Latest results from the MoEDAL experiment

Philippe Mermod, University of Geneva
Particle Physics Seminar, Geneva, 8 March 2017

Illustration: Corinne Mucha

Physics beyond the Standard Model

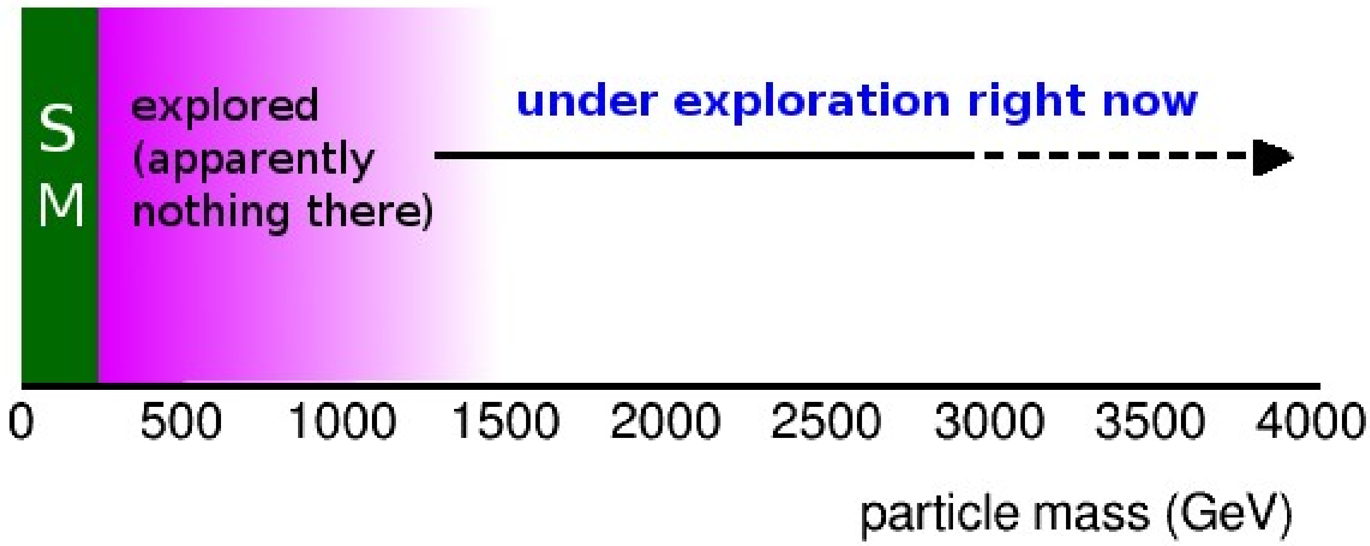
Theoretical hints

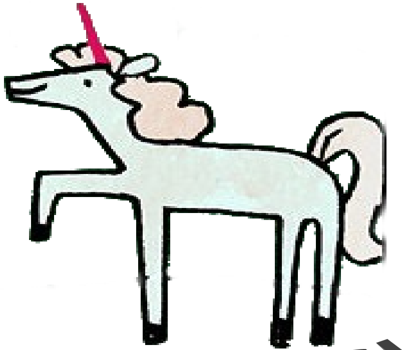
- Many free parameters
- Forces do not unify
- Naturalness
- Gravity

Experimental evidence

- Neutrino masses
- Dark matter
- Matter-antimatter asymmetry

The LHC is a discovery machine





The search for new physics

hidden sectors

Technicolor

SUSY

RS gravitons

large extra dimensions

Right-handed neutrinos

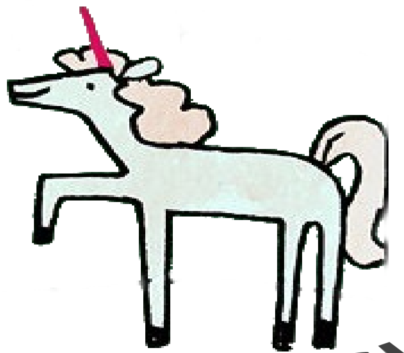
Right-handed neutrinos

heavy gauge bosons

monopoles

Etc.....

The search for new physics



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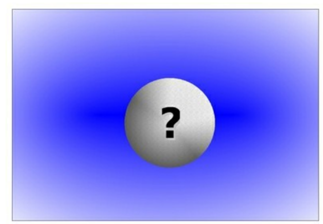

blue sky,
uncharted territory

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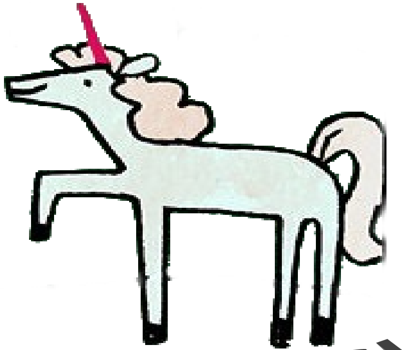

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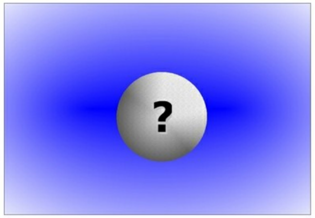

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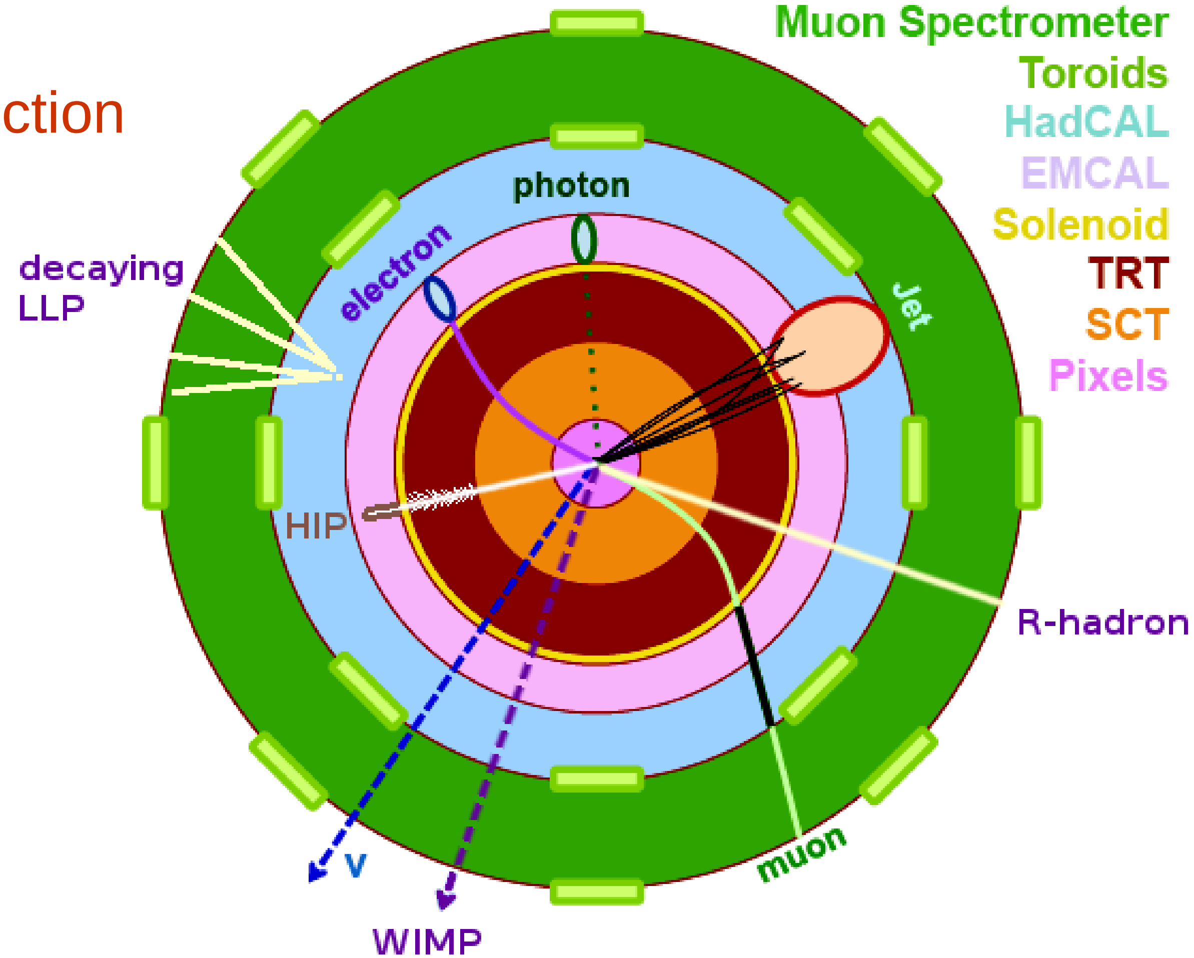
- We have no clue really...
- **What matters is to**
  <u>make sure to cover all possible signatures</u>
  - Photons, leptons, jets, missing energy...
  - Resonances, excesses, deviations, rare decays...
  - New long-lived particles

Long-lived particles in a general-purpose detector

Unconventional signatures, issues with:

- Electronics (eg saturation, timing)
- Triggers
- Object reconstruction
- Acceptance



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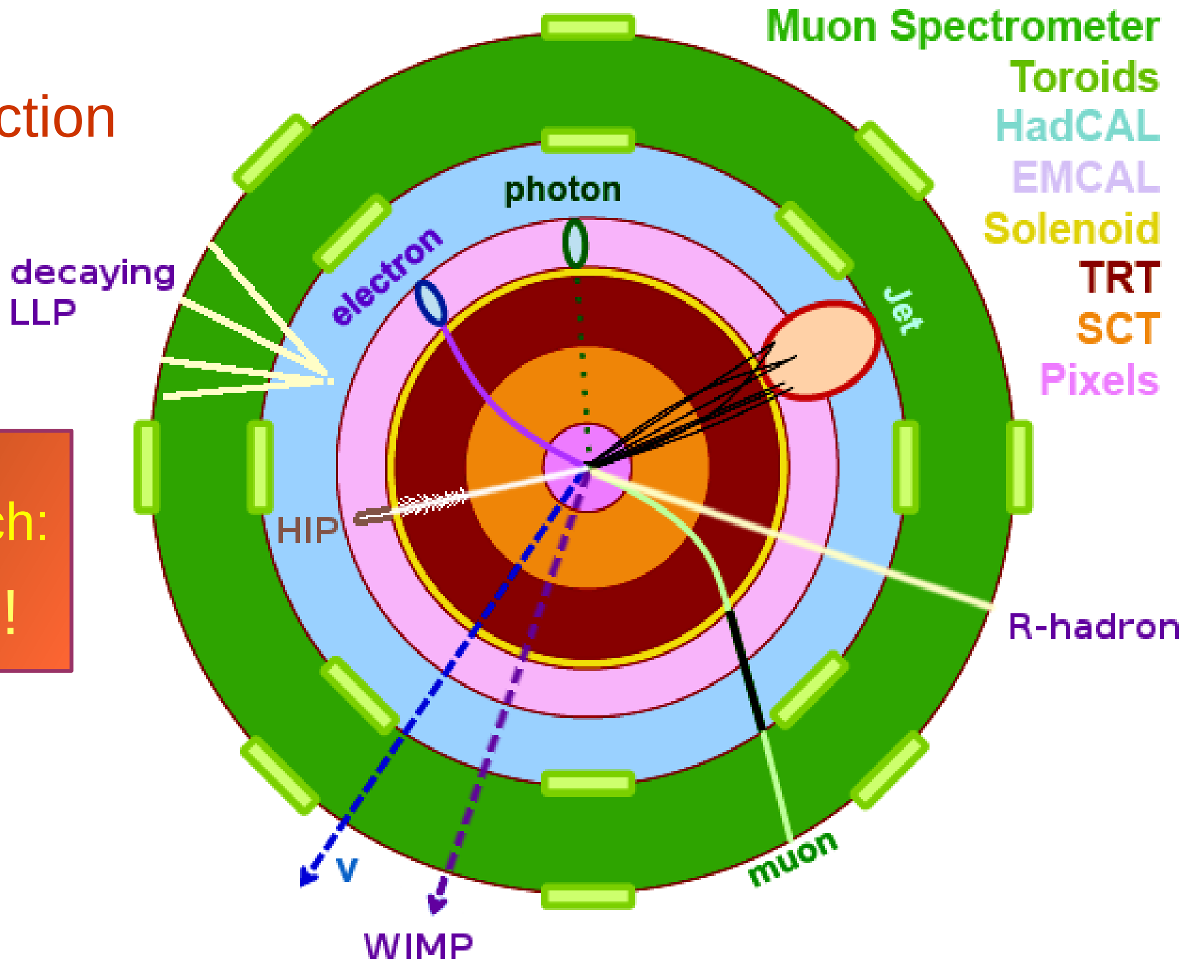

Complementary approach:

Dedicated detectors!

The Monopole & Exotics Detector at the LHC

- Dedicated searches for new long-lived highly-ionising particles (HIPs)

- The 7th LHC experiment, located at IP8
- ~70 members, 25 institutes

http://moedal.web.cern.ch/

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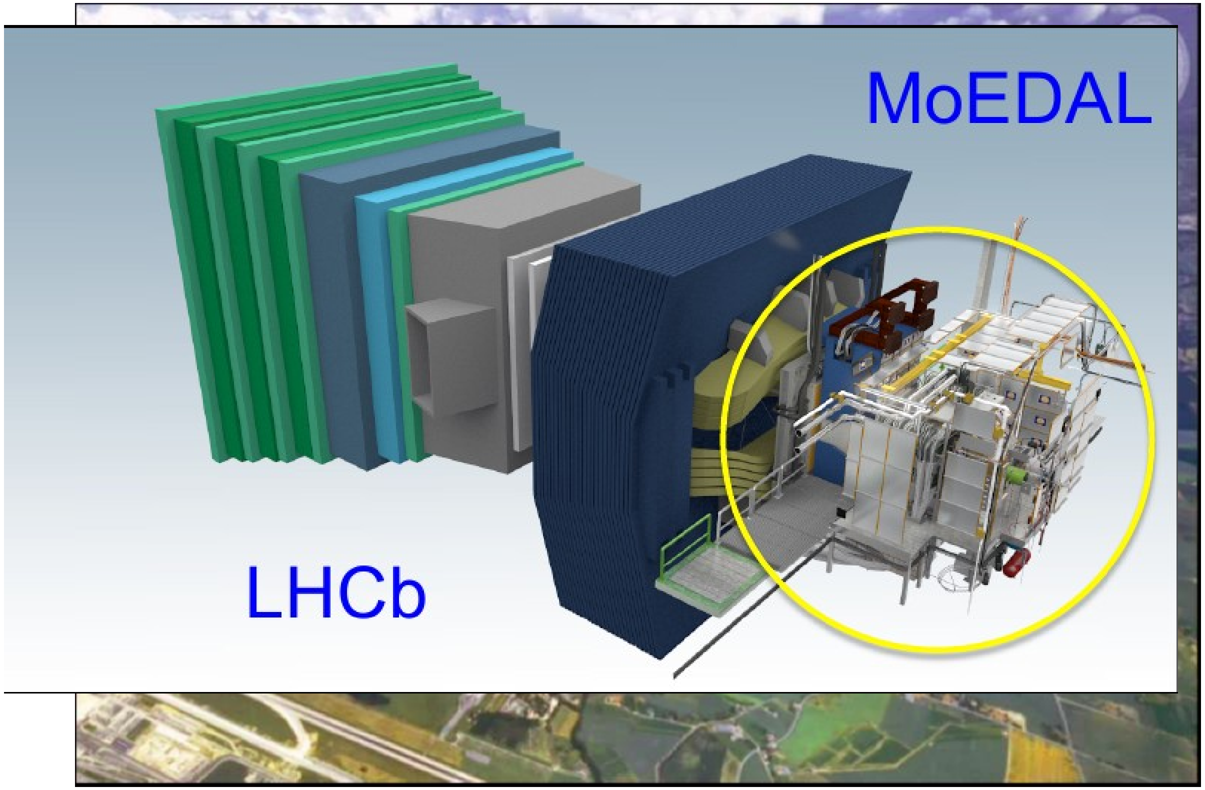

Detector subsystems

- Low-threshold NTD array ($z/\beta > 5$)
- High-charge catcher NTD array ($z/\beta > 50$)
- TimePix radiation background monitor
- Monopole trapping detector

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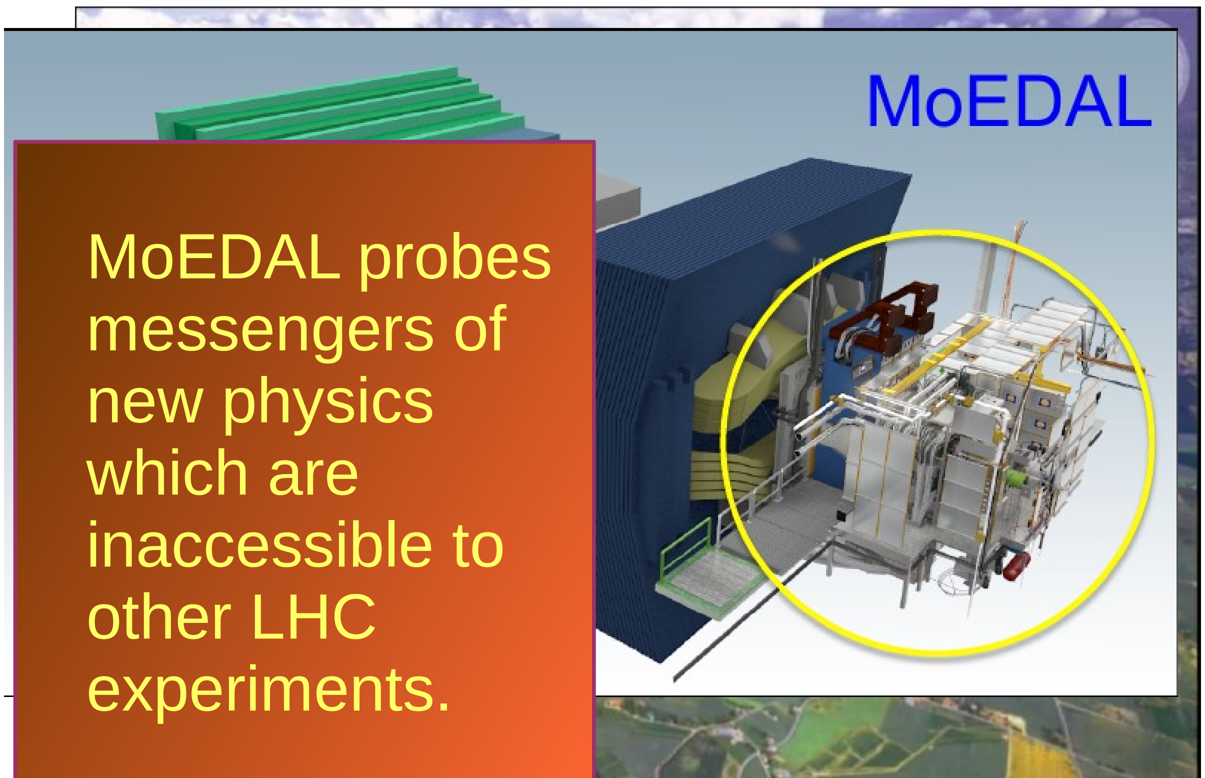

MoEDAL probes messengers of new physics which are inaccessible to other LHC experiments.

Detector subsystems

- Low-threshold NTD array (z/β > 5)
- High-charge catcher NTD array (z/β > 50)
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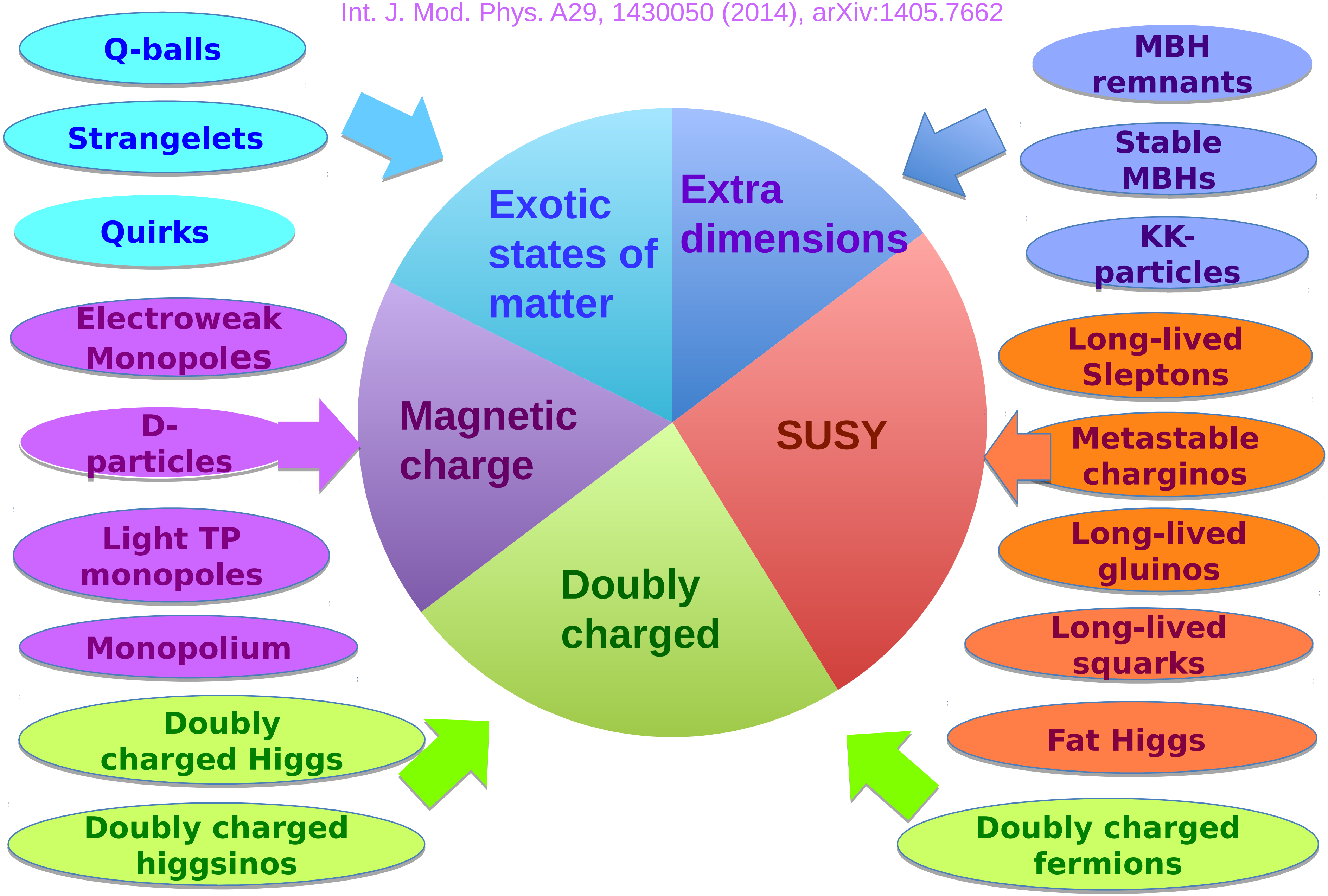
The MoEDAL physics programme

Int. J. Mod. Phys. A29, 1430050 (2014), arXiv:1405.7662



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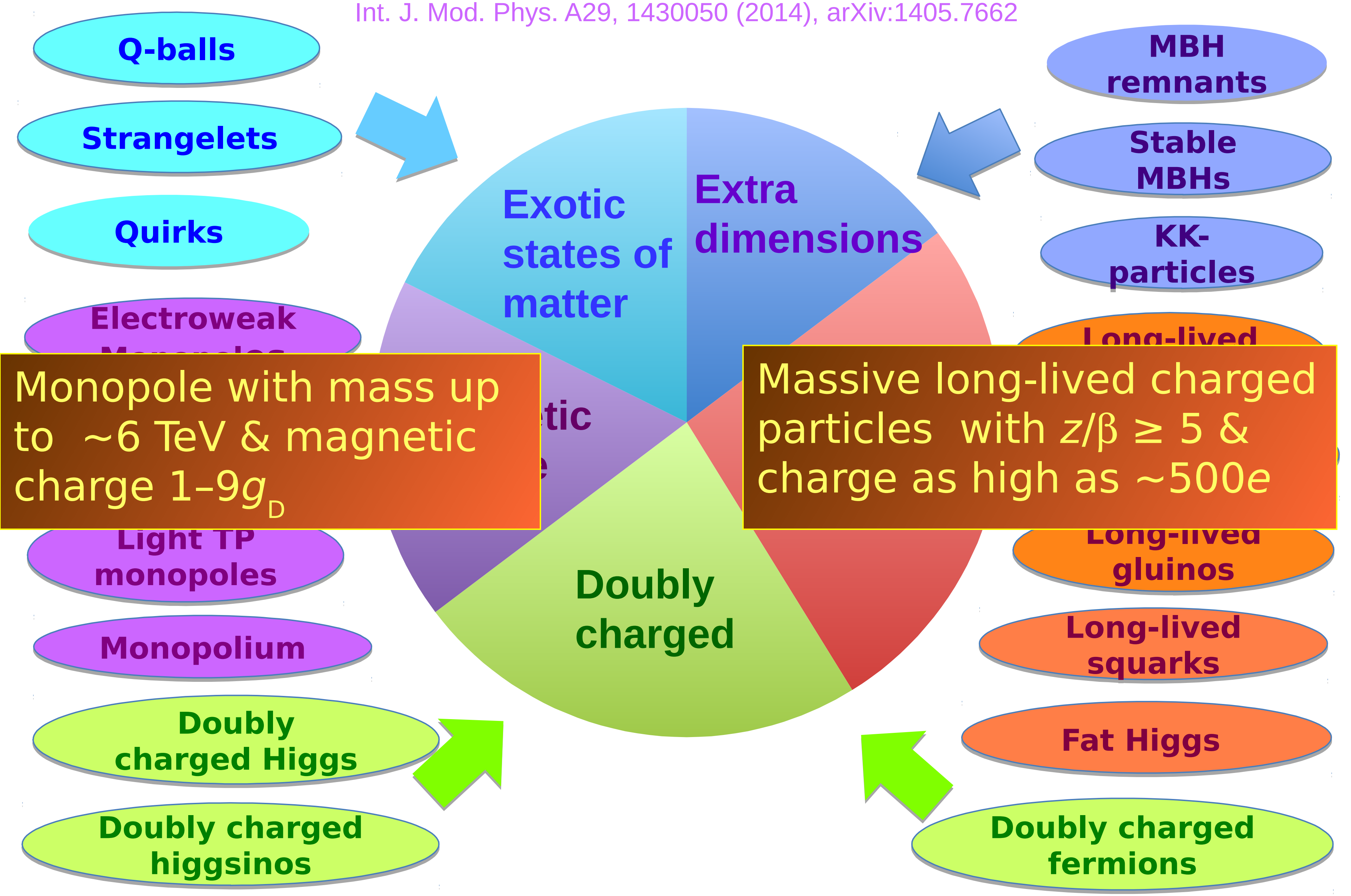
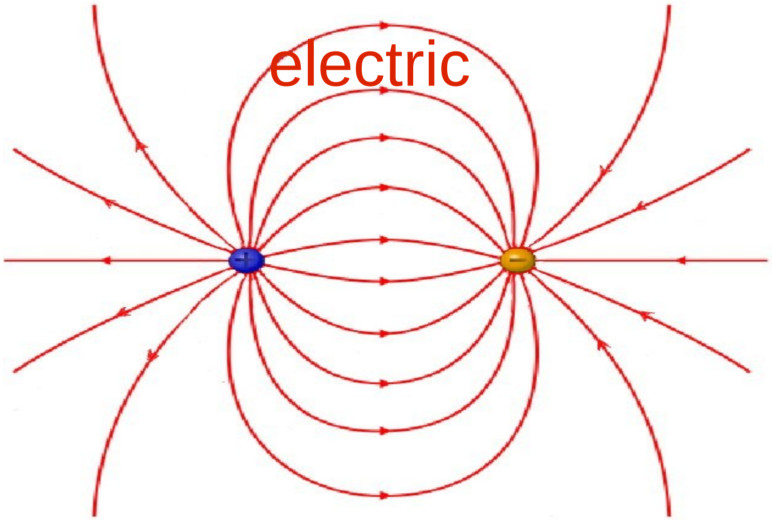
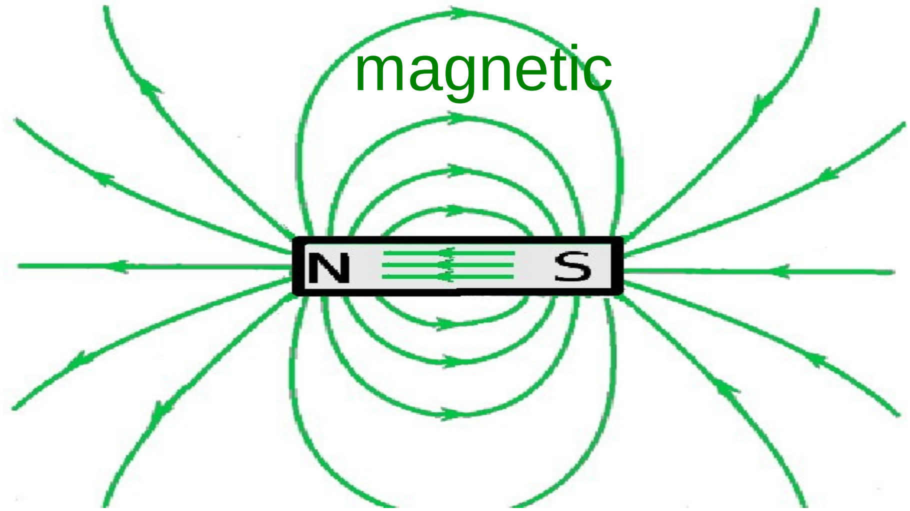


The monopole

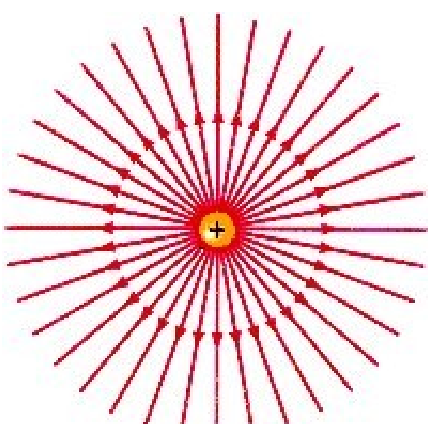




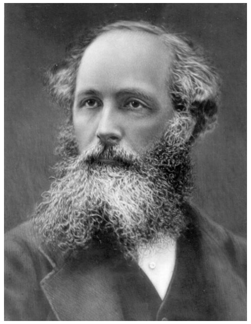
Sources of electric field exist

– Are there magnetic equivalents?

proton



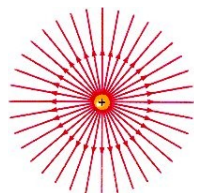
magnetic monopole



Maxwell's equations
(1862)

Without monopoles

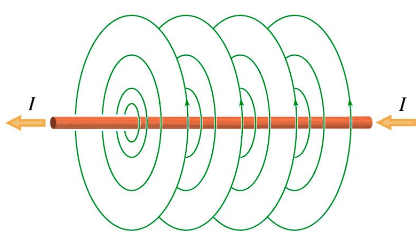
$$\nabla \cdot \mathbf{E} = 4\pi\rho_e$$



$$\nabla \cdot \mathbf{B} = 0$$

$$-\nabla \times \mathbf{E} = \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j}_{\mathrm{e}}$$



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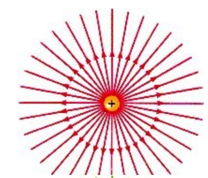
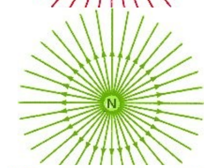
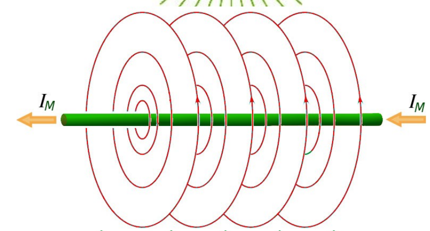


$$\nabla \cdot \mathbf{B} = 4\pi\rho_m$$



$$-\nabla \times \mathbf{E} = \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} + \frac{4\pi}{c}\mathbf{j}_{\mathrm{m}}$$



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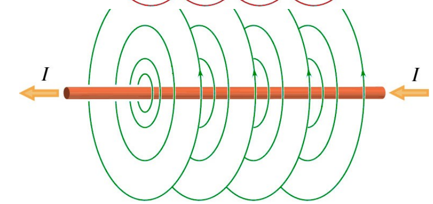
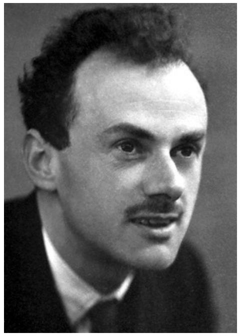
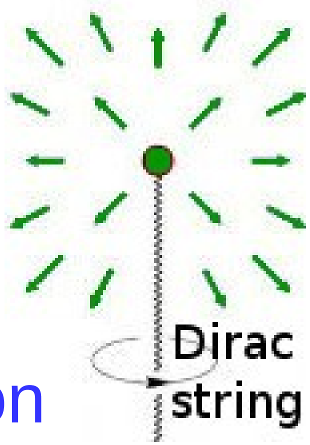




Dirac's quantisation condition
(1931)

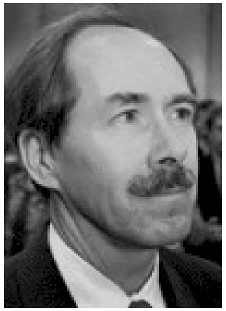


Side result of quantum-field theory formulation

$$q_e q_m = n \frac{h}{\mu_0} \; (n \text{ integer number})$$

- **explains electric charge quantisation!**
- Fundamental magnetic charge g_D = 68.5 (with $q_m = gec$ and $n = 1$)
- Very high ionisation energy loss

Schwinger generalised this to dyons (1966)



't Hooft and Polyakov's GUT monopole

(1974)

U(1) group of electromagnetism is a subgroup of a broken gauge symmetry

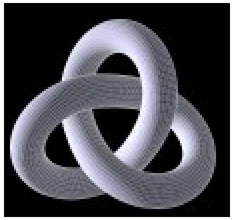
➔ **Topological monopole solution. Very general result!**

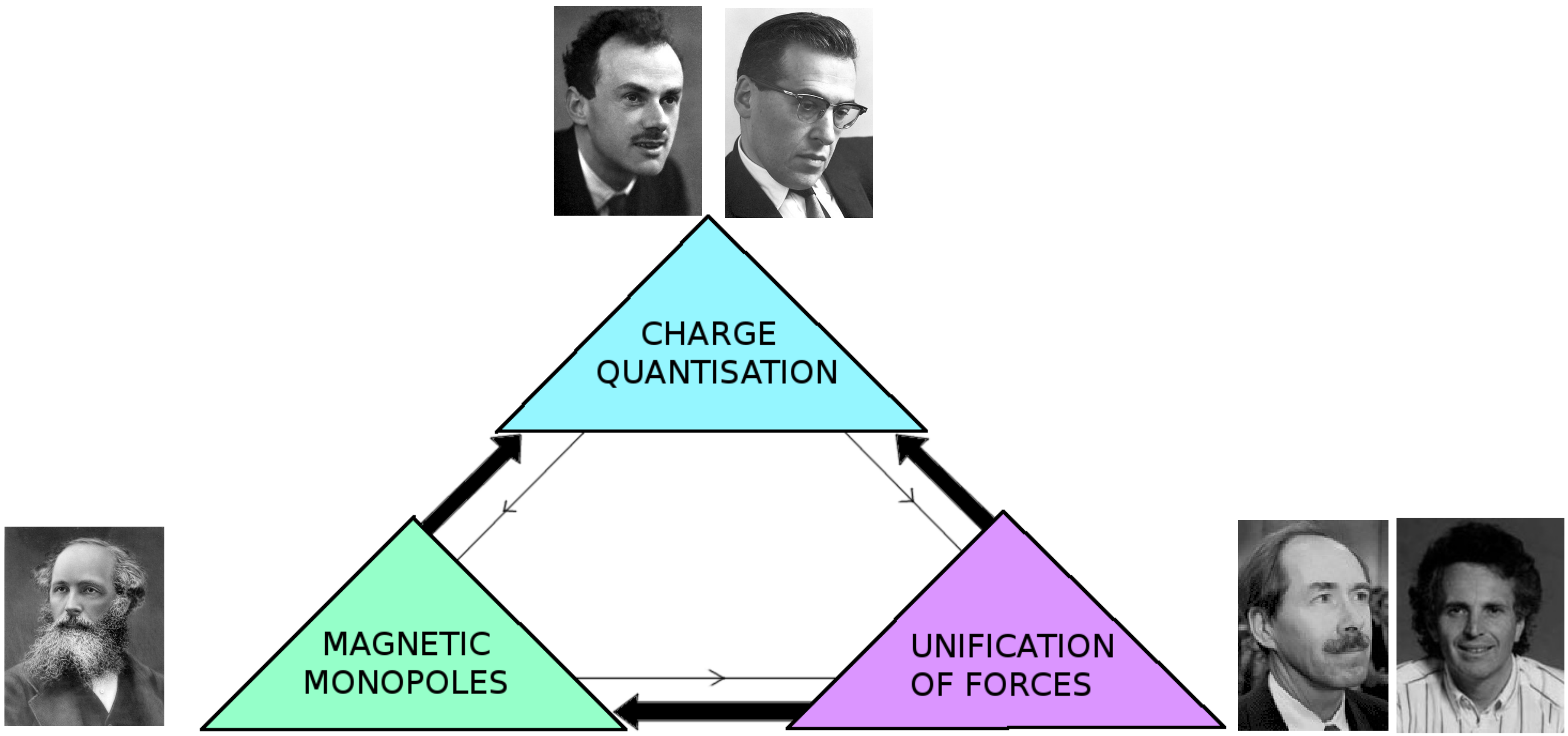
- Minimum magnetic charge g_D or $2g_D$ (depending on model)
- Mass ~ 10^{16} GeV (unification scale)

Non-trivial solutions are allowed in the electroweak theory itself

- Charge $2g_D$
- Mass ~ few TeV

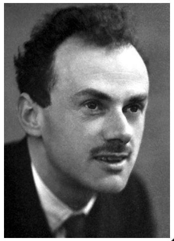
PLB 391, 360 (1997)
PLB 756, 29 (2016)

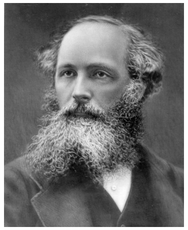


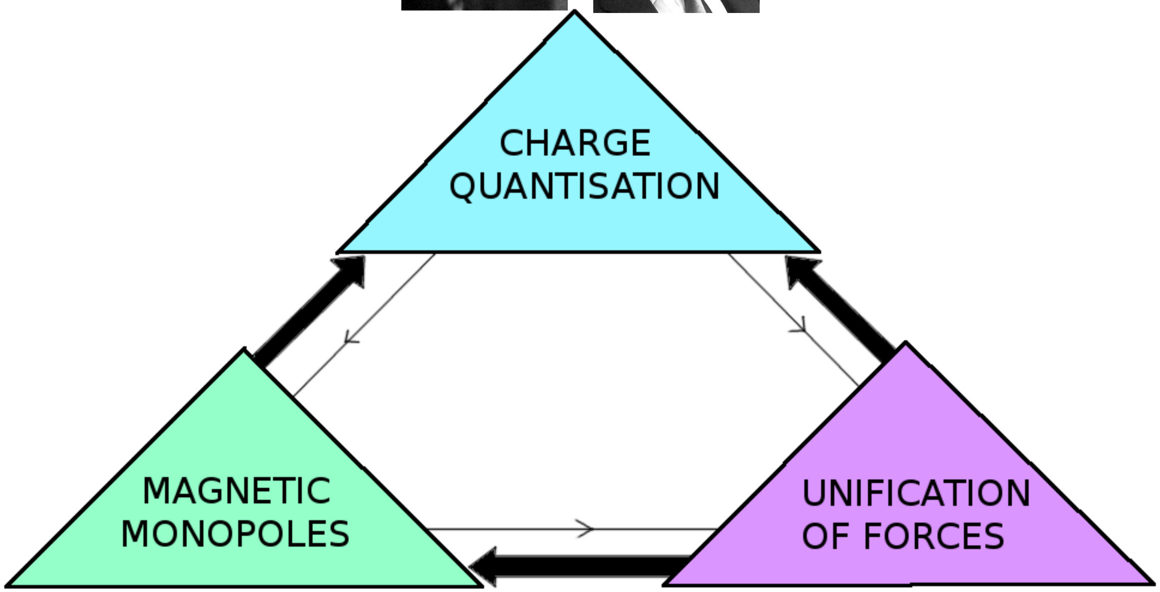

CHARGE QUANTISATION
MAGNETIC MONOPOLES
UNIFICATION OF FORCES

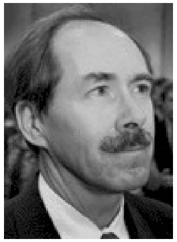
Under these circumstances one would be surprised if nature had made no use of it.

(1931)









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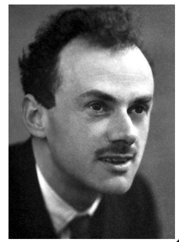
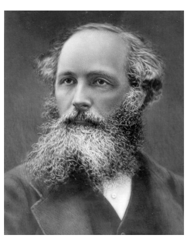
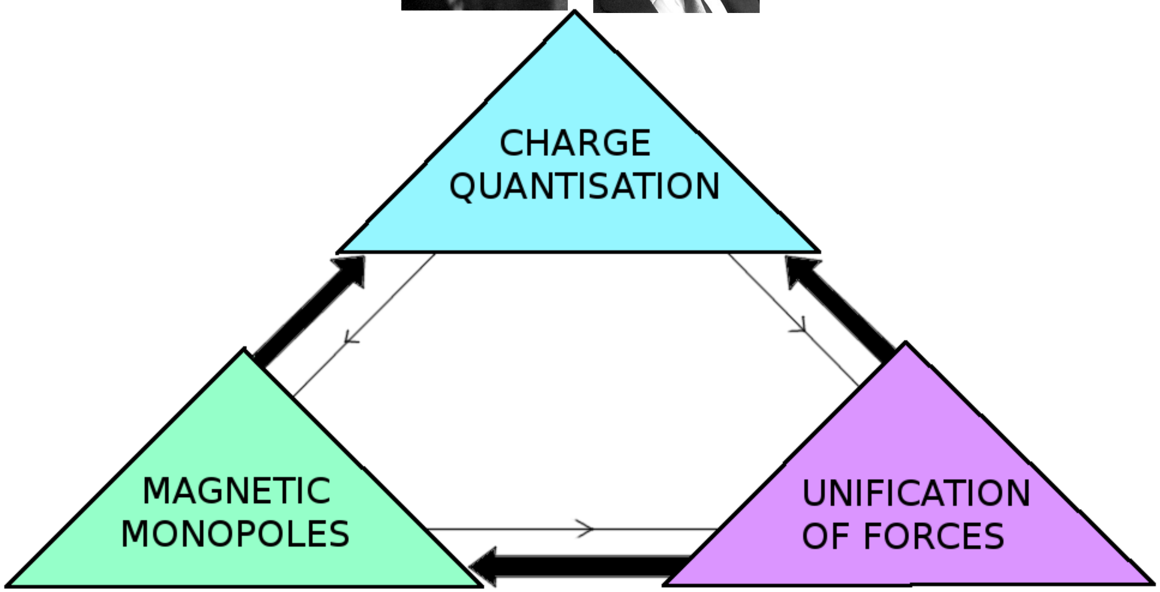
The magnetic monopole is the most venerable member of the mythological bestiary of physics.

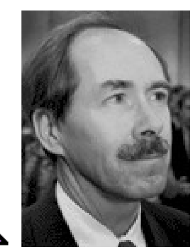
(1986)

Don Groom









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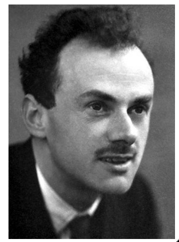

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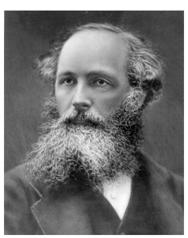

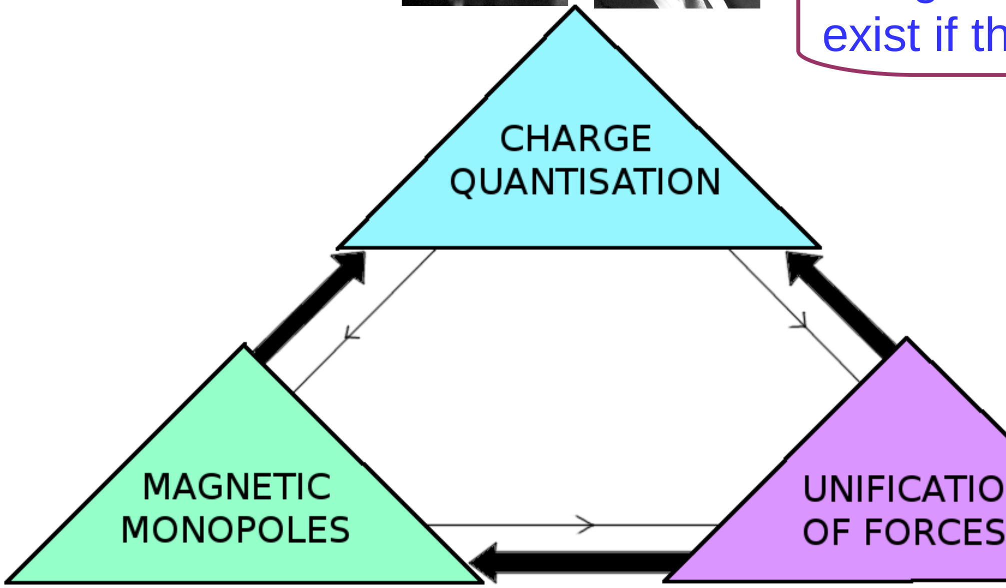

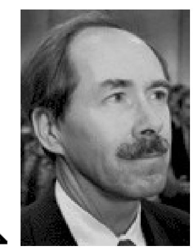

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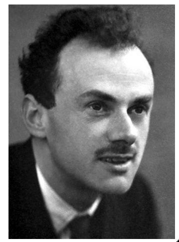

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(2002)

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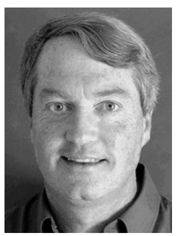
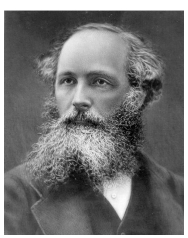
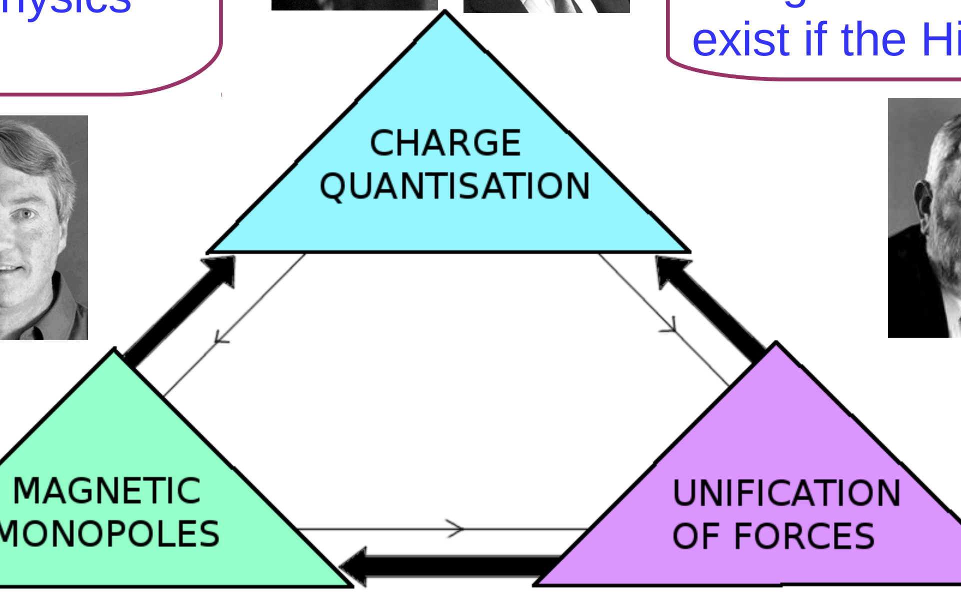
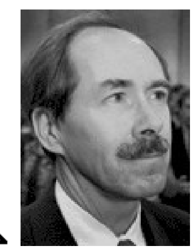


Joe Polchinski

Tini Veltman







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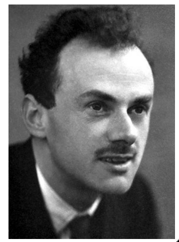

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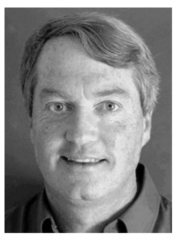

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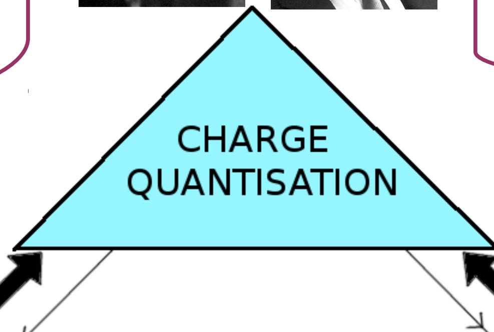

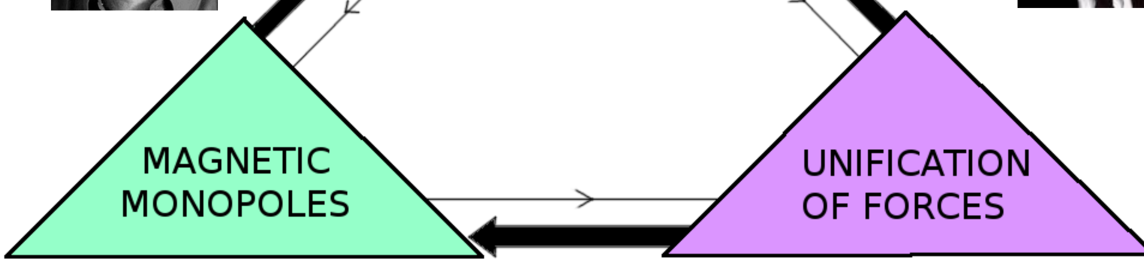

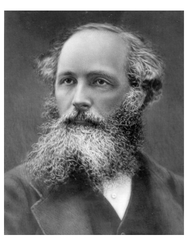

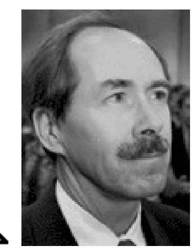

John Preskill

But it is one thing to say that monopoles must exist, and quite another to say that we have a reasonable chance of observing one.

(1984)

Where to look for monopoles?

- In cosmic rays and in matter

  (Phys. Rep. 582, 1 (2015), arXiv:1410.1374)

- At colliders

  (Phys. Rep. 438, 1 (2007), arXiv:hep-ph/0611040)

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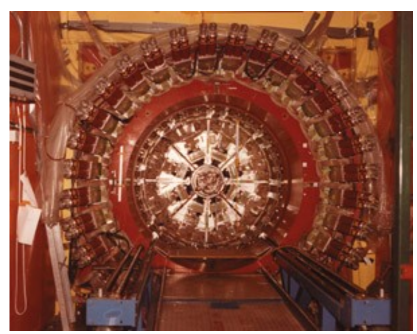
Monopole searches are performed at colliders every time a new energy regime is made accessible

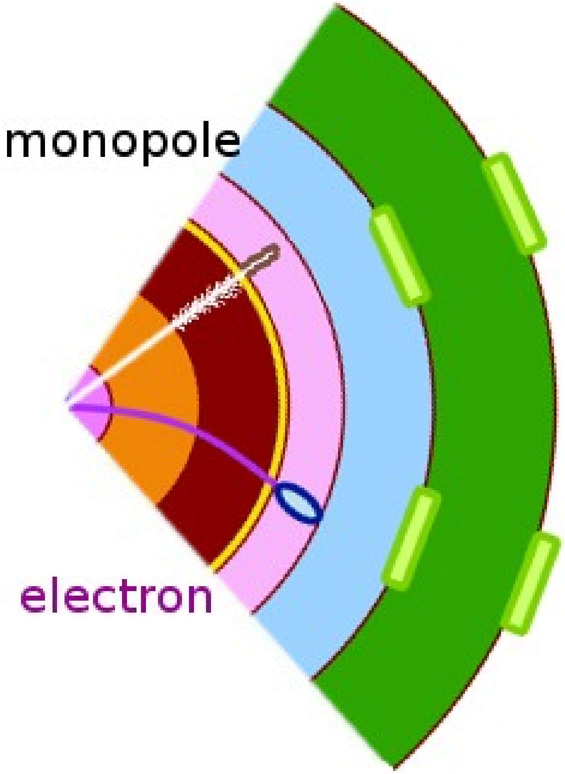


Direct HIP/monopole detection at colliders (1)

signature of very highly ionising particle (HIP)

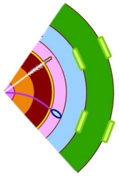
1) General-purpose detectors (OPAL, CDF, ATLAS, CMS...)

- High ionisation
- Pencil-like calorimeter deposit
- Anomalous bending



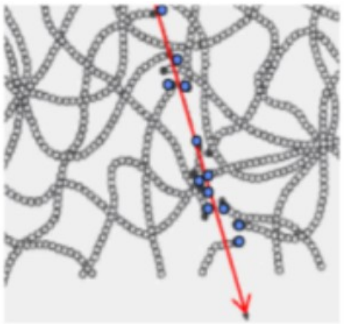
Direct HIP/monopole detection at colliders (2)

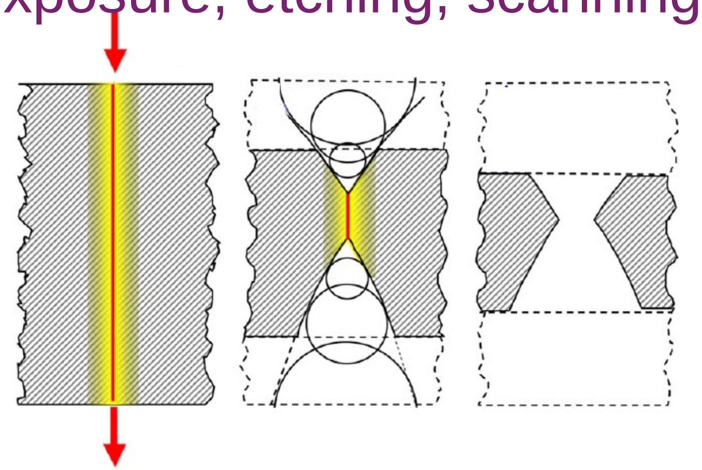
signature of very highly ionising particle (HIP)

1) General-purpose detectors 

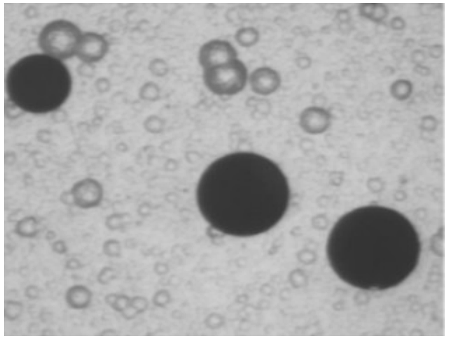
2) Nuclear-track detectors

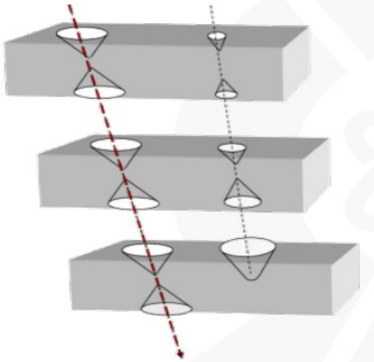
– Plastic NTD foil – exposure, etching, scanning





– Etch-pit cones (~50 μm) in successive sheets

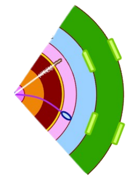


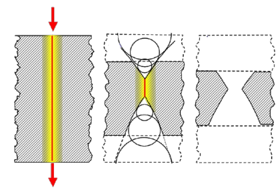


Direct HIP/monopole detection at colliders (3)

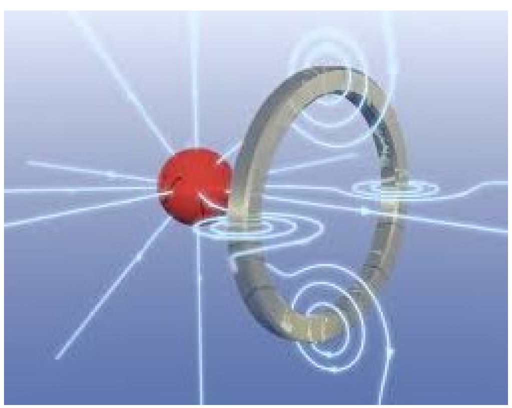
signature of very highly ionising particle (HIP)

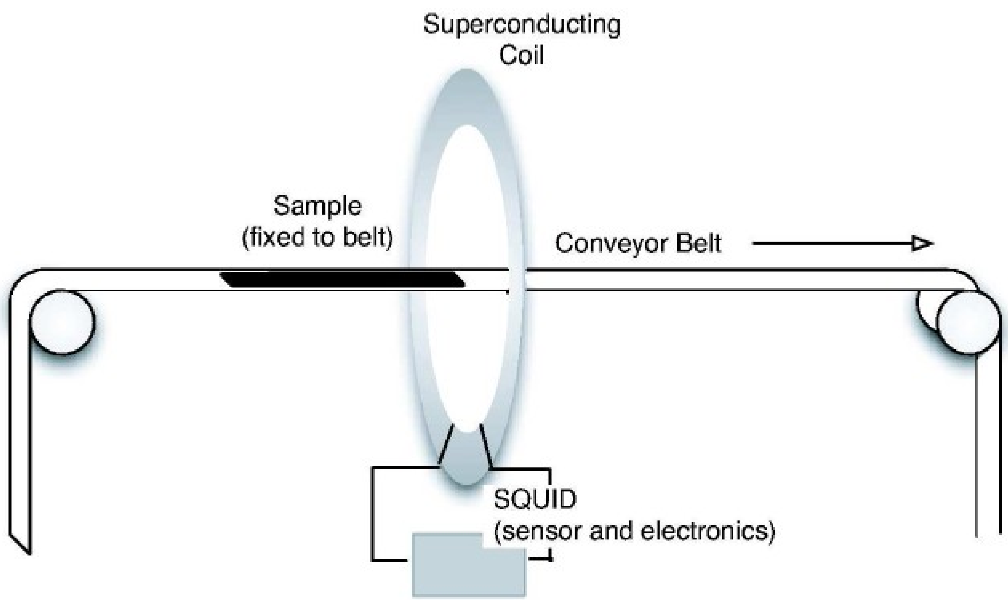
1) General-purpose detectors
2) Nuclear-track detectors
3) Induction technique





- Expect monopole-nucleus binding energy ~100 keV
  (Rept. Prog. Phys. 69, 1637 (2006), arXiv:hep-ex/0602040)
- Persistent current after passage through superconducting coil

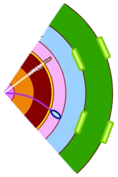


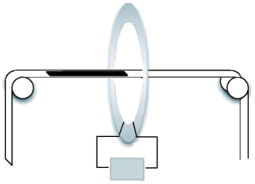


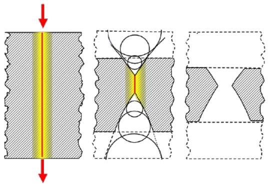
Direct HIP/monopole detection at colliders

signature of very highly ionising particle (HIP)

1) General-purpose detectors
2) Nuclear-track detectors
3) Induction technique



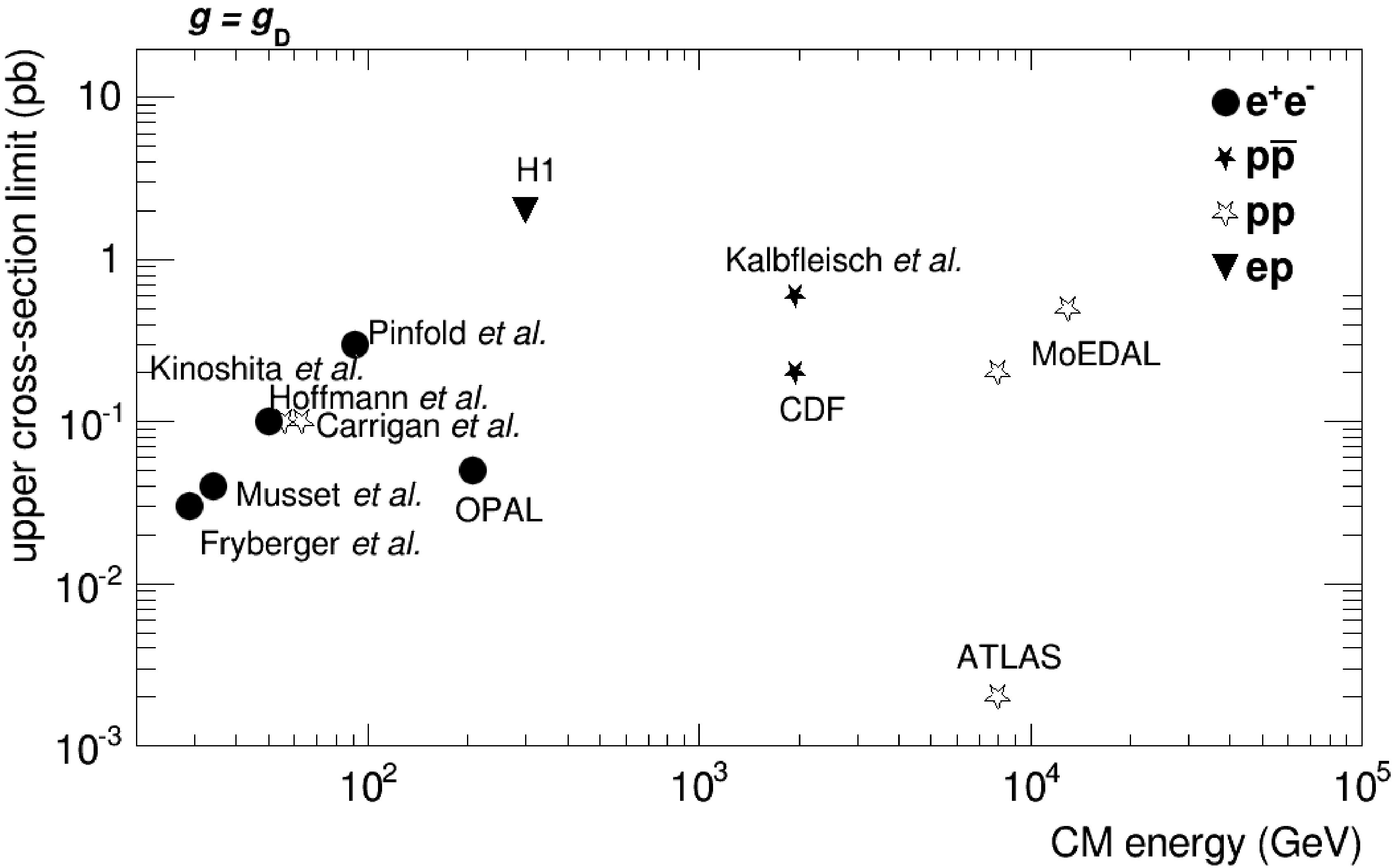




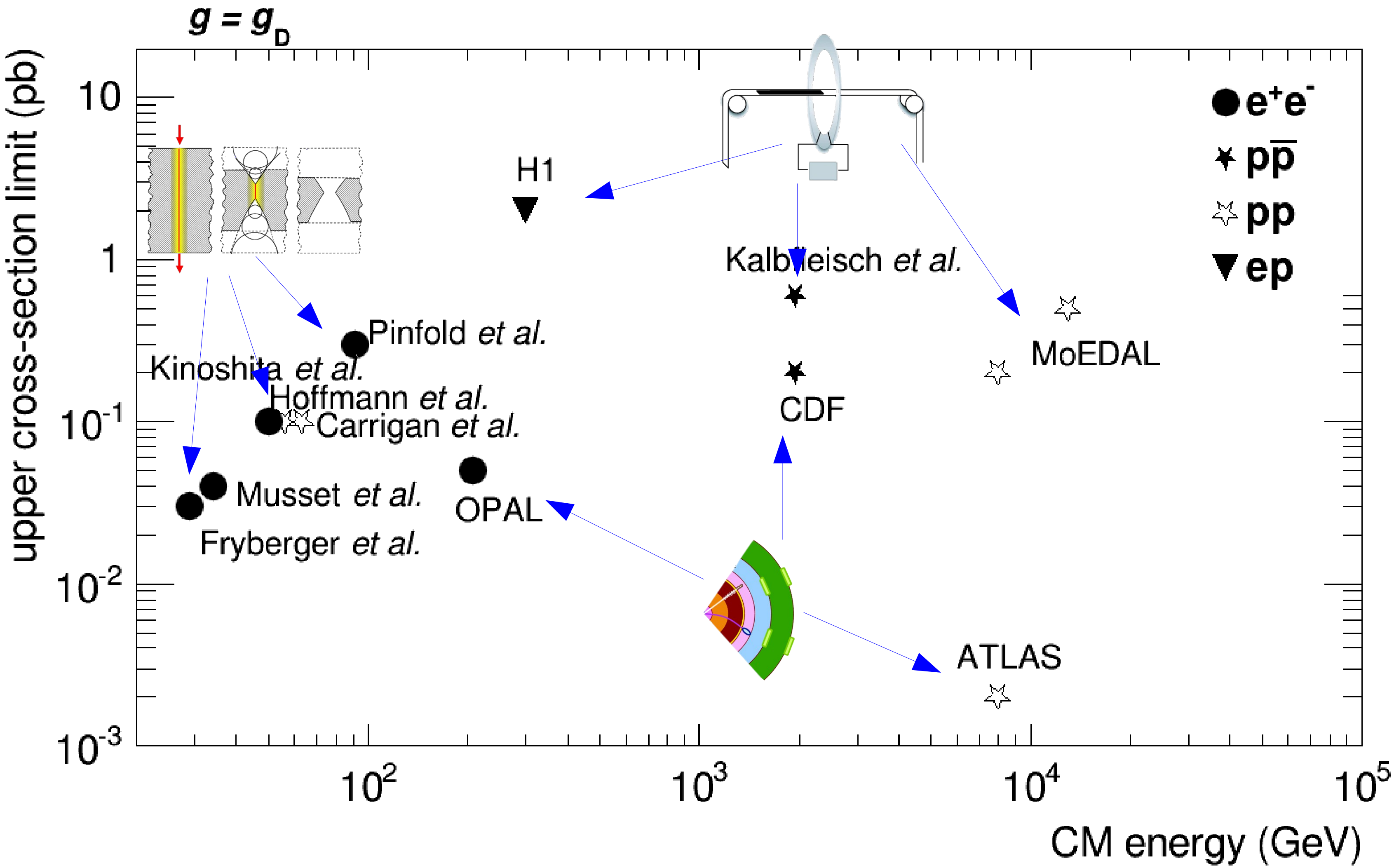
All three techniques are needed
to cover the full parameter space

(see EPJC 72, 1985 (2012), arXiv:1112.2999)

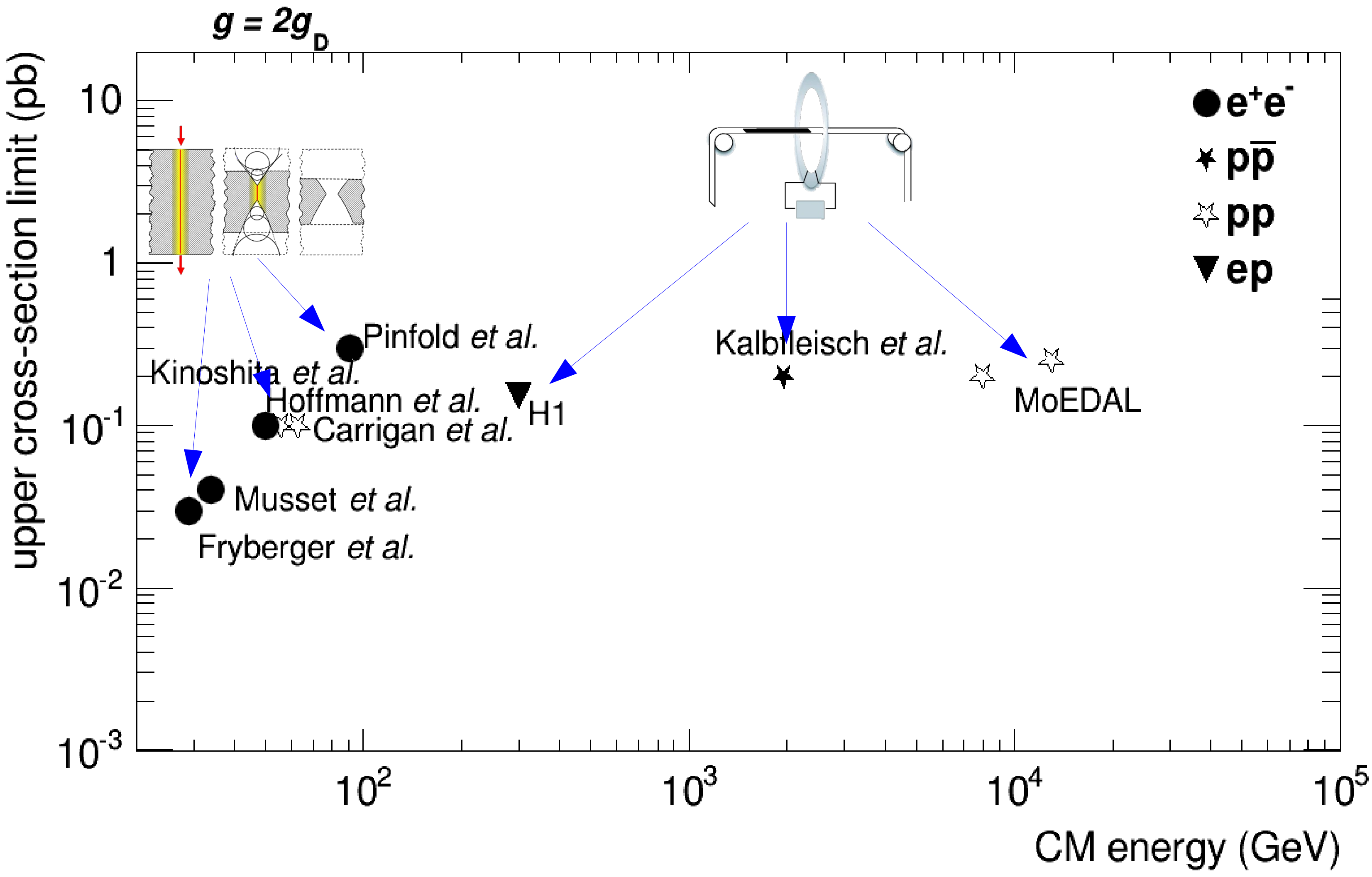
Direct collider monopole searches
current limits (assuming $|g| = g_D$)



Direct collider monopole searches
current limits (assuming $|g| = g_D$)



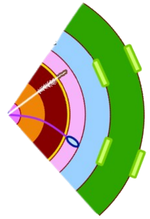
Direct collider monopole searches
current limits (assuming $|g| = 2g_D$)



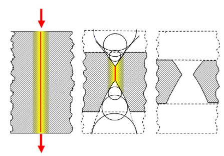
HIP searches at the LHC

(see EPJC 72, 1985 (2012), arXiv:1112.2999)

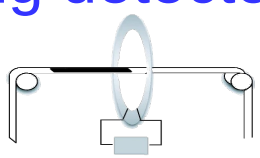
- ATLAS and CMS
  - → $|g| \leq 2g_D$
  - → $0.3 \leq |z|/\beta \leq 100$



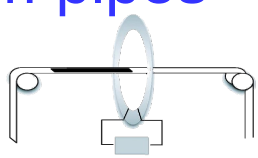
- MoEDAL NTD detectors
  - → $|g| \leq 9g_D$
  - → $5 \leq |z|/\beta \leq 500$



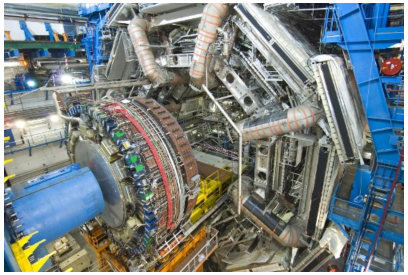
- MoEDAL trapping detector
  - → $|g| \leq 4g_D$

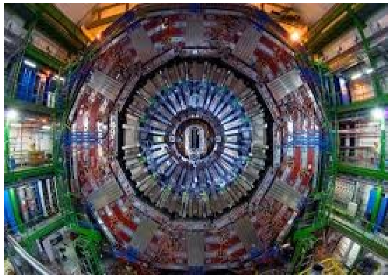


- Trapping in beam pipes
  - → $|g| \geq 4g_D$

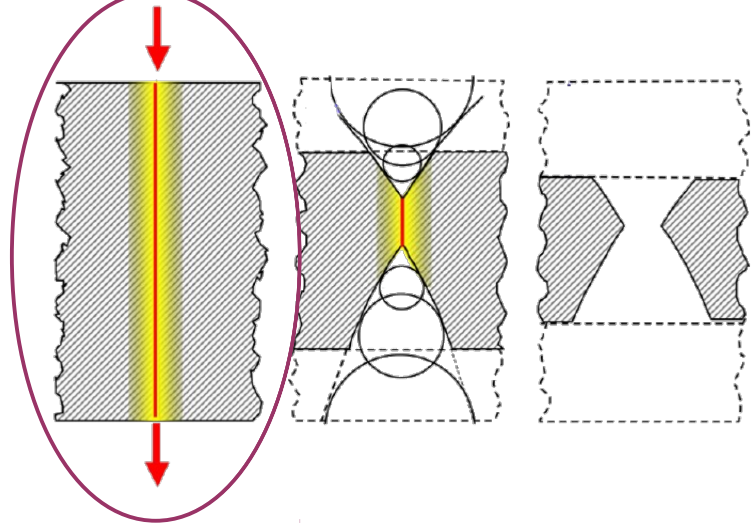


Complementary techniques!



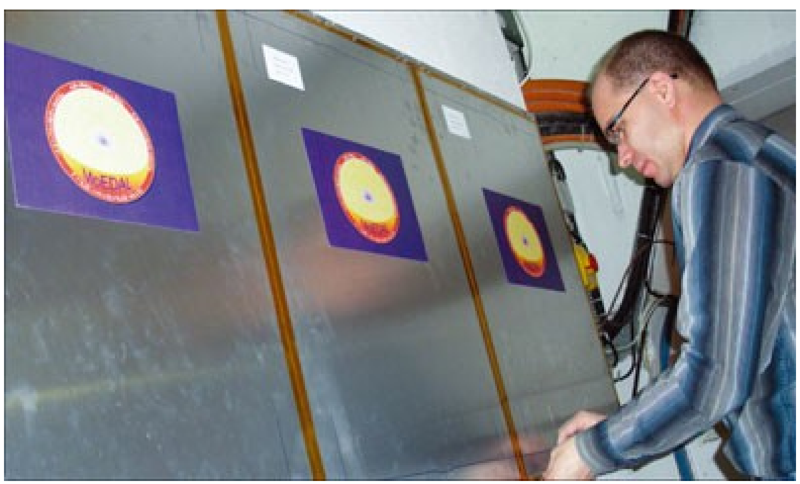


Passive detection with NTDs in MoEDAL (1)

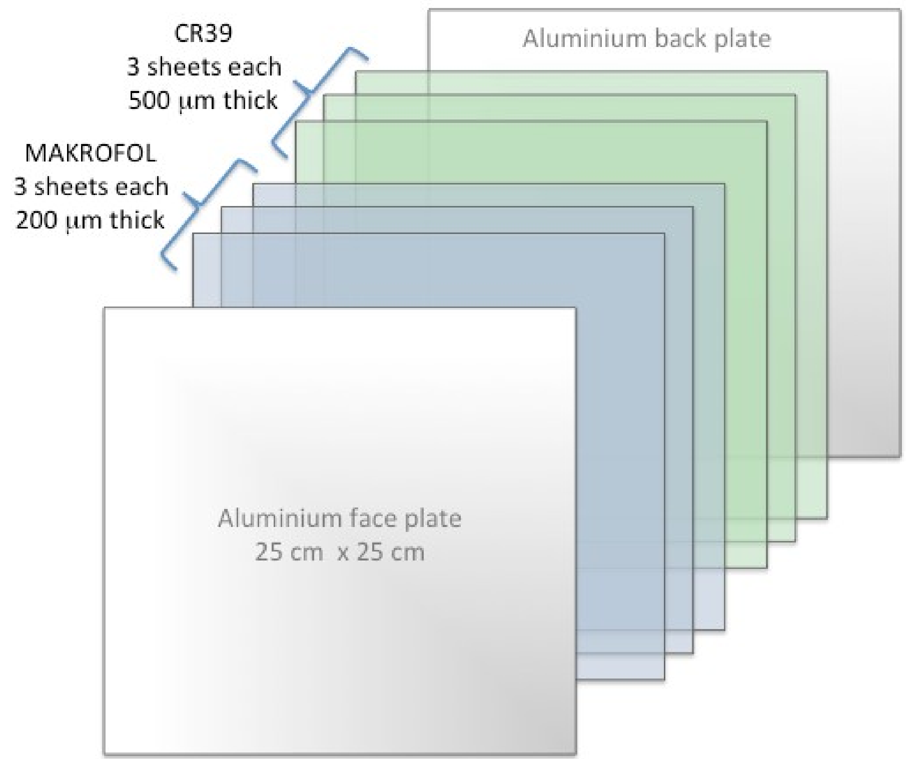


installation

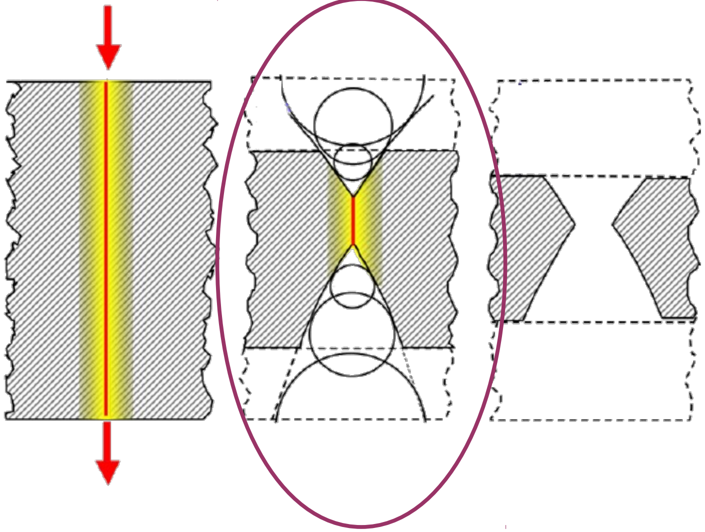
Exposure
(IP8)



25 m^2



Passive detection with NTDs in MoEDAL (2)



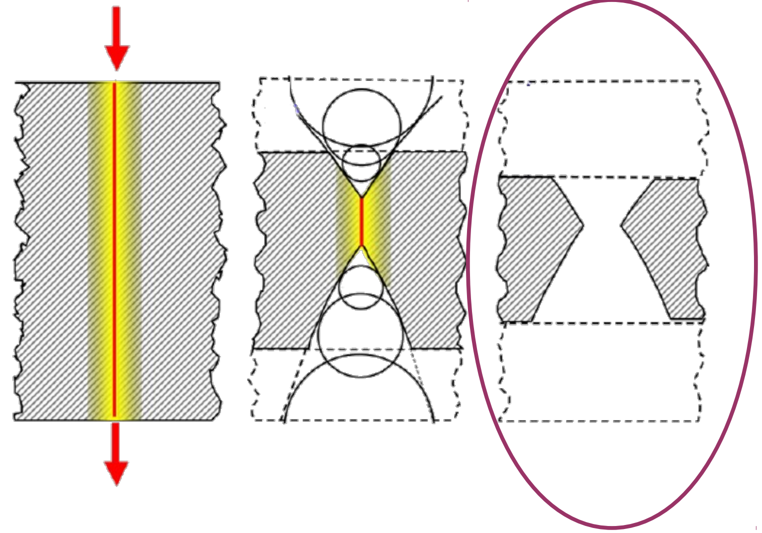
installation

Exposure
(IP8)

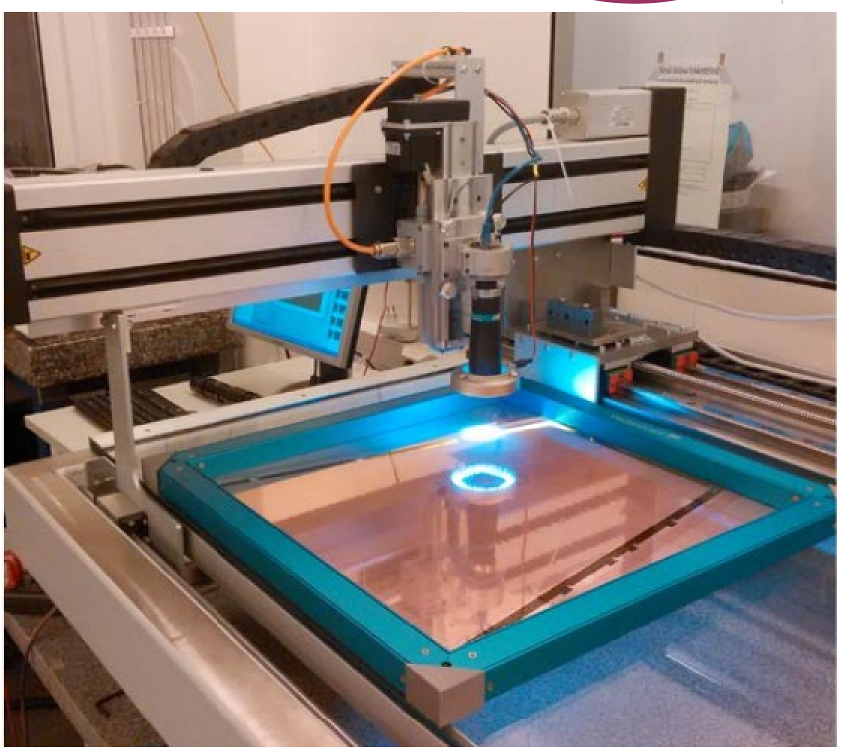
Removal

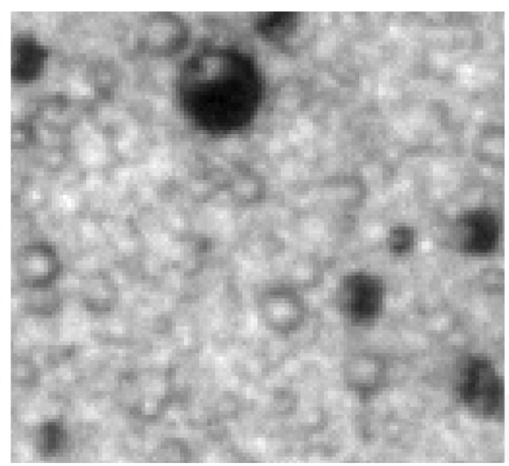
Etching
(Bologna)

Passive detection with NTDs in MoEDAL (3)



installation → **Exposure** (IP8) → Removal → **Etching** (Bologna) → **Scanning** (Bologna, Münster, Helsinki)

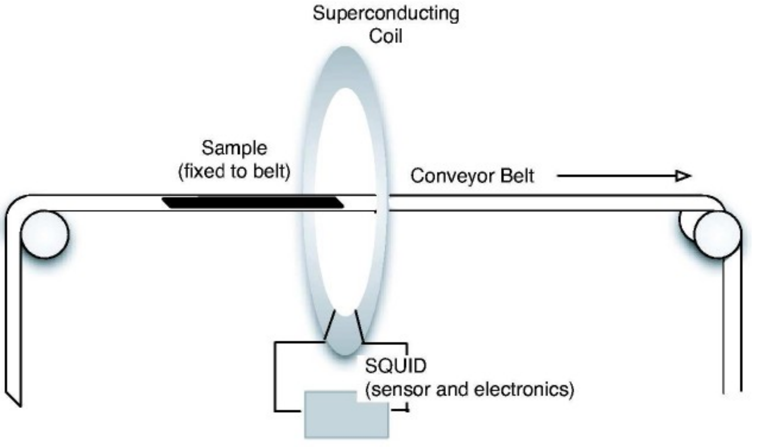




Typical pit:
10-50 µm

Typical foil thickness after etching:
200-1400 µm

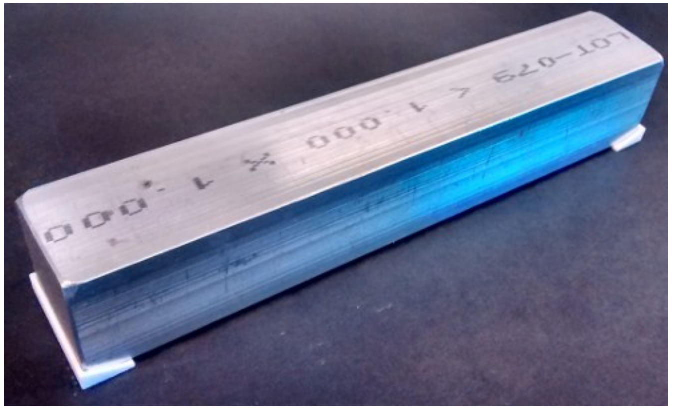
Passive detection with MoEDAL trapping array (1)



installation

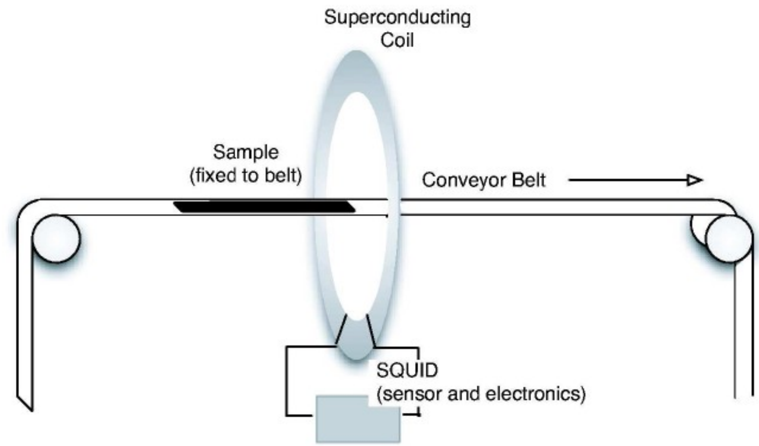
Exposure
(IP8)

3 x 222 kg

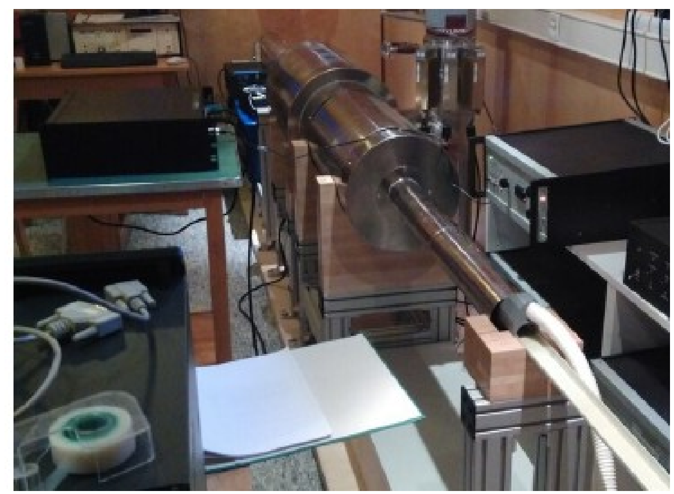


19 x 2.5 x 2.5 cm^3

Passive detection with MoEDAL trapping array (2)



installation → **Exposure** (IP8) → Removal → **Scanning** (ETH Zurich)



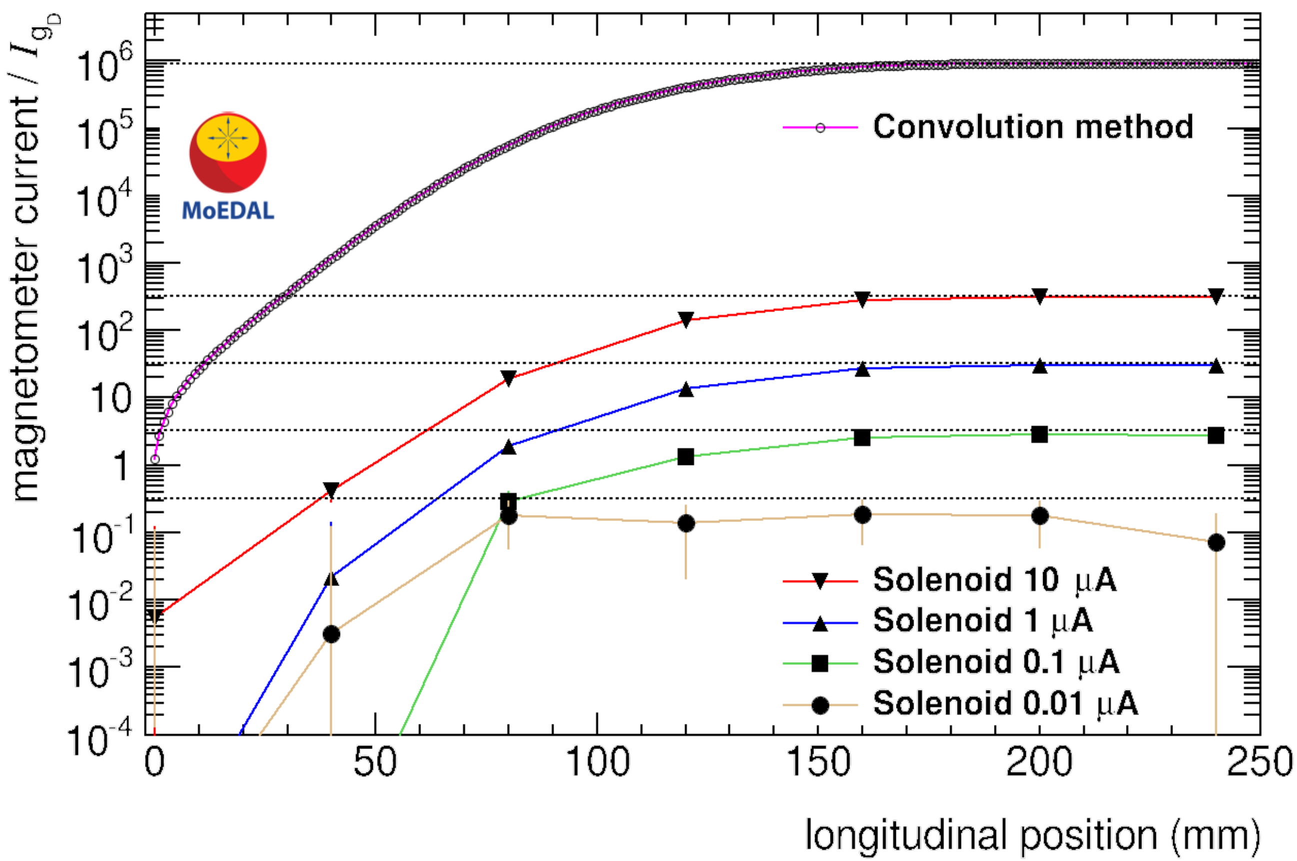
Laboratory of Natural Magnetism, ETH Zurich

Magnetically shielded room

DC-SQUID magnetometer

Magnetometer calibration

- Two independent methods: convolution and solenoid
- Very good agreement between the two
- Linearity demonstrated in range 0.3-10^6 g_D

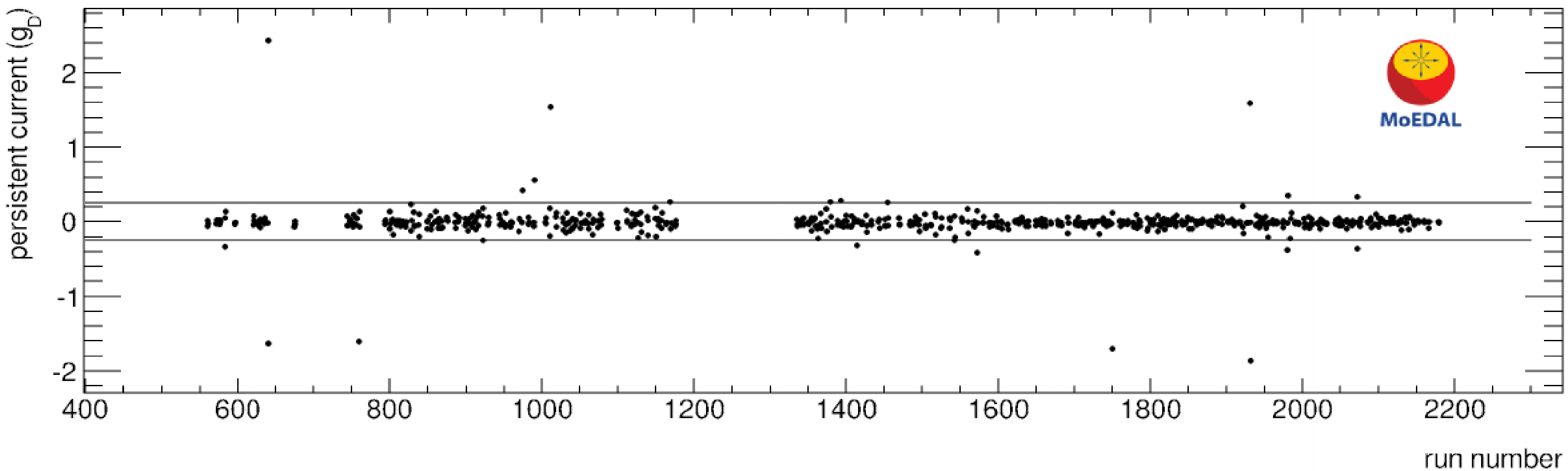


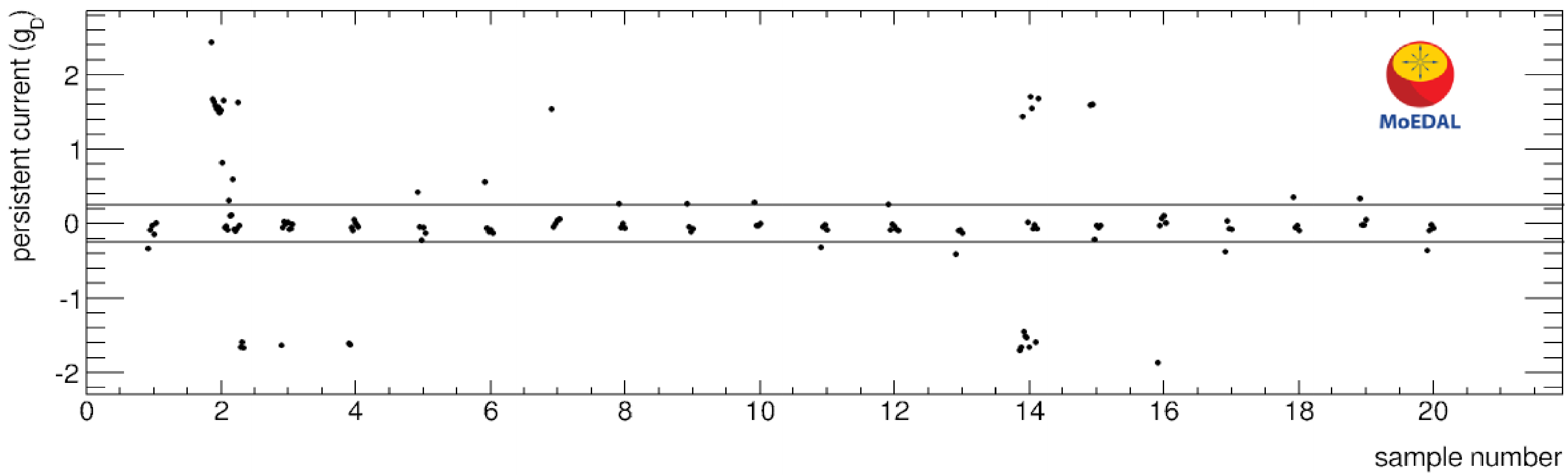
Magnetometer scans

- > 1000 samples
- Persistent current measured for each sample
- Samples with persistent current > 0.25 g_D are set aside as candidates
- Multiple measurements rule out the monopole hypothesis

Magnetic charges in samples (13 TeV exposure in 2015)

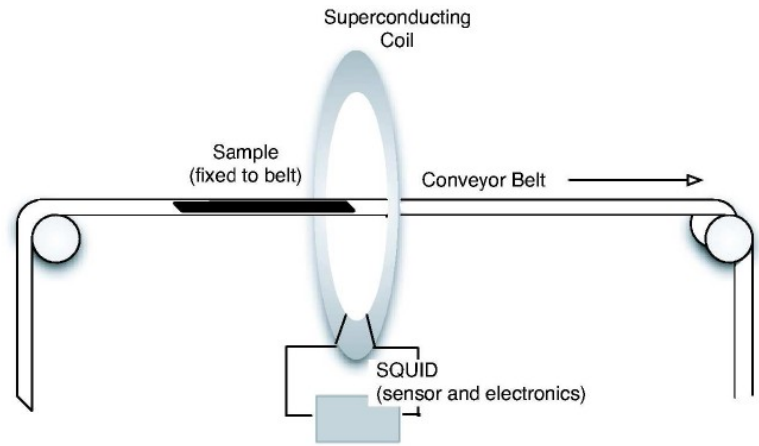
PRL 118, 061801 (2017)





- Exclude > 0.5 g_D in all samples

Passive detection with MoEDAL trapping array (3)



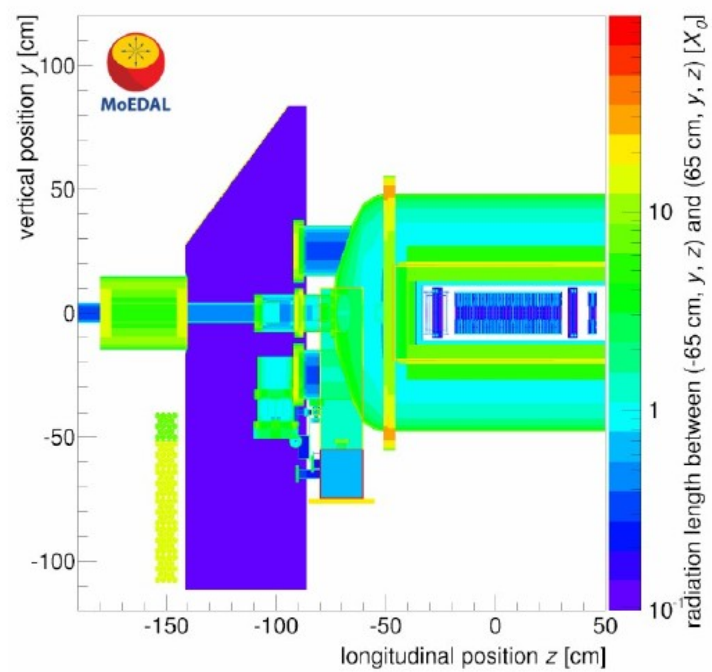
installation

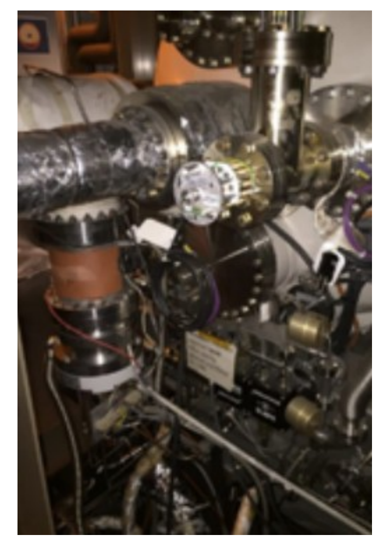
Exposure
(IP8)

Removal

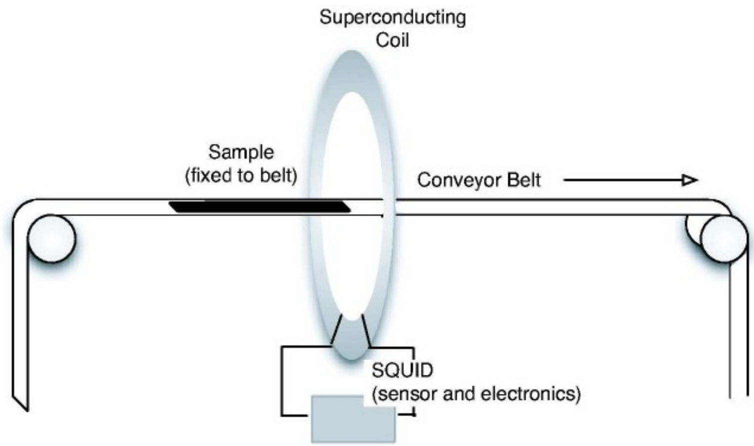
Scanning
(ETH Zurich)

Material
description





Passive detection with MoEDAL trapping array (4)

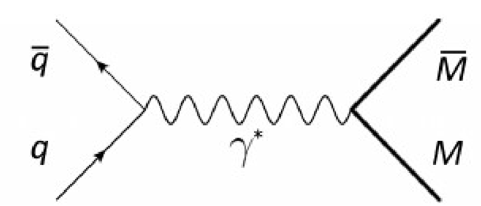


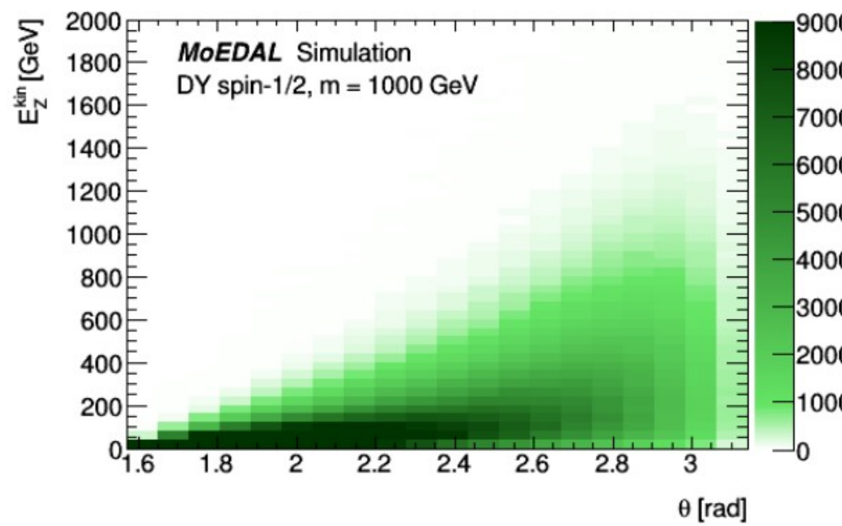
installation → **Exposure** (IP8) → Removal → **Scanning** (ETH Zurich)

Material description

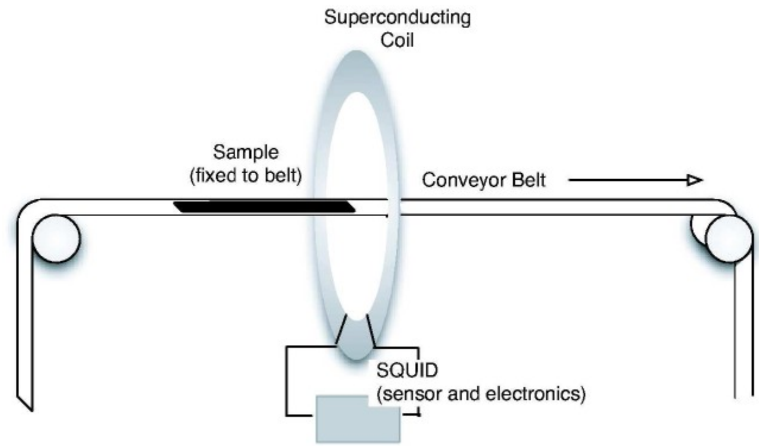
Event Generation (Madgraph)

Coupling >> 1
→ non-perturbative dynamics !





Passive detection with MoEDAL trapping array (5)

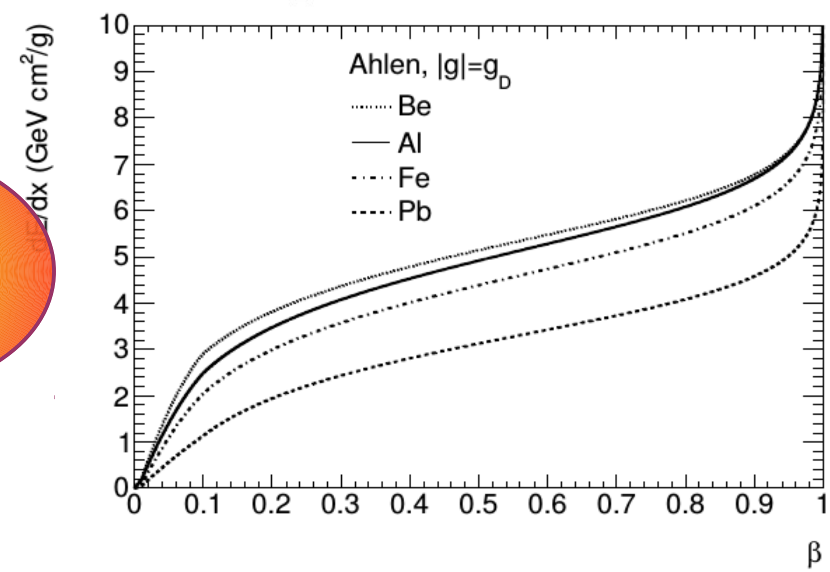


installation → **Exposure** (IP8) → Removal → **Scanning** (ETH Zurich)

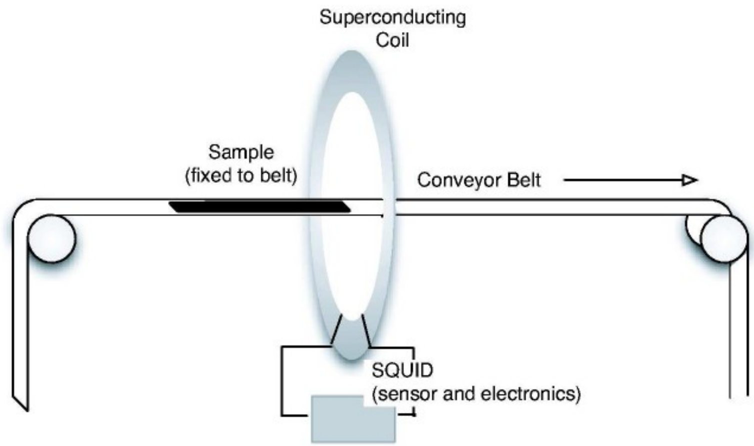
Material description → **Simulation** (Geant4)

Event Generation (Madgraph) → **Simulation** (Geant4)

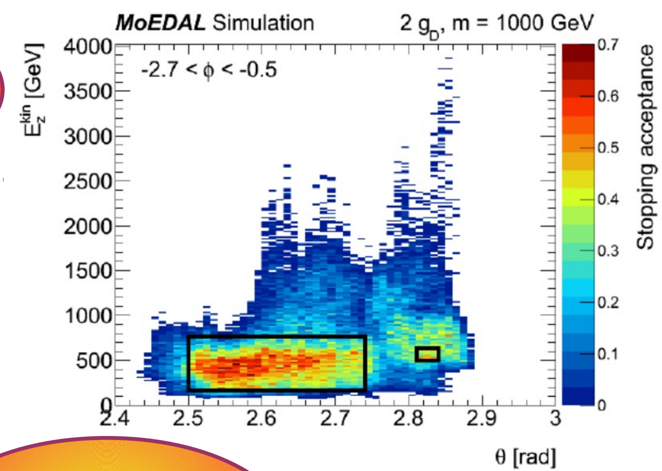
$$-\frac{\mathrm{d}E}{\mathrm{d}x} = C\frac{Z}{A}g^2\left[\ln\frac{2m_e c^2\beta^2\gamma^2}{I} + \frac{K(|g|)}{2} - \frac{1}{2} - B(|g|)\right]$$



Passive detection with MoEDAL trapping array (6)



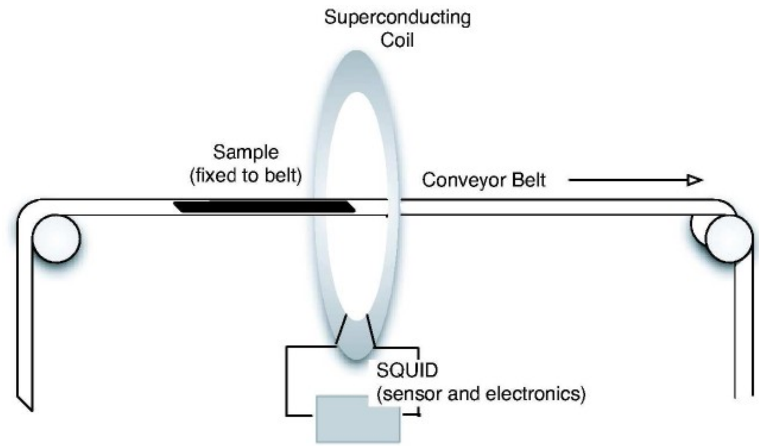
installation → **Exposure** (IP8) → Removal → **Scanning** (ETH Zurich)

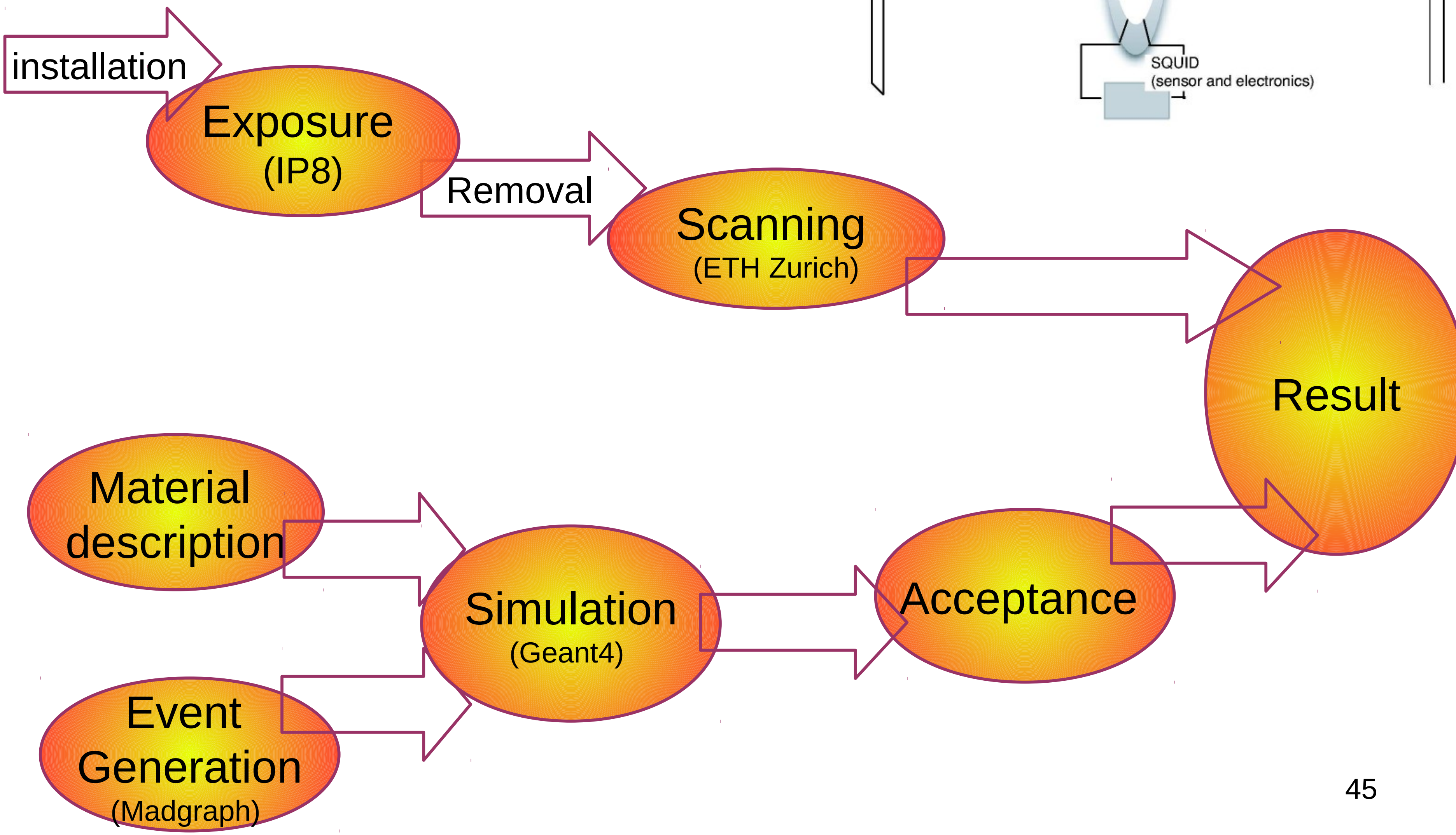


Material description → **Simulation** (Geant4) → **Acceptance**

Event Generation (Madgraph) → **Simulation** (Geant4)

Passive detection with MoEDAL trapping array (7)

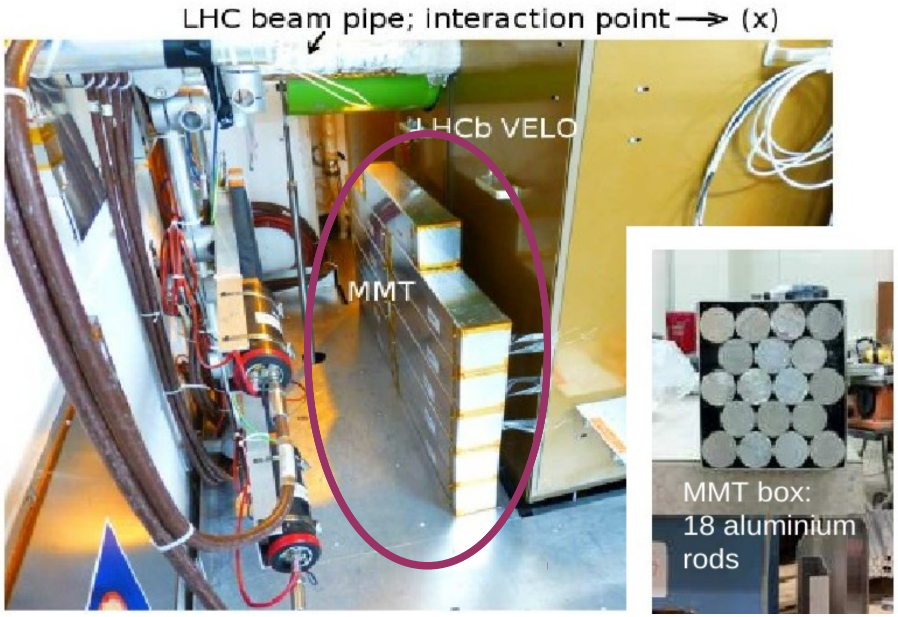




MoEDAL in 2012

NTD stacks
on surrounding walls

1 array trapping detector prototype
Below beam pipe opposite to LHCb



Test arrays exposed to 8 TeV *pp* collisions

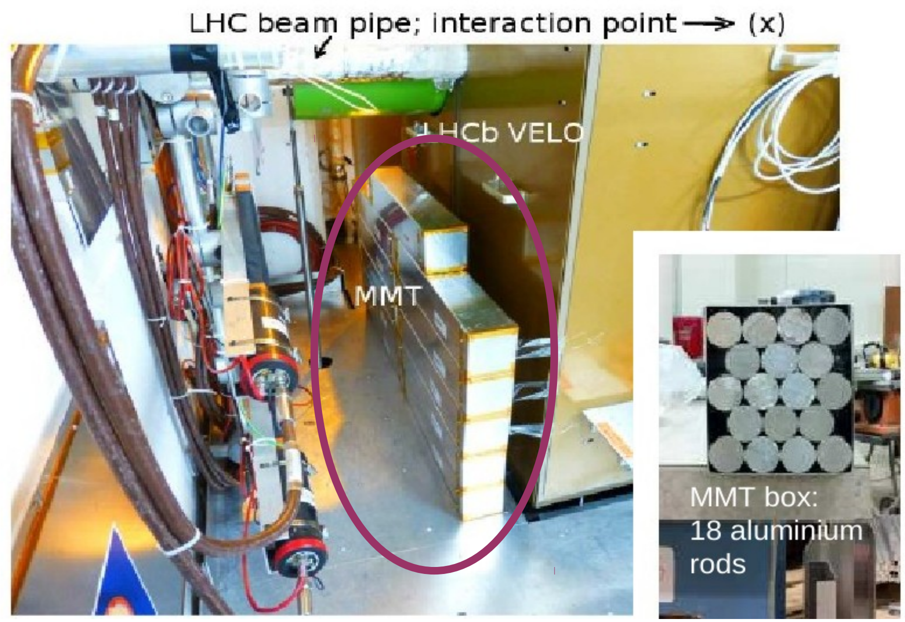
MoEDAL in 2012

NTD stacks
on surrounding walls

First LHC constraints on particles with multiple magnetic charge

JHEP 08, 067 (2016)

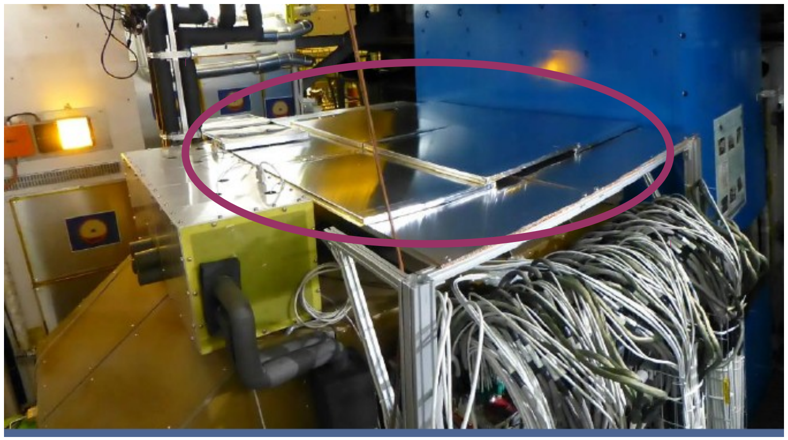
1 array trapping detector prototype
Below beam pipe opposite to LHCb



Test arrays exposed to 8 TeV *pp* collisions

MoEDAL in 2015/2016

NTD stacks on top of VELO, close to IP + on surrounding walls



TimePix for online monitoring

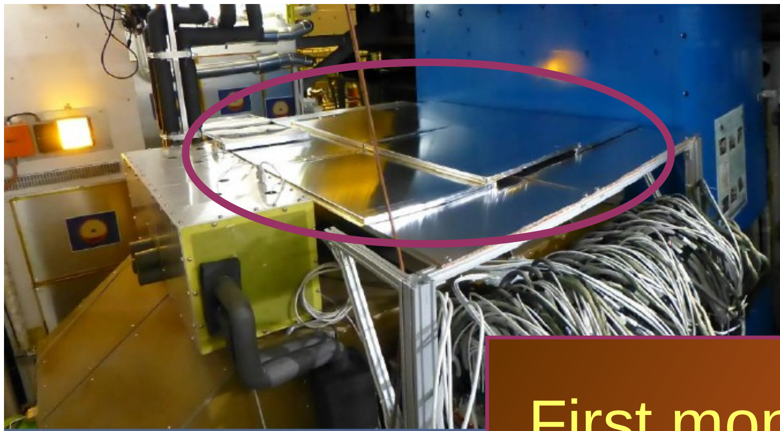
3 arrays trapping detectors

Thin “shower curtain” NTD within LHCb acceptance

Full arrays exposed to 13 TeV *pp* collisions

MoEDAL in 2015/2016

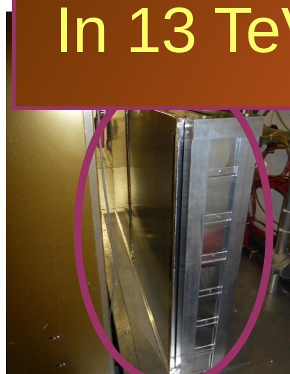
NTD stacks on top of VELO, close to IP + on surrounding walls



Thin “shower curtain” NTD within LHCb acceptance

PRL 118, 061801 (2017)

First monopole constraints
In 13 TeV collisions



3 arrays trapping detectors

Full arrays exposed to 13 TeV *pp* collisions

Cross-section limits with 2015 exposure

PRL 118, 061801 (2017)

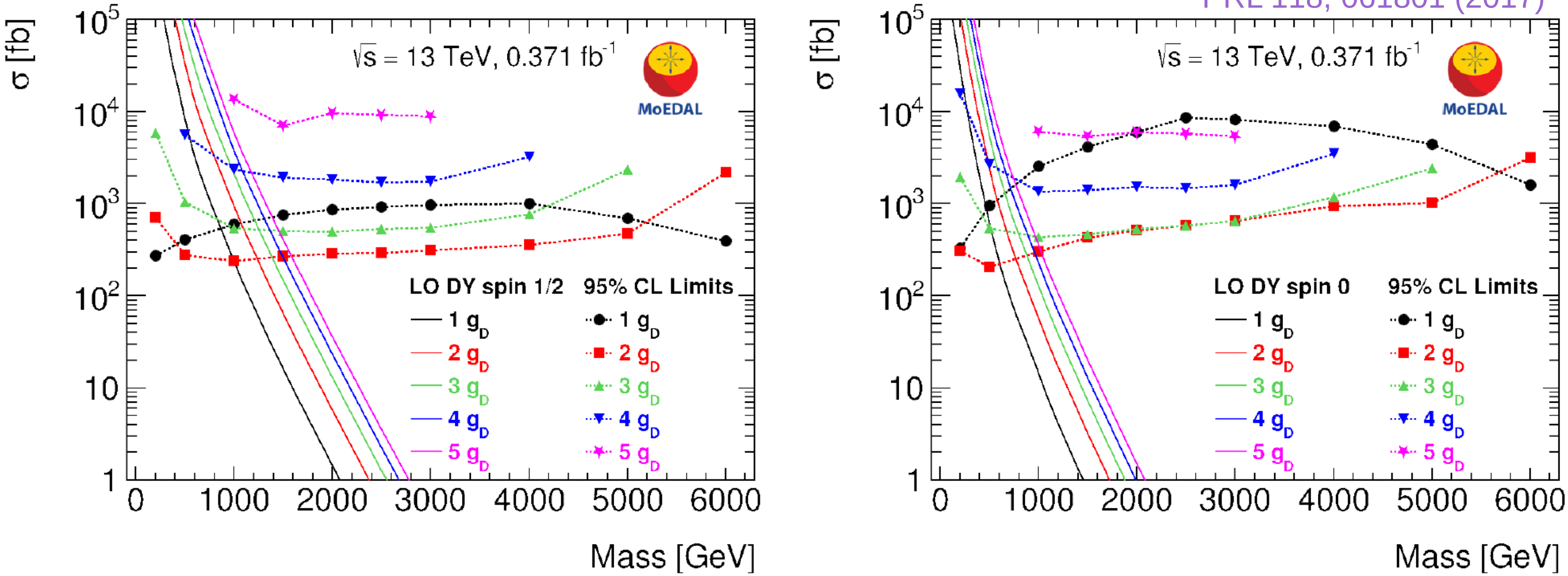


FIG. 2. Cross-section upper limits at 95% confidence level for DY monopole production in 13 TeV *pp* collisions as a function of mass for spin-1/2 (left) and spin-0 (right) monopoles. The colours correspond to different monopole charges. The solid lines are DY cross-section calculations at leading order.

- First monopole constraints in 13 TeV *pp* collisions
- Probe masses in the TeV regime for up to 5g_D

Results from 2016 exposure

- Same cavern conditions as 2015 with 6x more luminosity
- Scans finished last week! No monopoles found!
- Take the limits from previous page and multiply by 1/6

Mass limits (DY model)

Very preliminary

mass limits [GeV]	$1g_D$	$2g_D$	$3g_D$	$4g_D$
MoEDAL 13 TeV *preliminary* (2015+2016 exposure)				
DY spin-1/2	1150	1550	1600	1450
DY spin-0	610	1000	1100	1000
MoEDAL 13 TeV (2015 exposure)				
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	–	–	–

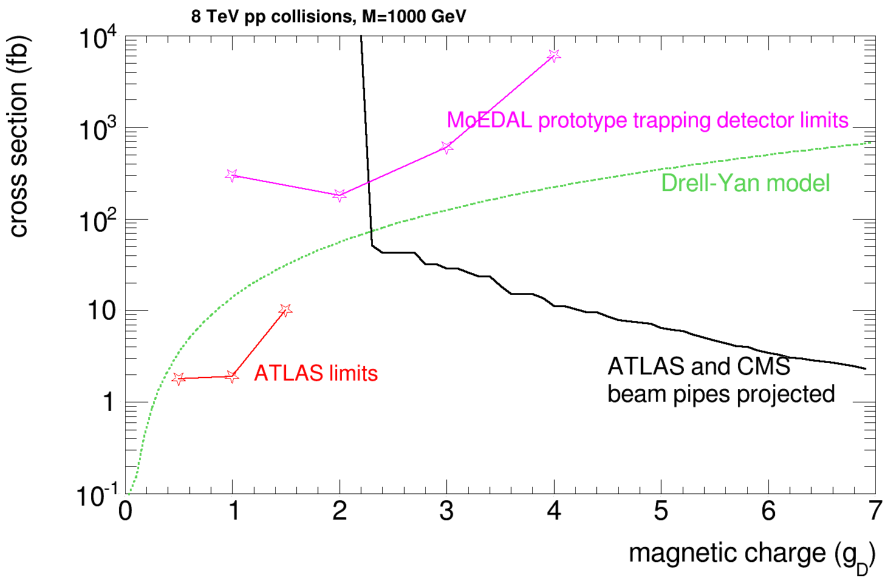
- Best collider limits for $|g| > g_D$
- Constrain $|g| = 4g_D$ for the first time at the LHC

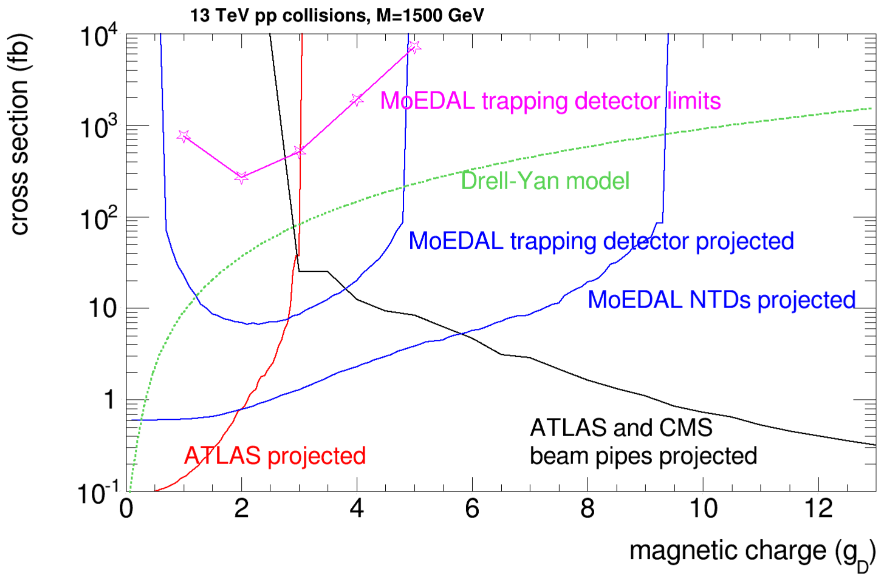
- Cross-section calculation is highly model-dependent

Near-future prospects

Rough discovery reach estimates

- Assuming 0.2 background events in ATLAS/CMS and ~0.00 background events in MoEDAL



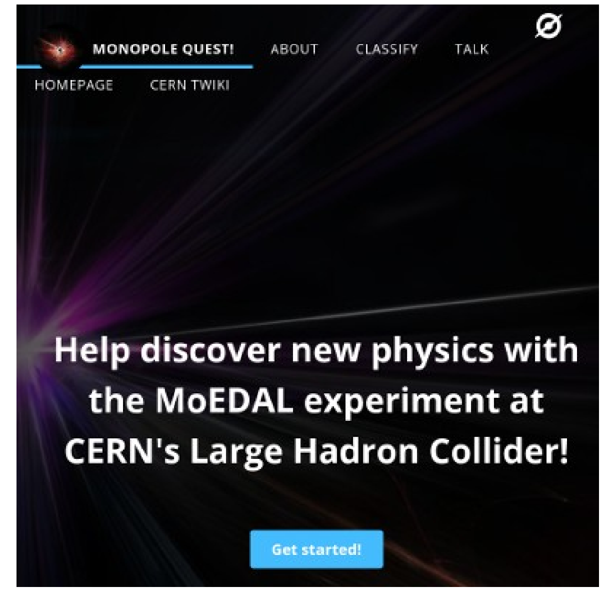


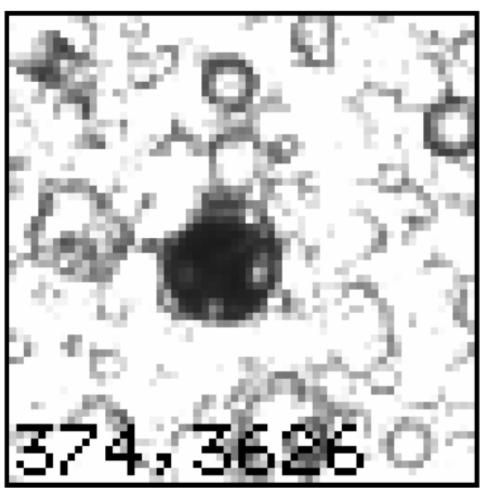
EPJC 72, 1985 (2012)

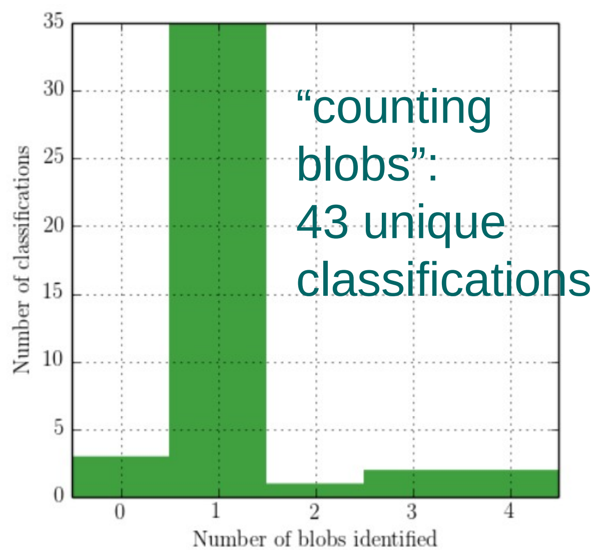
MoEDAL's unique patterns

https://www.zooniverse.org/projects/twhyntie/monopole-quest

- Machine vision
  - Modern fast scanners
  - Automatic pattern recognition
- Citizen science – the Zooniverse
  - Analysis of images from TimePix and NTDs







NTD exposed to collisions and ion beam

Use human brains
- signal identification in big messy images
- "anything odd?"

Summary

MoEDAL is a dedicated LHC experiment for searching for new charged long-lived particles

- Passive detector techniques – robust design
- Complementary to general-purpose experiments
- Pioneering MoEDAL trapping detector first results surpass existing constraints for a range of monopole charges and masses

A few shots left to complete the LHC monopole hunt

- ATLAS@13 TeV
- MoEDAL NTDs
- Trapping in beam pipes