MoEDAL physics results and future plans

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for the MoEDAL Collaboration

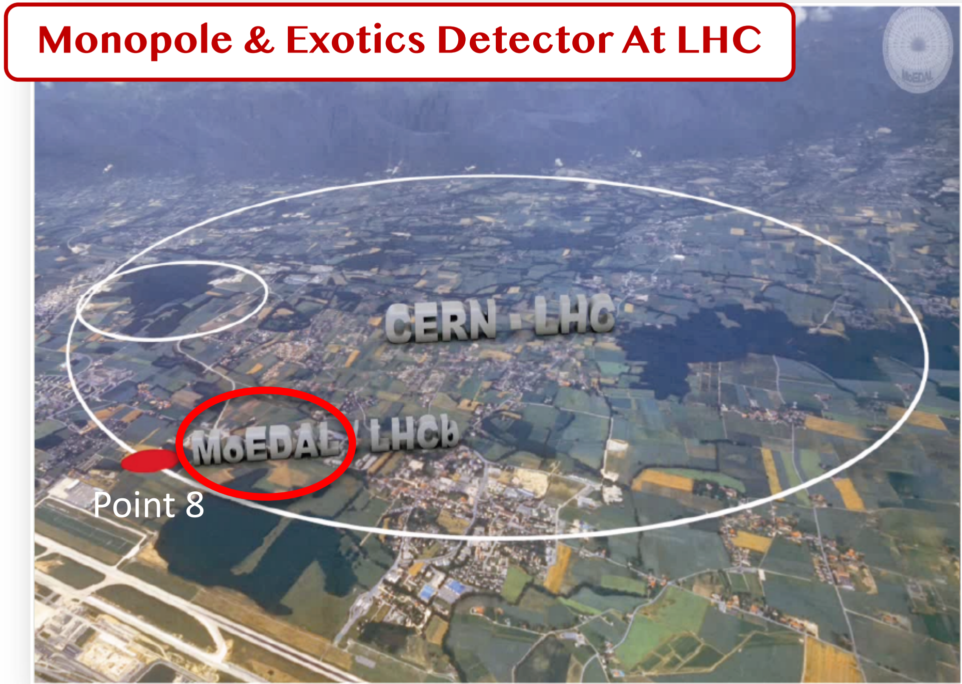
19th HELLENIC SCHOOL AND WORKSHOPS ON ELEMENTARY PARTICLE PHYSICS AND GRAVITY

Workshop on Connecting Insights in Fundamental Physics: Standard Model and Beyond

August 31 - September 11, 2019, Corfu, Greece

MoEDAL at LHC

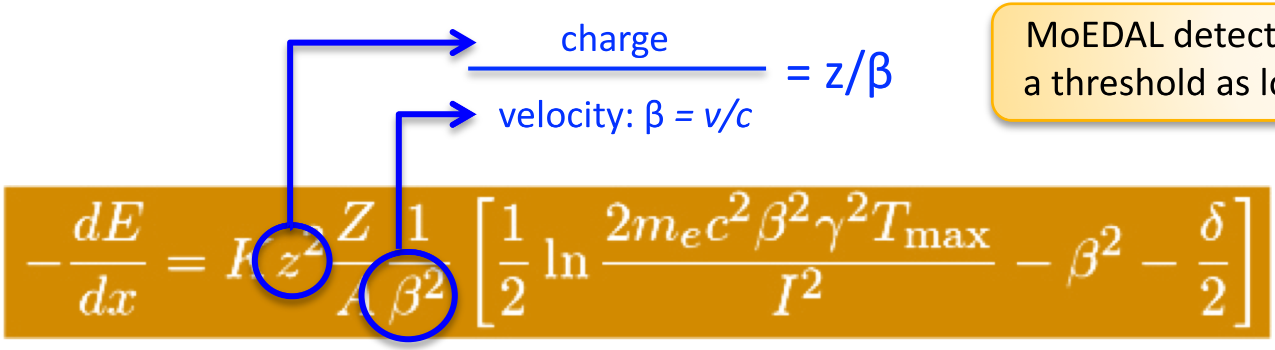
Monopole & Exotics Detector At LHC



International collaboration
~70 physicists from 22 institutions

UNIVERSITY OF ALABAMA
UNIVERSITY OF ALBERTA
INFN & UNIVERSITY OF BOLOGNA
UNIVERSITY OF BRITISH COLUMBIA
UNIVERSITÉ DE GENÈVE
UNIVERSITY OF HELSINKI
UNIVERSITY OF MONTREAL
CERN
CONCORDIA UNIVERSITY
GANGNEUNG-WONJU NATIONAL UNIVERSITY
IMPERIAL COLLEGE LONDON
KING'S COLLEGE LONDON
KONKUK UNIVERSITY
NATIONAL INSTITUTE OF TECHNOLOGY, KURUKSETRA
TECHNICAL UNIVERSITY IN PRAGUE
QUEEN MARY UNIVERSITY OF LONDON
INSTITUTE FOR SPACE SCIENCES, ROMANIA
INSTITUTE FOR RESEARCH IN SCHOOLS, CANTERBURY
TUFT'S UNIVERSITY
VAASA UNIVERSITIES
IFIC VALENCIA
RUDER BOSCOVIC INSTITUTE IN ZAGREB

Key feature: high ionisation



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

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

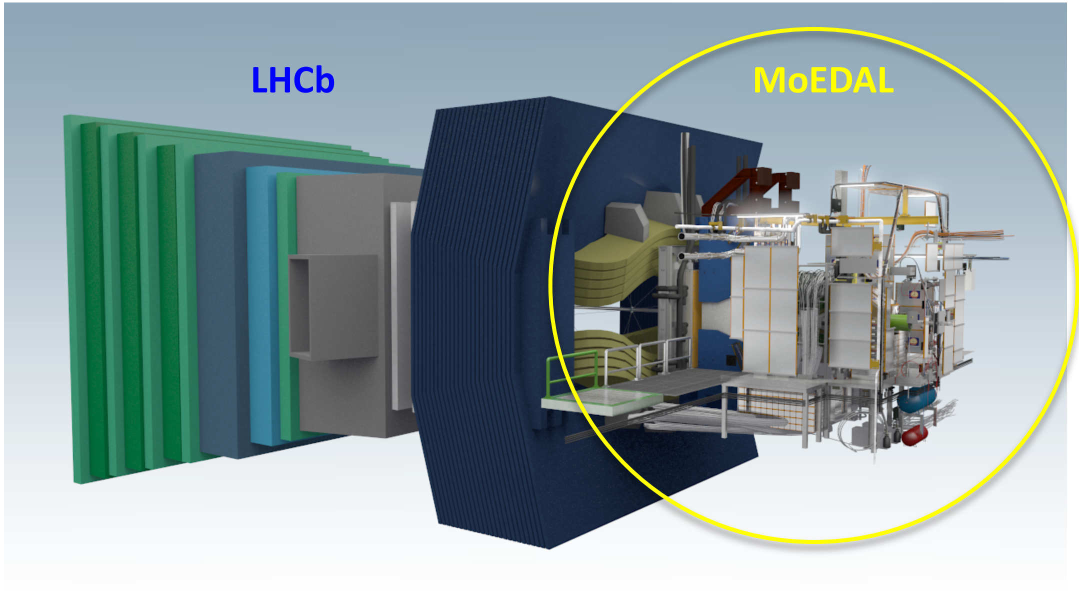
Bethe-Bloch formula

MoEDAL detectors can have a threshold as low as **$z/\beta \sim 5$**

- Achieved, e.g., by **magnetic monopoles** due to ionisation $68.5^2 \approx 4700$ times higher than minimum ionising particle
- Actually **any heavy, stable, electrically charged particle** (HSCP), either stable or metastable, will be slow moving, hence it should give a track in MoEDAL
    - H^{++}, Q-balls, black hole remnants, SUSY partners, etc.
- For singly-charged particles to be detected in nuclear track detectors, velocity should be **$\beta \lesssim 0.1$-0.2**

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

The MoEDAL detector



DETECTOR SYSTEMS

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

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

③ **TimePix** radiation background monitor

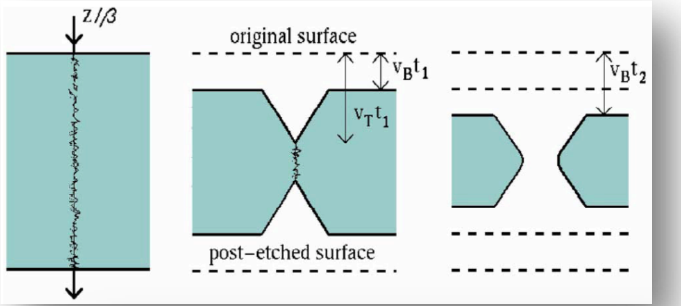
④ Monopole Trapping detector (**MMT**)

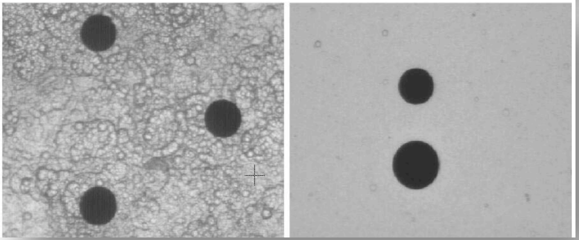
- Mostly **passive detectors**; no trigger; no readout
- Largest deployment of passive **Nuclear Track Detectors (NTDs)** at an accelerator
- First time that **trapping detectors** are deployed as a detector

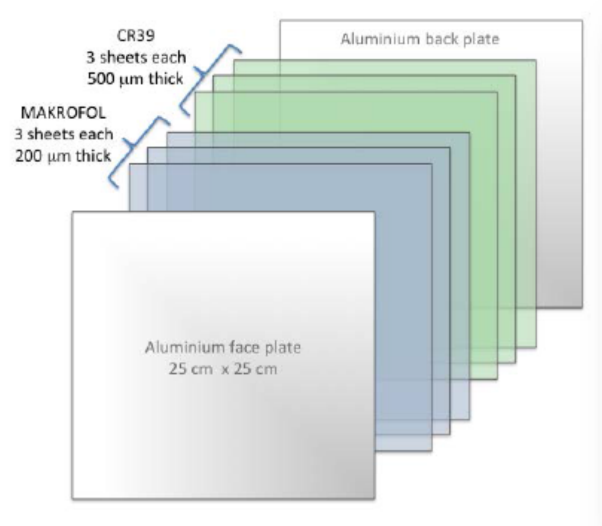
MoEDAL physics program
Int. J. Mod. Phys. A29 (2014) 1430050

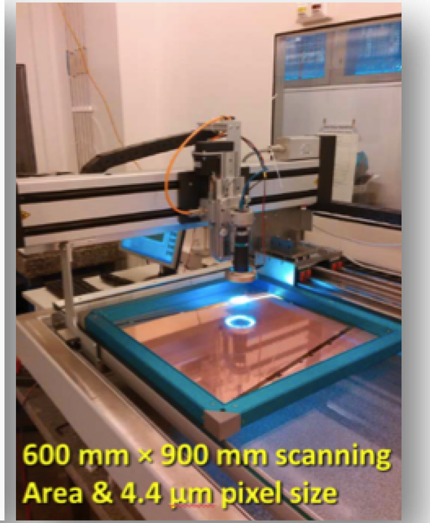
1 & 2 HI particle detection in NTDs

- 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

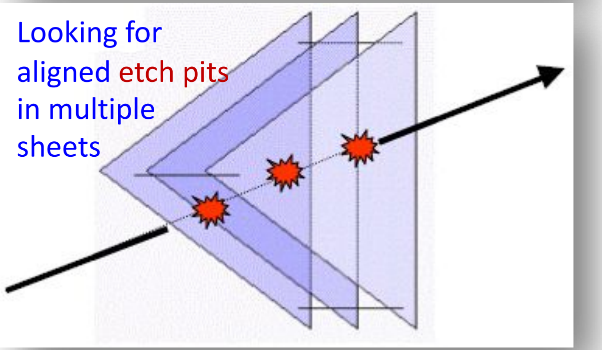








600 mm × 900 mm scanning Area & 4.4 µm pixel size

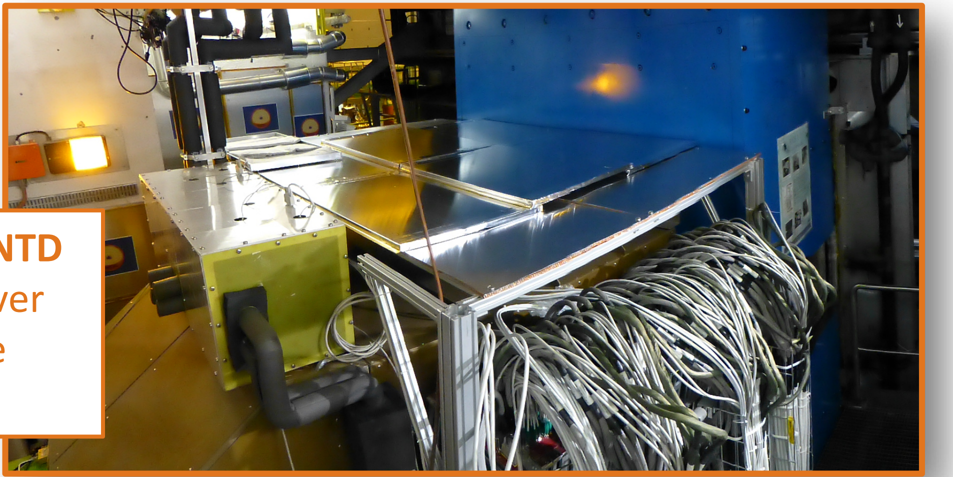


Looking for aligned etch pits in multiple sheets

1 & 2 NTDs deployment

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

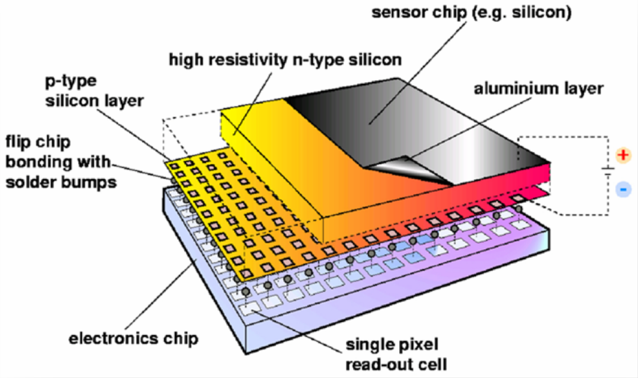
2015-2018: LT-NTD
Top of VELO cover
Closest possible location to IP

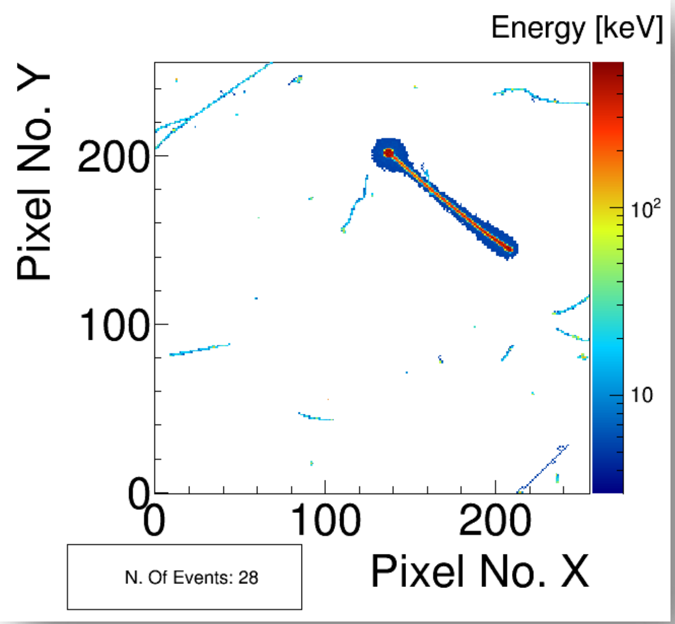


2015-2018: HCC-NTD
Installed in LHCb acceptance between RICH1 and TT

3 TimePix radiation monitor

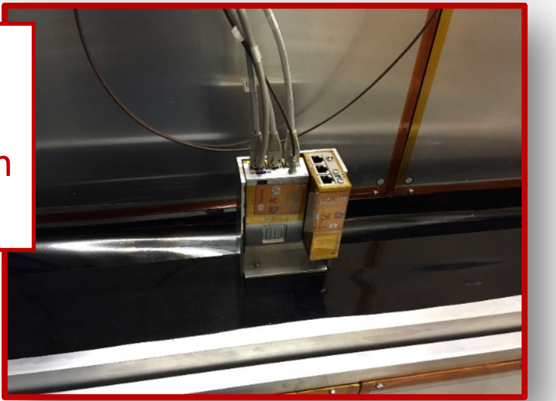
- Timepix (MediPix) chips used to measure online the radiation field and monitor spallation product background
- Essentially act as little electronic "bubble-chambers"
- The only active element in MoEDAL





Sample calibrated frame in MoEDAL TPX04

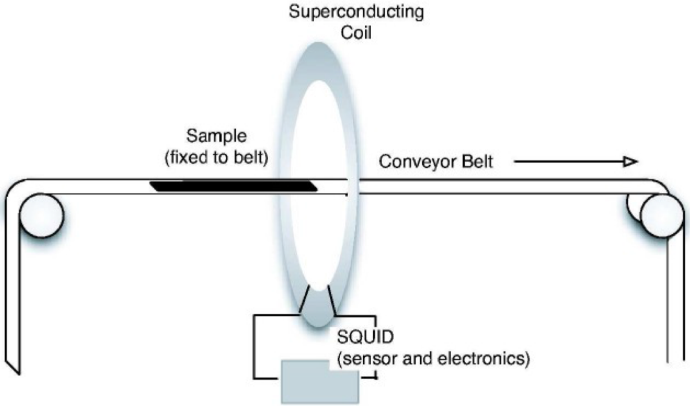
2015 deployment of MediPix chips in MoEDAL

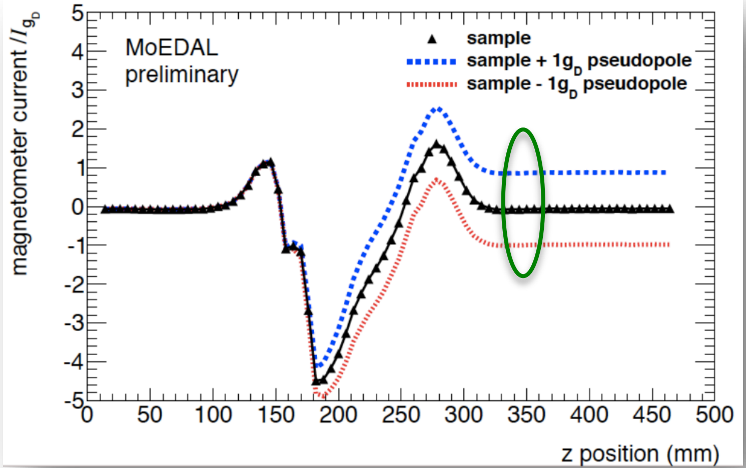


- 256×256 pixel solid state detector
- 14×14 mm active area
- amplifier + comparator + counter + timer

4 MMT: Magnetic Monopole Trapper

- Monopoles can bind to nuclei
    - large binding energy ~ $\mathcal{O}$(100 keV)
- Monopole trapping volumes analysed with superconducting quantum interference device (SQUID)
- **Persistent current:** difference between resulting current after and before
    - first, subtract current measurement for empty holder
    - calibration constant P = 32.4 g_D / A
    - if difference other than zero → *monopole signature*



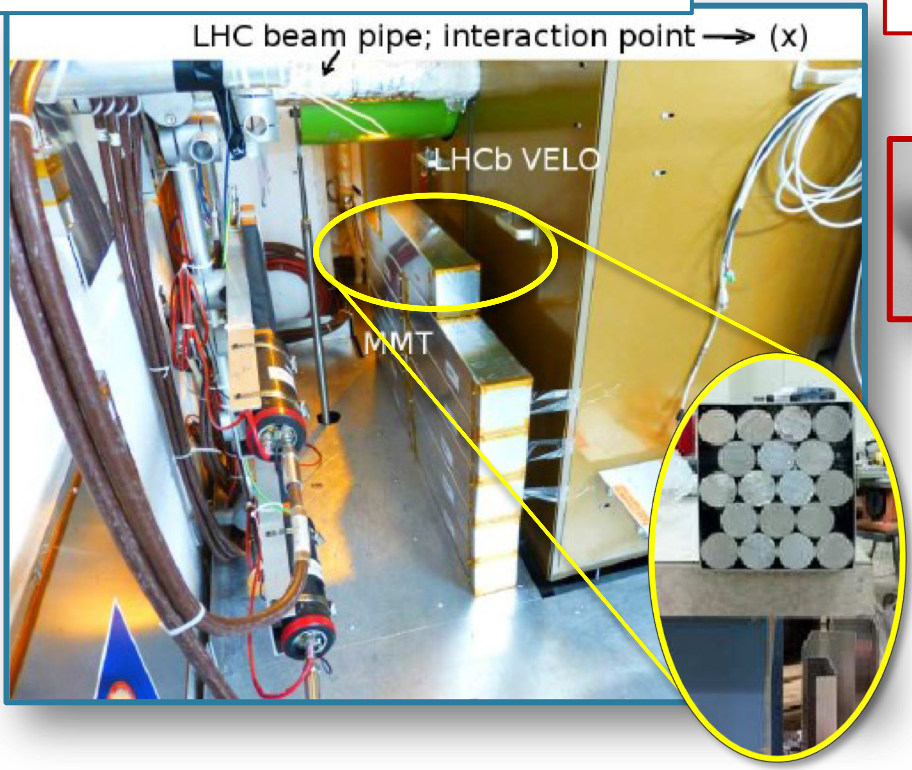


Typical sample & pseudo-monopole curves

MMTs deployment

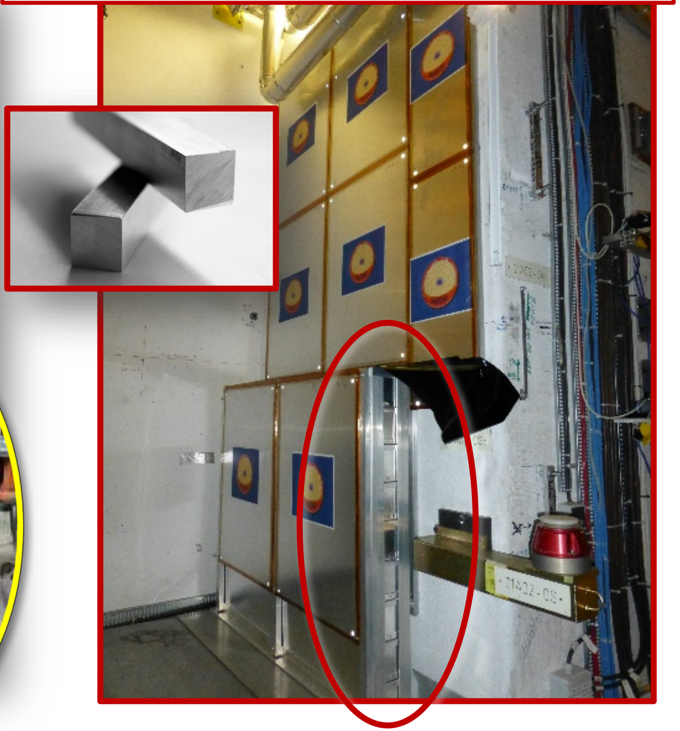
2012

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



2015-2018

- Installed in forward region under beam pipe
- Installed in **sides A & C**, too
- Approximately **800 kg** of Al
- Total 2400 aluminum bars



Searches for magnetic monopoles

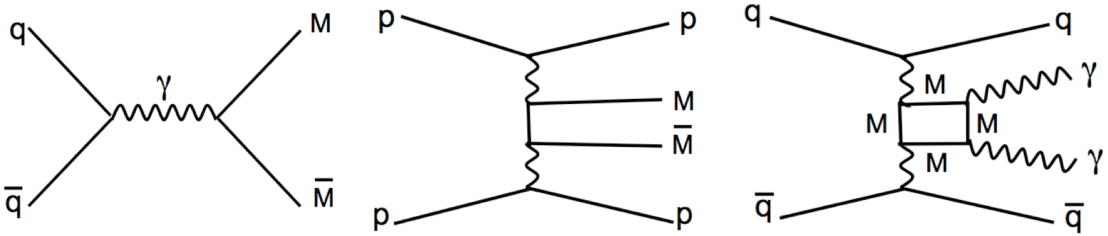
- Magnetic monopoles
- Production at LHC via photon fusion
  [Baines, Mavromatos, VAM, Pinfold, Santra, Eur.Phys.J. C78 (2018) 966]
- Latest MoEDAL MMT search [B. Acharya et al, Phys.Rev.Lett. 123 (2019) 021802]

Magnetic monopoles

- Motivation
  - symmetrisation of Maxwell's equations
  - electric charge quantisation
- Properties
  - single magnetic (Dirac) charge: $g_D = 68.5e$ → highly ionising
  - magnetic charge = ng_D
  - large coupling constant $g/\hbar c \sim 20$ (precise value depends on units)
  - spin and mass not predicted

Laws	**Without monopoles**	**With magnetic monopoles**
Gauss's law	$\nabla \cdot \mathbf{E} = 4\pi\rho_e$	$\nabla \cdot \mathbf{E} = 4\pi\rho_e$
Gauss's law for magnetism	$\nabla \cdot \mathbf{B} = 0$	$\nabla \cdot \mathbf{B} = 4\pi\rho_m$
Faraday's law	$-\nabla\times\mathbf{E} = \frac{\partial\mathbf{B}}{\partial t}$	$-\nabla\times\mathbf{E} = \frac{\partial\mathbf{B}}{\partial t} + 4\pi\mathbf{J}_m$
Ampère's law	$\nabla\times\mathbf{B} = \frac{\partial\mathbf{E}}{\partial t} + 4\pi\mathbf{J}_e$	$\nabla\times\mathbf{B} = \frac{\partial\mathbf{E}}{\partial t} + 4\pi\mathbf{J}_e$

Production mechanisms at LHC



Drell-Yan

Photon fusion

Box diagram

- Feynman-like diagrams do *not* account for ***non-perturbative*** nature of large monopole-photon coupling
- Tree-level calculations for cross section are only used indicatively

Electric-magnetic duality

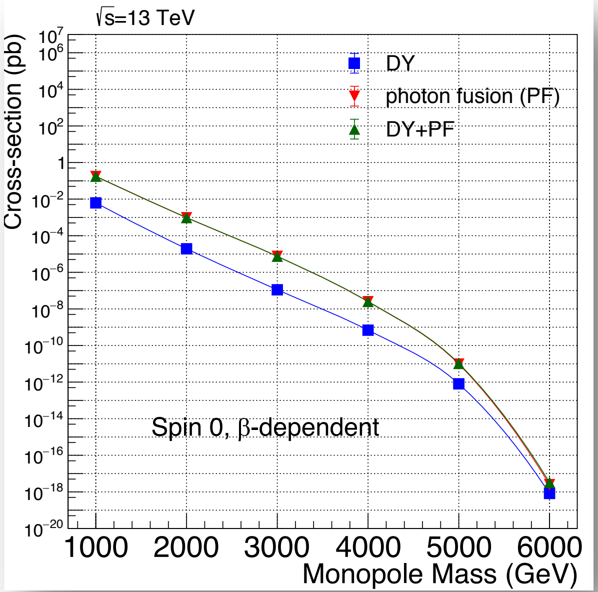
- The monopole enters the field as a matter field in a U(1) gauge theory
  - S = 0 : Scalar Quantum Electrodynamics
  - S = ½ : Dirac Quantum Electrodynamics
  - S = 1: Lee-Yang Field Theory
- β-dependent coupling
  - monopole boost expressed by $\beta = \sqrt{1 - \frac{4M^2}{s}}$
  - calculations hold in both the *β-dependent* (gβ) and *β-independent* (g) cases
- New magnetic-moment parameter κ
  - **Spin ½**: SM case: $\tilde{\kappa} = 0$ ($\tilde{\kappa}$ dimensionless parameter), unitary & renormalisable
  - **Spin 1:** SM case: $\kappa = 1$, unitary, renormalisable, no ghosts or gauge fixing
  - lack of unitarity and renormalisability in the non-SM cases not necessarily an issue, from an effective-field-theory point of view ➜ possibility of restoration of unitarity in extended theoretical frameworks with new degrees of freedom

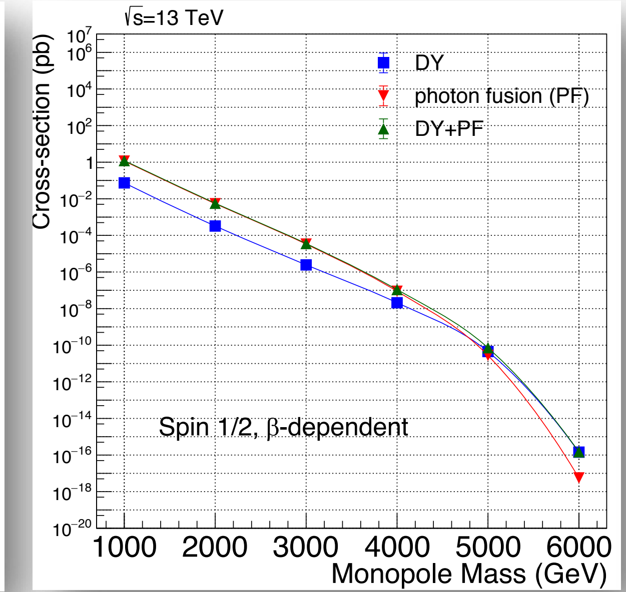
$$\boxed{\frac{g}{c} \to \frac{e}{v_0}}$$

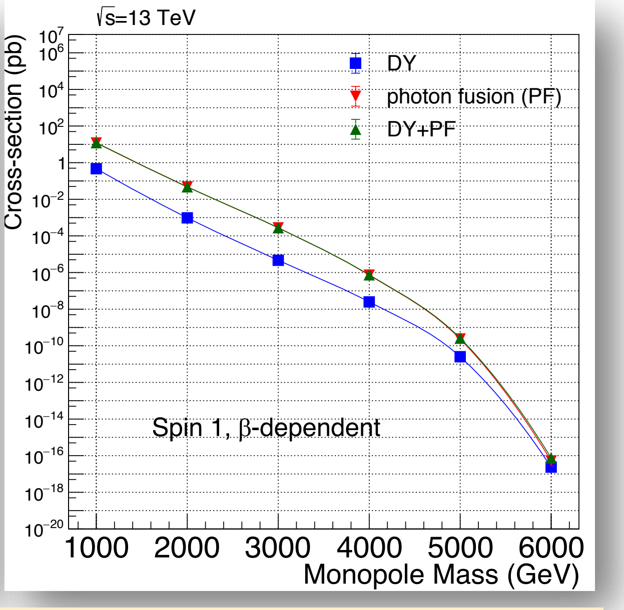
Baines, Mavromatos, VAM, Pinfold, Santra, EPJC 78 (2018) 966

Cross section comparison

- Photon fusion most abundant than DY for almost the whole mass range at LHC energies
  - important to be included in interpretations of searches at colliders
- No interference effects between Drell-Yan and γγ processes
  → total cross section = sum DY + γγ







Baines, Mavromatos, VAM, Pinfold, Santra, EPJC 78 (2018) 966

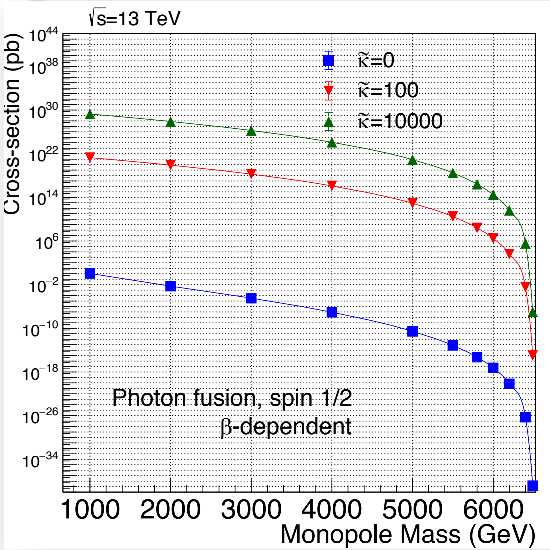
Photon fusion & perturbative couplings

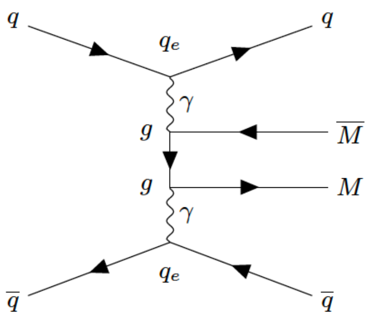
- Both photon fusion and Drell-Yan processes suffer from large γMM coupling making perturbative calculations problematic
- This situation may be resolved in photon fusion with
  - β-dependent photon-monopole coupling
  - magnetic-moment parameter κ
- In this case, perturbative treatment may be guaranteed for
  - very slow monopoles, β → 0
  - parameter κ becomes very large, κ → ∞
  - condition for perturbative coupling:

$$\boxed{g\kappa\,\beta^2 < 1}$$

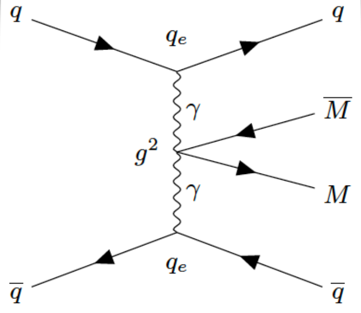
- Cross section remains finite at this limit for photon fusion while it vanishes for Drell-Yan

Baines, Mavromatos, VAM, Pinfold, Santra, EPJC 78 (2018) 966





(c) Three-vertex PF process.



(d) Four-vertex PF process.

MoEDAL monopole results

- **2016** – First MMT results: Drell-Yan for spin 0 and spin ½ monopoles @ 8 TeV ☛ *CERN Press Release*
  JHEP 1608 (2016) 067 [arXiv:1604.06645]
- **2017** – First results @ 13 TeV
  Phys.Rev.Lett. 118 (2017) 061801 [arXiv:1611.06817]
- **2018** – MMT results with
  - spin-1 monopoles
  - β-dependent $\gamma M\bar{M}$ coupling

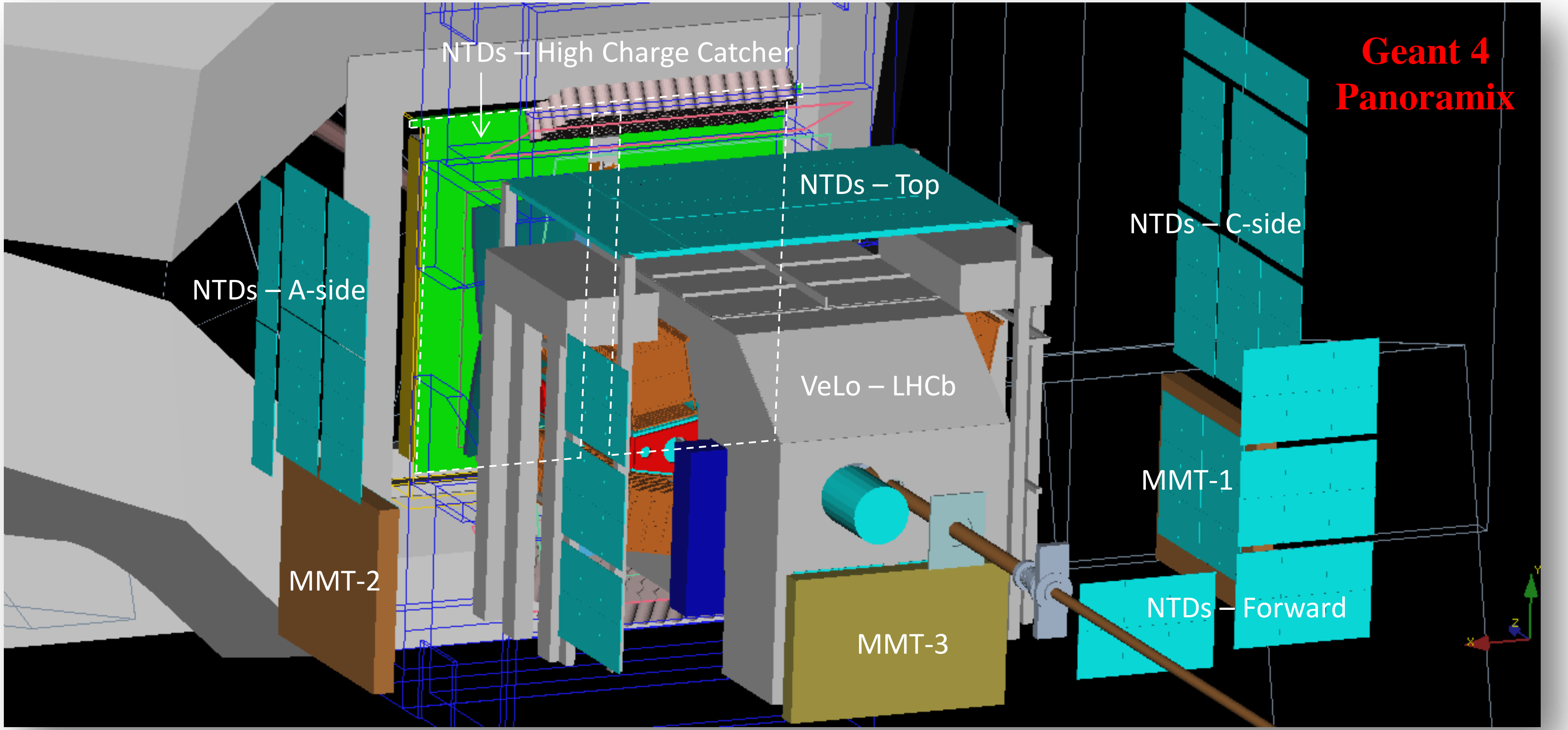
  Phys.Lett.B 782 (2018) 510–516 [arXiv:1712.09849]
- **2019** – MMT results with
  - full MMT detector – ~4 times than previous
  - ~2 more integrated luminosity
  - **photon fusion interpretation**

  Phys.Rev.Lett. 123 (2019) 021802 [arXiv:1903.08491]

NEW

2015-2017 MoEDAL deployment

- Latest analysis is based on data extracted from all three MMT components
- MMT-1 and MMT-2 (sides) are newly added with respect to previous MoEDAL analyses



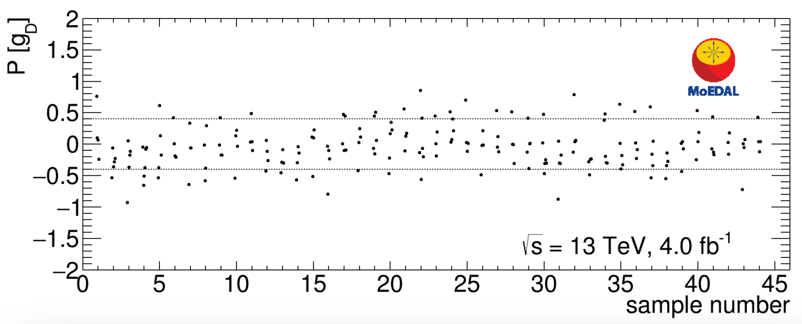
MoEDAL, PRL 123 (2019) 021802

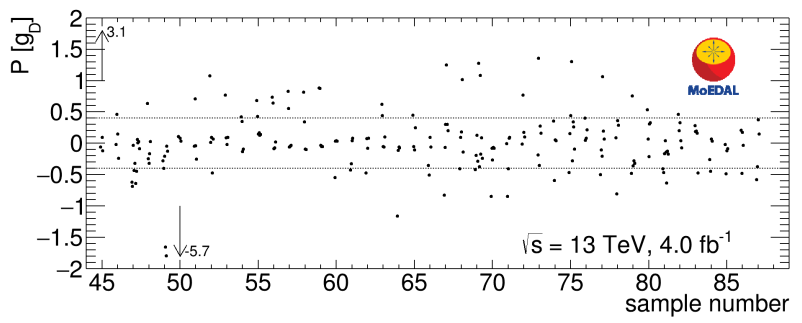
MMT 2015-2017 scanning

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

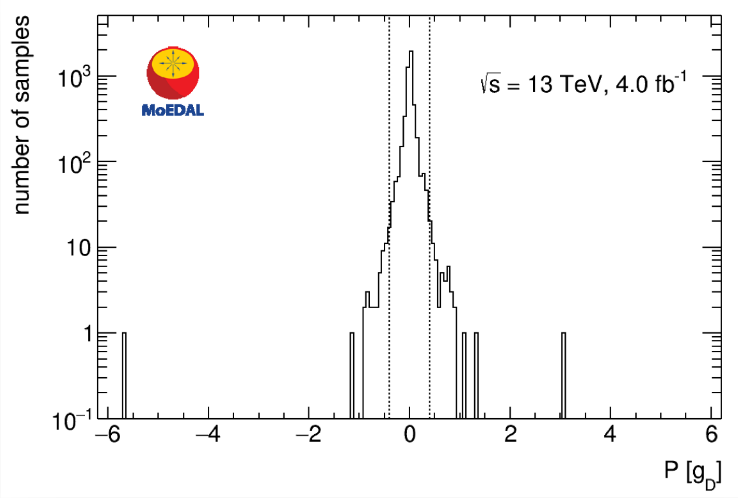
Detector: **794 kg** of aluminium bars

Exposure: **4.0 fb^{-1}** of **13 TeV** *pp* collisions during 2015-2017





Persistent current after first two passages for all samples

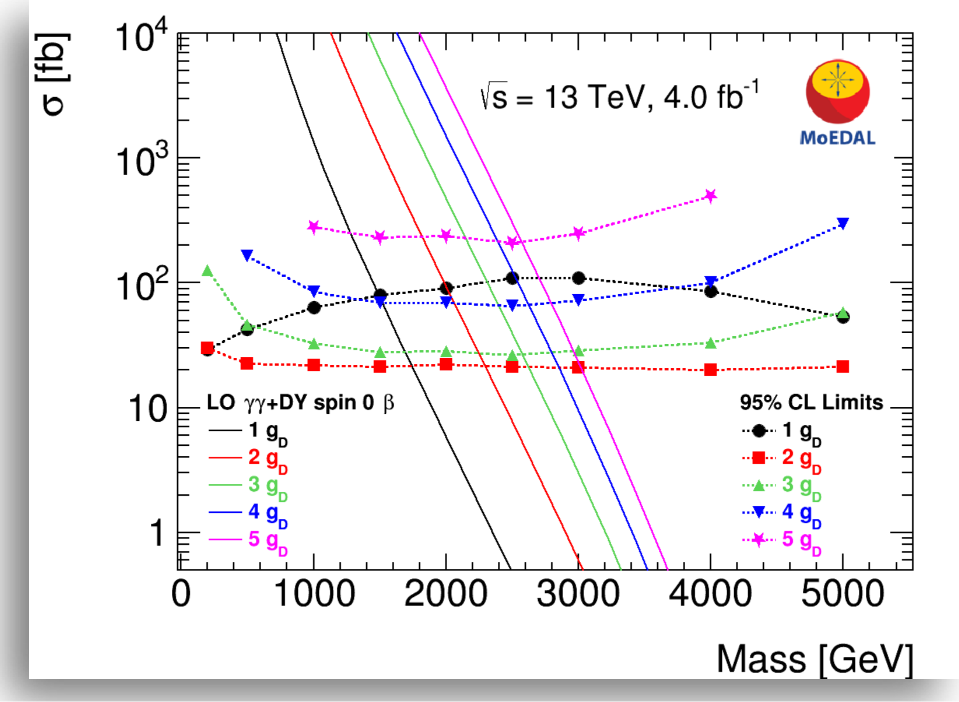


MoEDAL, PRL 123 (2019) 021802

No monopole with charge > 0.5 g_D observed in MMT samples

MMT 2015-2017 results I

- Acceptance losses
  - |g| = g_D: predominantly from punching through the trapping volume,
  - |g| > g_D: stopping in the material upstream of the trapping volume
- Acceptance < 0.1% for monopoles of $6g_D$ or higher
  - insufficient energy to traverse upstream material



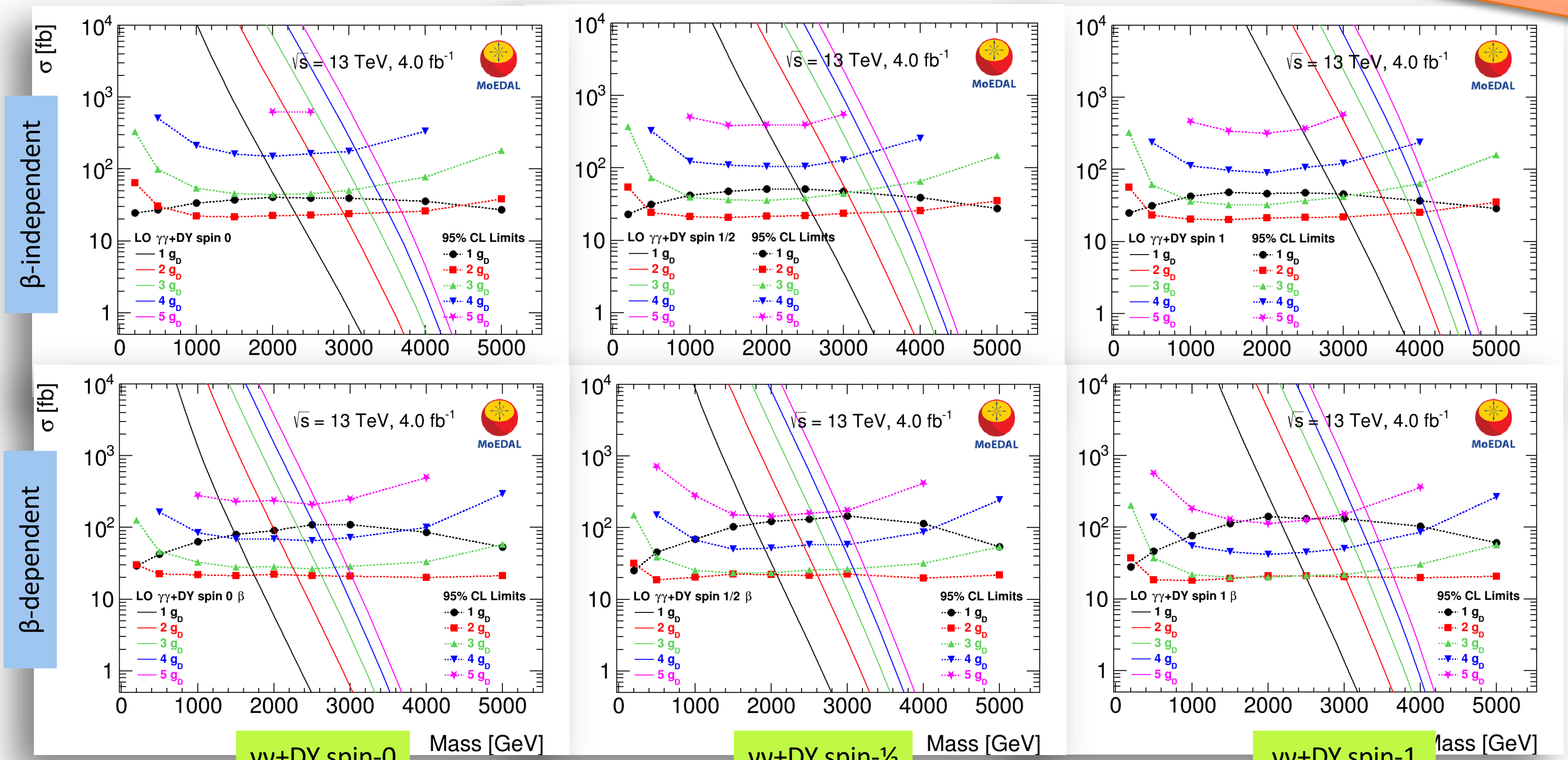
MoEDAL, PRL 123 (2019) 021802

MMT 2015-2017 results II

First results for γ-fusion production at LHC

β-independent

β-dependent



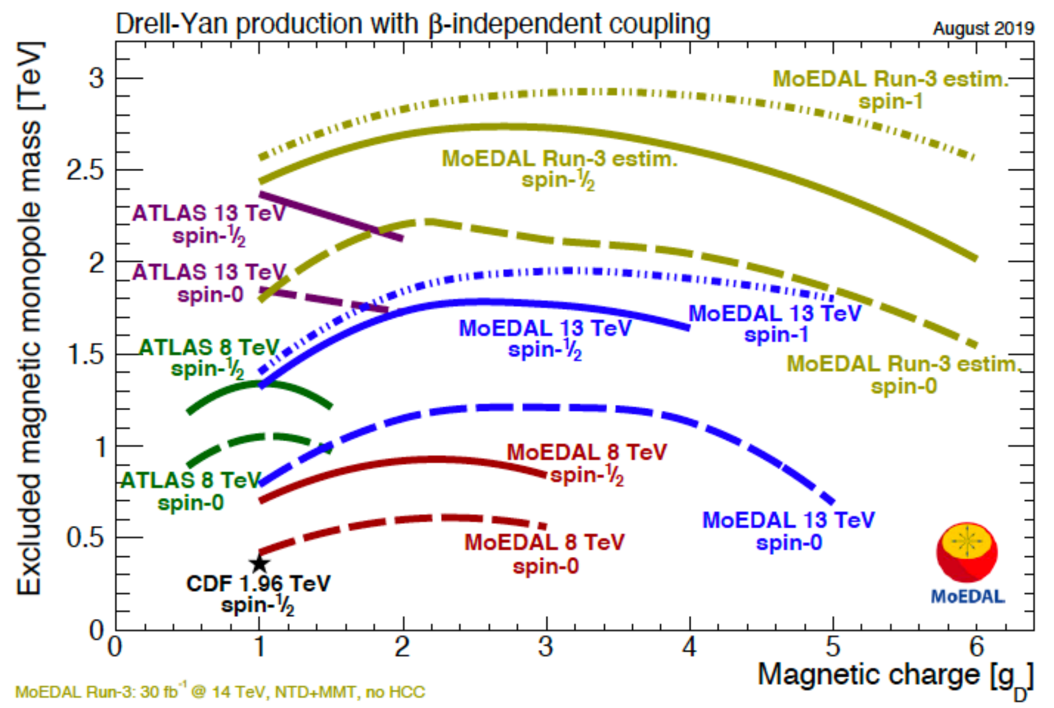
γγ+DY spin-0

γγ+DY spin-½

γγ+DY spin-1

MoEDAL, PRL 123 (2019) 021802

Magnetic monopoles summary



Mass limits calculated with Feynman-like diagrams. They *only* serve as benchmarks to facilitate comparisons

MoEDAL has set the world-best collider limits for **|g| > 2 g_D**

Possible solutions to *perturbative* treatment of monopole production in colliders

1. thermal Schwinger production in heavy-ion collisions [Gould & Rajantie, Phys.Rev.Lett. 119 (2017) 241601]
2. photon fusion: perturbative coupling can be achieved for [Eur.Phys.J. C78 (2018) 966]
   - very slow monopoles, β → 0, AND
   - very large magnetic-moment parameter, κ → ∞

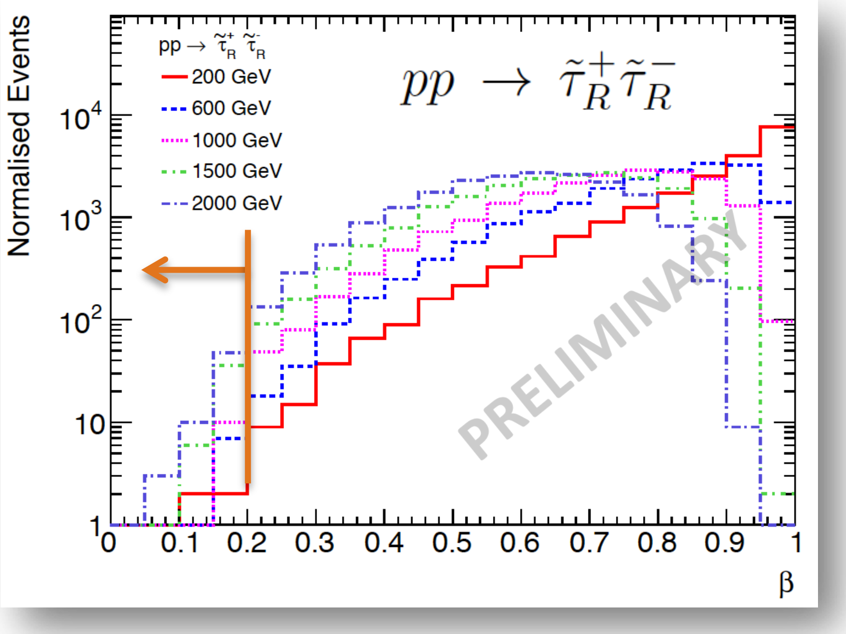
Beyond magnetic monopoles

- What about *electrically*-charged particles?
- Focusing of **supersymmetric** partners

  [K. Sakurai, D. Felea, J. Mamuzic, N.E. Mavromatos, VAM, J.L. Pinfold, R. Ruiz de Austri, A. Santra, O. Vives, arXiv:1903.11022 [hep-ph]]

$\tilde{\tau}$ direct production

- For the metastable particle to have high probability to reach the NTDs a lifetime of **$\tau \gtrsim 10^{-8}$ s** is required
- High geometrical acceptance in central region η≈0
  - back-to-back pair production ⇒ high probability that at least one HSCP hits an NTD



- Light particle
  - ⇒ high cross section 😄
  - ⇒ large β 😞

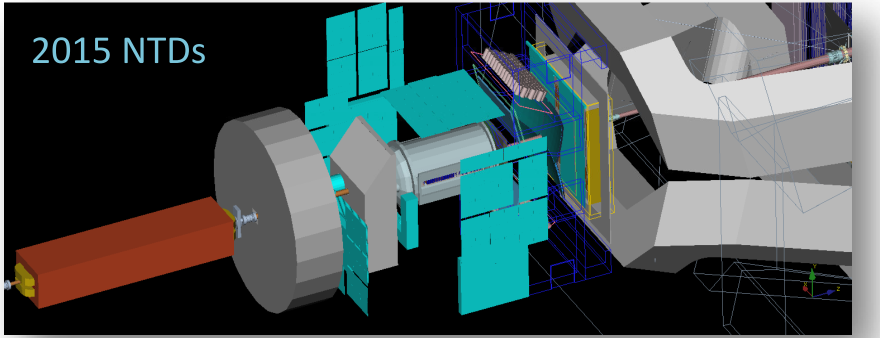
☞ Need **heavy particle** to achieve low β and increase acceptance

Sakurai et al, arXiv:1903.11022

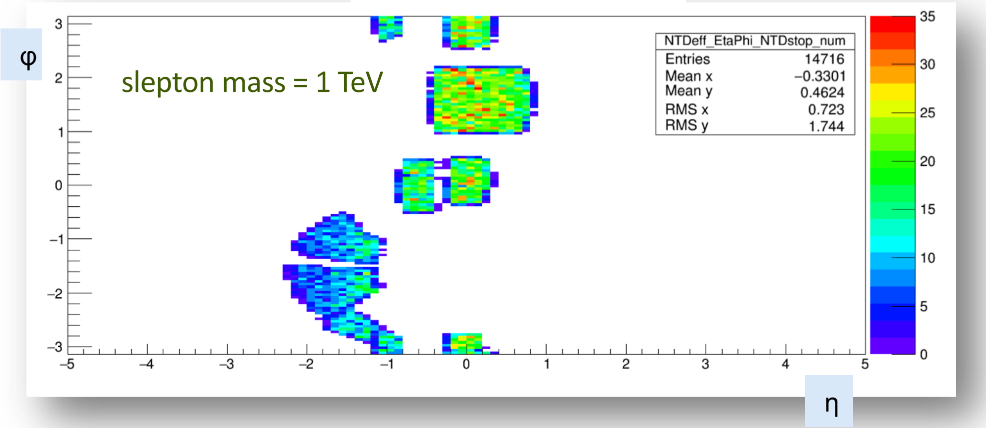
NTD geometry & efficiency

- MoEDAL geometry modelling
  - spherical NTD coverage at **2 m** distance from interaction point
    - some NTDs nearer to IP: ~0.5 m
  - factor for NTD coverage: ~18.7%
- For particles over z/β threshold, detection efficiency 100%
  - for singly-charged particles, $\beta_{\max} \approx 0.1 - 0.2$

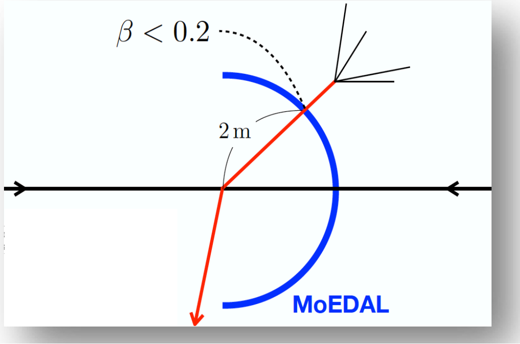
$$\varepsilon = \begin{cases} 1, & \beta \le \beta_{max} \\ 0, & \beta > \beta_{max} \end{cases}$$



NTD position in η, ϕ

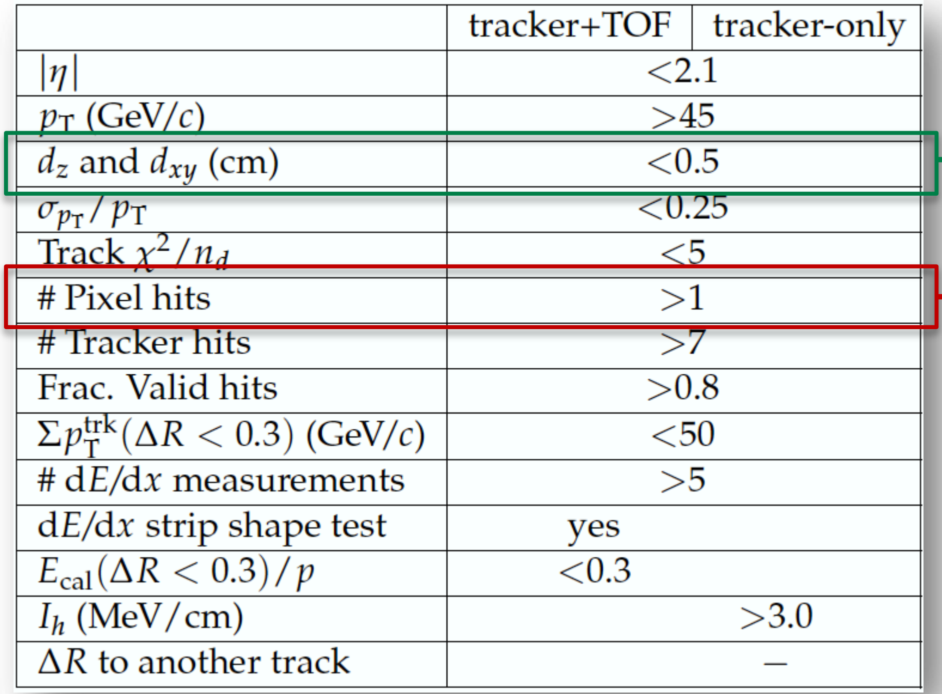


Sakurai et al, arXiv:1903.11022



Relaxing constraints in CMS selections

- Example: CMS dE/dx analysis @7-8 TeV [JHEP07 (2013) 122]
- Applying recast recipe provided by CMS [Eur.Phys.J. C75 (2015) 325]



	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		—

Long-lived charged track must point to the primary vertex

- imposed against cosmic-ray background
- if a particle in the decay chain is long-lived and a kink is present, event may be missed

Requires presence of charged particle in the Pixel detector

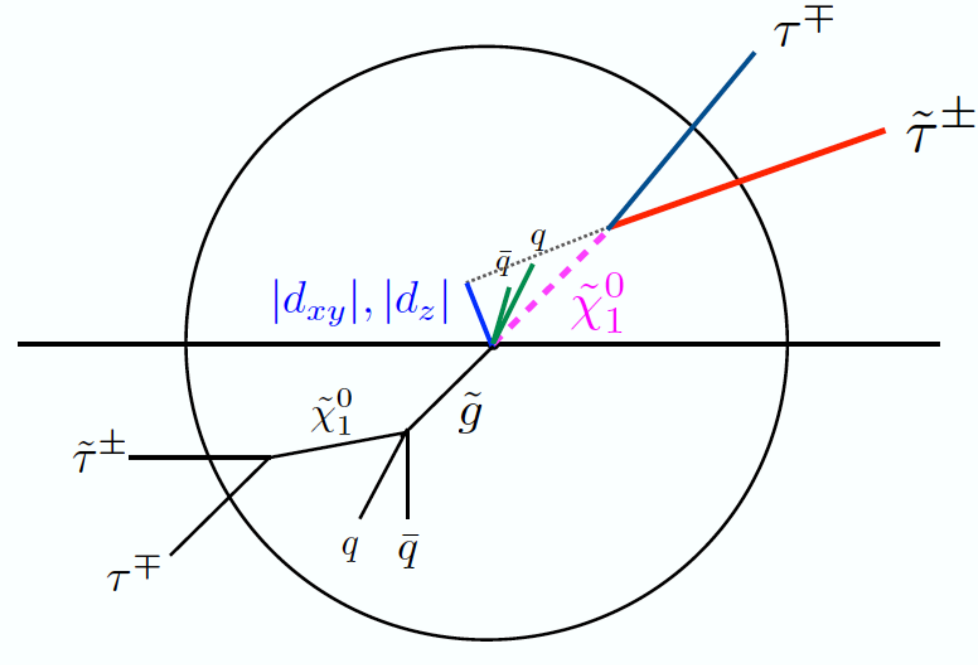
- if g̃ decays via long-lived *neutral* particle, event may be missed
- candidate: **neutralino**

$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow jj\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow\tau^{\pm}\tilde{\tau}_1$ (I)

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

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

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



CMS sensitivity suffers two-ways:

a) no pixel hit due to long-lived neutralino
b) too large impact parameter for stau

Sakurai et al, arXiv:1903.11022

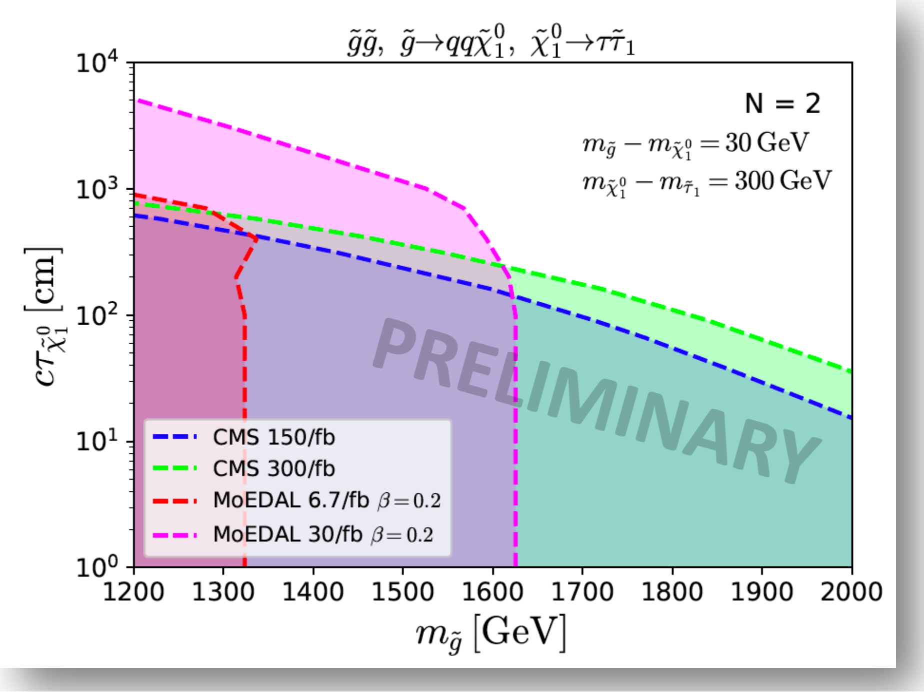
$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow jj\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow\tau^\pm\tilde{\tau}_1$ (II)

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

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

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

Run 2 (2018, 13 TeV) vs. Run-3 (2023, 14 TeV) luminosity



Comparison of CMS *exclusion* with MoEDAL *discovery* potential requiring 2 signal events for MoEDAL

MoEDAL can cover long-lifetime region with nominal NTD performance **$z/\beta > 5$**

Sakurai et al, arXiv:1903.11022

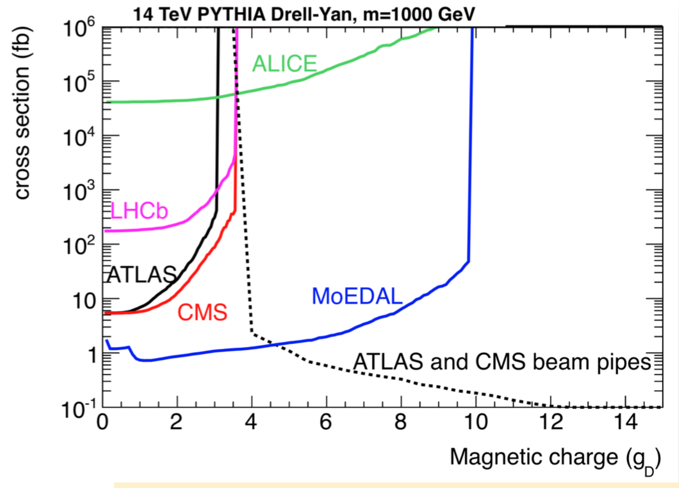
Future developments

- CMS beam pipe
- MAPP – Monopole Apparatus for Penetrating Particles
- MALL – Monopole Apparatus for very Long Lived particles

CMS beam pipe

Beam pipe

- most directly exposed piece of material
- covers very high magnetic charges, which may be trapped in upstream material before reaching MoEDAL



De Roeck et al, EPJC72 (2012) 1985

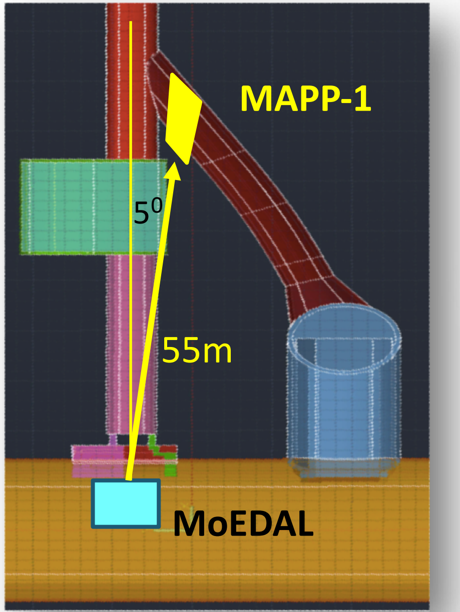
- **1990's:** materials from CDF, D0 (Tevatron) and H1 (HERA) subject to SQUID scans for trapped monopoles
- **2012:** first pieces of CMS beam pipe tested [EPJC72 (2012) 2212]; far from collision point
- **Feb 2019:** CMS and MoEDAL collaborations signed agreement transferring ownership of the Run-1 CMS beam pipe to MoEDAL
  - beryllium (highly toxic); 6 m long; Ø 4 cm
- Status & plans
  - beam pipe cut into small pieces at Univ. Alberta, Canada
  - scanned in SQUID at ETH Zurich

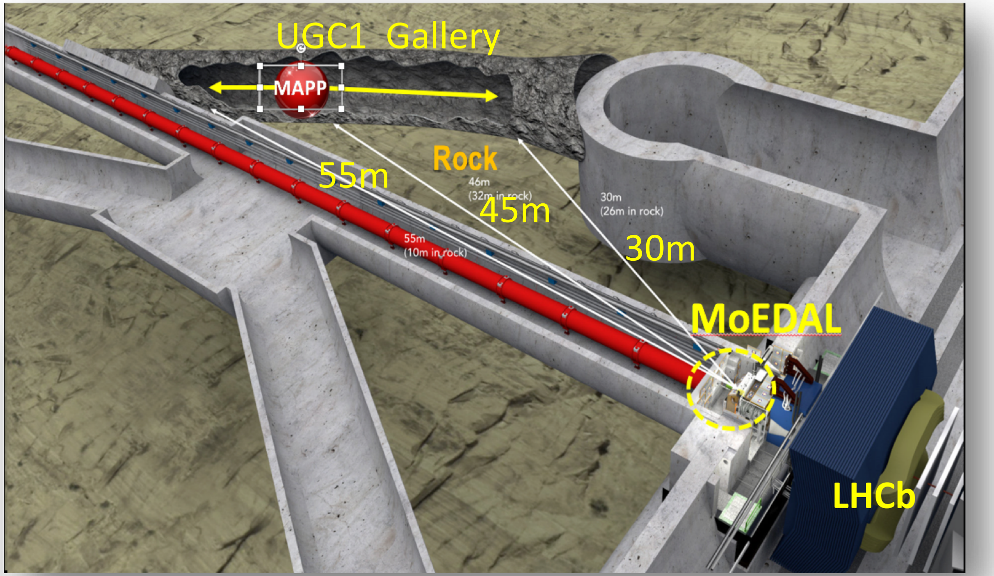
CERN Courier, Mar-Apr 2019

MAPP – MoEDAL Apparatus for Penetrating Particles

MAPP (to be installed for LHC Run-3) has 3 motivations

- particles with charges ≪ 1*e* (ATLAS & CMS sensitive to particles of charge $e \gtrsim 1/3$)
- new pseudo-stable weakly interacting neutrals with long lifetime
- anomalously penetrating particles





Prototype installed in 2017

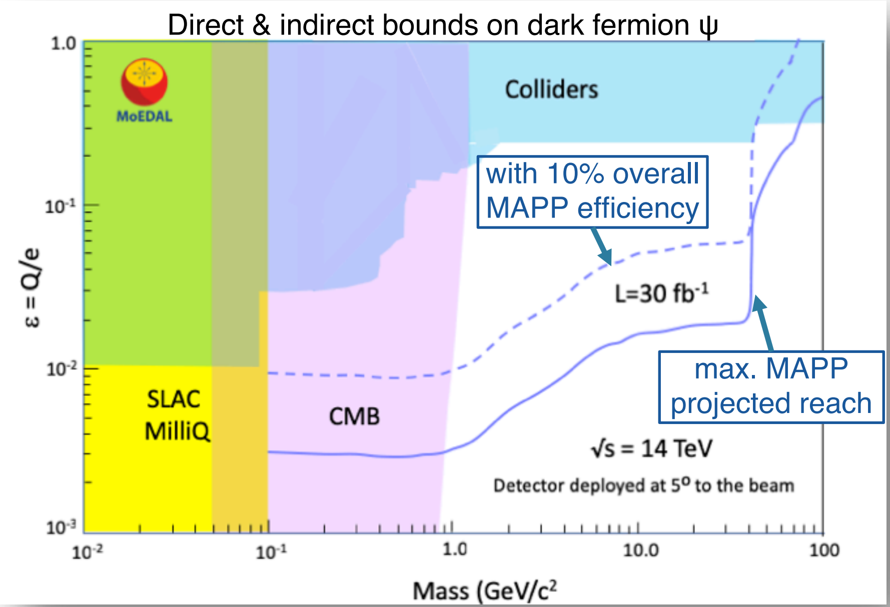
- 3×3 bars (~30×30 cm)
- ~10% of full detector

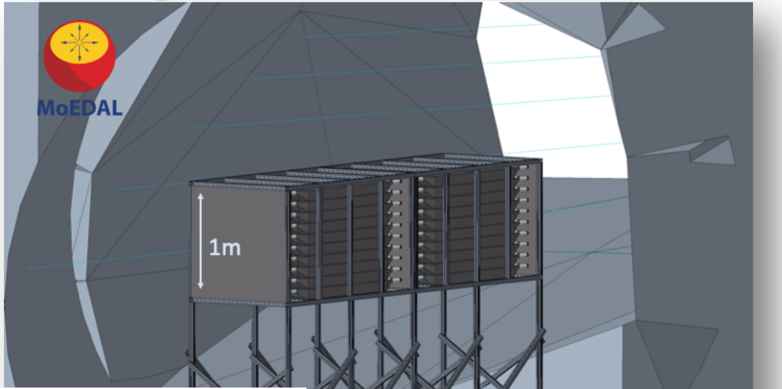
J. Pinfold, Universe 5 (2019) no.2, 47

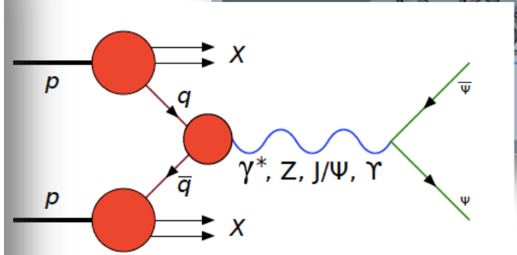
MAPP – mQP detector & sensitivity

Central milli-charged (mQP) detection section

- 100 × (10 cm × 10 cm × 75 cm) scintillator bars in each of 4 (2×2) sections readout by 4 low-noise PMTs in coincidence
- no background from dark counts or radiogenic bkg.







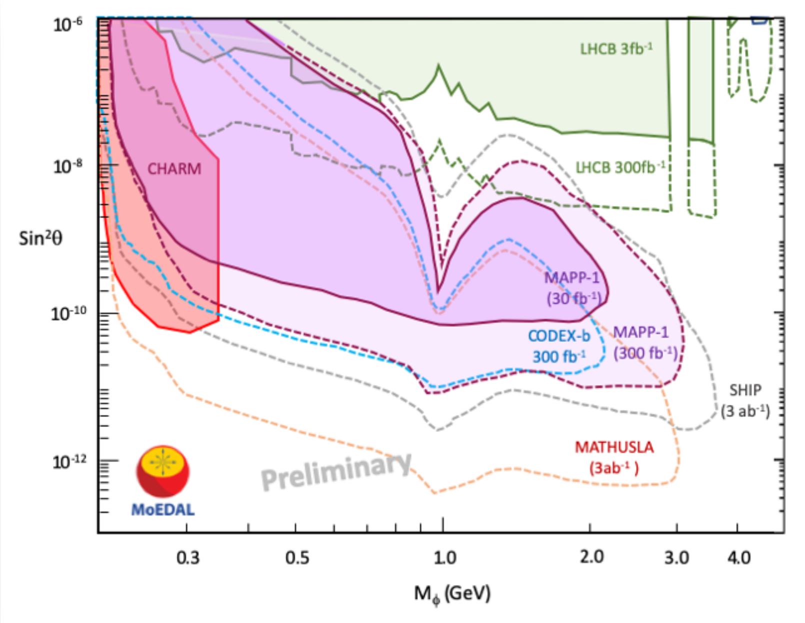
Dark photon scenario: massless dark photon which mixes with γ/Z & mQP dark fermion ψ

- MAPP sensitivity to a charge of $\mathcal{O}(10^{-3})$–$\mathcal{O}(10^{-2})$ e for mass of $\mathcal{O}(1)$ GeV & charge $\mathcal{O}(10^{-2})$ e for mass of $\mathcal{O}(10)$ GeV

MAPP – LLP detector & sensitivity

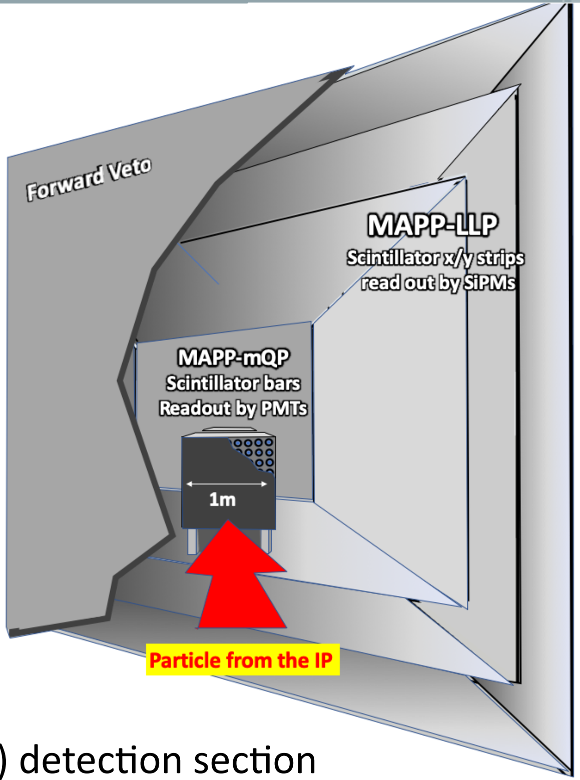
Full MAPP detector planned to operate in Run-3 (2021–2024)

- max. fiducial efficiency for $B \rightarrow X_s\phi$ is ~ 5×10^{-4}
- background from K_L^0, n, μ & ν under study with full GEANT simulation incl. detectors, beamline and surrounding material



100% tracking efficiency assumed; no background

Benchmark scenario:
dark Higgs ϕ mixes with SM H^0 ($\theta \ll 1$), leading to exotic $B \rightarrow X_s\phi$ decays with $\phi \rightarrow \ell^+\ell^-$

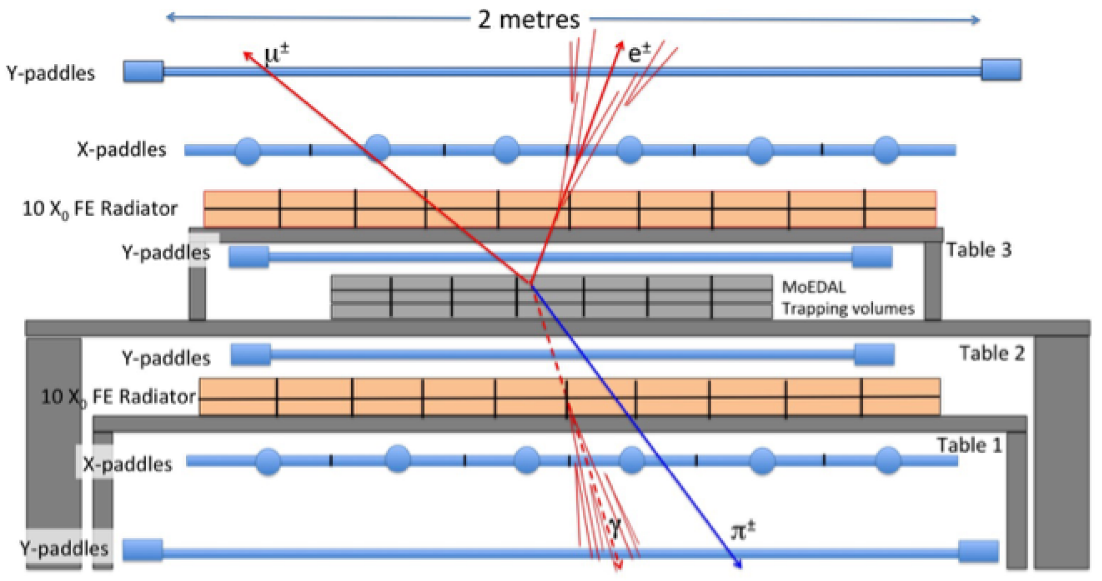


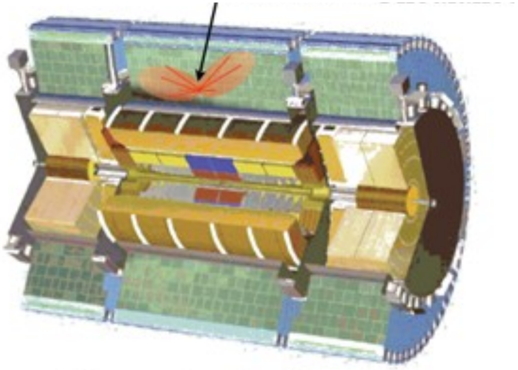
Long Lived Particle (LLP) detection section

- scintillator x/y strip “hodoscope-type“ planes
- 3 sets of detectors nested in “Russian Doll” configuration
- outer set: front veto layer forms front face
- envisaged ToF resolution ~500 ps with spatial resolution $\sigma_{x/y}$ ~ 1 cm

MALL – MoEDAL Apparatus for very Long Lived particles

- After exposure and SQUID scan, MoEDAL MMTs will be monitored for decaying *electrically charged* particles that may have been trapped in their volume
  - ATLAS & CMS similar analyses in empty bunch crossings for trapped R-hadrons decaying into jets
- Sensitive to charged particles and to photons with energy as small as 1~GeV
- MALL planned to be installed deep underground at SNOLAB in Canada





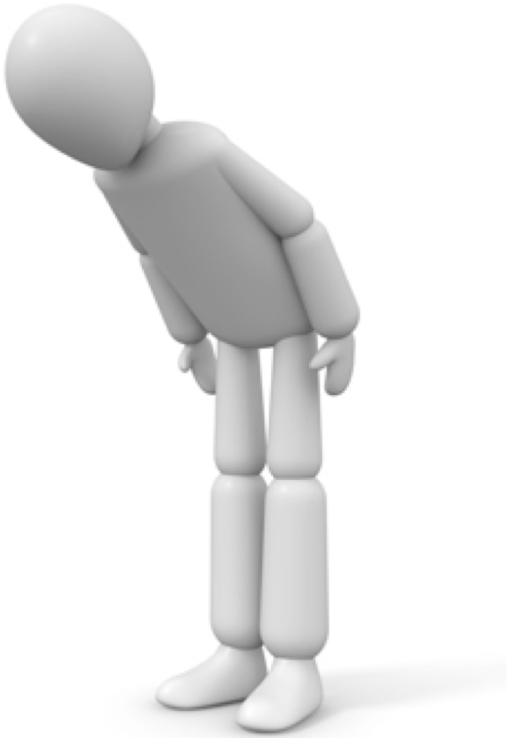
Estimated MALL probed lifetimes ~10 yrs

J. Pinfold, Universe 5 (2019) no.2, 47

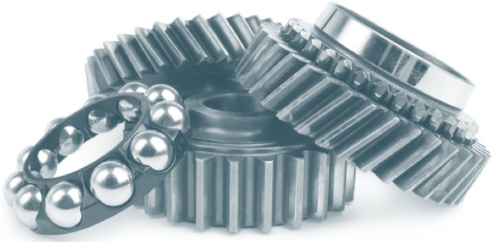
Summary

- Magnetic monopoles continue to excite interest and have been the subject of numerous experimental searches
- The MoEDAL experiment at the LHC is one of the key players in this quest
  - search for dyons in progress
- MoEDAL can also search for **(meta)stable *electrically-charged* massive particles**
  - such particles arise in numerous **supersymmetric** scenarios
  - search for HECOs is underway
- Much higher charges can be probed by looking for trapped monopoles, e.g. CMS run 1 beam pipe
- Further **detector extensions** in various stages of advancement
  - in particular, **MAPP** searching for penetrating particles
- **Stay tuned for upcoming results !**

Thank you for your attention!

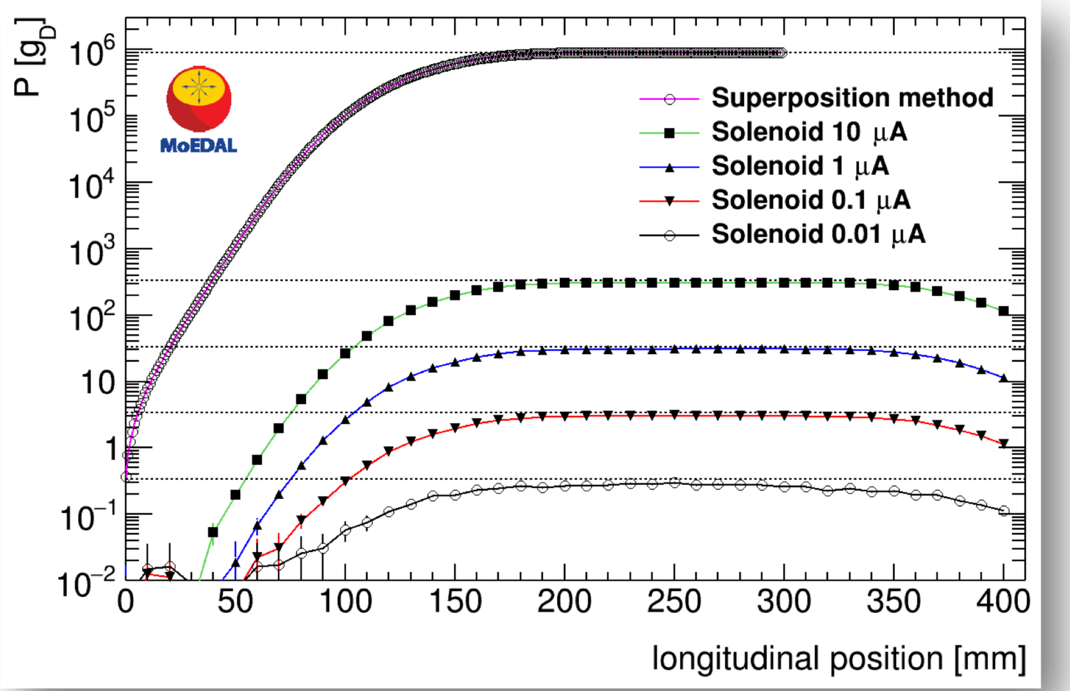


Spares



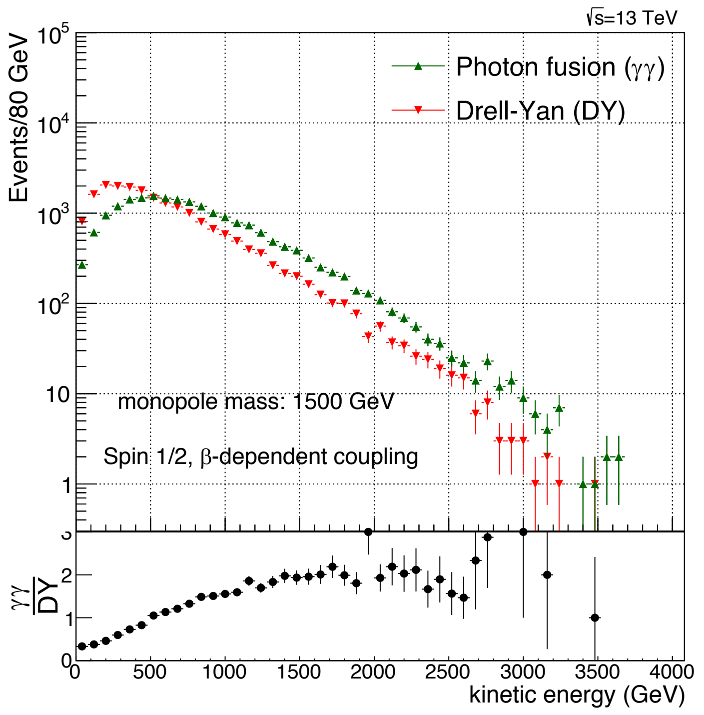
SQUID calibration

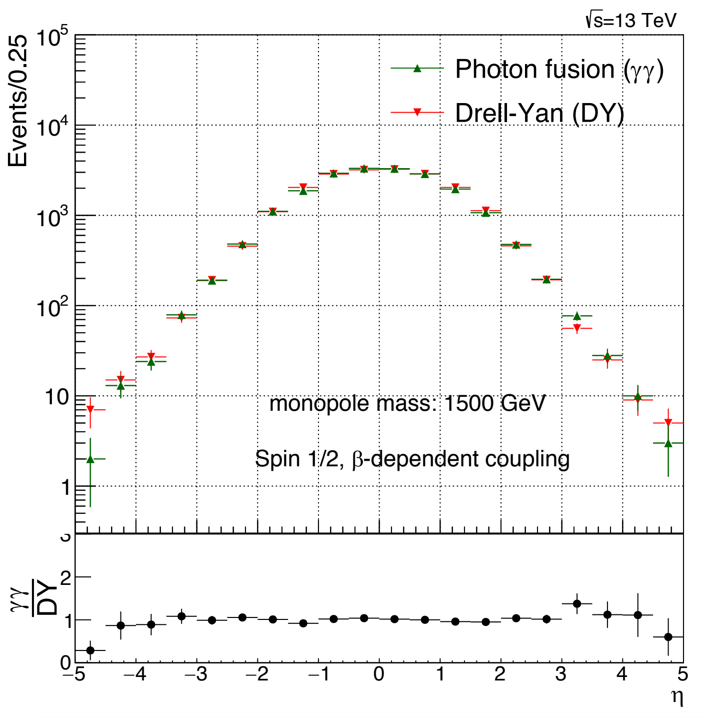
- Calibration measurements
  - superposition method using a magnetic dipole simple
  - solenoid method with P = 32.4 g_D / A and various currents



MoEDAL, PRL 123 (2019) 021802

Drell-Yan vs. γ-fusion: spin ½

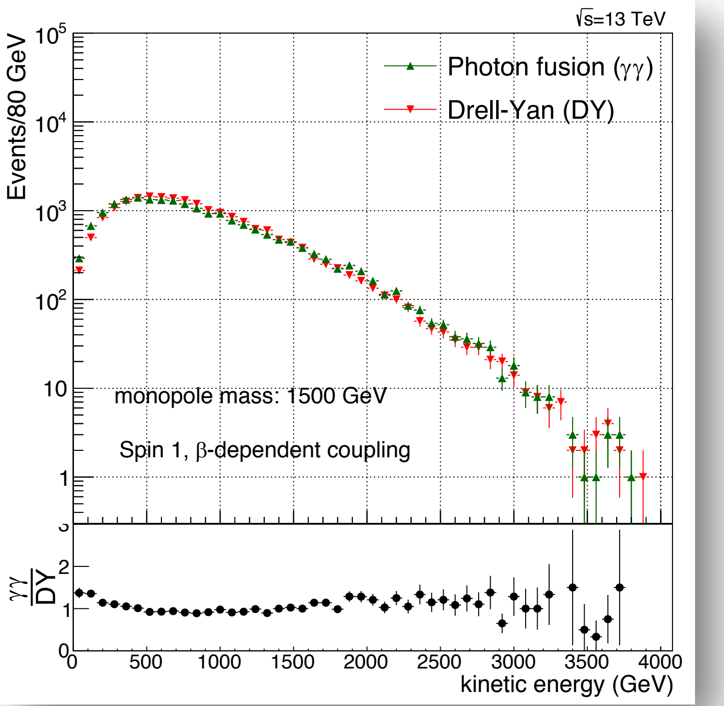


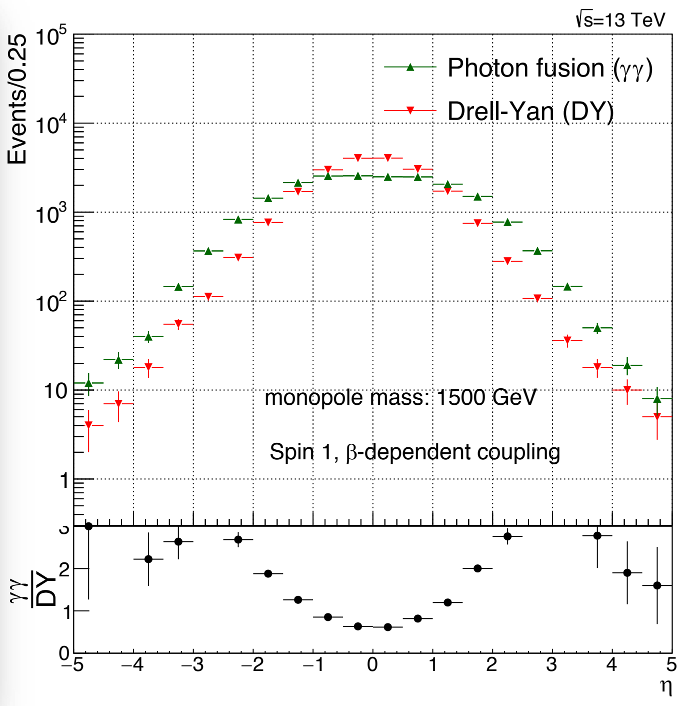


- DY events have a significantly "softer" spectrum than PF
- Angular distributions are similar

Baines et al, [Eur.Phys.J. C78 (2018) 966]

Drell-Yan vs. γ-fusion: spin 1





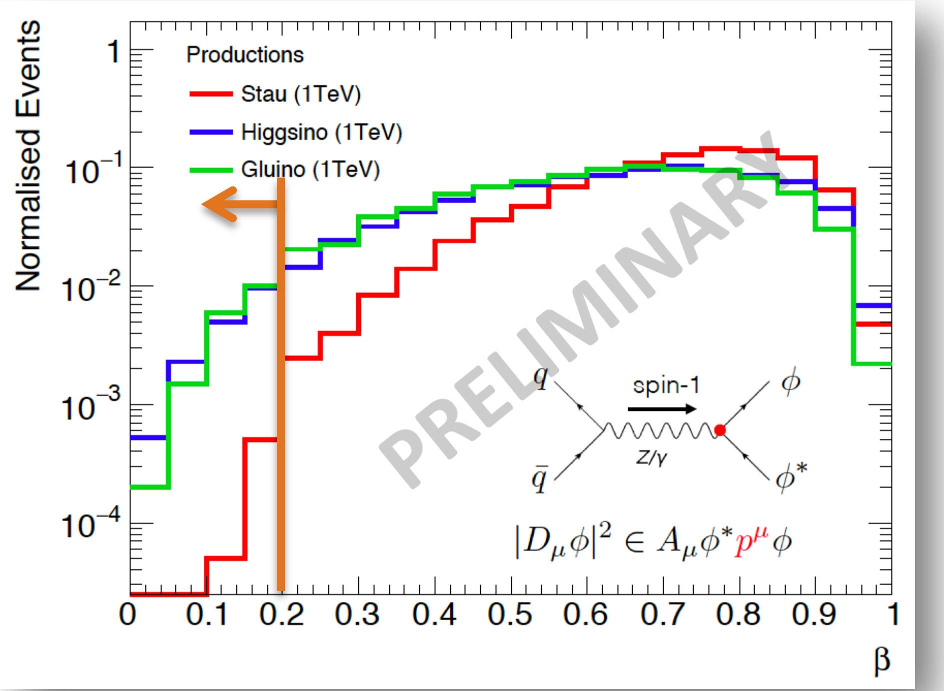
- DY events are characterised be a slightly "harder" spectrum and are more centrally produced than PF
- PF-DY comparison similar to scalar monopoles

Baines et al, Eur.Phys.J. C78 (2018) 966

Why MoEDAL when searching for HSCPs?

- **Trigger**
  - ATLAS/CMS must use trigger ➪ decreased efficiency even when using specialised triggers
  - MoEDAL has no trigger
- **Event selection**
  - ATLAS/CMS apply strict kinematic cuts to suppress background ➪ complex systematics estimation
  - in MoEDAL analyses are hardware oriented ➪ simple and robust
  - MoEDAL mostly limited by geometrical acceptance and low-β requirement
- **Timing**: signal from (slow-moving) HSCPs should arrive within the correct bunch crossings for ATLAS/CMS
  - MoEDAL is time-agnostic ➪ no problem with very slow particles
- When looking for ***trapped*** **particles**
  - monitoring of detector volumes in an underground/basement laboratory has less background than using empty butches in LHC cavern (MALL)

Velocity vs. type of particle



Sakurai et al, arXiv:1903.11022

- Scalar (spinless) pair production (stau) undergoes *p*-wave suppression, unlike fermion (spinful) production
- The velocity is smaller for fermion pair production scalar
    - gluinos
    - higgsinos / binos / winos
- Detectable particles must be *charged*
    - sleptons, i.e staus for most models/parameter space
    - charginos
    - gluinos

☛ Study **slepton (stau)** detection in **gluino-**mediated production

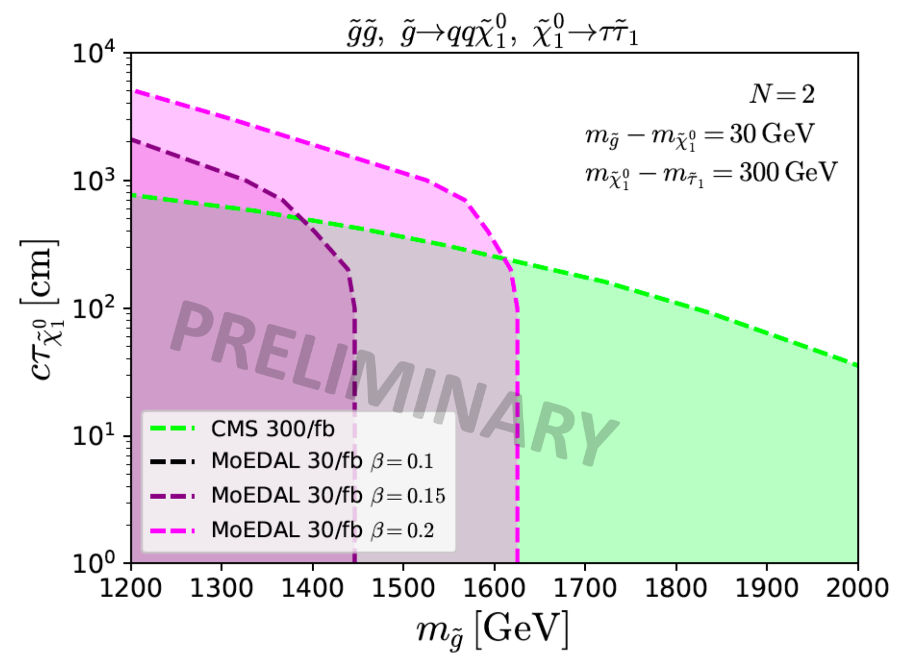
$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow jj\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow\tau^\pm\tilde{\tau}_1$ (III)

- Studying sensitivity with different β thresholds:
  - 0.1 ($z/\beta=10$)
  - 0.15 ($z/\beta\approx 6.7$)
  - **0.2 ($z/\beta=5$)**

MoEDAL can cover long-lifetime region with less-than-nominal NTD performance **$z/\beta > 6.7$**

Other decay chains studied too, e.g. $\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow jj\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow\pi^\pm\tilde{\tau}_1$
$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow jj\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm\rightarrow\nu_\tau\tilde{\tau}_1$

End-of-run-3 (2023, 14 TeV) projected luminosity



Sakurai et al, arXiv:1903.11022

SUSY charged long-lived particles

- Long-lived sleptons (staus mostly)
  - **Gauge-mediated symmetry-breaking (GMSB)**: stau NLSP decays via gravitational interaction to gravitino LSP
  - **Coannihilation region in CMSSM**: long lived stau, when $m(\tilde{\tau}) - m(\tilde{\chi}_1^0) < m(\tau)$

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

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

➜ naturally long lifetime for stau in both cases

- 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

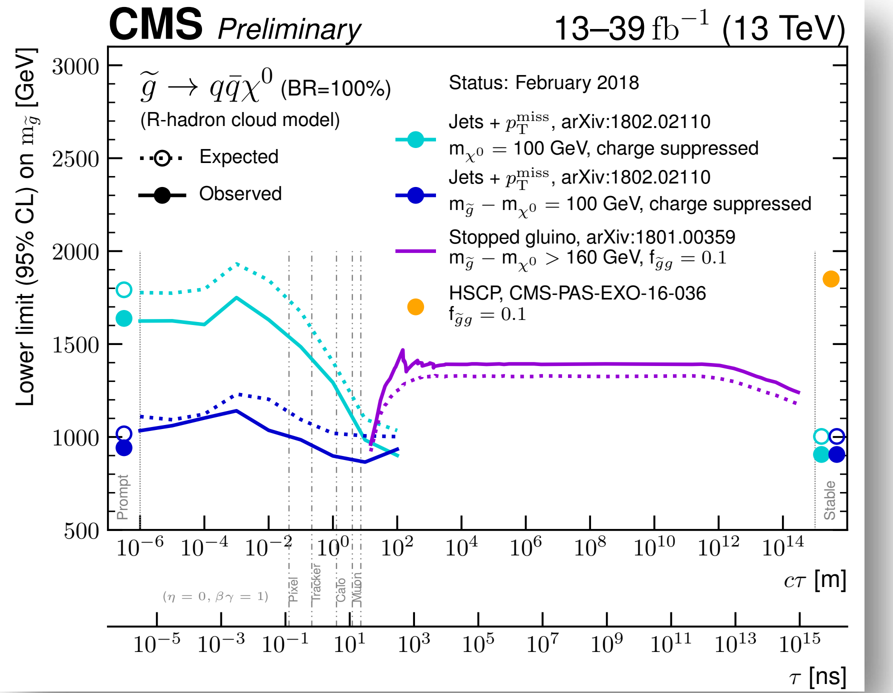
$$\tilde{t} \to t\tilde{G}$$

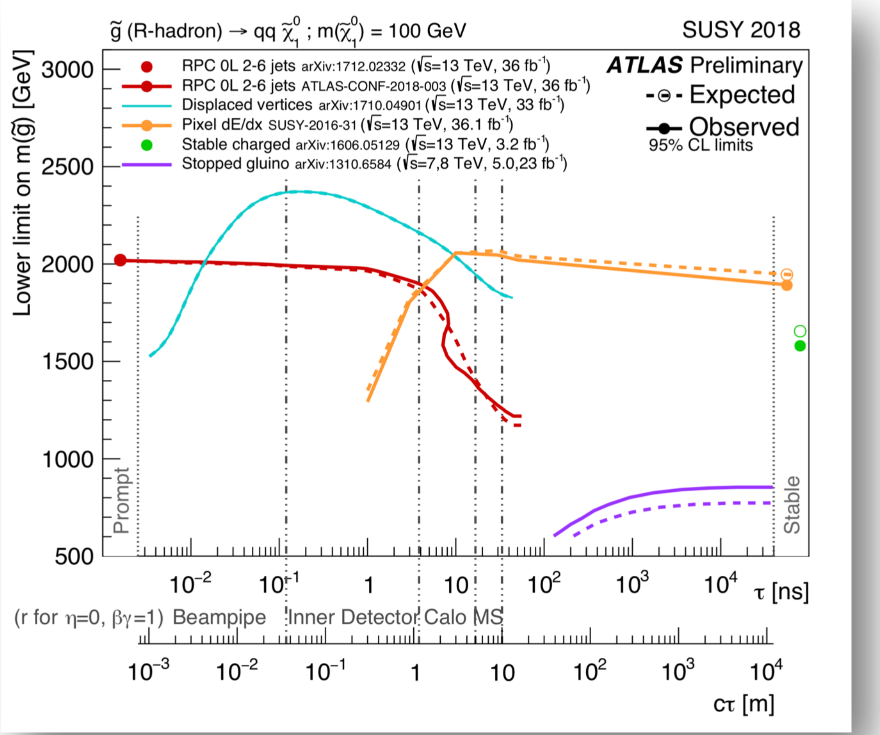
- Long-lived charginos
  - **Anomaly-mediated symmetry-breaking (AMSB)**: $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ are mass degenerate ⇒ $\tilde{\chi}_1^\pm$ becomes long-lived

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

ATLAS & CMS limits on LL gluinos

1. Energy deposition (dE/dx) in inner tracker, e.g. Pixel detector
2. Time-of-flight in outer muon system





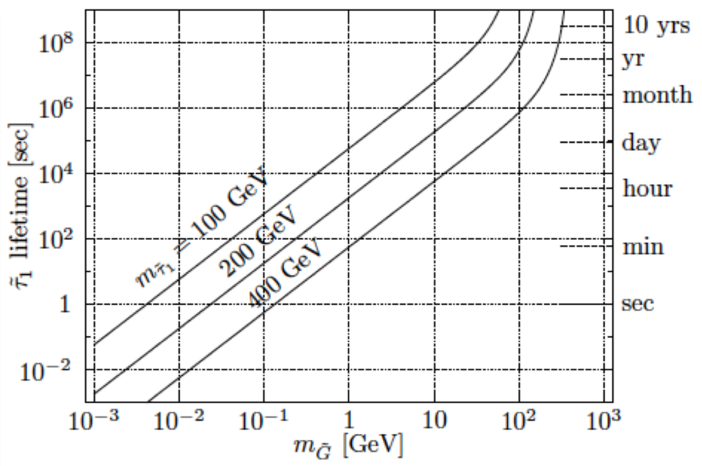
Detector response not fully calibrated for HIPs

Long-lived sleptons – GMSB

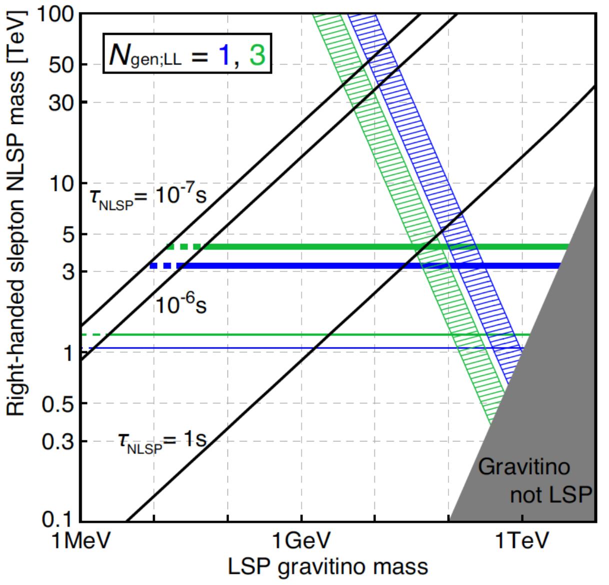
- Gauge-mediated Supersymmetry-Breaking (GMSB)
- Stau NLSP decays via gravitational interaction to gravitino LSP
  → naturally long lifetime
  → LSP dark matter candidate

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

- Long-lived sleptons
  - may be slow-moving when produced at LHC
  - → high ionisation



Hamaguchi, Nojiri, De Roeck, JHEP 03(2007)046



Feng, Iwamoto, Shadmi, Tarem, JHEP 12(2015)166

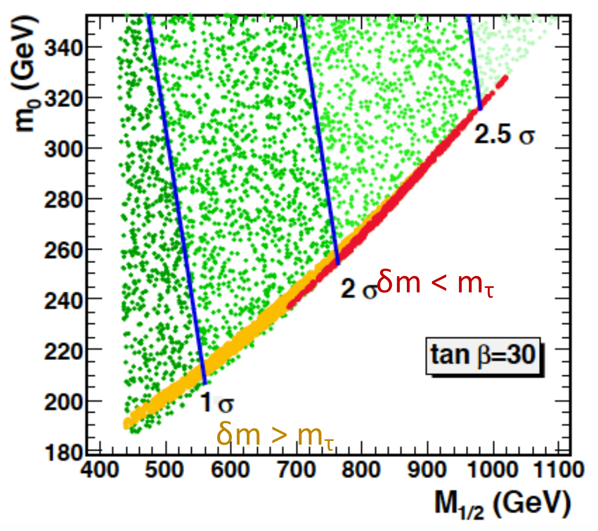
Long-lived sleptons – CMSSM

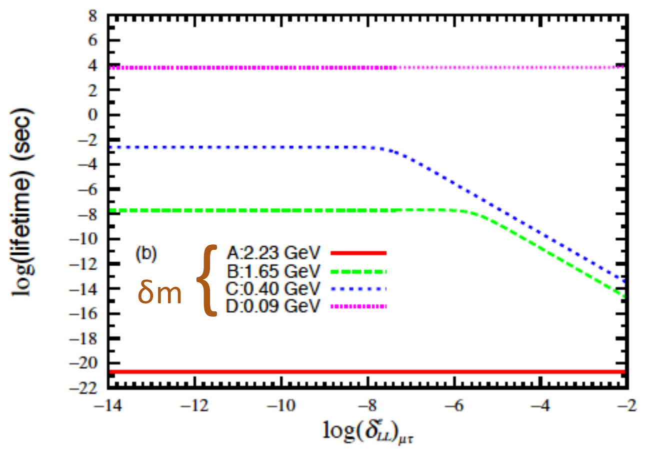
- Stau becomes long lived in MSSM when $\delta m = m(\tilde{\tau}) - m(\tilde{\chi}_1^0) < m(\tau)$
    - e.g. $\tau = 10^{-3}$ s (10^3 s) for $\delta m = 0.4$ GeV (0.1 GeV)
- Coannihilation region in CMSSM
- Consistent with cosmological constraints
- Lepton Flavour Violating (LFV) elements in slepton mass matrix may decrease stau lifetime

$$(\delta^e_{RR/LL})_{\alpha\beta} = \frac{\Delta M^{e\ 2}_{RR/LL_{\alpha\beta}}}{M^e_{R/L\alpha} M^e_{R/L\beta}},$$

- Stau remains metastable in large regions of parameter space

$$\Gamma_{2-\text{body}} = \frac{g_2^2}{2\pi m_{\tilde{\tau}_1}} (\delta m)^2 (|g^L_{1\alpha 1}|^2 + |g^R_{1\alpha 1}|^2),$$





Kaneko, Sato, Shimomura, Vives, Yamanaka, PRD87 (2013) 039904 [arXiv:0811.0703]

R-hadrons

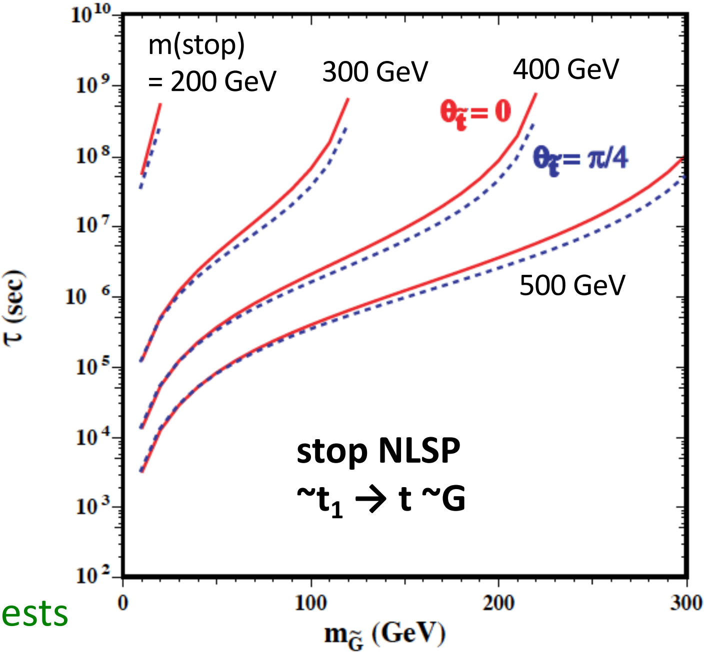
- Gluinos in Split Supersymmetry
  - long-lived because squarks very heavy
  - possible gluino hadrons: $R = \tilde{g}q\bar{q}, \tilde{g}qqq, \tilde{g}g$
  - gluino hadrons may flip charge as they pass through matter
    - e.g., g̃uū + uud → g̃uud + uū
    - ☛ may be missed by ATLAS and CMS
- *R*-parity violating SUSY

$$W_{RV} = \lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \lambda_{ijk}L_iL_j\bar{E}_k + \mu_iL_iH$$

  - if small λ’ or λ’’≠0 and stop LSP → stop R-hadron → metastable charged particle in material → detection in MoEDAL, if sufficiently slow
- Moreover R-hadrons may be “trapped” in MMTs and decay at later times ➜ monitoring of MMTs after SQUID tests

$$\tau \simeq 8\left(\frac{m_S}{10^9\ \mathrm{GeV}}\right)^4\left(\frac{1\ \mathrm{TeV}}{m_{\tilde{g}}}\right)^5 \mathrm{s}$$

Diaz-Cruz et al, JHEP 0705 (2007) 003



stop NLSP
$\tilde{t}_1 \rightarrow t\,\tilde{G}$