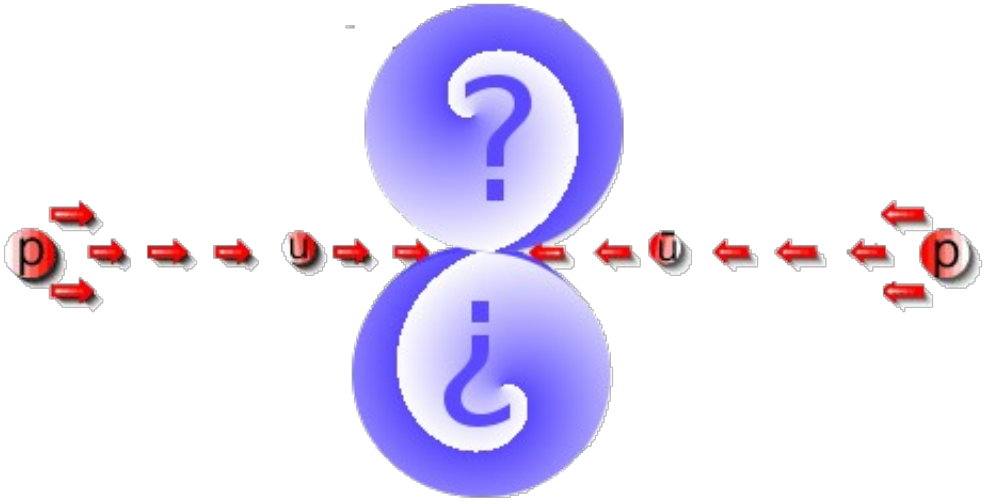
Search for magnetic monopoles with the MoEDAL prototype trapping detector in 8 TeV *pp* collisions at the LHC



Philippe Mermod, University of Geneva
CERN PH-LHC Seminar, 12 July 2016

Physics beyond the Standard Model

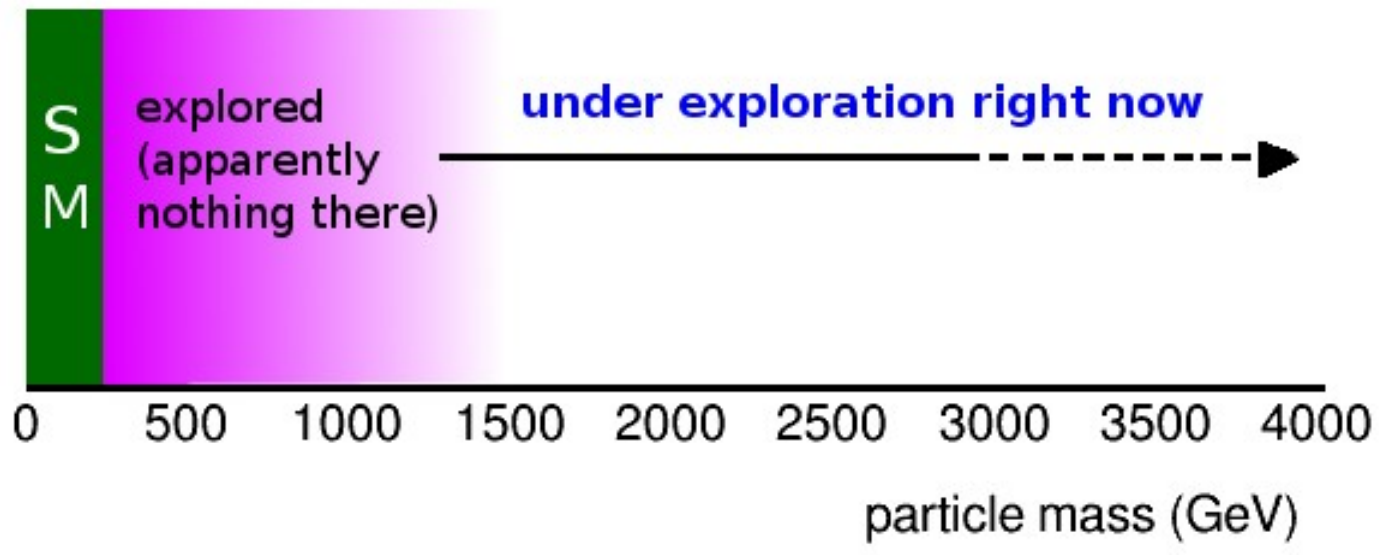
Theoretical hints

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

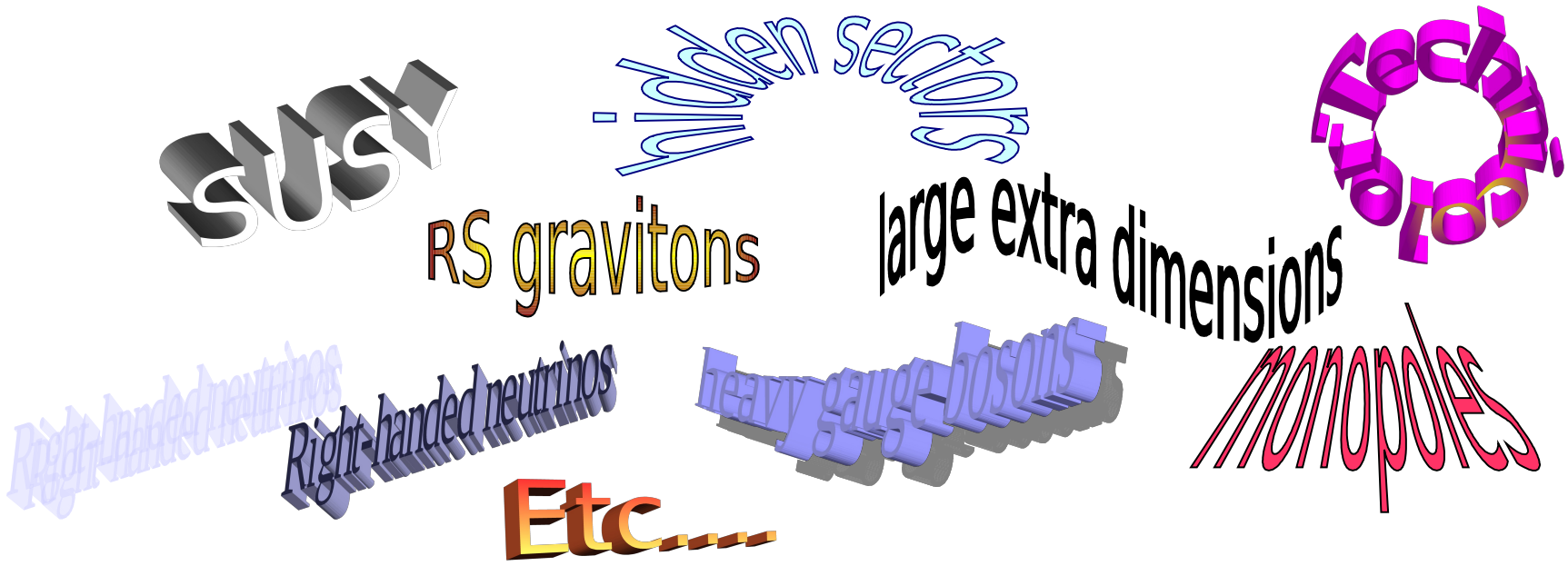
Experimental evidence

- Neutrino masses
- Dark matter
- Matter-antimatter asymmetry

The LHC is a discovery machine

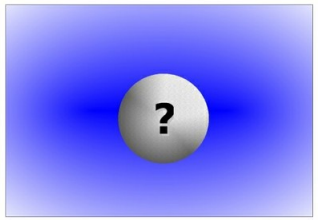


The search for new physics



The search for new physics

- We have no clue really...



blue sky,
uncharted territory

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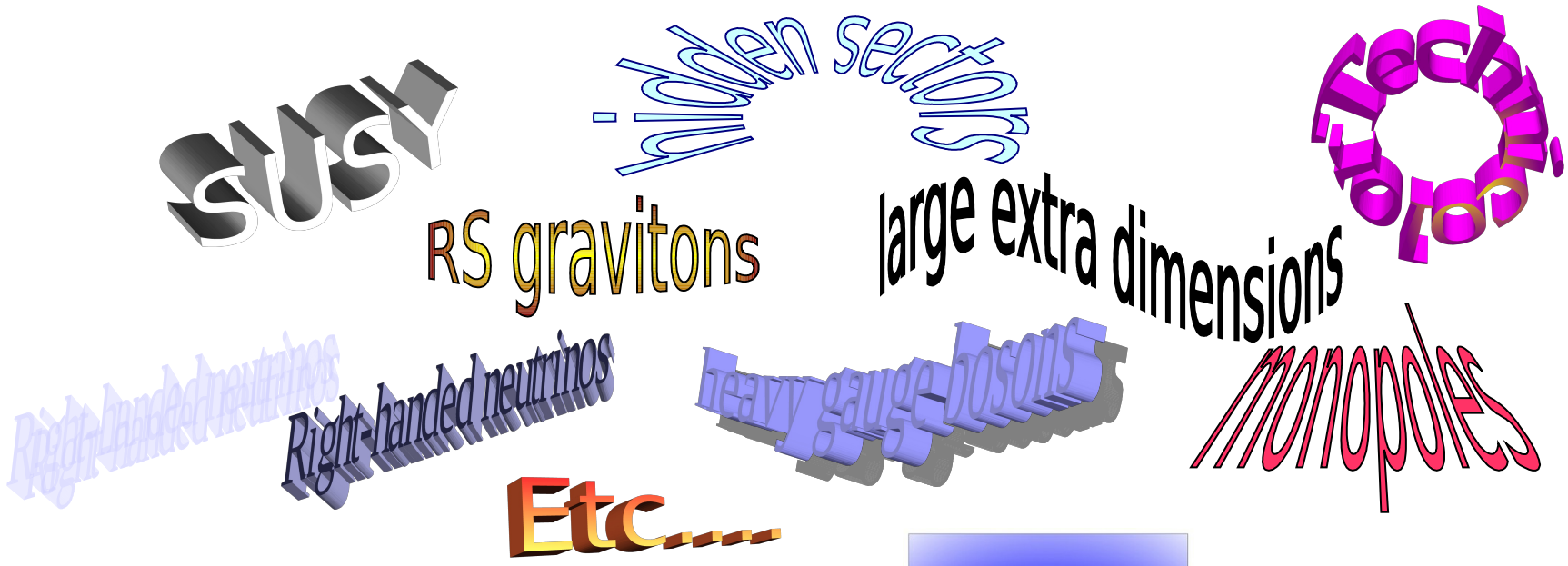

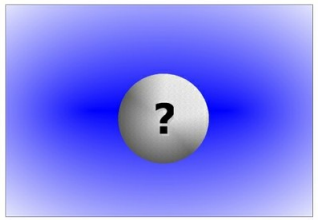

blue sky,
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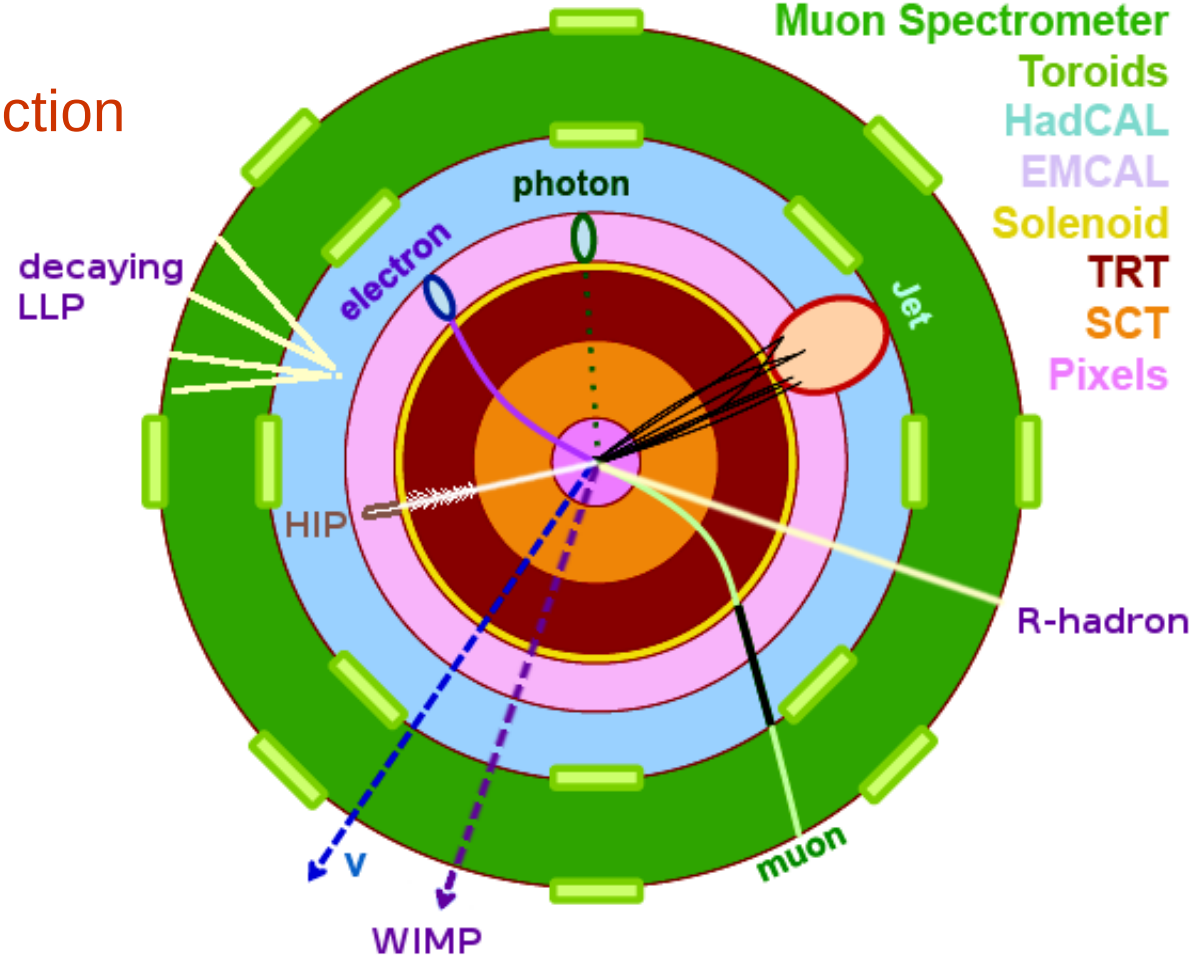
- We have no clue really...
- **What matters is to**
  make sure to cover all possible signatures
  - ➔ Photons, leptons, jets, missing energy...
  - ➔ Resonances, excesses, deviations, rare decays...
  - ➔ New long-lived particles

Long-lived particles in a general-purpose detector

Unconventional signatures, issues with:

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



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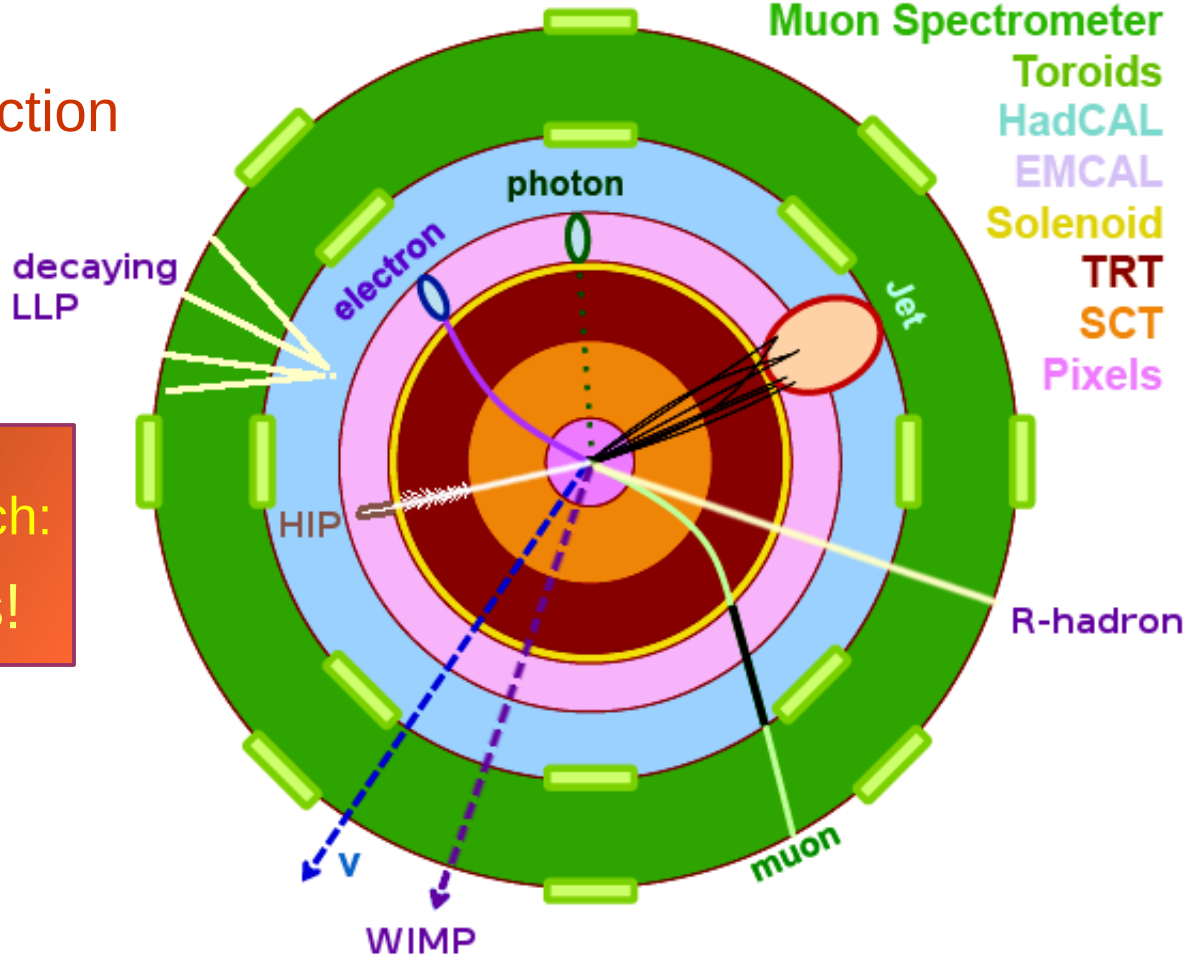


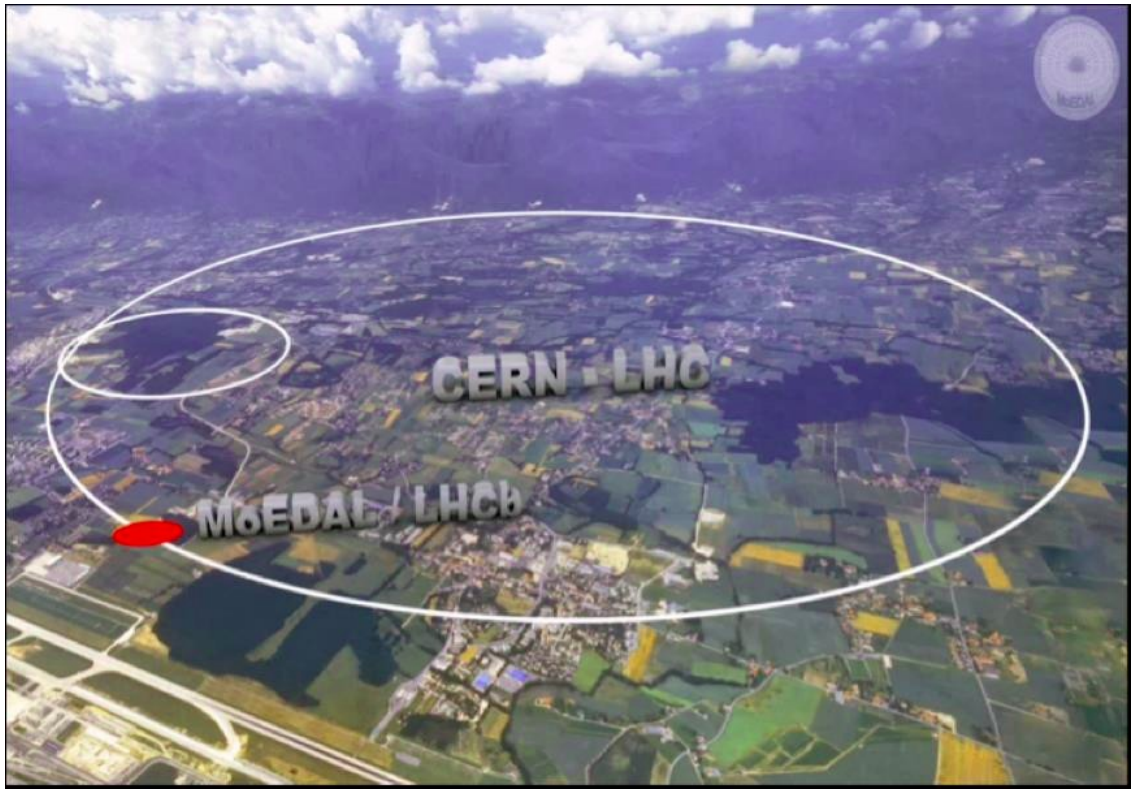
Complementary approach:

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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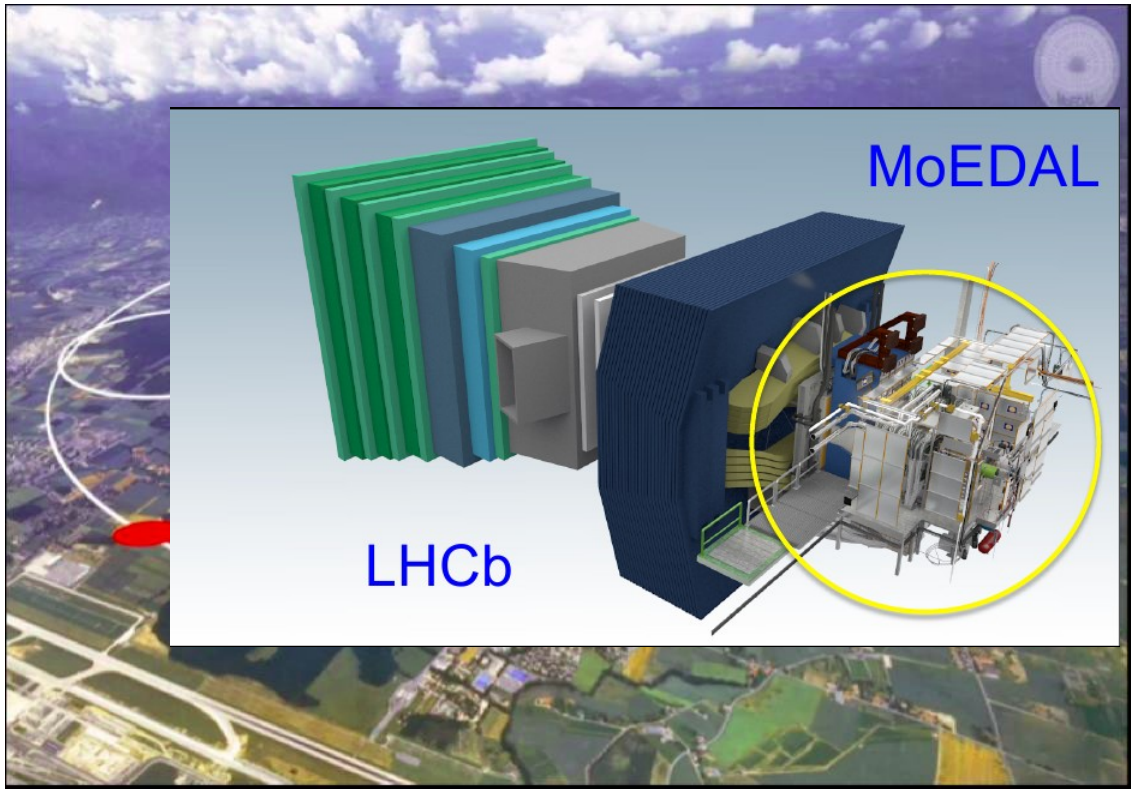

Detector subsystems

- 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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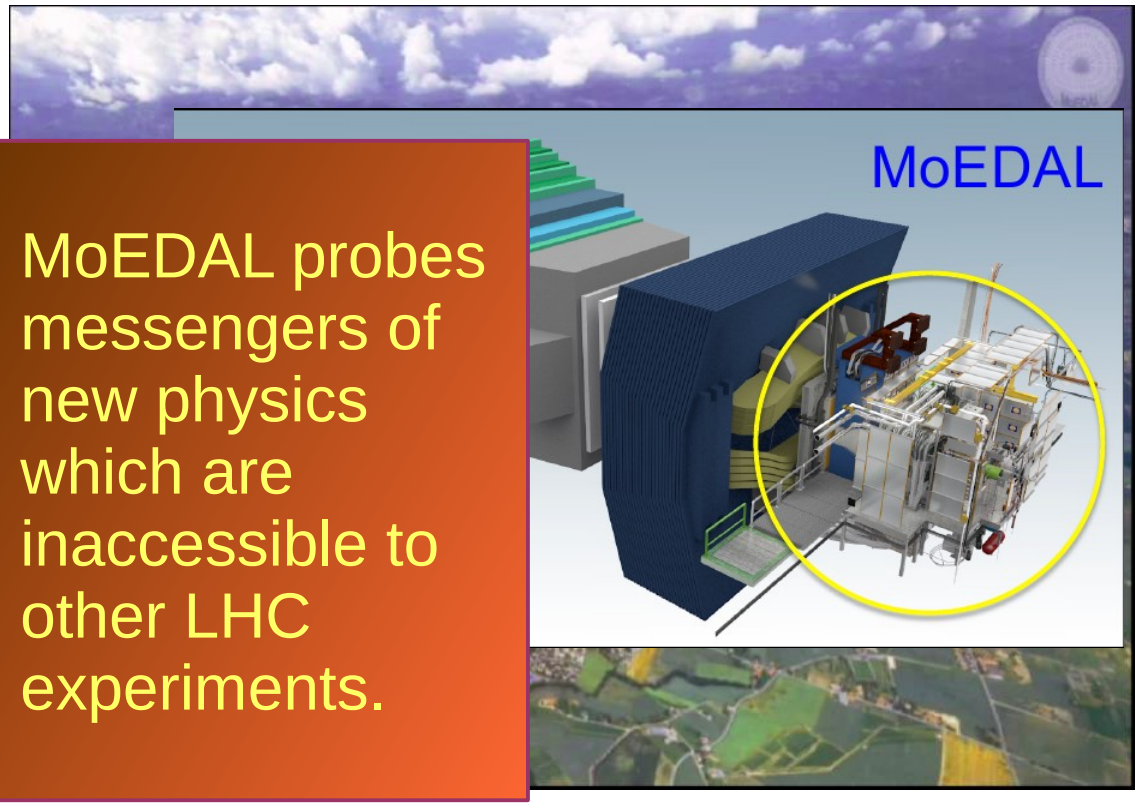

MoEDAL probes messengers of new physics which are inaccessible to other LHC experiments.

Detector subsystems

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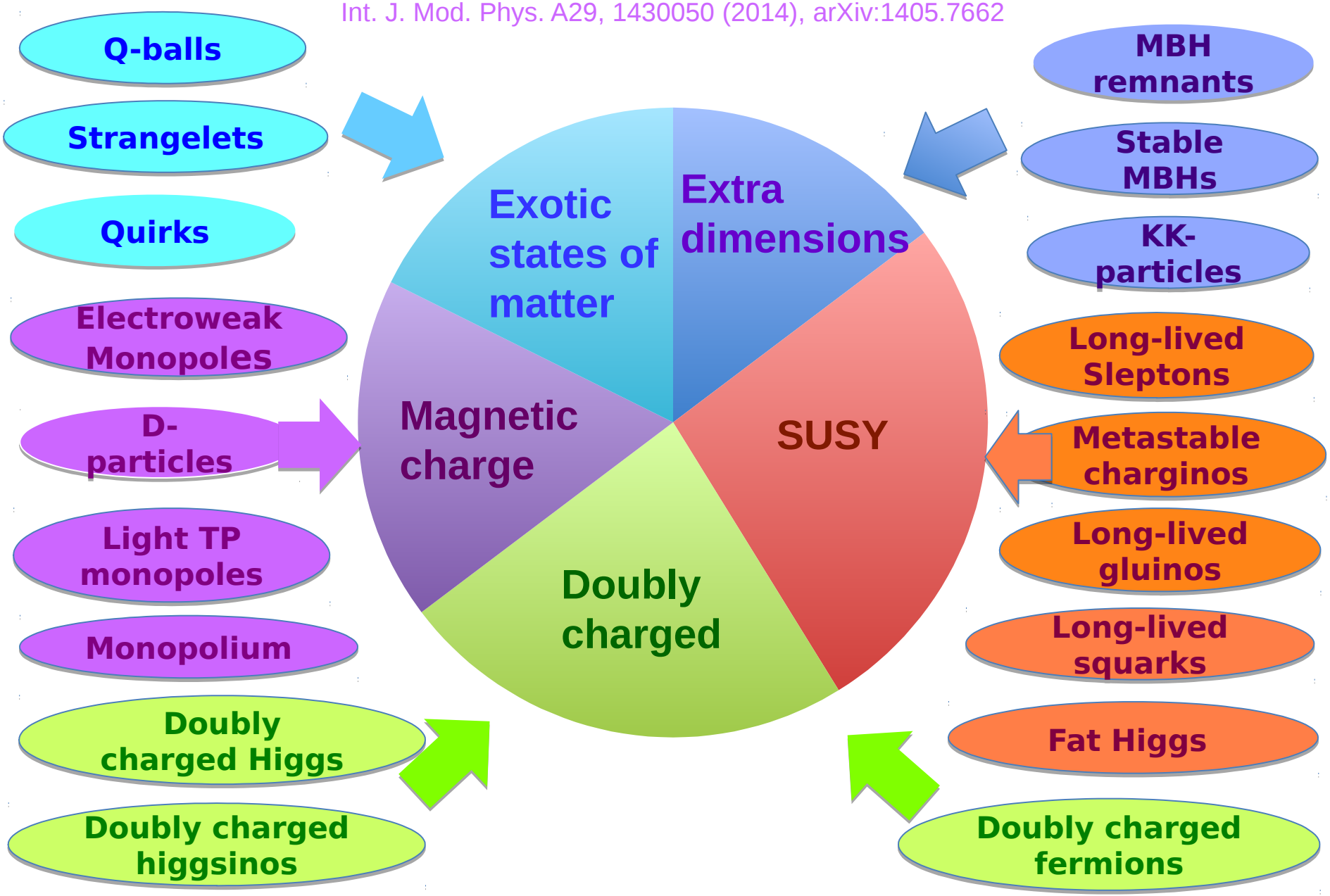
The MoEDAL physics programme

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



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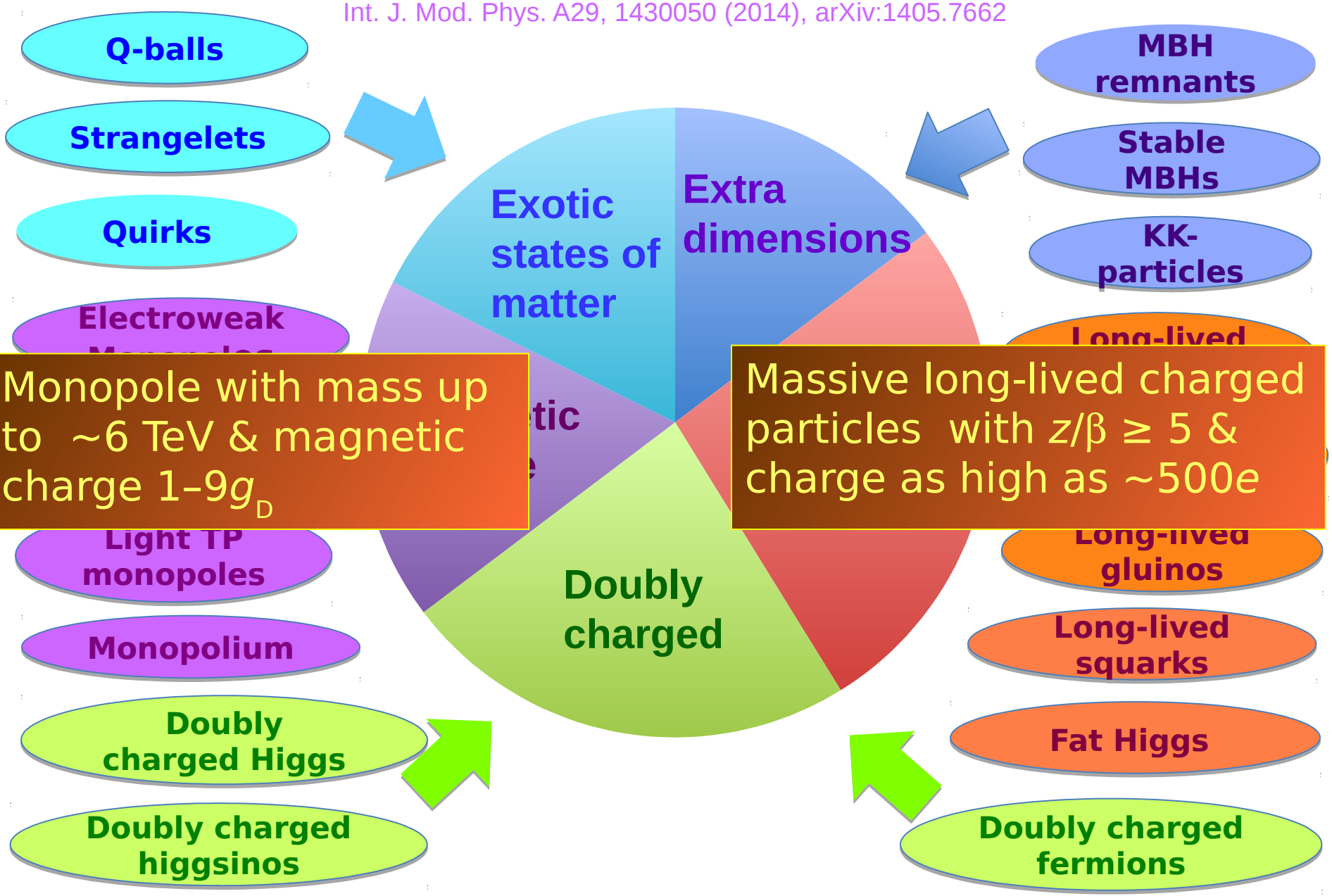
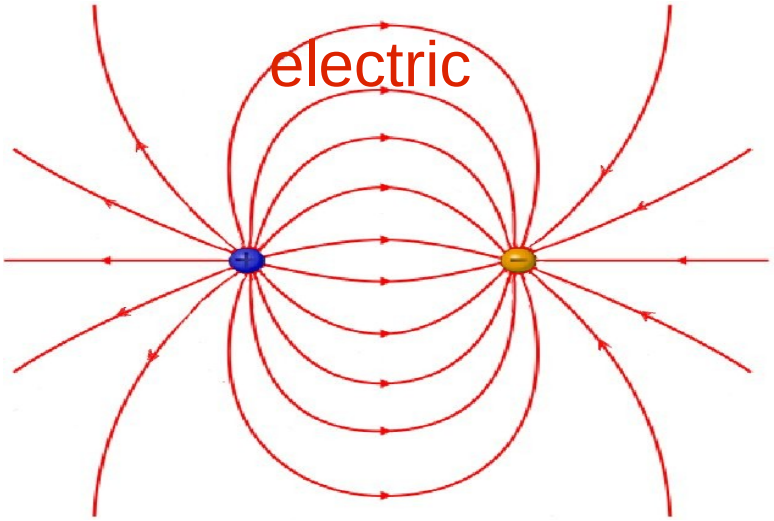
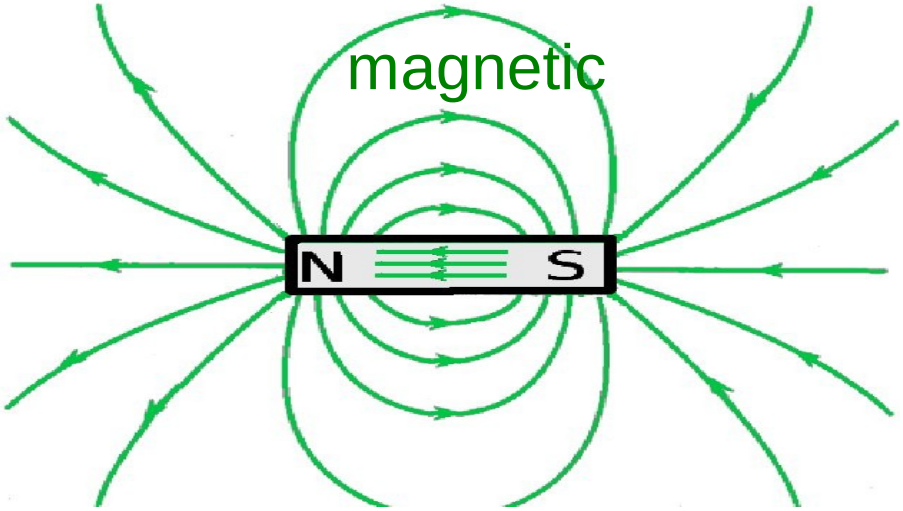


The monopole

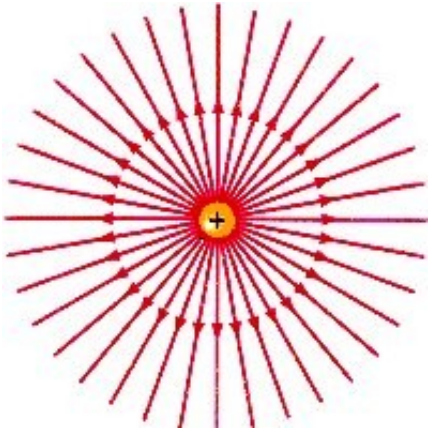




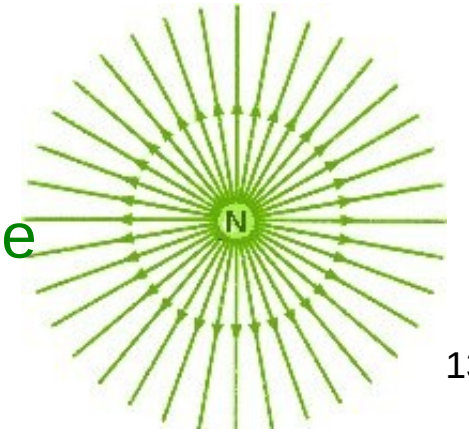
Sources of electric field exist (electrons, protons...)

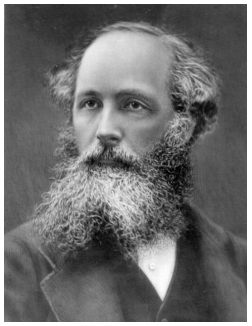
– Are there magnetic equivalents?

proton



magnetic monopole

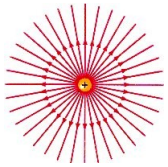




Maxwell's equations
(1862)

Without monopoles

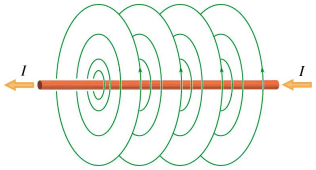
$$\nabla \cdot \mathbf{E} = 4\pi\rho_e$$



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

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

$$\nabla \times \mathbf{B} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j_e}$$



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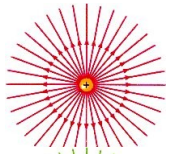
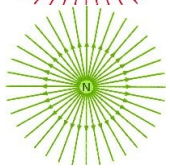


$$\nabla \cdot \mathbf{B} = 4\pi\rho_m$$



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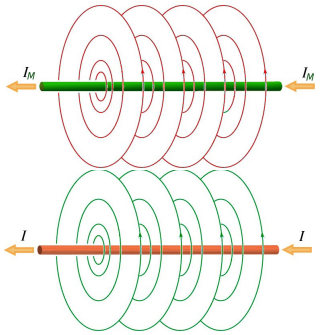
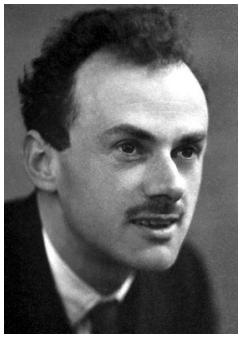
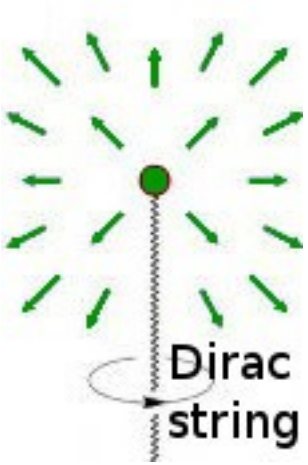




Dirac's quantisation condition (1931)



Proc. Roy. Soc. A 133, 60 (1931)

Valid quantum-field theory formulation

Side result:

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

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

PR 144, 1087 (1966)

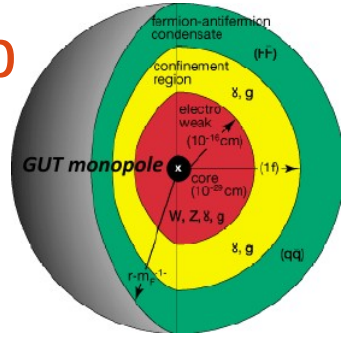
Schwinger's generalisation to dyons (1966)

$$q_{e1}q_{m2} - q_{e2}q_{m1} = 2n\frac{h}{\mu_0} \; (n \text{ integer number})$$

't Hooft and Polyakov's GUT monopole (1974)

Nucl. Phys. B 79, 276 (1974); JETP Lett. 20, 194 (1974)

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

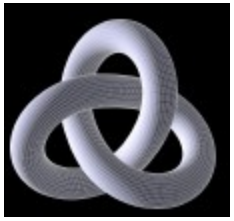


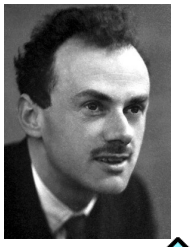
- **Topological monopole solution. Very general result!**
- Minimum magnetic charge g_D or $2g_D$ (depending on model)
- Mass ~ 10^{16} GeV (unification scale)

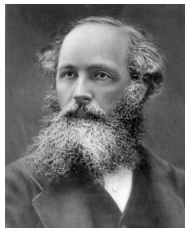
Monopole non-trivial solutions are allowed in the electroweak theory itself

- Charge $2g_D$
- Mass ~ few TeV

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



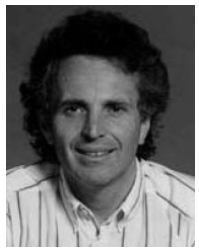


CHARGE
QUANTISATION

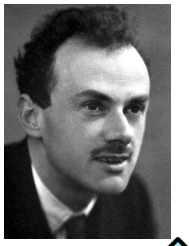
MAGNETIC
MONOPOLES

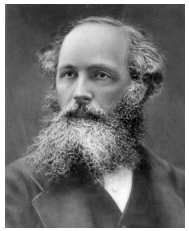
UNIFICATION
OF FORCES

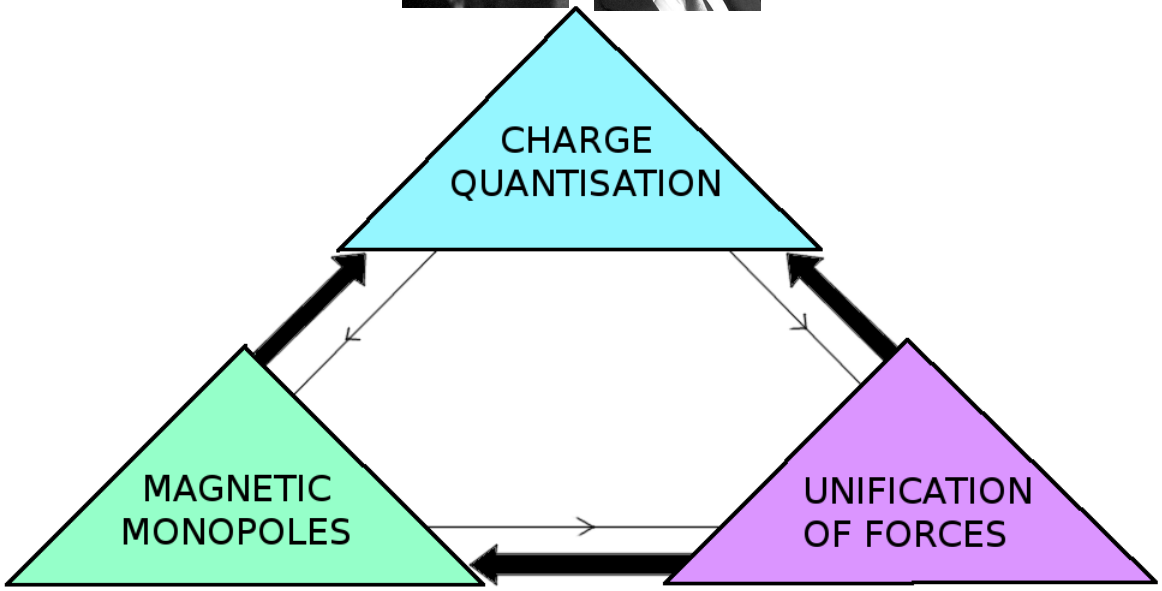



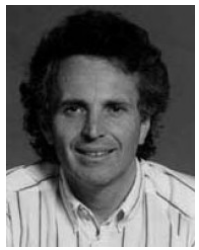
Under these circumstances one would be surprised if nature had made no use of it.

(1931)





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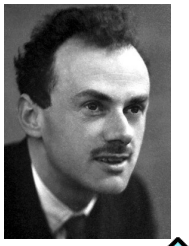
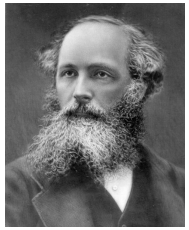
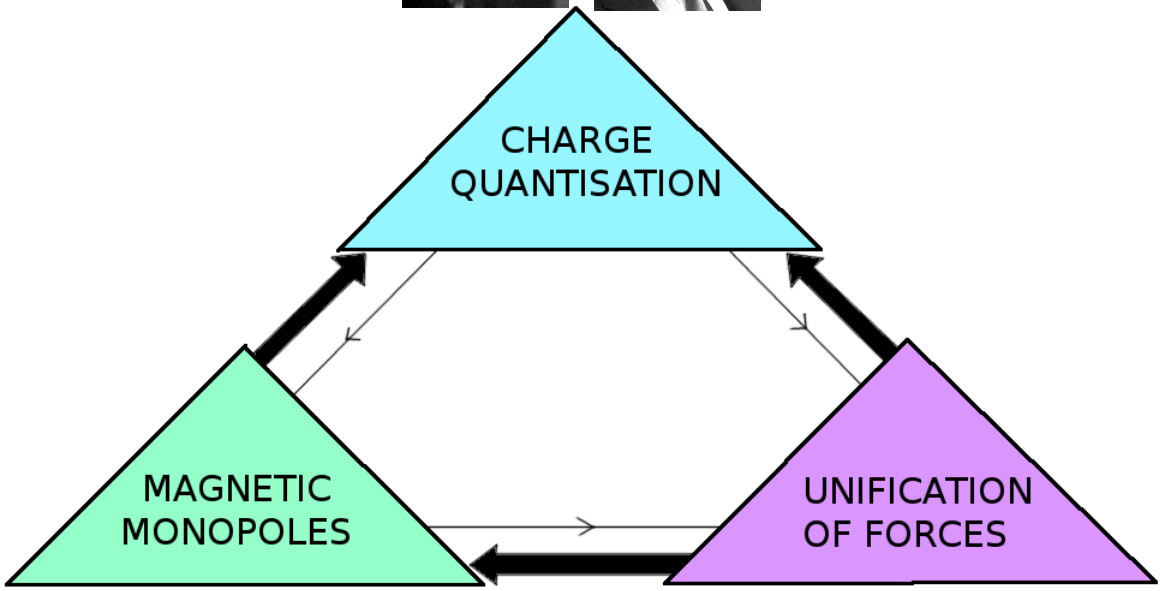


The magnetic monopole is the most venerable member of the mythological bestiary of physics.

(1986)

Don Groom





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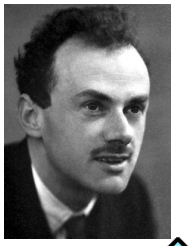

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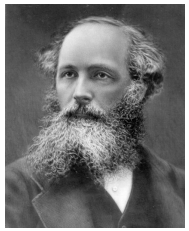

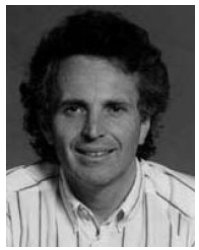

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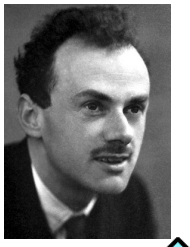

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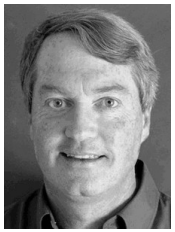
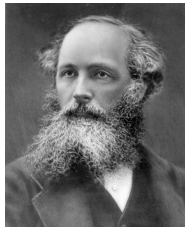


Joe Polchinski

Tini Veltman



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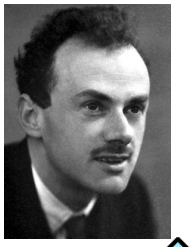

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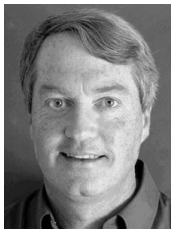

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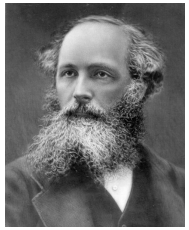
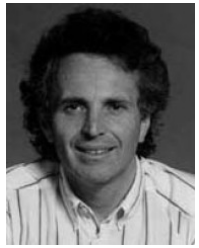




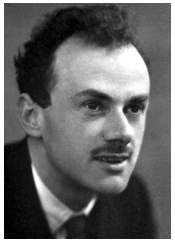
John Preskill

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.

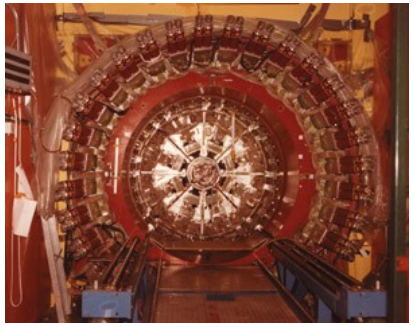
(1984)

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)



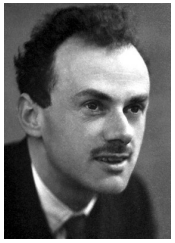


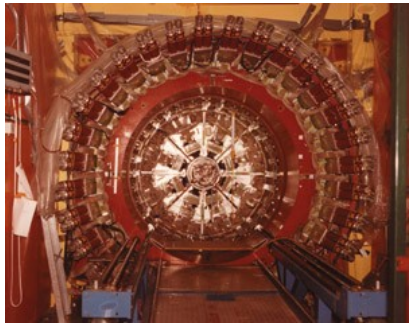



Where to look for monopoles?

- 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)

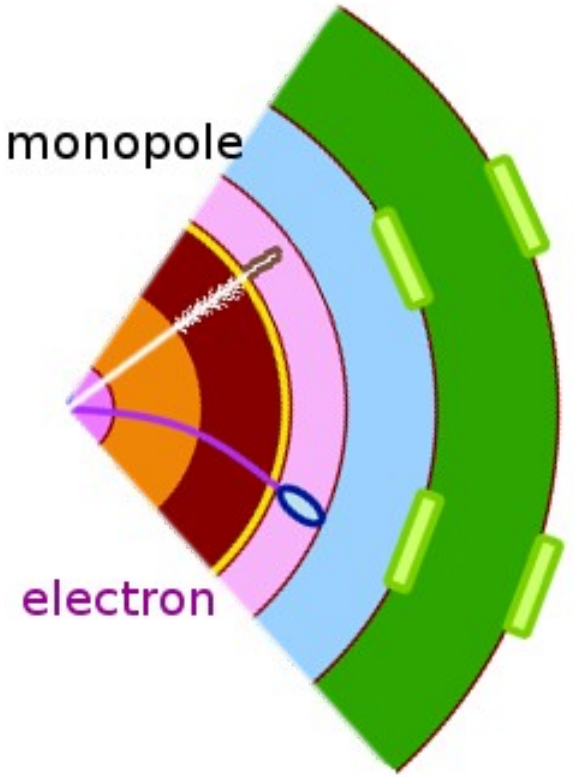
Monopole searches are performed at colliders every time a new energy regime is made accessible





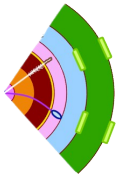
Direct HIP/monopole detection at colliders (1)

1) General-purpose detectors (OPAL, CDF, ATLAS, CMS...)
   - High ionisation
   - Pencil-like calorimeter deposit
   - Anomalous bending



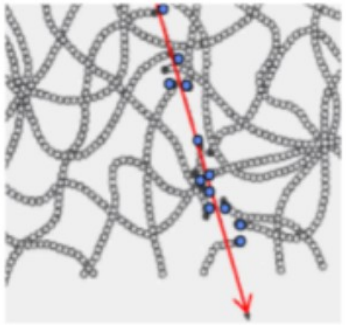
Direct HIP/monopole detection at colliders (2)

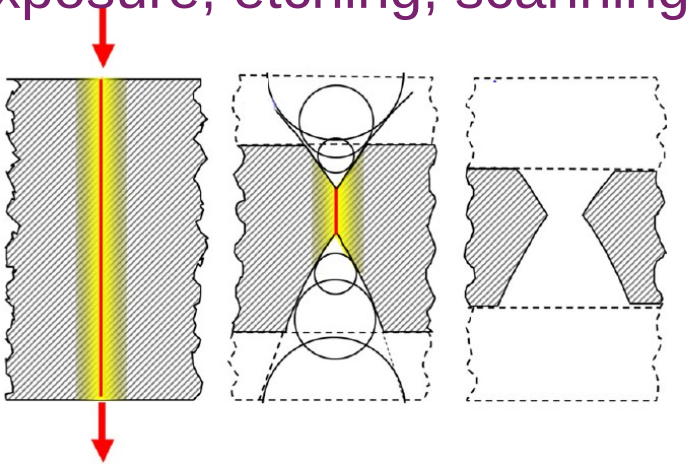
1) General-purpose detectors



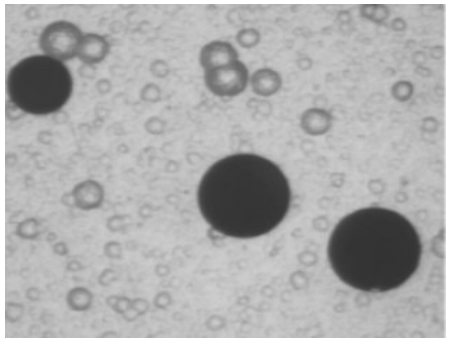
2) Nuclear-track detectors

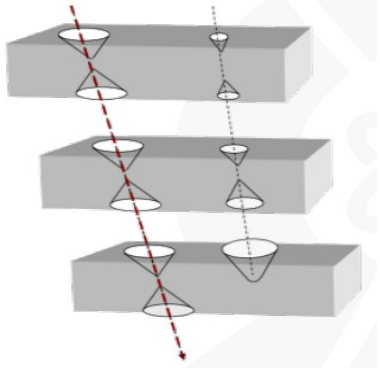
– Plastic NTD foil – exposure, etching, scanning





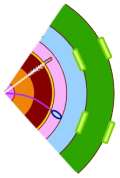
– Etch-pit cones (~50 μm) in successive sheets



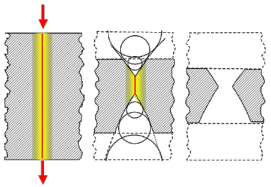


Direct HIP/monopole detection at colliders (3)

1) General-purpose detectors

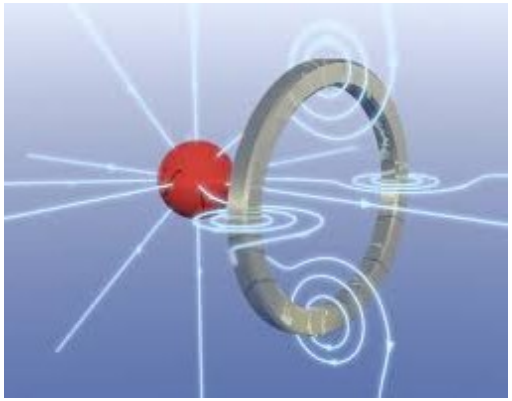


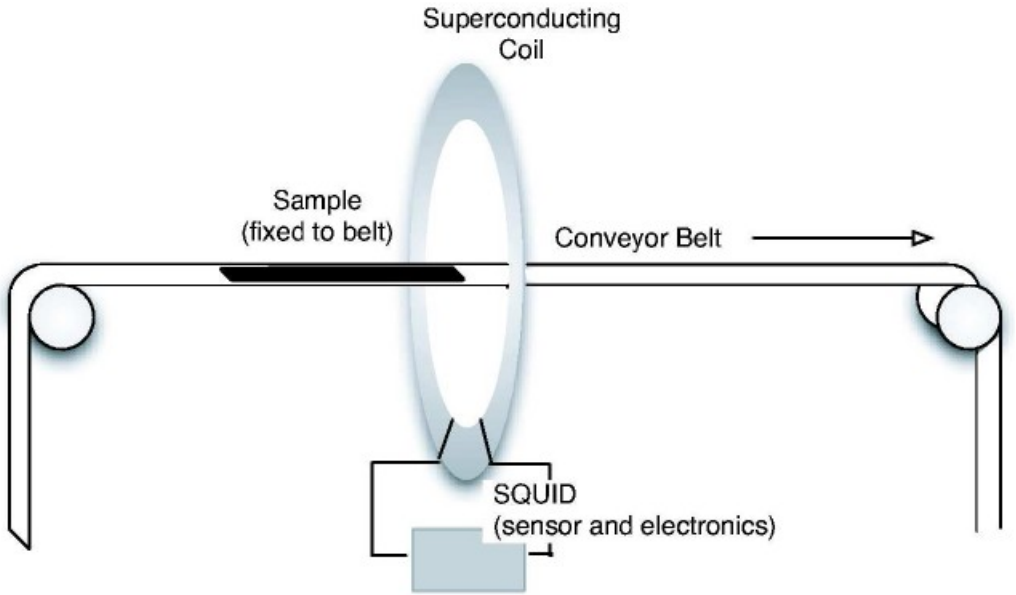
2) Nuclear-track detectors



3) Induction technique

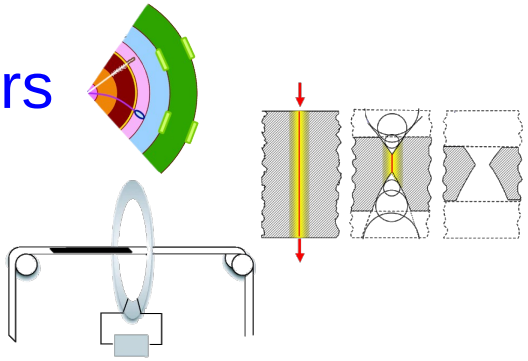
- Expect monopole-nucleus binding energy ~100 keV
  (Rept. Prog. Phys. 69, 1637 (2006), arXiv:hep-ex/0602040)
- Persistent current after passage through superconducting coil





Direct HIP/monopole detection at colliders (4)

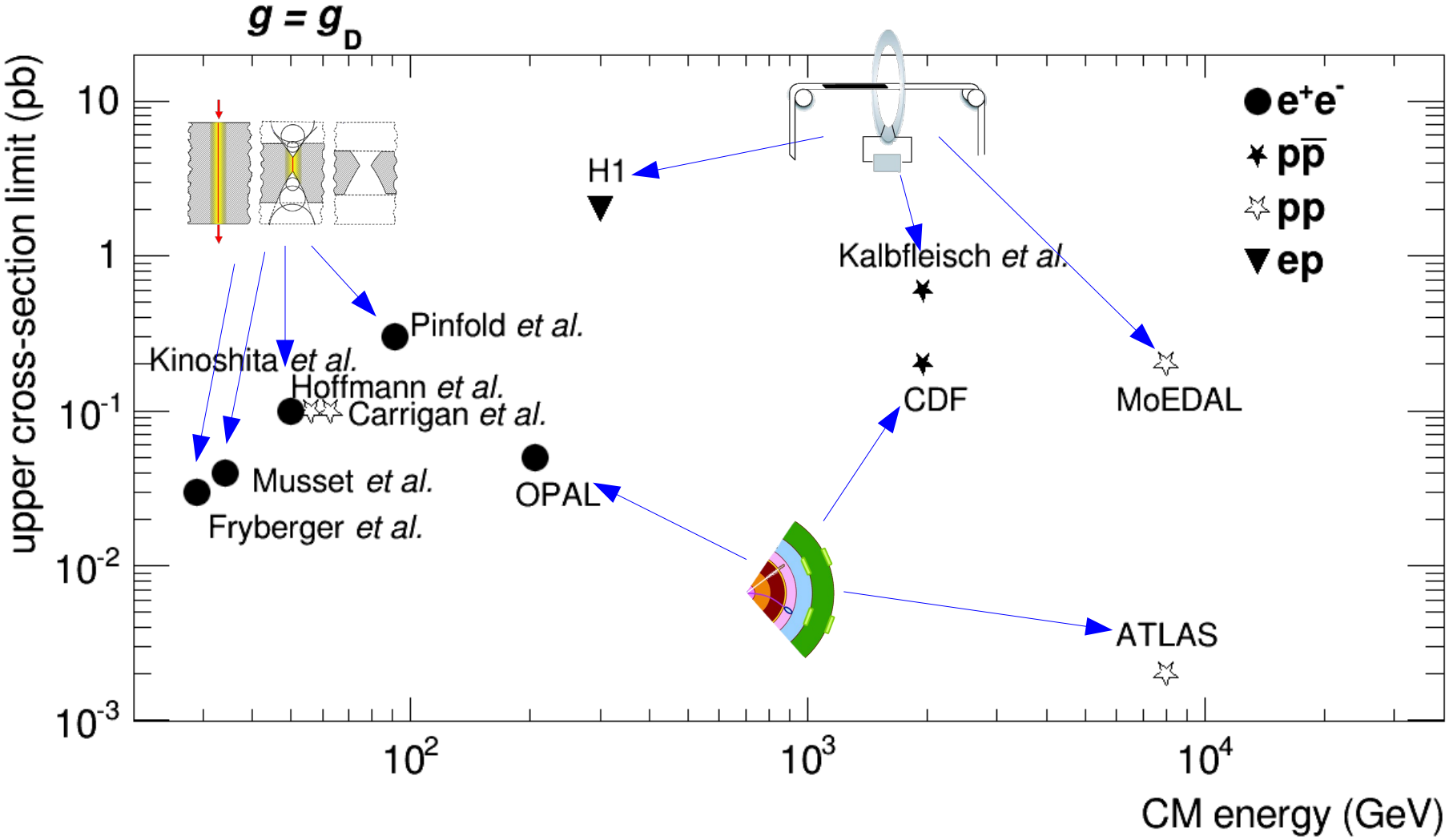
1) General-purpose detectors
2) Nuclear-track detectors
3) Induction technique



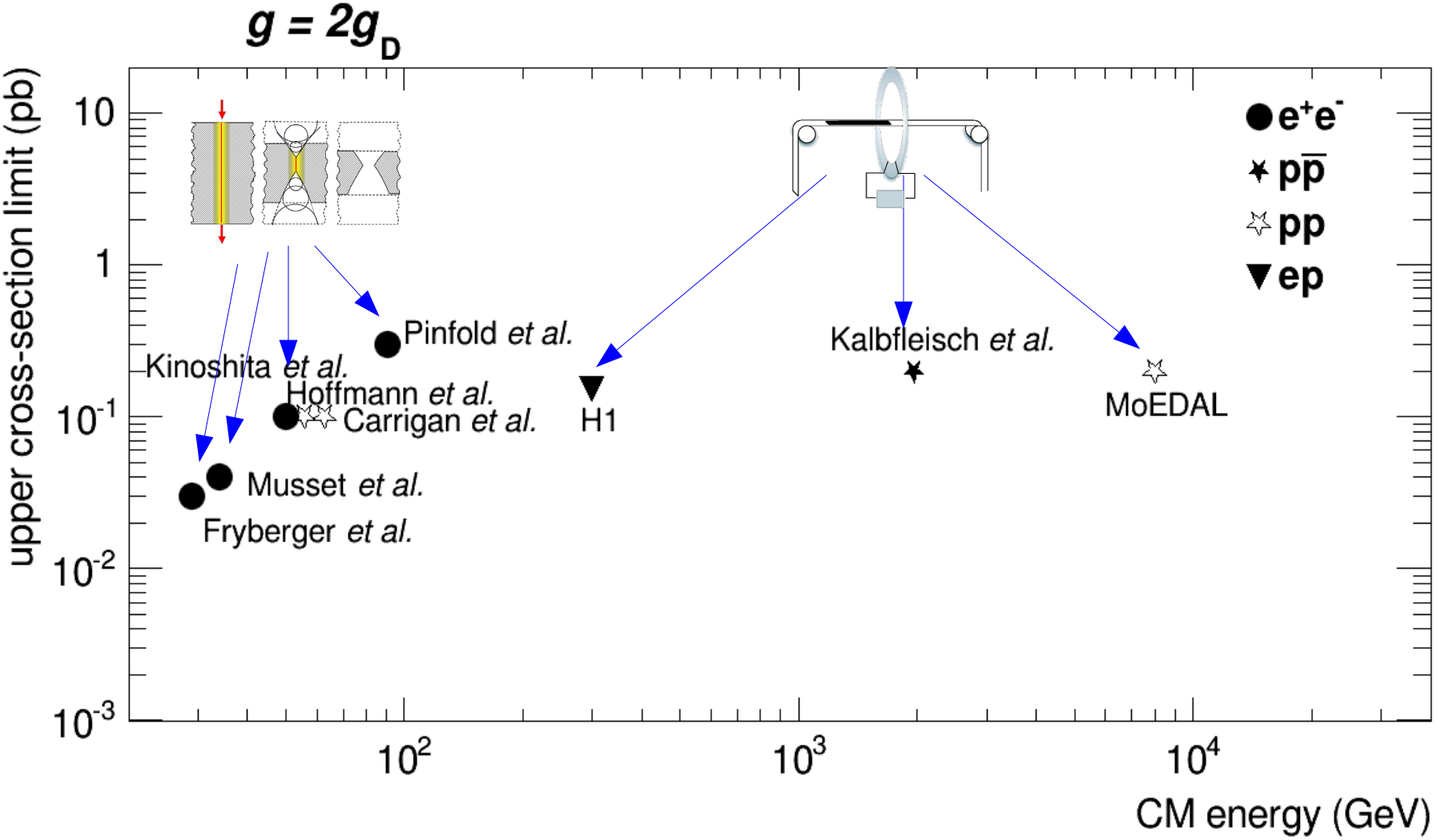
All three techniques are needed
to cover the full parameter space

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

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



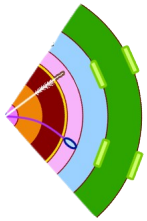
Direct collider monopole searches current limits (assuming $|g| = 2g_D$)



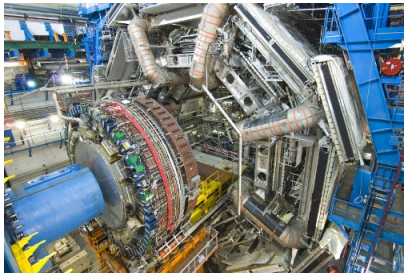
HIP searches at the LHC

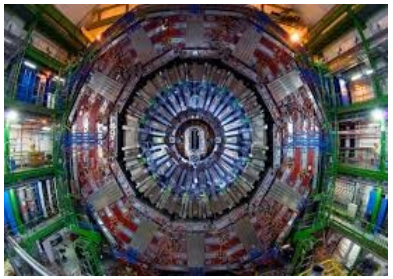
(see EPJC 72, 1985 (2012), arXiv:1112.2999)

- ATLAS and CMS

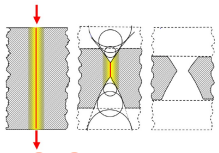


  - → $|g| \leq 2g_D$
  - → $0.3 \leq |z|/\beta \leq 100$



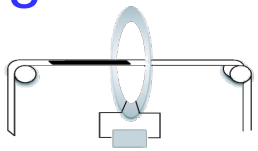


- MoEDAL NTD detectors

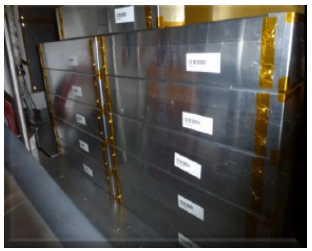


  - → $|g| \leq 9g_D$
  - → $5 \leq |z|/\beta \leq 500$

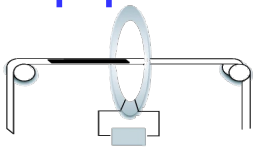
- MoEDAL trapping detector



  - → $|g| \leq 4g_D$



- Trapping in beam pipes



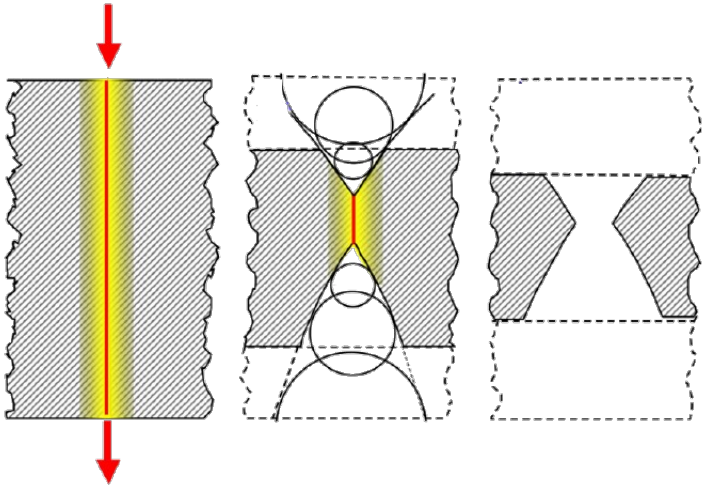
  - → $|g| \geq 4g_D$

Complementary techniques!

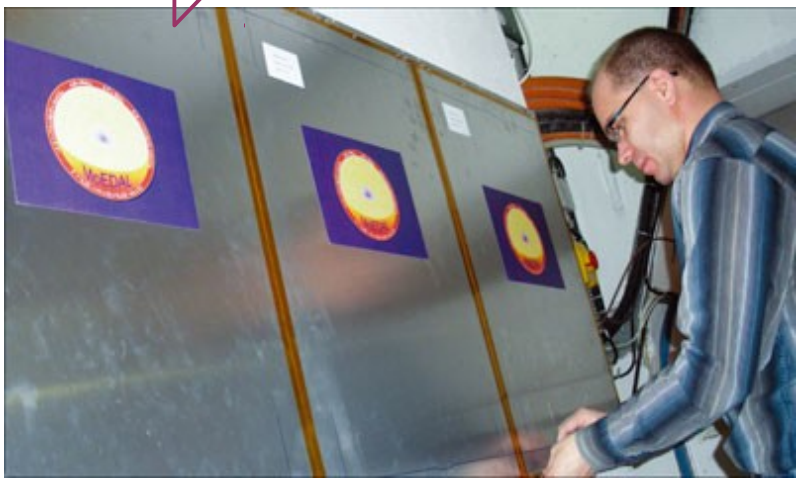
The advantages of a dedicated experiment

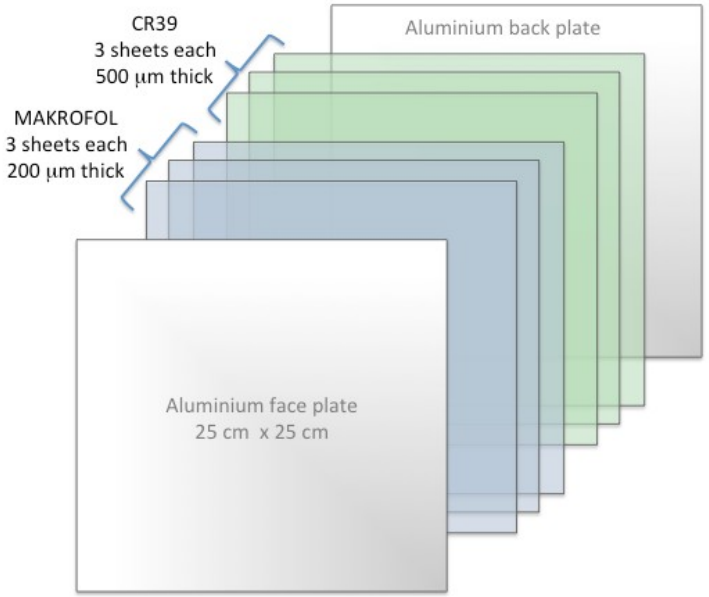
- Passive detectors
  - No electronics – no saturation, no timing constraints
  - No trigger – access high charges and masses
  - Tuned to specific signature – no backgrounds
  - Straightforward calibration – controlled response
  - Complementary techniques – different systematics
- Low budget
  - And high ingenuity
    → high *impact*/*cost* ratio!

Passive detection with NTDs in MoEDAL (1)

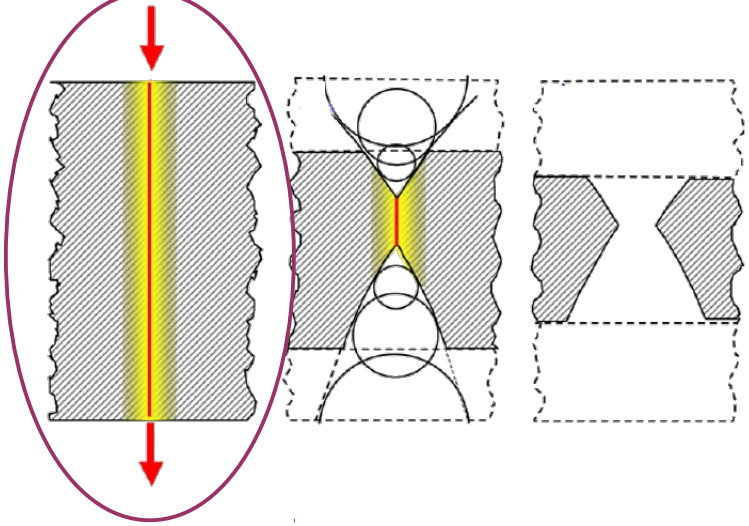


installation





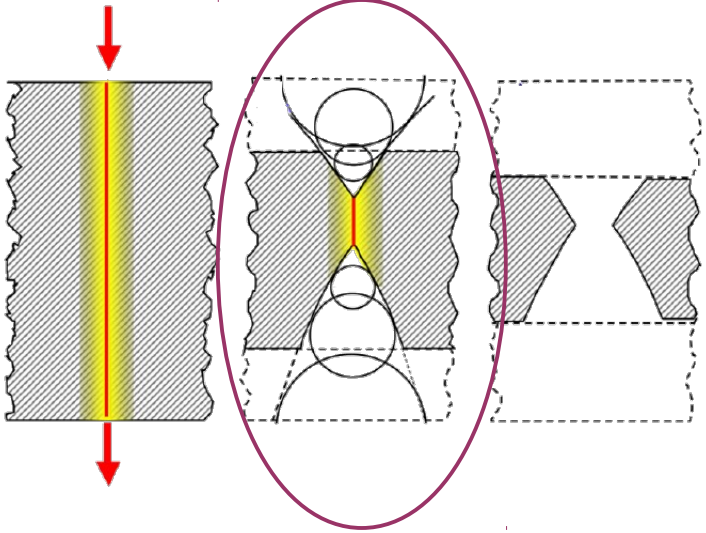
Passive detection with NTDs in MoEDAL (2)



installation

Exposure
(IP8)

Passive detection with NTDs in MoEDAL (3)



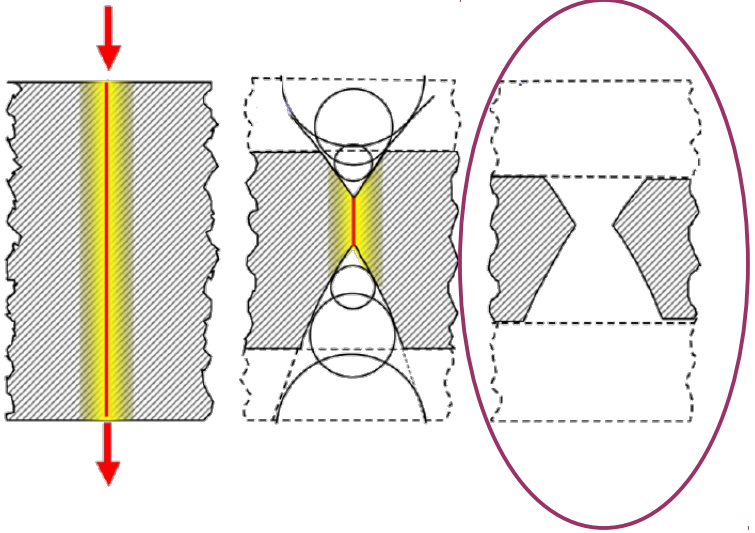
installation

Exposure
(IP8)

Removal

Etching
(Bologna)

Passive detection with NTDs in MoEDAL (4)



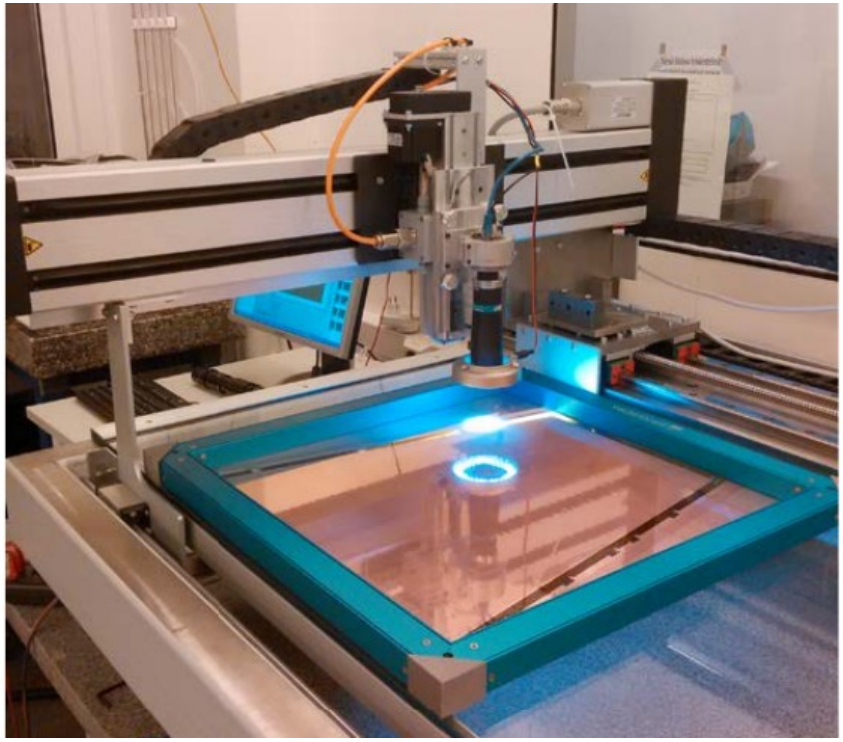
installation

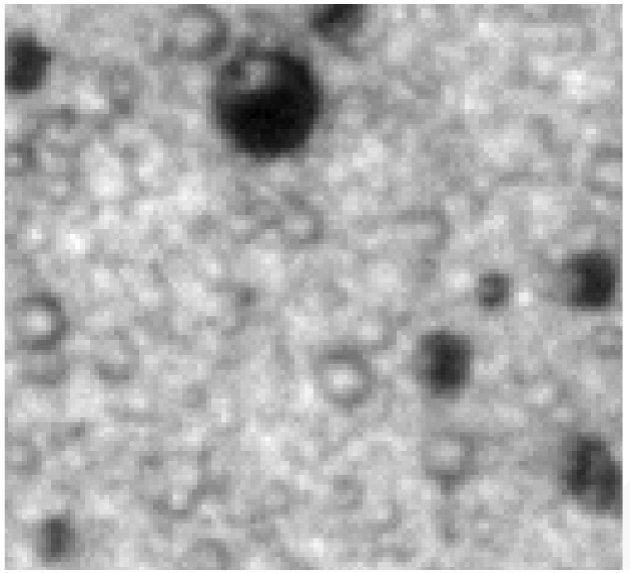
Exposure (IP8)

Removal

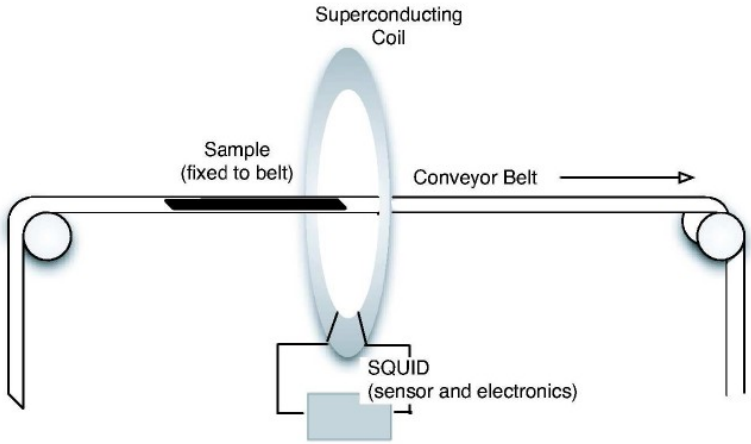
Etching (Bologna)

Scanning (Bologna, Münster, Helsinki)



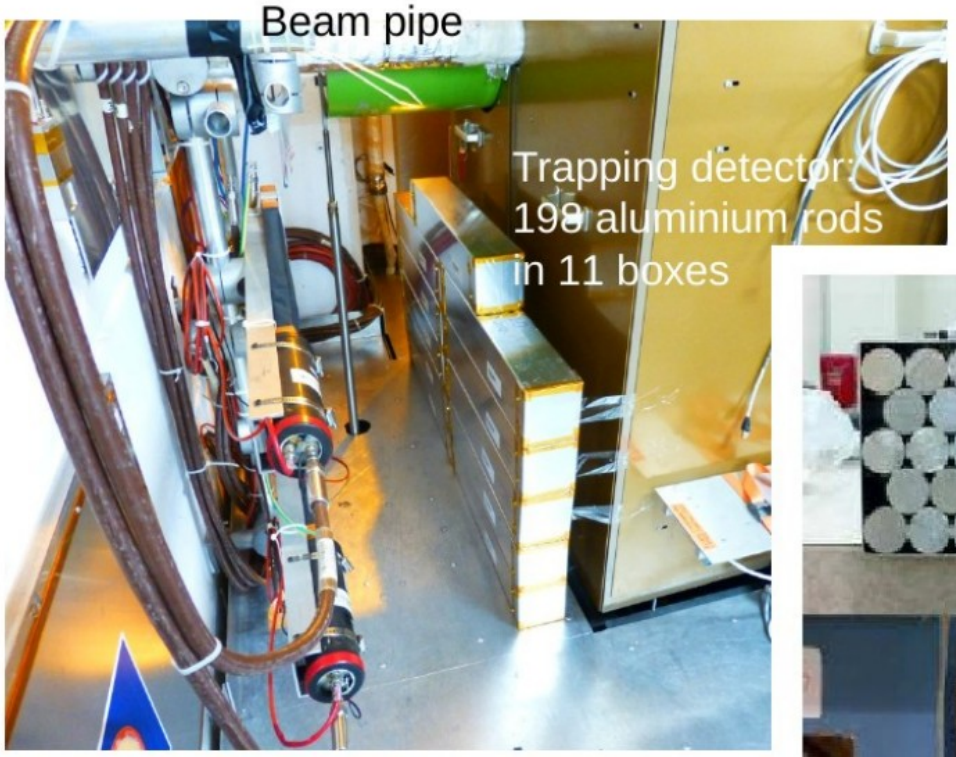


Passive detection with MoEDAL trapping array (1)



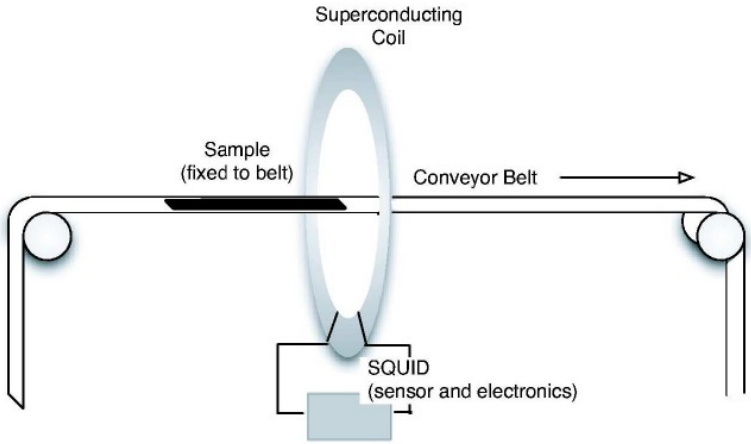
installation

Exposure (IP8)



Today's results are based on 0.75 fb^{-1} of exposure to 8 TeV *pp* collisions

Passive detection with MoEDAL trapping array (2)



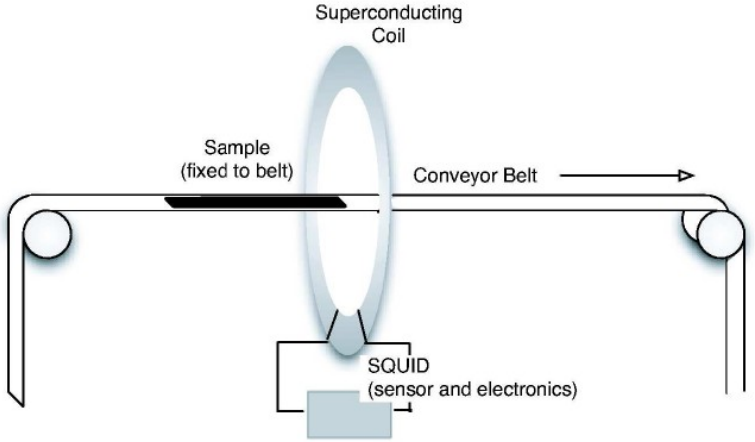
installation → Exposure (IP8) → Removal → Scanning (ETH Zurich)

Laboratory of Natural Magnetism, ETH Zurich

Magnetically shielded room

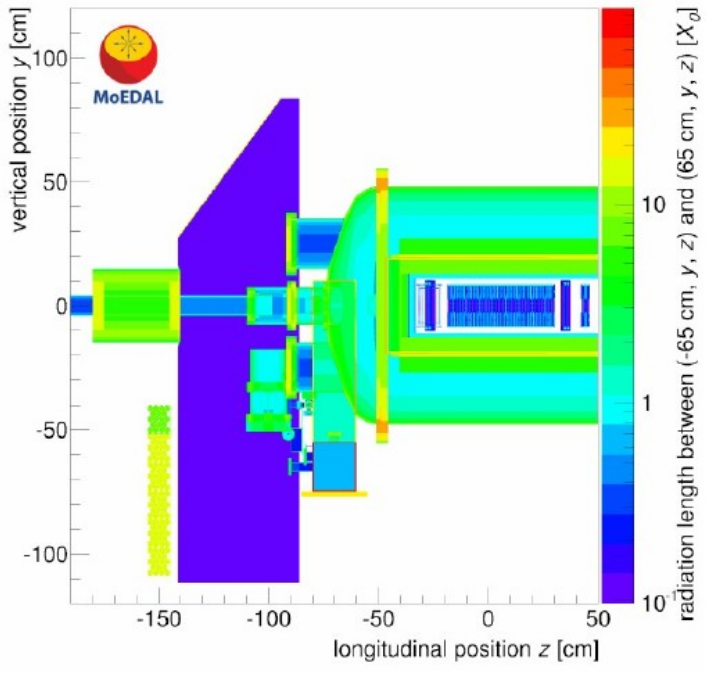
DC-SQUID magnetometer

Passive detection with MoEDAL trapping array (3)

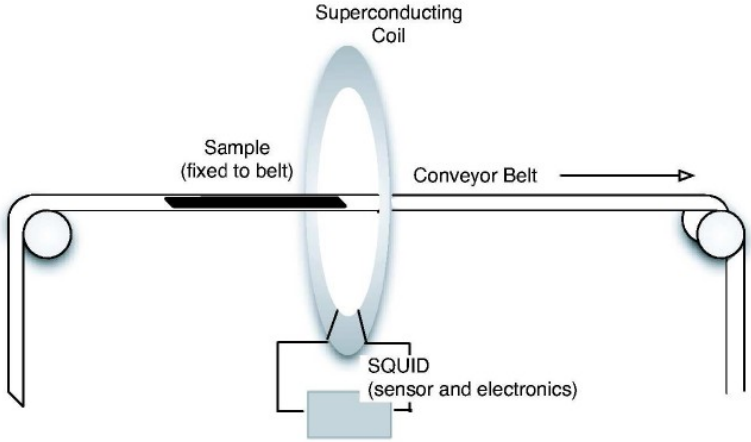


installation → Exposure (IP8) → Removal → Scanning (ETH Zurich)

Material description



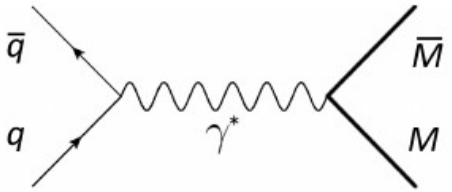
Passive detection with MoEDAL trapping array (4)

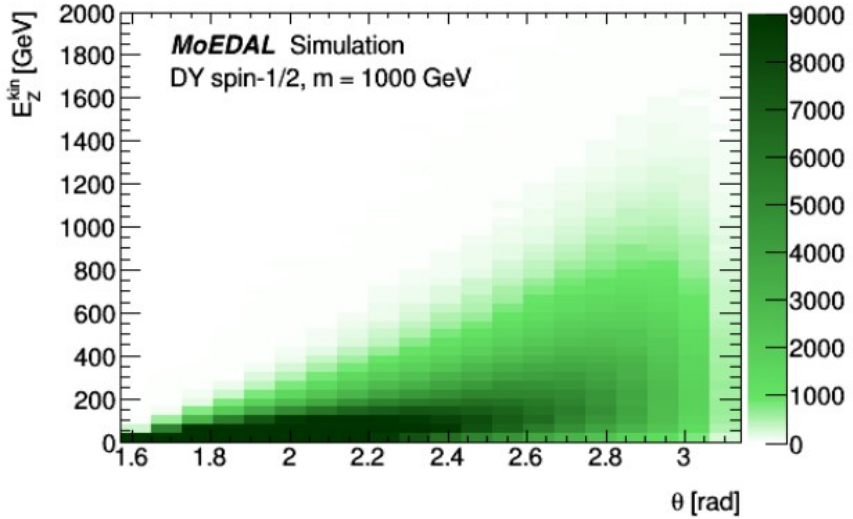


installation → **Exposure** (IP8) → Removal → **Scanning** (ETH Zurich)

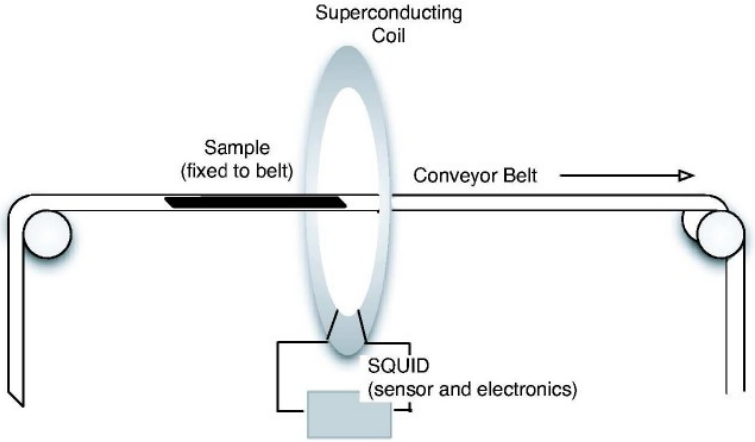
Material description

Event Generation (Madgraph)





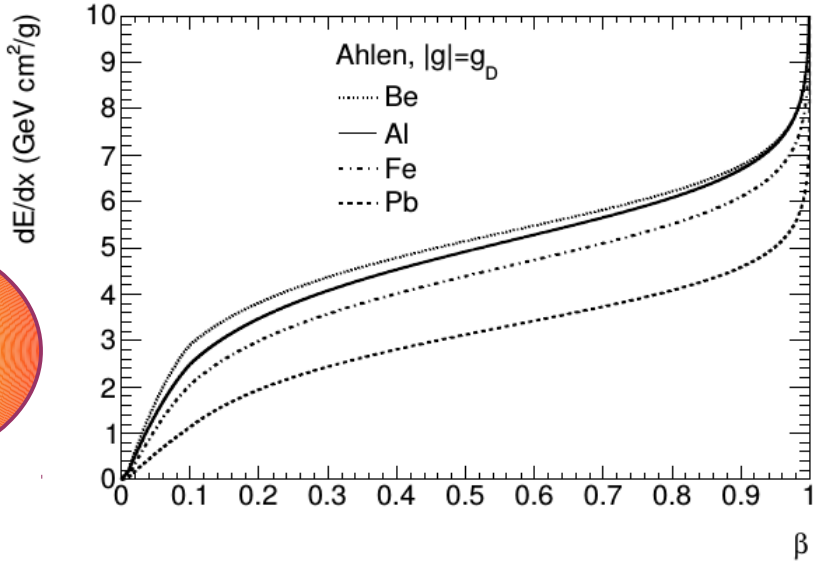
Passive detection with MoEDAL trapping array (5)



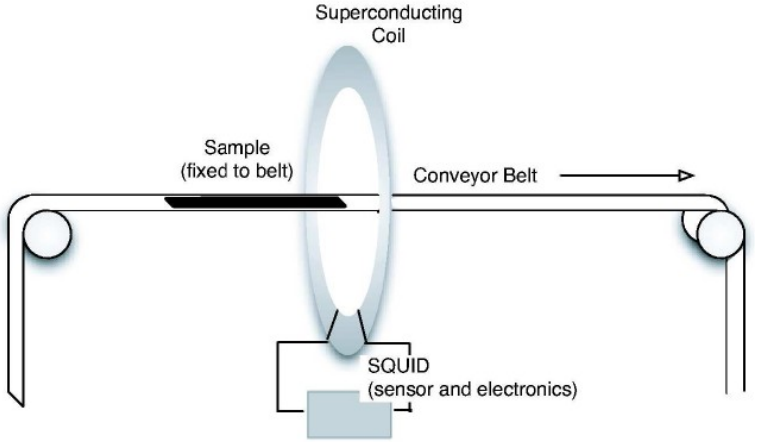
installation → Exposure (IP8) → Removal → Scanning (ETH Zurich)

Material description → Simulation (Geant4)

Event Generation (Madgraph) → Simulation (Geant4)



Passive detection with MoEDAL trapping array (6)

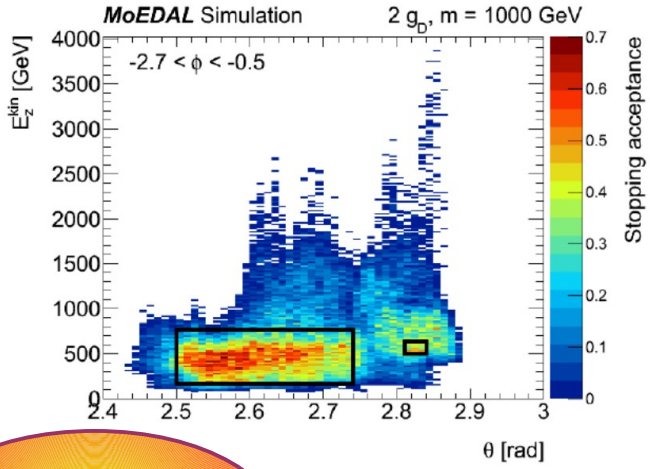


installation

Exposure (IP8)

Removal

Scanning (ETH Zurich)



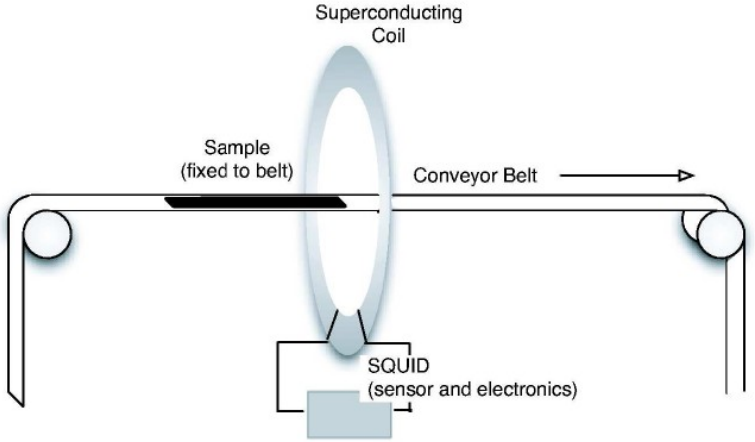
Material description

Event Generation (Madgraph)

Simulation (Geant4)

Acceptance

Passive detection with MoEDAL trapping array (7)



installation

Exposure (IP8)

Removal

Scanning (ETH Zurich)

Result

Material description

Simulation (Geant4)

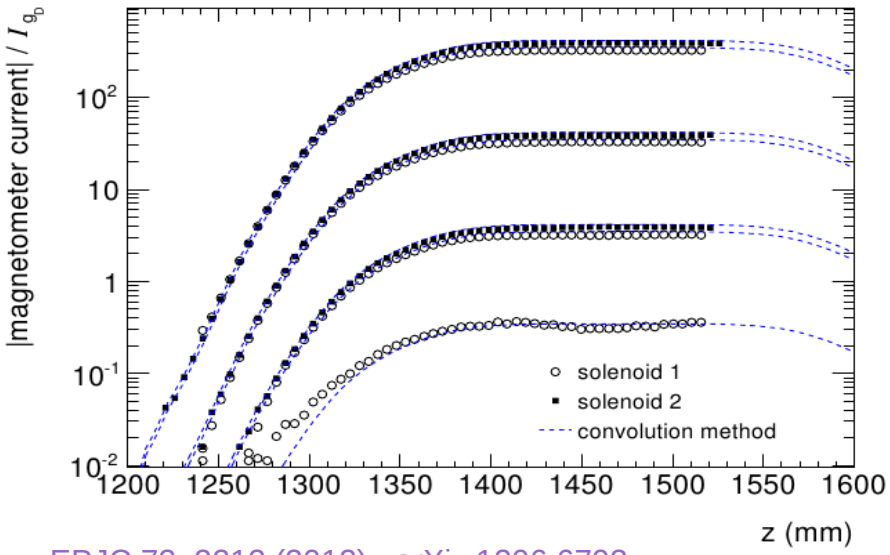
Acceptance

Event Generation (Madgraph)

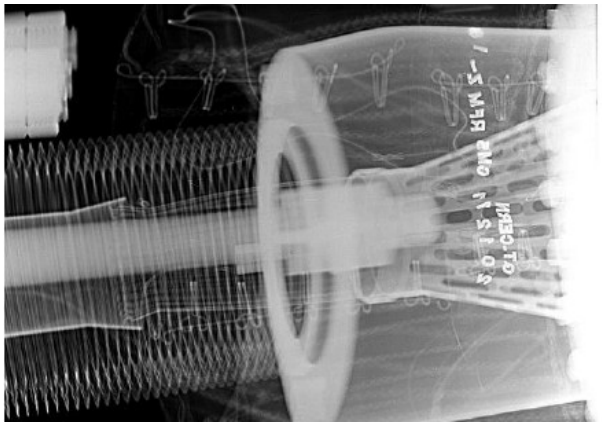
Magnetometer calibration and test

- Convolution method
  - Cumulative response profile of well-known magnetic moment
- Solenoid method
  - Long, thin solenoid with known properties and current

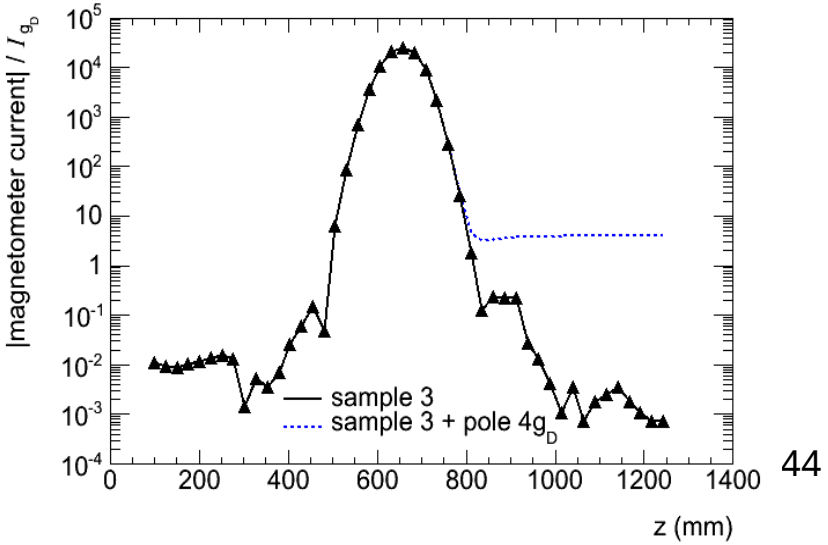
Linear and charge-symmetric response



EPJC 72, 2212 (2012), arXiv:1206.6793



Proof of concept with CMS "finger" samples

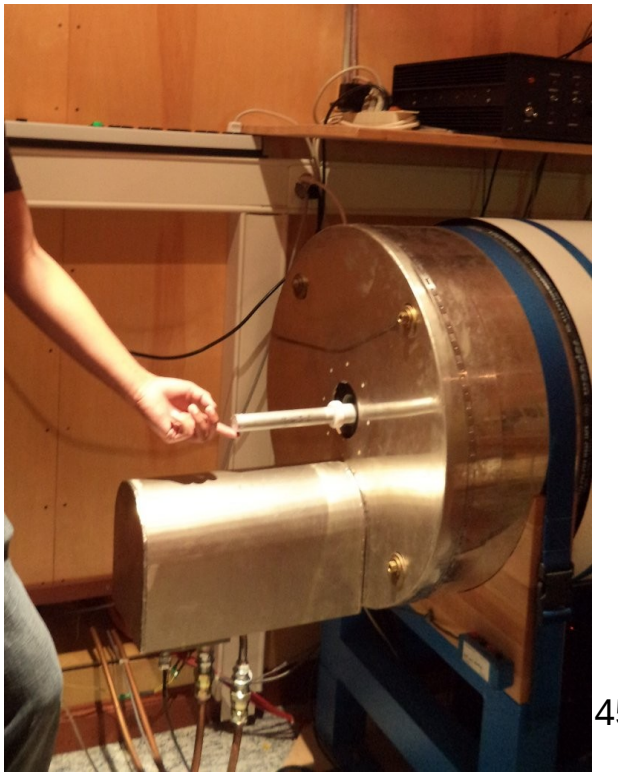


Magnetometer scans

Optimum length 20 cm

606 samples in 7 days

852 independent runs
(including calibration, backgrounds, and multiple measurements of candidates)

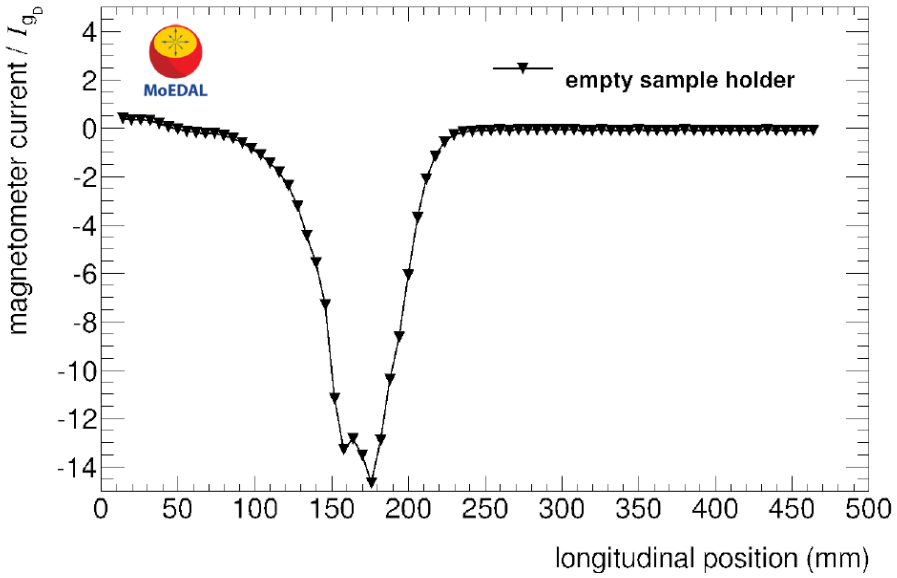


Magnetometer measurement procedure

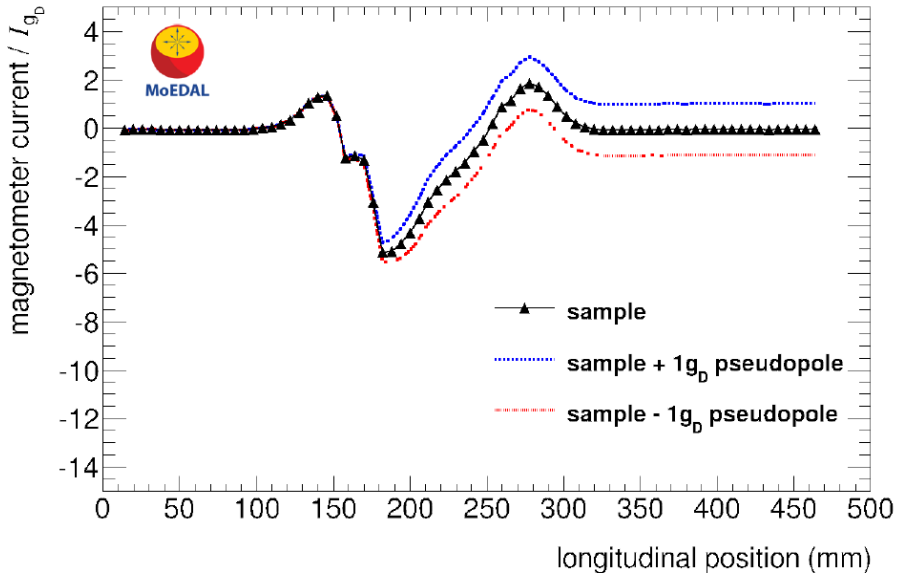
- Output measured before, during, and after passage of sample through sensing coil
- Subtract measurement with empty holder
- Difference between resulting current after and before = persistent current
  - deviation from zero → monopole signature

arXiv:1604.06645

Sample holder only



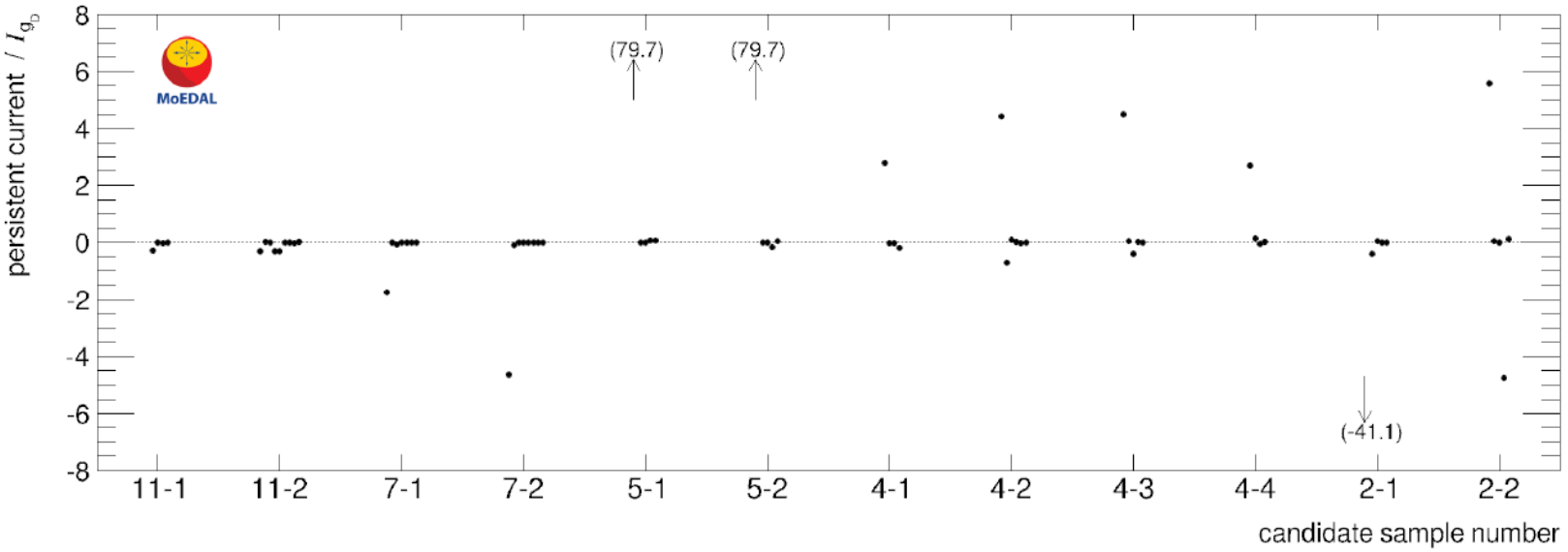
Typical sample after subtracting holder



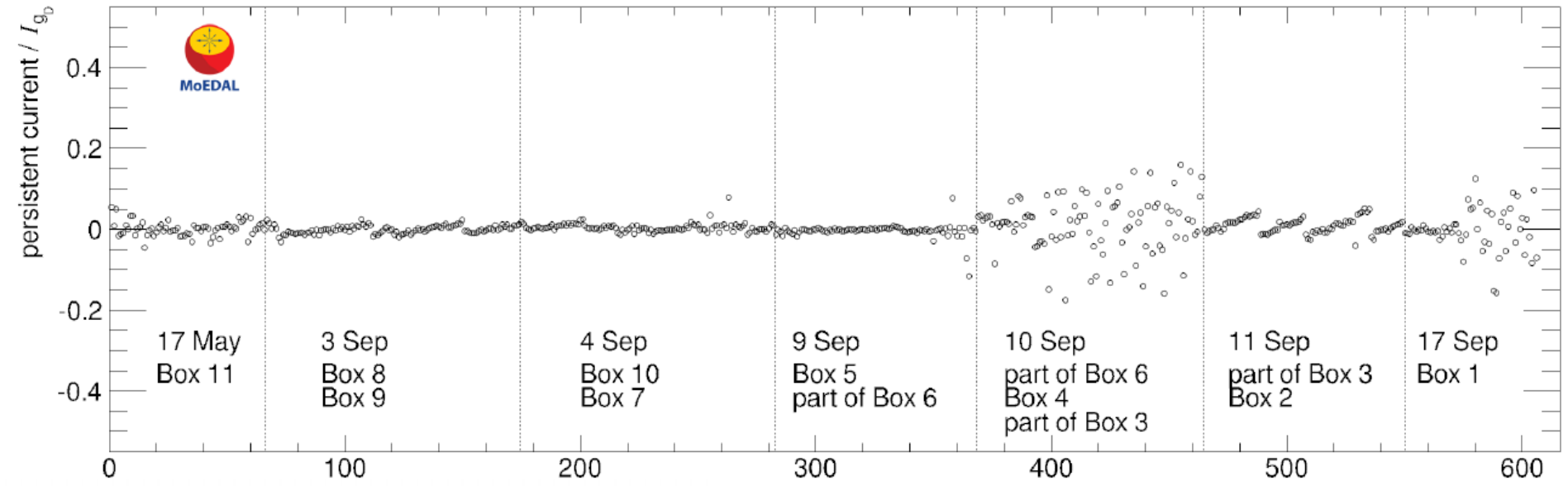
Procedure in case of a candidate signal

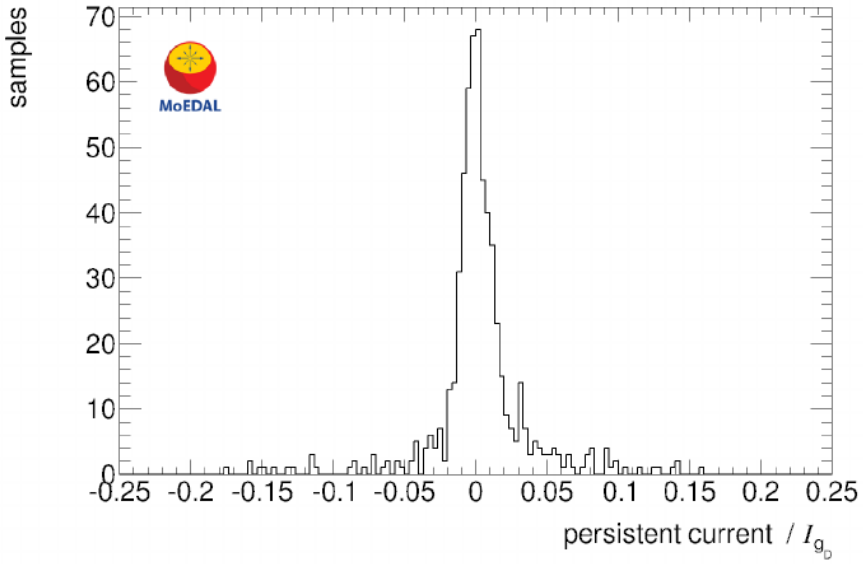
- Candidate criterion: persistent current larger than $0.25 g_D$
- Simply remeasure the same sample several times
- Persistent current consitently same non-zero value
  → unambiguous presence of a monopole, and precise charge measurement
- Persistent current consistently zero
  → the first was a spurious jump; take the second as measured value

arXiv:1604.06645



Measured magnetic charges – results



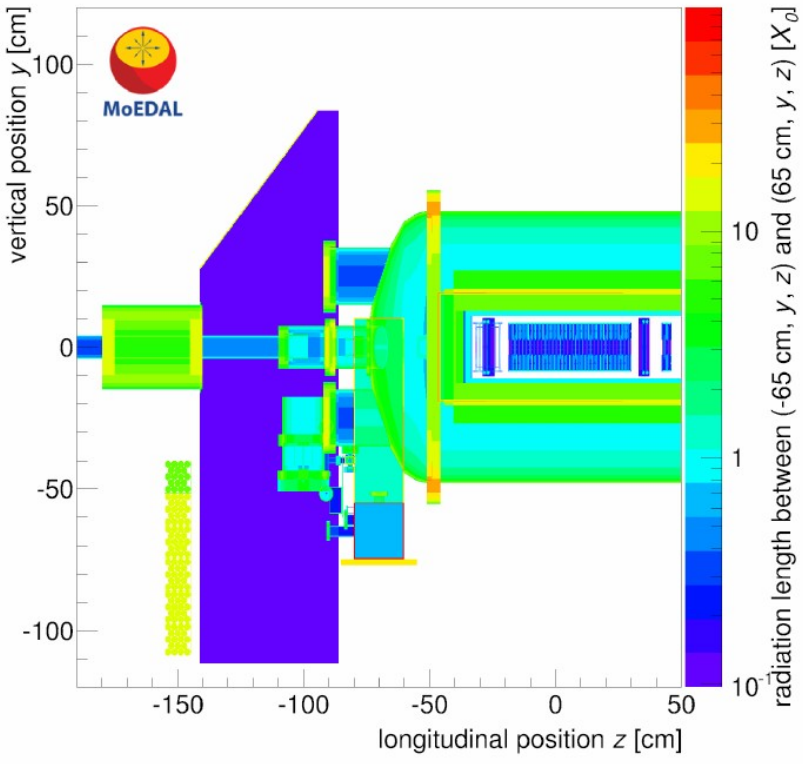


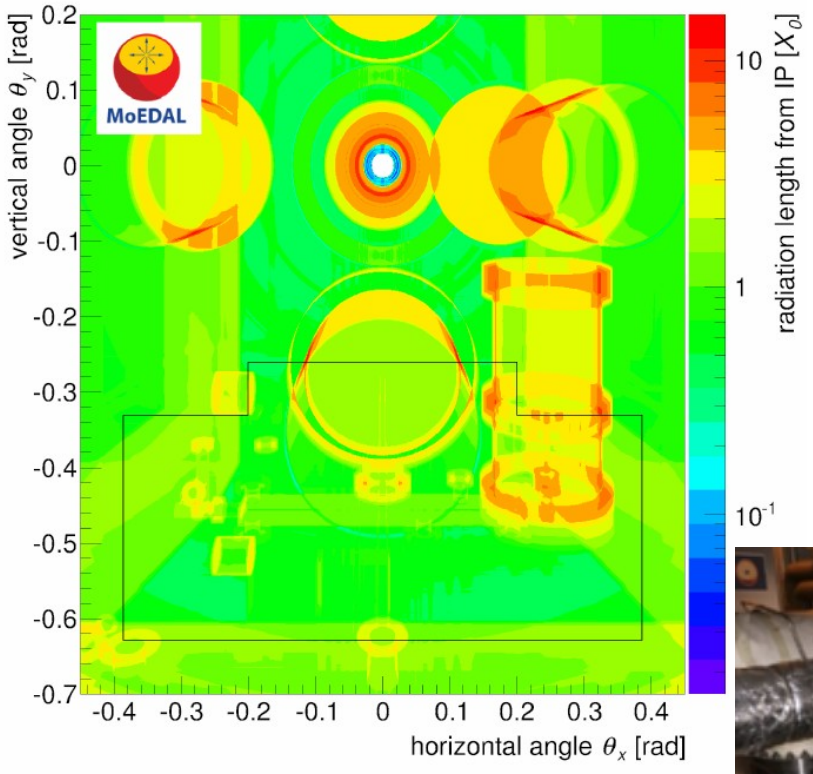
arXiv:1604.06645

No magnetic charge with $|g| > 0.5 g_D$

Geometry model

arXiv:1604.06645





± 3% uncertainty in material between IP and trapping volume → dominant systematic uncertainty in acceptance

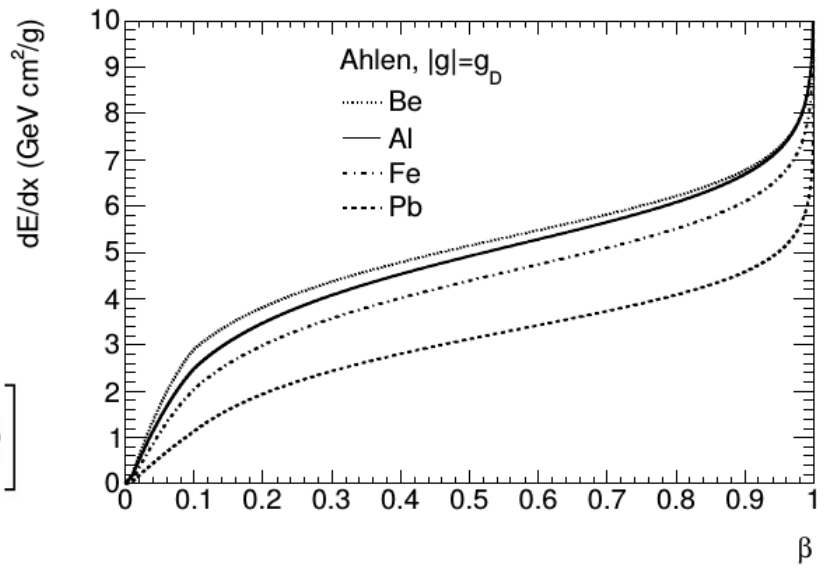
Monopole simulation

- Assume production of pair of free, stable HIPs

$pp \rightarrow M\bar{M}$

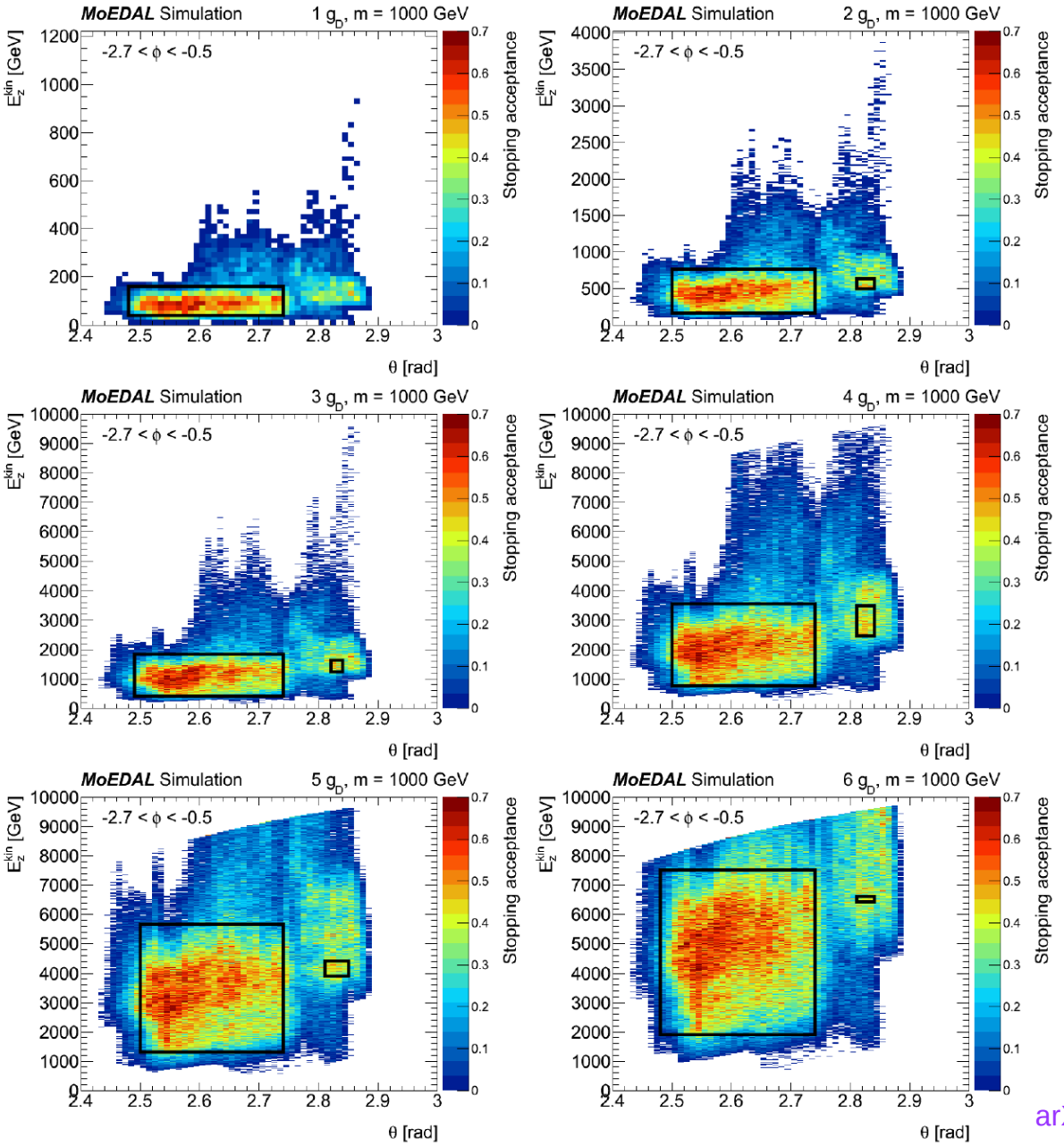
  - Coupling >> 1 → non-perturbative dynamics !
  - Particle gun with flat distributions for model-independent results
  - Kinematics from Drell-Yan massive spin-1/2 and spin-0 particles
- Monople propagation and energy loss handled by Geant4
  - Uncertainties in dE/dx → subdominant systematic uncertainty in acceptance

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



- Trapping criterion: monopole velocity falls below 0.001c

Model-independent acceptance fiducial regions



- Map in E^{kin}_z versus θ (averaged over $-2.7 < \varphi < -0.5$)
- Fiducial regions = uniform acceptance (40% average and <15% deviation)
- Cross-section limit of 10 fb for producing a monopole within any of the regions → independent from assumptions on monopole kinematics

arXiv:1604.06645

Trapping acceptance – Drell-Yan pair production

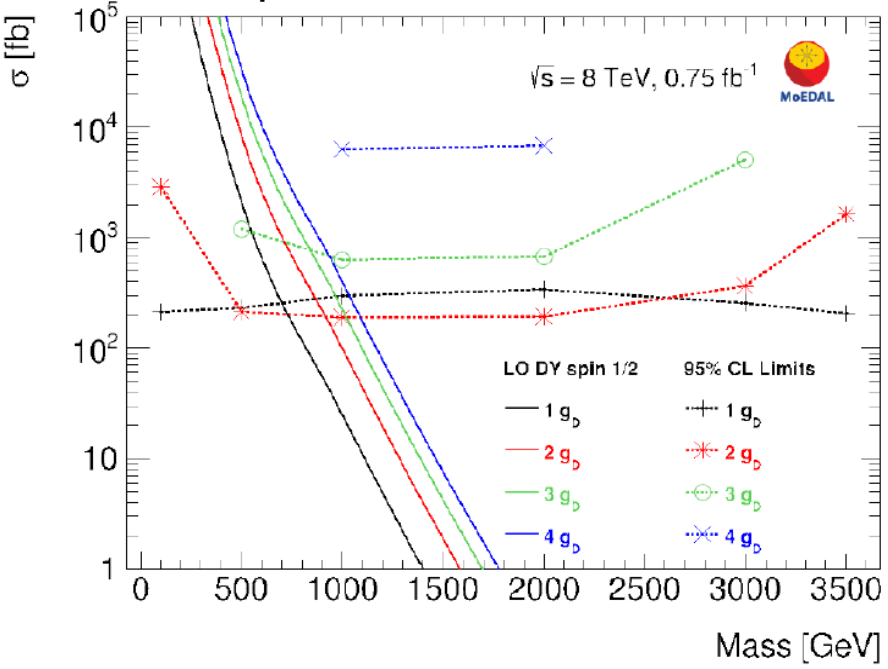
probability (per event) that at least one monopole stops in the trapping detector, obtained from full simulations

m [GeV]	$\|g\| = 1.0g_D$	$\|g\| = 2.0g_D$	$\|g\| = 3.0g_D$	$\|g\| = 4.0g_D$
spin-1/2				
100	0.019±0.003	0.002±0.002	—	—
500	0.017±0.001	0.021±0.005	0.005±0.003	—
1000	0.014±0.001	0.022±0.004	0.008±0.004	0.002±0.001
2000	0.012±0.001	0.022±0.003	0.008±0.004	0.001±0.001
3000	0.016±0.001	0.013±0.004	0.002±0.002	—
3500	0.020±0.001	0.004±0.003	—	—
spin-0				
100	0.028±0.002	0.007±0.004	—	—
500	0.0082±0.0010	0.027±0.004	0.010±0.005	0.002±0.002
1000	0.0038±0.0007	0.022±0.002	0.011±0.004	0.003±0.002
2000	0.0020±0.0004	0.014±0.001	0.008±0.003	0.002±0.002
3000	0.0032±0.0007	0.008±0.002	0.002±0.002	—
3500	0.0069±0.0007	0.004±0.002	—	—

Table 1. Trapping acceptances for spin-1/2 (top) and spin-0 (bottom) monopoles with DY production kinematic distributions. The quoted uncertainties include both statistical and systematic uncertainties. Empty entries mean that the acceptance is lower than 0.001. arXiv:1604.06645

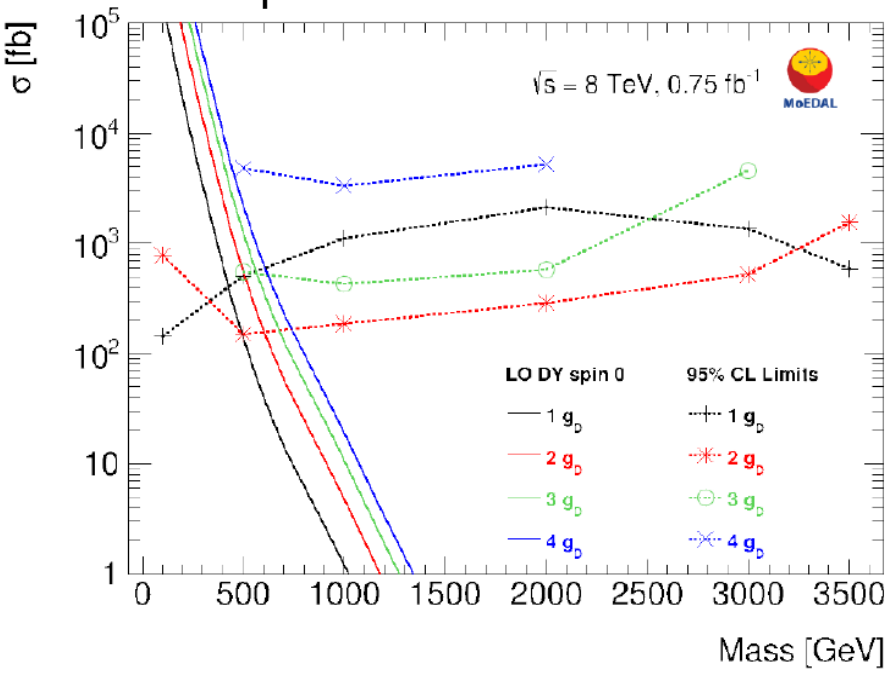
Cross section limits versus mass

DY spin-1/2



DY spin-0

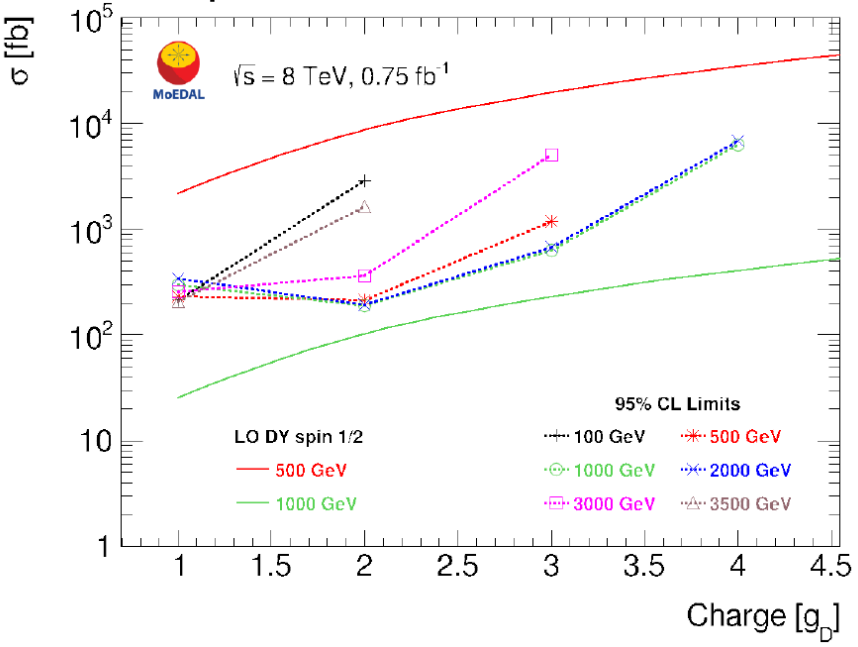
arXiv:1604.06645



Probe masses > 2500 GeV (up to 3500 GeV) for the first time at the LHC

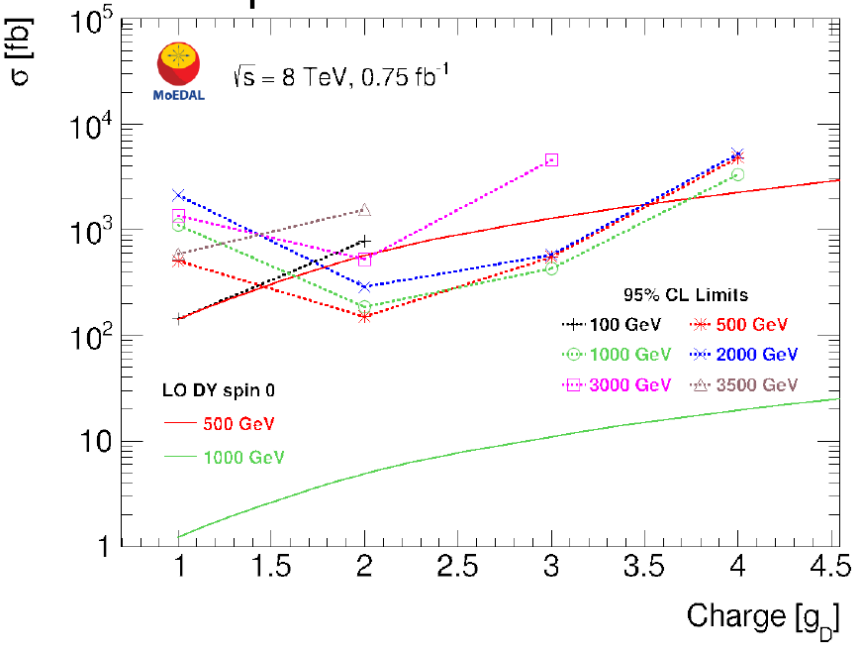
Cross section limits versus magnetic charge

DY spin-1/2



DY spin-0

arXiv:1604.06645



Probe masses > 2500 GeV (up to 3500 GeV) for the first time at the LHC

Probe magnetic charge $|g| > 1.5g_D$ (up to $4g_D$) for the first time at the LHC

Mass limits

- Highly model-dependent

DY Lower Mass Limits [GeV]	$\|g\| = g_D$	$\|g\| = 2g_D$	$\|g\| = 3g_D$
spin-1/2	700	920	840
spin-0	420	600	560

Table 2. Lower mass limits (95% confidence level) in models of spin-1/2 (top) and spin-0 (bottom) DY monopole pair production. These limits are based upon cross sections computed at leading order. These cross sections are only indicative since the monopole coupling to the photon is too large to allow for perturbative calculations. arXiv:1604.06645

For comparison

ATLAS 8 TeV

(arXiv:1509.08059)

$\|g\| = g_D$
1340
1050

Mass limits

- Highly model-dependent

For comparison
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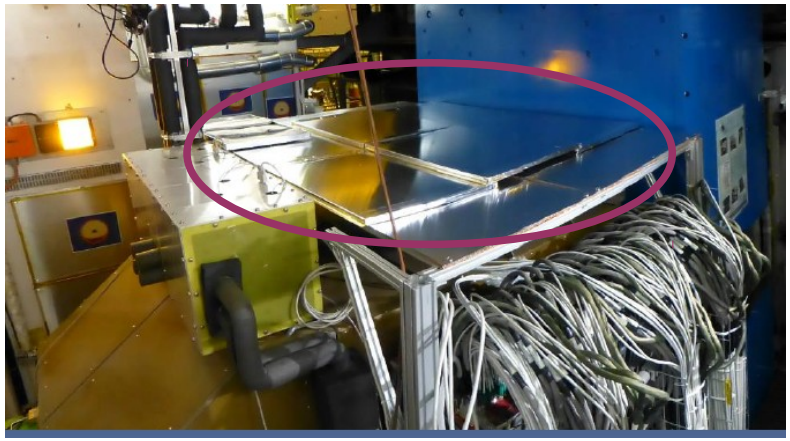
World best limits for $|g| > g_D$
(previously ~400 GeV at the Tevatron)

MoEDAL in 2015/2016

NTDs on top of VELO, close to IP
+ on surrounding walls



TimePix
for online
monitoring

3 arrays
trapping
detectors

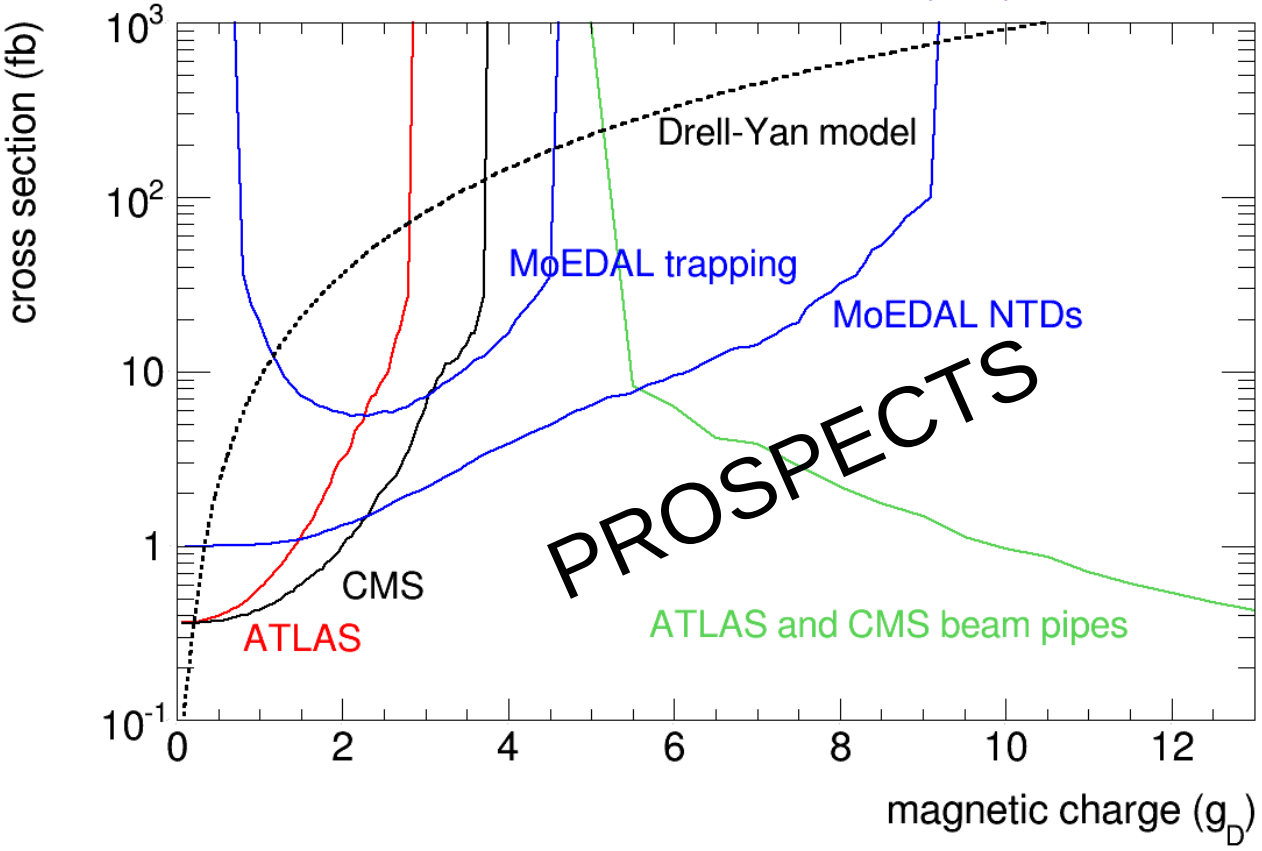
Thin “shower curtain” NTD
within LHCb acceptance

Full arrays being exposed to 13 TeV *pp* collisions

In 13 TeV collisions

- Rough discovery reach estimates from detector geometries after first year of LHC@13 TeV
- Assuming 0.2 background events in ATLAS/CMS and ~0.00 background events in MoEDAL
- M = 1600 GeV

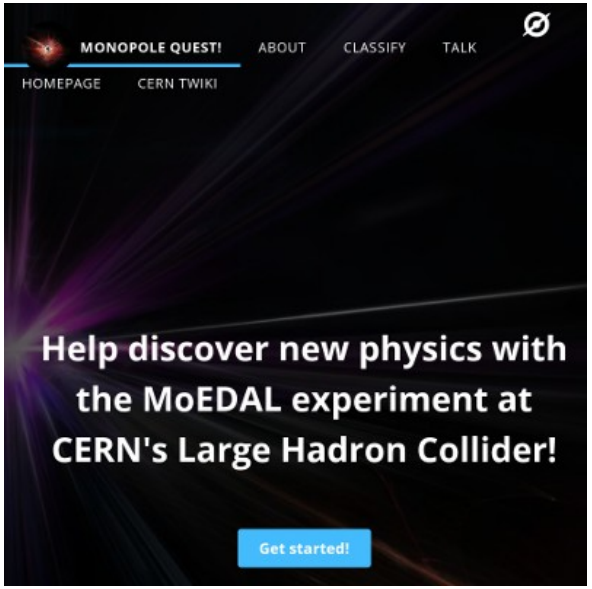
EPJC 72, 1985 (2012), arXiv:1112.2999

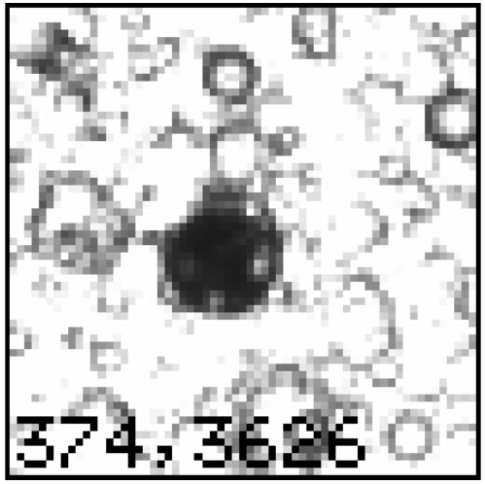


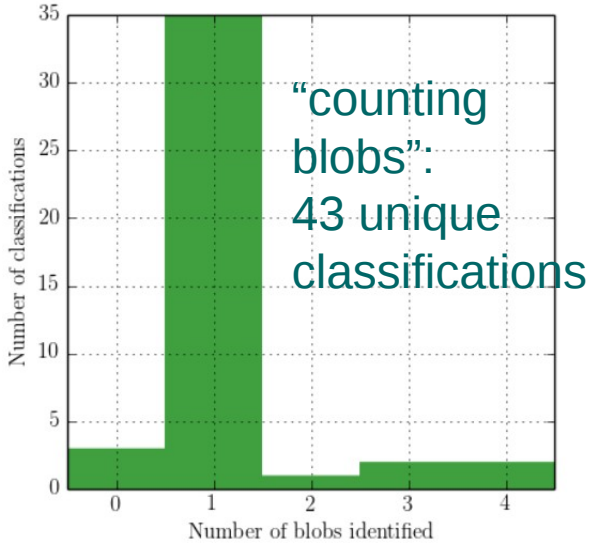
MoEDAL's unique patterns

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







"counting blobs": 43 unique classifications

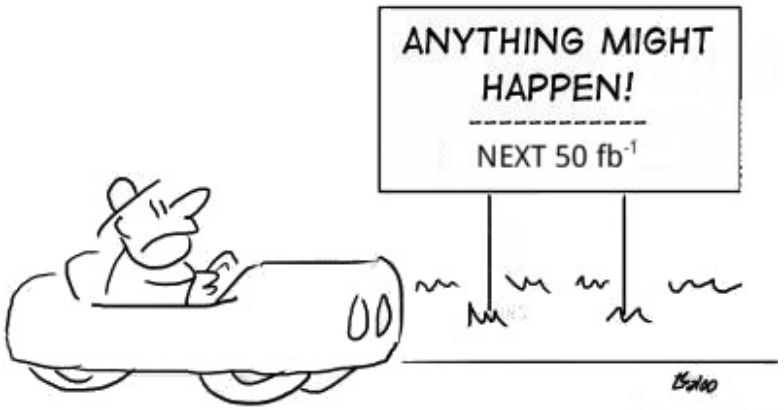
Use human brains
- signal identification in big messy images
- "anything odd?"

NTD exposed to collisions and ion beam

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 and unique of its kind – first results with prototype surpass existing constraints for a range of monopole charges and masses
- MoEDAL is now collecting “oddities” in 13 TeV collisions



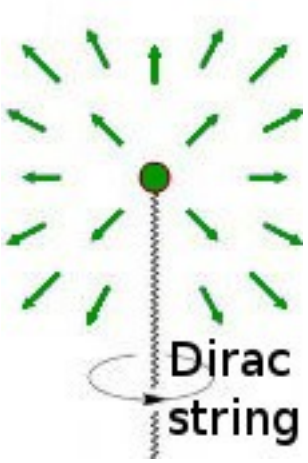
extras

“MONOPOLES” IN CONDENSED-MATTER SYSTEMS

Spin ice: quasi-particles resembling monopoles
(but N cannot be separated from S)

Superfluids: B* field mathematically analogous to magnetic field

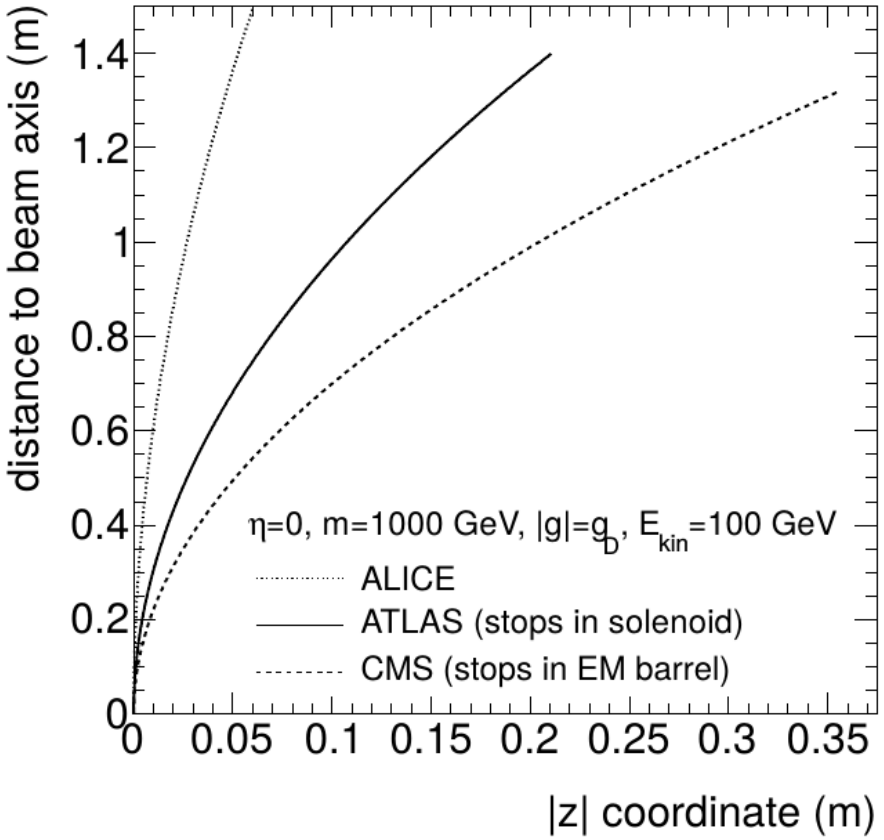
- Observation of B*-pole → example of quantum-field representation of monopole

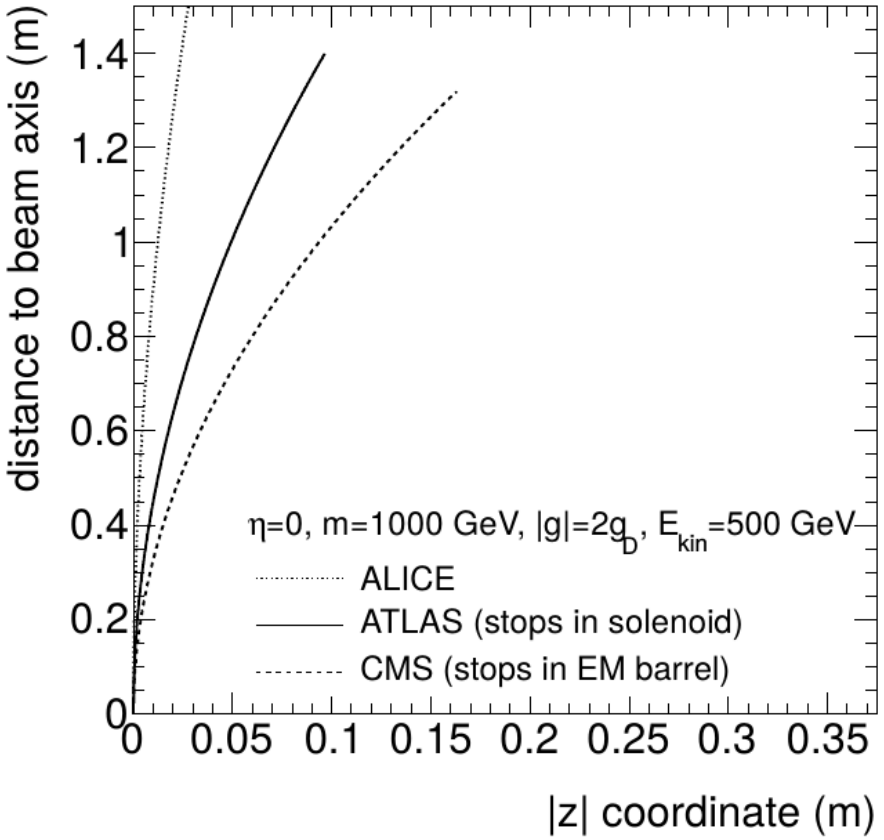


Monopole bending in magnetic fields

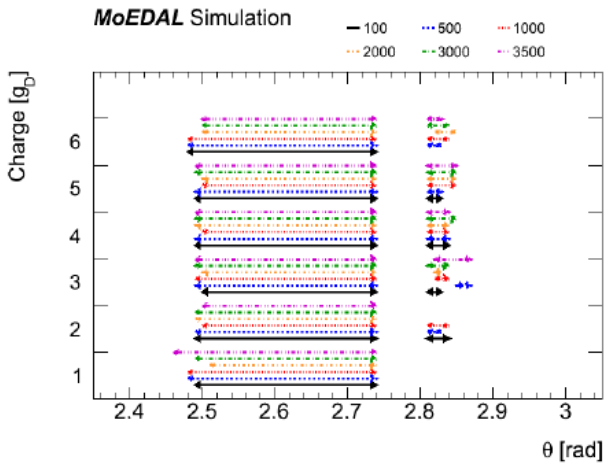
- Force along magnetic field direction: $F_m = q_m B$
- Solenoid magnetic field → parabola in *r-z* plane

$$z(r) - z_v = 0.5\frac{q_m|B|r^2}{p_T\beta_T c} + \frac{r}{\tan\theta_0}$$





Summary of trapping detector fiducial regions



arXiv:1604.06645