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EXCELENCIA SEVERO OCHOA
CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
VNIVERSITAT DE VALÈNCIA
GENERALITAT VALENCIANA
Fundación BBVA

MoEDAL

Searches for New Physics with the MoEDAL detector at the LHC

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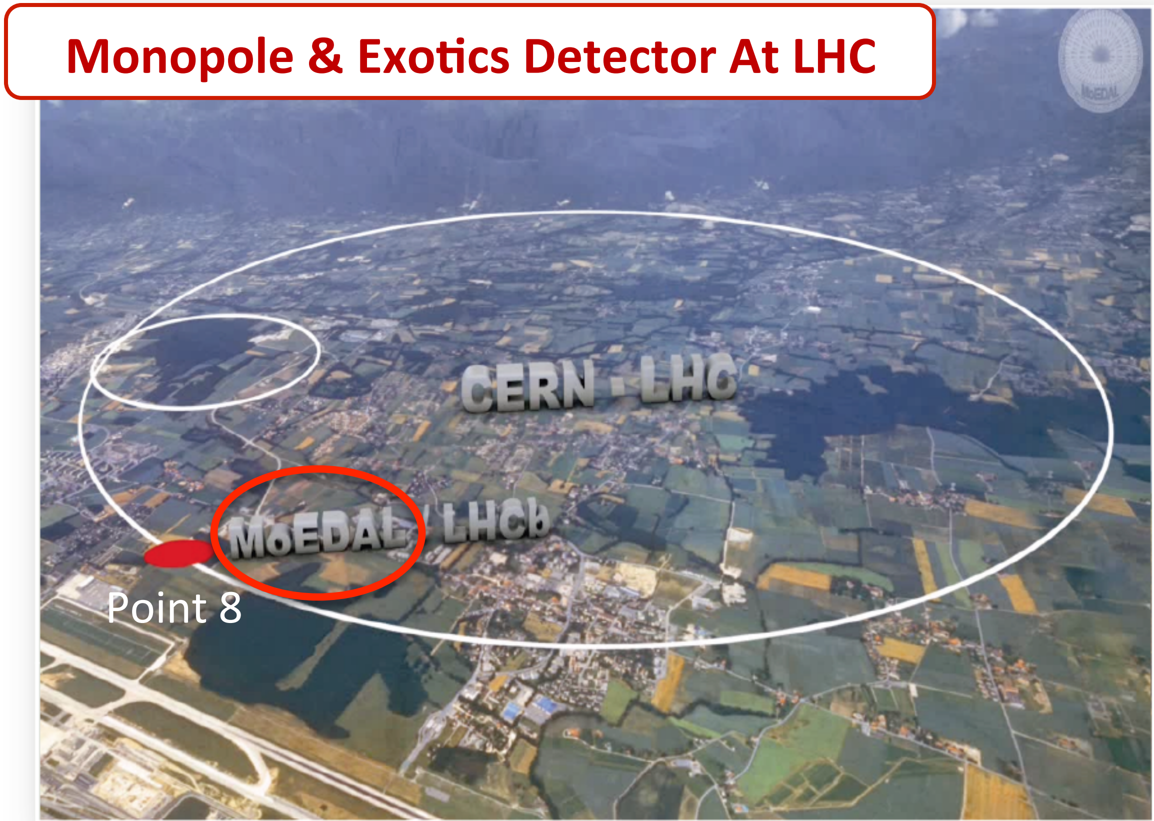
for the MoEDAL Collaboration

17th HELLENIC SCHOOL AND WORKSHOPS ON ELEMENTARY PARTICLE PHYSICS AND GRAVITY
Workshop on the Standard Model and Beyond
September 2 – 10, 2017, Corfu, Greece


Francesco Pige

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**

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

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

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

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

Magnetic charge

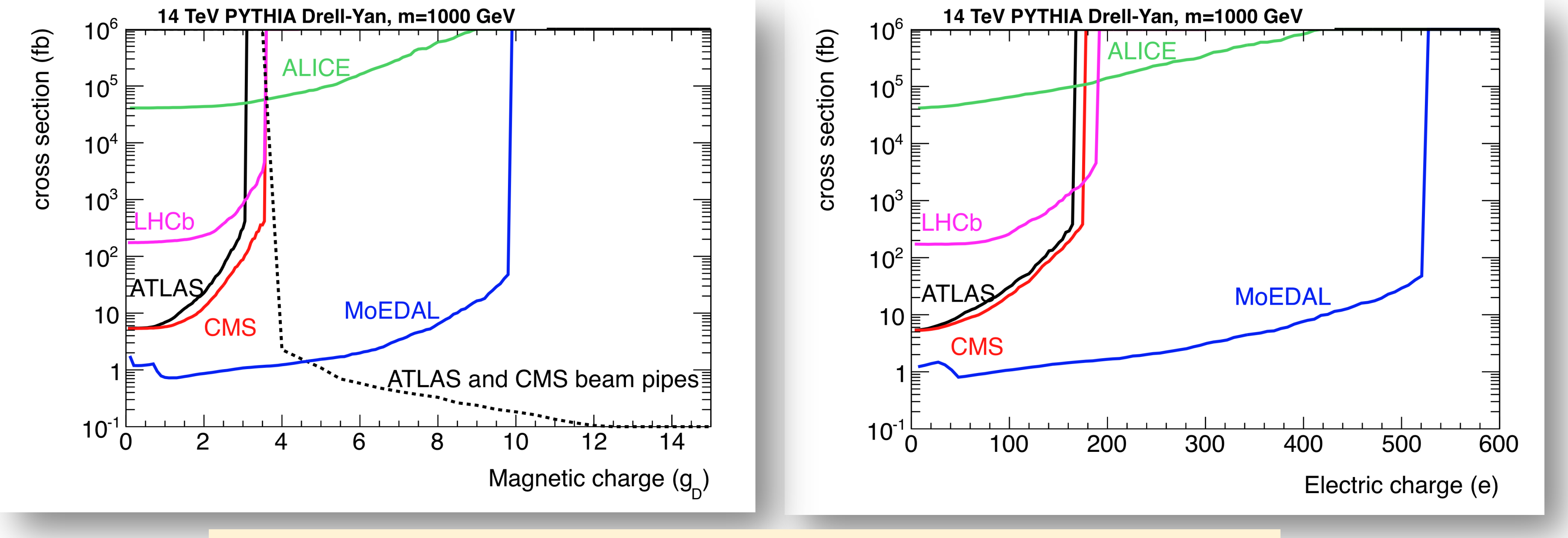
Ahlen formula

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:

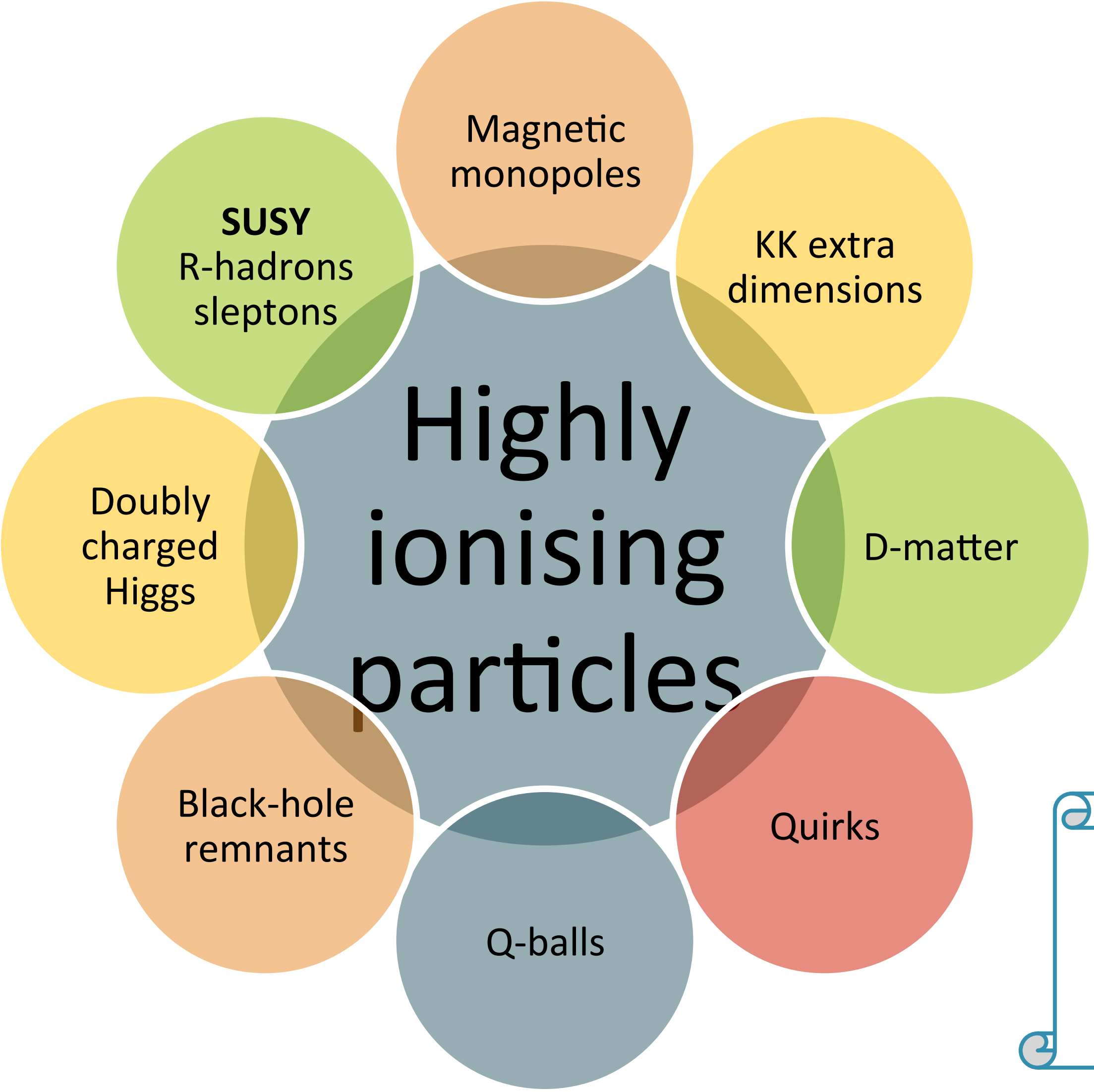
- ~ one MoEDAL event is required for discovery and ~100 events in the other LHC detectors
- integrated luminosities correspond to about two years of 14 TeV run



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



Highly ionising particles

Magnetic monopoles

KK extra dimensions

D-matter

Quirks

Q-balls

Black-hole remnants

Doubly charged Higgs

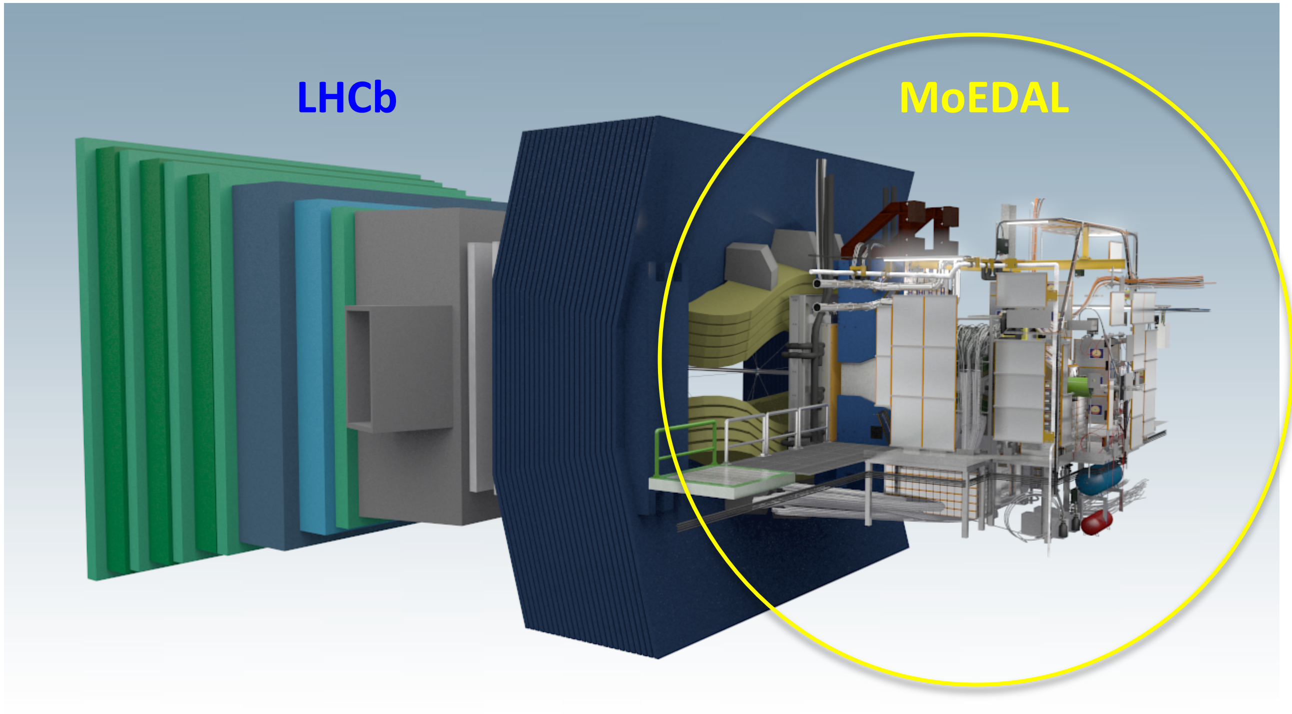
SUSY
R-hadrons
sleptons

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
  - $z/\beta >$ ~5 – 10

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

③ TimePix radiation background monitor

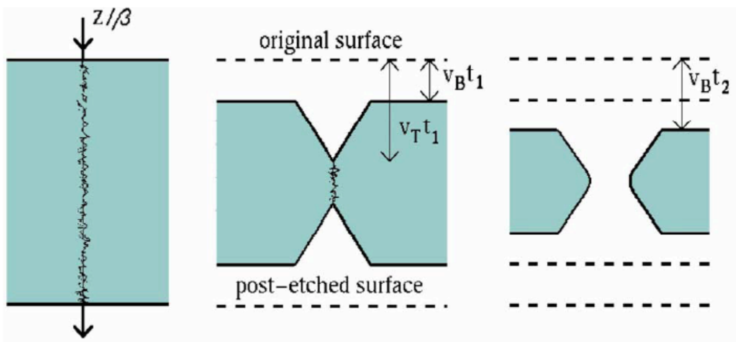
④ Monopole Trapping detector (**MMT**)

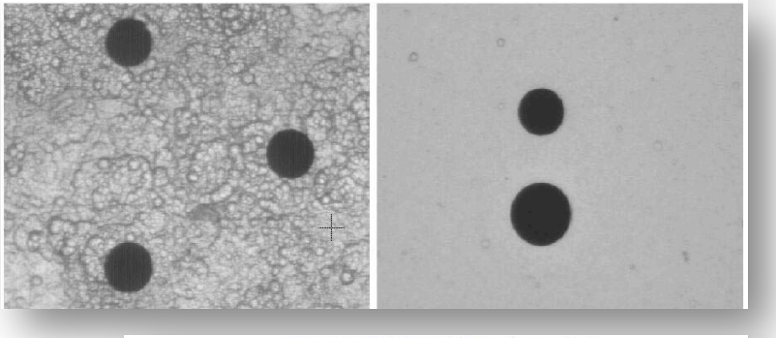
MoEDAL is unlike any other LHC experiment:

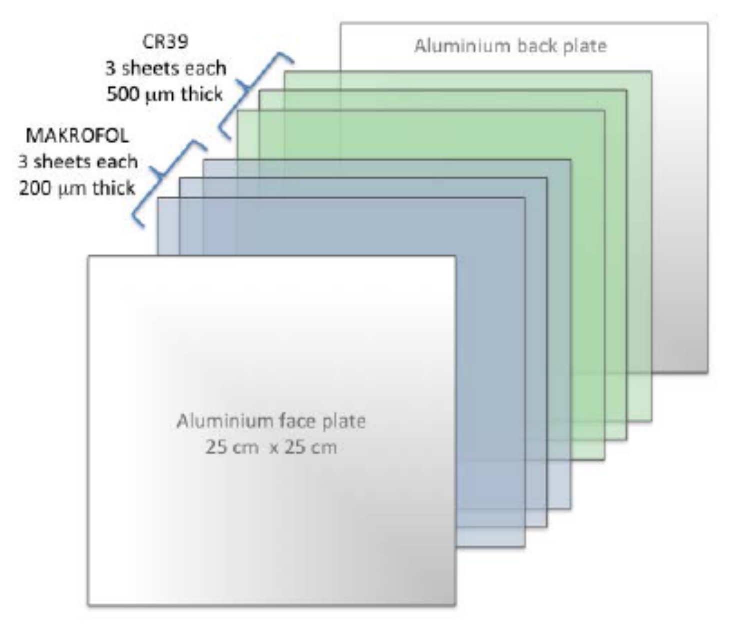
- mostly **passive detectors**; no trigger; no readout
- the largest deployment of passive **Nuclear Track Detectors (NTDs)** at an accelerator
- the 1st time **trapping detectors** are deployed as a detector

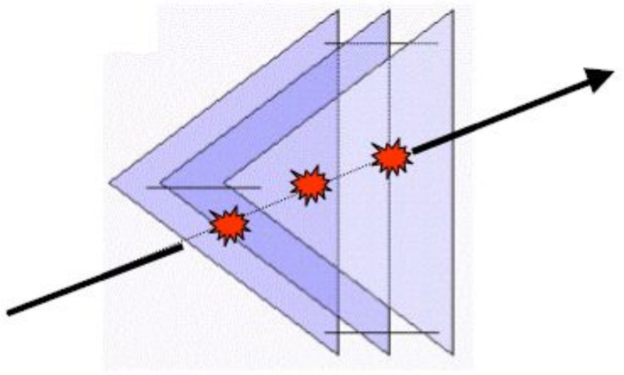
1 & 2 HI particle detection in NTDs

- 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







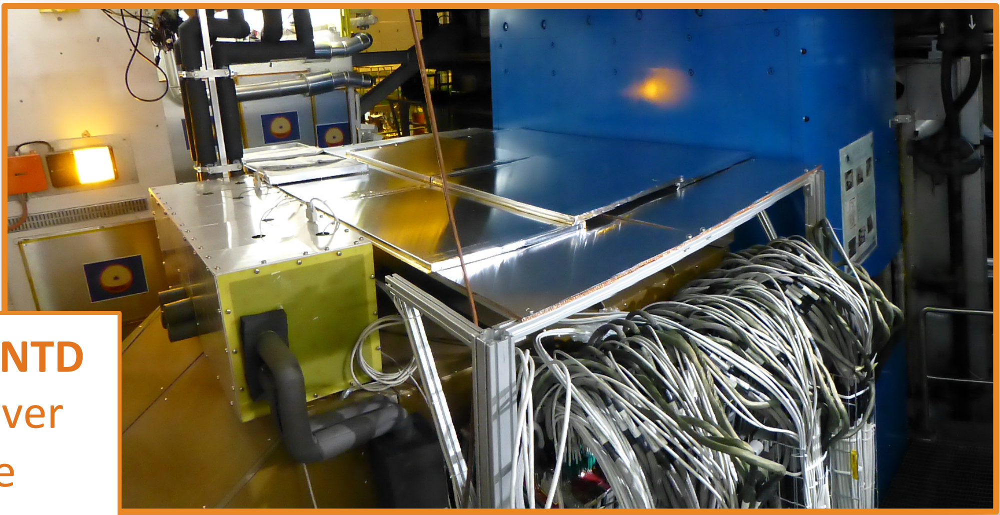


Looking for aligned etch pits in multiple sheets

1 & 2 NTDs deployment

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

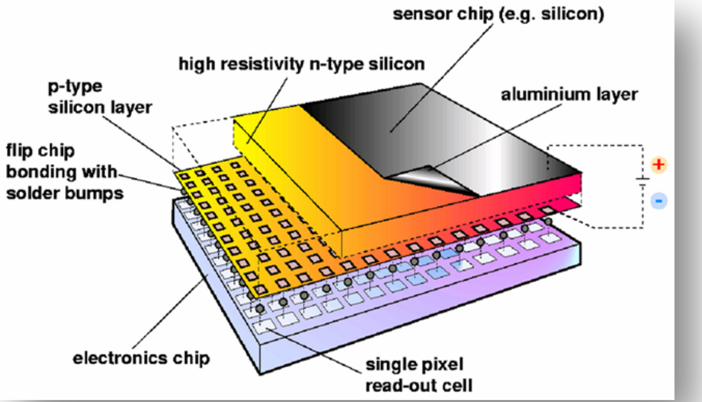
2015-2016: LT-NTD
Top of VELO cover
Closest possible location to IP

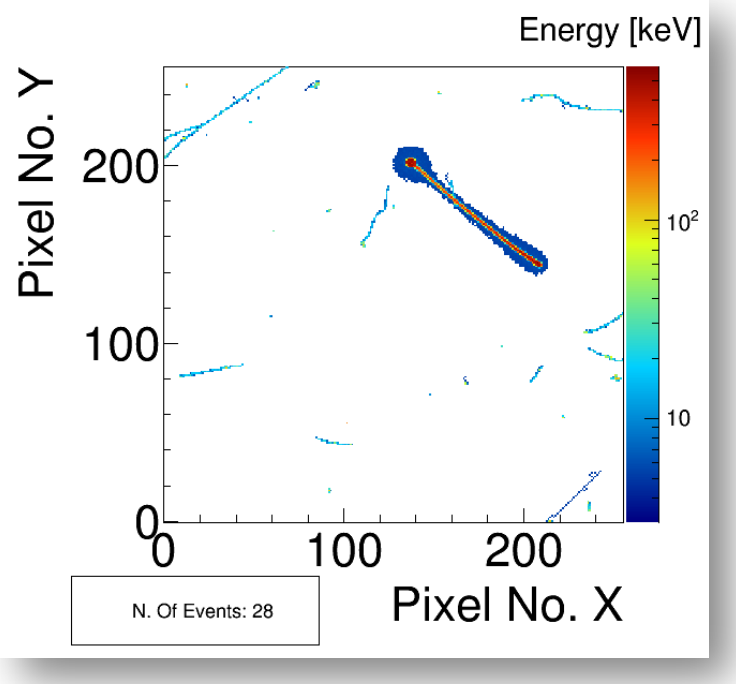


2015-2016: HCC-NTD
Installed in LHCb acceptance between RICH1 and TT

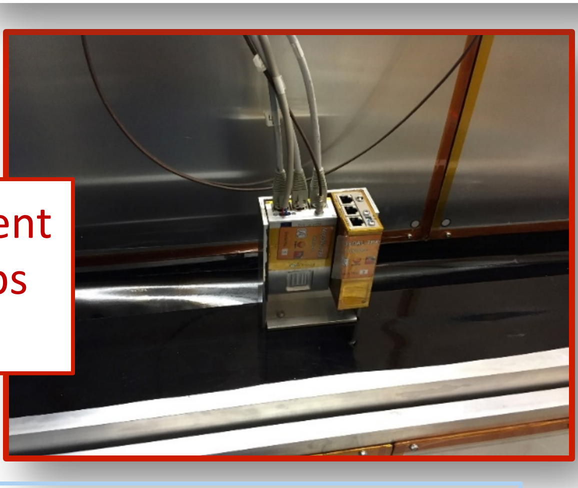
3 TimePix radiation monitor

- 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

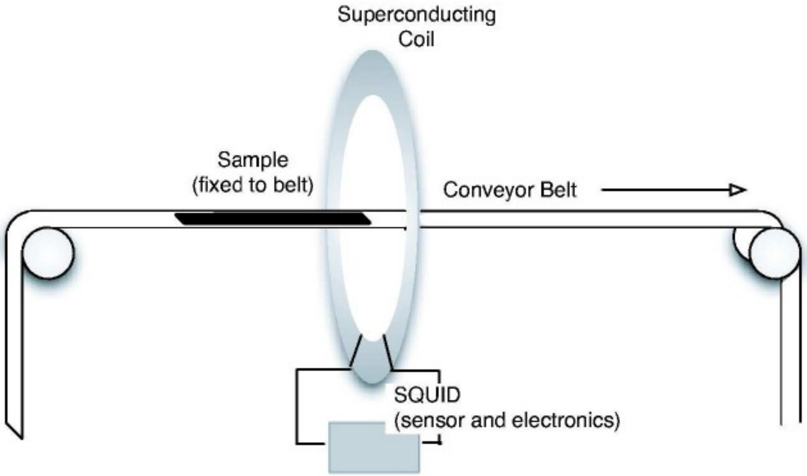


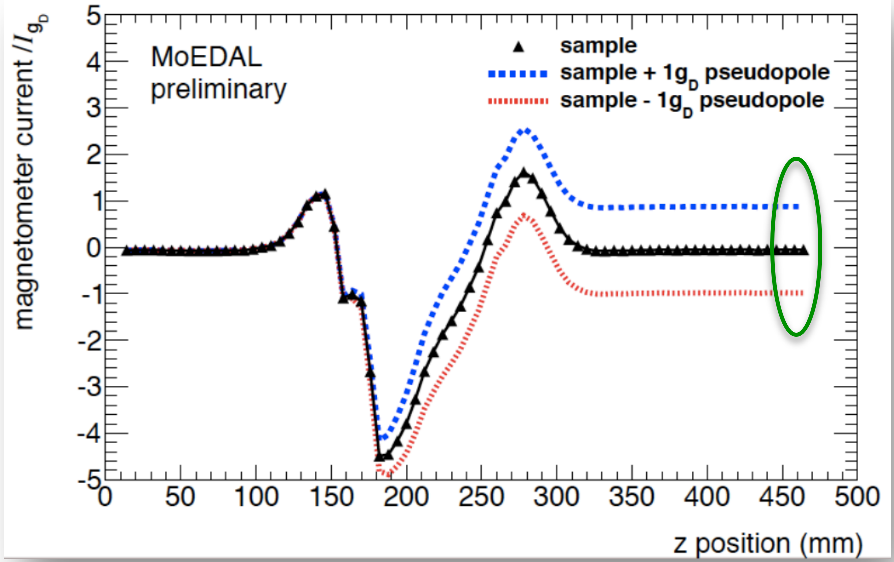
2015 deployment of MediPix chips in MoEDAL

- 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 of $\mathcal{O}$(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*



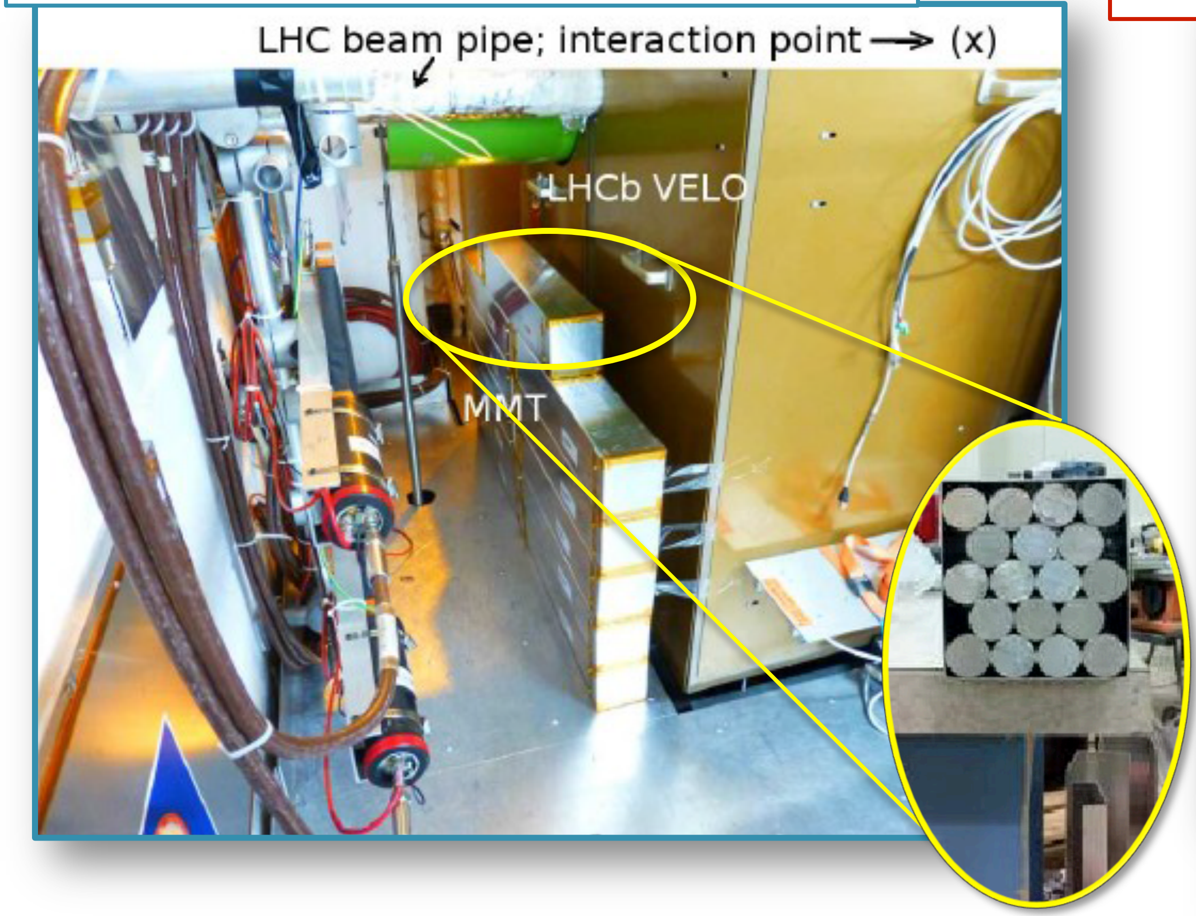


Typical sample & pseudo-monopole curves

MMTs deployment

2012

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



2015-2016

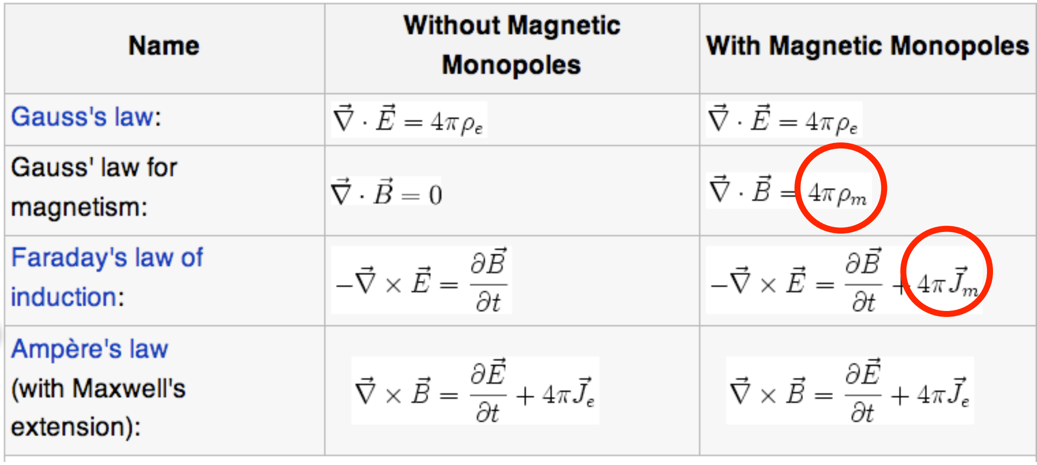
- Installed in additional locations: sides A & C, too
- Approximately **800 kg** of Al
- Total 2400 aluminum bars

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

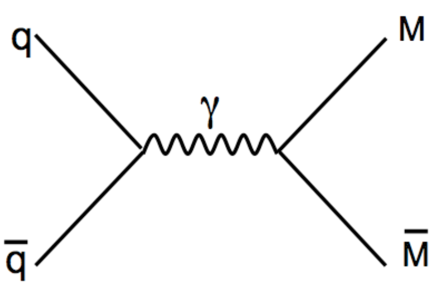
- Motivation
    - symmetrisation of Maxwell’s eqs.
    - electric charge quantisation
- Properties
    - magnetic charge = ng = n×68.5e
      coupling constant = g/ħc ~34
    - spin and mass not predicted



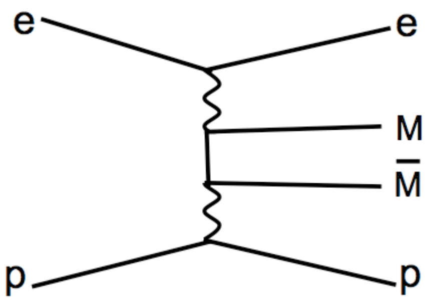
Name	Without Magnetic Monopoles	With Magnetic Monopoles
Gauss's law:	$\vec{\nabla}\cdot\vec{E} = 4\pi\rho_e$	$\vec{\nabla}\cdot\vec{E} = 4\pi\rho_e$
Gauss' law for magnetism:	$\vec{\nabla}\cdot\vec{B} = 0$	$\vec{\nabla}\cdot\vec{B} = 4\pi\rho_m$
Faraday's law of induction:	$-\vec{\nabla}\times\vec{E}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

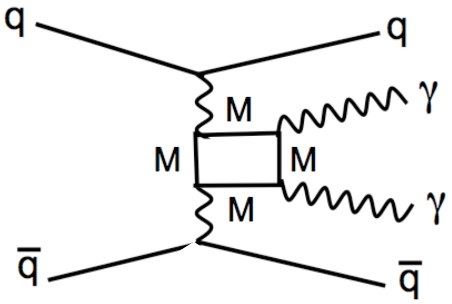
Production mechanisms in colliders



Drell Yan mechanism



Photon fusion



Box diagram

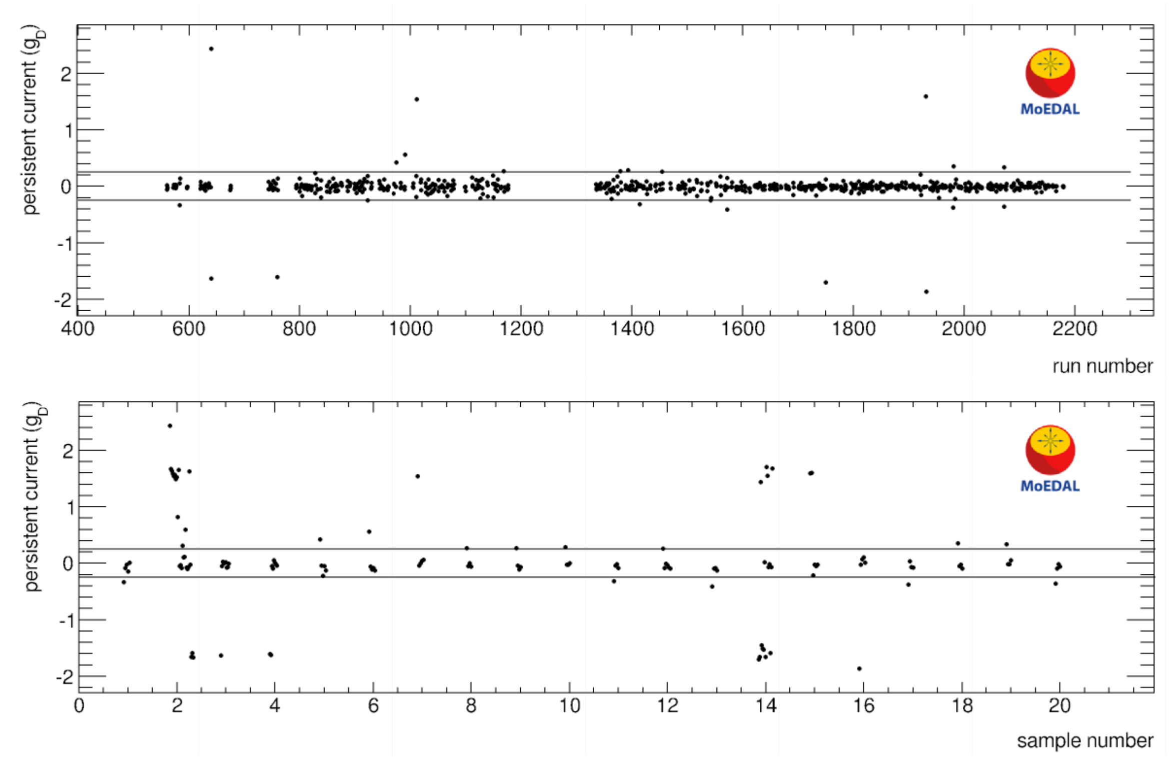
MoEDAL improves reach of monopole searches w.r.t. cross section & charge

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

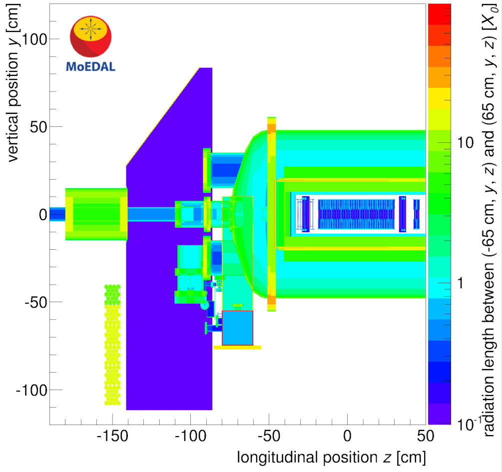
PRL 118 (2017) 061801 [arXiv:1611.06817]

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

MMT2015: analysis

Geometry

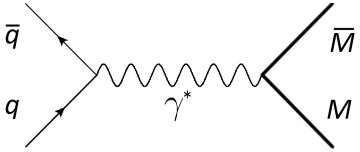
Material description between IP & detector

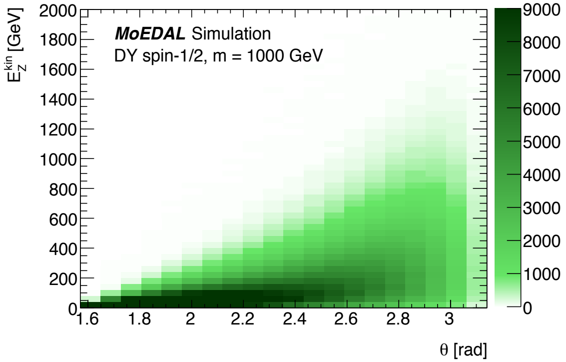


Kinematics

Event generation of Drell Yan production

coupling ≫ 1 ⇒ non-perturbative!

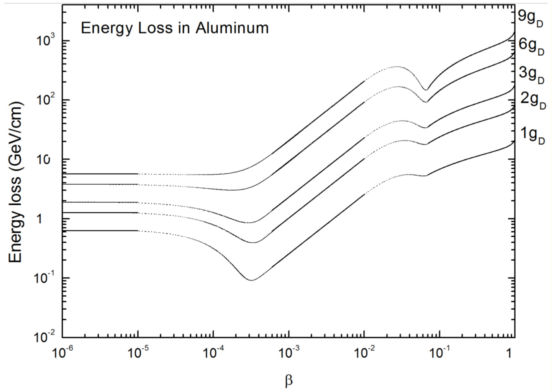




JHEP 1608 (2016) 067

Propagation in matter

- Ahlen formula
- Monopole energy loss
- Stopping range



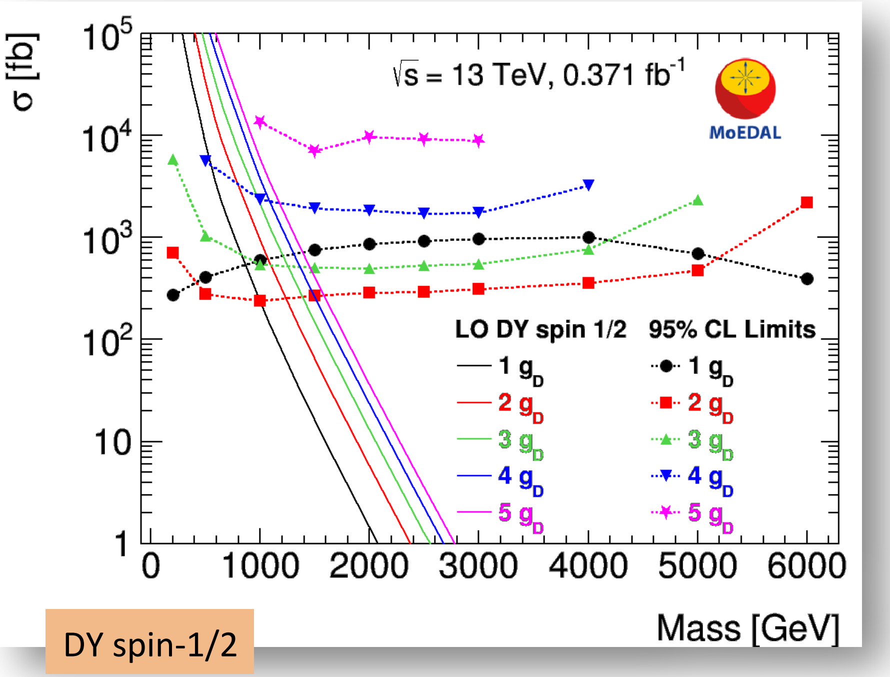
arXiv:1606.01220

MMT2015: results

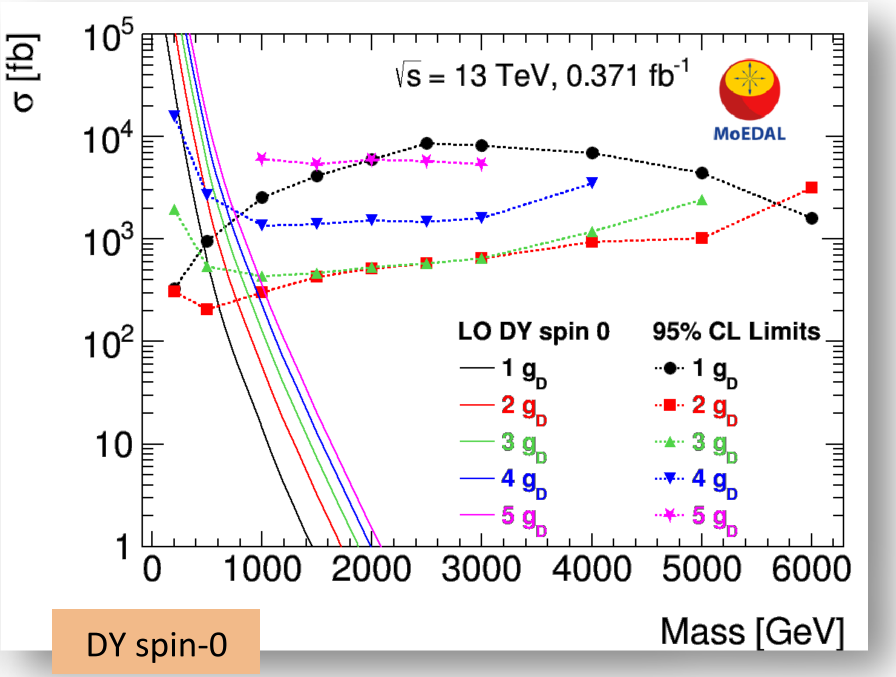
Detector: prototype of **222 kg** of aluminium bars

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

PRL 118 (2017) 061801
[arXiv:1611.06817]



DY spin-1/2

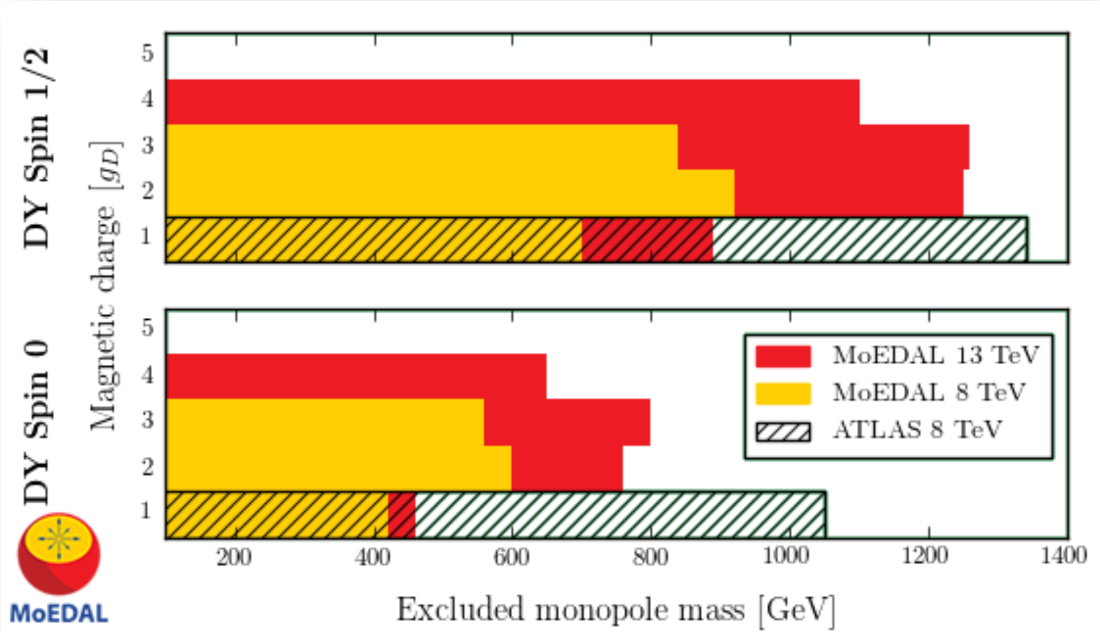


DY spin-0

- 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

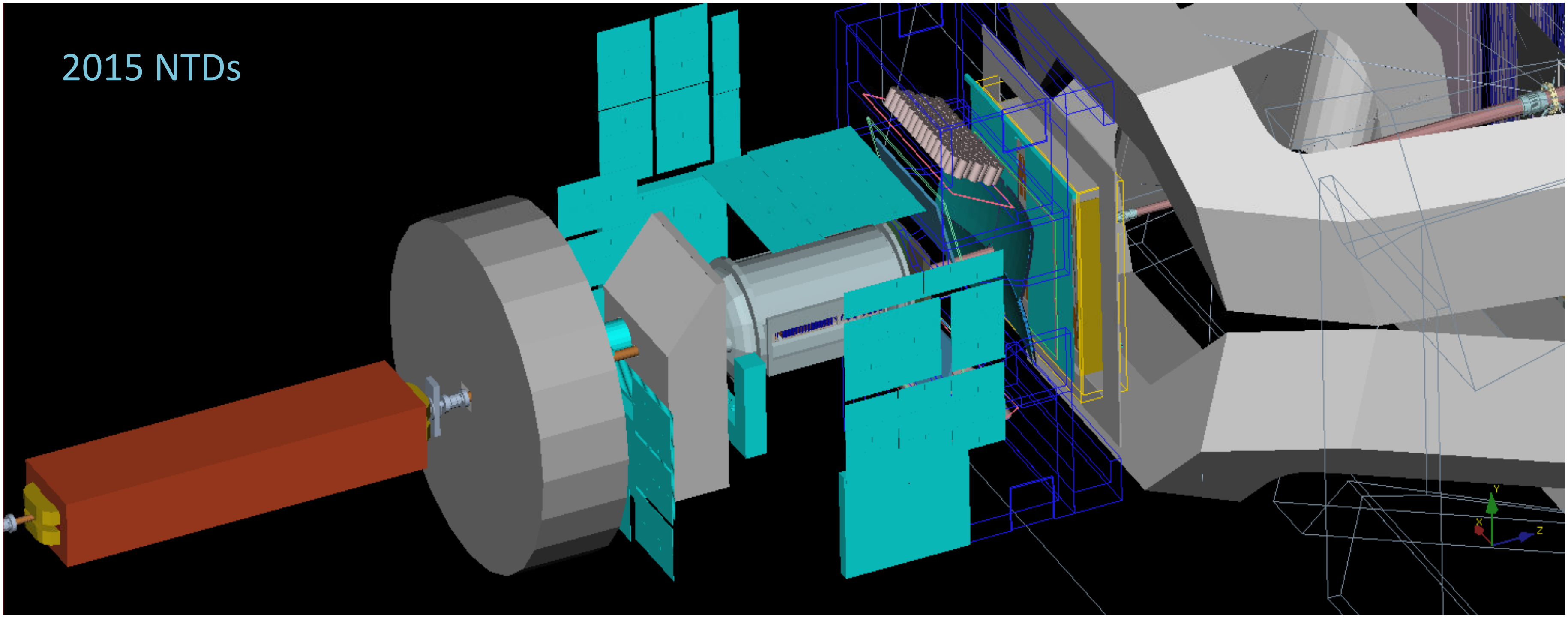
Slepton searches comparison*

* Indicative numbers

	ATLAS / CMS	MoEDAL	comments
Velocity	$\beta > 0.2$ Constrained by LHC bunch pattern	$\beta < 0.2$ 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	$\varepsilon \times A$ 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
        - e.g. as LSP in R-parity violating SUSY, long-lived when RPV coupling(s) small

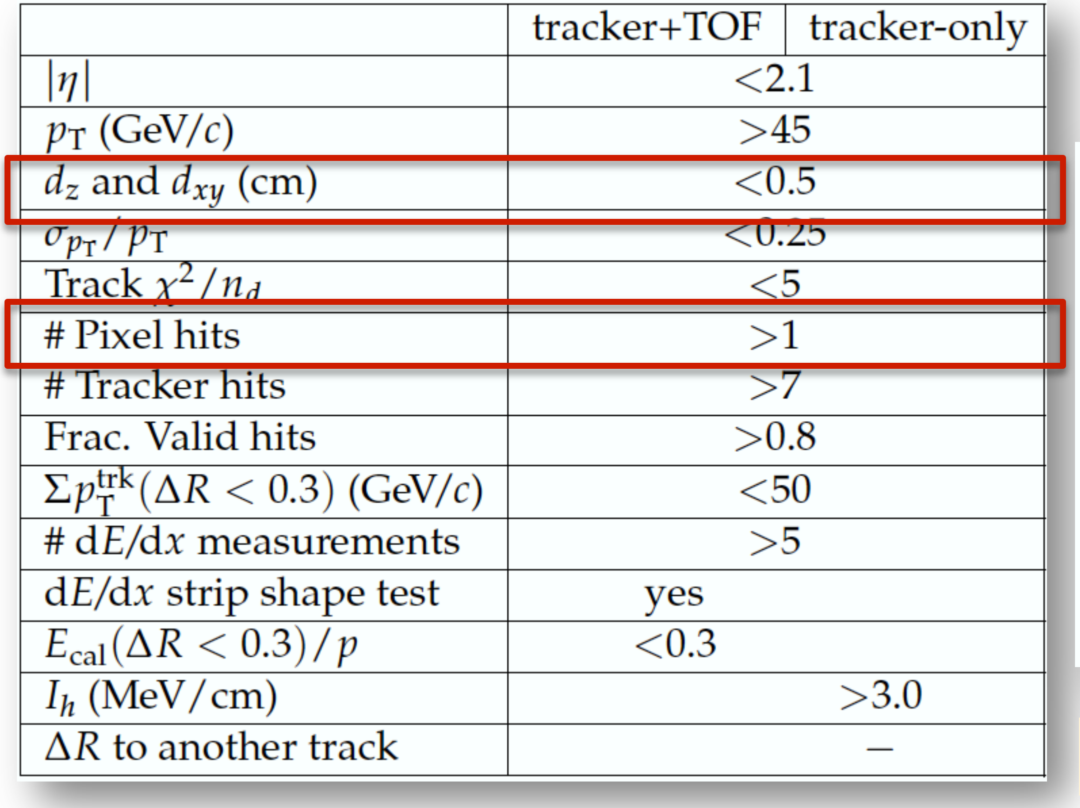
$$\tilde{t} \to t\tilde{G}$$

- 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

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

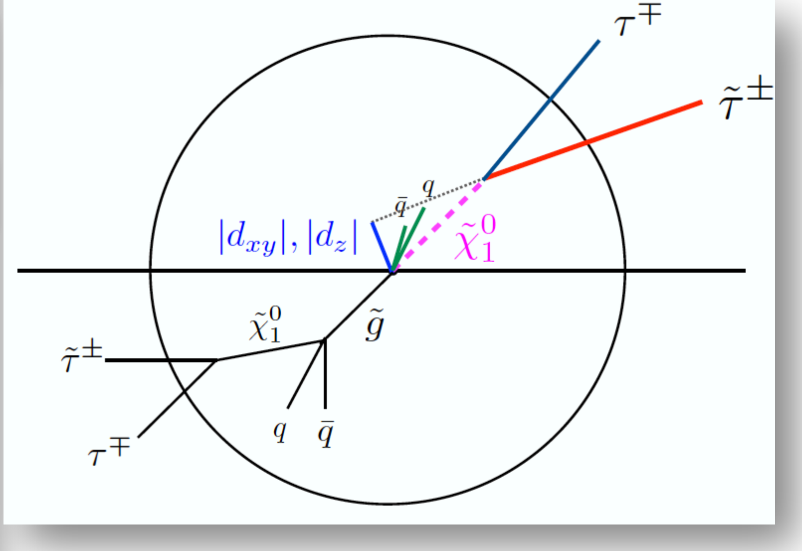
Improving complementarity

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



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

Relaxing *both* constraints



In collaboration with Kazuki Sakurai

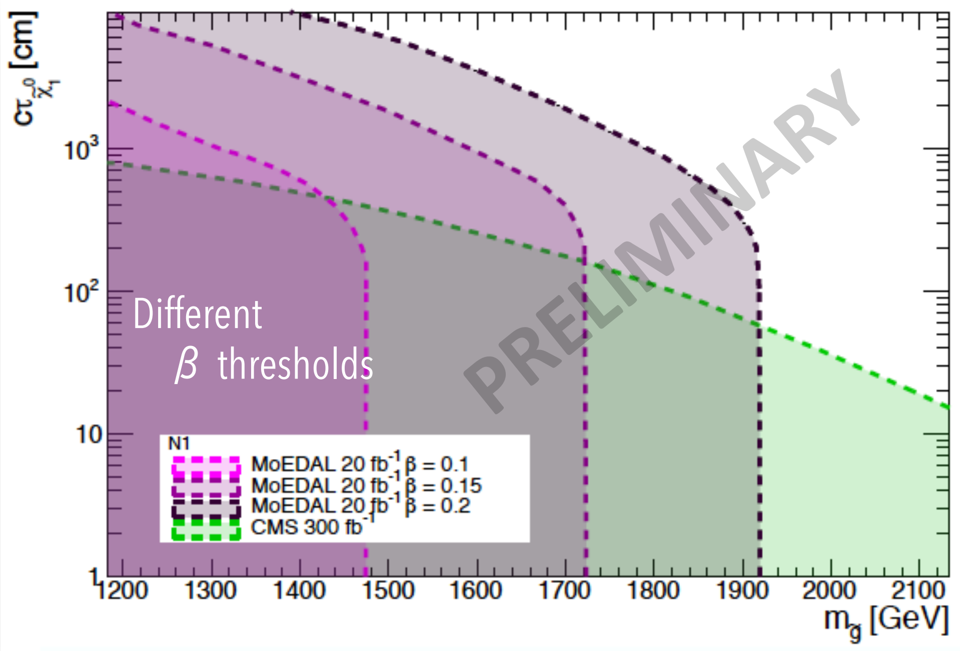
Results for $\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow jj\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow\tau^\pm\tilde{\tau}_1$

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

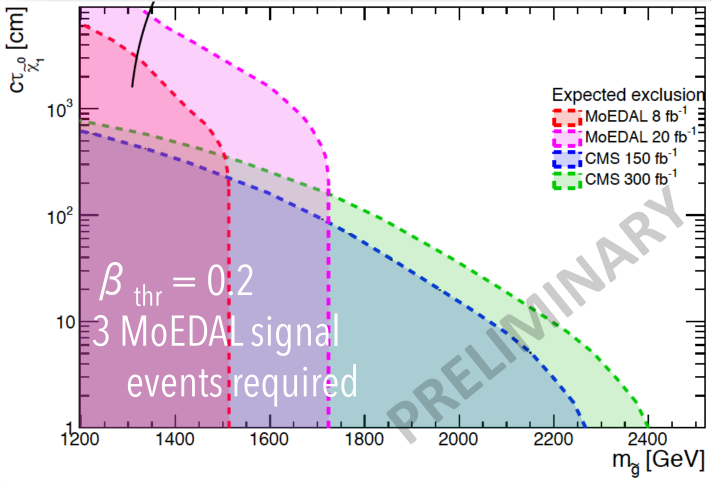
(massive) $\tau^\pm$ produces a kink between $\tilde{\chi}_1^0$ and $\tilde{\tau}_1$ tracks
⇒ large impact parameters d_{xy}, d_z

$\tilde{\tau}_1$ 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

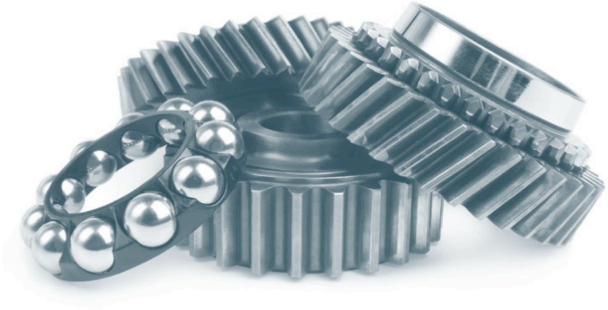
MoEDAL can cover long-lifetime region inaccessible by ATLAS/CMS even with a *moderate* NTD performance **z/β > 10**

Summary & outlook

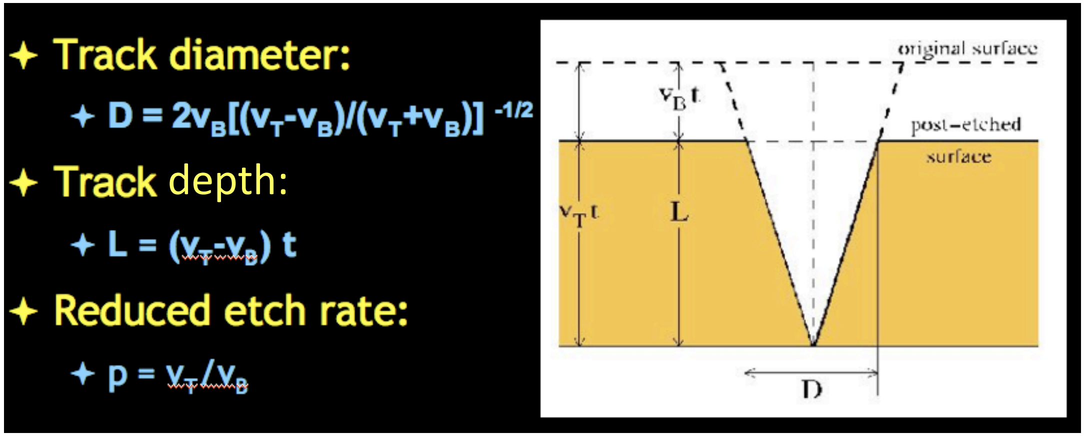
- MoEDAL is searching for **(meta)stable highly ionising particles**
  - least tested signals of New Physics
  - predicted in variety of theoretical models
  - design *optimised* for such searches
  - combining various detector technologies
- Results on monopole searches at 8 TeV & 13 TeV published
  - 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 other monopole interpretations
    - production via photon fusion
    - spin 1 monopoles
  - with NTDs
  - for electrically-charged particles

Thank you for your attention!

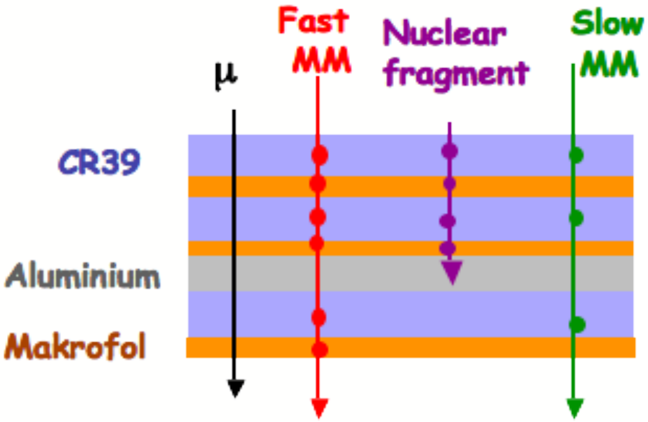
Spares



Analysis procedure



- Track diameter:
  - $D = 2v_B[(v_T-v_B)/(v_T+v_B)]^{-1/2}$
- Track depth:
  - $L = (v_T-v_B)\ t$
- Reduced etch rate:
  - $p = v_T/v_B$



- 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 = $(dE/dx)_{\text{10nm from track}}$

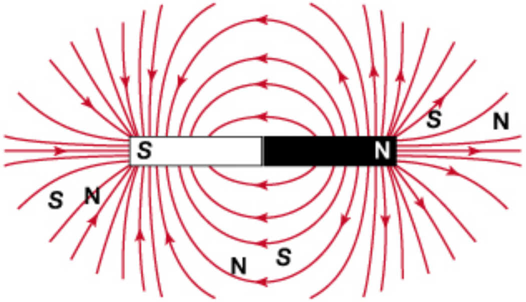
Dirac's Monopole

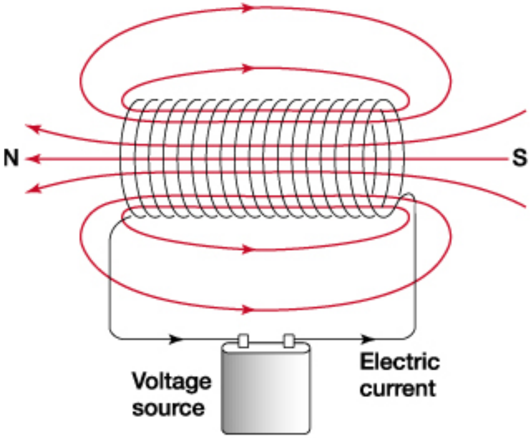
- Paul Dirac in 1931 hypothesized that the magnetic monopole exists
- In his conception the monopole was the end of an infinitely long and infinitely thin solenoid
- Dirac's quantisation condition:

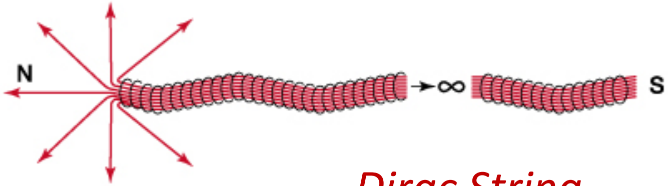
$$ge = \left[\frac{\hbar c}{2}\right] n \quad OR \quad g = \frac{n}{2\alpha} e \quad \left(from \ \frac{4\pi e g}{\hbar c} = 2\pi n \quad n = 1,2,3..\right)$$

- 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:

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





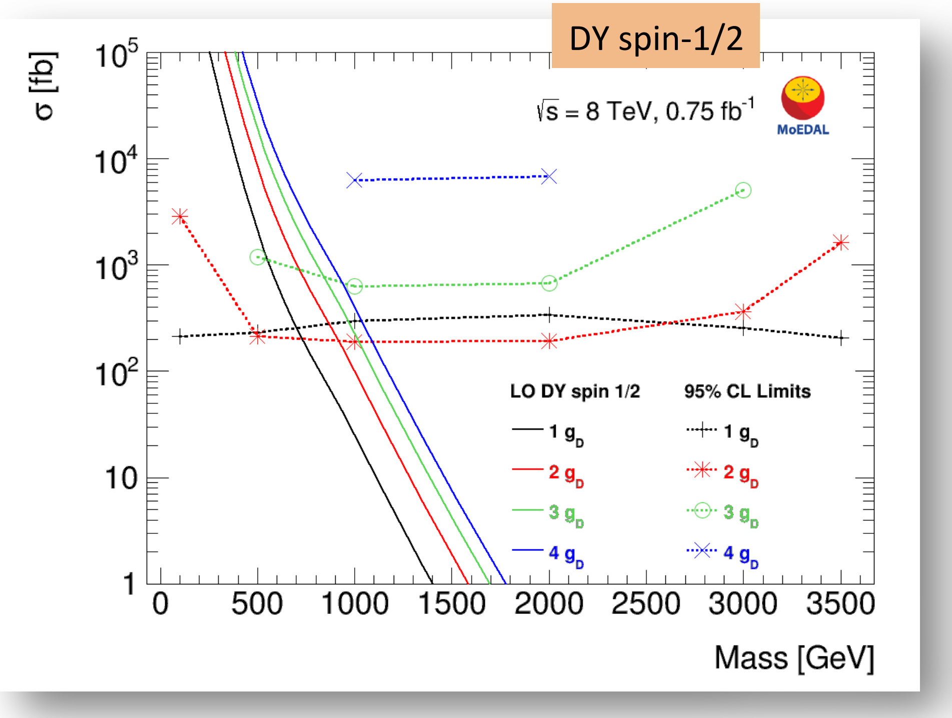


Dirac String

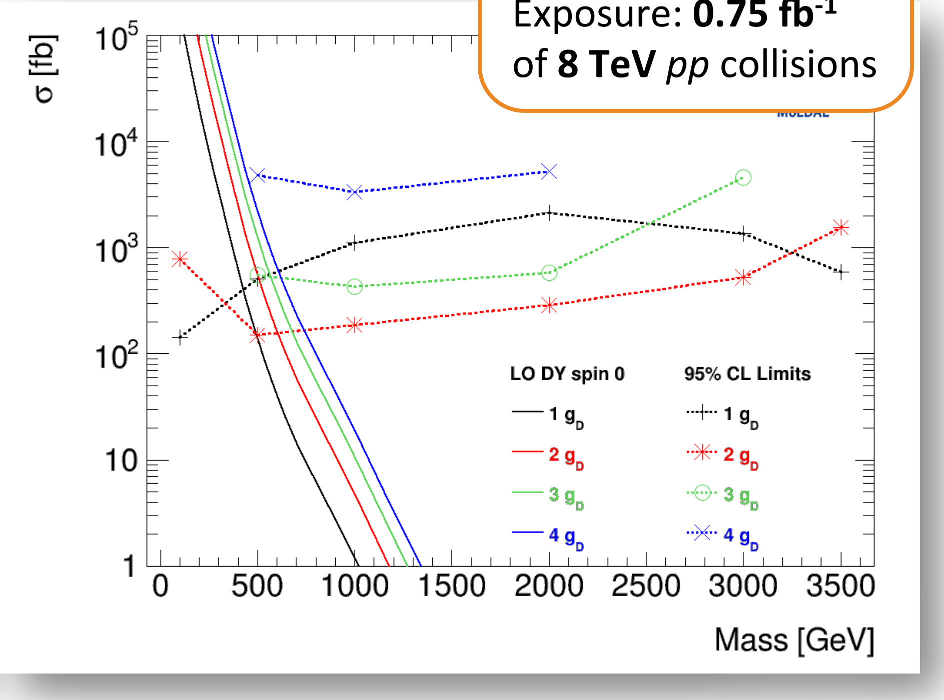
Cross section limits versus mass

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

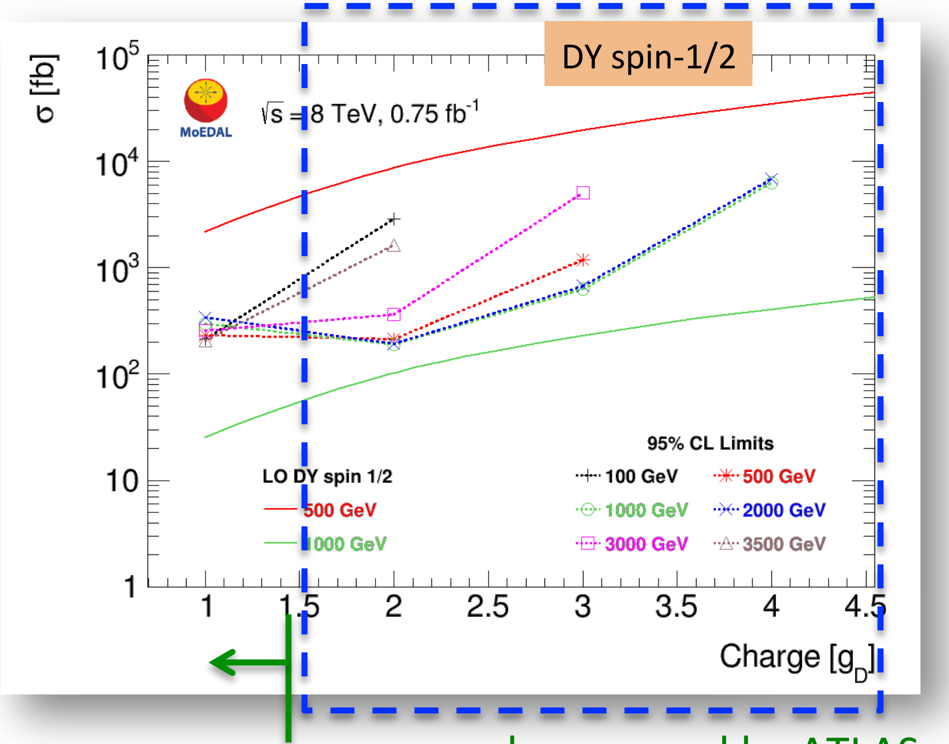
- reminder: shown (tiny) LO DY cross sections are not reliable
  ⇒ makes sense to probe and constrain very high masses

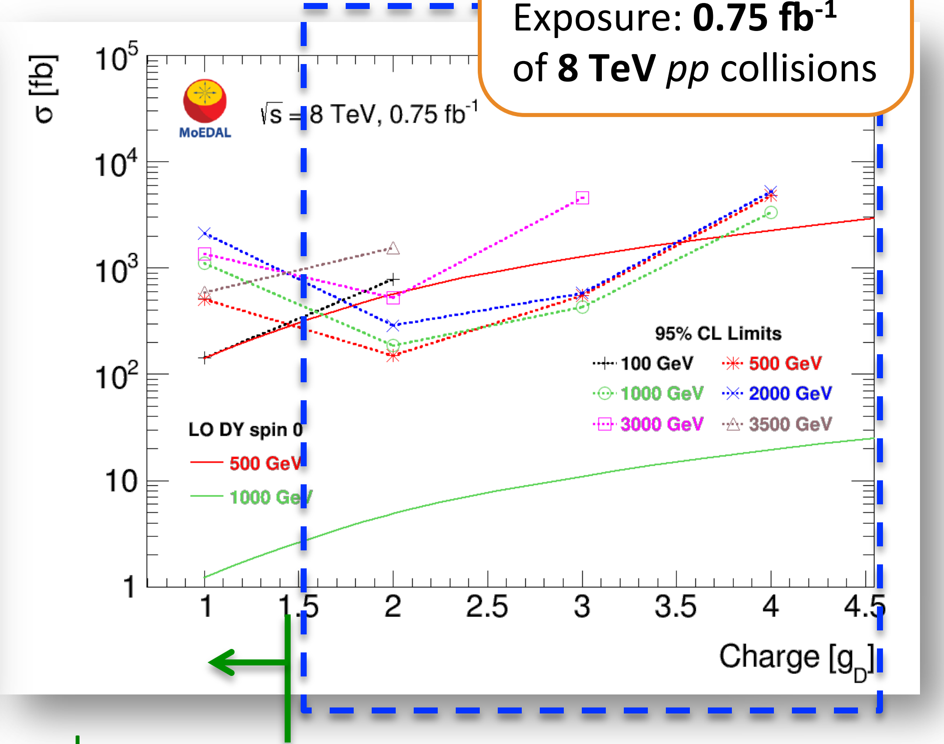
JHEP 1608 (2016) 067 [arXiv:1604.06645]

Cross section limits versus charge

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

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





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

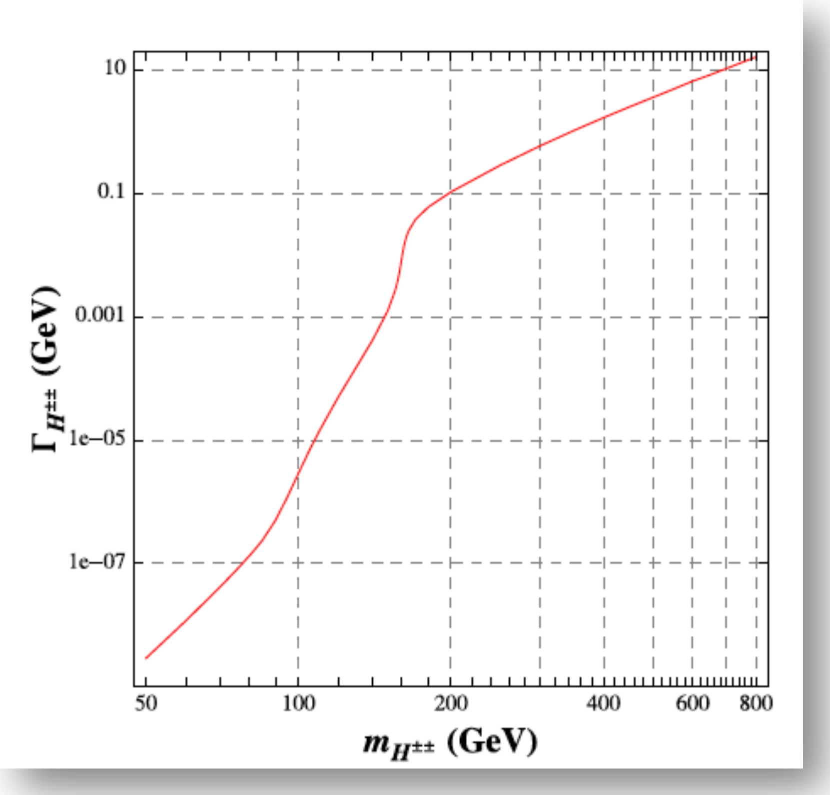
MoEDAL

- 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]

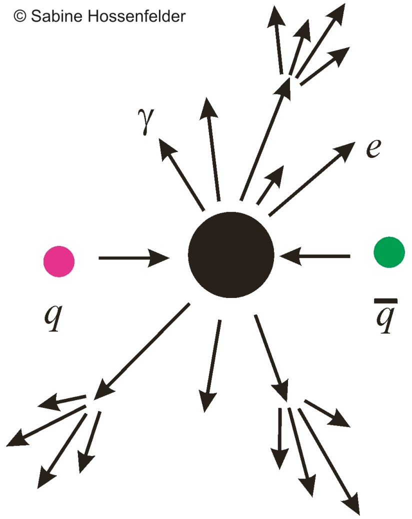
Black-hole remnants

- 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

© Sabine Hossenfelder



Hossenfelder, Koch, Bleicher, hep-ph/0507140

BHR charges @ 14 TeV LHC [CHARYBDIS+PYTHIA]