Searching for Charged FIPs & HIPS at the LHC

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LHCP 2021

MENU

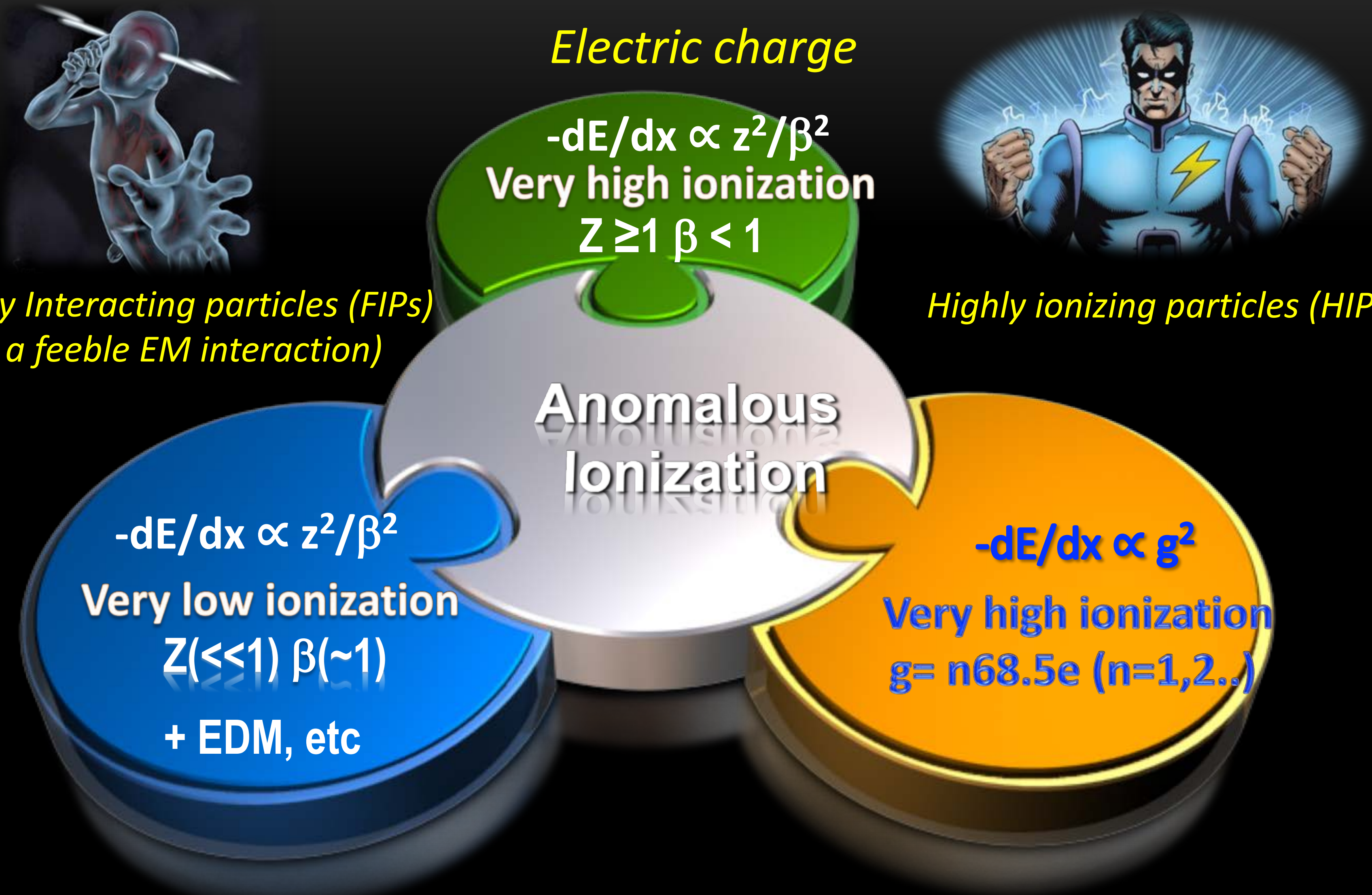
a) The Detectors Involved

b) HIPS (Highly Ionizing particles)

c) Charged FIPS (Feeble EM Interacting Particles)

d) Concluding remarks

Anomalously Ionizing Avatars of New Physics

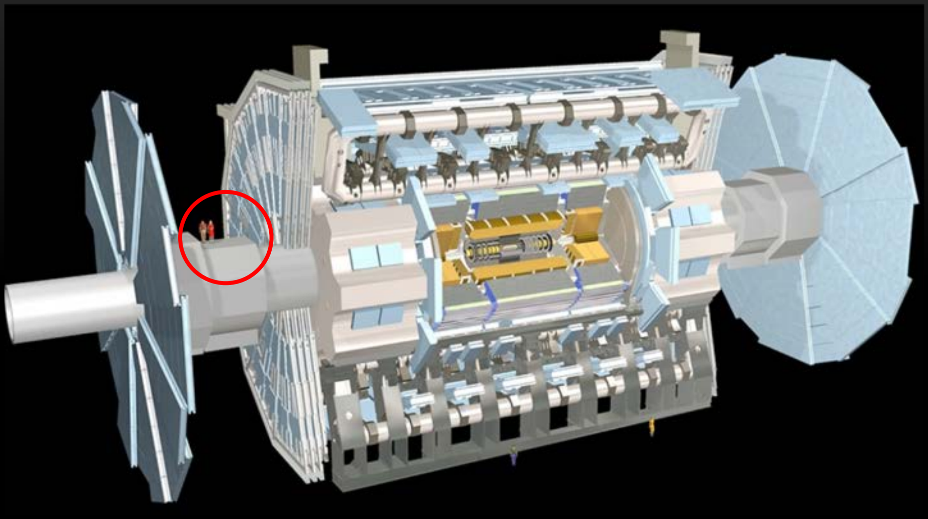


Fractional electric charge, EDM, etc

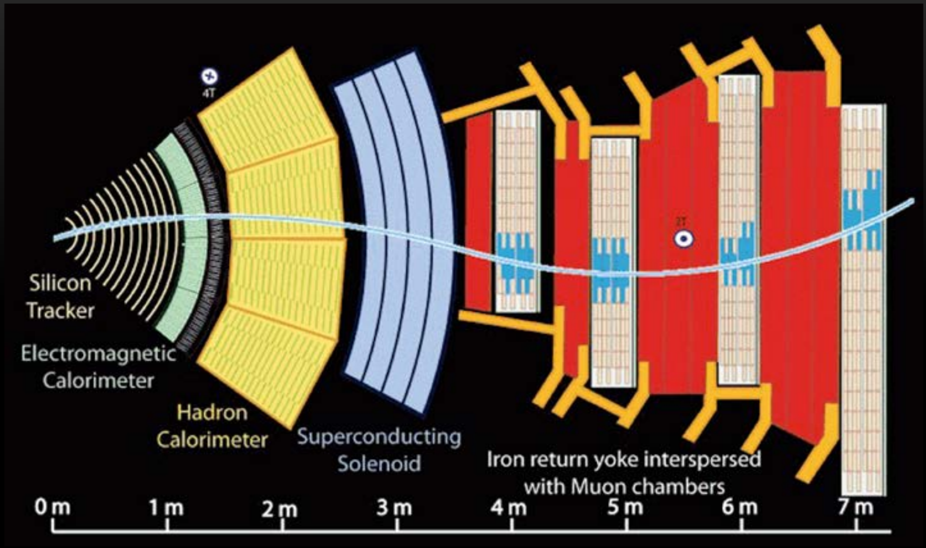
*Magnetic charge**

**The velocity dep. of the Lorentz force cancels $1/\beta^2$ term*

The General Purpose LHC Detectors



The ATLAS Detector



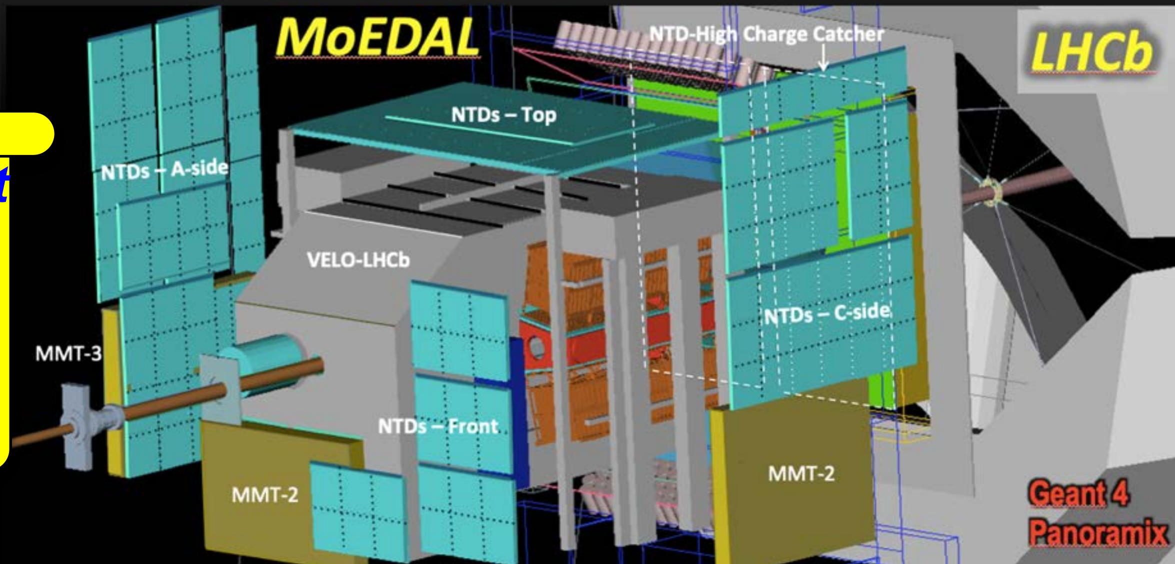
A section of the CMS detector

- ATLAS/CMS is 46/21 m long, 25/15 m in diameter, weighs ~7,000/14,000 tonnes with average density 0.3/3.0 g.cm^{-2}
  - *The two experiments share many basic design features eg the need for hermiticity and very selective triggering*
  - *The baseline physics process for both detectors was the detection and study of Higgs boson production through a number of decay channels.*
  - *Designed to: detect relativistic, single charged particles and EM neutrals; detect unstable particles with maximum lifetime (ct) < ofo metres; and, to measure missing energy*

The MoEDAL Detector at Run-2 and Run-3

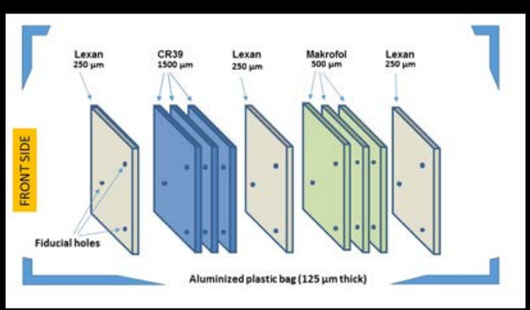
Started data taking in 2015– ***the LHC's first dedicated search experiment***

Permanent Physical record of new physics

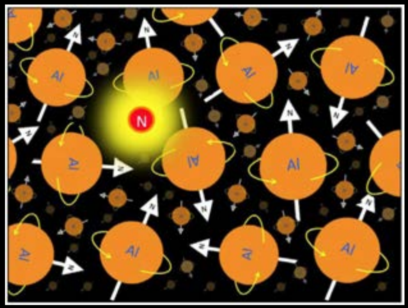


No Standard Model Physics Backgrnds

MoEDAL is made up of 3 detector system designed to search for HIPs.



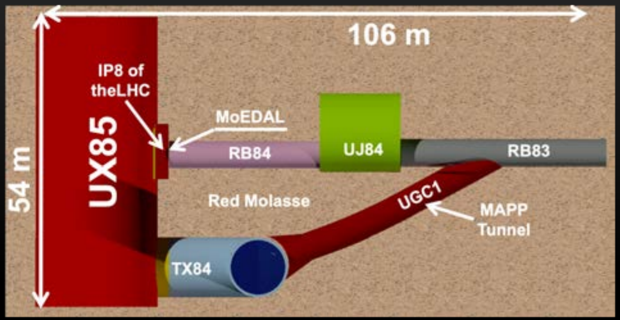
NUCLEAR TRACK DETECTOR
Plastic array (185 stacks, 12 m^2) – Like a big Camera

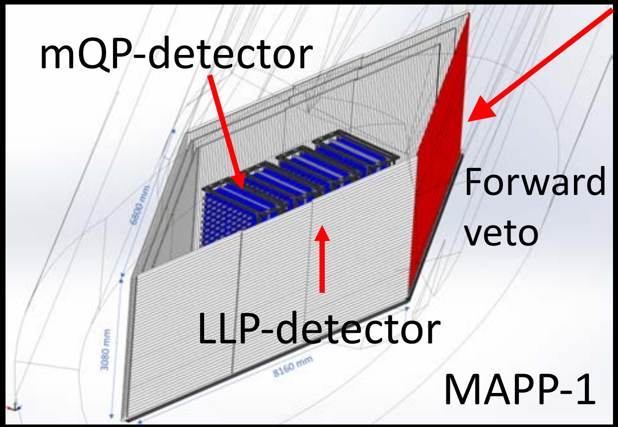


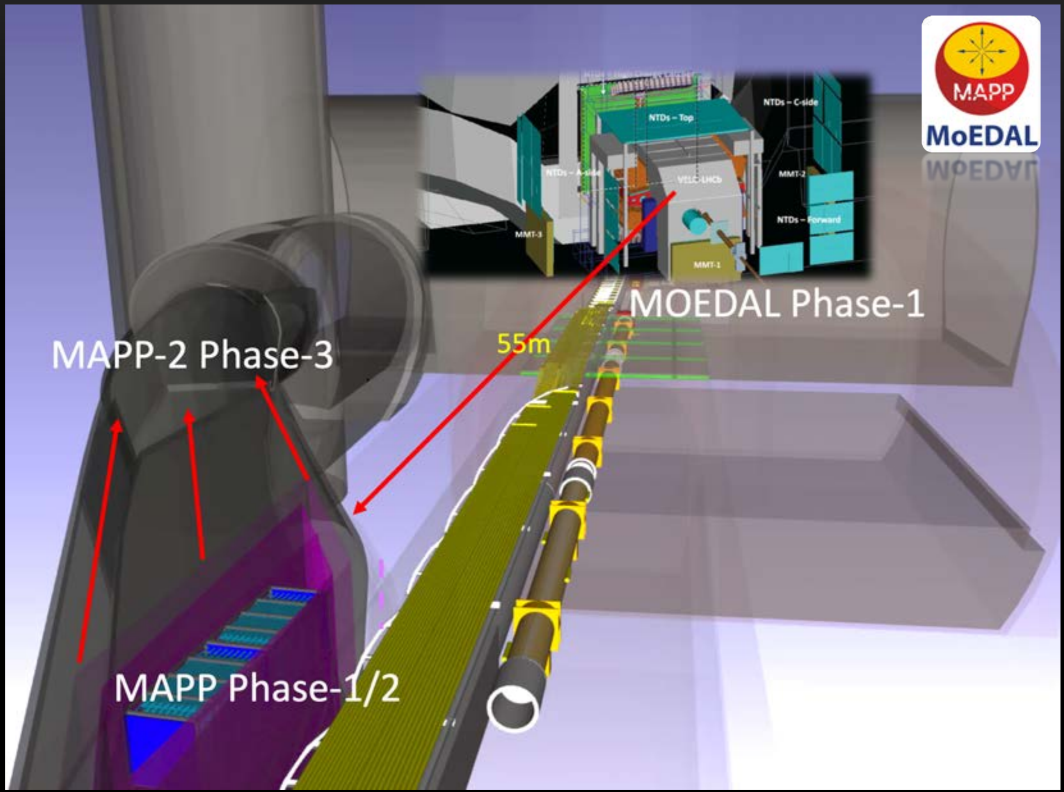
TRAPPING DETECTOR ARRAY
A tonne of Al to trap Highly Ionizing Particles for analysis

TIMEPIX Array a digital
Camera for real time radiation monitoring

The MoEDAL-MAPP Project



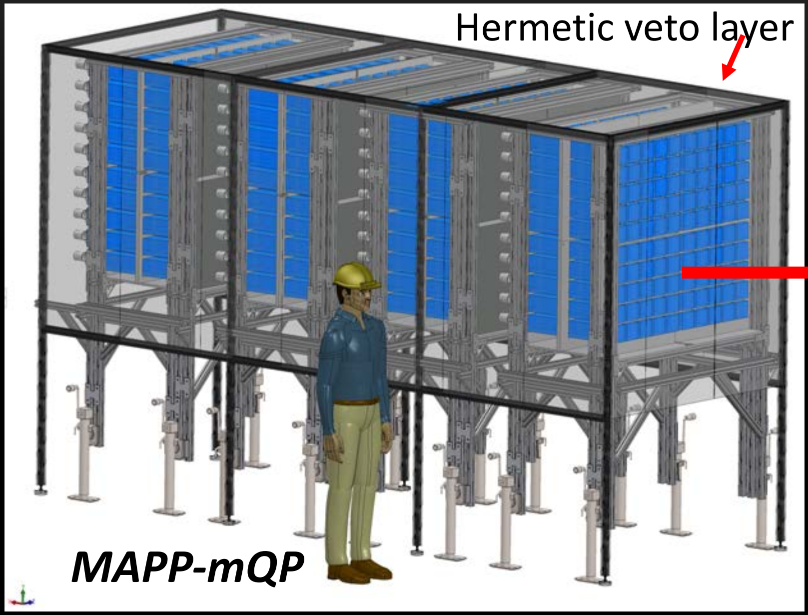


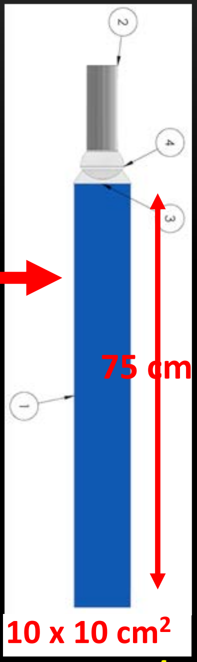


- *Phase-1 of MoEDAL-MAPP for Run-3 (TP submitted):*
  - *Redeploy MoEDAL detector   (Spring 2022)*
  - *Deploy MAPP-1 milli-charged particle detector (MAPP-mQP) (Spring 2023)*
- *Phase-2: Deploy MAPP-1 LLP detector (MAPP-LLP) for Run-4*
- *Phase-3 Deploy MAPP-2 extended LLP detector for Run-5*

Phase-1 MAPP-mQP for Run-3 (2023)

Currently under construction

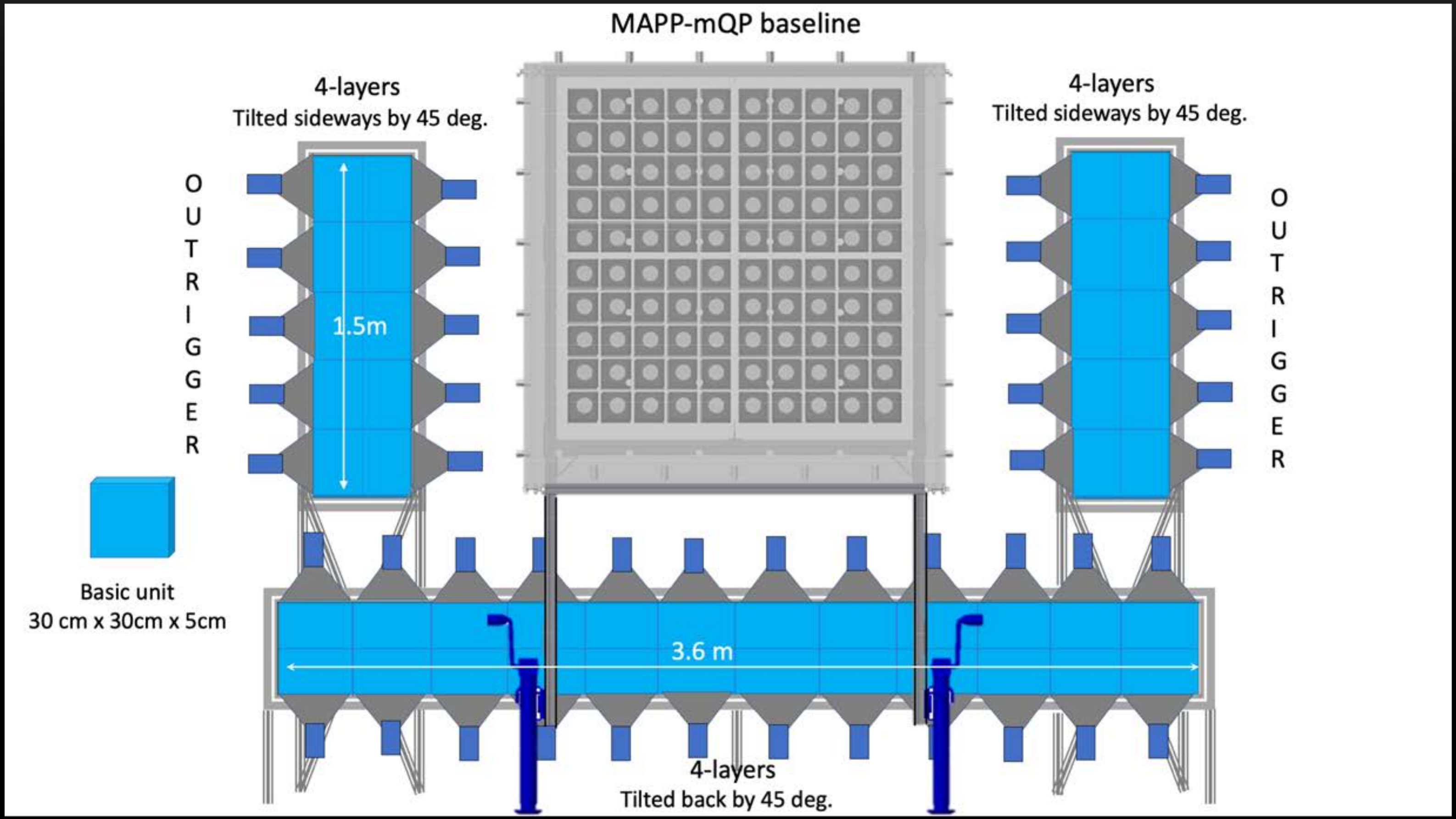




- *For Phase-1 at Run-3 MoEDAL with redeployed to continue the HIP search + the MAPP-mQP detector will be ready to quest for mQPs in 2023.*
  - *Deployed in the UGC1 gallery that is ~level with the floor of the LHC tunnel – thus support structure is ~horizontal - It weighs 4-5 tonnes with size ~1.5 X 2.5 x 4.0m^3*
  - *It is surrounded by a veto layer to help eliminate cosmic ray backgrounds.*
  - *Consists of 400 scint. bars (10x10x75 cm^3) in 4 sections readout by 400 low noise PMTs*
  - *Uses SW (FPGAs) trigger and is readout over the internet. It operates in a standalone mode in the UGC1 cavern*
  - *Calibration using blue LEDs (in each bar) + neutral density filter absolute calibration*

The MAPP-mQP Outrigger for Run-3

Currently under construction



- *Lower sensitivity to smaller fractional charges but much larger area: ~16m deployed in 4 layers*
- *Greater reach at larger fractional charges*

THE MILLIQAN EXPERIMENT

milliQan: A search for millicharged particles

milliQan demonstrator overview

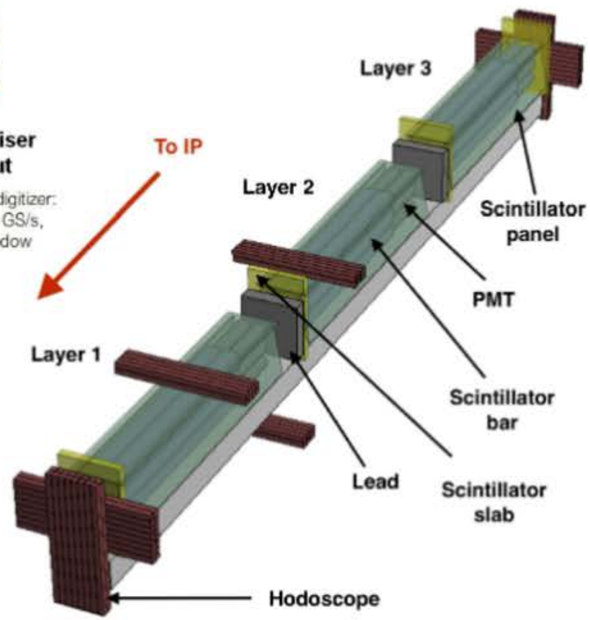
Proof of concept: We constructed a ~1% prototype of the full milliQan detector design: the **milliQan demonstrator**

Demonstrator is built from:

- 3x2 Scintillator + PMTs
- Scint + Pb slabs between layers, veto throughgoing background, radiation
- Scint panels surrounding each layer, identify cosmic muons
- All channels read out with high speed digitizer to enable triggering
    - Self trigger on 3 channels above 1 PE

dual digitiser readout

CAEN V1743 digitizer: 16 chan, 1.6 GS/s, 640 ns window



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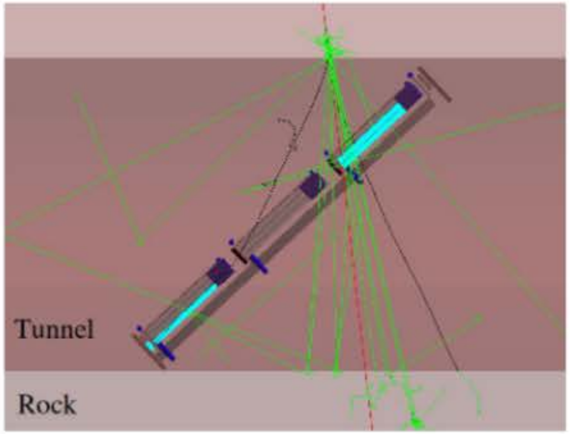
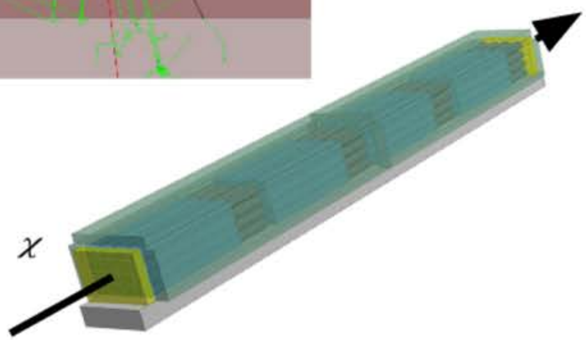
channels above 1 PE

Run-3 Plan for milliQan (1)

Run 3 milliQan bar detector design

- **Important lesson:** Cosmic muon shower secondaries form a significant background. **Four layers of scintillator bars are needed** to control background from cosmic ray showers
- **Expanded size of each layer** (2x3 --> 4x4 scintillator bars) to improve background rejection and increase signal acceptance. **Self shielding** becomes important the larger the detector becomes
- **Increased thickness of scintillator veto "panels/slab"** to 5cm for improved shower tagging
- **Dedicated signal amplification** to improve reconstruction of very low energy deposits. Means we can reuse PMTs, minimize cost!
- Make use of LED "flashers" and radioactive sources to **improve response and timing calibrations**





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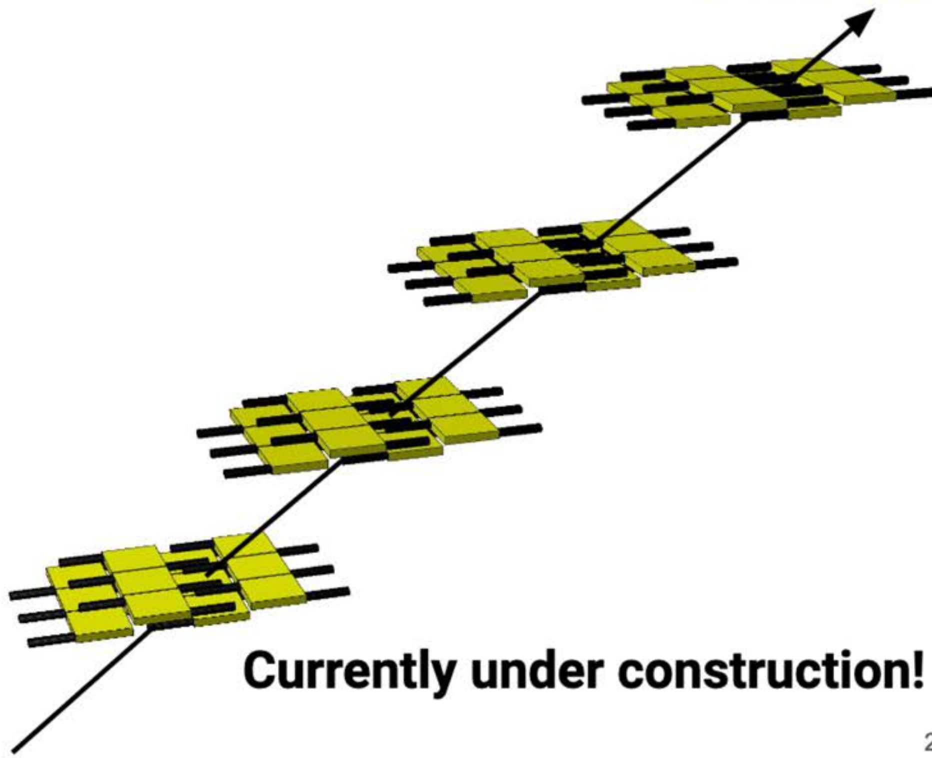
Run-3 Plan for milliQan (2)

Run 3 milliQan Slab Detector design

- Twelve 40x60x5cm slabs per layer, 4 layers. Design developed and studied extensively in full simulation
- Surface area equivalent to 1100 5x5cm bars, greater in acceptance than even the HL-LHC design
  - Attacks high-mass phase space in a very efficient, targeted way
- To extend charge sensitivity, using 2 PMTs per slab
- **Huge advantage:** Modularity! We can easily modify number of layers, number of PMTs, slabs per layer, etc. Not space-limited like with bars



Currently under construction!

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milliQan Beyond Run-3

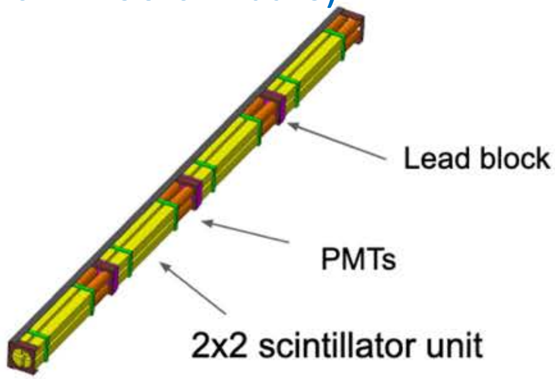
2027

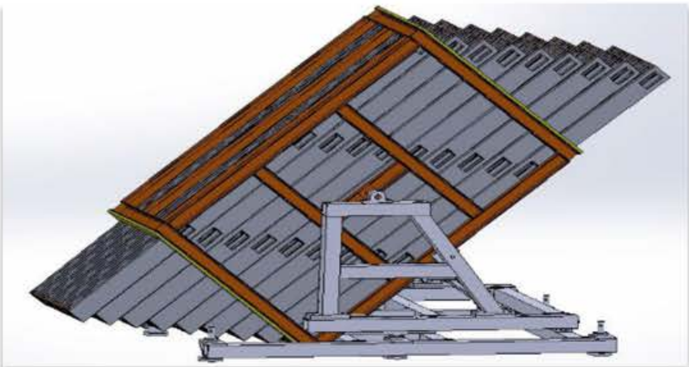
HL-LHC milliQan bar detector design

Beyond Run 3, we plan to expand the milliQan design to fill the entirety of the available space:

9 units x 6 units x (2x2 bars per unit) x 4 layer = 864 bars (1 x 1 x 3 m)

(5 cm x 5 cm x 60 cm bars)





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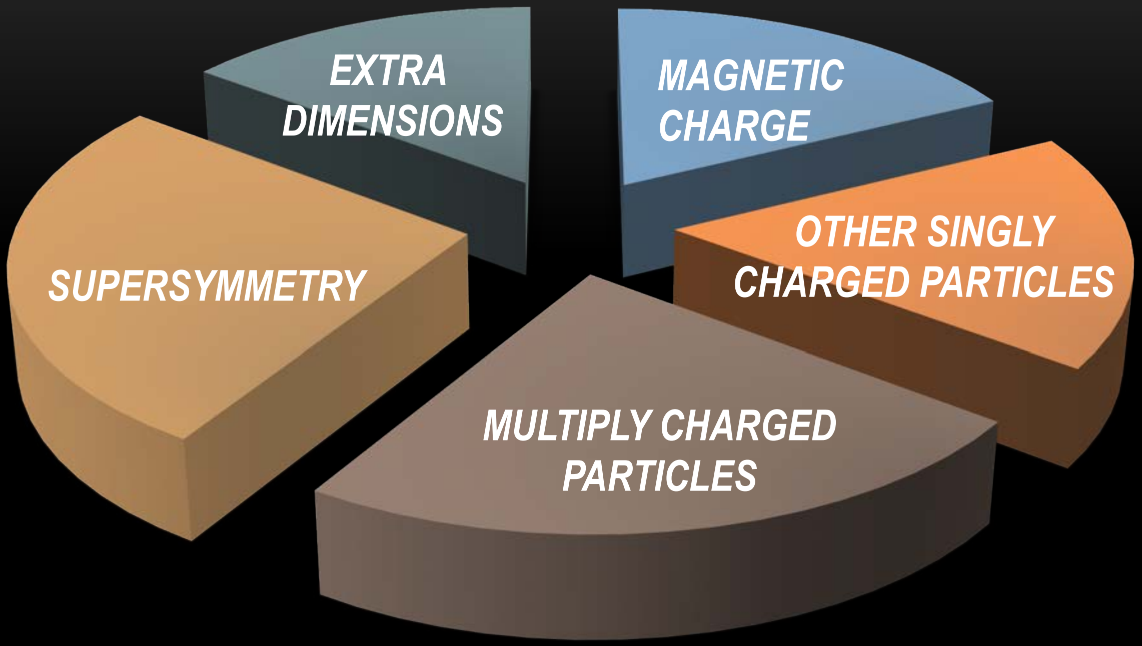
HIP Physics at the LHC

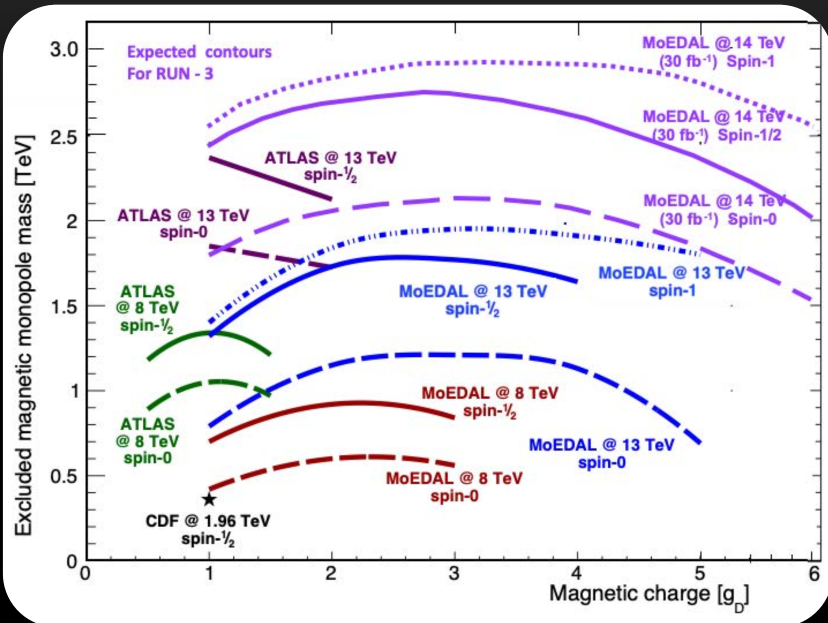


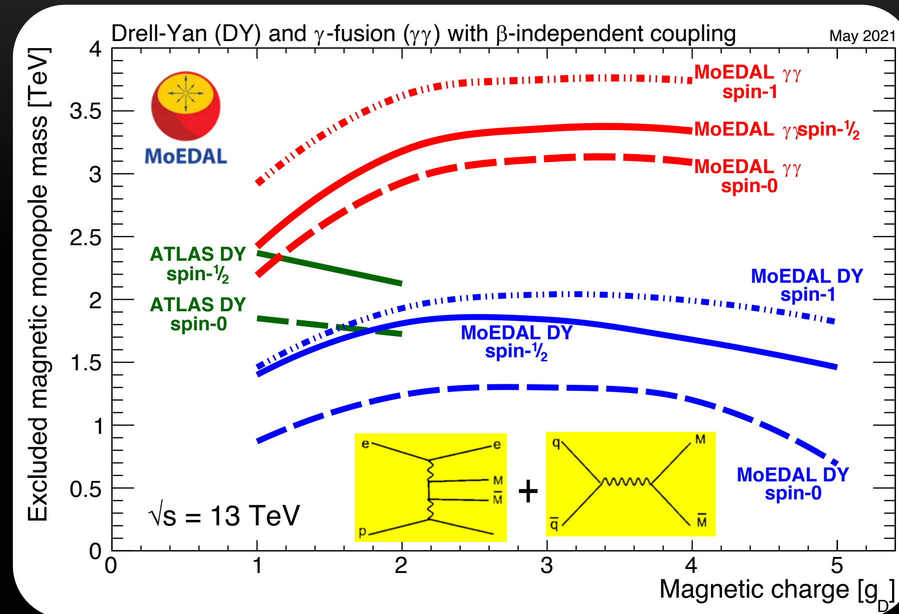
Highly ionizing particles (HIPs)

HIP physics accessible at the LHC summarized in: IJMPA, 2014, Vol. 29, No. 23

- *MAGNETIC CHARGE*
  - *Dyons/Monopoles*
  - *Electroweak Monopoles*
  - *Electroweak strings*
  - *Light t'Hooft-Polyakov monopoles*
  - *D-particles*
- *ELECTRICAL CHARGE*
  - *Q-balls & Strangelets*
  - *SUSY – eg massive sleptons, etc*
  - *Stable microscopic black holes & remnants*
  - *Doubly charged Higgs (LR Sym. Models)*
  - *Multiply charged exotic states, etc*

Mass Limits on Multiply Charged Monopoles

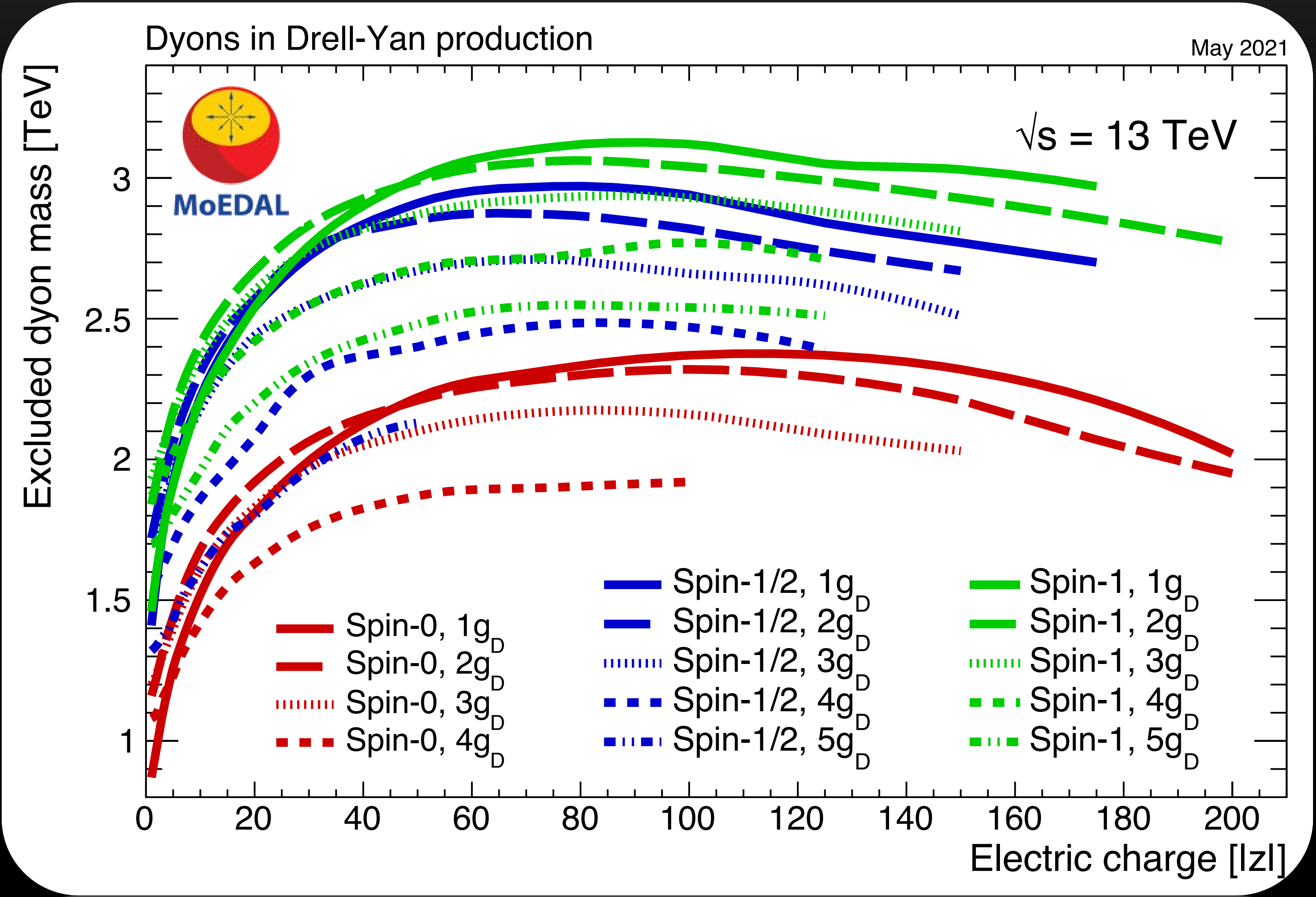




JHEP 1608 (2016) 067 PRL 118 (2017) 061801 Phys.Lett. B782 (2018) 510 PRL 123 (2019) 021802

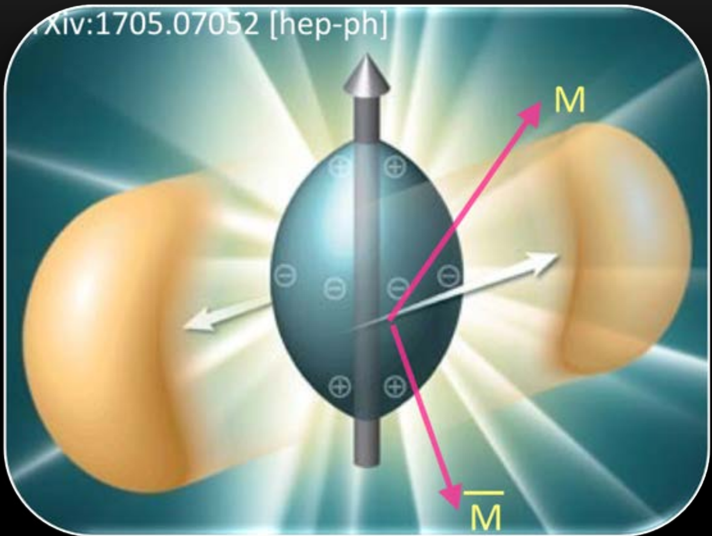
- *So far MoEDAL has placed the world's best published direct limits on:*
  - *Multiply charged magnetic monopoles*
  - *Spin-1 monopoles*
  - *DY + Photon fusion production of monopoles*
  - *Dyons – electrically and magnetically charged particles.*

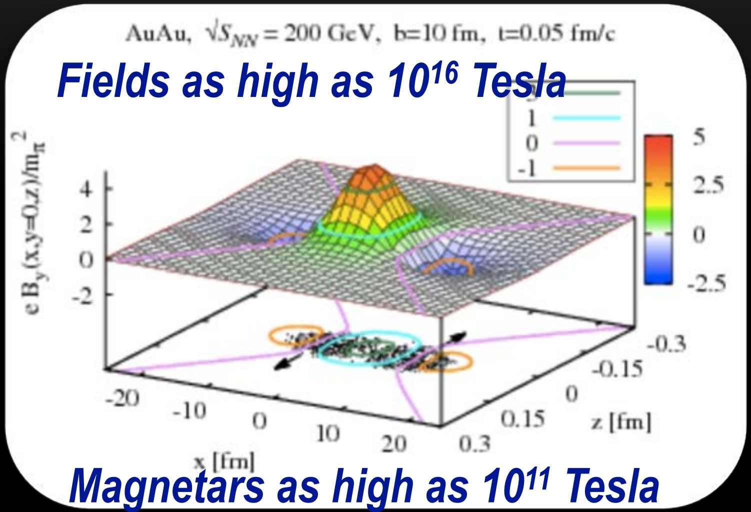
First Direct Search Specifically for a Dyon



•*Phys.Rev.Lett. 126 (2021) 7, 071801*

Monopoles From Heavy-ion Collisions via the Schwinger Mechanism (paper near submission)





- Schwinger mechanism originally described spontaneous creation of $e^{-} - e^{+}$ pairs in presence of an extremely strong electric field.
- Probability of producing a monopole pair $\sigma_{MM} = \sigma_{Inl} V_{ST}\, \Gamma_T$ (where V_{st} is the space-time volume of the field, Γ_T is the rate/unit volume & σ_{inl} is the inelastic nuclear cross-section)
- Important benefits:
  - No exponential suppression for finite sized monopoles
  - X-sec calculation does not suffer from non-perturbative couplings as in DY

MoEDAL @ Run-3 –Seeking SUSY

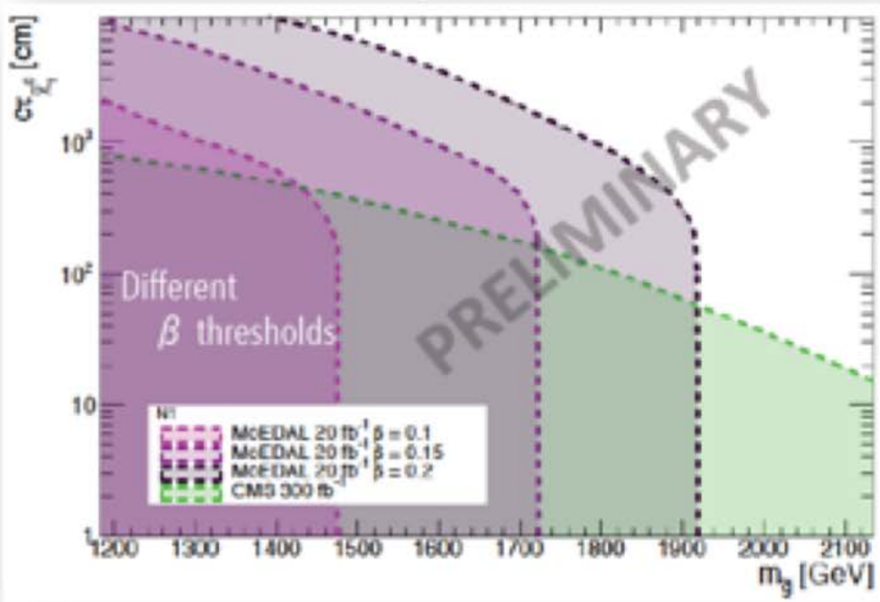
Results for $\tilde{g}\tilde{g}$, $\tilde{g} \rightarrow jj\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \rightarrow \tau^{\pm}\tilde{\tau}_1$

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

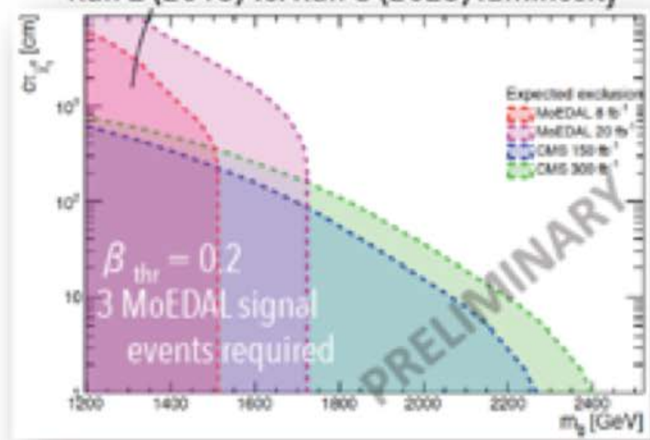
(massive) $\tau^{\pm}$ produces a kink between $\tilde{\chi}_1^0$ and $\tilde{\tau}_1$ tracks ⇒ large impact parameter d_{xy}, d_z

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

End-of-run-3 (2023) luminosity



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



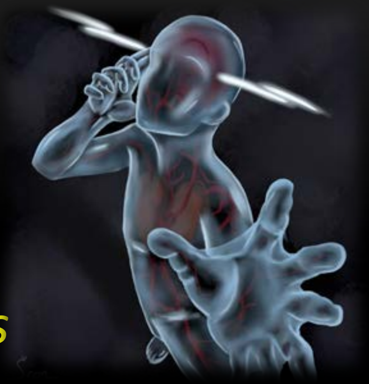
- CMS suffers twice:
  - a) no pixel hit
  - b) too large impact parameters

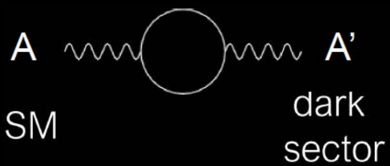
- MoEDAL can cover long-lifetime region inaccessible by ATLAS/CMS even with a *moderate* NTD performance **$z/\beta > 10$**

⚠ Comparison of CMS exclusion with MoEDAL discovery potential requiring 1 event

Searching for Charged FIPs at the LHC

- *The SM can be extended by consistently introducing fields eg just adding a mini-charged field to the SM Lagrangian.*
- *Another Standard motivation:- Introduce a new, hidden U(1) with a massless field A', a "dark photon" that couples to a massive "dark fermion" ψ'*





$$\mathcal{L}_{\text{dark-sector}} = -\frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + \underbrace{i\bar{\psi}'(\gamma^\mu\partial_\mu + ie'\gamma^\mu A'_\mu + iM_{\text{mCP}})\psi'}_{\text{"dark fermion" with mass } M_{mCP}\text{, charge } e'} - \frac{\kappa}{2}A'_{\mu\nu}B^{\mu\nu}$$

massless "dark photon"

mixing term

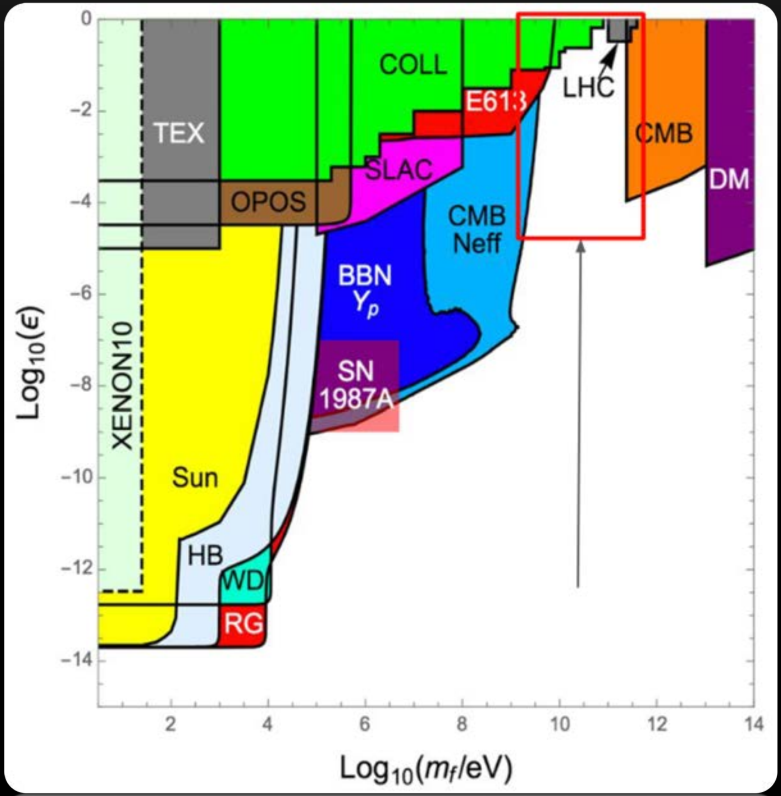
$\kappa \sim 10^{-3} - 10^{-2}$

(naturally $\sim \alpha/\pi$)

- *Ψ' has a charge under the new U(1) of e' and a mass M_{mQP}*
- *A Gauge transformation of* $A'_\mu \to A'_\mu + \kappa B_\mu$ *introduces the coupling* $\overline{\psi'}\kappa e'\gamma^\mu B_\mu \psi'$
- *As a result a coupling emerges between a dark fermion and SM photon of charge* $\kappa e' \cos\theta_W$
- *mQP parameters are entirely defined by their mass and charge*

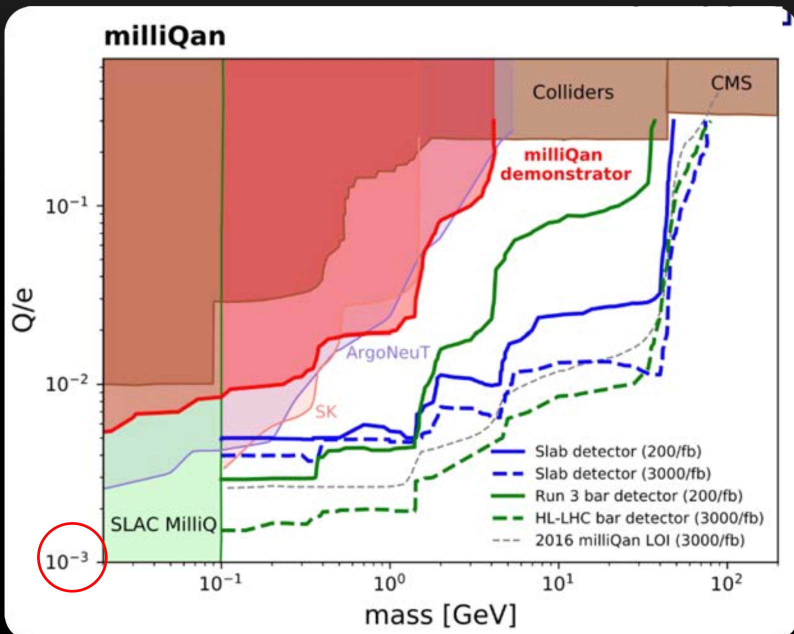
The mQP Phase Space

- Direct constraints on mQPs from collider + beam dump experiments and indirect constraints from cosmological, supernova and solar bounds cover a wide range of masses/charges shown in the figure
- The GeV mass region marked in the figure is reachable by MAPP-mQP and milliQan.
- However, the general purpose LHC detectors ATLAS and CMS can only reach down to a charge of greater than ~ e/3

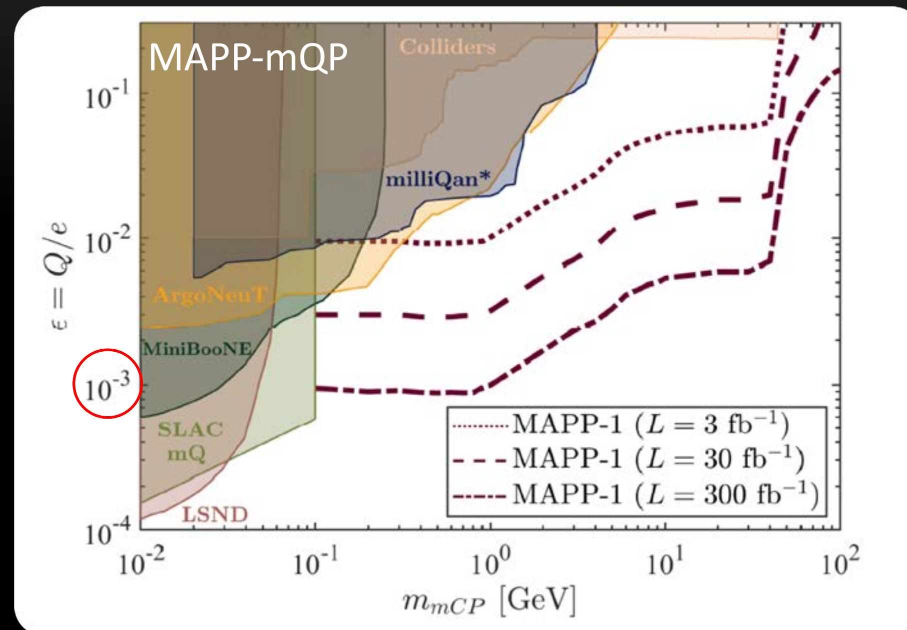


mQp particles from the Sun arXiv:1511.01122

The MAPP-mQP & milliQan Sensitivity



https://arxiv.org/abs/2104.07151

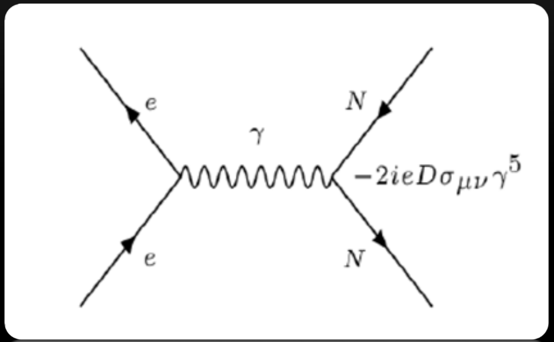


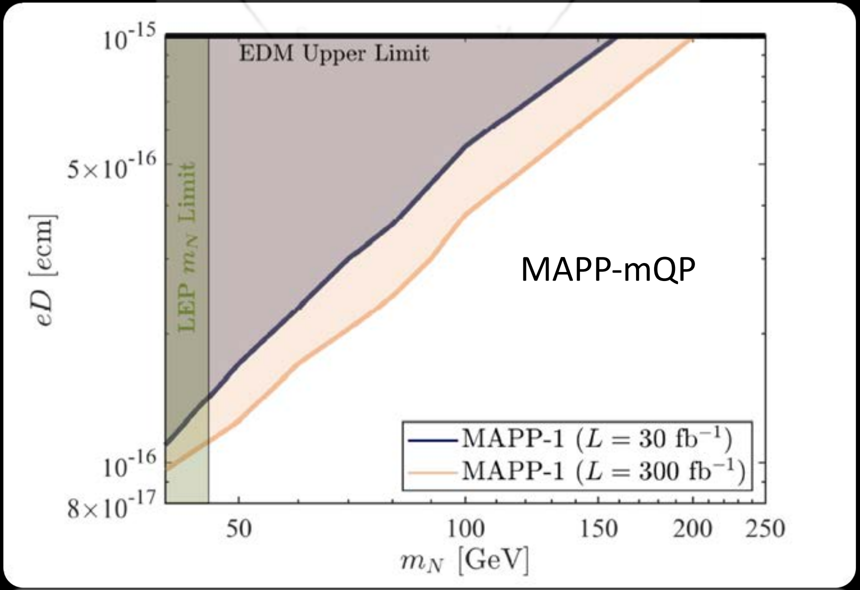
Michael Staelen's Thesis, UofA

- *NB the MAPP-mQP sensitivity assumes no backgrounds and 100% efficiency and does not include the outriggers.*
- *Expect to define the world's limits for 0.1 < mf < 45 GeV*

A FIP Particle Due to Large EDM*
(*Electric Dipole Moment)

- *There are many BSM models which predict large particle EDMs.*
- *EG, a heavy neutrino a member of a 4th generation lepton doublet,with EDM introduced within a dimension-five operator has been hypothesized (Phys. Lett. B* 802 (2020) 135204)
- *An EDM can cause ionization although at a very low level. but it can be detected by MAPP-mQP and milliQan if the EDM > ~ 10^{-16} e.cm*
- *Hence the heavy neutrino in this model can be considered to be a charged FIP*
- *The limits for heavy neutrino DY production at the LHC are shon opposite*





Phys. Lett. B 802 (2020) 135204
Inspired by M. Sher and J. Stevens, Phys. Lett. B777(2018)

Concluding Remarks

"The real voyage of discovery consists, not in seeking new landscapes, but in having new eyes." Marcel Proust

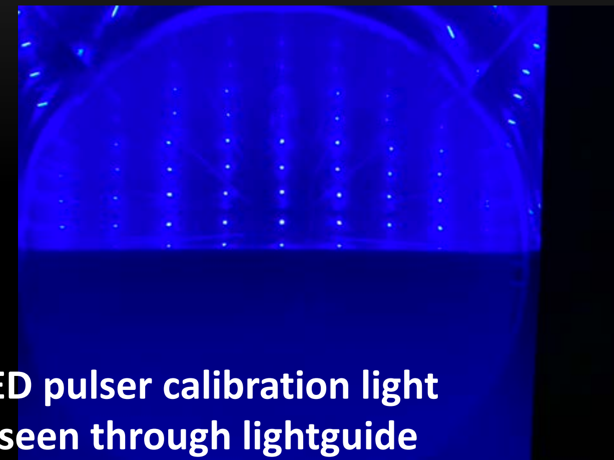
Dedicated search experiments are the "new eyes" of the LHC

EXTRA SLIDES

Construction of the MAPP-mQP Bar Detector

1 section of MAPP-mQP with bars, under load test

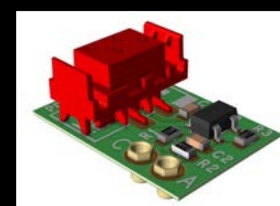
PMTS arrive



LED pulser calibration light seen through lightguide

Wrapped scintillator bars

Light guides ready



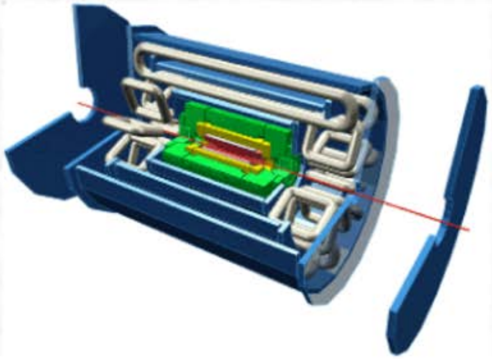
LED pulser board

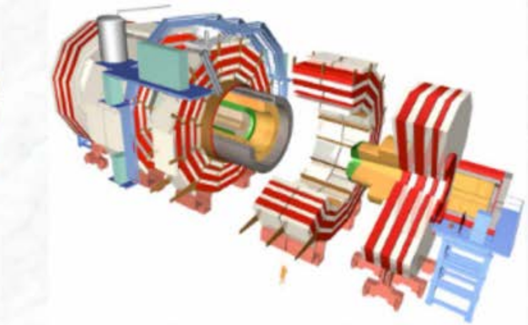
Cockroft Walton PMT base

Prototype readout board

A comparison of ATLAS and CMS

	ATLAS	CMS
Magnetic field	2 T solenoid + toroid: 0.5 T (barrel), 1 T (endcap)	4 T solenoid + return yoke
Tracker	Silicon pixels and strips + transition radiation tracker $\sigma/p_T \approx 5 \cdot 10^{-4} p_T + 0.01$	Silicon pixels and strips (full silicon tracker) $\sigma/p_T \approx 1.5 \cdot 10^{-4} p_T + 0.005$
EM calorimeter	Liquid argon + Pb absorbers $\sigma/E \approx 10\%/\sqrt{E} + 0.007$	$PbWO_4$ crystals $\sigma/E \approx 3\%/\sqrt{E} + 0.003$
Hadronic calorimeter	Fe + scintillator / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV	Brass + scintillator (7 λ + catcher) $\sigma/E \approx 100\%/\sqrt{E} + 0.05$ GeV
Muon	$\sigma/p_T \approx$ 2% @ 50GeV to 10% @ 1TeV (Inner Tracker + muon system)	$\sigma/p_T \approx$ 1% @ 50GeV to 10% @ 1TeV (Inner Tracker + muon system)
Trigger	L1 + HLT (L2+EF)	L1 + HLT (L2 + L3)





ET-miss Resolution of ATLAS & CMS

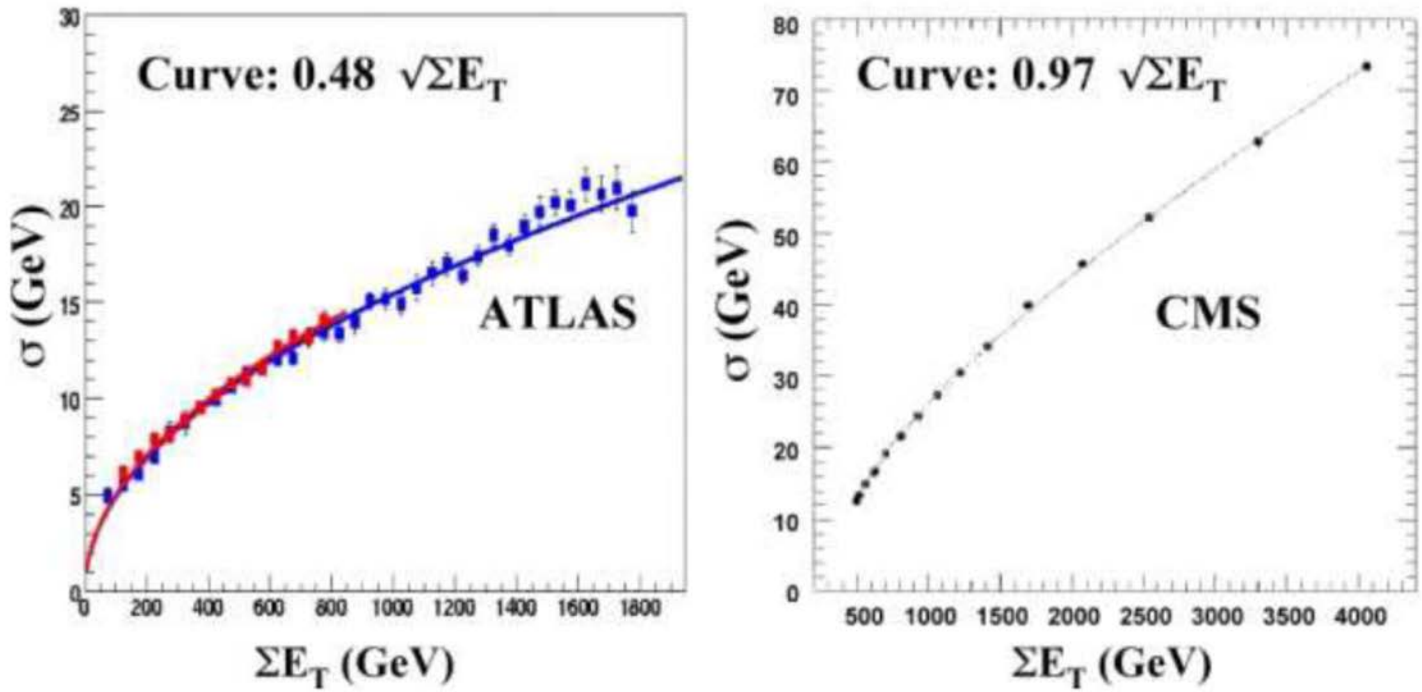


Fig. 1. The ATLAS (left) and CMS (right) Missing Transverse Energy resolution as function of the total transverse energy (ΣE_T) in the event for QCD jet production.