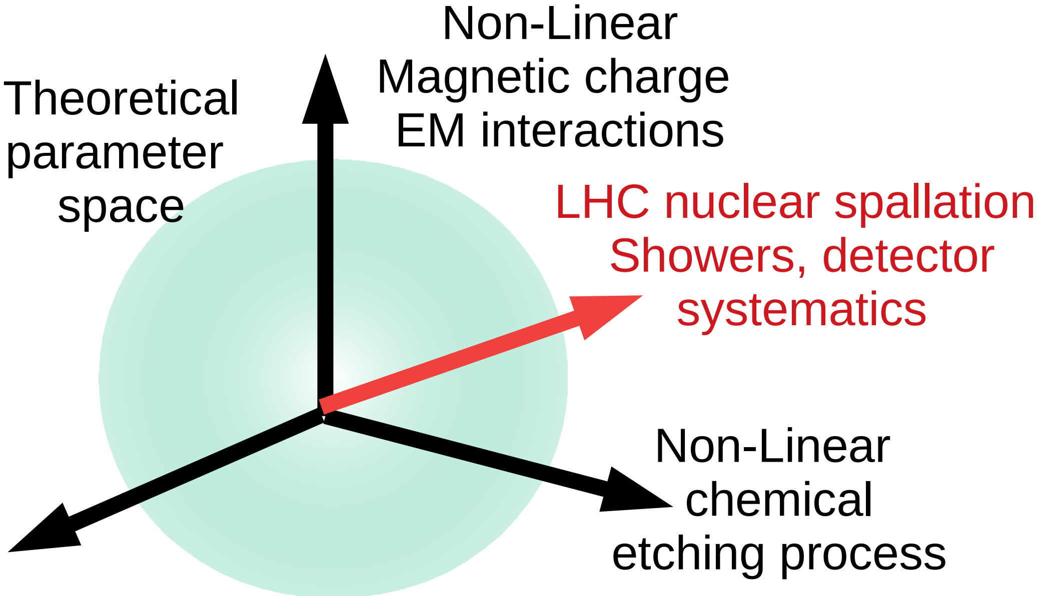
1. Initial High energy causes minimal ionisation. Doesn't show up as etch pit
2. Particle loses energy, lower velocity, efficient 'electronic' ionisation. 'Ranging in'
3. Reaches peak energy loss
   larger etch-pits form at point of entry and exit
4. Energy loss, 'electronic' ionisation ceases, etch-pit formation stops. 'Ranging out'

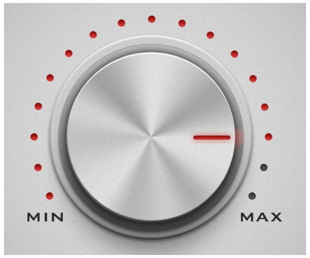


Anomalously large ionisation appears in all layers
Approx no β dependance
~ TeV Energy Momentum
Primary vertex origin
Direct search
No SM background

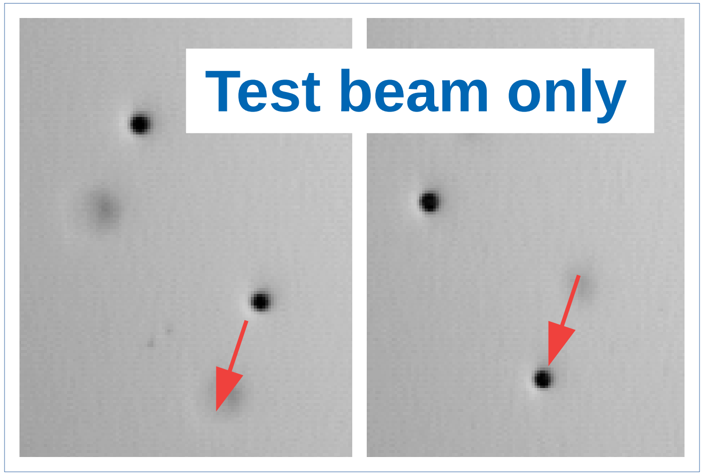
#1: Training / Modelling

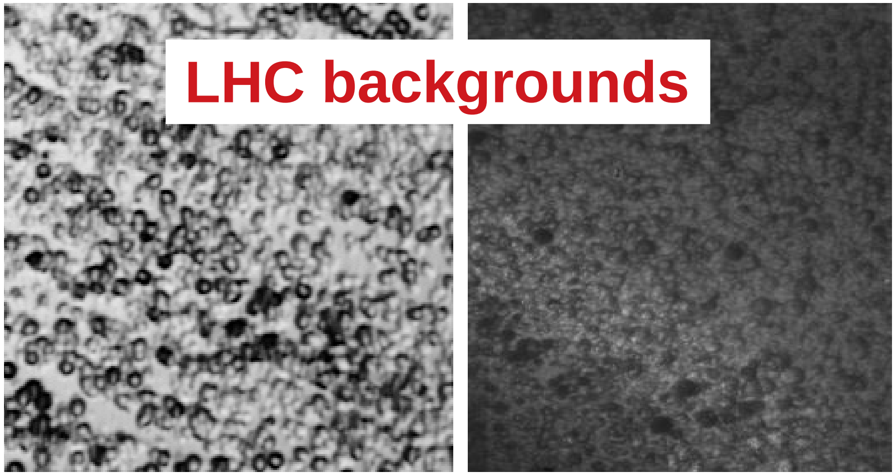
l.millward@qmul.ac.uk





- Large variability, huge uncertainties, many parameters. First principles modelling / Monte-Carlo impractical
- No 'real' magnetic monopole examples to train from
- Can simulate HIP signal in given foil layer with calibrated heavy ion beam
- Different ions for different parts of possible energy spectrum
- Realistic signal examples require presence of real background





l.millward@qmul.ac.uk

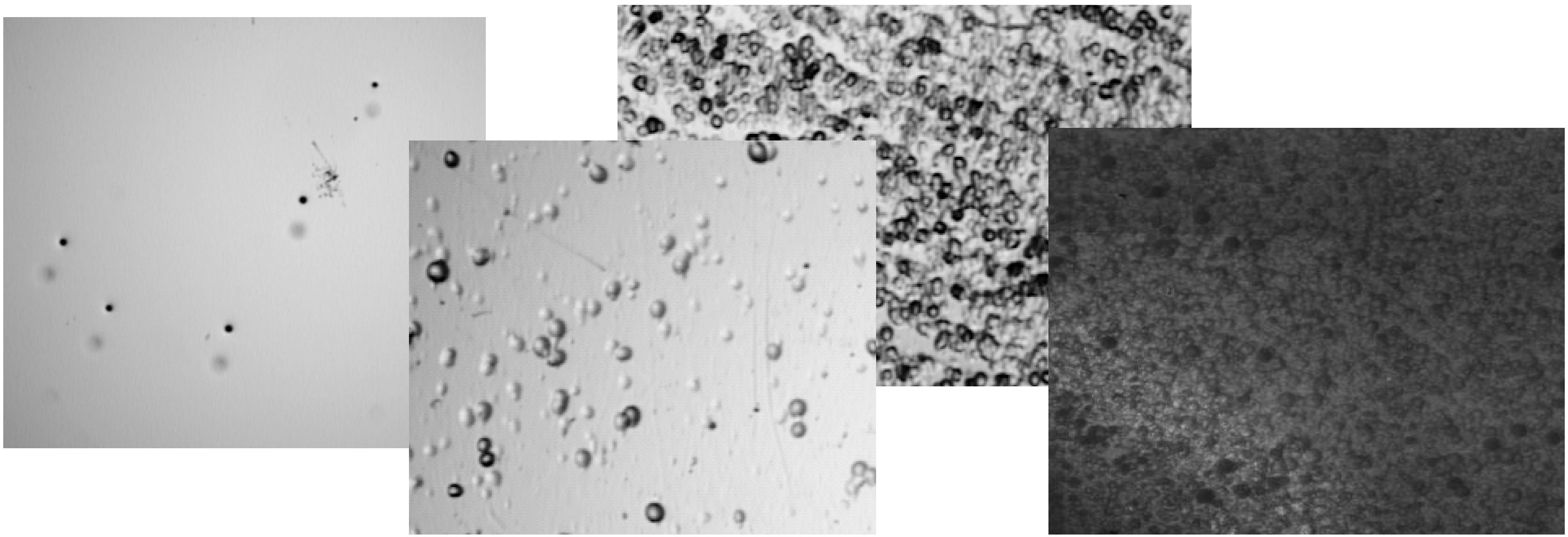
#2: Background density

CR39, Heavy ion test beam

Makrofol, heavy ion test beam
+ 8 months LHC background

2yrs LHC background
pile-up

LHC Exposure

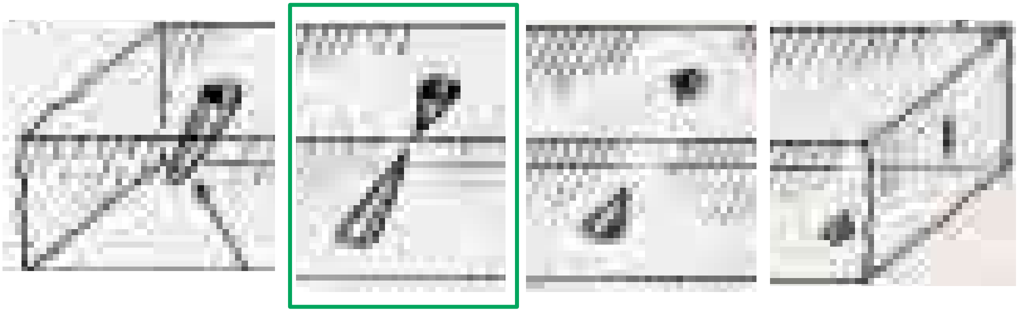


- Problem changes as density increases,
- Images represent ~mm^2
  Millions of etch-pits in each cm^2
- O(100) m^2 macroscopic foil area
  Trillions of etch-pits total

- Foil structure altered by γ – rays changes detector response
- Etch-pit clusters merge under etching
- Foil thickness fluctuates

l.millward@qmul.ac.uk

#3: Accurate identification

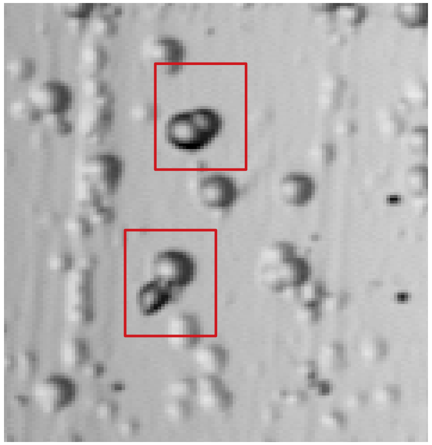


Want to find peak ionisation events

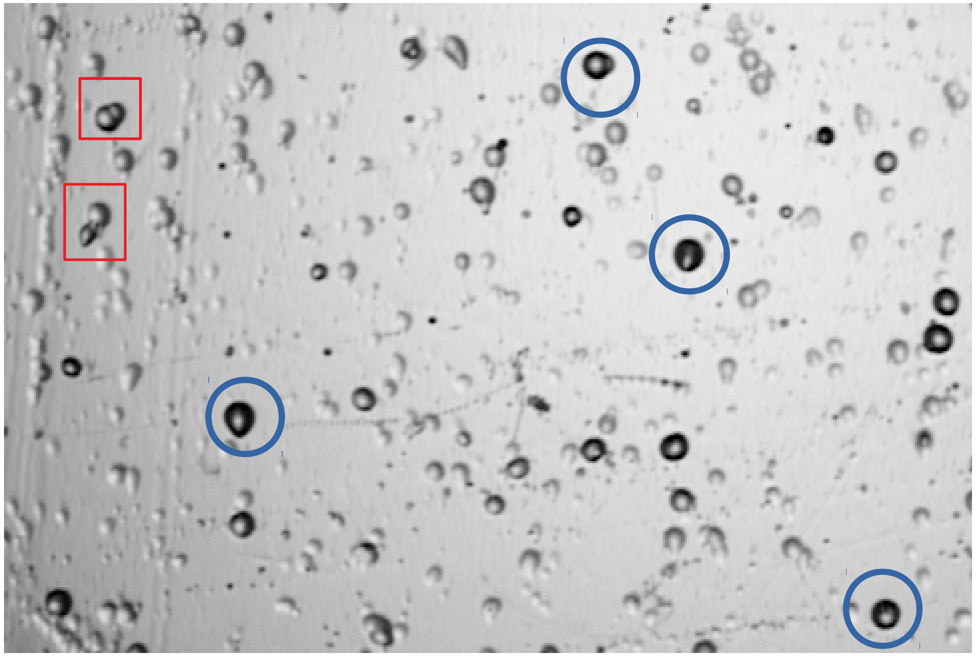
Need robust ~**99%** signal efficiency and ~**99%** background rejection

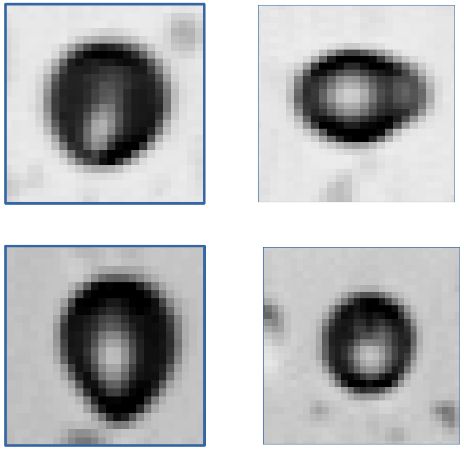
- LHC particle flux; all different SM ionisation behaviour happening
- Pits start to cluster and overlap
- Accurate ID requires detailed 3D inspection. Incompatible with rapid automated scanning
- Supervised learning requires accurate labelling. Have to locate

Example



Entry Exit pair?
Background cluster?





Strong Visual Symmetry between different physics objects / backgrounds

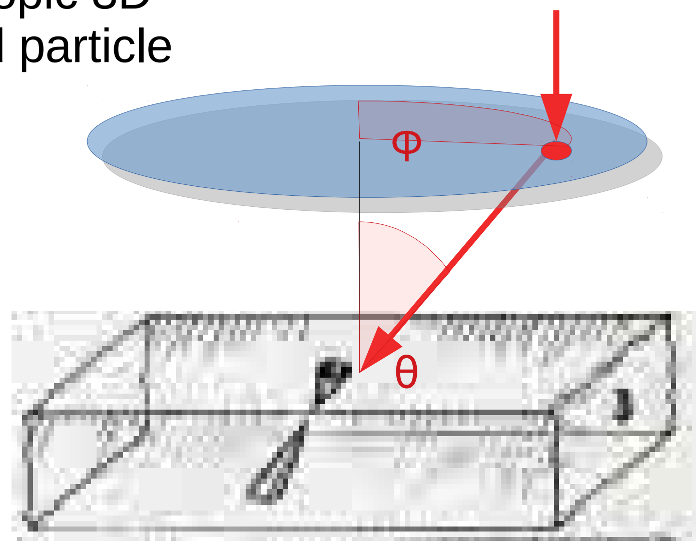
3D Dark-field imaging

l.millward@qmul.ac.uk

- Want to probe microscopic 3D structure to understand particle event interpretation

VS

- Want to rapidly scan macroscopic area with minimal motion and large field of view



- CAN parametrise illumination angle
- LED grid, passing through Fresnell lens. Allows control of θ , φ
- Retain microscopic focal plain alignment over macroscopic area

---

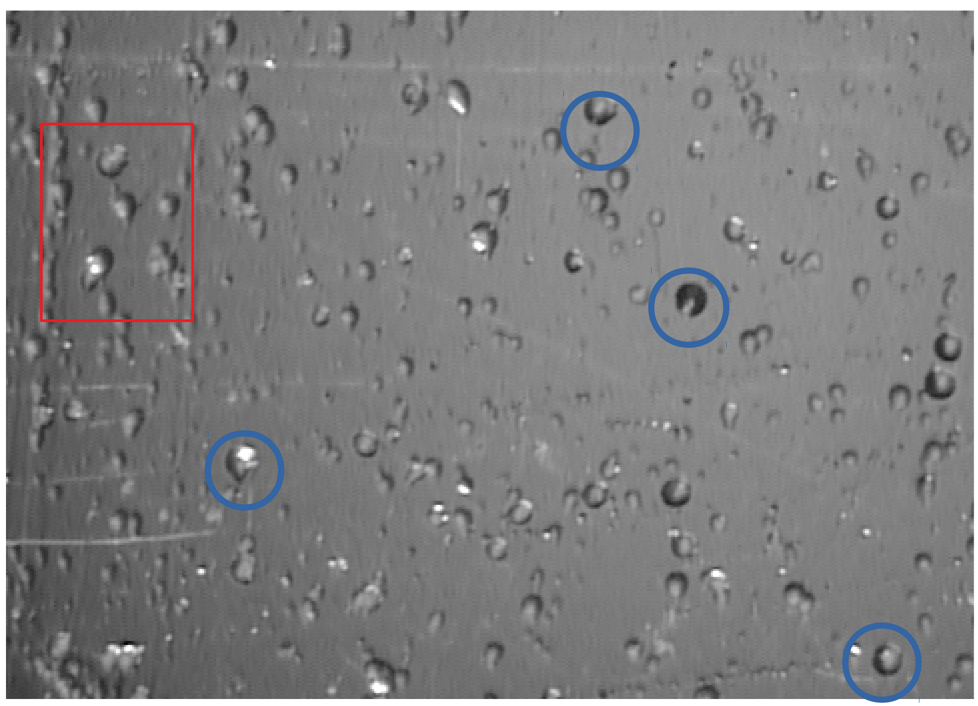
Example

X, Y, Phi becomes 3d data-space

Animation
In-phase rotation common origin

Opposite phase possible entry exit

ML / CNN sees all angles at once



Entry exit pairs look different to overlapping bkg

Resolve different 3D structures

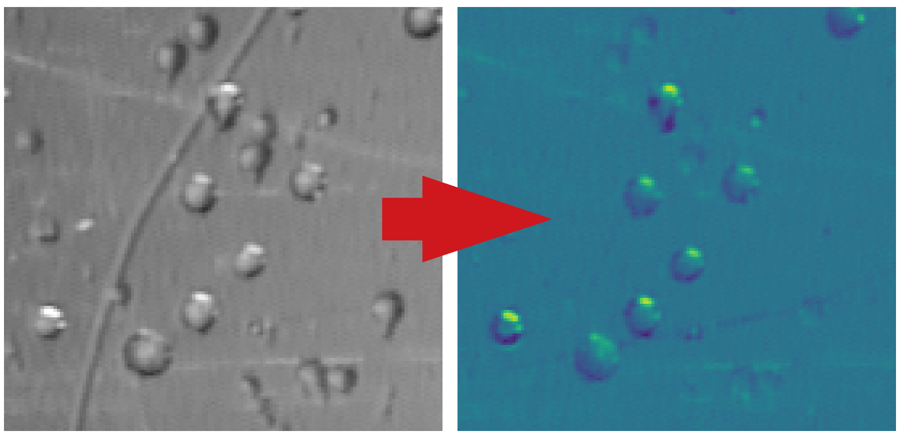
Spot anomalies eg; connected entry exit or heavy ionisations that etch all the way through

ML – Training / Analysis

IOP HEPP APP 08/04/19

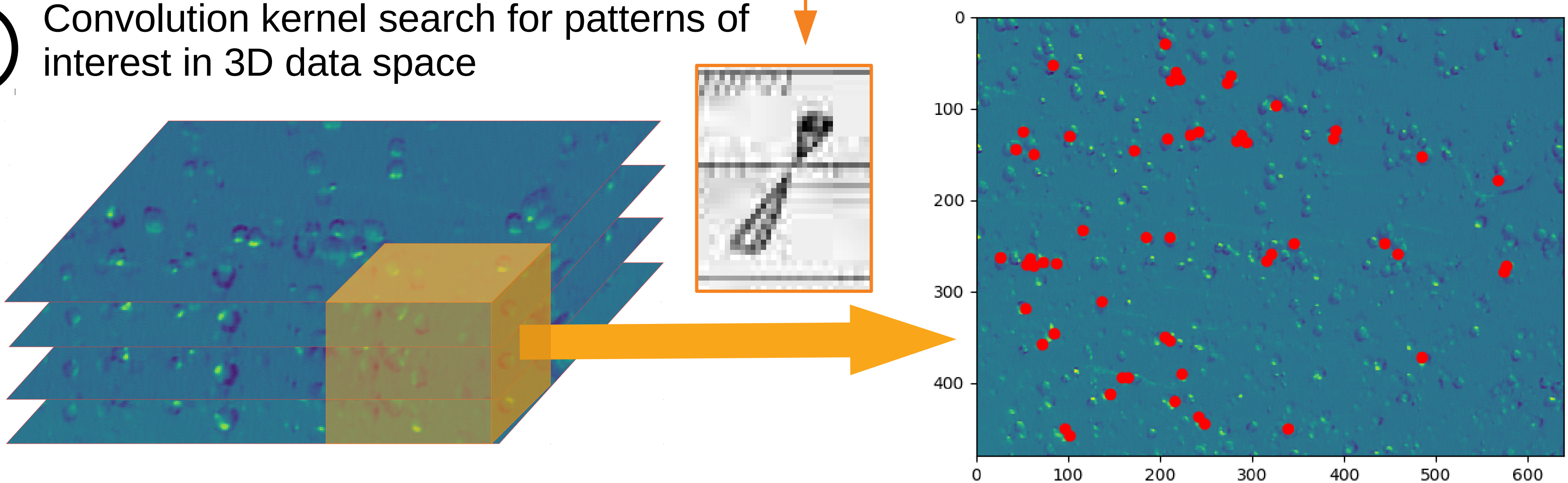
l.millward@qmul.ac.uk

1 “Normalisation” - Redefine relative to local zero, ‘clean’ up low ionisation pits / de-clutter. Remove systematic imaging biases + non-etch pit visual backgrounds



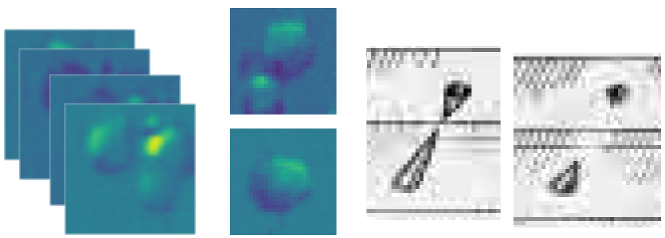
2 Convolution kernel search for patterns of interest in 3D data space

3 Pre-select etch-pits, reject trivial backgrounds, reduce labelling, storage, requirement ~ 1000



4 Build supervised ML dataset from preselection. Train sub-classifiers, eg, entry exit asymmetry ~ dE/dx

can replace initial search with learnt models

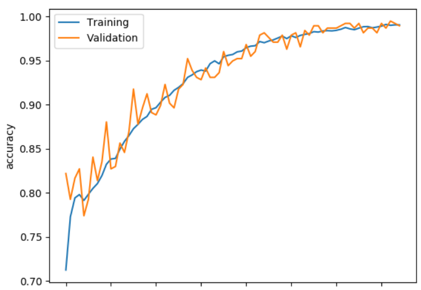


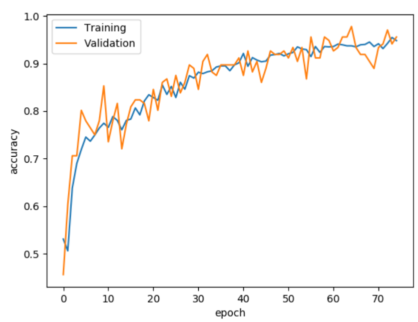
ML – Ensemble + inference

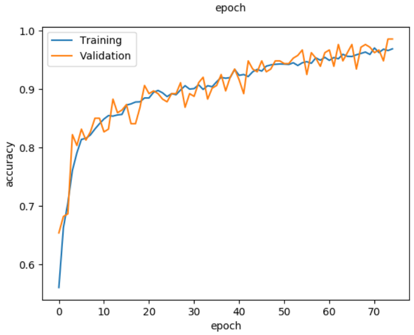
l.millward@qmul.ac.uk

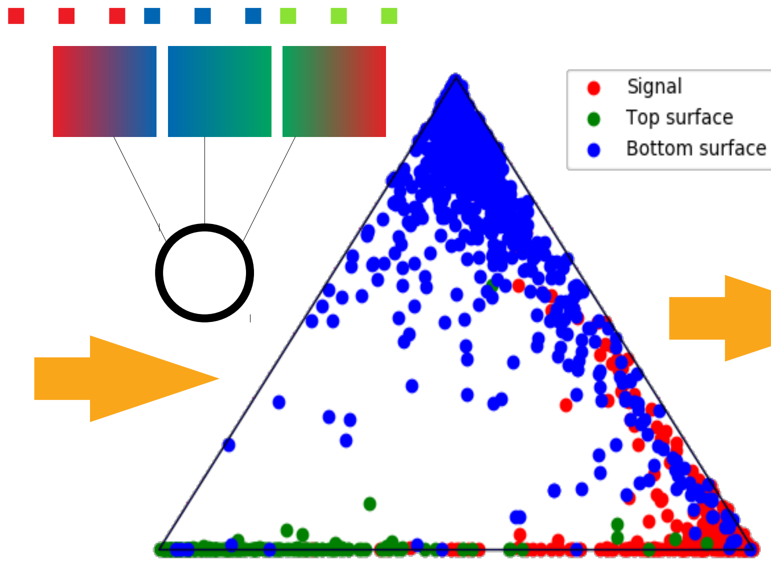
- Train specialist experts to handle specific sub-classifications eg, B vs C

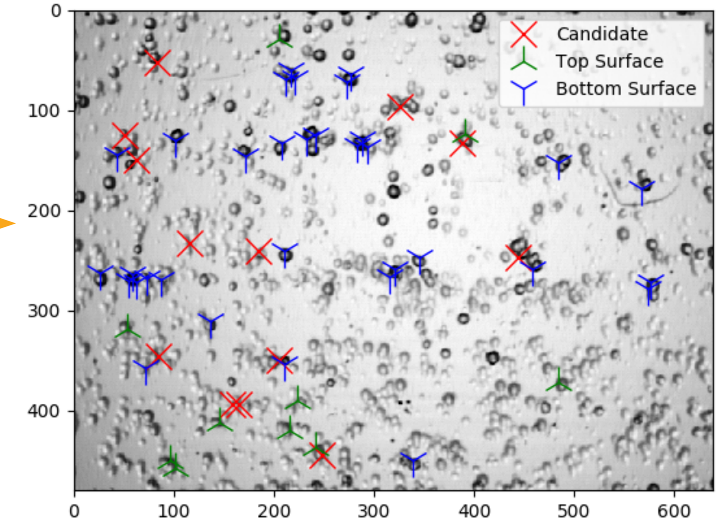
Eg, top / bottom surface biased ionisation indicating SM range in/out











- Combine in Ensemble
- Hetrogenous vs Homogenus (classifiers trained on different tasks with different data)
- Geometric combination $C' = C_1 * C_2$ vs arithmetic $C' = aC_1 + bC_2$

Can use in inference to label new areas of foil,

Can extend further and use a dense neural network to form the ensemble