MoEDAL

Exploring supersymmetry at the LHC using the MoEDAL detector

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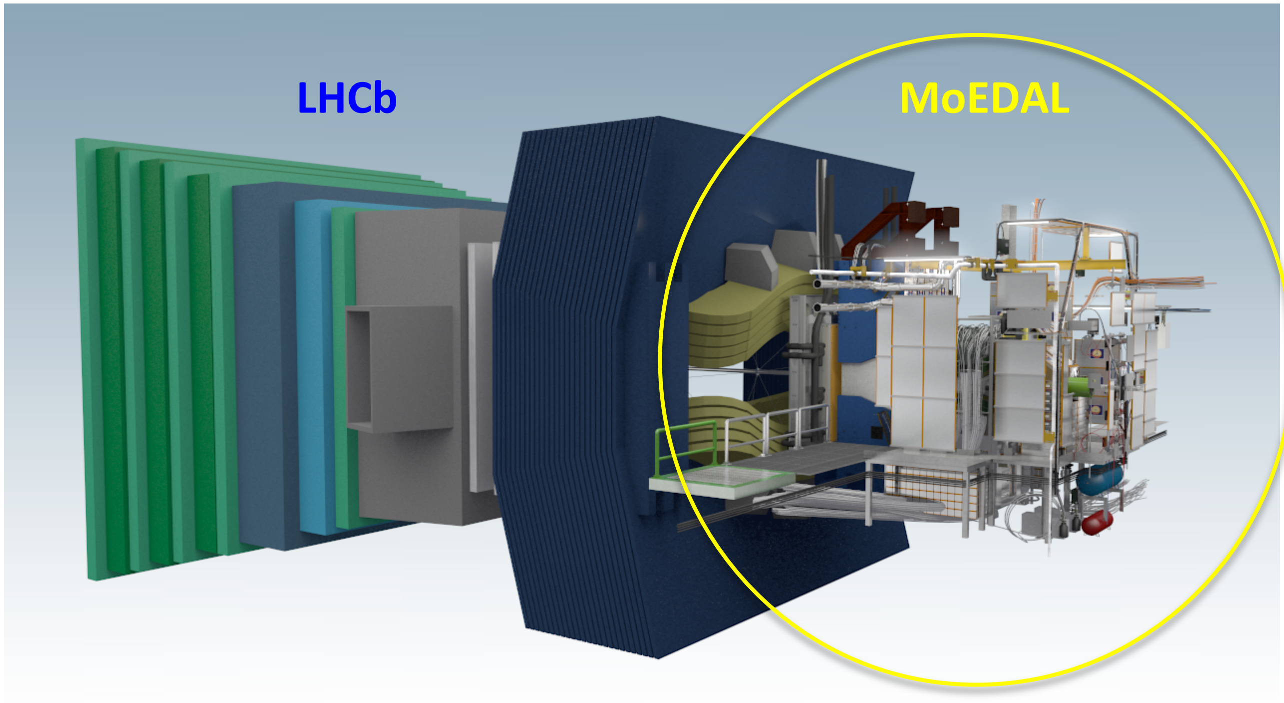
The MoEDAL detector



DETECTOR SYSTEMS

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

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

Beyond magnetic monopoles

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

- Key feature: **high ionisation**

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

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

Electric charge

Bethe-Bloch formula

- Achieved, e.g., by magnetic monopoles due to ionisation 68.5^2 times higher than minimum ionising particle
- Actually any (meta-)stable massive charged particle, (M)SMCP, (hence slow moving) with electric charge should give a track in Nuclear Track Detectors
- For singly charged particles to be detected in NTDs, velocity should be **$\beta \lesssim 0.2$**
- Moreover in some cases they may lose all of their momentum, mainly from ionisation energy loss, and come to rest within the magnetic trappers, MMTs
  - if metastable, they may be monitored with a dedicated detector system in an underground laboratory over a long period for their decay

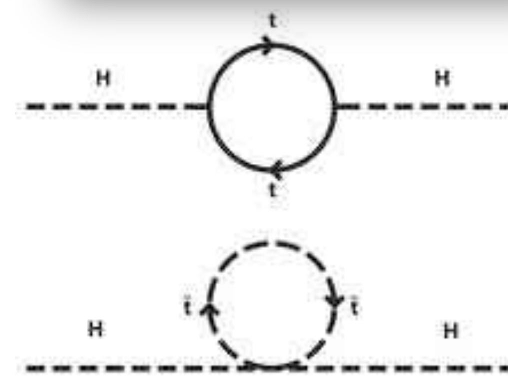
Stable charged particles in BSM scenarios

- Scenarios with Extra Dimensions
  - long-lived microscopic black holes
  - microscopic black hole remnants
  - long-lived Kaluza-Klein particles from UED
- D matter
  - electrically-charged D-particles
- Long-lived heavy quarks
- Fourth-generation fermions
- Multiparticle excitations
  - Q-balls
  - strangelets
  - quirks
- …
- **Supersymmetry**

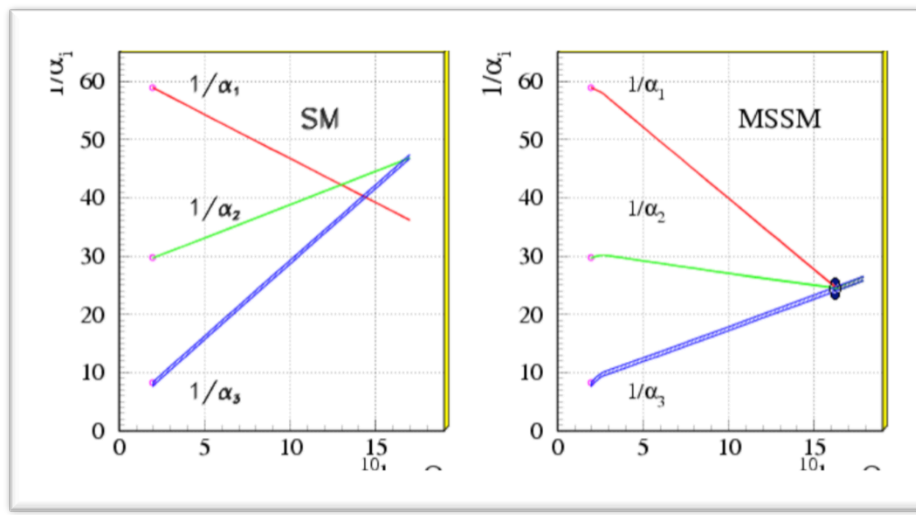
See previous talk by Nick Mavromatos

Supersymmetry (SUSY)

- Global symmetry between fermions & bosons
- Motivation
  - Higgs mass stabilisation against loop corrections (**fine-tuning** problem)
  - **unification** of gauge couplings at single scale
  - **dark matter** candidate



- Particle stability mechanisms
  a) lightest state (LSP) carrying a conserved quantum number:
     R-parity: $R = (-1)^{3(B-L)+2s}$
  b) suppressed (effective) coupling
  c) lack of phase space for decay, e.g. mass degeneracies

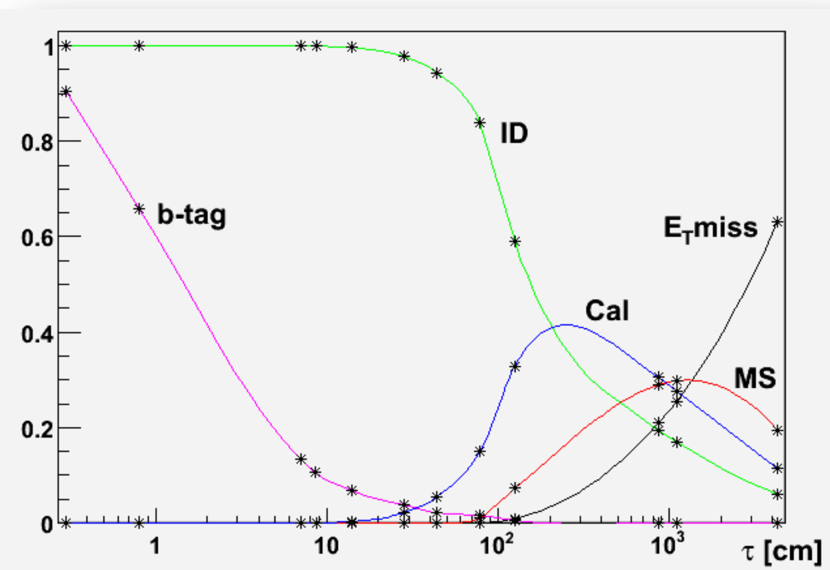


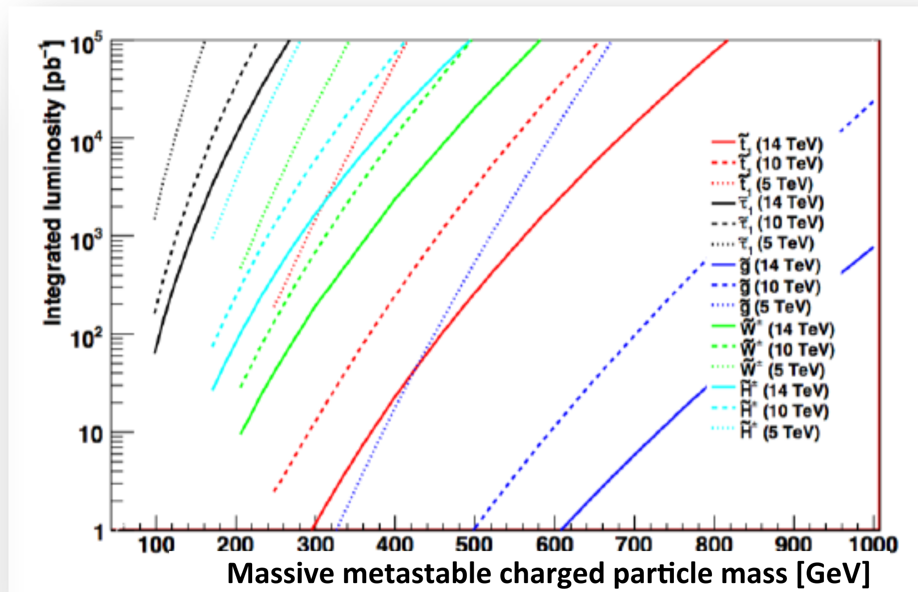
LHC sensitivity to sparticle direct production

- Metastable particles ≡ they live long enough to pass through detector
- Detection in ATLAS and CMS
  - large ionisation energy loss dE/dx, e.g. time-over-threshold in ATLAS Transition Radiation Tracker
  - nuclear interactions (R-hadron) in calorimeters
  - delay (time of flight) reconstructed in muon chambers

Integrated luminosities needed for discovery at LHC at 14 TeV (solid), 10 TeV (dashed) and 5 TeV (dotted)

- signal efficiency of 20% (5%) for electrically charged (strongly interacting) SMCPs
- 1 bkg event for 100 pb^{-1}





Raklev, Mod.Phys.Lett. A24 (2009) 1955

Long-lived particles in SUSY scenarios

- **GMSB**: NLSP decays to gravitino LSP only via (small) gravitational coupling
  - $N_{mes} = 1$: non-pointing photons

$$\tilde{\chi}_1^0 \rightarrow \tilde{G} + \gamma$$

  - $N_{mes} > 1$: **penetrating sleptons**

$$\boxed{\tilde{\ell} \xrightarrow{\text{long}} \tilde{G} + \ell}$$

- **Split SUSY**: squarks heavy, suppressing gluino decays ➞ colored heavy particles

R-hadrons $\boxed{R = \tilde{g}q\bar{q},\ \tilde{g}qqq,\ \tilde{g}g}$

- **AMSB:** $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^0$ are mass degenerate
  - long-lived chargino (→ kink track)

$$\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^0 + \pi^{\pm}$$

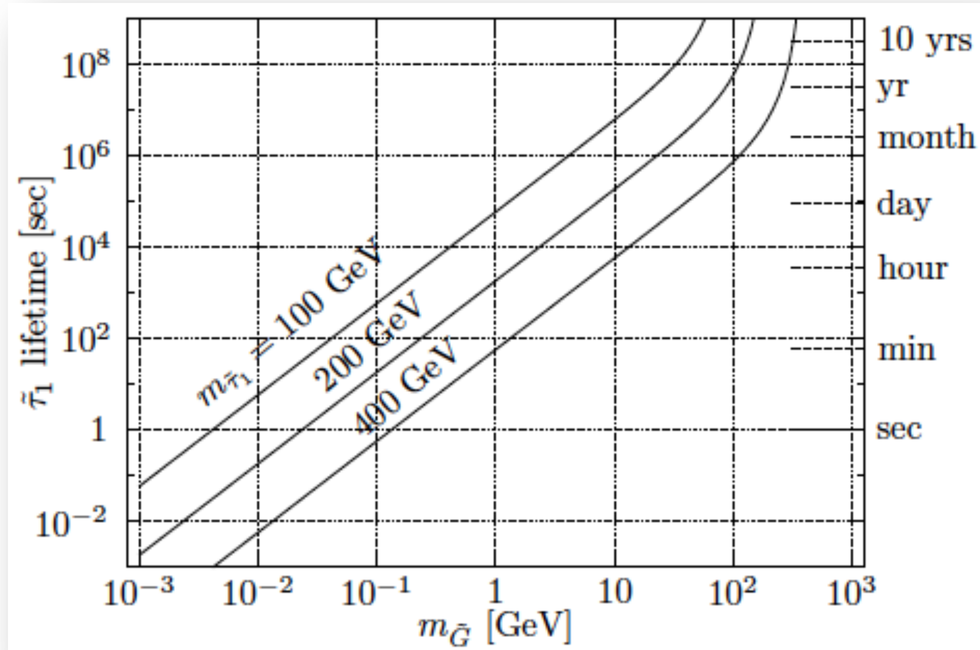
SMP	LSP	Scenario	Conditions
$\tilde\tau_1$	$\tilde\chi_1^0$	MSSM	$\tilde\tau_1$ mass (determined by $m^2_{\tilde\tau_{L,R}}$, μ, $\tan\beta$, and A_τ) close to $\tilde\chi_1^0$ mass.
	$\tilde G$	GMSB	Large N, small M, and/or large $\tan\beta$.
		$\tilde g$MSB	No detailed phenomenology studies, see [20].
		SUGRA	Supergravity with a gravitino LSP, see [21].
	$\tilde\tau_1$	MSSM	Small $m_{\tilde\tau_{L,R}}$ and/or large $\tan\beta$ and/or very large A_τ.
		AMSB	Small m_0, large $\tan\beta$.
		$\tilde g$MSB	Generic in minimal models.
$\tilde\ell_{i1}$	$\tilde G$	GMSB	$\tilde\tau_1$ NLSP (see above). $\tilde e_1$ and $\tilde\mu_1$ co-NLSP and also SMP for small $\tan\beta$ and μ.
	$\tilde\tau_1$	$\tilde g$MSB	$\tilde e_1$ and $\tilde\mu_1$ co-LSP and also SMP when stau mixing small.
$\tilde\chi_1^+$	$\tilde\chi_1^0$	MSSM	$m_{\tilde\chi_1^+} - m_{\tilde\chi_1^0} \lesssim m_{\pi^+}$. Very large $M_{1,2} \gtrsim 2$ TeV $\gg \lvert\mu\rvert$ (Higgsino region) or non-universal gaugino masses $M_1 \gtrsim 4M_2$, with the latter condition relaxed to $M_1 \gtrsim M_2$ for $M_2 \ll \lvert\mu\rvert$. Natural in O-II models, where simultaneously also the $\tilde g$ can be long-lived near $\delta_{GS} = -3$.
		AMSB	$M_1 > M_2$ natural. m_0 not too small. See MSSM above.
$\tilde g$	$\tilde\chi_1^0$	MSSM	Very large $m^2_{\tilde q} \gg M_3$, e.g. split SUSY.
	$\tilde G$	GMSB	SUSY GUT extensions [22–24].
	$\tilde g$	MSSM	Very small $M_3 \ll M_{1,2}$, O-II models near $\delta_{GS} = -3$.
		GMSB	SUSY GUT extensions [22–26].
$\tilde t_1$	$\tilde\chi_1^0$	MSSM	Non-universal squark and gaugino masses. Small $m^2_{\tilde q}$ and M_3, small $\tan\beta$, large A_t.
$\tilde b_1$			Small $m^2_{\tilde q}$ and M_3, large $\tan\beta$ and/or large $A_b \gg A_t$.

Several SUSY-model signatures accessible to MoEDAL

Fairbairn *et al*, Phys Rept 438 (2007) 1

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
- Long-lived staus
  - may be slow-moving when produced at LHC
  - ➜ high ionisation



Hamaguchi, Nojiri, De Roeck,
JHEP 0703 (2007) 046 [hep-ph/0612060]

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

average distance travelled

$$L = \frac{1}{\kappa_\gamma} \left(\frac{100\mathrm{GeV}}{m}\right)^5 \left(\frac{\sqrt{F/k}}{100\mathrm{TeV}}\right)^4 \sqrt{\frac{E^2}{m^2} - 1} \times 10^{-2} cm \quad \sqrt{F} \gtrsim 10^6\ \mathrm{GeV}$$

Long-lived sleptons – CMSSM

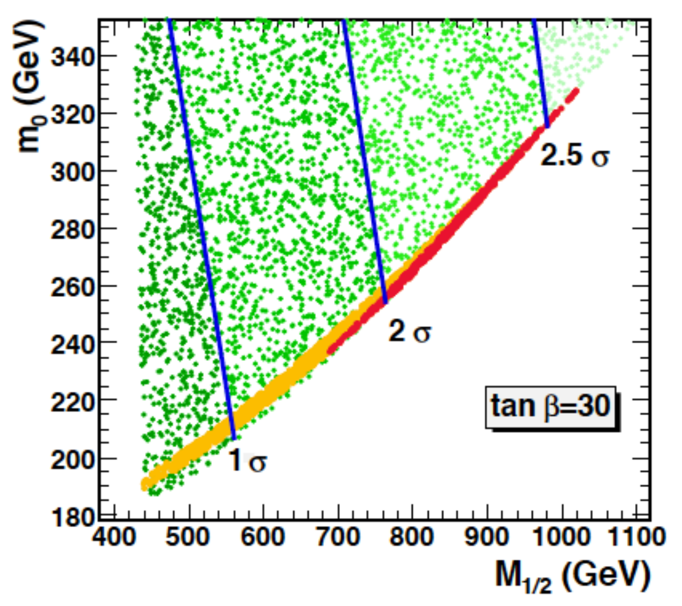
- Stau becomes long lived in MSSM when $m(\tilde{\tau}) - m(\tilde{\chi}_1^0) < m(\tau)$
- Coannihilation region in CMSSM
- Consistent with cosmological constraints
- Lepton Flavour Violating (LFV) elements in slepton mass matrix may decrease stau lifetime

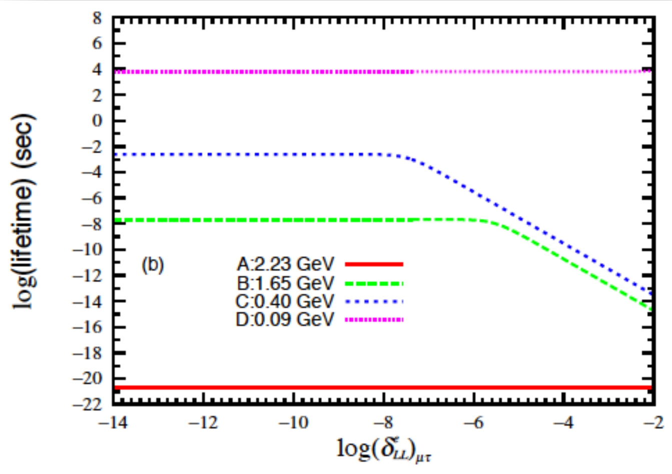
$$(\delta^e_{RR/LL})_{\alpha\beta} = \frac{\Delta M^{e\ 2}_{RR/LL_{\alpha\beta}}}{M^e_{R/L\alpha} M^e_{R/L\beta}},$$

- Stau remains metastable in large regions of parameter space

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

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

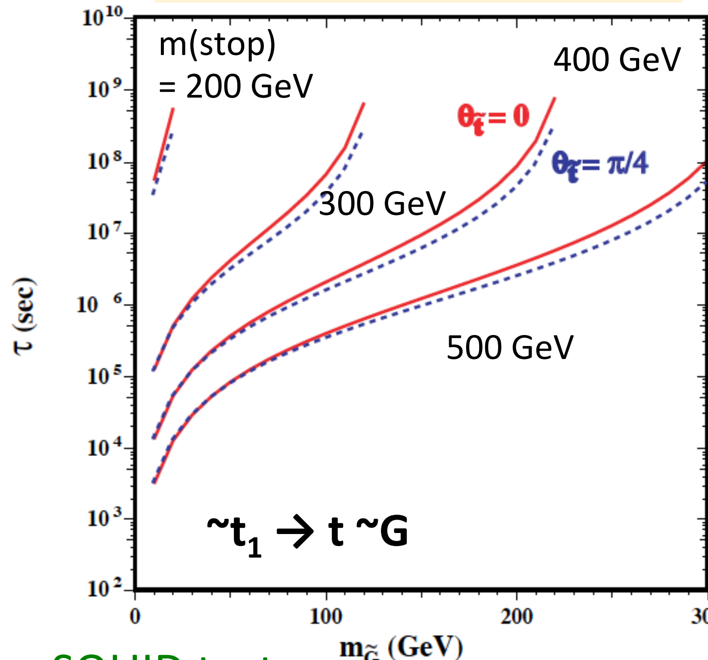
$$\tau \simeq 8 \left(\frac{m_S}{10^9\ \mathrm{GeV}}\right)^4 \left(\frac{1\ \mathrm{TeV}}{m_{\tilde{g}}}\right)^5 \mathrm{s}$$

- *R*-parity violating SUSY

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

  - if λ' or λ''≠0, stop NLSP case → stop R-hadron → metastable charged particle in material → detection in MoEDAL, if sufficiently slow

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



- Moreover R-hadrons may be "trapped" in MMTs and decay at later times ➜ monitoring of MMTs after SQUID tests

Why MoEDAL when searching MSPs?

- ATLAS and CMS triggers have to
  - rely on other “objects”, e.g. E_T^{miss}, that accompany MSCP, 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) MSCP 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 laboratory has less background than using empty butches in LHC cavern

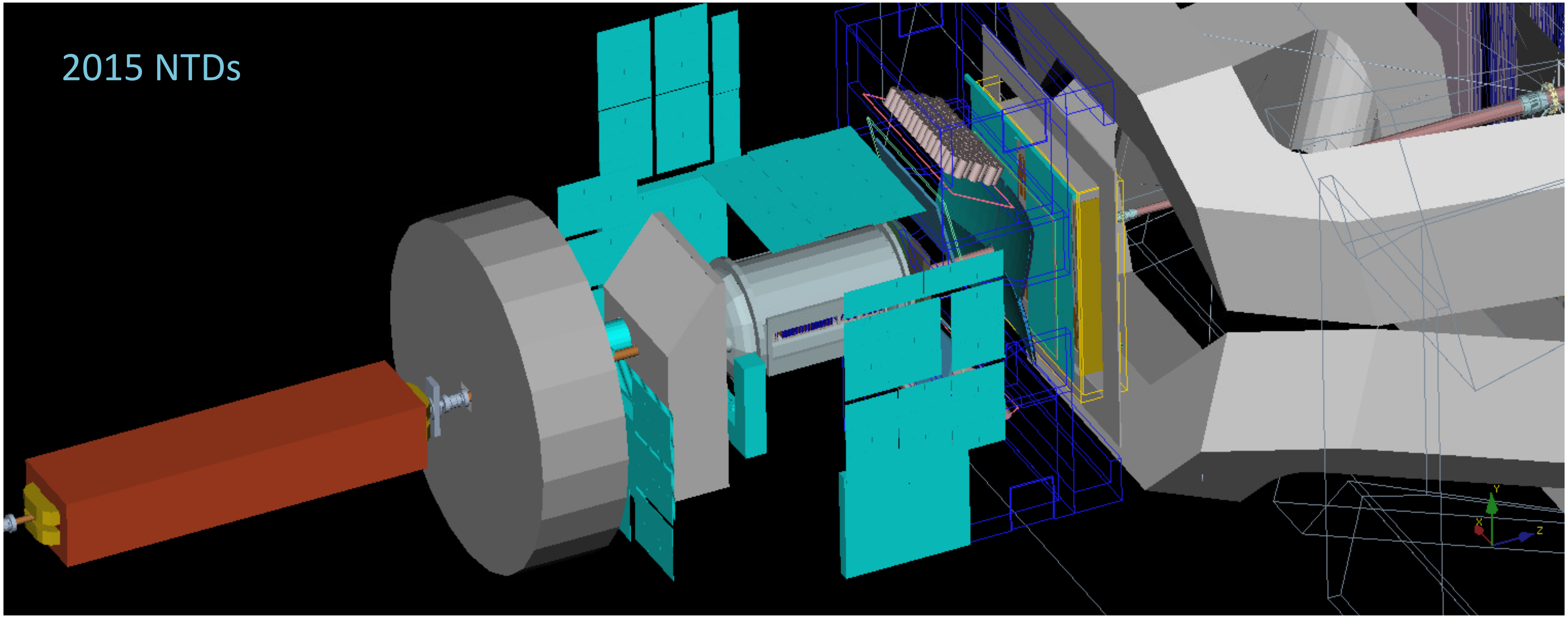
Slepton searches comparison*

	ATLAS / CMS	MoEDAL	comments
Velocity	$\beta > 0.2$ Constrained by LHC bunch patern	$\beta < 0.2$ Constrained by NTD Z/β threshold	Complementarity 😀
Efficiency	$\varepsilon \times A$ order of 20% *See limitations in previous slide*	~ 100% (if $\beta < 0.2$)	😐
Acceptance		~ 50% for 2015 Scalable to higher coverage	
Background	May be considerable or difficult to estimate	Practically zero	For same signal yield, MoEDAL should obtain better cross-section upper limits 😊
Luminosity	high	factor of 10 less	😕

* Numbers are indicative

Nuclear Track Detectors coverage

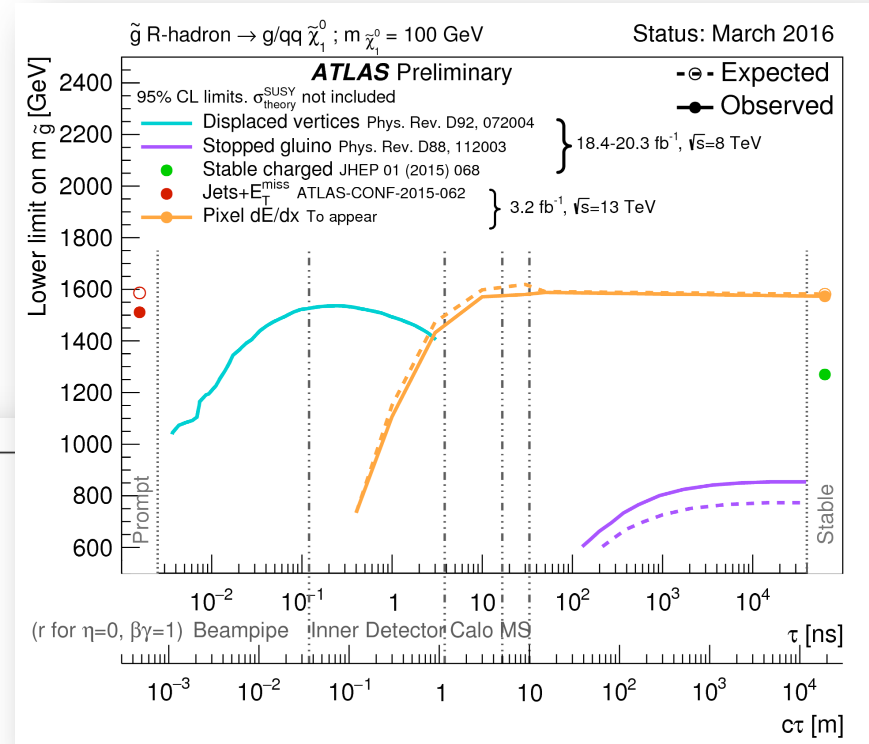
- High acceptance in central region η~0
  - back-to-back pair production means probability >~ 70% for at least one SMCP to hit NTD
- For particles over Z/β threshold, detection efficiency practically 100%

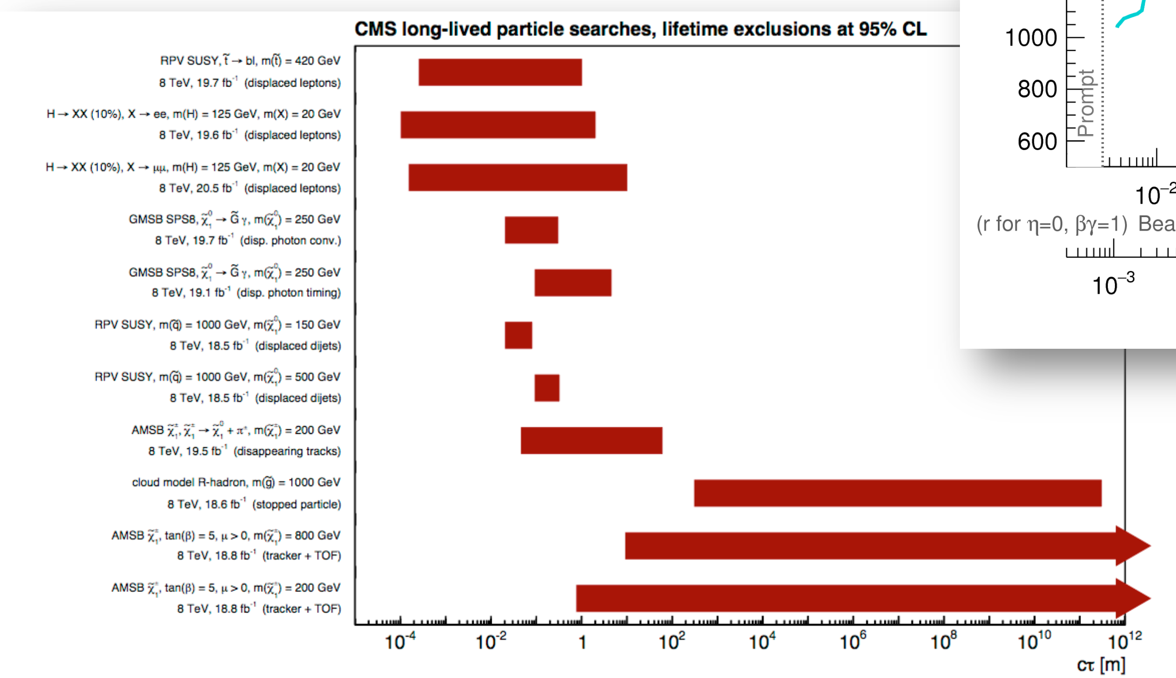


Credit: Daniel Felea

ATLAS & CMS limits on LL SUSY particles

1. Stable charged (dE/dx)
2. Stopped gluinos

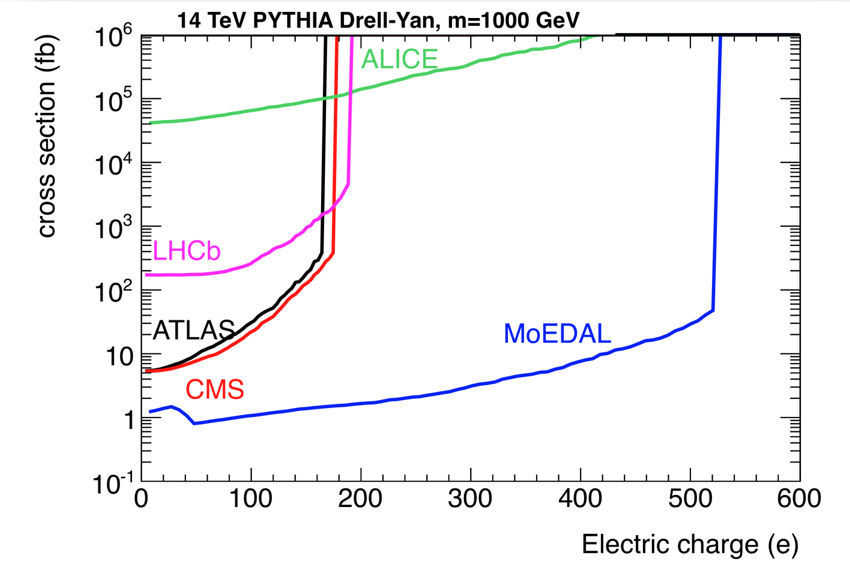




MoEDAL sensitivity in SMCPs

Cross-section limits for 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
- These results can be propagated to SUSY models featuring SMCPs in order to assess the discovery reach

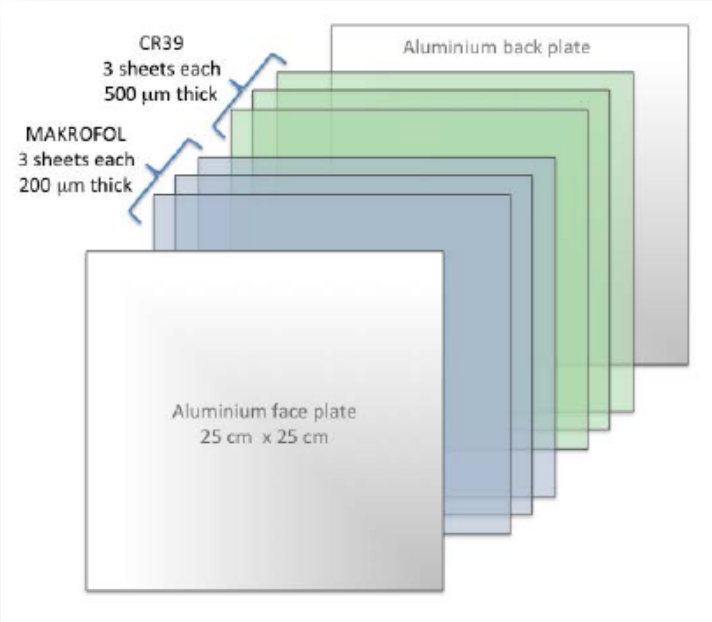
Summary

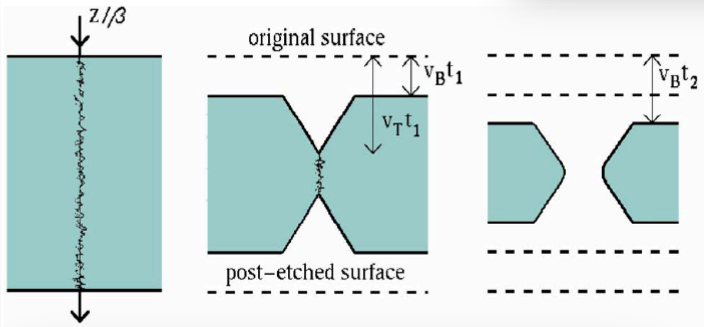
- Apart from magnetic monopoles, MoEDAL is also searching for **(meta)stable *electrically-charged* massive particles**
- Such particles arise in numerous supersymmetric scenarios (an not only)
- MoEDAL should extend significantly the discovery reach of the LHC w.r.t. such states thanks to its trigger-free concept of passive detectors
- Studies to assess discovery potential in specific SUSY models currently underway

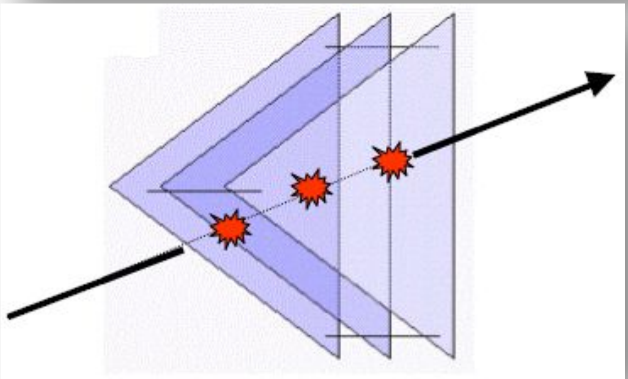
Spares

1 & 2 HI particle detection in NTDs

- The passage of a highly ionising particle through the plastic track-etch detector (e.g. CR39®) is 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 detector is etched in a controlled manner using a hot sodium hydroxide solution



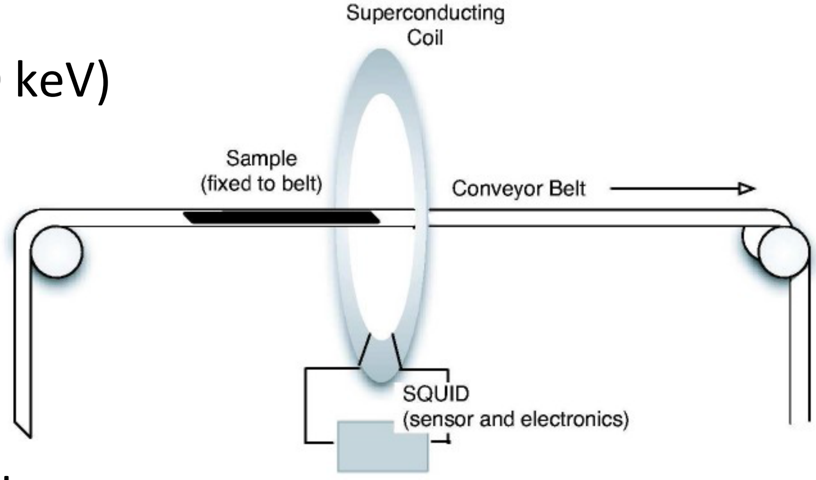


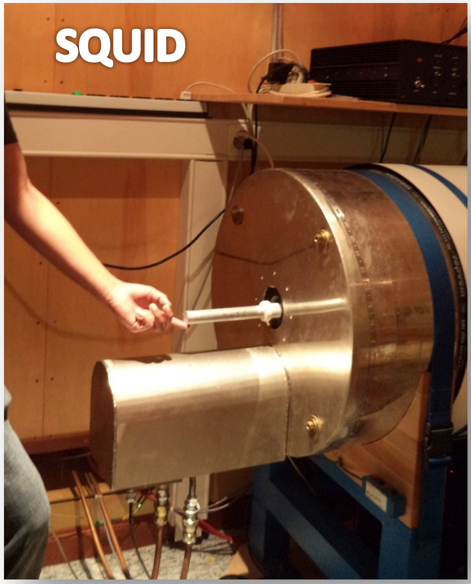


Looking for aligned etch pits in multiple sheets

4 MMT: Magnetic Monopole Trapper

- Binding energies 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
- Disadvantage: rather low geometrical acceptance
- Advantages:
  - speed: SQUID measurements & analysis take ~2 weeks
  - complementarity: totally different concept from NTDs ➜ different systematic uncertainties
  - magnetic charge measurement with < 5% precision
  - **Bonus**: monitoring for decay products of trapped electrically-charged particles at underground laboratory





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The physics programme of the MoEDAL experiment at the LHC

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Many more interesting theoretical scenarios relevant and accessible to MoEDAL not presented here:
- doubly-charged Higgs
- black-hole remnants
- quirks
- Q-balls
- CHAMPS
- ….

Complete and detailed review on MoEDAL impact on searches for exotic models

MoEDAL physics program:

IJMP A29 (2014) 1430050

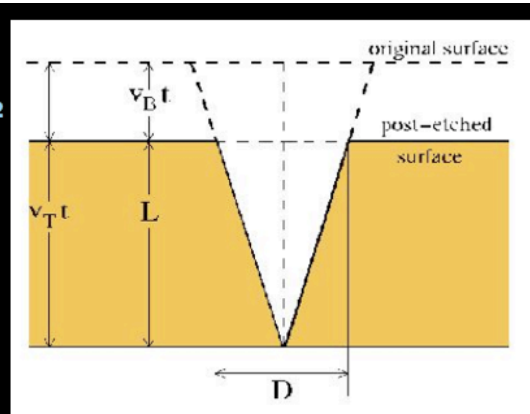
arXiv:1405.7662

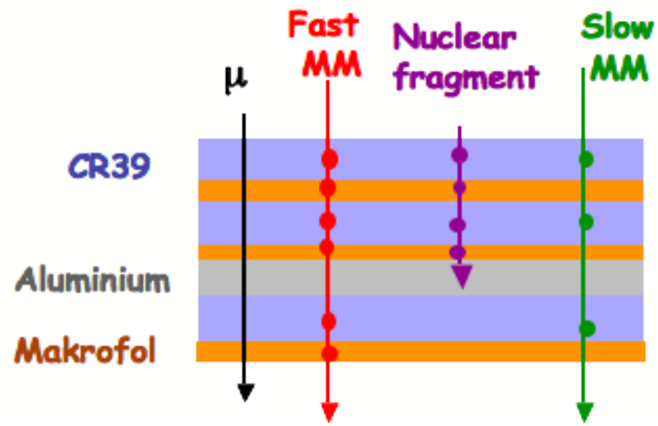
MoEDAL web page:

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

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 ~ β^{-2} ➔ slows down appreciably within NTD ➔ opening angle of etch-pit cone becomes **smaller**
- Magnetic monopole: dE/dx ~ lnβ
  - 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 = $(dE/dx)_{\text{10nm from track}}$