Searches for magnetic monopoles and beyond with MoEDAL at the LHC

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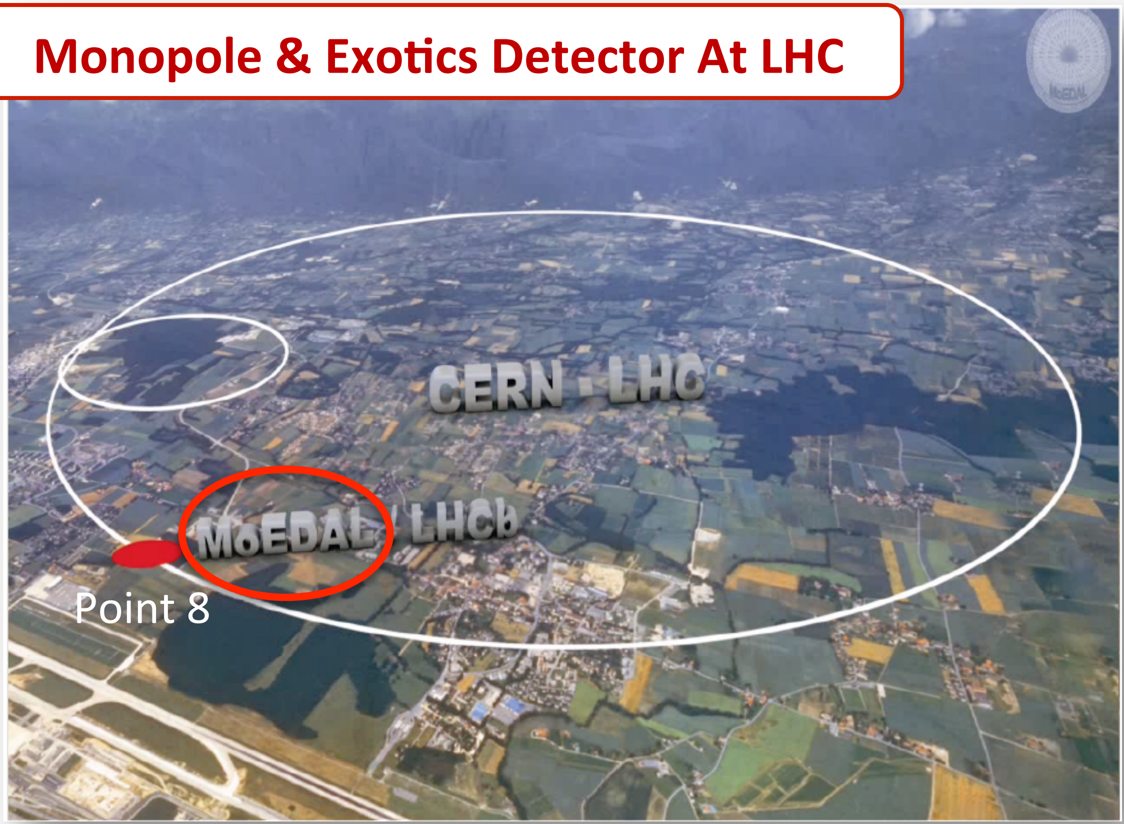
International Conference on Exotic Atoms and Related Topics
11-15 September 2017, Vienna, Austria

MoEDAL at LHC

Monopole & Exotics Detector At LHC



International collaboration ~70 physicists from ~20 participating institutions

UNIVERSITY OF ALABAMA
UNIVERSITY OF ALBERTA
INFN & UNIVERSITY OF BOLOGNA
UNIVERSITY OF BRITISH COLUMBIA
CERN
UNIVERSITY OF CINCINNATI
CONCORDIA UNIVERSITY
GANGNEUNG-WONJU NATIONAL UNIVERSITY
UNIVERSITÉ DE GENÈVE
UNIVERSITY OF HELSINKI
IMPERIAL COLLEGE LONDON
KING'S COLLEGE LONDON
KONKUK UNIVERSITY
UNIVERSITY OF MÜNSTER
MOSCOW INSTITUTE OF PHYSICS AND TECHNOLOGY
NORTHEASTERN UNIVERSITY
TECHNICAL UNIVERSITY IN PRAGUE
QUEEN MARY UNIVERSITY OF LONDON
INSTITUTE FOR SPACE SCIENCES, ROMANIA
STAR INSTITUTE, SIMON LANGTON SCHOOL
TUFT'S UNIVERSITY
IFIC VALENCIA

Key feature: **high ionisation**

$$\frac{\text{charge}}{\text{velocity: } \beta = v/c} = z/\beta$$

$$-\frac{dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2} \right]$$

Electric charge

Bethe-Bloch formula

MoEDAL detectors have a threshold of **z/β ~ 5 – 10**

High ionisation (HI) possible when:

- multiple electric charge (H^{++}, Q-balls, etc.) = n × e
- very low velocity & electric charge, i.e. Stable Massive Charged Particles (SMCPs)
- magnetic charge (monopoles, dyons) = ng_D = n × 68.5 × e
  - a singly charged relativistic monopole has ionisation ~4700 times MIP!!
- any combination of the above

$$-\frac{dE}{dx} = K \frac{Z}{A} g^2 \left[\ln \frac{2 m_e c^2 \beta^2 \gamma^2}{I_m} + \frac{K|g|}{2} - \frac{1}{2} - B(g) \right]$$

Magnetic charge

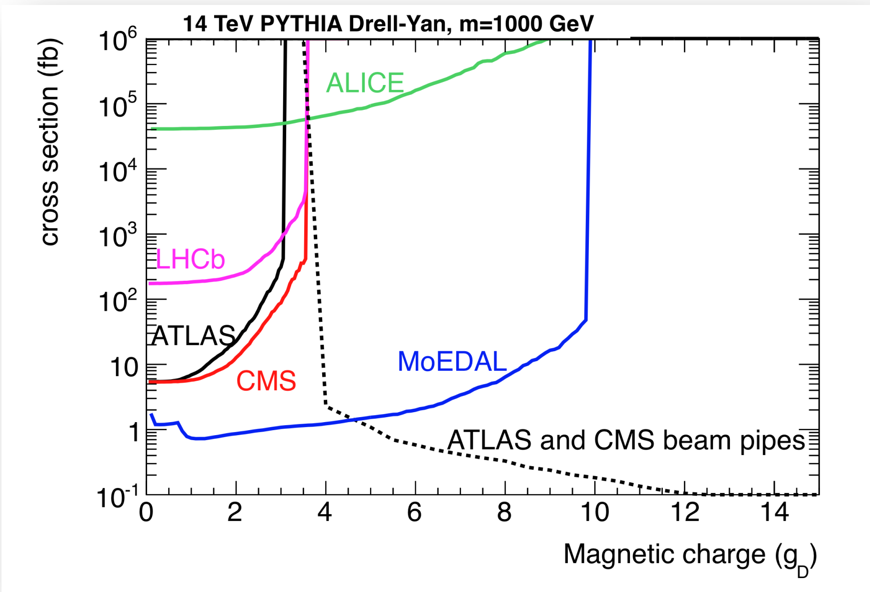
Ahlen formula

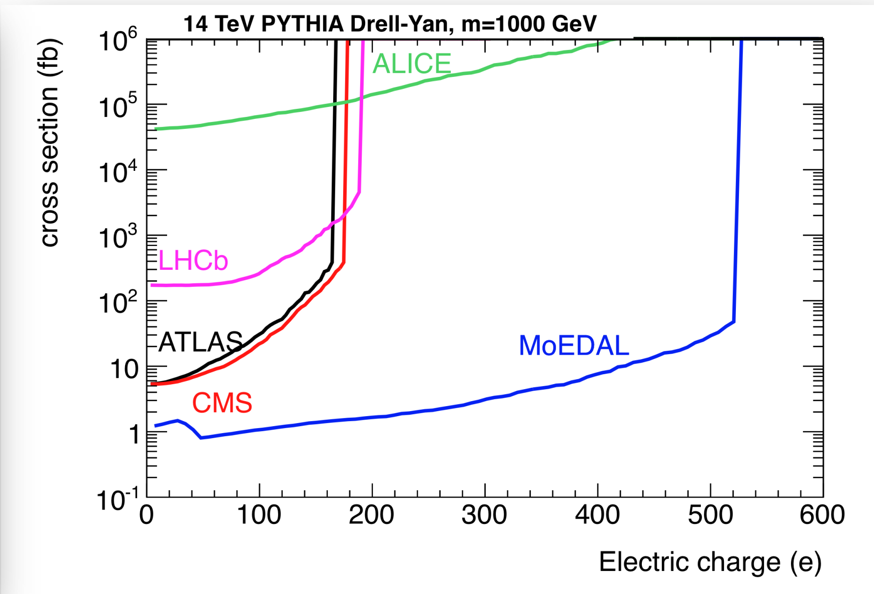
Particles must be *massive*, *long-lived* & *highly ionising* to be detected at *MoEDAL*

MoEDAL sensitivity

Cross-section limits for magnetic and electric charge assuming that:

- ~ one MoEDAL event is required for discovery and ~100 events in the other LHC detectors
- integrated luminosities correspond to about two years of 14 TeV run

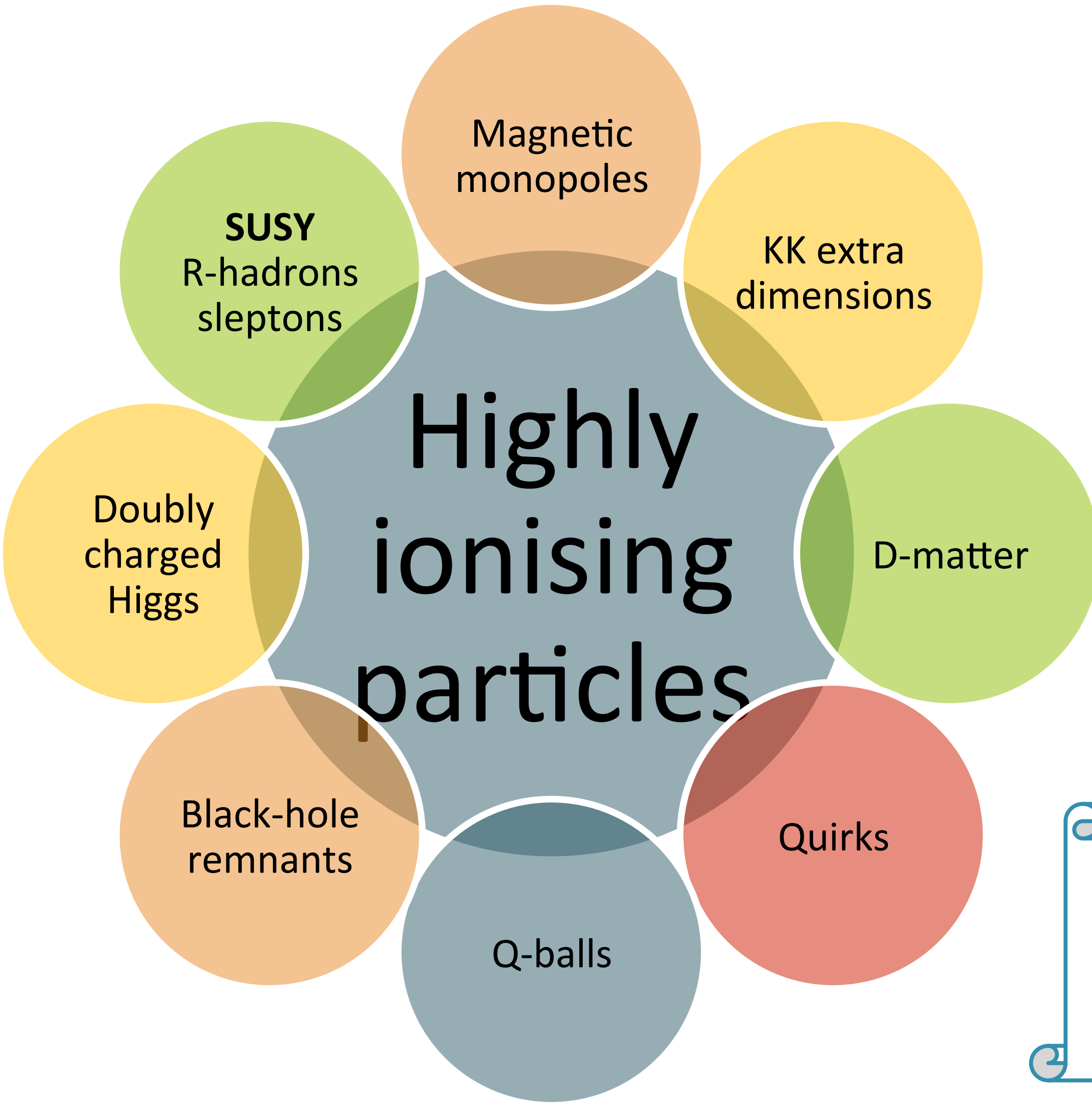




De Roeck, Katre, Mermod, Milstead, Sloan, EPJC72 (2012) 1985 [arXiv:1112.2999]

MoEDAL offers robustness against timing and well-estimated signal efficiency

MoEDAL physics programme

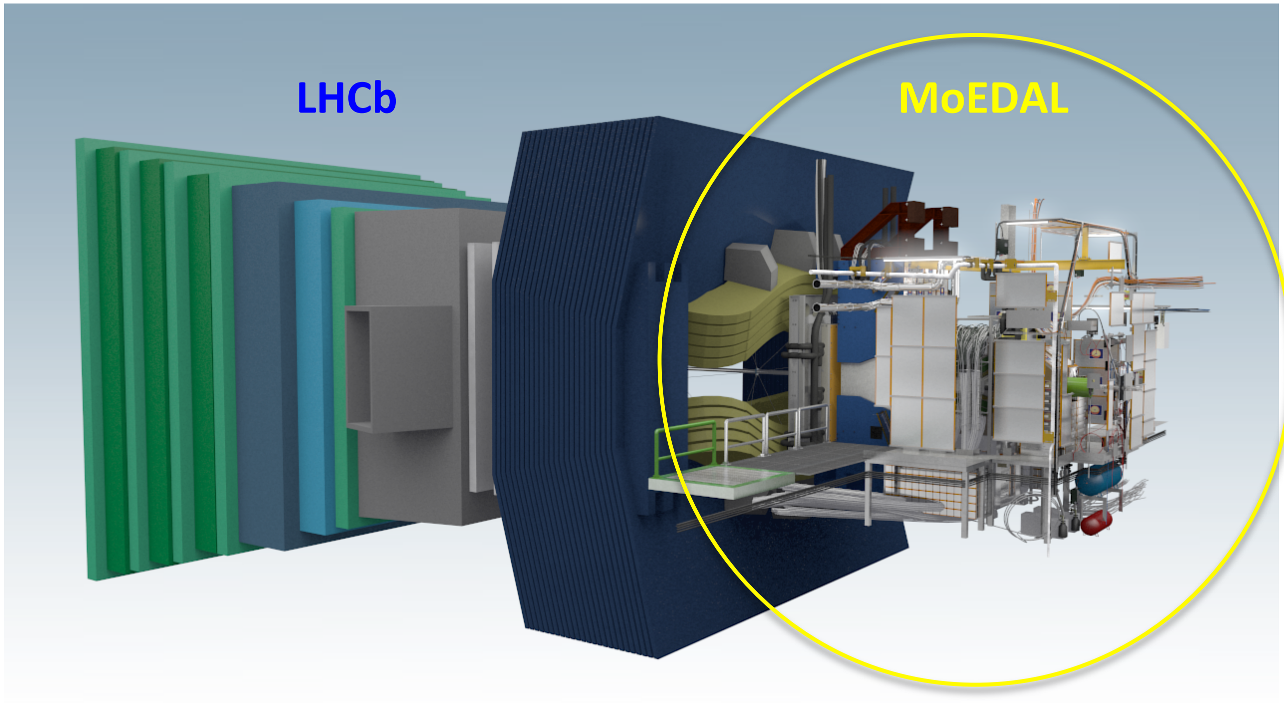


Searching for *massive*, *long-lived* & *highly ionising* particles

MoEDAL physics program
Int. J. Mod. Phys. A29 (2014) 1430050
[arXiv:1405.7662]

The MoEDAL detector components

MoEDAL detector



DETECTOR SYSTEMS

① Low-threshold NTD (**LT-NTD**) array
- $z/\beta > \sim 5 - 10$

② Very High Charge Catcher NTD (**HCC-NTD**) array
- $z/\beta > \sim 50$

③ TimePix radiation background monitor

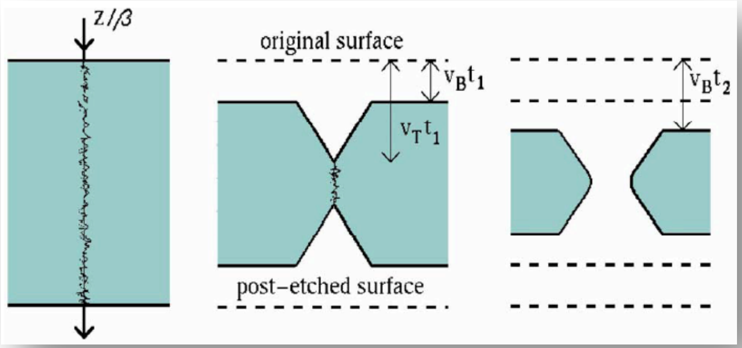
④ Monopole Trapping detector (**MMT**)

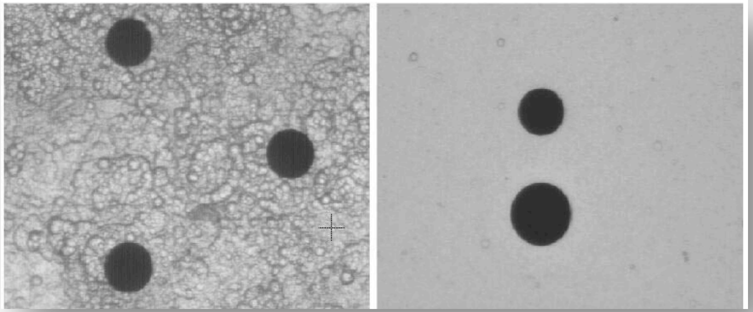
MoEDAL is unlike any other LHC experiment:

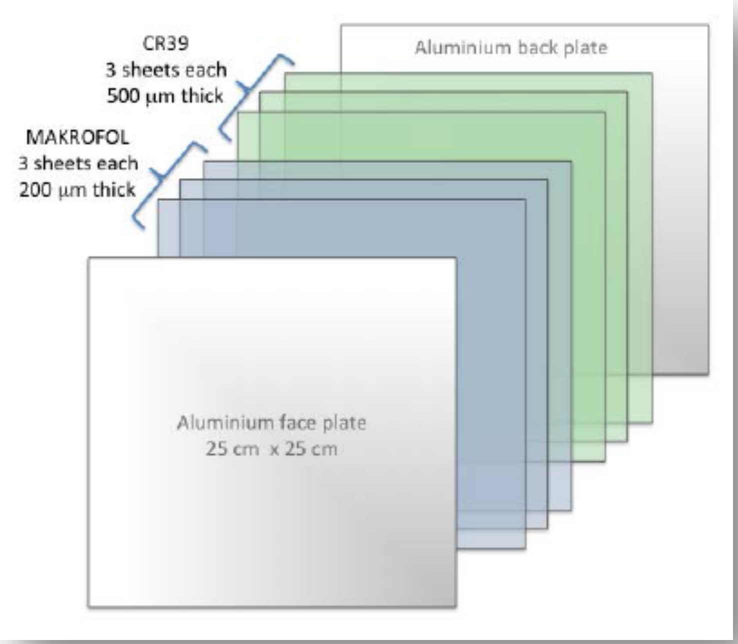
- mostly **passive detectors**; no trigger; no readout
- the largest deployment of passive **Nuclear Track Detectors (NTDs)** at an accelerator
- the 1st time **trapping detectors** are deployed as a detector

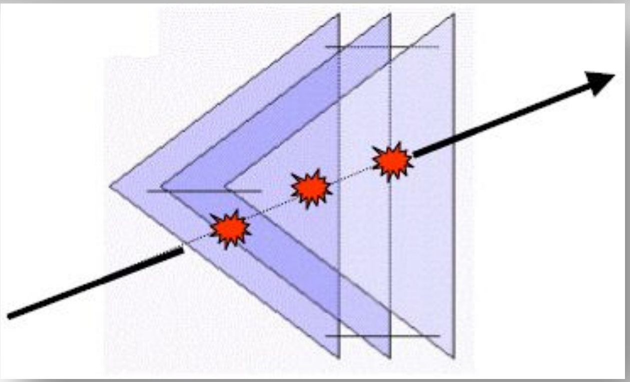
1 & 2 HI particle detection in NTDs

- Passage of a highly ionising particle through the plastic NTD marked by an invisible damage zone (**"latent track"**) along the trajectory
- The damage zone is revealed as a **cone-shaped etch-pit** when the plastic sheet is chemically **etched**
- Plastic sheets are later **scanned** to detect etch-pits





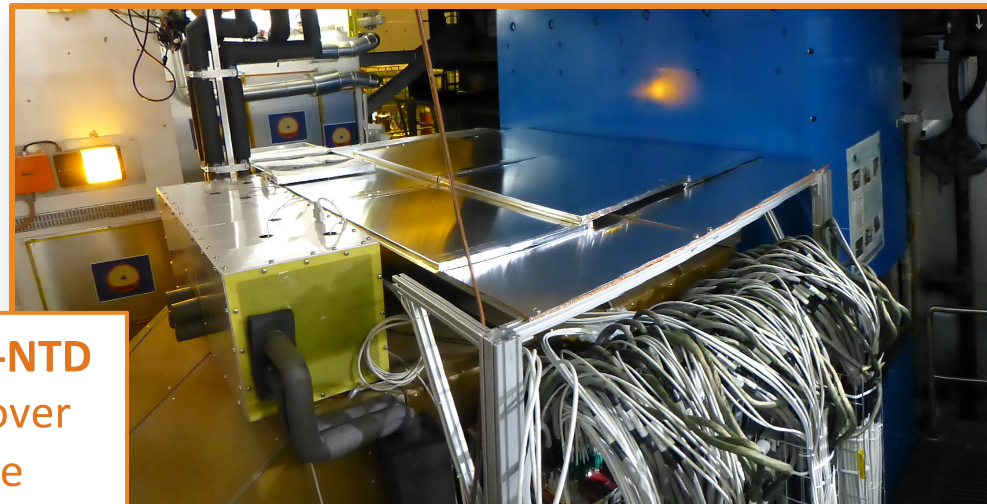




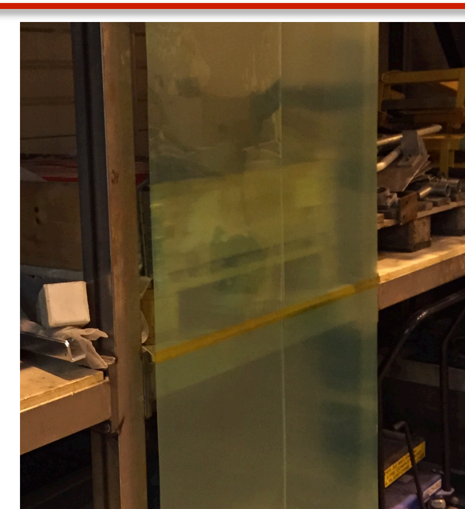
Looking for aligned etch pits in multiple sheets

1 & 2 NTDs deployment

2012: LT-NTD
NTDs sheets kept in boxes mounted onto LHCb VELO cavern walls



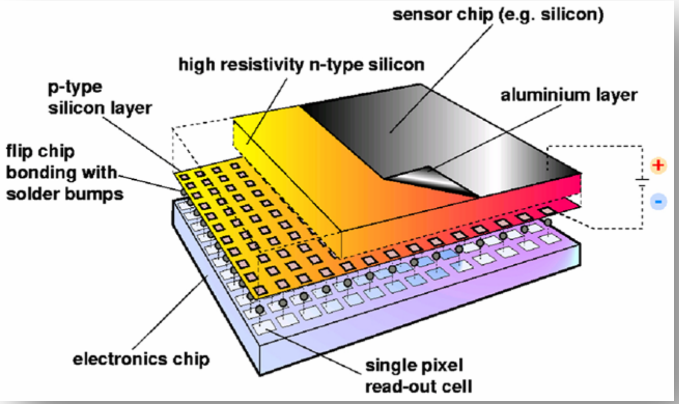
2015-2016: LT-NTD
Top of VELO cover
Closest possible location to IP

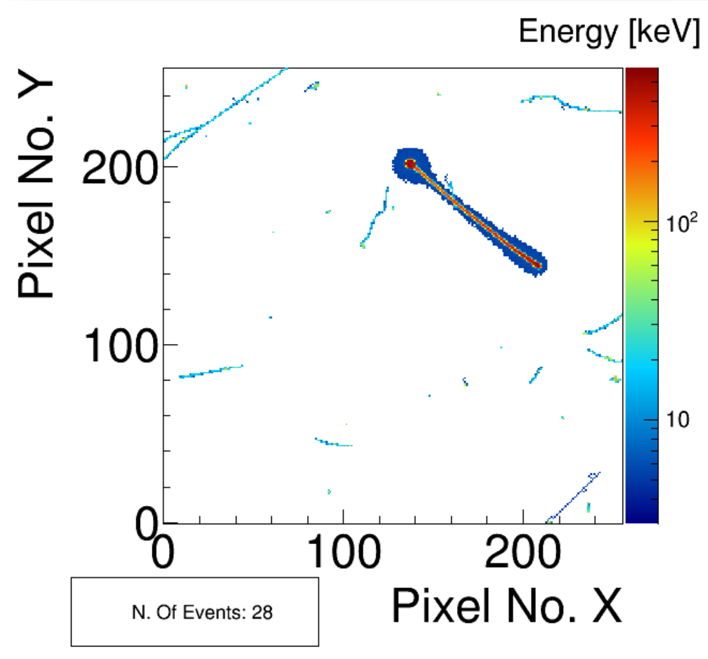


2015-2016: HCC-NTD
Installed in LHCb acceptance between RICH1 and TT

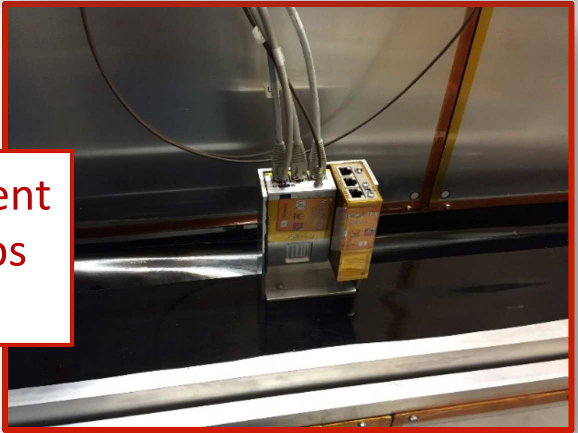
3 TimePix radiation monitor

- Timepix (MediPix) chips used to measure online the radiation field and monitor spallation product background
- Essentially act as little electronic "bubble-chambers"
- The only active element in MoEDAL





Sample calibrated frame in MoEDAL TPX04

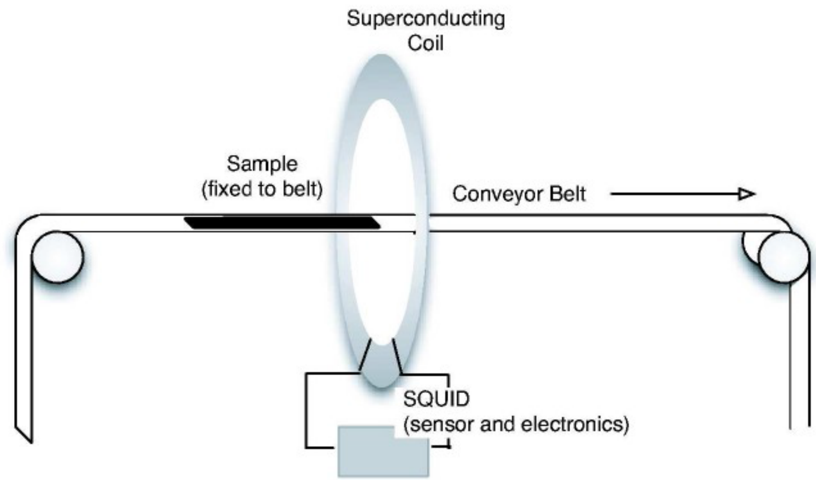


2015 deployment of MediPix chips in MoEDAL

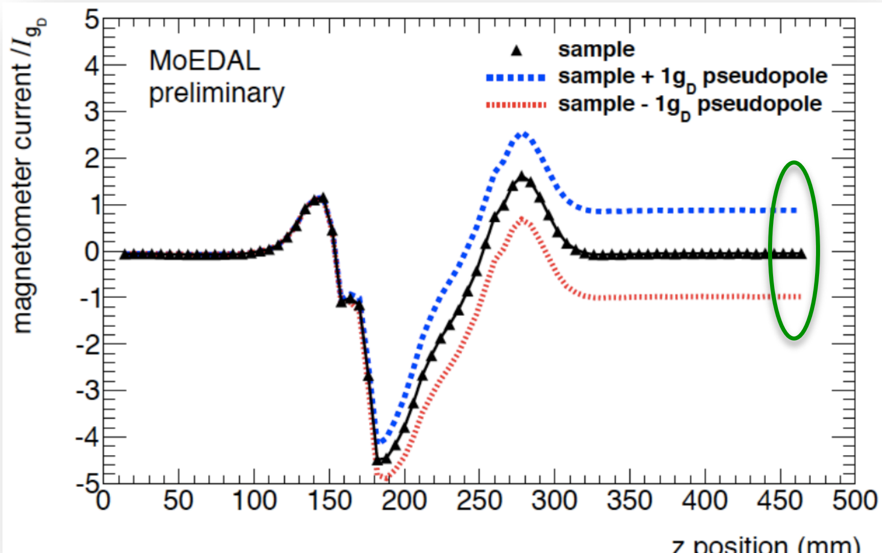
- 256×256 pixel solid state detector
- 14×14 mm active area
- amplifier + comparator + counter + timer

4 MMT: Magnetic Monopole Trapper

- Binding energy of monopoles in nuclei with finite magnetic dipole moments: $\mathcal{O}$(100 keV)
- MMTs analysed with superconducting quantum interference device (SQUID)
- Material: Aluminium
  - large nuclear dipole moment
  - relatively cheap
- **Persistent current:** difference between resulting current after and before
  - first subtract current measurement for empty holder
  - if other than zero → *monopole signature*

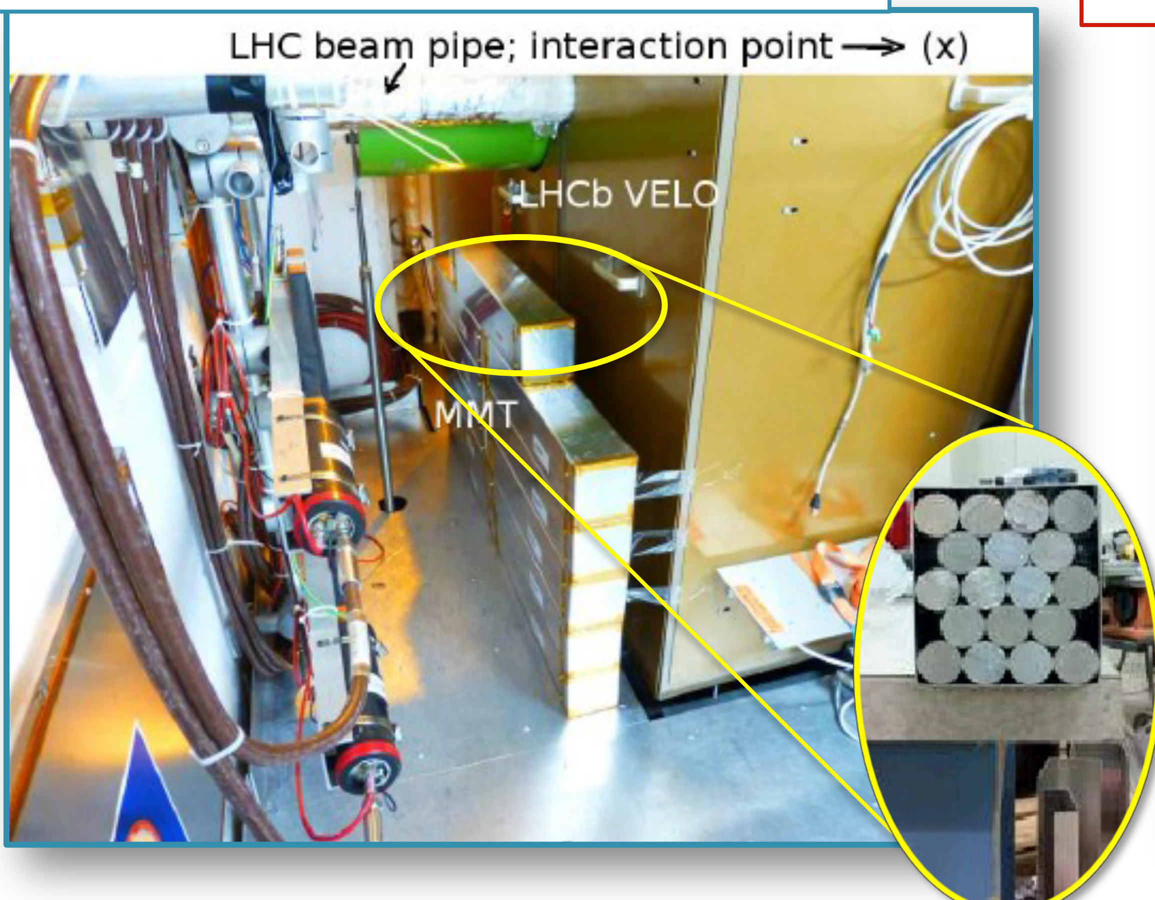


Typical sample & pseudo-monopole curves



MMTs deployment

2012
11 boxes each containing 18 Al rods of 60 cm length and 2.54 cm diameter (**160 kg**)



2015-2016
- Installed in additional locations: sides A & C, too
- Approximately **800 kg** of Al
- Total 2400 aluminum bars

Results on monopole mass & charge from MMTs

- **@ 8 TeV** JHEP 1608 (2016) 067 [arXiv:1604.06645]
- **@ 13 TeV** Phys.Rev.Lett. 118 (2017) 061801 [arXiv:1611.06817]

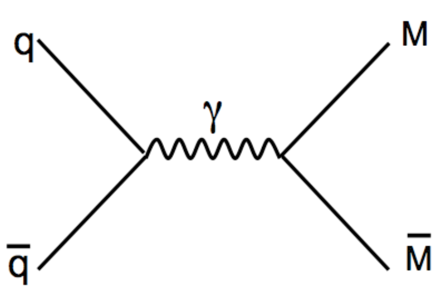
Magnetic monopoles

- Motivation
  - symmetrisation of Maxwell's eqs.
  - electric charge quantisation
- Properties
  - magnetic charge = ng = n×68.5e
  - coupling constant = g/ħc ~34
  - spin and mass not predicted

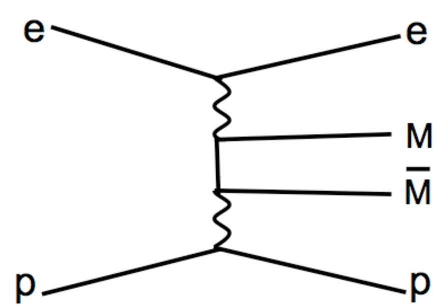
Name	Without Magnetic Monopoles	With Magnetic Monopoles
Gauss's law:	$\vec{\nabla}\cdot\vec{E} = 4\pi\rho_e$	$\vec{\nabla}\cdot\vec{E} = 4\pi\rho_e$
Gauss' law for magnetism:	$\vec{\nabla}\cdot\vec{B} = 0$	$\vec{\nabla}\cdot\vec{B} = 4\pi\rho_m$
Faraday's law of induction:	$-\vec{\nabla}\times\vec{E} = \frac{\partial\vec{B}}{\partial t}$	$-\vec{\nabla}\times\vec{E} = \frac{\partial\vec{B}}{\partial t} + 4\pi\vec{J}_m$
Ampère's law (with Maxwell's extension):	$\vec{\nabla}\times\vec{B} = \frac{\partial\vec{E}}{\partial t} + 4\pi\vec{J}_e$	$\vec{\nabla}\times\vec{B} = \frac{\partial\vec{E}}{\partial t} + 4\pi\vec{J}_e$

HIGHLY IONISING

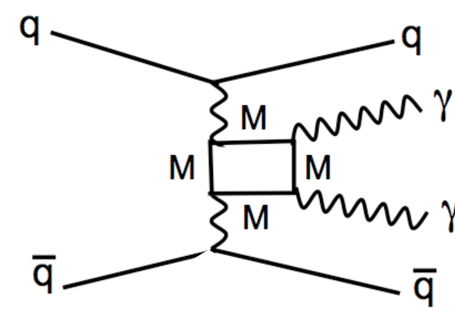
Production mechanisms in colliders



Drell Yan mechanism



Photon fusion



Box diagram

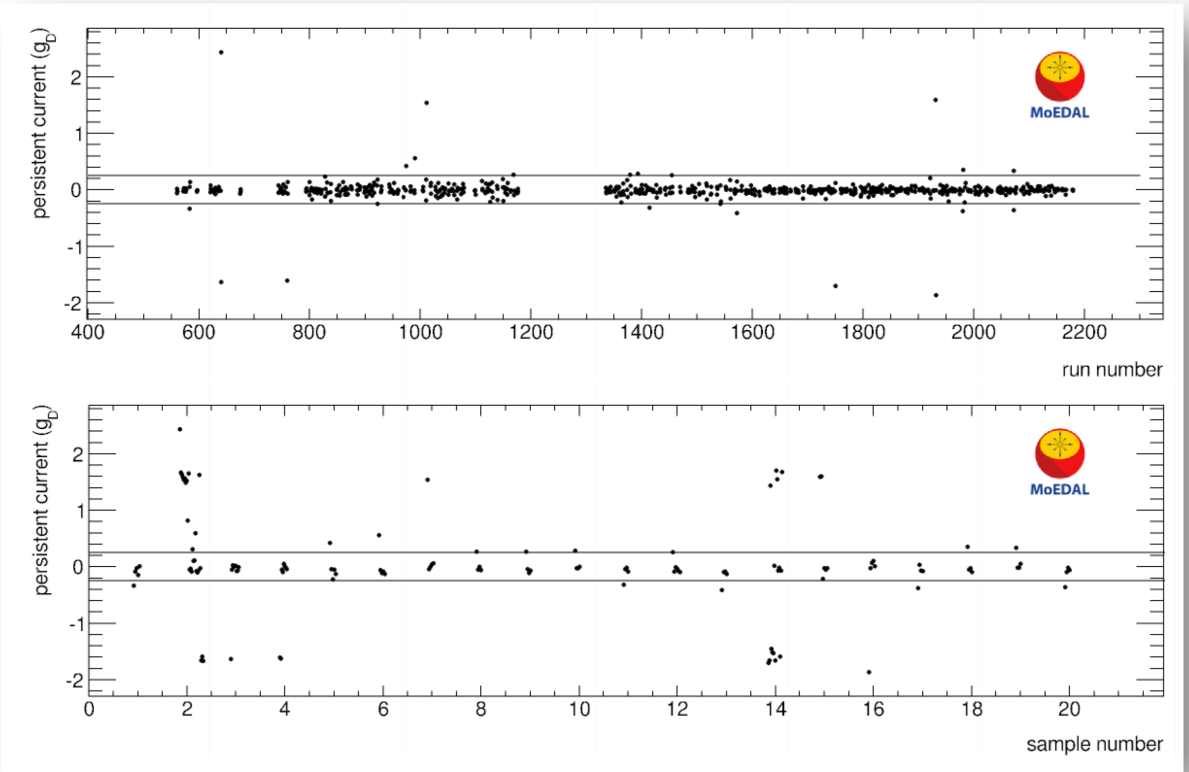
MoEDAL improves reach of monopole searches w.r.t. cross section & charge

MMT2015: scanning

Detector: prototype of **222 kg** of aluminium bars

Exposure: **0.371 fb^{-1}** of **13 TeV** *pp* collisions during 2015

- Analysed with SQUID at ETH Zürich
- Excellent charge resolution (< 0.1 g_D) except for outliers



Persistent current after first passage for all samples

Persistent current for multiple measurements of candidates

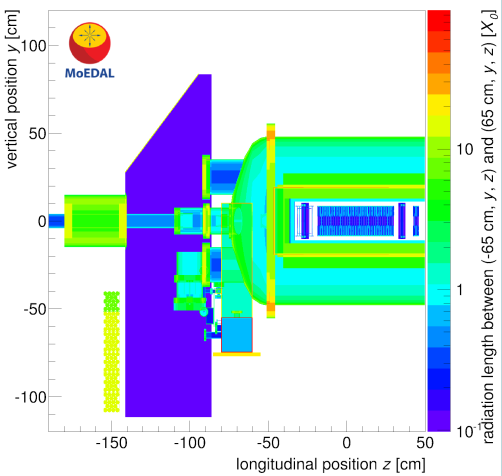
PRL 118 (2017) 061801 [arXiv:1611.06817]

No monopole with charge > 0.5 g_D observed in MMT samples at 99.5% CL

MMT2015: analysis

Geometry

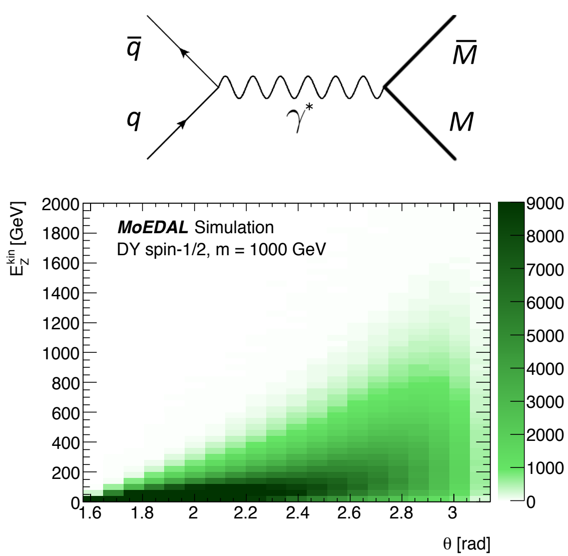
Material description between IP & detector



Kinematics

Event generation of Drell Yan production

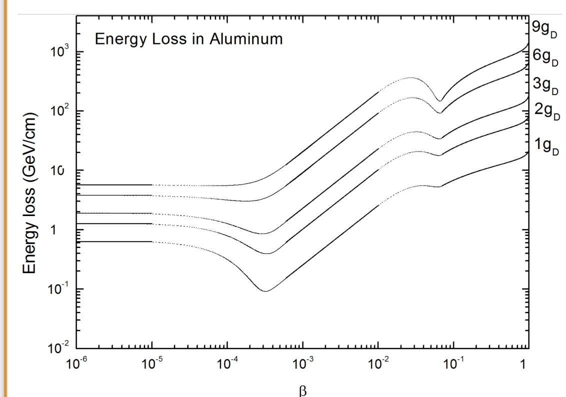
coupling ≫ 1 ⇒ non-perturbative!



JHEP 1608 (2016) 067

Propagation in matter

- Ahlen formula
- Monopole energy loss
- Stopping range



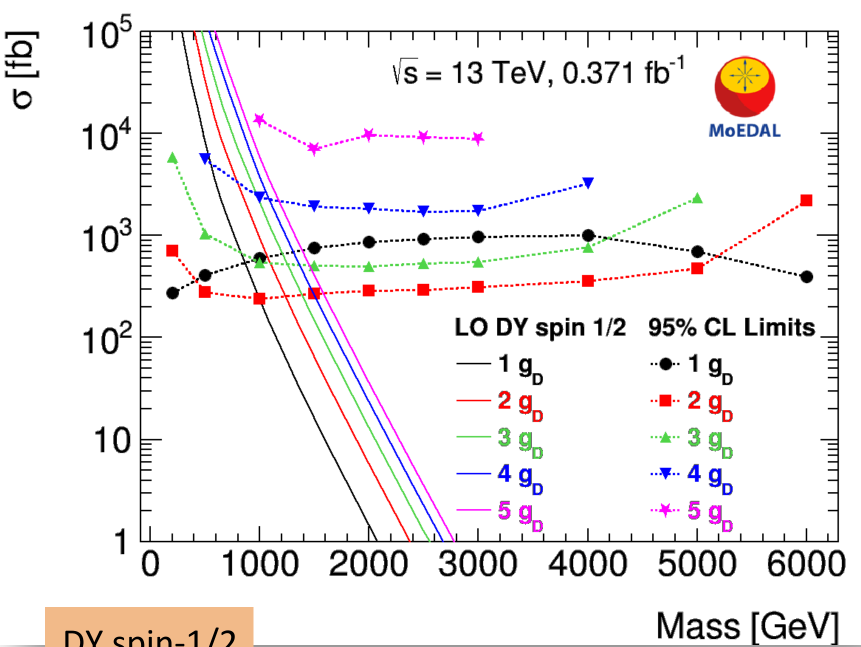
arXiv:1606.01220

MMT2015: results

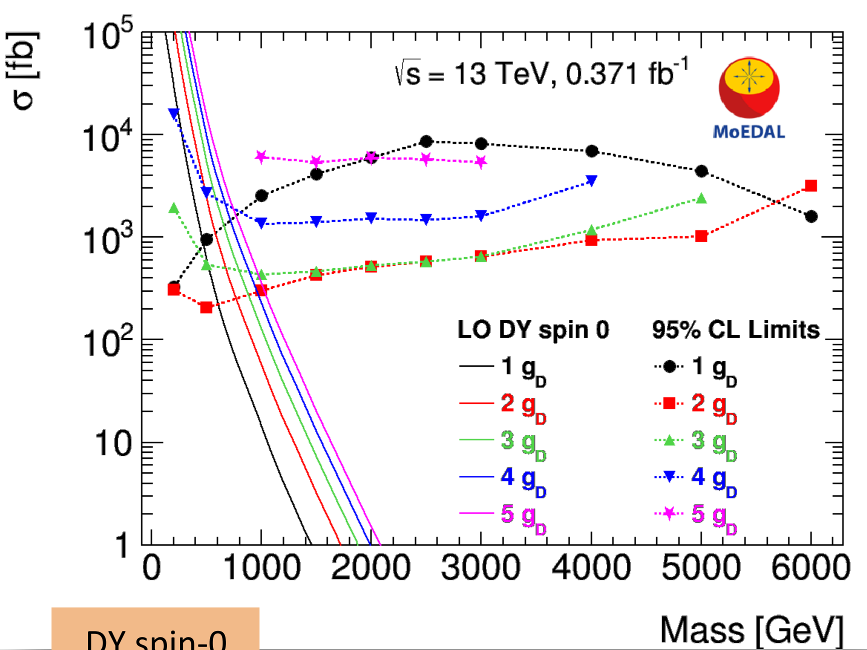
Detector: prototype of **222 kg** of aluminium bars

Exposure: **0.371 fb^{-1}** of **13 TeV** *pp* collisions during 2015

PRL 118 (2017) 061801
[arXiv:1611.06817]



DY spin-1/2

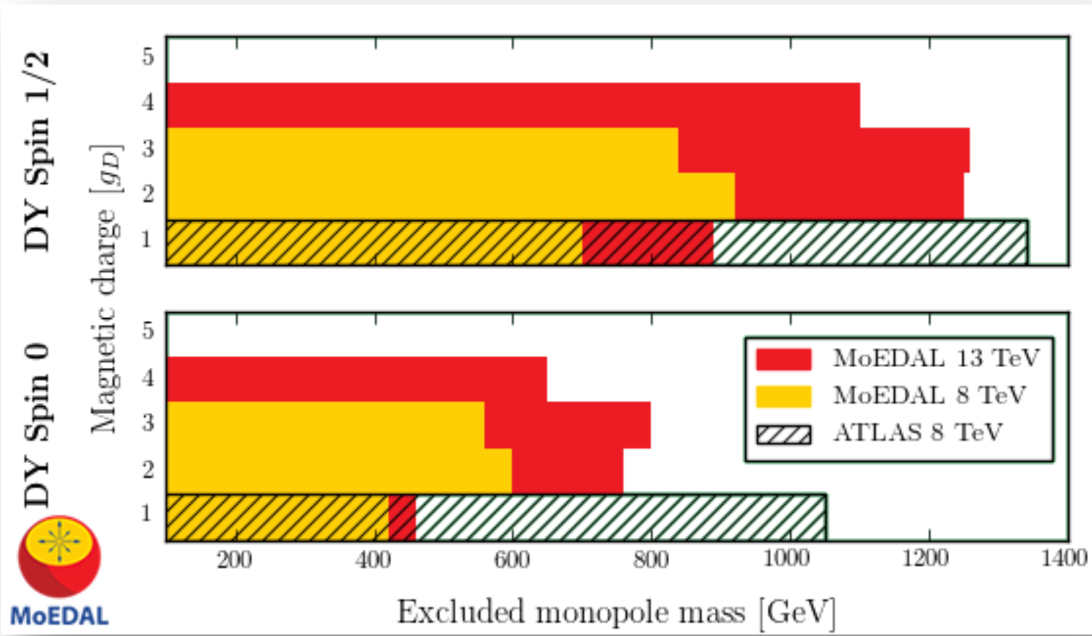


DY spin-0

- First monopole searches at **13 TeV** at LHC
- First limits for magnetic charge of **5 g_D** and masses **> 3.5 TeV**

Monopole mass limits

PRL 118 (2017) 061801
[arXiv:1611.06817]



DY lower mass limits [GeV]		$\lvert g\rvert = g_D$	$\lvert g\rvert = 2g_D$	$\lvert g\rvert = 3g_D$	$\lvert g\rvert = 4g_D$
MoEDAL 13 TeV	spin ½	890	1250	1260	1100
	spin 0	460	760	800	650
MoEDAL 8 TeV	spin ½	700	920	840	—
	spin 0	420	600	560	—
ATLAS 8 TeV	spin ½	1340	—	—	—
	spin 0	1050	—	—	—

- Mass limits are *highly model-dependent*
  - Drell-Yan production does *not* take into account non-perturbative nature of the large monopole-photon coupling
- Exclude low masses for **$|g| = 4g_D$** for the first time at LHC
- World-best collider limits for **$|g| \geq 2\, g_D$**

Beyond magnetic monopoles

- What about *electrically*-charged particles?

Why MoEDAL when searching SMCPs?

- ATLAS and CMS triggers have to
  - rely on other "objects", e.g. E_T^{miss}, that accompany SMCPs, thus limiting the reach of the search
    - final states with associated object present
    - trigger threshold set high for high luminosity
  - develop specialised triggers
    - dedicated studies needed
    - usually efficiency significantly less than 100%
- Timing: signal from (slow-moving) SMCP should arrive within the correct bunch crossing
- MoEDAL mainly constrained by its geometrical acceptance
- When looking for trapped particles
  - monitoring of detector volumes in an underground/basement laboratory has less background than using empty butches in LHC cavern

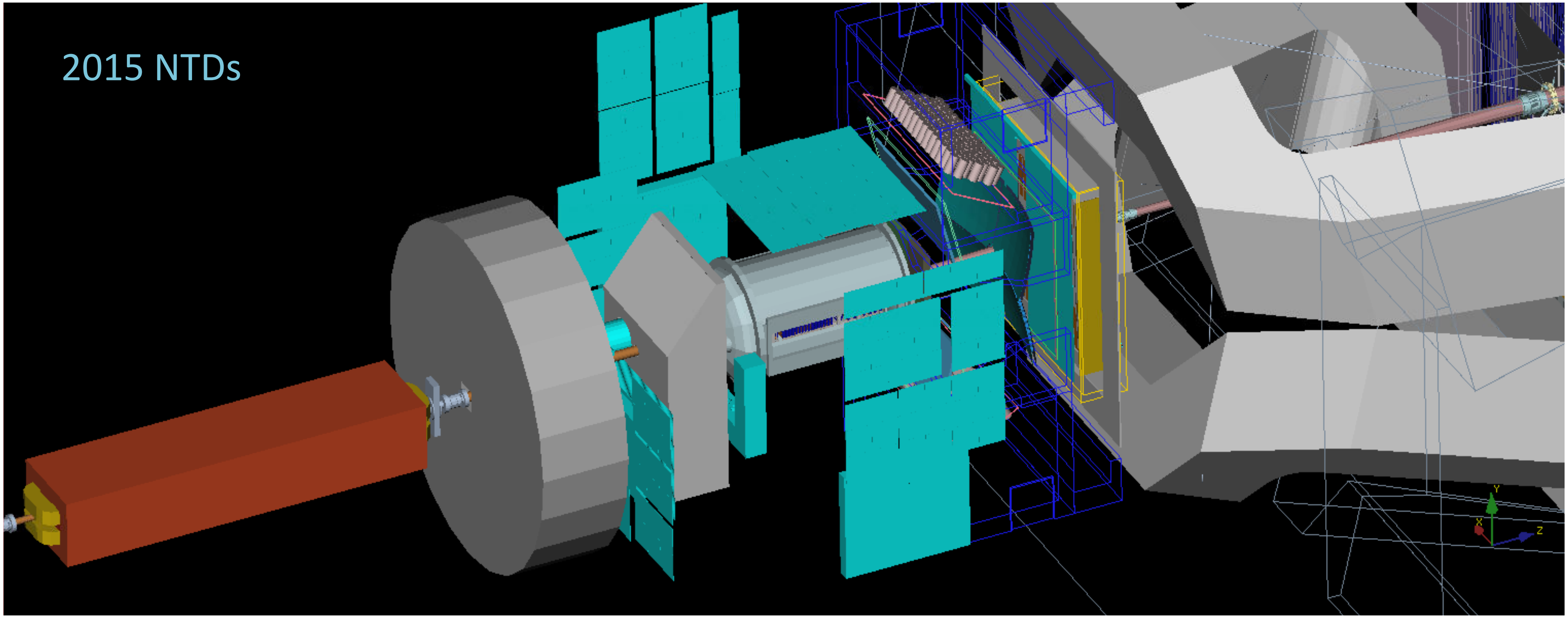
Slepton searches comparison*

* Indicative numbers

	ATLAS / CMS	MoEDAL	comments
Velocity	β > 0.2 Constrained by LHC bunch pattern	β < 0.2 Constrained by NTD Z/β threshold	Complementarity 😀
Analysis	Not simple, involving several detector components, electronics, triggers, …	Simple and robust	😊
Efficiency		~ 100% (if $\beta \lesssim 0.2$)	😐
Acceptance	ε × A order of 20% *See limitations in previous slide*	• Geometry: ~ 50% for 2015; scalable to higher coverage • β-cut yield: ~10% ☞ *highly model dependent*	
Background	May be considerable or difficult to estimate	Practically zero	For same signal yield, MoEDAL should have better sensitivity 😊
Luminosity	high	factor of 10-50 less	LIMITING FACTOR 😕

Nuclear Track Detectors coverage

- High acceptance in central region η~0
  - back-to-back pair production means probability >~ 70% for at least one SMCP to hit NTD
- For particles over z/β threshold, detection efficiency practically 100%



Credit: Daniel Felea

SUSY long-lived particles *(relevant for MoEDAL)*

- Long-lived sleptons (staus mostly)
  - **Gauge-mediated symmetry-breaking (GMSB)**: stau NLSP decays via gravitational interaction to gravitino LSP

$$\Gamma(\tilde{l} \to l\tilde{G}) = \frac{1}{48\pi M_*^2} \frac{m_{\tilde{l}}^5}{m_{\tilde{G}}^2} \left[1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{l}}^2}\right]^4$$

  - **Coannihilation region in CMSSM**: long lived stau, when $m(\tilde{\tau}) - m(\tilde{\chi}_1^0) < m(\tau)$

  ➜ naturally long lifetime for stau in both cases

$$\tilde{\tau} \to \tau\tilde{\chi}_1^0$$

- R-hadrons
  - **Gluinos in Split Supersymmetry**: $\tilde{g}q\bar{q}$, $\tilde{g}qqq$, $\tilde{g}g$
    - long-lived because squarks very heavy
    - gluino hadrons may flip charge as they pass through matter
  - **Stops**: $\tilde{t}\bar{q}$, $\tilde{t}qq$
    - e.g. stop NLSP in gravitino dark matter

$$\tilde{t} \to t\tilde{G}$$

    - e.g. as LSP in R-parity violating SUSY, long-lived when RPV coupling(s) small
- Long-lived charginos
  - **Anomaly-mediated symmetry-breaking (AMSB)**: $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ are mass degenerate ⇒ $\tilde{\chi}_1^\pm$ becomes long-lived

$$\tilde{\chi}_1^\pm \to \pi^\pm\tilde{\chi}_1^0$$

Improving complementarity

- Relaxing constraints imposed in ATLAS/CMS selections
- Example: CMS dE/dx analysis @7-8 TeV
  [JHEP07 (2013) 122, arXiv:1305.0491]

<table>
<tr><th></th><th>tracker+TOF</th><th>tracker-only</th></tr>
<tr><td>$|\eta|$</td><td colspan="2"><2.1</td></tr>
<tr><td>p_T (GeV/c)</td><td colspan="2">>45</td></tr>
<tr><td>d_z and d_{xy} (cm)</td><td colspan="2"><0.5</td></tr>
<tr><td>σ_{p_T}/p_T</td><td colspan="2"><0.25</td></tr>
<tr><td>Track χ^2/n_d</td><td colspan="2"><5</td></tr>
<tr><td># Pixel hits</td><td colspan="2">>1</td></tr>
<tr><td># Tracker hits</td><td colspan="2">>7</td></tr>
<tr><td>Frac. Valid hits</td><td colspan="2">>0.8</td></tr>
<tr><td>$\Sigma p_T^{trk}(\Delta R < 0.3)$ (GeV/c)</td><td colspan="2"><50</td></tr>
<tr><td># dE/dx measurements</td><td colspan="2">>5</td></tr>
<tr><td>dE/dx strip shape test</td><td>yes</td><td></td></tr>
<tr><td>$E_{cal}(\Delta R < 0.3)/p$</td><td>$<0.3$</td><td></td></tr>
<tr><td>I_h (MeV/cm)</td><td></td><td>>3.0</td></tr>
<tr><td>ΔR to another track</td><td colspan="2">–</td></tr>
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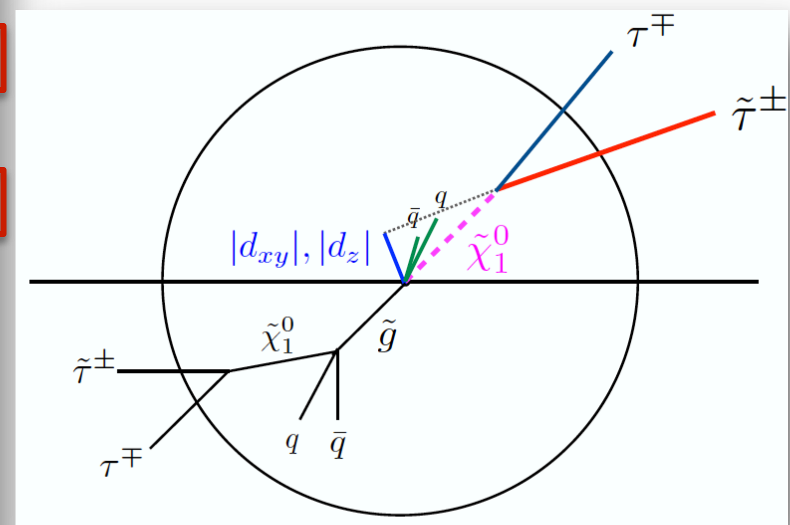
Relaxing *both* constraints



In collaboration with Kazuki Sakurai

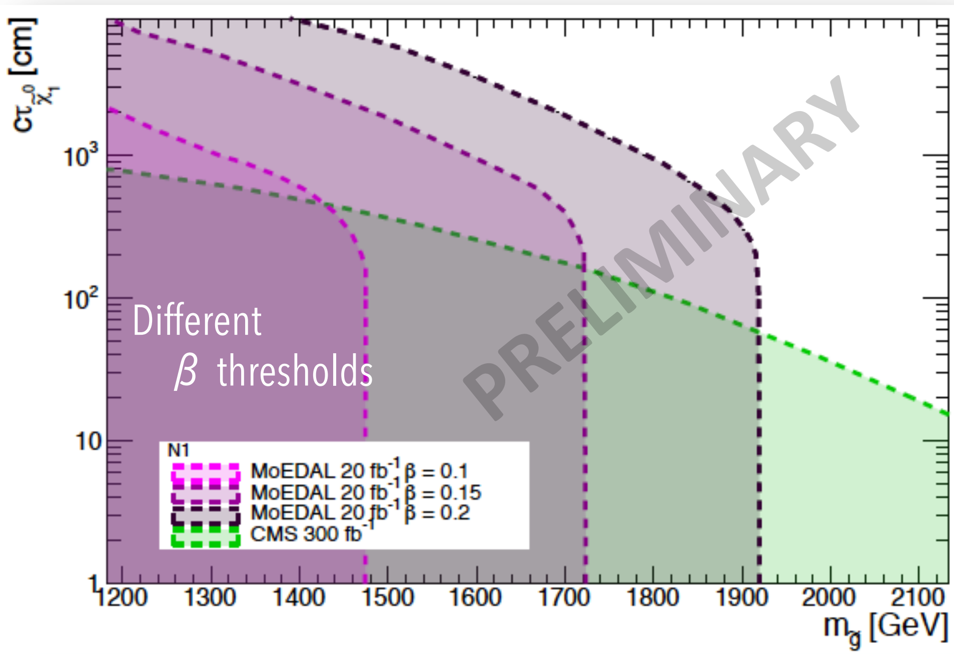
Results for $\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow jj\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow\tau^\pm\tilde{\tau}_1$

$\tilde{\chi}_1^0$ long-lived despite large mass split between $\tilde{\chi}_1^0$ and $\tilde{\tau}_1$ ➜ decays in tracker

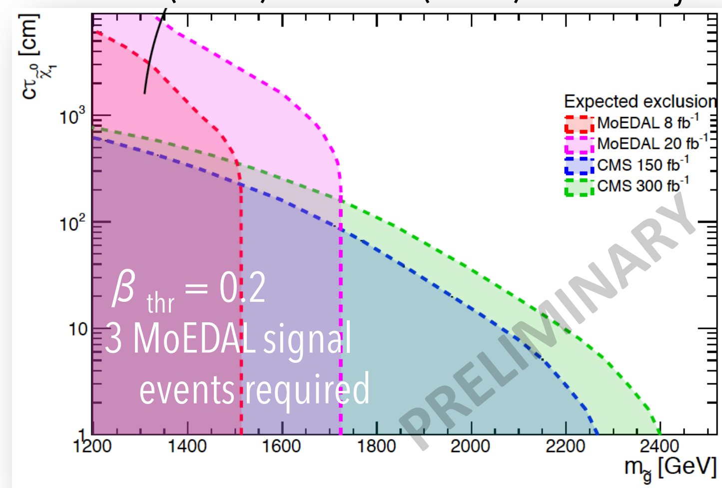
(massive) $\tau^\pm$ produces a kink between $\tilde{\chi}_1^0$ and $\tilde{\tau}_1$ tracks ⇒ large impact parameters d_{xy}, d_z

$\tilde{\tau}_1$ metastable, e.g. gravitino LSP ➜ detected by MoEDAL

End-of-run-3 (2023) luminosity



Run 2 (2018) vs. Run-3 (2023) luminosity



CMS affected two-ways:

a) no pixel hit

b) too large impact parameters

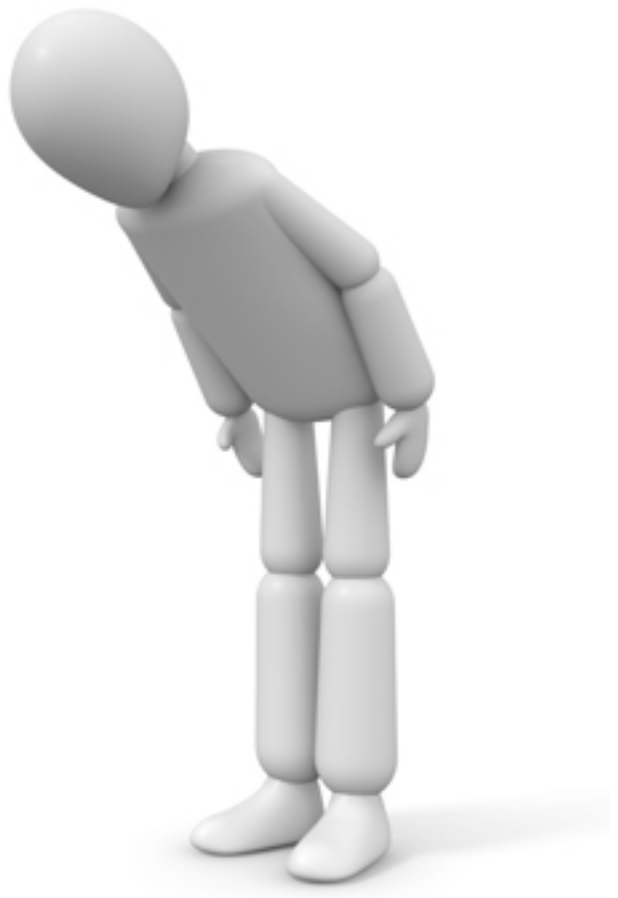
- Comparison of CMS exclusion with MoEDAL discovery potential requiring 1 event
- Conservative estimate of MoEDAL luminosity

MoEDAL can cover long-lifetime region inaccessible by ATLAS/CMS even with a *moderate* NTD performance **z/β > 10**

Summary & outlook

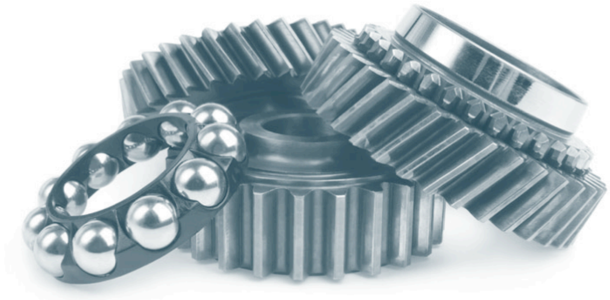
- MoEDAL is searching for **(meta)stable highly ionising particles**
  - least tested signals of New Physics
  - predicted in variety of theoretical models
  - design *optimised* for such searches
  - combining various detector technologies
- Results on monopole searches at 8 TeV & 13 TeV published
  - no magnetic monopole detected
  - bounds set significantly extend previous results at high charges
- Looking forward to many more results from Run-II and beyond
  - for more monopole interpretations
    - production via photon fusion
    - spin 1 monopoles
  - with NTDs
  - for electrically-charged particles

Thank you for your attention!

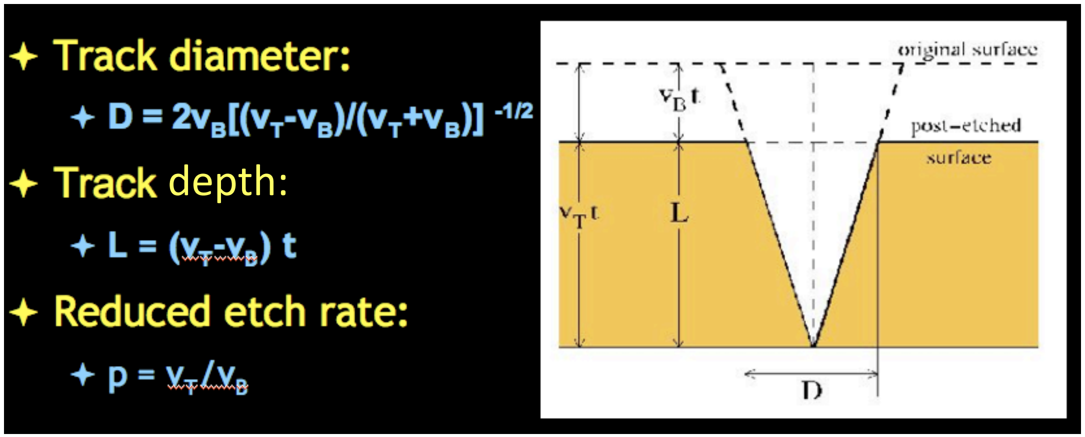


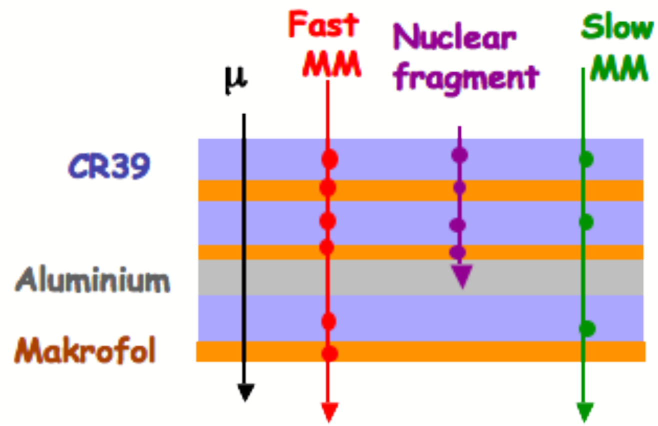
Project supported by a 2017 Leonardo Grant for Researchers and Cultural Creators, BBVA Foundation

Spares



Analysis procedure





- Electrically-charged particle: $dE/dx \sim \beta^{-2}$ ➔ slows down appreciably within NTD ➔ opening angle of etch-pit cone becomes **smaller**
- Magnetic monopole: $dE/dx \sim \ln\beta$
  - slow MM: slows down within an NTD stack ➔ its ionisation falls ➔ opening angle of the etch pits would become **larger**
  - relativistic MM: dE/dx essentially constant ➔ trail of equal diameter etch-pit pairs
- The reduced etch rate is simply related to the *restricted energy loss* REL = $(dE/dx)_{\text{10nm from track}}$

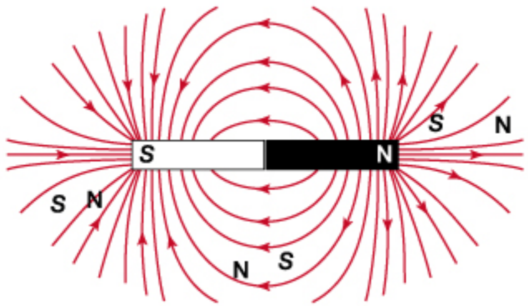
Dirac's Monopole

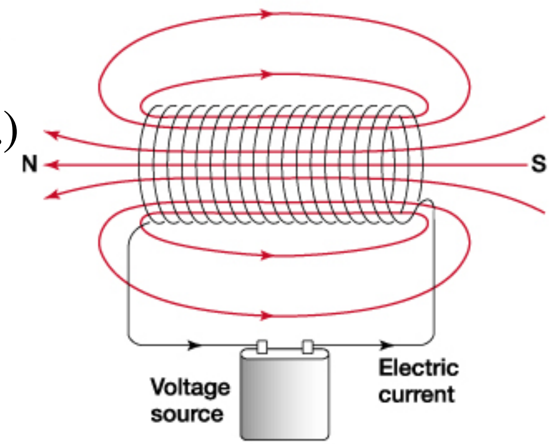
- Paul Dirac in 1931 hypothesized that the magnetic monopole exists
- In his conception the monopole was the end of an infinitely long and infinitely thin solenoid
- Dirac's quantisation condition:

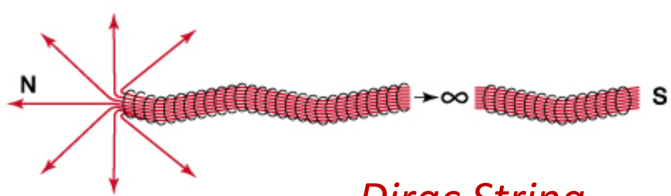
$$ge = \left[\frac{\hbar c}{2}\right]n \quad OR \quad g = \frac{n}{2\alpha}e \quad \left(from \quad \frac{4\pi e g}{\hbar c} = 2\pi n \quad n = 1,2,3..\right)$$

- Where g is the "magnetic charge" and α is the fine structure constant 1/137
- This means that **g = 68.5e** (when n=1)!
- The other way around: IF there is a magnetic monopole then charge is quantised:

$$e = \left[\frac{\hbar c}{2g}\right]n$$







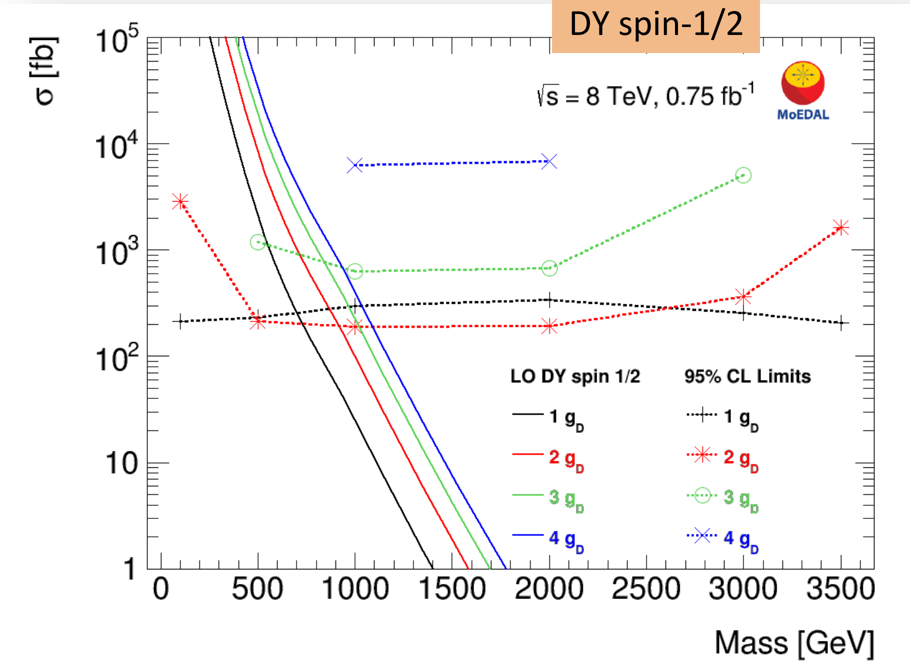
Dirac String

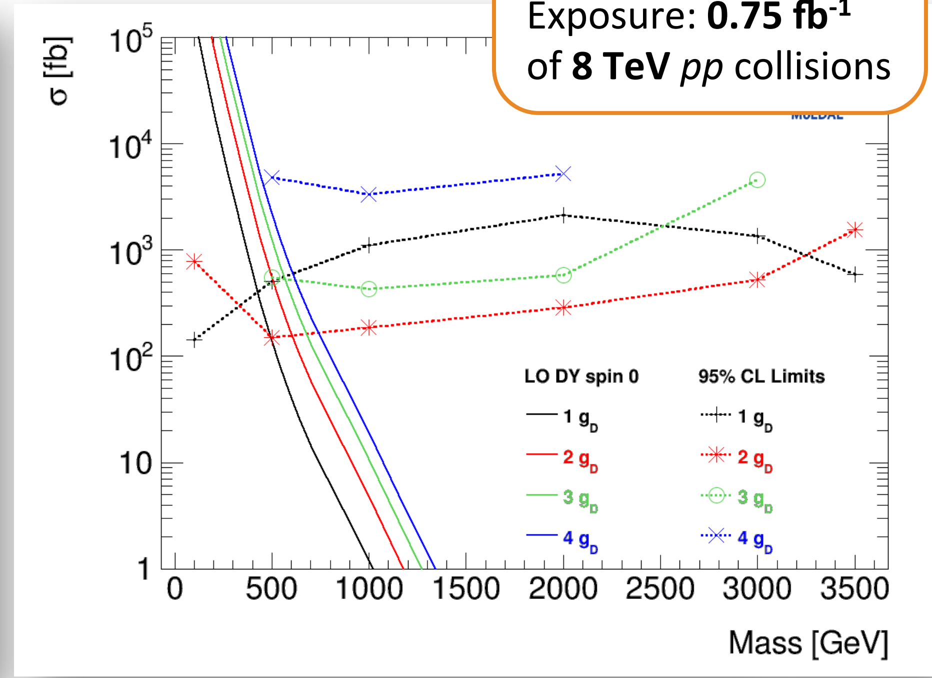
Cross section limits versus mass

Detector: prototype of **160 kg** of Al rods

Exposure: **0.75 fb^{-1}** of **8 TeV** *pp* collisions

DY spin-1/2





Limits extend up to masses **> 2500 GeV** for the first time at the LHC

- reminder: shown (tiny) LO DY cross sections are not reliable
  ⇒ makes sense to probe and constrain very high masses

JHEP 1608 (2016) 067 [arXiv:1604.06645]

Cross section limits versus charge

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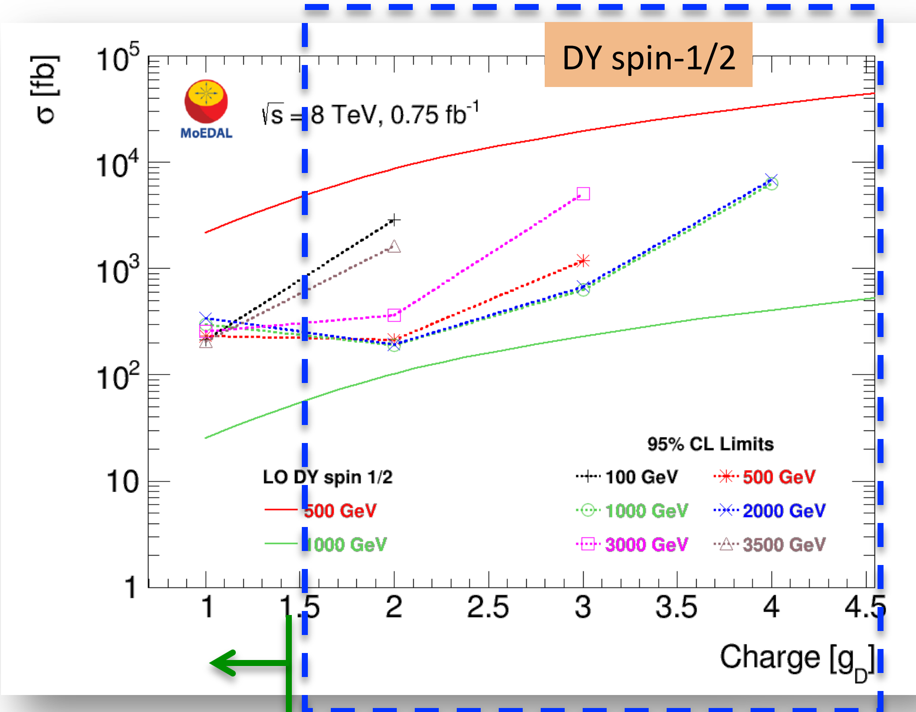
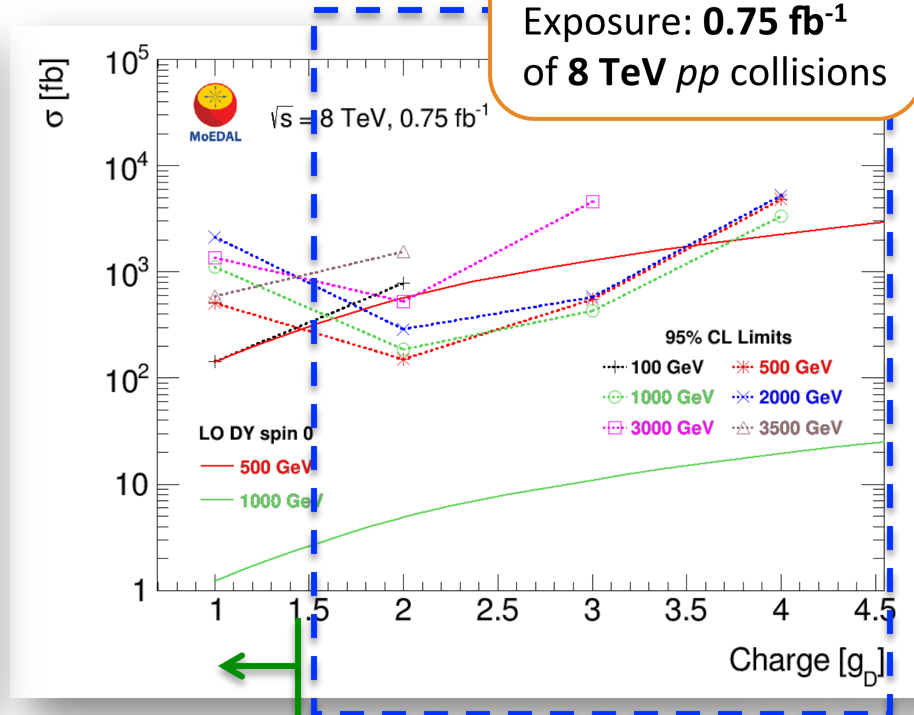




also covered by ATLAS search

World-best limits for |g| > 1.5 g_D

- previously ~400 GeV at Tevatron [e.g. CDF hep-ex/0509015]
- **first time at the LHC**

JHEP 1608 (2016) 067
[arXiv:1604.06645]

Complementarity of MoEDAL & other LHC exps

ATLAS+CMS

- Optimised for *singly* electrically charged particles ($z/\beta \sim 1$)
- LHC timing/trigger restricts sensitivity to (nearly) *relativistic* particles ($\beta \approx 1$)
- Typically a largish statistical sample is needed to establish a signal
- ATLAS & CMS cannot be calibrated for highly ionising objects
- Magnetic charge detection via its trajectory in non-bend plane → calibration introduces large systematics

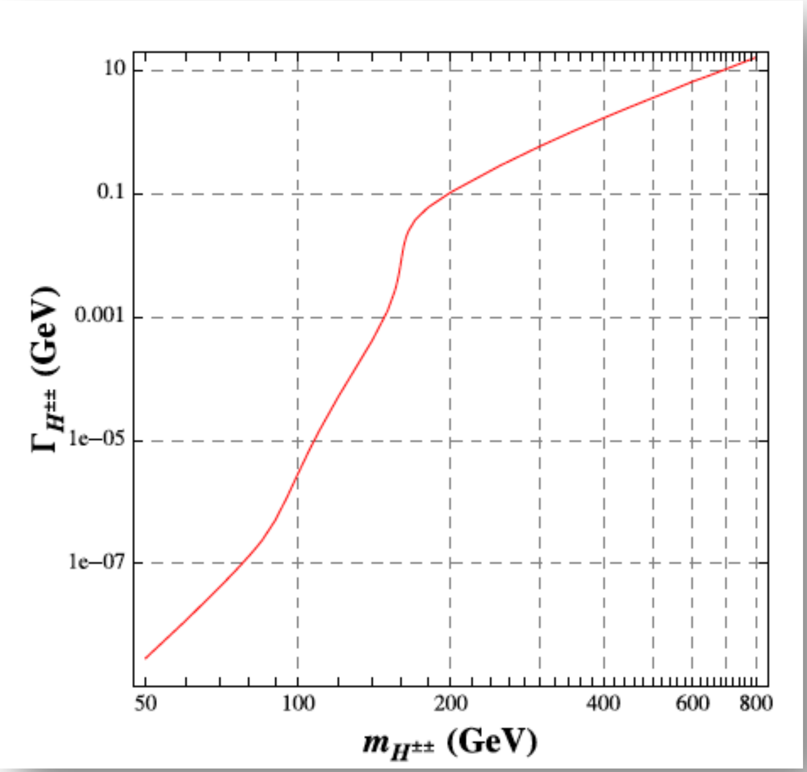
MoEDAL

- Designed to detect charged particles, with effective or actual $z/\beta > 5$
- No trigger/electronics → slowly moving ($\beta <$ ~0.5) particles are no problem
- One candidate event should be enough to establish a signal (no SM bkg)
- MoEDAL NTDs are calibrated using heavy ion beams
- Magnetic-charge sensitivity directly calibrated in a clear way

MoEDAL strengthens & expands the physics reach of LHC

Doubly-charged Higgs

- Extended Higgs sector in BSM models: $SU_L(2) \times SU_R(2) \times U_{B-L}(1)$ P-violating model
- Higgs triplet model with massive left-handed neutrinos but not right-handed ones
- Common feature: **doubly charged Higgs bosons $H^{\pm\pm}$** as parts of a Higgs triplet
- Lifetime
  - depends on many parameters: Yukawa h_{ij} (long if < 10^{-8}), $H^{\pm\pm}$ mass, ...
  - essentially there are no constraints on its lifetime ➜ relevant for MoEDAL



Partial decay width of $H^{\pm\pm} \to W^{\pm}W^{\pm}$

Chiang, Nomura, Tsumura,
Phys.Rev. D85 (2012) 095023 [arXiv:1202.2014]

Black-hole remnants

- In some **Large Extra Dimension** models the formation of **TeV Black Holes (BH)** by high energy SM particle collisions is predicted
  - BH average charge 4/3
  - slowly moving ($\beta \lesssim 0.3$)
- Charged Hawking BH evaporate but not completely

  ➜ certain fraction of final BH remnants carry **multiple charges**

  ➜ highly ionising, relevant to MoEDAL

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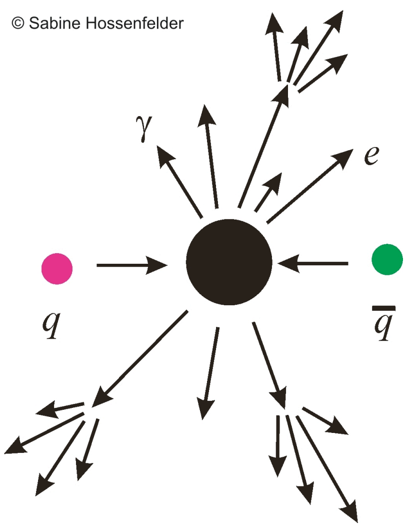

Hossenfelder, Koch, Bleicher, hep-ph/0507140

BHR charges @ 14 TeV LHC [CHARYBDIS+PYTHIA]