

AITANA

Electrically charged (meta)stable particles in MoEDAL

Vasiliki A. Mitsou

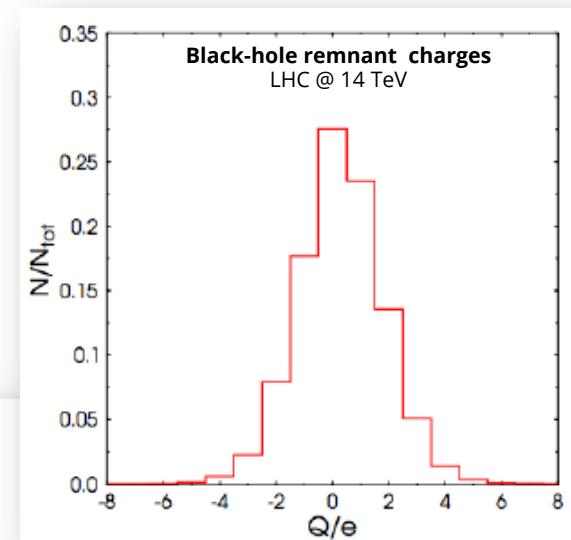
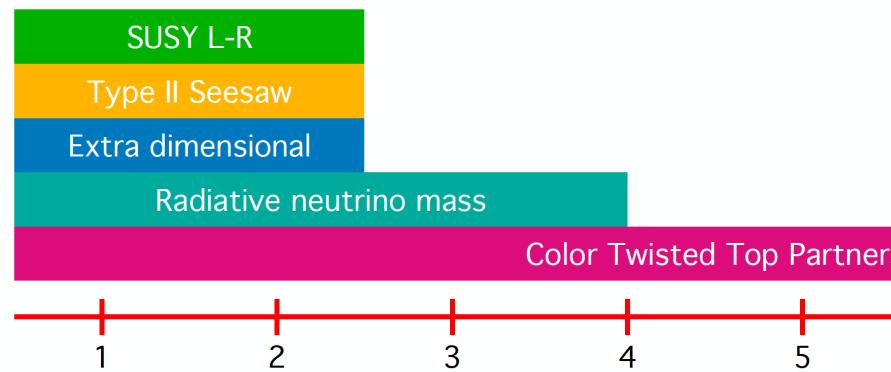
SUSY-2022

29th International Conference on Supersymmetry and
Unification of Fundamental Interactions

27 June – 2 July 2022, Ioannina, Greece

Multiply charged quasi-stable particles

- Highly Electrically Charged Objects (HECOs) predicted in many scenarios of physics beyond the SM
 - finite-sized objects (Q-balls)
 - condensed states (strangelets)
 - microscopic black holes (through their remnants)
 - ...
- They eventually decay into other particles
- Detected by **high ionisation**



High ionisation

Highly ionising particles (HIPs) characterised by one or both of these properties:

- high charges (**high z**) ⇒ electric and/or magnetic charges
- slow moving (**low β**) ⇒ massive particles

Bethe-Bloch formula

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

Figure of merit for large energy loss: **z/β**

MoEDAL detector optimised for HIP discovery with a detection threshold as low as **$z/\beta = 5$**

MoEDAL – Monopole & Exotics Detector At LHC

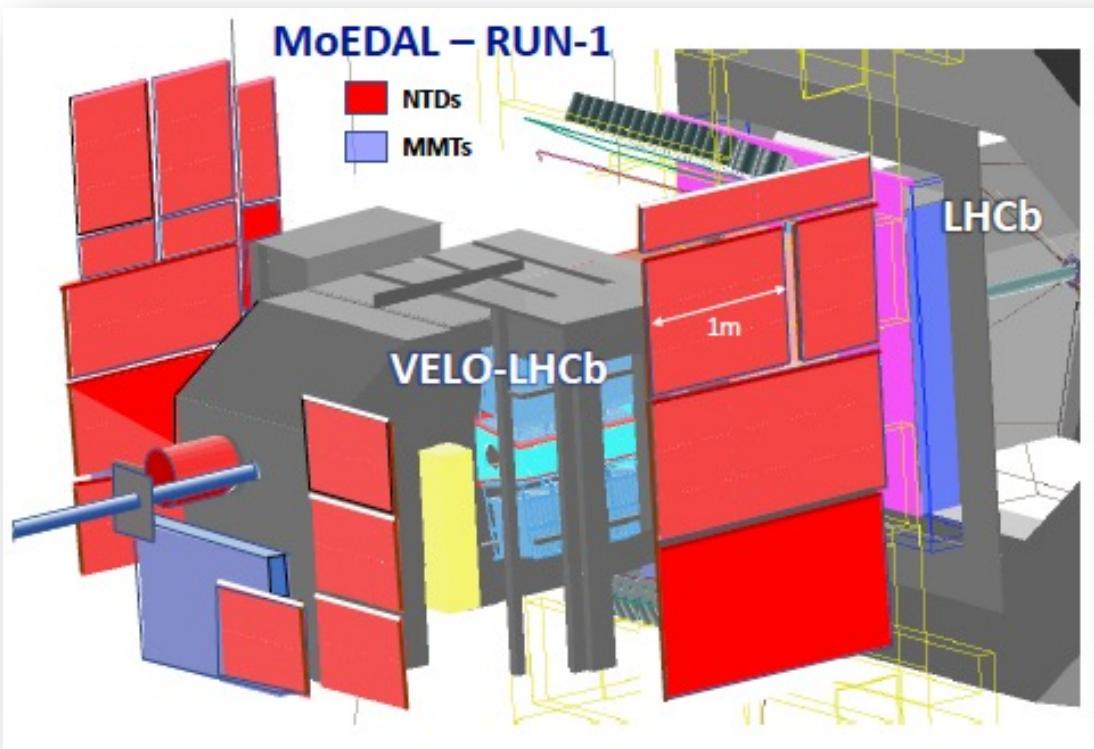


MoEDAL

LHC's first dedicated
search experiment
(approved 2010)

More on MoEDAL in VAM's talk
on Friday

MoEDAL detector



MoEDAL, [arXiv:2112.05806](https://arxiv.org/abs/2112.05806) [hep-ex]

DETECTOR TECHNOLOGIES

- ① Nuclear Track Detectors (**NTD**)
- ② Monopole Trapping detector (**MMT**) – aluminum bars
- ③ **TimePix** radiation background monitor

- Mostly **passive detectors**; no trigger; no readout
- Permanent physical record of new physics
- No Standard Model physics backgrounds

NTD+MMT search for HECOs & monopoles

- MoEDAL exposed to 2.2 fb^{-1} of pp collisions at 8 TeV
- **First MoEDAL NTD analysis**
- **First constraints on multiply charged particles by MoEDAL**
- [arXiv:2112.05806](#) [hep-ex]

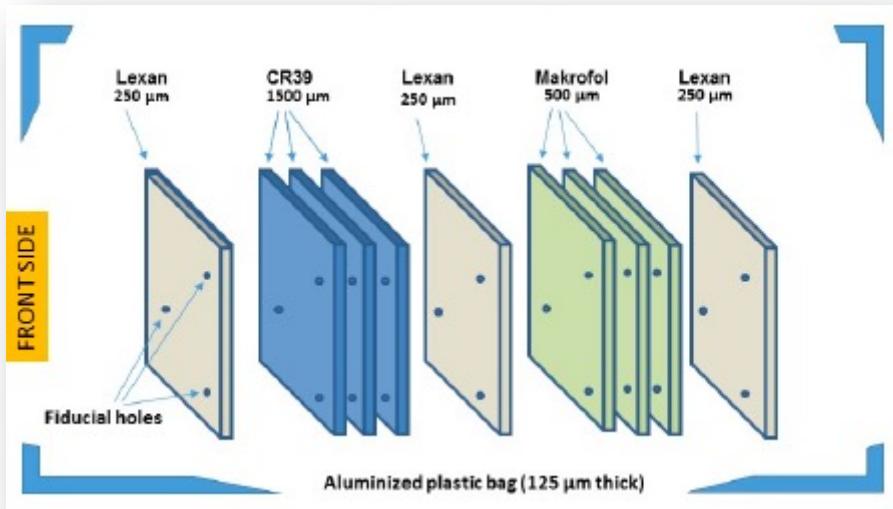


NTD+MMT search for HECOs and monopoles



Prototype NTD array of $125 \times 25 \text{ cm} \times 25 \text{ cm}$ stacks (7.8 m^2)

- 3 layers of CR39® polymer → low threshold $z/\theta \sim 5 \Rightarrow$ time intensive analysis
- 3 layers of Makrofol DE® ~~→~~ used in analysis (less “visual noise”);
threshold $z/\theta \sim 50$
- 3 layers of Lexan® → protective layers only



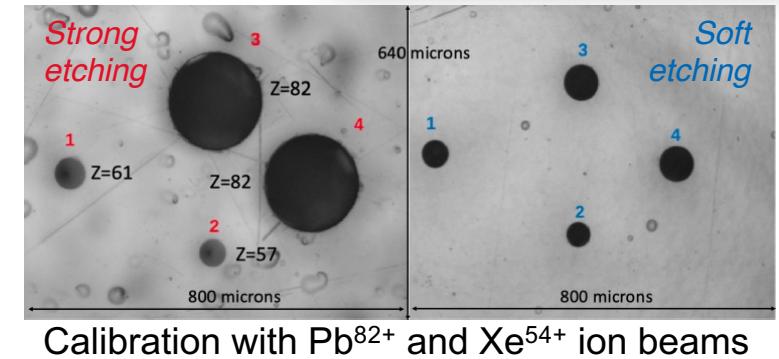
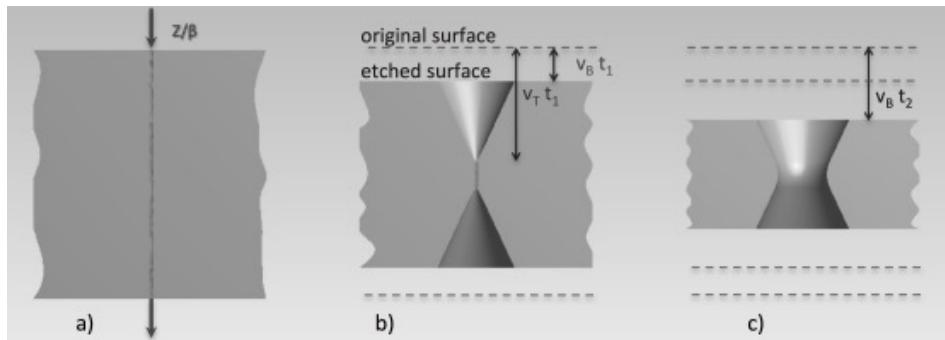
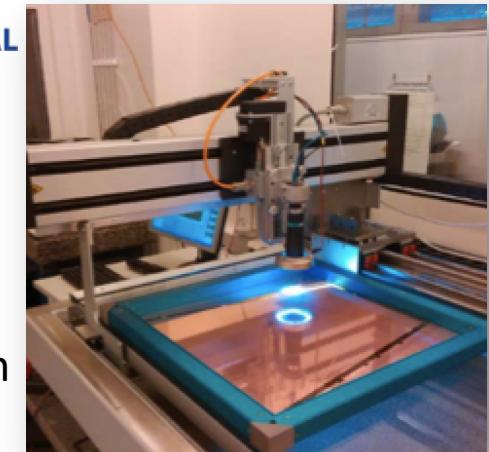
NTDs sheets kept in boxes mounted onto LHCb VELO alcove walls





NTD analysis

- Passage of HIP through plastic NTD marked by *invisible* damage zone (“**latent track**”) along the trajectory
- Damage zone revealed as a **cone-shaped etch-pit** when plastic sheet **chemically etched** → in ethyl alcohol solution in INFN Bologna
- NTDs **scanned** to detect etch-pits with automatic scanning system
- Scanning efficiency for detection above threshold is **>99%**

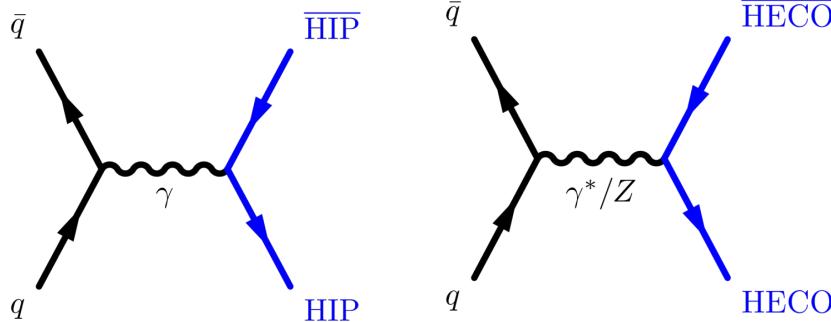


No candidates were found in the stacks examined

MoEDAL, [arXiv:2112.05806 \[hep-ex\]](https://arxiv.org/abs/2112.05806)

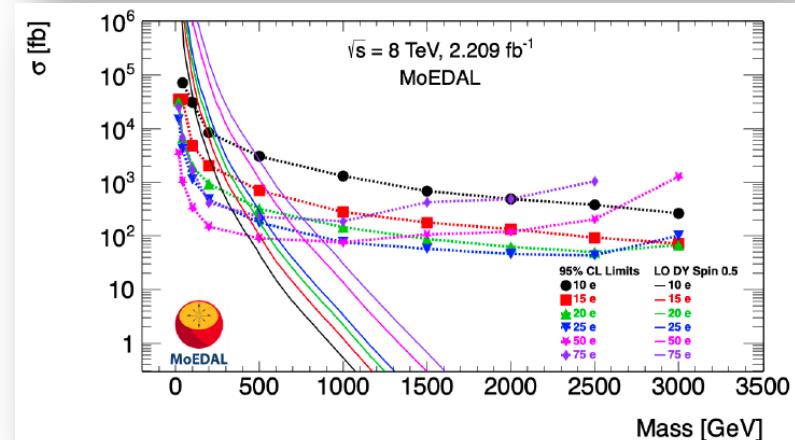
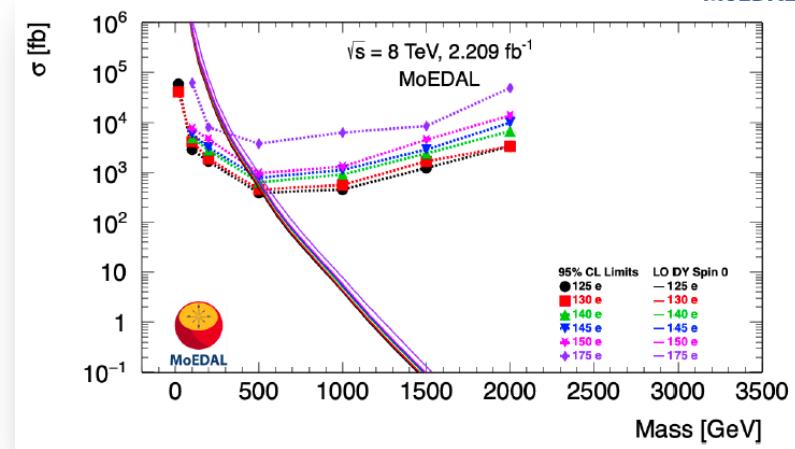
NTD results on HECOs

- Drell-Yan production
 - Z exchange is also taken into account for fermions [Song & Taylor, [J.Phys.G 49 \(2022\) 045002](#)]



- non-perturbativity of large coupling can be tackled by appropriate resummation [Alexandre, Mavromatos, *in progress*]
- Limits set on HECO pairs with cross-sections from **$\sim 30 - 70 \text{ pb}$**

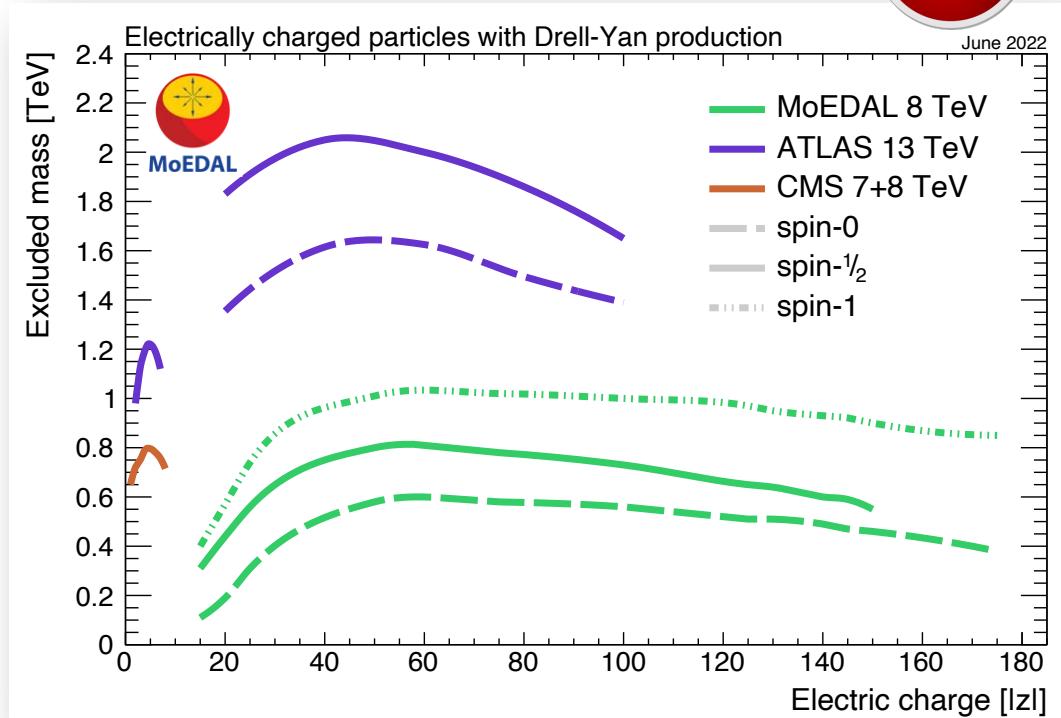
MoEDAL, [arXiv:2112.05806](#) [hep-ex]





HECOs summary

- MoEDAL set limits on HECOs with electric charges in the range **$15e - 175e$** and masses from **$110 - 1020 \text{ GeV}$**
- Better sensitivity expected in ongoing **Run 2 analysis**
 - higher c.m.s. energy: 13 TeV
 - larger integrated luminosity
 - larger exposed NTD surface
 - lower CR39 Z/β threshold (5) than Macrofol (50)

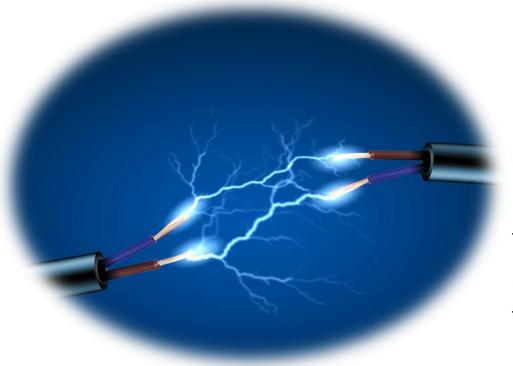


Only published ATLAS/CMS results shown

MoEDAL HECOs limits are the strongest to date, in terms of charge, at any collider experiment

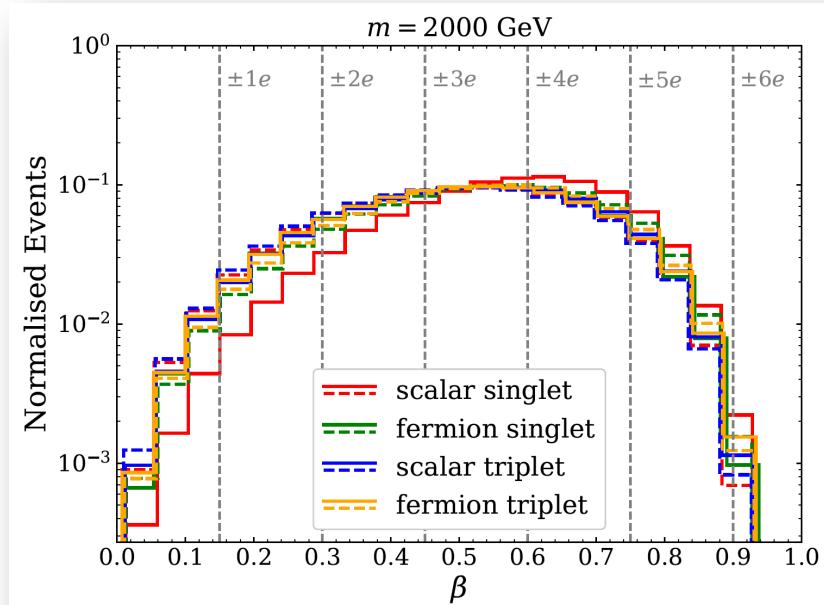
Prospects for 'low' electric charges

- Supersymmetric long-lived particles
- Charges $\sim 1e - 10e$



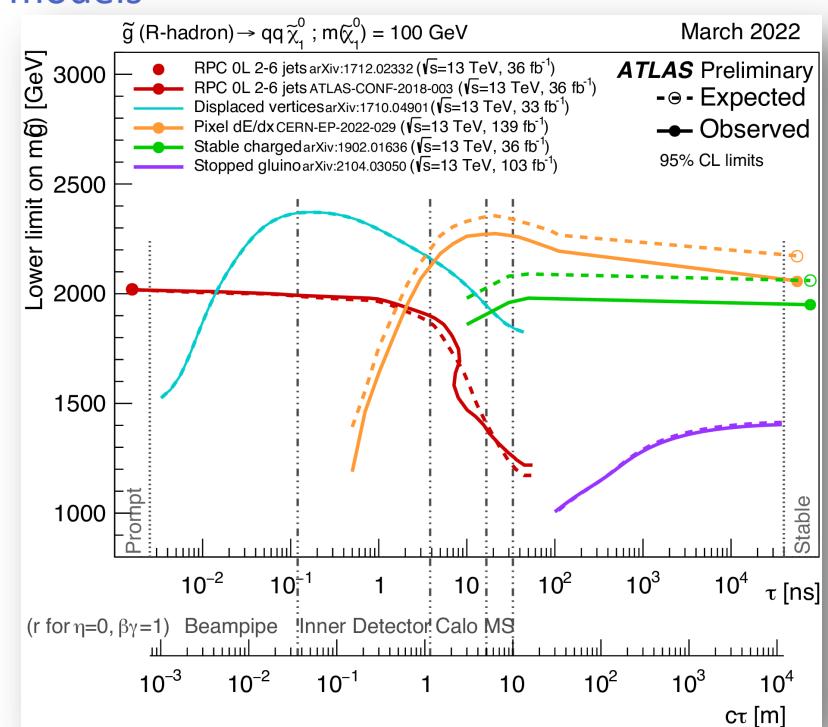
HIP kinematics

- MoEDAL NTDs sensitive to highly ionising particles with velocities $\beta < 0.15 |Q|$
 - if sufficiently slow moving, even low charges may be detected
- Assumed to be “detector-stable”, i.e. they decay after passing the whole detector volume
- MoEDAL is background-free experiment
→ discovery scenarios require **1, 2 or 3 signal events (N_{sig})**
- Integrated luminosities at IP8 (LHCb/MoEDAL)
 - Run-3 → 30 fb^{-1}
 - High Luminosity LHC (HL-LHC) → 300 fb^{-1}
 - roughly 10 times less than ATLAS & CMS



Long-lived SUSY partners

- Supersymmetric charged long-lived states: **sleptons, R-hadrons, charginos**
 - plus **doubly charged higgsinos** in *L-R* symmetric models
- ATLAS & CMS have constrained these spartners. Analyses limited by:
 - trigger requirements
 - offline selections to suppress SM backgrounds
 - timing: signal from slow-moving particles to arrive within correct bunch crossings
- Due to absence of **trigger, timing and SM backgrounds**, MoEDAL can *relax* selection requirements and increase sensitivity to charged long-lived SUSY particles

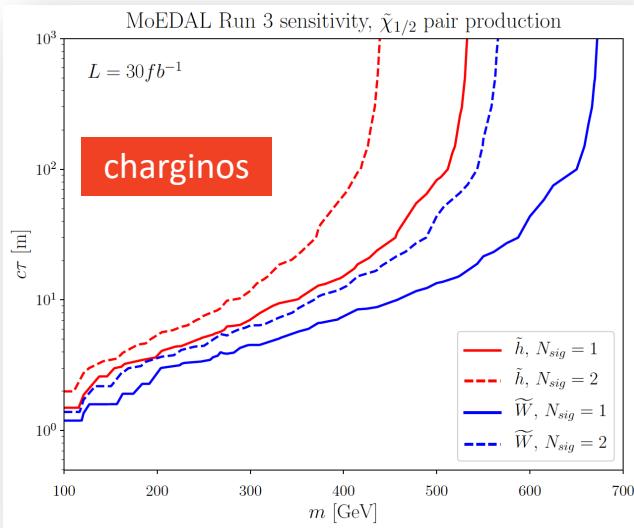


See Dev Panchal's talk on Monday

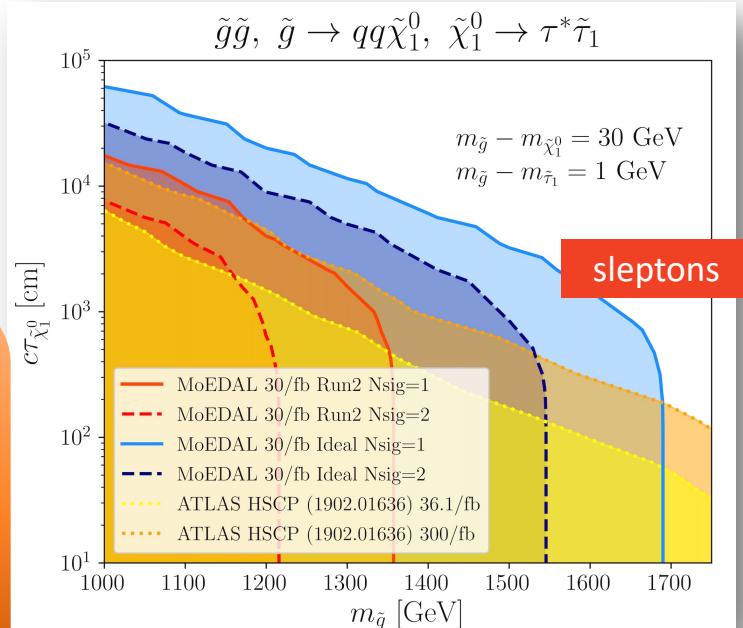
Long-lived SUSY partners in MoEDAL

- Benchmark decay chain: $\tilde{g}\tilde{g}$ production with $\tilde{g} \rightarrow jj\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \rightarrow \tau^\pm\tilde{\tau}_1$
 - $\tilde{\chi}_1^0$ moderately long-lived \rightarrow decays in tracker
 - $\tilde{\tau}_1$ charged long-lived \rightarrow interacts with detector
- Other decay chains studied too:
 $\tilde{g} \rightarrow jj\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \rightarrow \pi^\pm\tilde{\tau}_1$ & $\tilde{g} \rightarrow jj\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm \rightarrow \nu_\tau\tilde{\tau}_1$

Acharya *et al.*, EPJC 80 (2020) 572



MoEDAL can cover long-lifetime region in Run 3 for gluinos, stops, sleptons and charginos



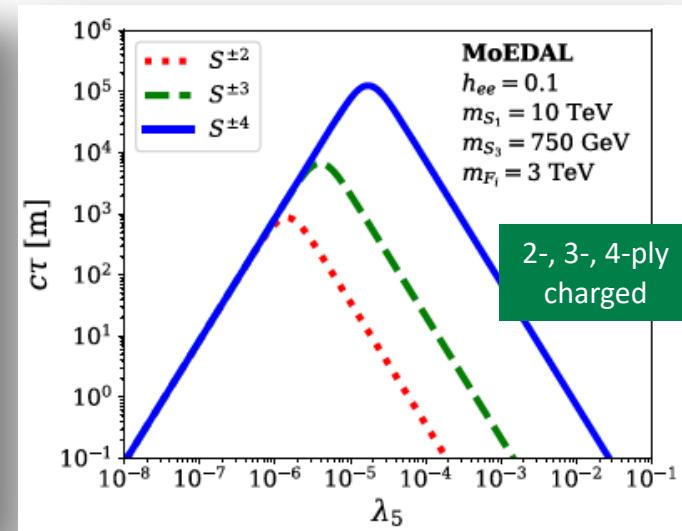
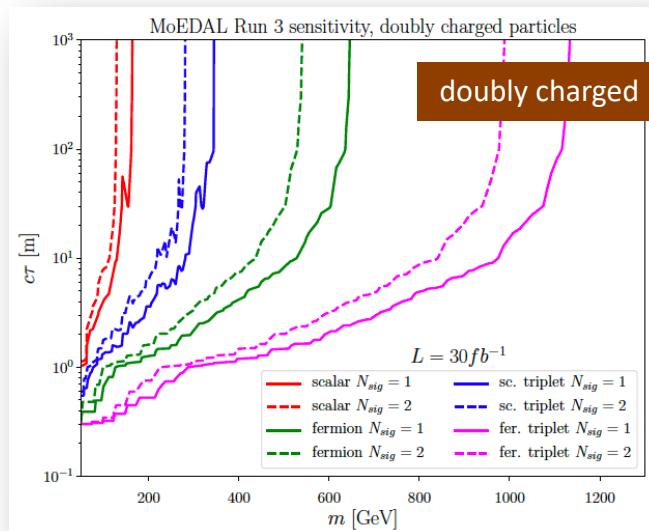
Feleă, VAM *et al.*, EPJC 80 (2020) 431

Study comparing MoEDAL vs. CMS:
Sakurai, VAM *et al.*, J.Phys.Conf.Series 1586 (2020) 012018

Multiply charged particles – model-specific

- Doubly charged particles
 - Predicted in left-right symmetric models, seesaw neutrino models, little Higgs models, ... (+ SUSY extensions), extra dimensions, ...
 - models considered: (scalar, fermion) \times ($SU(2)$: singlet, triplet)
- 2-, 3-, 4-ply charged states occur in some radiative neutrino mass models
 - long-lived due to small neutrino mass and high electric charge

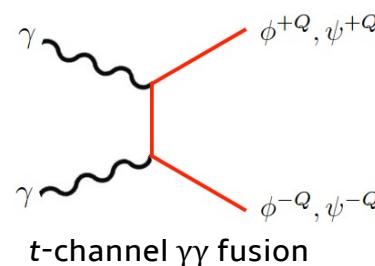
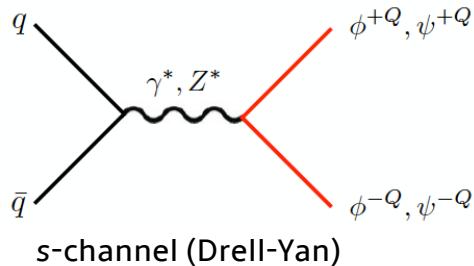
MoEDAL can cover long-lifetime region in Run 3 and HL-LHC



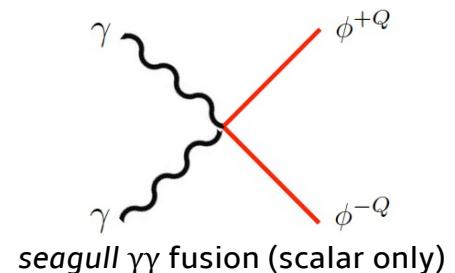
Multiply charged particles – generic case



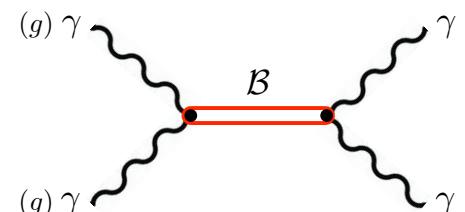
- Phenomenological study independent of underlying model
- Includes all production processes, including those with photons
 - most experimental searches only assume Drell-Yan
 - for high charges, photon contributions become very relevant



SU(2) singlet	color singlet	color triplet
spin 0	colorless scalar	colored scalar
spin 1/2	colorless fermion	colored fermion

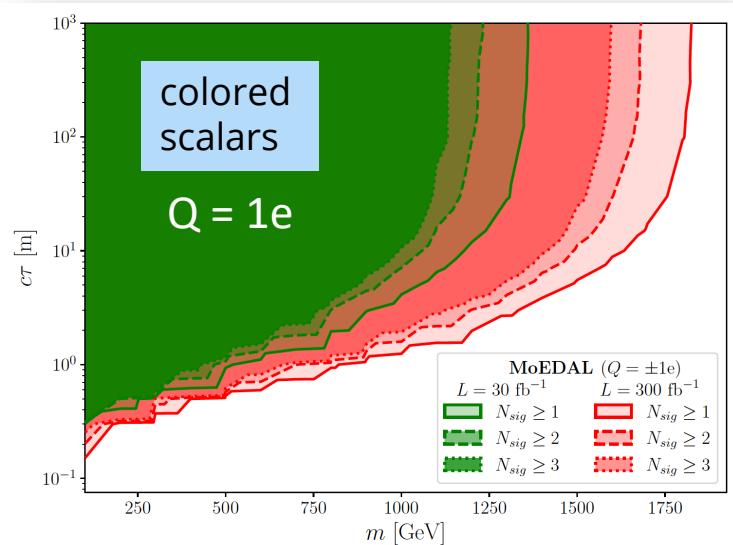


- Production of a bound state is considered
 - constrained by ATLAS and CMS searches for diphoton events
 - not relevant for MoEDAL



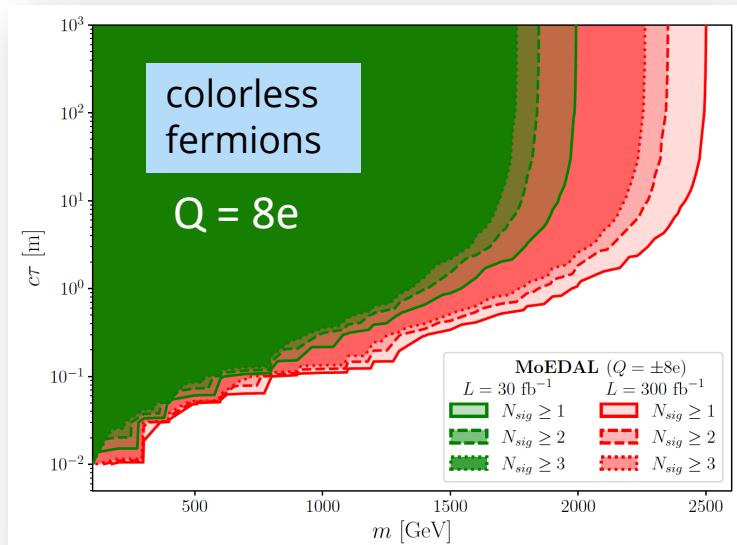
MoEDAL reach

- Singly charged colorless scalars only observable at HL-LHC
- MoEDAL sensitivity to colored scalars similar to colored fermions
- For high charges up to $8e$ good sensitivity expected from MoEDAL even in Run 3



Run 3
Masses up to
2 TeV can be
probed

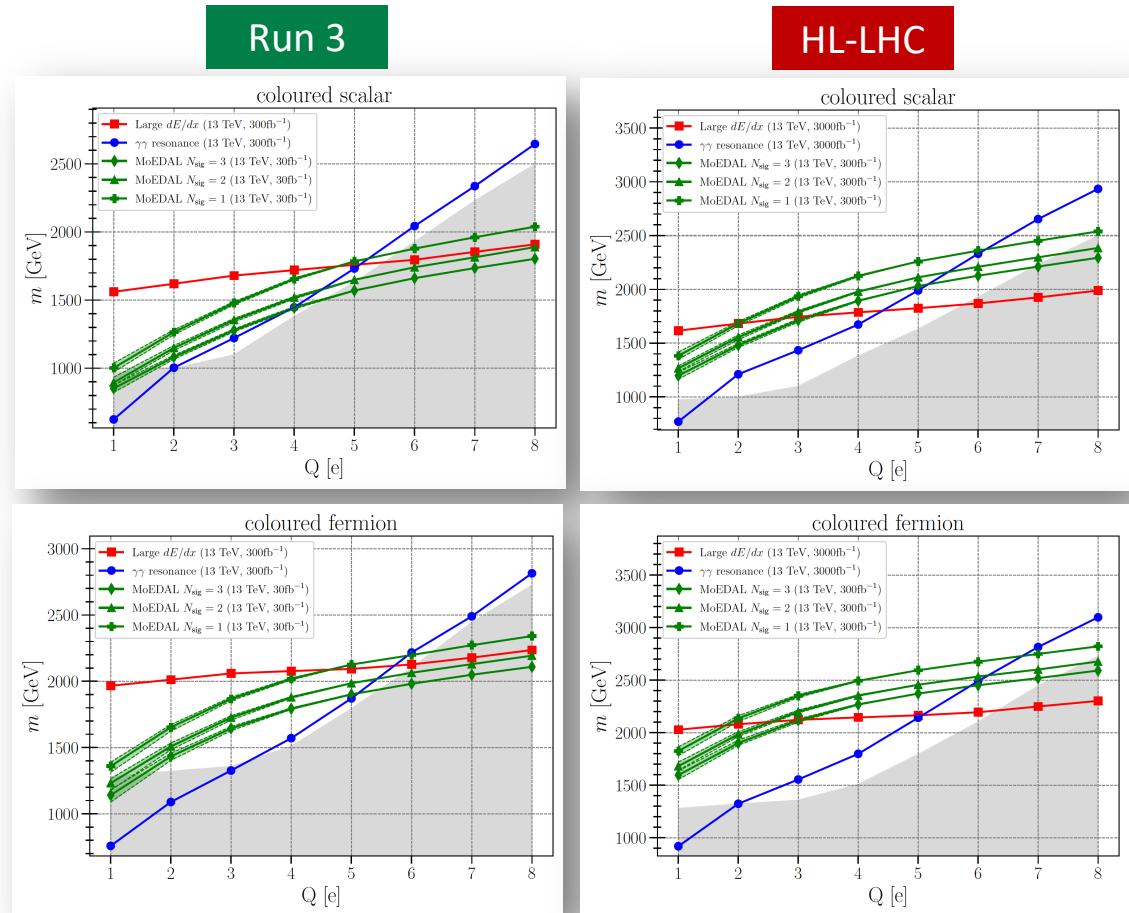
HL-LHC
Masses up to
2.5 TeV can be
probed



MoEDAL vs. ATLAS/CMS

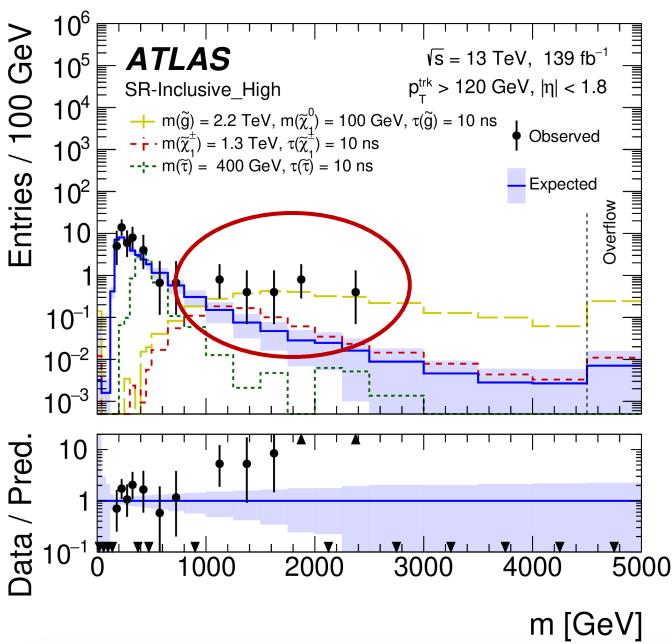
- Grey region excluded by ATLAS/CMS Run 1 / Run 2 searches
- ATLAS/CMS direct detection based on searches for **large dE/dx** → better sensitivity at **low charges**
- ATLAS/CMS searches for **diphoton resonances** offer better coverage at **high charges**
- **MoEDAL has the best sensitivity at intermediate electric charges at HL-LHC**

Altakach, Lamba, Masełek, VAM,
Sakurai, [2204.03667](https://arxiv.org/abs/2204.03667) [hep-ph]



For inspiration...

ATLAS, arXiv:2205.06013 [hep-ex]



- **3.3 σ excess with large dE/dx observed by ATLAS**
- **β measured in calorimeter & muon spectrometer too large for measured dE/dx**
- **Charge $z > 1$?**

1.5 σ ($p_0 = 0.06$) excess for $Q = 2$ observed by ATLAS (preliminary) in dE/dx multi-detector analysis

Selection	N_{data}^A observed	N_{data}^B observed	N_{data}^C observed	N_{data}^D expected	N_{data}^D observed
$z = 2$	24 294	4039	9	$1.5 \pm 0.5 \text{ (stat.)} \pm 0.5 \text{ (syst.)}$	4
$z > 2$	192 036 934	15 004	441	$0.034 \pm 0.002 \text{ (stat.)} \pm 0.004 \text{ (syst.)}$	0

See talks by Jackson Burzynski on Monday and Leonardo Rossi on Friday

ATLAS-CONF-2022-034

Summary & outlook

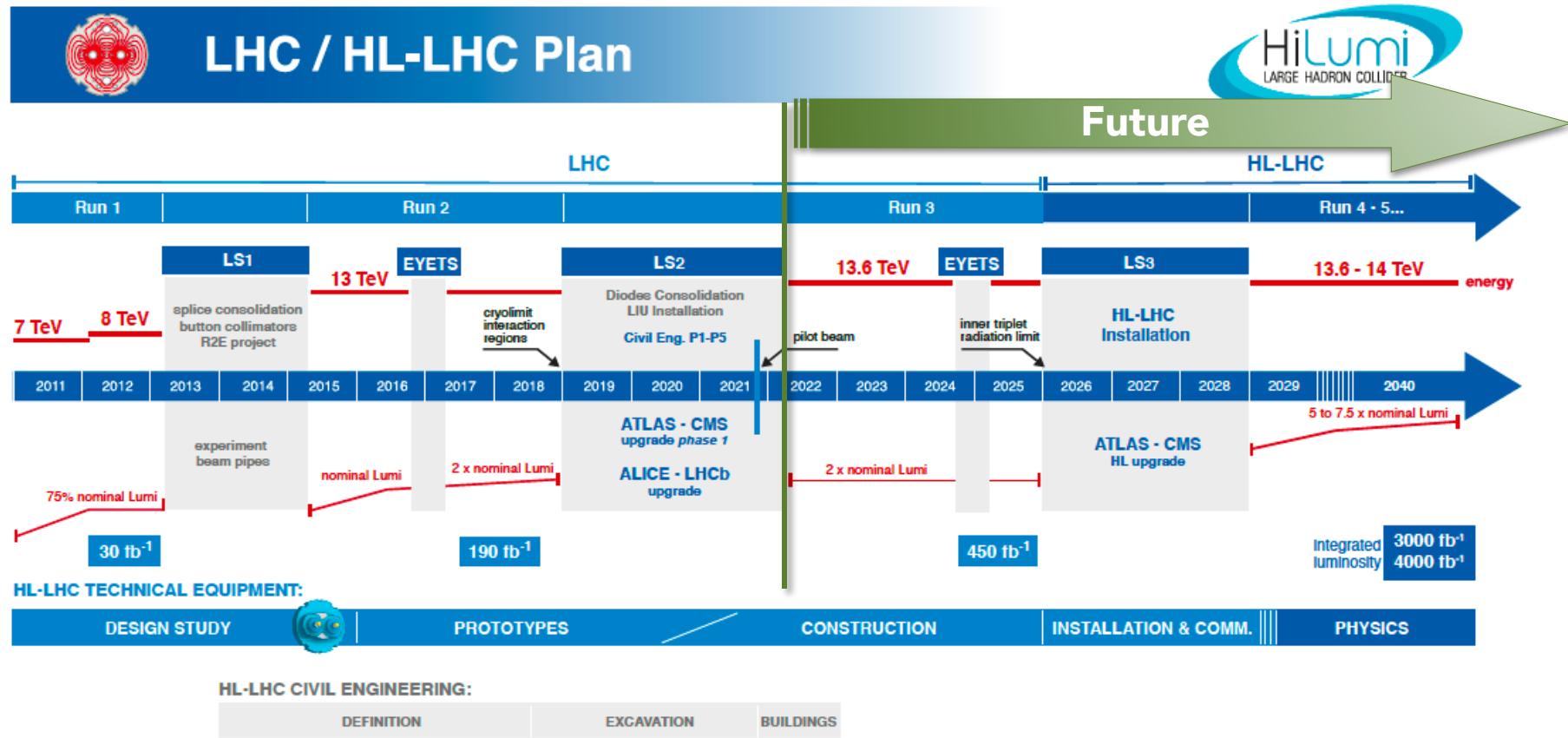
- Particles of high electric charges predicted in various scenarios of New Physics
- Supersymmetry provides such (mostly singly charged) long-lived particles
- MoEDAL just entered the arena of ***electrically charged particles***
 - other experiments have constrained such states
- Several studies showed very promising prospects for MoEDAL to explore charges 1-8e in future runs
- Stay tuned for upcoming MoEDAL results!
 - Run-2 NTD analysis @ 13 TeV → improved sensitivity to electric charges
 - detectors redeployed for Run-3 and planned to operate during HL-LHC

Thank you for your attention!

Spares



LHC & High Luminosity LHC (HL-LHC)



NTD deployment

Low-threshold NTD

NTDs sheets kept in boxes mounted onto cavern walls



Low-threshold NTD

- Top of VELO cover
- Closest possible location to IP

HCC-NTD
Installed in LHCb
acceptance between RICH1
and Trigger Tracker



Monopole results

- 2016 – **First results @ 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** [Phys.Lett.B 782 \(2018\) 510–516](#) [arXiv:1712.09849]
 - spin-1 monopoles ← FIRST in colliders
 - β -dependent coupling
- 2019 – **MMT results** [Phys.Rev.Lett. 123 \(2019\) 021802](#) [arXiv:1903.08491]
 - photon fusion interpretation ← FIRST at LHC
- 2020 – **MMT search for Dyons** ← FIRST in colliders
[Phys.Rev.Lett. 126 \(2021\) 071801](#) [arXiv:2002.00861]
- 2021 – **Schwinger thermal production** ← FIRST
[Nature 602 \(2022\) 7895, 63](#) [arXiv:2106.11933]
- 2021 – **NTD & MMT combination** ← FIRST NTD analysis [arXiv:2112.05806](#)
 - First limits in highly electrically charged objects

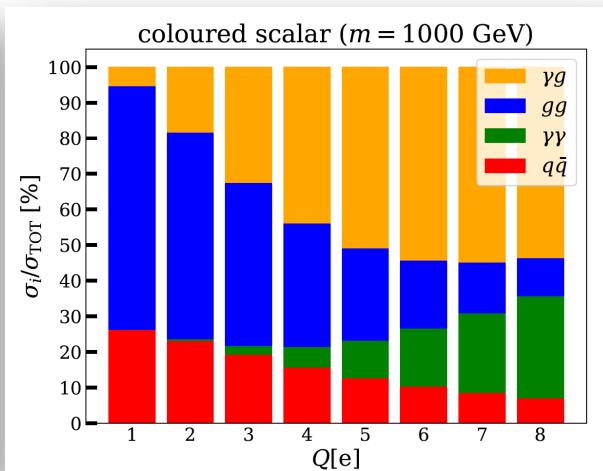
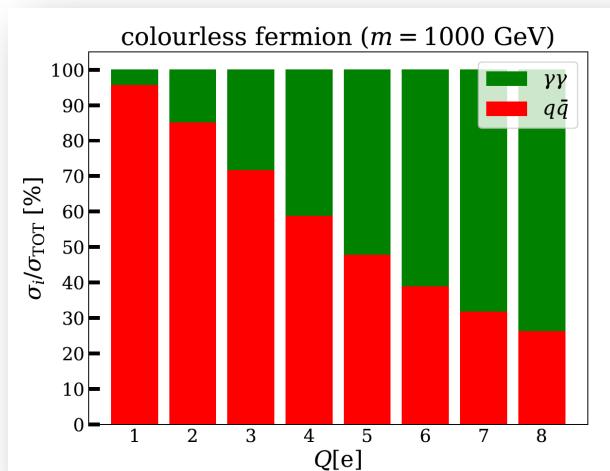




Electric charges – photon fusion

Study includes all production processes, including those involving **photons in initial state**

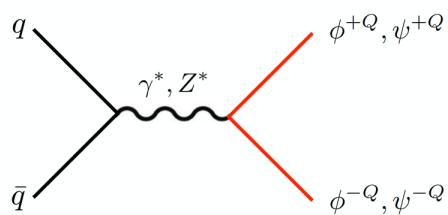
- most experimental searches only assume Drell-Yan
- for high charges, contribution from photon and photon-gluon fusion becomes very relevant



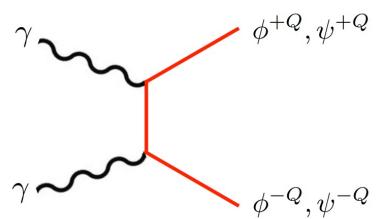
For $\gamma\gamma$ -fusion impact in monopoles, see: Baines, Mavromatos, VAM, Pinfold, Santra,
[Eur.Phys.J.C 78 \(2018\) 966](https://doi.org/10.1088/1475-7516/78/9/0966)

Electric charges – production diagrams

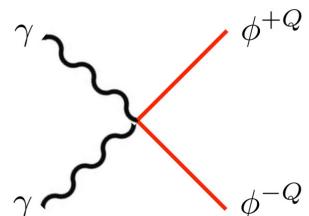
Color singlet/triplet



s-channels

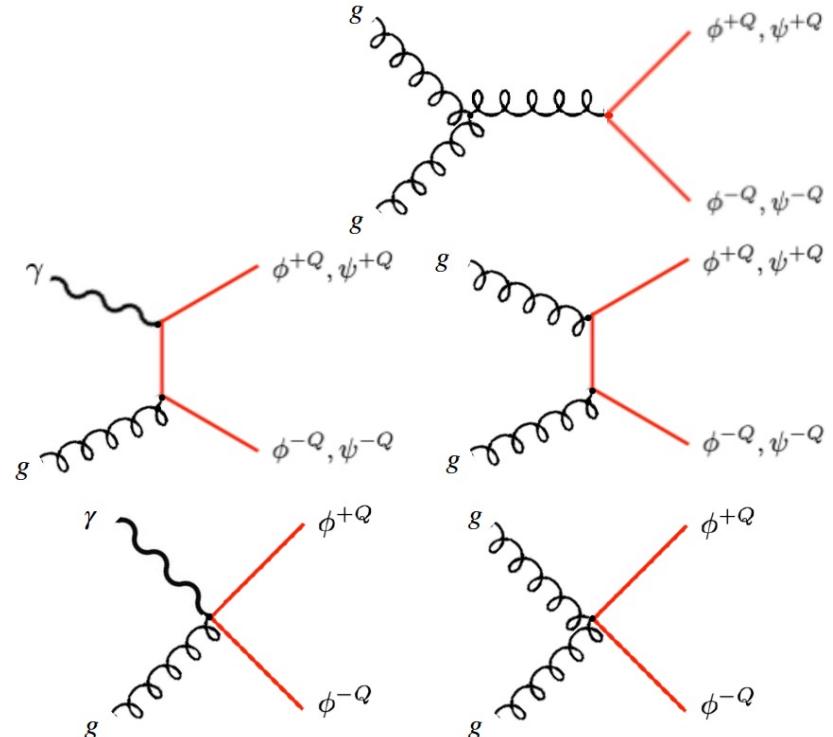


t-channels



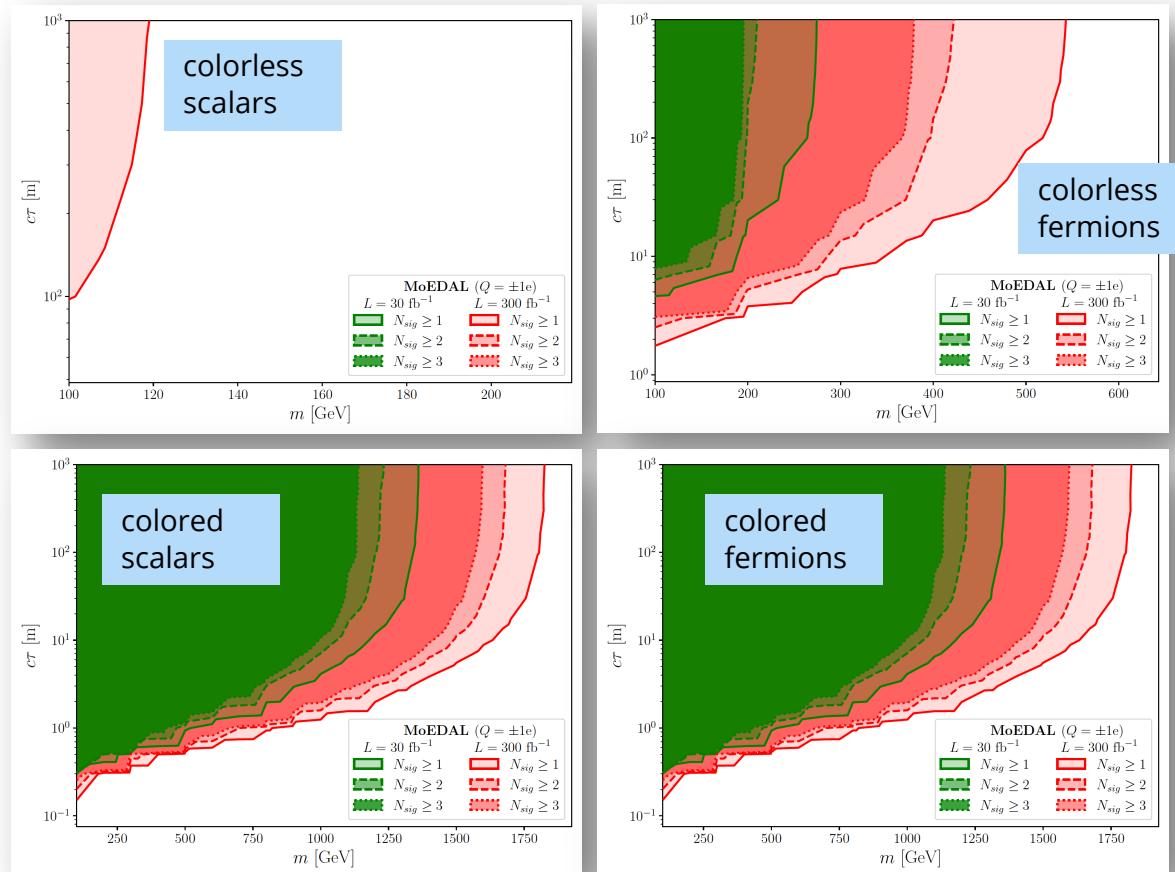
seagull diagrams
(scalars only)

Color triplet



Electric charges – MoEDAL reach for $Q = 1e$

- Singly charged colorless scalars only observable at HL-LHC with $N_{\text{sig}} = 1$
- Colorless fermions of mass $\lesssim 200$ GeV can be probed in Run 3
- MoEDAL sensitivity to colored scalars similar to colored fermions
- Sensitivity to color-triplets up to masses of **1200 GeV** (**1500 GeV**) in Run 3 (HL-LHC)



Altakach, Lamba, Maselek, VAM,
Sakurai, [2204.03667](https://arxiv.org/abs/2204.03667) [hep-ph]