# A Brief Discussion on the Performance of the MoEDAL and the LHCf Experiments

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On behalf of
**MoEDAL and LHCf collaborations**

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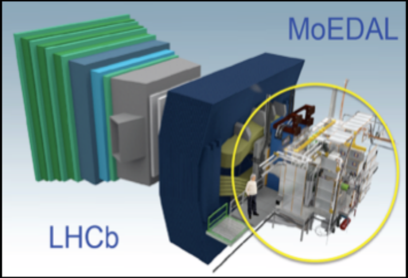
- **The MoEDAL Experiment.**

# The MoEDAL Detector:

## MoEDAL – a Unique Collider Detector

**Permanent Physical record of new physics**



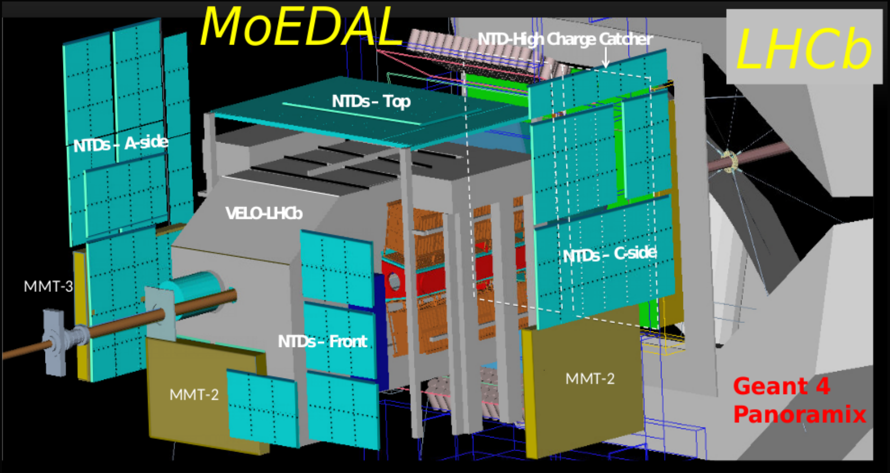

**No Standard Model Physics Backgrnds**

*MoEDAL is largely passive;made up of three detector systems:*

*NUCLEAR TRACK DETECTOR*
*Plastic array (~200 sqm)*
*– Like a Giant Camera*

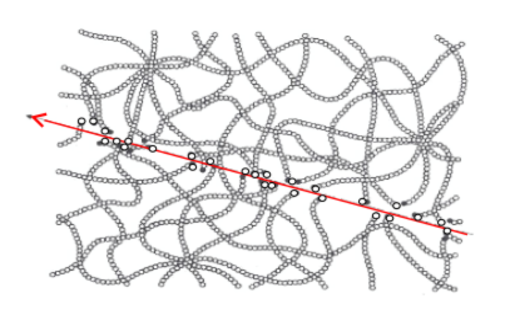
*TRAPPING DETECTOR ARRAY*
*A tonne of Al to trap Highly Ionizing Particles for analysis*

*TIMEPIX Array ,a digital Camera for real time radiation monitoring*




- Acceptance for at least one monopole from monopole pair production to hit NTDs is around 70%.

# Details about the NTDs: I



**Insulating solid materials - plastics CR39, Makrofol, Lexan**

- The passage of a charged particle through NTDs breaks the chemical bonds inside the NTDs.
- Creates invisible 'latent tracks'.
- These tracks ($\sim$ 10 nm diameter) are made visible to an optical microscope through an appropriate chemical etching.
- Etch pit size becomes 10-30 $\mu$m.

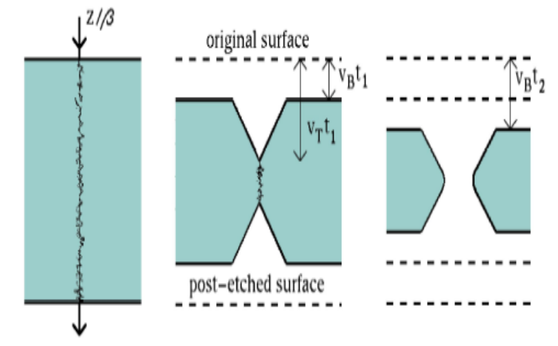
## CR39® (PPG Industries Inc.) ($C_{12}H_{18}O_7$)

- Density 1.32g/cm$^3$ (in crude form, used in sunglass manufacturing).
- Detection threshold $Z/\beta \sim 5$, which is very low.
- Maximum tolerable number of detected etch pits per cm$^2$ is $\sim 10^8$ (2 Mrad radiation).
- Stable sensitivity over the years.
- Needs dosimeter grade plastic - free of contamination.

## Makrofol (Bayer) and Lexan (multiple producers)

- Density of Makrofol - 1.29 g/cm$^3$, density of Lexan - 1.20 g/cm$^3$.
- High quality surface and light transmission.
- Maximum tolerable number of detected etch pits per cm$^2$ is $\sim 10^8$ (200 Mrad radiation).

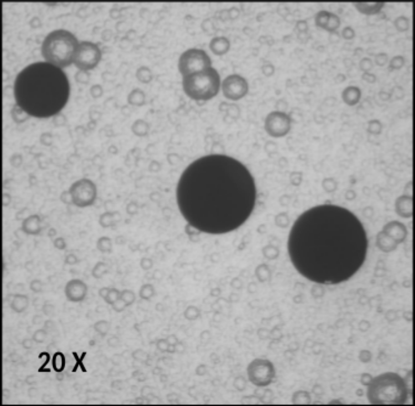
# Chemical Etching of the NTDs: Making of the Visible Pits




| S.N | Etching Conditions | $v_B$ (μm/h) |
|---|---|---|
| 1 | 6N NaOH, 50 °C | $0.24 \pm 0.01$ |
| 2 | 6N KOH + Ethyl alcohol, 50 °C 80 : 20 % by volume | $2.97 \pm 0.05$ |
| 3. | 6N KOH + Ethyl alcohol, 50 °C 50 : 50 % by volume | $5.87 \pm 0.05$ |
| 4. | 6N KOH+ Ethyl alcohol, 60 °C 80 : 20 % by volume | $13.0 \pm 1$ |
| 5. | 6N KOH+ Ethyl alcohol, 65 °C 80 : 20 % by volume | $23.0 \pm 1$ |

- Solutions used for etching: 6N/8N NaOH, 6N/8N KOH etc.
  - The bulk etch rate ($v_B$) increases with the increase of the etching temperature and the percentage of the alcohol mixture in the etchant, as shown in the table above.
  - The presence of the alcohol polishes the surface and improves the sharpness of the post-etched surface of the detector.

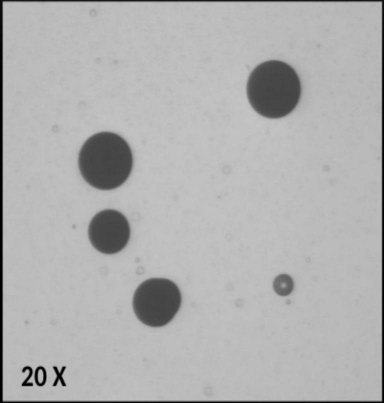
**Old**




6N NaOH, 70 °C, 30 hr

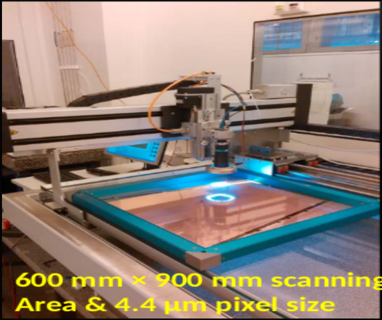
Z/β (min.) ~ 5

**New**



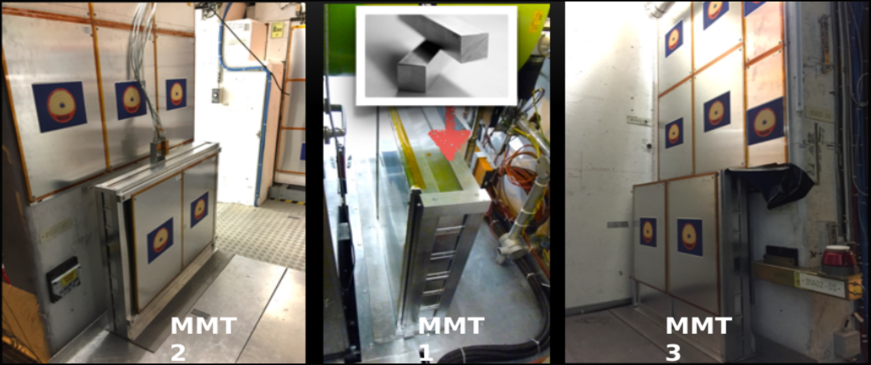

6N NaOH + 1% alcohol 70 °C, 40 hr

Z/β (min.) ~ 7

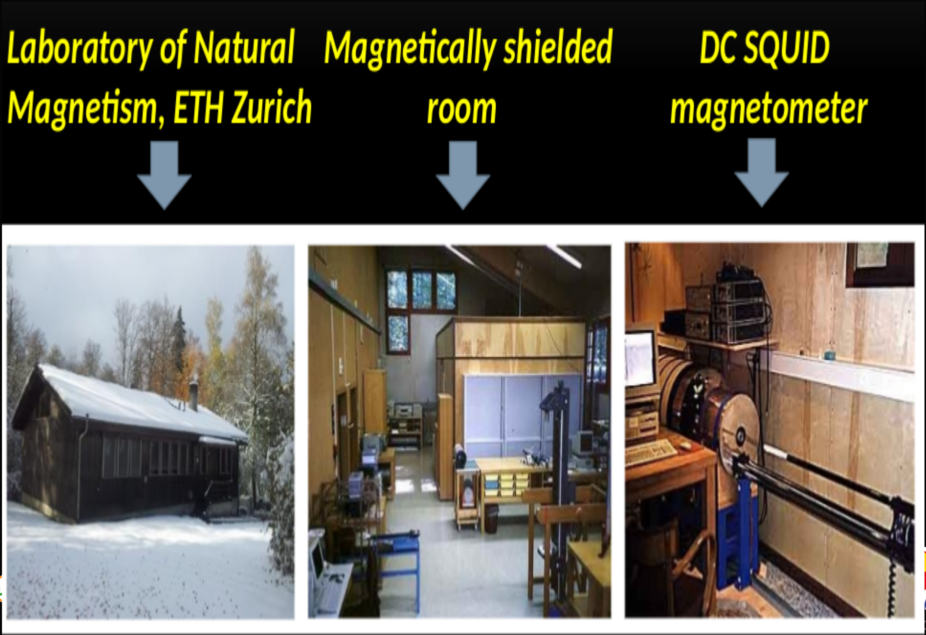

- Exposed NTDs will be scanned through automated high rate CCD based scanning microscope developed by the groups at Bologna, Muenster and Helsinki (etch-pit size $\sim 30\ \mu$m)
  - Specialized image enhancement/pattern recognition software.
  - Helsinki scanner can scan 100 cm$^2$ in 20 minutes.

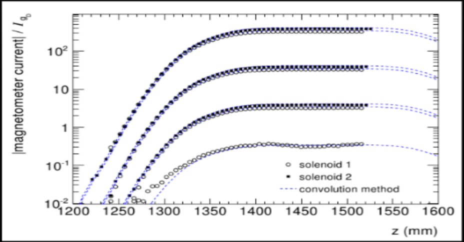
# The Trapping Detector:



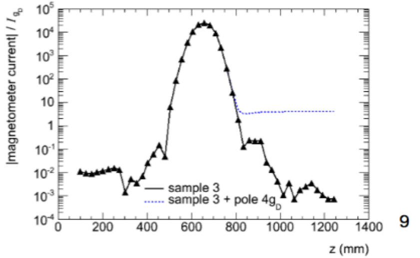

- The trapping detectors (MMT) are deployed to slow down, stop and trap highly ionizing particles for later study.
- They are composed of an array of 672 square aluminium rods with dimension $19 \times 2.5 \times 2.5$ $cm^3$.
- The total mass of 222 kg is kept in 14 boxes. These boxes are placed $\sim 1.62$ m from the interaction point.

# The SQUID Magnetometer:



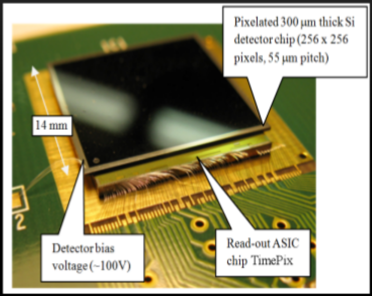



EPJC 72, 2212 (2012), arXiv:1206.6793

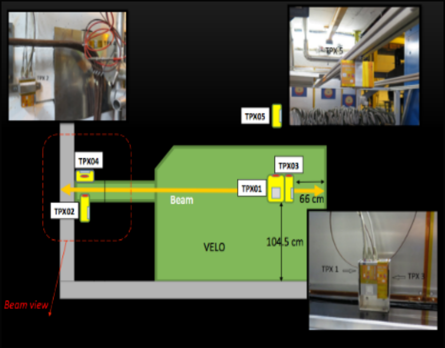



| Calibration coil | 1 | 2 |
|---|---|---|
| Pseudopole strength/current ($g_D/\mu A$) | 32.4 | 41.4 |
| Coil length $l$ (mm) | 250 | 250 |
| Number of turns $n$ | 2750 | 7500 |
| Wire diameter (mm) | 0.18 | 0.1 |
| Number of wire layers | 2 | 3 |
| Mean coil area $S$ (mm$^2$) | 9.7 | 4.5 |
| Uncertainty in area | 6% | 10% |

- A more direct approach to inferring the magnetometer response to a monopole is to use a long solenoid since the magnetic field from one end of a “semi-infinite” solenoid acts just like a monopole.




TimePix pixel device




- TimePix devices are used to measure the radiation and the spallation product background.
  - Instrumented with an preamplifier, a discriminator with threshold adjustment, synchronization logic and a 14-bit counter.
  - $256 \times 256$ square pixels with a pitch of 55 $\mu$m.
  - Essentially electronic bubble chambers.

## NTDs

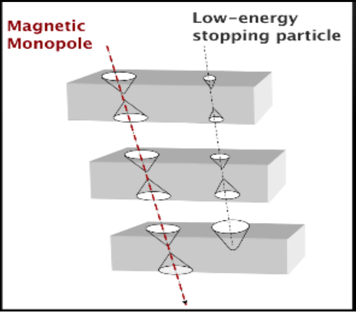
- Tracking resolution: 10 mm/pit (∼10 pits).
- Pointing resolution to the interaction point: ∼ 1 cm.
- Charge resolution: 0.1e.

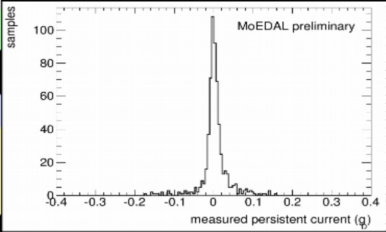
## Trapping Detector:

- Magnetic charge resolution: $< 0.1\ g_D$.

## TimePix chips

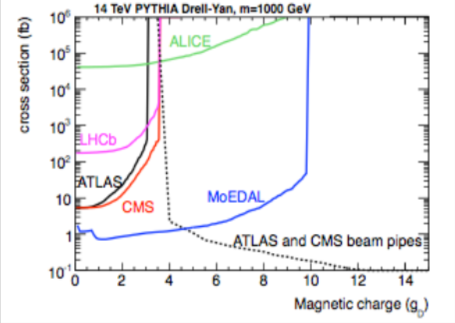
- Pixel size 55× 55 mm$^2$.
- Silicon thickness: 300 $\mu$m.

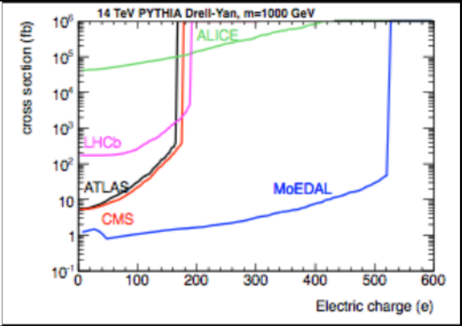


# MoEDAL's sensitivity:

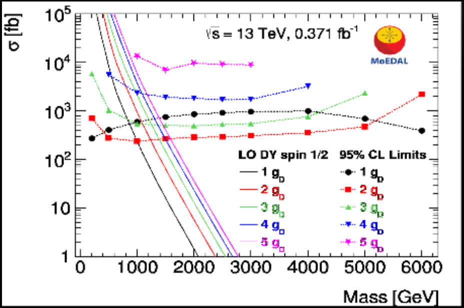
| detector | energy threshold | angular coverage | luminosity | robust against timing | robust efficiency |
|---|---|---|---|---|---|
| ATLAS | medium | central | high | no | no |
| CMS | relatively low | central | high | no | no |
| ALICE | very low | very central | low | yes | no |
| LHCb | medium | forward | medium | no | no |
| MoEDAL | low ✔ | full ✔ | medium ✔ | yes ✔ | yes ✔ |

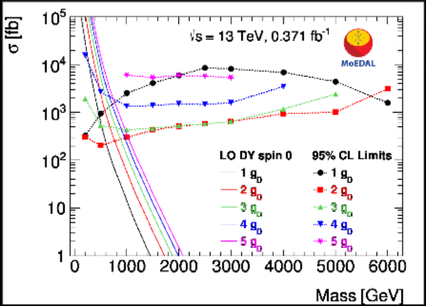



- Cross-section limits for magnetic (left) and electric charge (right) [arXiv:1112.2999v2 [hep-ph]].
- MoEDAL compliments the physics reach of the existing LHC experiments.

# Latest MoEDAL Monopole Search Result at $\sqrt{s} = 13$ teV (PRL 118 061811 (2017)):

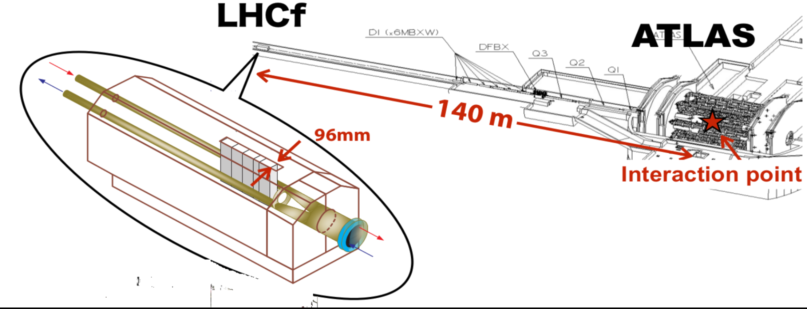


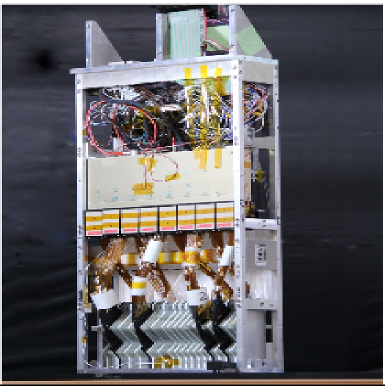

| mass limits [GeV] | $1g_D$ | $2g_D$ | $3g_D$ | $4g_D$ |
|---|---|---|---|---|
| MoEDAL 13 TeV (this result) | | | | |
| DY spin-1/2 | 890 | 1250 | 1260 | 1100 |
| DY spin-0 | 460 | 760 | 800 | 650 |
| MoEDAL 8 TeV | | | | |
| DY spin-1/2 | 700 | 920 | 840 | – |
| DY spin-0 | 420 | 600 | 560 | – |
| ATLAS 8 TeV | | | | |
| DY spin-1/2 | 1340 | – | – | – |
| DY spin-0 | 1050 | – | – | – |

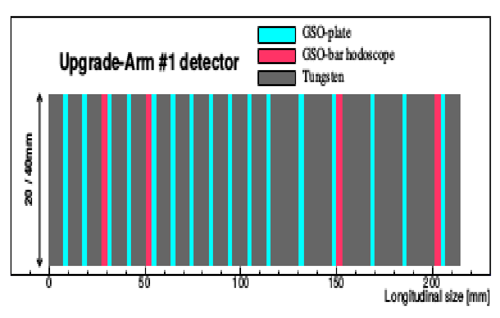
- First monopole constraints at LHC (Run2) p-p collision
  - Probe TeV masses up to 5 $g_D$ for the first time at the LHC.
  - Exclude monopole with $|g| = 4$ $g_D$ for the first time at the LHC.

- **The LHCf Experiment.**



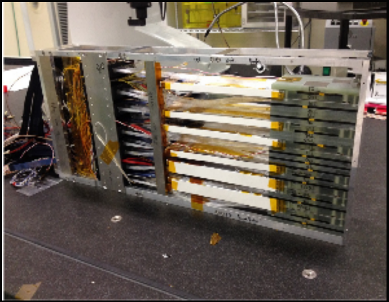

- Two independent detectors (Arm1 and Arm2) are placed ±140 m apart from the Interaction point 1 (both sides of the ATLAS detector).
- Covers the region $\eta > 8.4$.
- Measures neutral particles: $\gamma$, neutron and $\pi^0$.
- Charged particles are taken out by the dipole magnets.

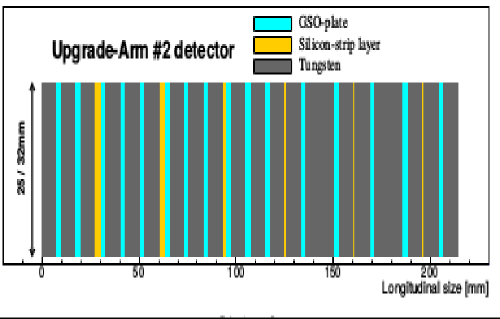





## Calorimeter Tower

- Each tower is made of 16 sampling layers and four position sensitive layers interleaved in the tungsten absorbers.
- $Gd_2SiO_4$ scintillator (GSO) used, one of the best inorganic scintillators.
- Position sensitive layers for Arm1: the hodoscope layers are made of GSO bars.
- Position sensitive layers for Arm2: the silicon strip sensors.






### Calorimeter Tower (continued)

- In the first half, the width of tungsten absorber is 2 radiation length ($X_0$) - used mainly for electromagnetic (EM) shower measurement.
- In the second half, the width of tungsten absorber is $4X_0$ - used mainly for the hadronic shower.
- Total length of the calorimeter tower: $44X_0$ - the leakage from the EM showers is negiligible.

### Expected performance:

- Energy resolution ($> 100$ GeV):
  - $< 5\%$ for photons.
  - 40% for neutrons.
- Position resolution:
  - $< 200$ $\mu$m for photons.
  - a few mm for neutrons.

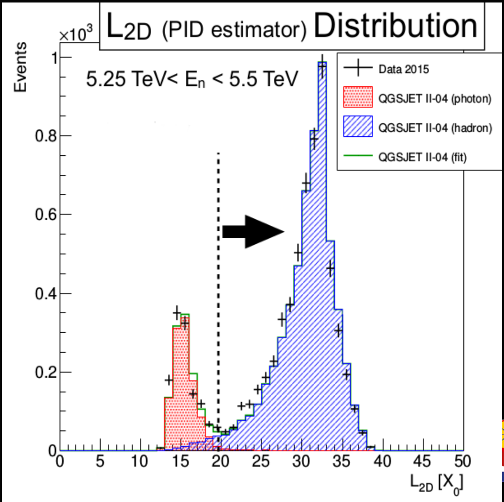
- Motivation:
  - Measurement of inelasticity: $k_{in} = 1 - E_{lead}/E_{beam}$.
  - Large discrepancies between data and model prediction was found in p-p collision at $\sqrt{s} = 7$ TeV.

## Data used:

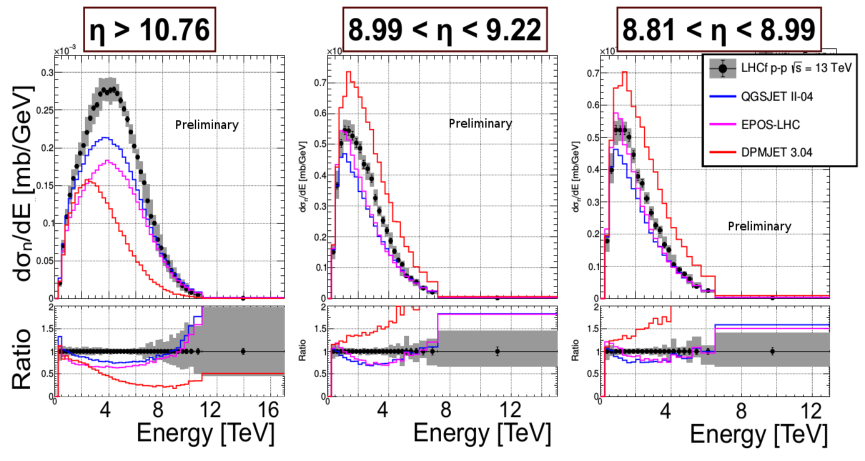
- June 2015, 3 hour data.
- Low pile up with $\mu \sim 0.01$.

## Analysis

- Identification of particles:
  - Electromagentic shower in the shallow layers.
  - Hadronic shower in the deep layers.
- Energy resolution of 40%.

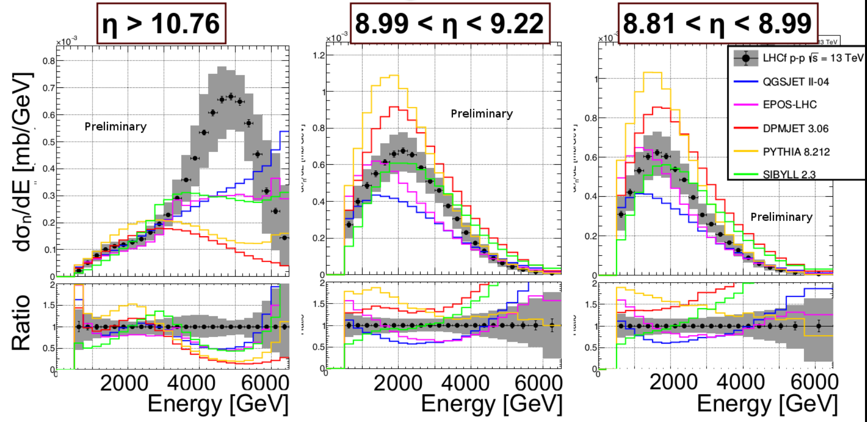


# Neutron, proton-proton collision at $\sqrt{s} = 13$ TeV, Folded Spectra




- No model matches with the experimental data.

# Neutron, proton-proton collision at $\sqrt{s} = 13$ TeV, Unfolded Spectra




**Note:**

- No model matches with the experimental data for $\eta > 10.76$ where neutron production increases in the high energy region.
- EPOS-LHC matches in the $8.99 < \eta < 9.22$ region and SIBYLL 2.3 has best agreement in $8.81 < \eta < 8.99$.

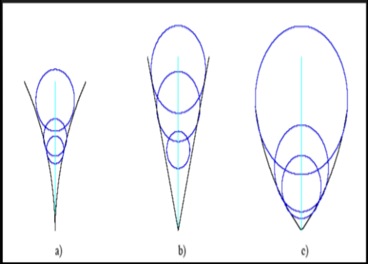
# Summary

- The MoEDAL detector and its present performance have been discussed briefly.
  - Added Very High Charge Catcher (high threshold NTD array, $Z/\beta \sim 50$) in the forward region, expected to considerably enhance the overall geometrical coverage of MoEDAL NTDs.
  - $\sqrt{s} = 13$ TeV, 0.371 fb$^{-1}$ results were published last year.
  - $\sqrt{s} = 13$ TeV, 2.28 fb$^{-1}$ results are submitted to journal (accepted by PLB).
  - Gearing up for the next iteration of data at $\sqrt{s} = 13$ TeV.
- Result from LHCf experiments was also shown.
  - Results shown for neutron cross-section in the proton-proton collision at $\sqrt{s} = 13$ TeV.
  - It has results for forward photon energy spectrum at p-Pb, $\sqrt{s} = 13$ TeV.
  - ATLAS and LHCf jointly work on the measurement of contribution of diffractive processes to the forward particle production.
  - In future:
    - Measurements of forward $\pi^0$ and $\eta$ production cross-section at p-p, $\sqrt{s} = 13$ TeV.
    - Discussion for an operation with p-O collisions at the LHC.

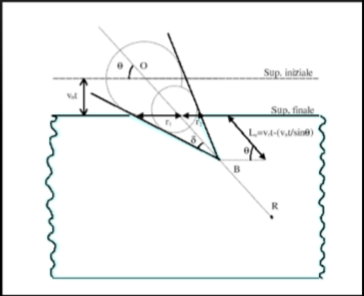

THANK YOU
for your
ATTENTION!

- Bonus slides

# Etch Pits:



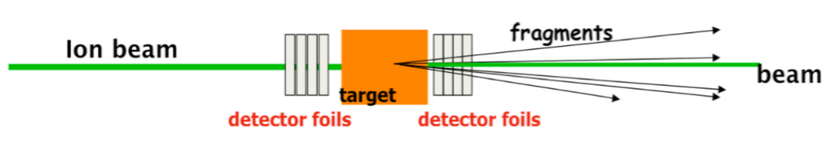

dE/dx Increasing | dE/dx constant | dE/dx decreasing



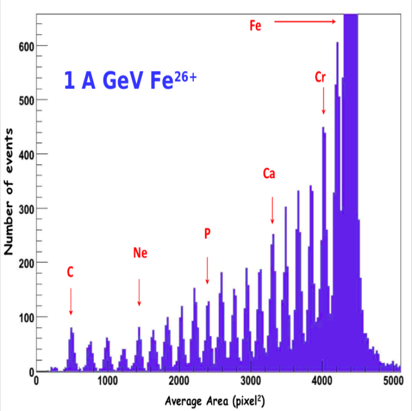

Only possible to reconstruct tracks < ~ 45 deg. to normal

- Identification of the tracks are possible:
  - Decreasing ionization (magnetic monopoles)
  - Increasing ionization (slowing electric charges)

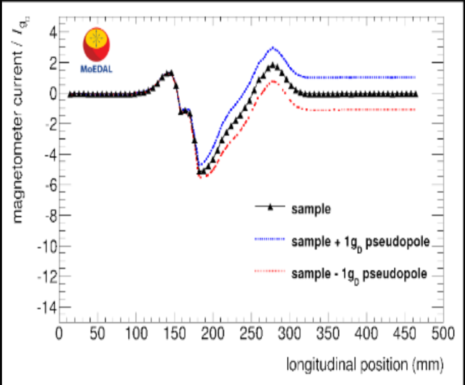
# Calibration of NTDs:

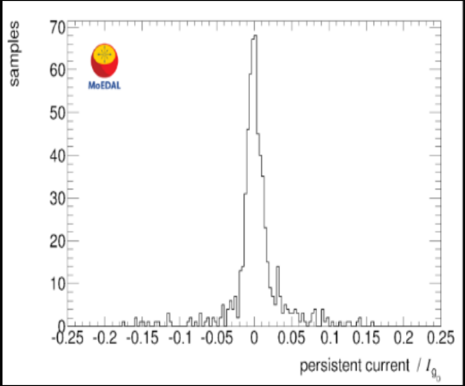



- Uses the NASA Space Radiation facility
  - $Fe^{26}$ - 1.5 GeV/nucleon (max), $Xe^{132}$ - 0.35 GeV/nucleon (max), $O^{16}$ - 1.5 GeV/nucleon (max) and $C^{12}$ - 1.5 GeV/nucleon (max).
- NA61 (CERN)
  - Pb - 30 GeV/nucleon, Ar up to 150 GeV/nucleon
- Used tracking to reconstruct the path of the fragment and the incident particles (3 hits per track).
- If properly calibrated, the charge of the particle can be measured to 0.1e.



# The SQUID Response:



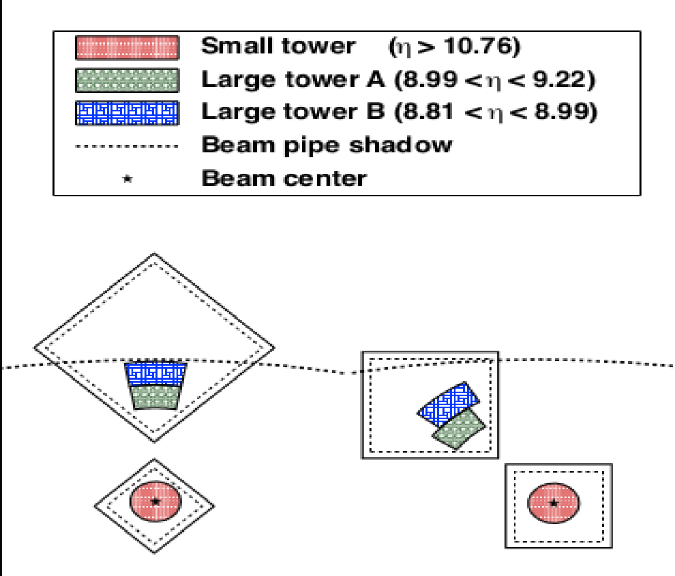




- The monopoles with magnetic charge ($g$) less than 0.1 of the Dirac charge ($g_D$) can be ruled out overwhelming majority of time.
- Used a threshold of 0.25 $g_D$ to rule out any background in the first publication.

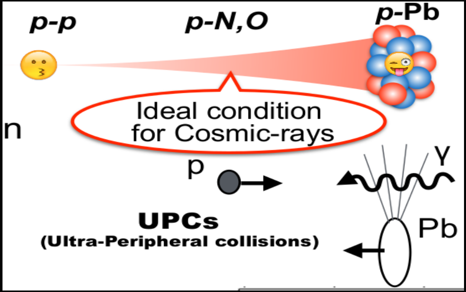
# $L_{2D}$ plot:

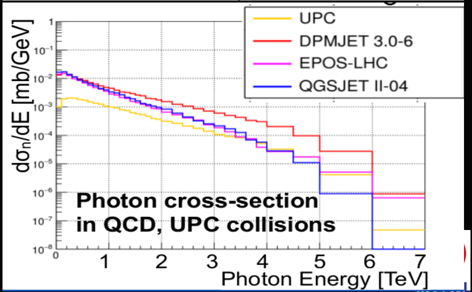
- $L_{2D}$ is PID estimator, which parameterizes a longitudinal-shower shape in the calorimeter.
- They calculated the depths containing 20% or 90% of total dE from the first layer and then $L_{2D}$ is a combination of two depths (so we call "2D").
- The importance of the distribution is not for physics but for our analysis. The good agreement between data and MC shows our good understanding of the detector and it is used also for estimation of efficiency and contamination.

# LHCf acceptance plot:



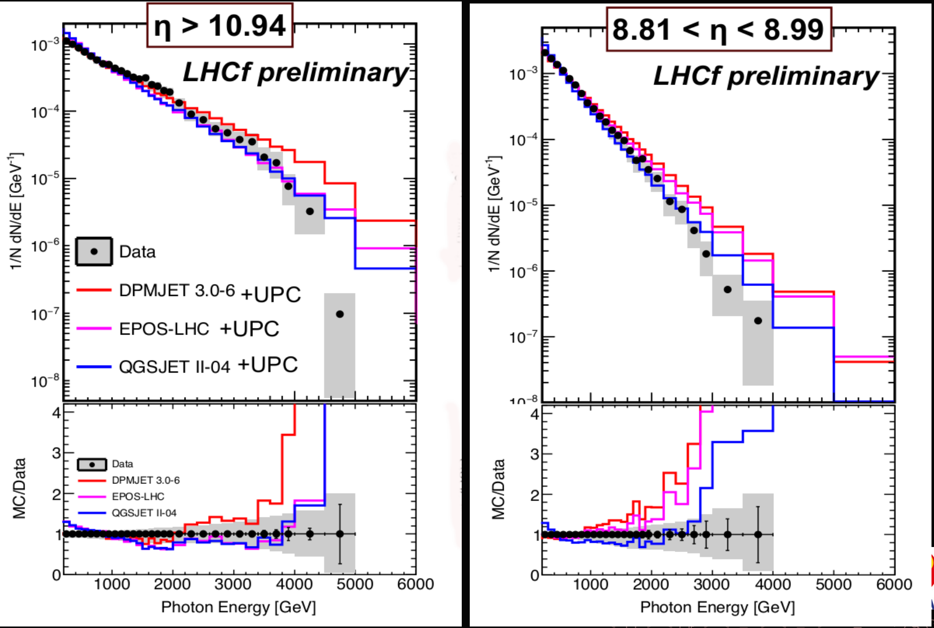
- Motivation
  - Measurement of the nuclear effect, CR interaction (p-N,O) $\neq$ p-p.
  - Large suppression of forward $\pi^0$ production was measured at p-Pb, $\sqrt{s_{NN}} = 5$ TeV.
- Data
  - Data taken in 2 hour in Nov, 2016.
  - Pile up $\mu \sim 0.01$.
- Analysis
  - Used photon analysis at p-p, 13 TeV
  - Contribution of UPC collisions

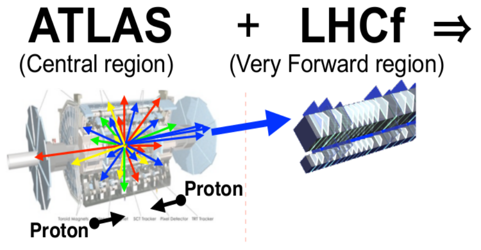



- 20-50% of total photon events estimated by STARLIGHT simulator.

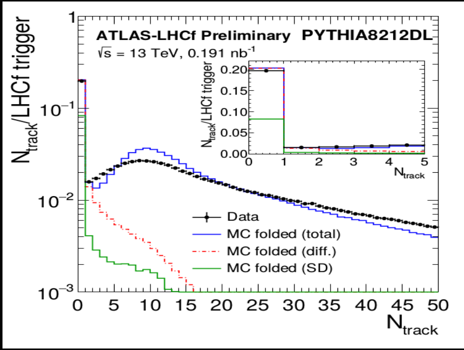
# Photon, p-Pb $\sqrt{s_{NN}} = 8$ TeV: Results





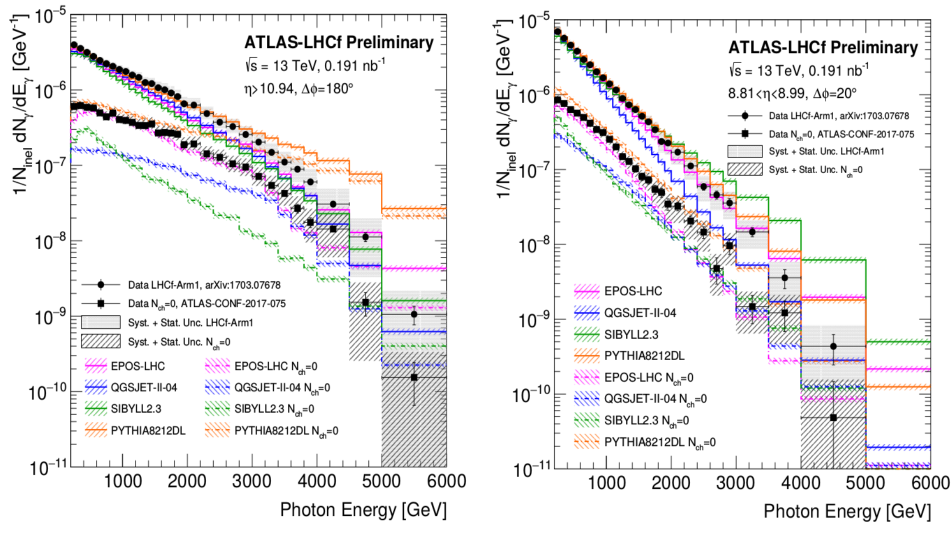

- Powerful tool to understand the processes of forward particle production.
- Provides detailed tests of models.
- Provides some parameters like the low-mass diffractive cross-section.

- Measurement of contribution of diffractive processes to the forward particle production
- Method
  - Event selection by $N_{track} = 0$ where $N_{track}$ is the number of tracks detected by ATLAS inner trakcer ($|\eta| < 2.5$ and $p_T > 100$ MeV).
  - Selecting pure sample of proton dissociation.
  - Sensitive to low mass dissociations with $M_X \lesssim 50$ GeV.

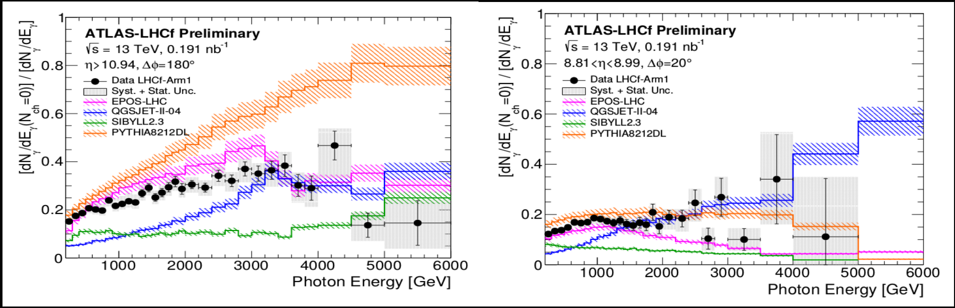


# Measurement of contributions of diffractive processes to forward photon spectra in pp collisions at $\sqrt{s} = 13$ TeV

- Preliminary result has been published in ATLAS-CONF-2017-075.



# Measurement of contributions of diffractive processes to forward photon spectra in pp collisions at $\sqrt{s} = 13$ TeV:Ratio of $N_{ch=0}$/Inclusive




- For $\eta > 10.94$, the ratio of data increased from 0.15 to 0.4 with the increasing of the photon energy up to 4 TeV.
- Prediction of fraction from PYTHIA8212DL is higher at the higher energies.
- SIBYLL2.3 shows small fraction compared to data at $\eta > 10.94$.
- For $8.81 < \eta < 8.99$, the ratio of data is almost constant at 0.17.
- For $8.81 < \eta < 8.99$, EPOS-LHC and PYTHIA8212DL show good agreement with the data.