# The MoEDAL Experiment at the LHC

## Searching Beyond the Standard Model

ICNFP 2017

James Pinfold
For the MoEDAL Collaboration
University of Alberta

# The Experiment

# The MoEDAL Experiment & Collaboration

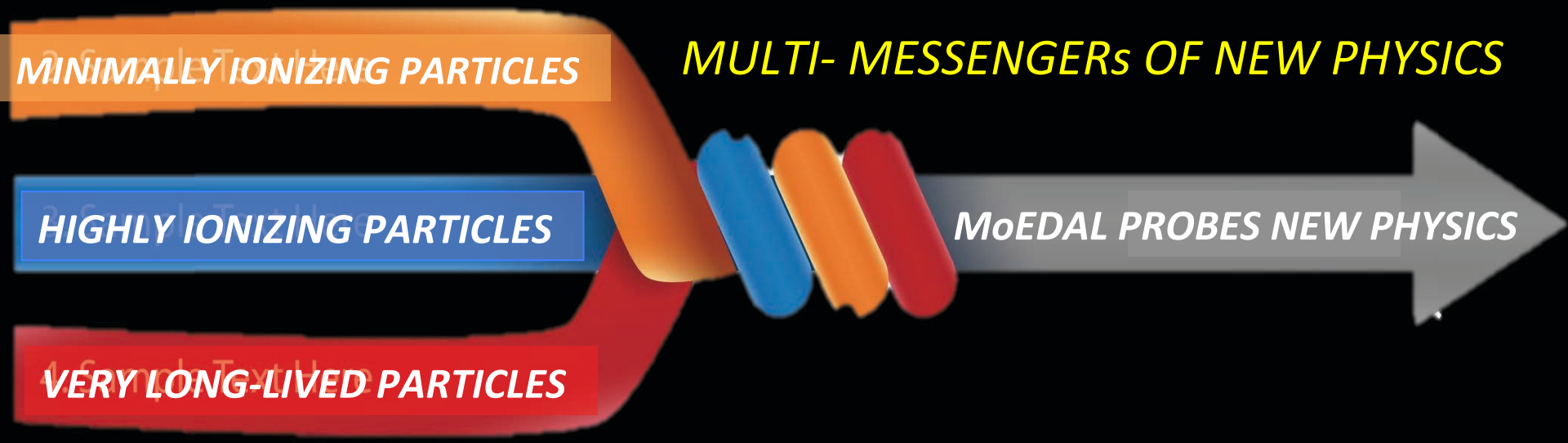
ATLAS CMS ALICE LHCb TOTEM LHCf ***MoEDAL***

*66 physicists from 14 countries & 26 institutes. on 4 continents:*

*1) U. Alberta, 2) U. Alabama,3) UBC, 4) INFN Bologna, 5) U. Bologna,6) CAAG-Algeria, 7) U. Cincinatti, 8) Concordia U., 9) CSIC Valencia,10) Gangneung-Wonju Nat. U.,11) 12) U. Geneva, 13) U. Helsinki, 14) IEAP/ CTU Prague, 15) IFIC Valencia, 16) Imperial College London, 17) ISS Bucharest,18) King's College London, 19) Konkuk U., 20) U. Montréal,21) MISiS Moscow, 22) Muenster U., 23) National Inst. Tec. (india), 24) Northeastern U., 25) Queen Mary College UK, 25) IRIS/Simon Langton School UK, 26) Tuft's.*

# MoEDAL's Physics Approach

*DIRECTLY SEARCH FOR ANOMALOUSLY IONIZING AND VERY LONG-LIVED AVATARS OF NEW PHYSICS*



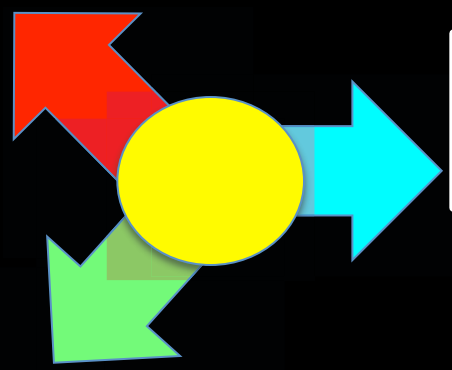

*MoEDAL COMPLEMENTS ATLAS & CMS*

# Key Anomalous Ionization Signature

ELECTRIC CHARGE (e)

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

VERY HIGH IONIZATION
Z↑ β(=v/c)↓



MINI-ELECTRIC CHARGE (mQe)

$$-\frac{dE}{dx} \approx K z^2 \frac{Z}{A}\frac{1}{\beta^2}$$

VERY LOW IONIZATION
Z(<<1) β(~1)

VERY HIGH IONIZATION
g= n68.5e (n=1,2..)

MAGNETIC CHARGE (g)

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

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

# MoEDAL's Complementarity

*Designed & Optimized for highly ionizing particles*

*Insensitive to SM particles*

*Mass ~ 1 ton*

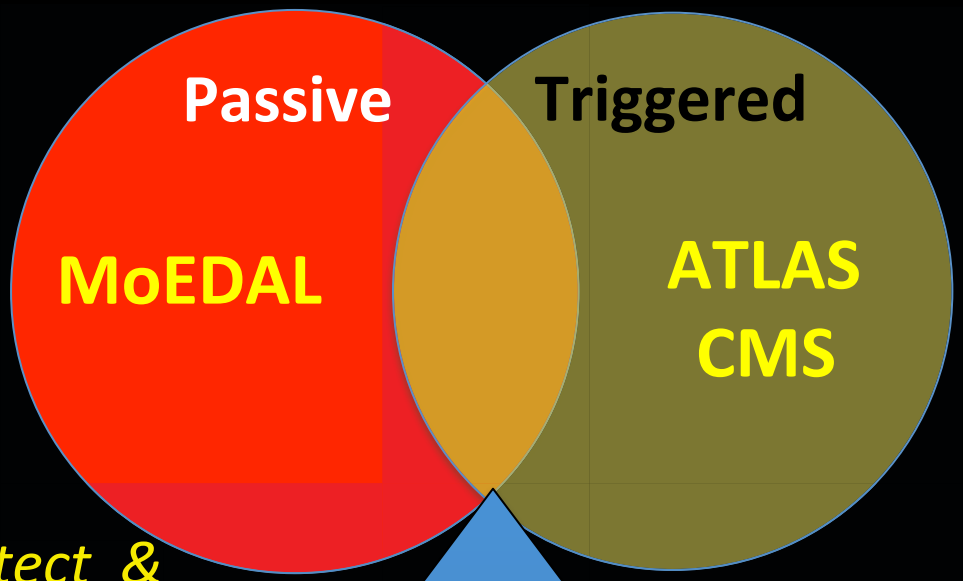
*Size ~ 5m$^3$*

*Thickness in RL ~ 0.02 $X_0$*

*Can directly detect & trap magnetic charge*

*Calibrated by heavy-ions*

*Soon able to detect ~ 0.01e*




*Designed & optimized for SM rel. charged particles & photons*

*Mass ~10K tons*

*Size ~ 25m diam. x 46 m length*

*~ 25 $X_0$ RLs thick*

*Cannot detect magnetic charge*

*Cannot be calibrated for highly ionizing particles*

*Can only detect charge > ~0.3e*

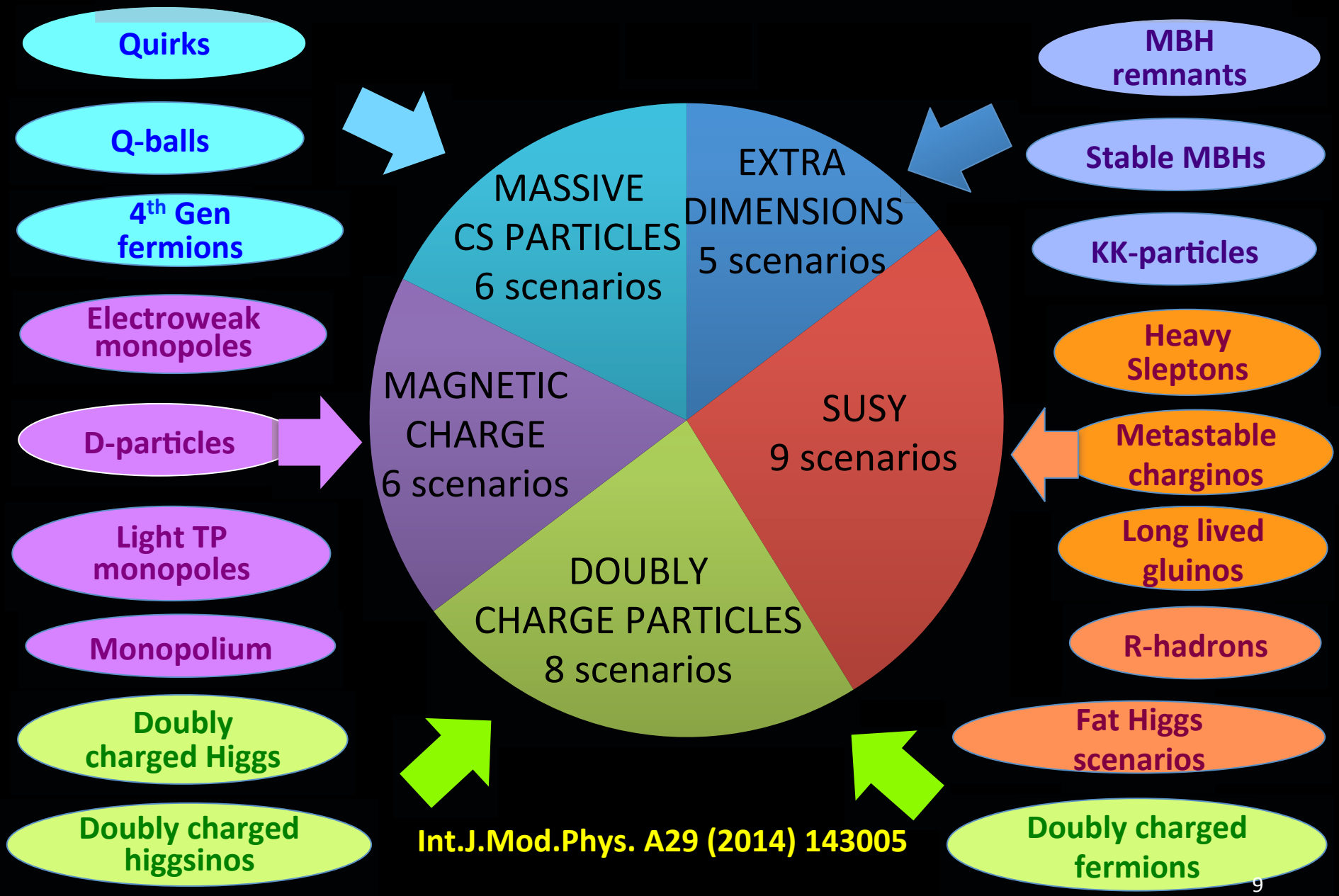
*The different systematics and mode of detection of MoEDAL allow important validation of joint LHC observations*

# The Physics Program

# The Monopole & the Higgs Boson

- *The general purpose experiments have as their prime physics purpose the discovery & elucidation of the Higgs boson….*
- *The corresponding "baseline" physics prpose for MoEDAL is the search for the Magnetic Charge*
- *BUT ATLAS, CMS & MOEDAL CAN DO MUCH MORE*

# MoEDAL – Physics Scenarios (34+)

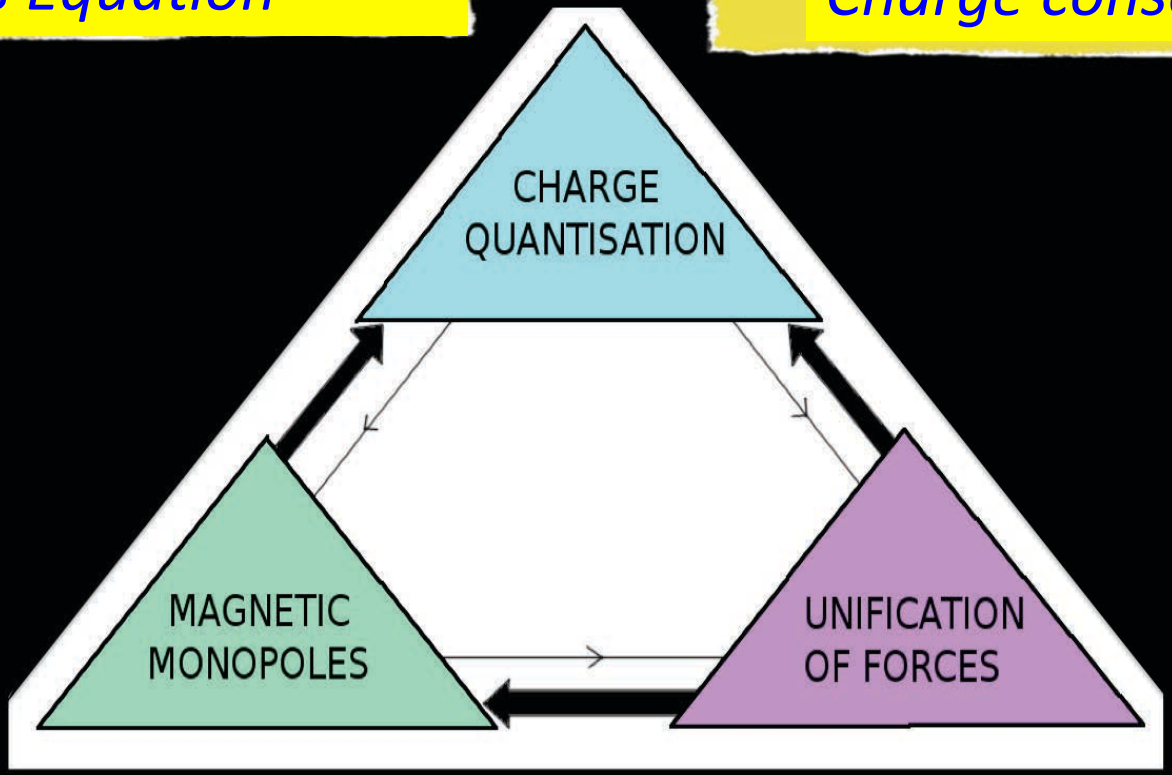



Int.J.Mod.Phys. A29 (2014) 143005

# The Magnetic Monopole's Importance

*They restore symmetry to Maxwell's Equation*

*They explain electric Charge conservation*




*GUT &EW monopoles are Excitations of the Higgs field*

*Monopoles are required By string theory & M-theory*

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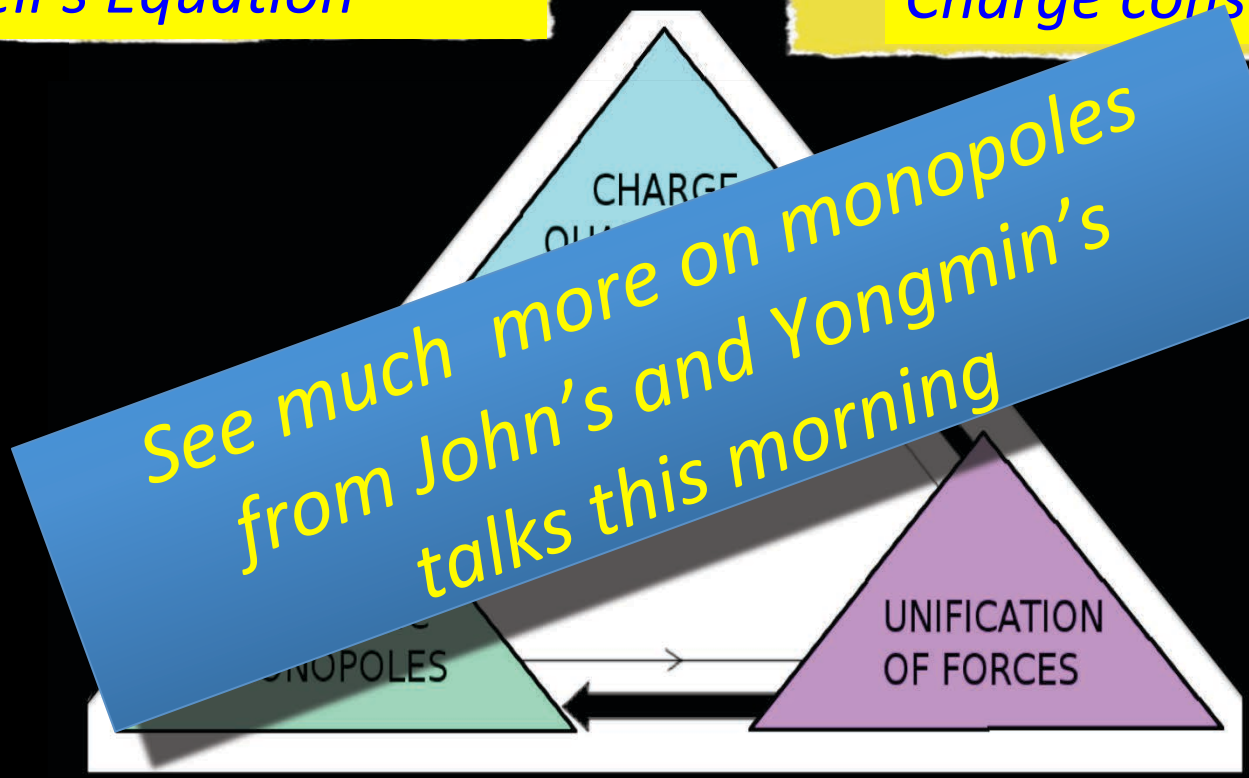



See much more on monopoles from John's and Yongmin's talks this morning

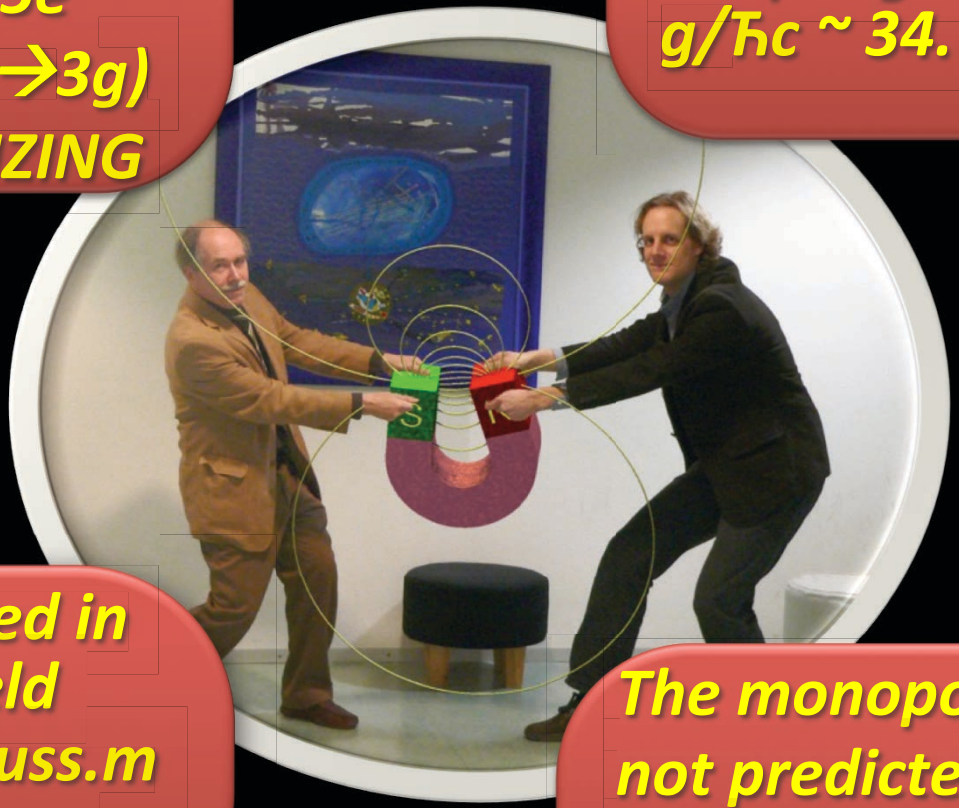
*GUT &EW monopoles are Excitations of the Higgs field*

*Monopoles are required By string theory & M-theory*

# Magnetic Monopole Properties

*Magnetic charge = ng = n68.5e (if e→1/3e; g→3g) HIGHLY IONIZING*

*Coupling constant = g/ħc ~ 34. Spin ½?*

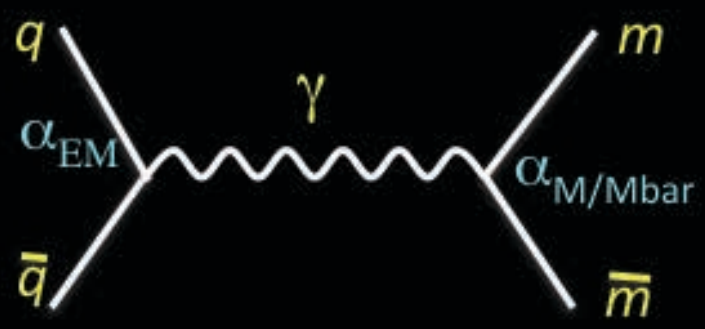


*Energy acquired in a magnetic field =2.06MeV/gauss.m = 2TeV in a 10m, 10T solenidal field*

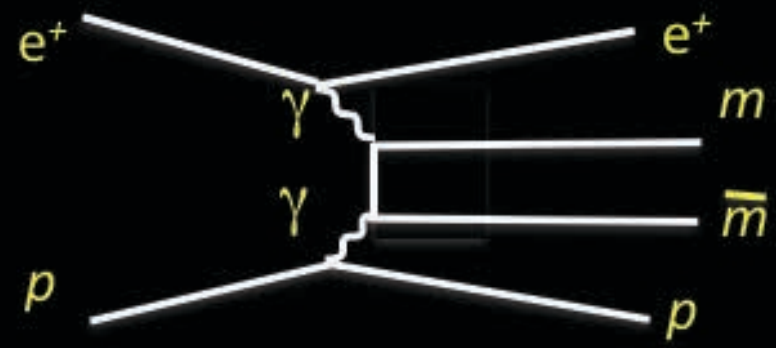
*The monopole mass is not predicted within the Dirac's theory, ~ 4-7 TeV EW monopole*

# Monopole Production at Colliders

$e^+e^- \to M\bar{M}$, $pp \to M\bar{M}$, $e^+p \to e^+pM\bar{M}$, etc.

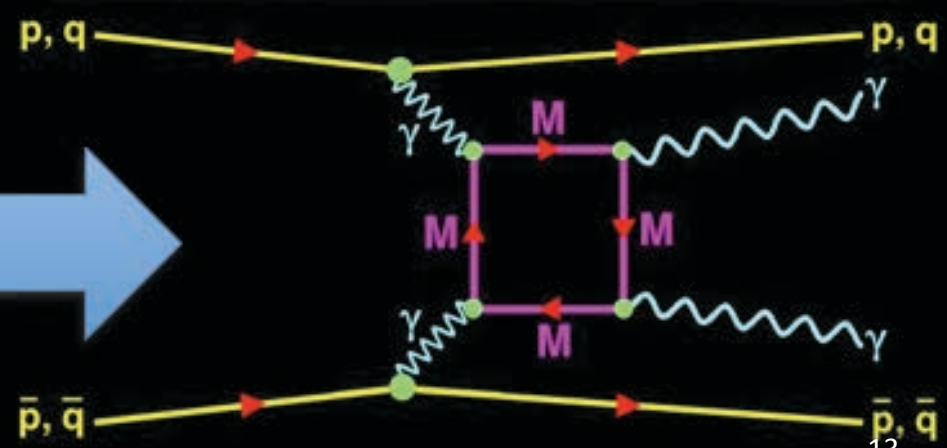



Drell-Yan Production



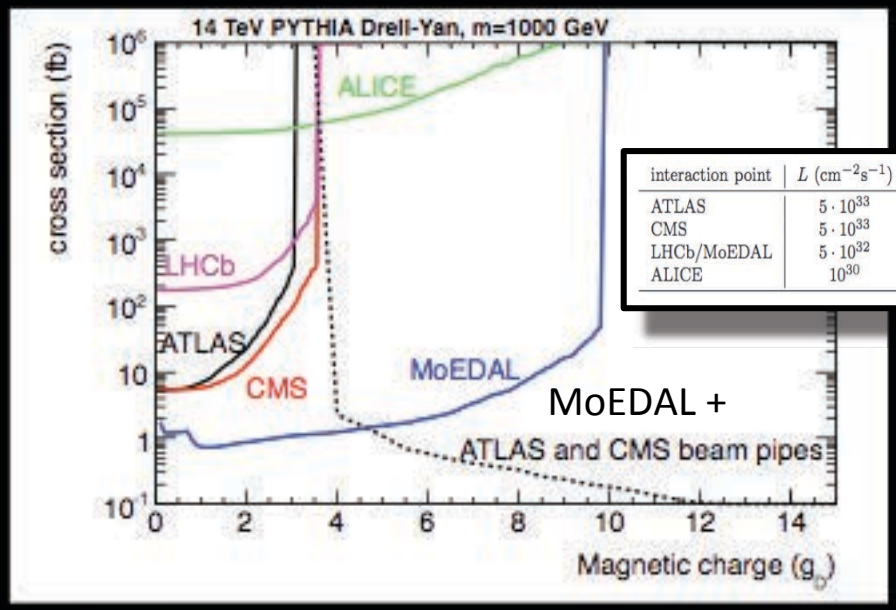

Two-photon production

Indirect search using virtual monopole box diagrams allow – observable two high energy gammas.

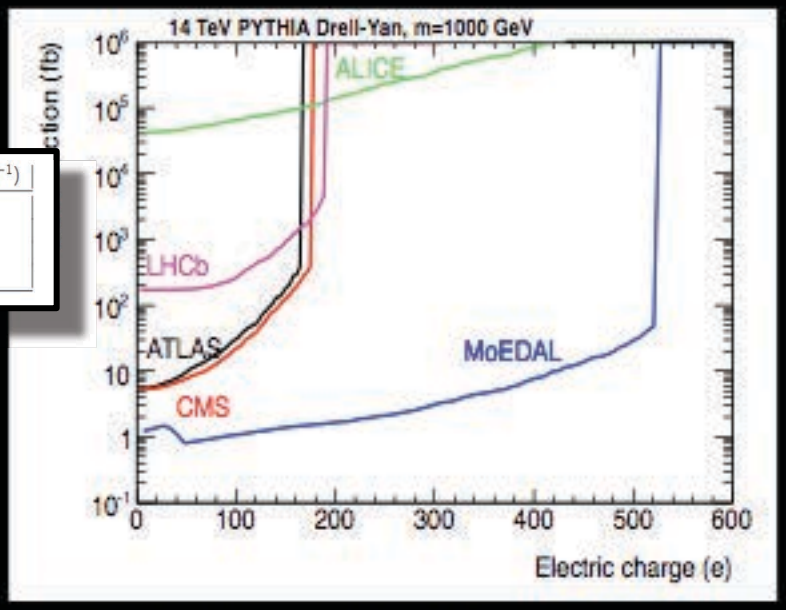


# MoEDAL's Sensitivity

| detector | energy threshold | angular coverage | luminosity | robust against timing | robust efficiency |
|---|---|---|---|---|---|
| ATLAS | medium | central | high | no | no |
| CMS | relatively low | central | high | no | no |
| ALICE | very low | very central | low | yes | no |
| LHCb | medium ✔ | forward | medium | no | no |
| MoEDAL | low | full ✔ | medium ✔ | yes ✔ | yes ✔ |




| interaction point | $L$ (cm$^{-2}$s$^{-1}$) | $\int Ldt$ (fb$^{-1}$) |
|---|---|---|
| ATLAS | $5 \cdot 10^{33}$ | 20 |
| CMS | $5 \cdot 10^{33}$ | 20 |
| LHCb/MoEDAL | $5 \cdot 10^{32}$ | 2 |
| ALICE | $10^{30}$ | 0.004 |



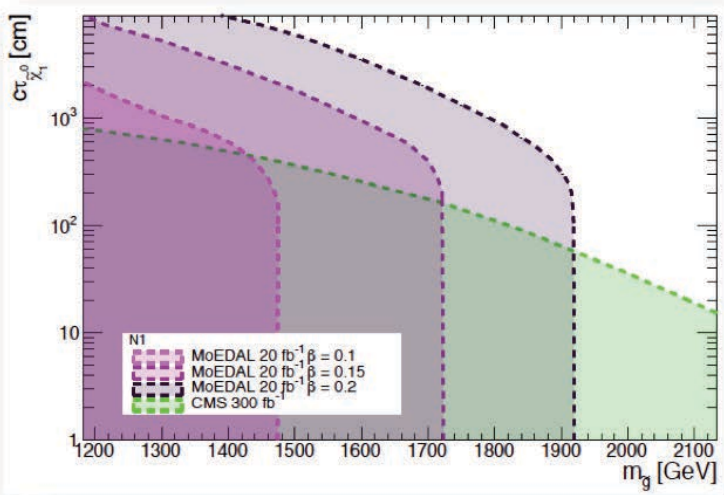

- *Cross-section limits for magnetic (LEFT) and electric charge (RIGHT) (from **arXiv:1112.2999V2** [hep-ph])*
- *MoEDAL COMPLEMENTS the physics reach of the existing LHC experiments*

# The Search for SUSY Using MoEDAL

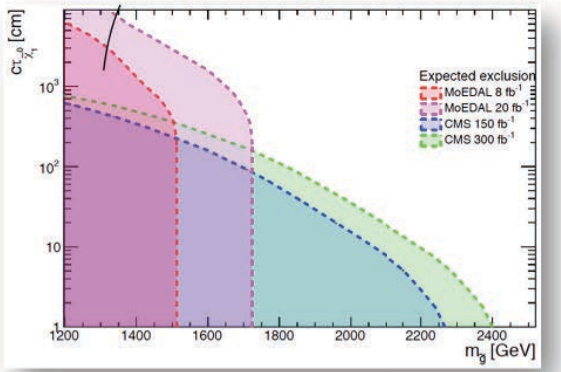
## Results for $\tilde{g}\tilde{g}$, $\tilde{g} \rightarrow jj\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \rightarrow \pi^{\pm}\tilde{\tau}_1$

(Thanks to: K. Sakurai and V. Mitsou)

Different β thresholds
End-of-run-3 (2023) luminosity




$\beta_{thr} = 0.2$
Run 2 (2018) & Run-3 (2023) luminosity




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

Comparison of CMS exclusion with MoEDAL discovery potential requiring 1 event

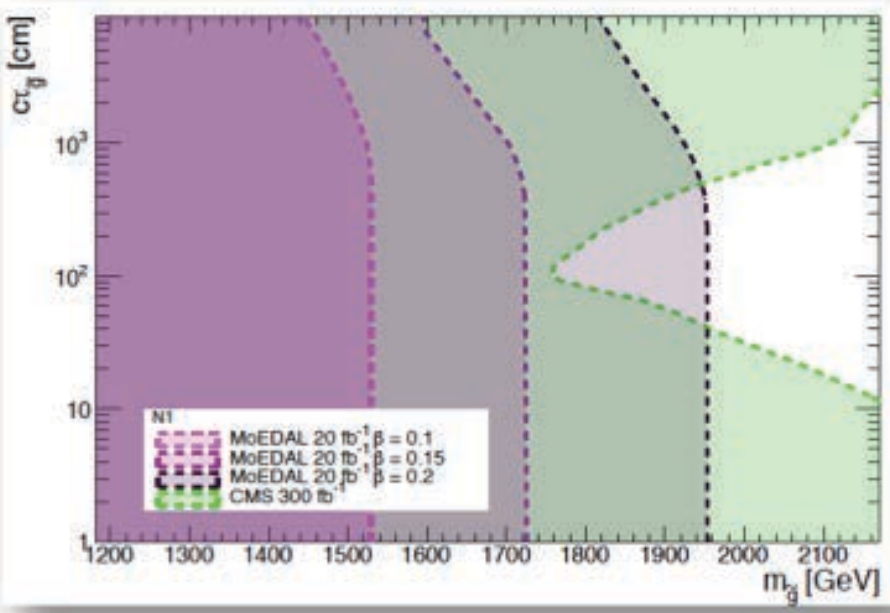
*As you will see from Vasia's talk for MoEDAL can improve LHC limits on mass slow moving Long lived SUSY particles even with relatively modest luminosity*

# Another Example



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

Different β thresholds
End-of-run-3 (2023) luminosity

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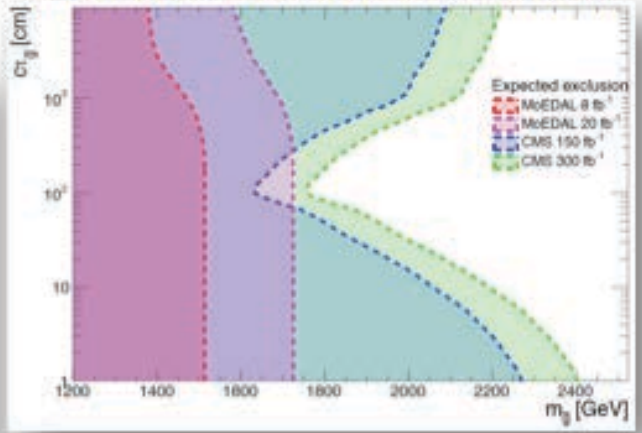


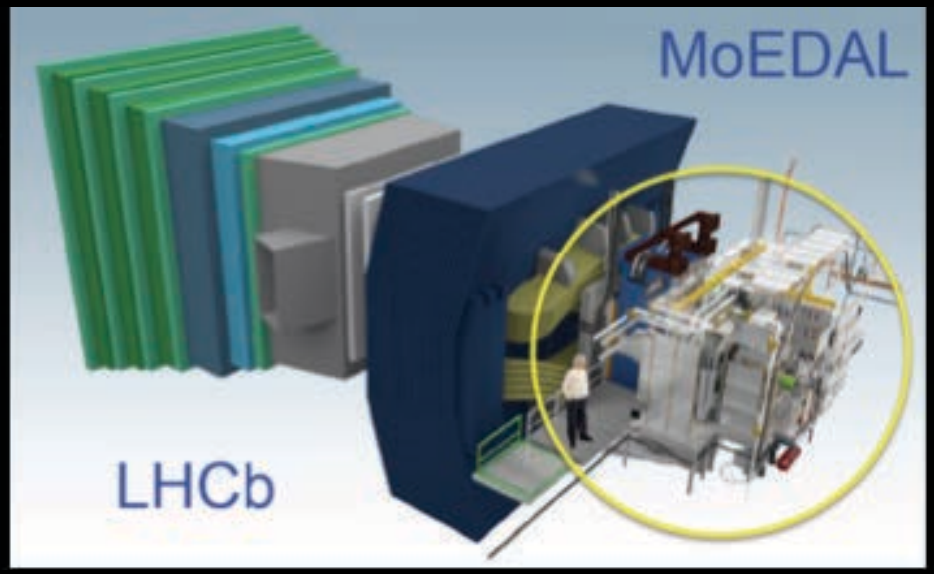

- cτ > 100 cm: gluinos detected as R-hadrons by CMS
  - assuming BR(charged R-hadron) ~ 0.5
- MoEDAL can cover medium-lifetime region (inaccessible by ATLAS/CMS) if NTD threshold reaches z/β = 5

Comparison of CMS exclusion with MoEDAL discovery potential requiring 1 event

# The Detector

# The LHC Detectors with Results - MoEDAL

Permanent Physical record of new physics




No Standard Model Physics Backgrnds

*MoEDAL is largely passive and made up of three detector systems*

*NUCLEAR TRACK DETECTOR*
*Plastic array (~200 sqm)*
*– Like a Giant 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 LHC Detectors with Results - MoEDAL

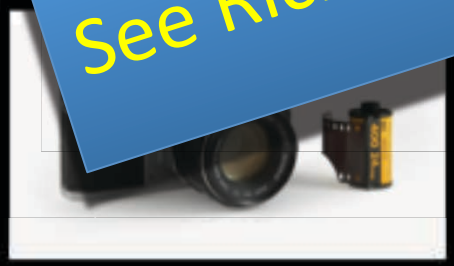
Permanent Physical record of new physics

rd

Backgrnds

See Richard's talk for details on the detector

*Mo* *d made up of three detector systems*

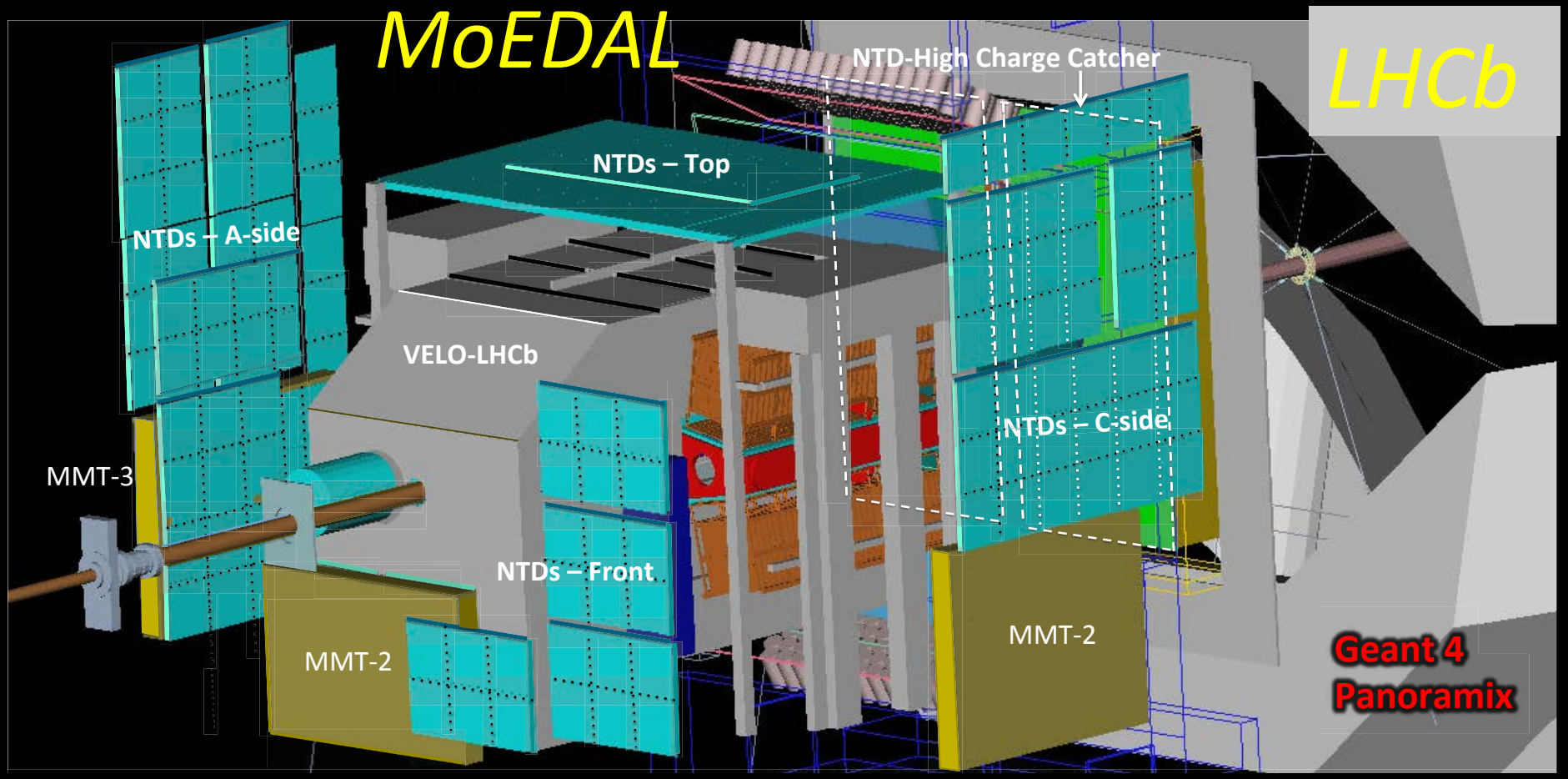


*NUCLEAR TRACK DETECTOR*
*Plastic array (~200 sqm)*
*– Like a Giant Camera*

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

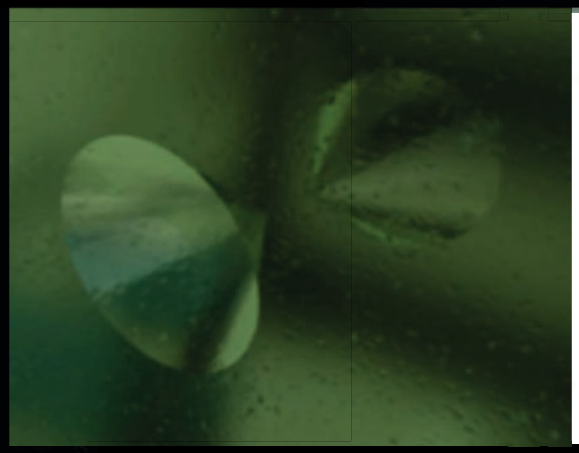
*TIMEPIX Array a digital Camera for real time radiation monitoring*

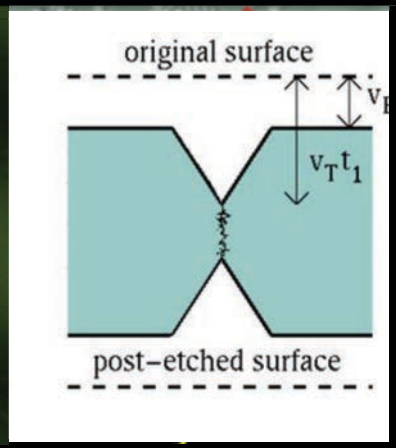
# Full NTD Deployment in 2015/16

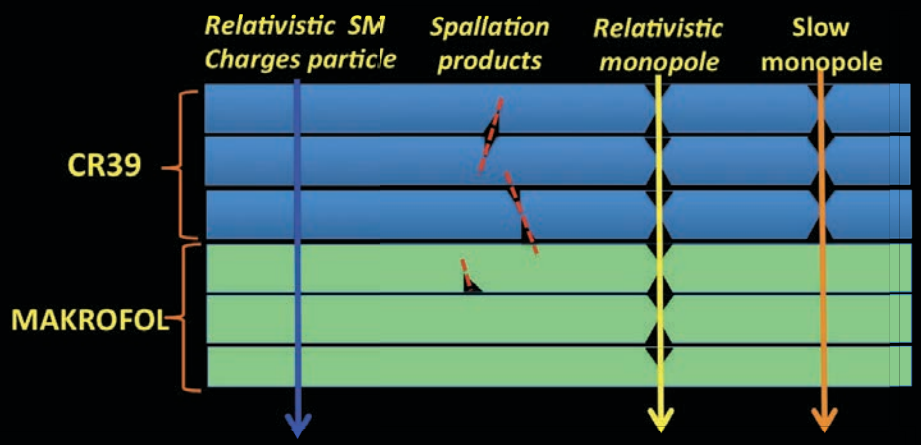



- *Acceptance for at least one monopole from monopole pair production to hit NTDs ~70% (over 150 m$^2$ of plastic)*

# The Signal in the NTDS

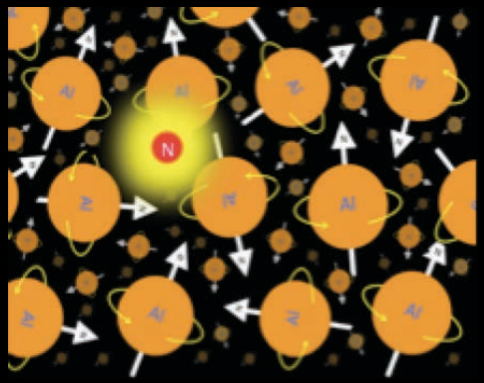





- *Largest NTD array (**150m²** tot) ever deployed at an accelerator*
  - *NTD tacks consist of CR39 (Thr. 5 mip) & Makrofol (Thr. 50 mip)*
  - *Damage revealed by controlled etching - etch pits are formed*
  - *Charge resolution is ~|0.1|e, where |e| is the electron charge*
  - *Precision of each etcha pit measurement ~20-50 microns*
- *NTDs are calibrated at heavy-ion beams at NSRL & NA61*
- *ATLAS and CMS cannot calibrate for highly ionizing plastic*

# Signal in the MMT & SQUID Detectors



*Monopole trapped by aluminium nuclei*

*The MoEDAL trapping detectors at IP8*

*THE Zurich DC-SQUID magnetometer*

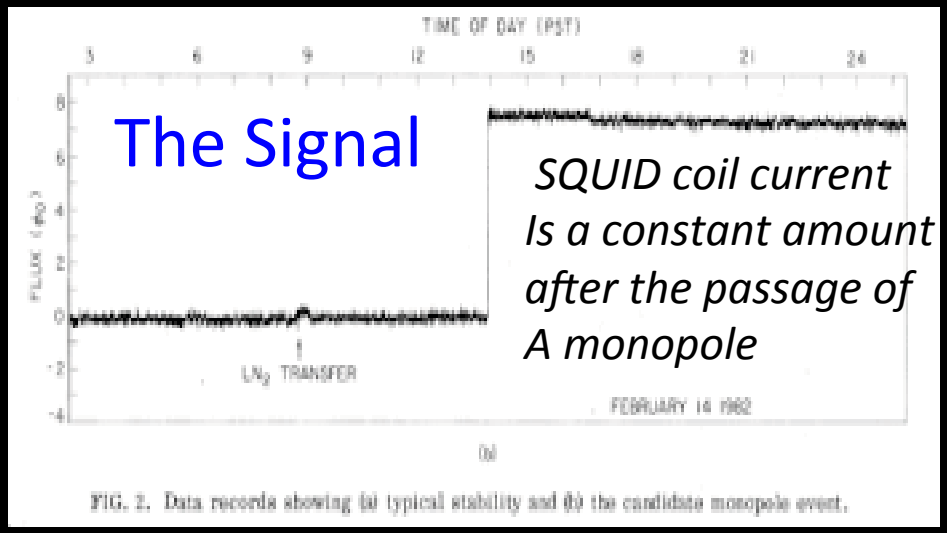
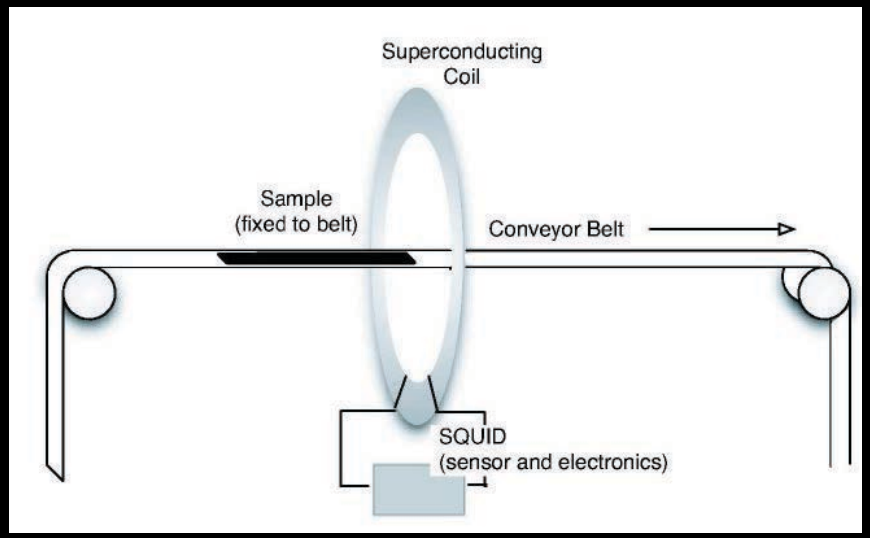
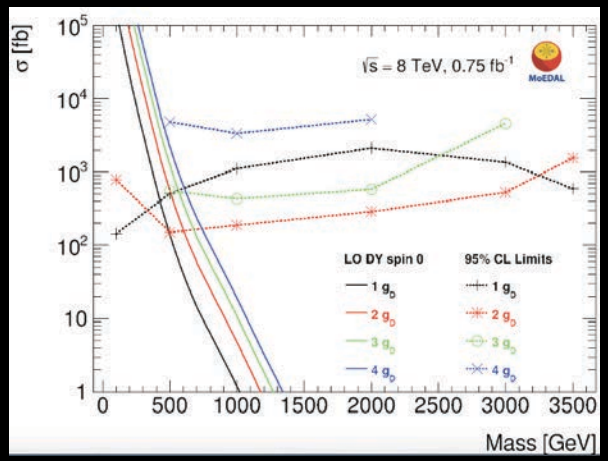


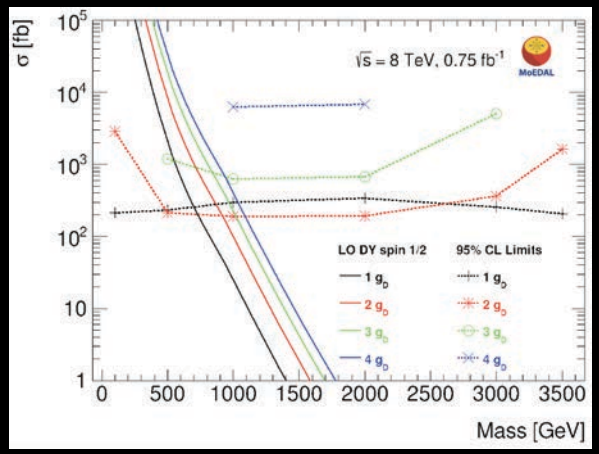

FIG. 2. Data records showing (a) typical stability and (b) the candidate monopole event.

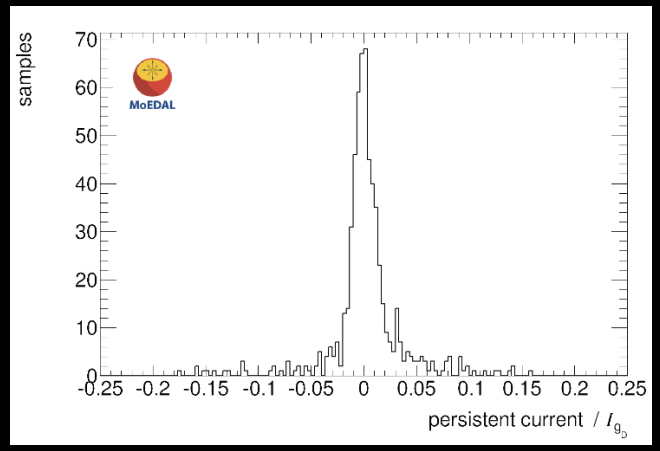


# First Results

# The MoEDAL Monopole Search at s = 8 TeV - JHEP 1608 (2016) 067




MoEDAL

| DY Lower Mass Limits [GeV] | $\lvert g\rvert = g_D$ | $\lvert g\rvert = 2g_D$ | $\lvert g\rvert = 3g_D$ |
|---|---|---|---|
| spin-1/2 | 700 | 920 | 840 |
| spin-0 | 420 | 600 | 560 |

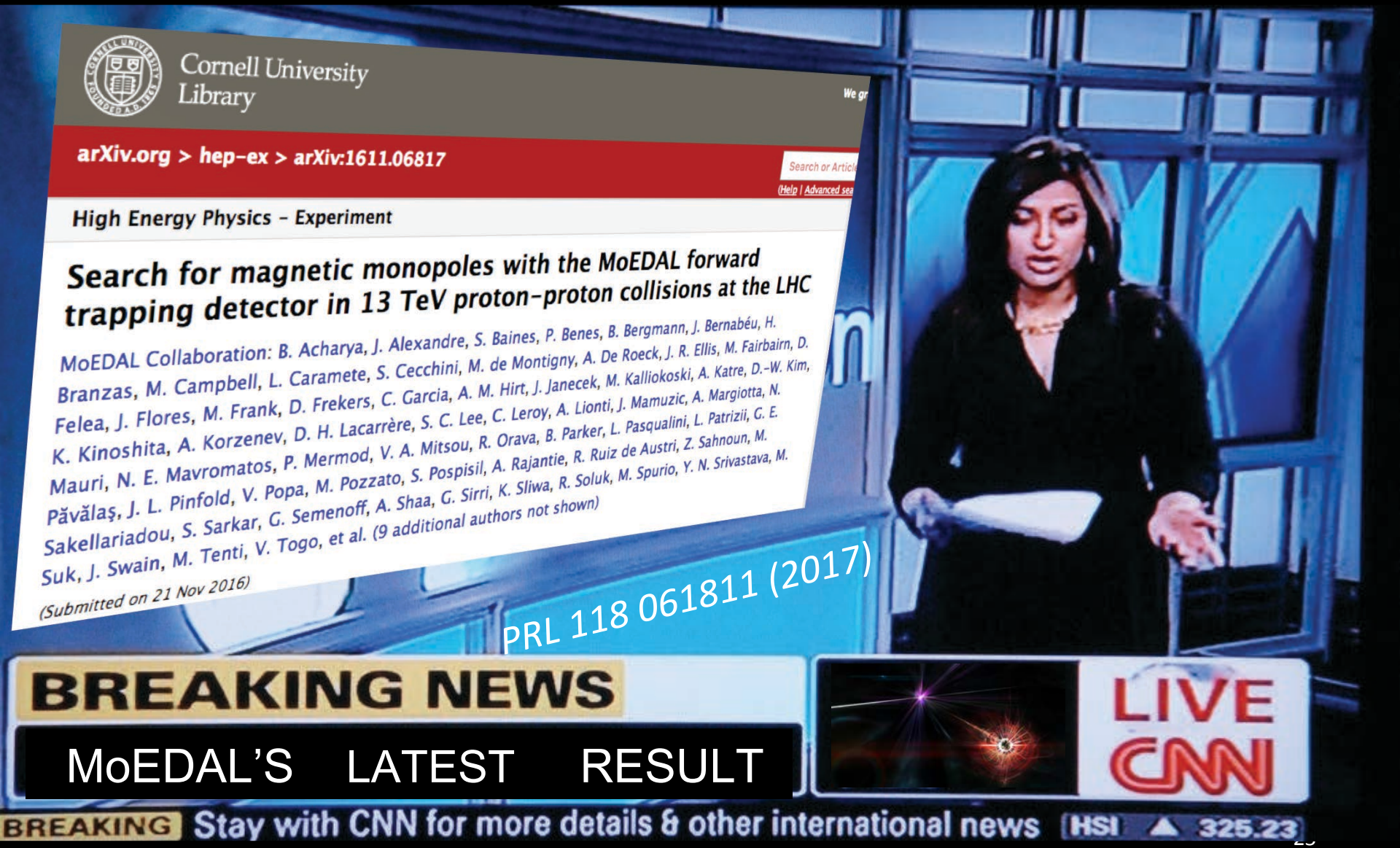
ATLAS

| $\lvert g\rvert = g_D$ |
|---|
| 1340 |
| 1050 |

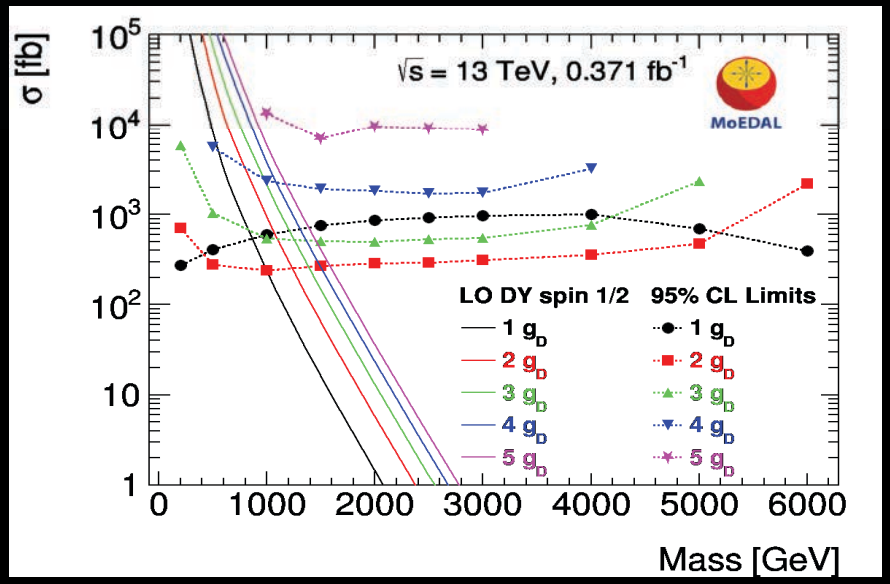
World best limits for $|g| > g_D$

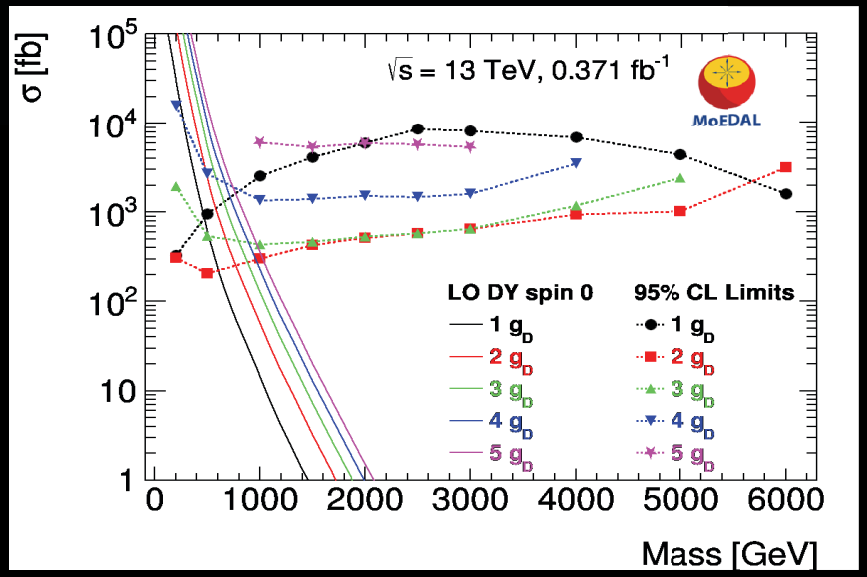
(previously ~400 GeV at the Tevatron)

# LHC's First 13 TeV Results on Monopoles



# MoEDAL Monopole Search Results at- √s =13 TeV - PRL 118 061811 (2017)




- *First monopole constraints in 13 TeV pp collisions*
  - *Probe TeV masses for up to $5g_D$ for the 1st time at the LHC*
  - *Exclude monopole with $|g|=4g_D$ for the 1st time at the LHC*

| mass limits [GeV] | $1g_D$ | $2g_D$ | $3g_D$ | $4g_D$ |
|---|---|---|---|---|
| MoEDAL 13 TeV (this result) | | | | |
| DY spin-1/2 | 890 | 1250 | 1260 | 1100 |
| DY spin-0 | 460 | 760 | 800 | 650 |
| MoEDAL 8 TeV | | | | |
| DY spin-1/2 | 700 | 920 | 840 | – |
| DY spin-0 | 420 | 600 | 560 | – |
| ATLAS 8 TeV | | | | |
| DY spin-1/2 | 1340 | – | – | – |
| DY spin-0 | 1050 | – | – | – |

# Things to Come

# Some Analyses in the Pipeline & Planned

Beam-pipe search(CMS+)
High magnetic charge >6g

Search for
mini-charged (< 1/3e)
particles

Trapping detector
2015/2016 data
DY & γγ –prod.
Spins 0,1/2 & 1
considered

8 TeV NTD plastic 2012 search
for high electric charge (>50e)
& combo monopole x-sec. lims

Heavy-ion search
for monopoles
(Perturbative )

2015-2017 full detector
trapping & NTDs results for
electric & magnetic charge

Search for Long-lived
charged SUSY particles

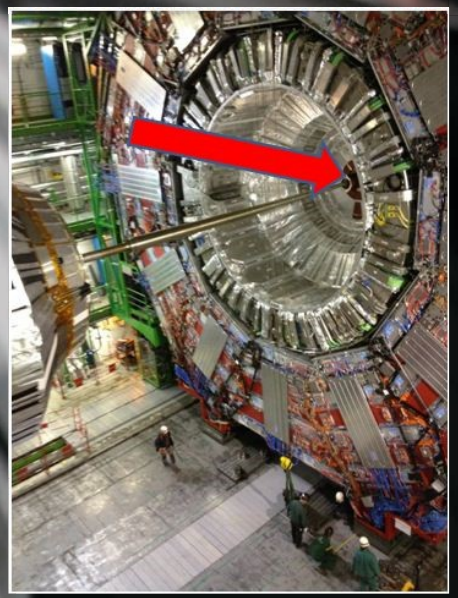
See Arka's talk

See Oliver's talk

See Vasia's talk

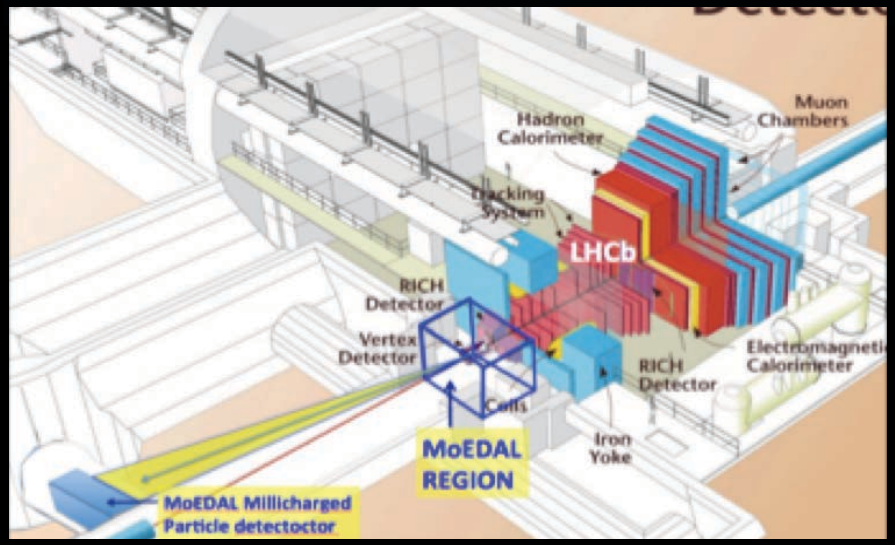
# Beampipe Searches for Very Highly Ionizing Particles – Now in Play

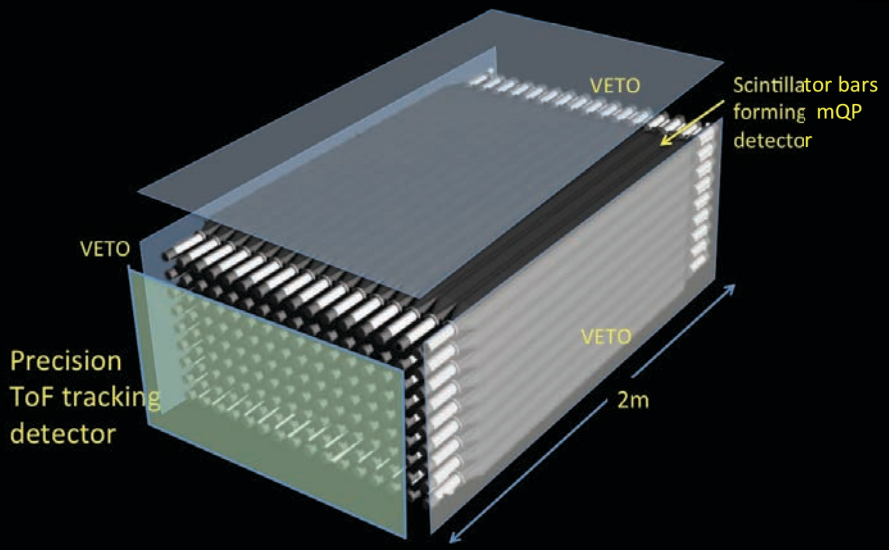
**CMS Beryllium beampipe**



***MoEDAL- Beampipe Consortium have submitted a proposal to CMS to utilize their replaced tIP region Be beam pipe to scan them for the presence of very highly ionizing monopoles trapped in the beam pipe walls***

# MoEDAL Apparatus for Penetrating Particles (MAPP)



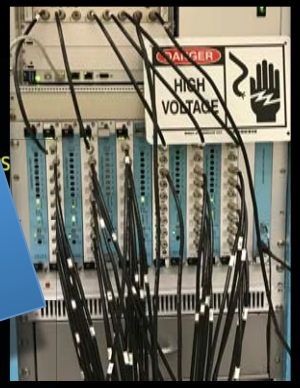




- *MAPP will be able to take data in p-p, p-A,A-A and also fixed target interactions using SMOG (an internal gas target in LHCb)*
- *MAPP has three motivations*
  - *To search for particles with charges <<1e (ATLAS & CMS limited to searches with particles of charge e ≥ 1/3)*
  - *To search for new pseudo-stable neutrals with long lifetime and anomalously penetrating particles*

# MAPP is Coming Together

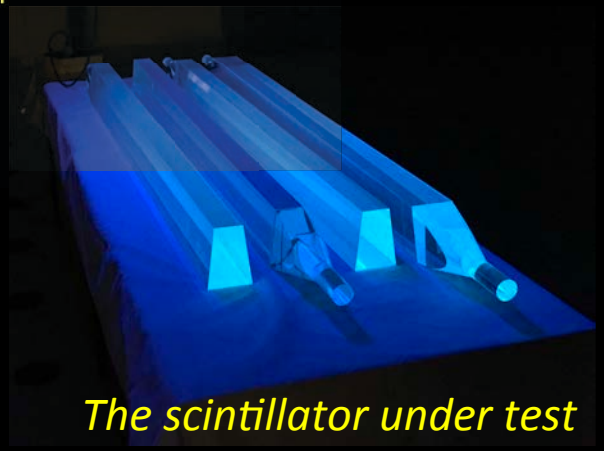
*RCE – Connecting to the LHC*

See Richard's Talk for more details




*The VETO & readout system*

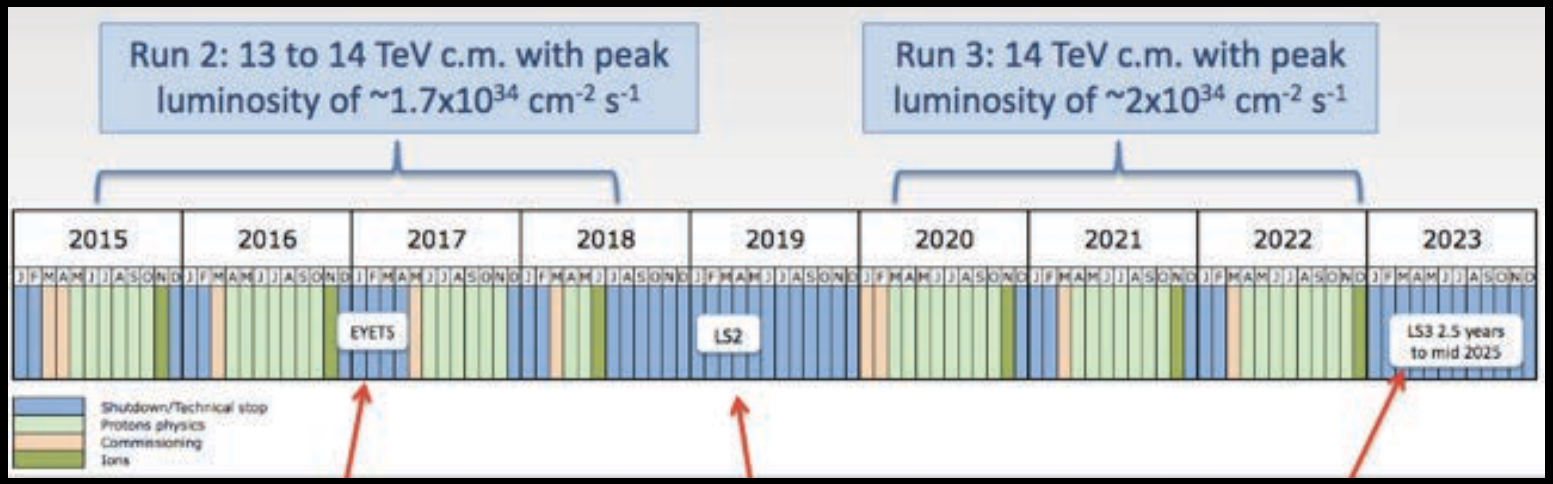
*Precision ToF with resolution ~15ps*



*The scintillator under test*

- *A MAPP prototype will be installed at IP8 in Sept. 2017*

# More Luminosity and Higher Energy

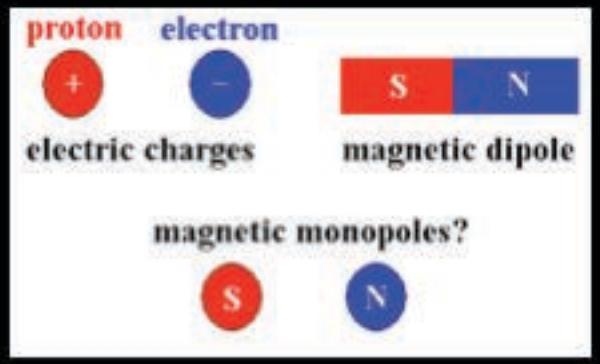



- *Luminosity acquired by MoEDAL before the end of RUN-2 is likely to be ~6 fb$^{-1}$. Our request was for 10 fb$^{-1}$*
- *We will be requesting an additional 20-30 fb$^{-1}$ of data in RUN-3 to Run 1t the increased $E_{cm}$ of 14 TeV*
  - *Continue the search for magnetic charge to higher energy & luminosity*
  - *A higher luminosity is necessary to push the search for electrically charged massive( pseudo)-stable particles from, e.g., SUSY scenarios.*
  - *Start the search in earnest for mini-charged particles and long-lived secondaries using MAPP*

# MoEDAL Addresses Fundamental Questions:

*Are there extra dimensions?*

*What happened just after the big bang?*



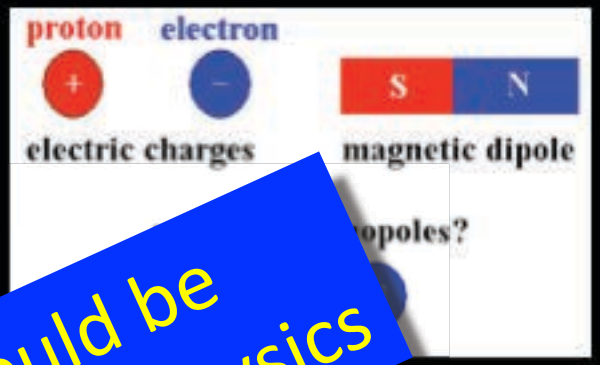

*Does magnetic charge exist?*

***What is the nature of Dark matter?***

*Are there new symmetries of nature?*

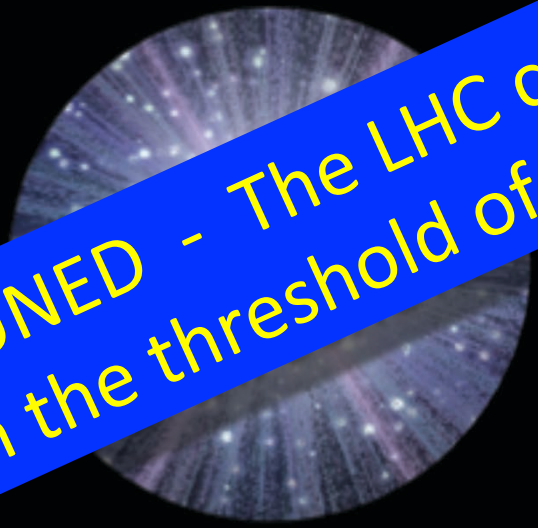
# MoEDAL Addresses Fundamental Questions:

*Are there extra dimensions?*



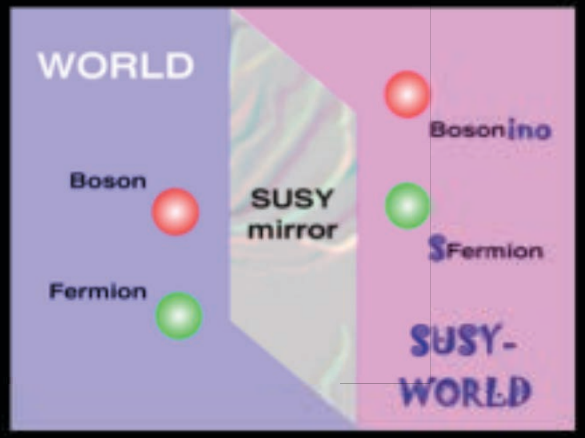

*ic charge exist?*

STAYED TUNED - The LHC could be poised on the threshold of new physics



*What happened just after the big bang?*

***What is the nature of*** *Dark matter?*

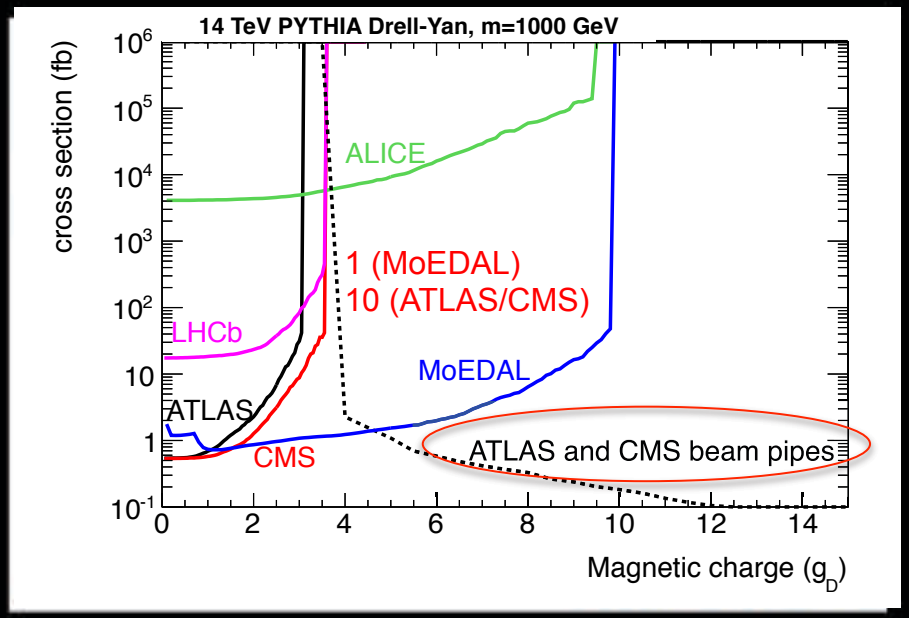


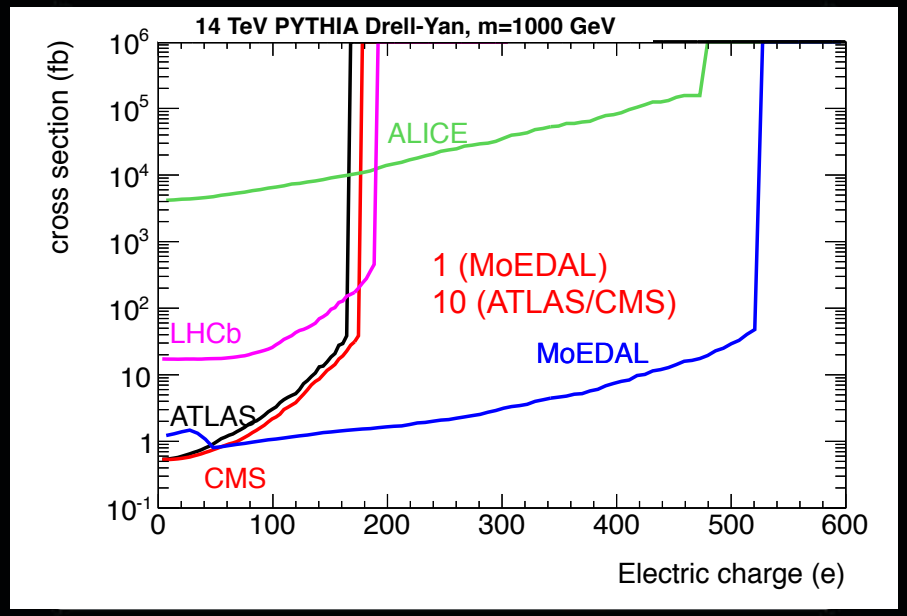

*Are there new symmetries of nature?*

# ADDITIONAL SLIDES

# LHC Sensitivity to Monopoles

| detector | energy threshold | angular coverage | luminosity | robust against timing | robust efficiency |
|---|---|---|---|---|---|
| ATLAS | medium | central | high | no | no |
| CMS | relatively low | central | high | no | no |
| ALICE | very low | very central | low | yes | no |
| LHCb | medium ✔ | forward | medium | no | no |
| MoEDAL | low | full ✔ | medium ✔ | yes ✔ | yes ✔ |




- *Cross-section limits for magnetic (LEFT) and electric charge (RIGHT) (from **arXiv:1112.2999V2** [hep-ph])*
- *MoEDAL COMPLEMENTS the physics reach of the existing LHC experiments*

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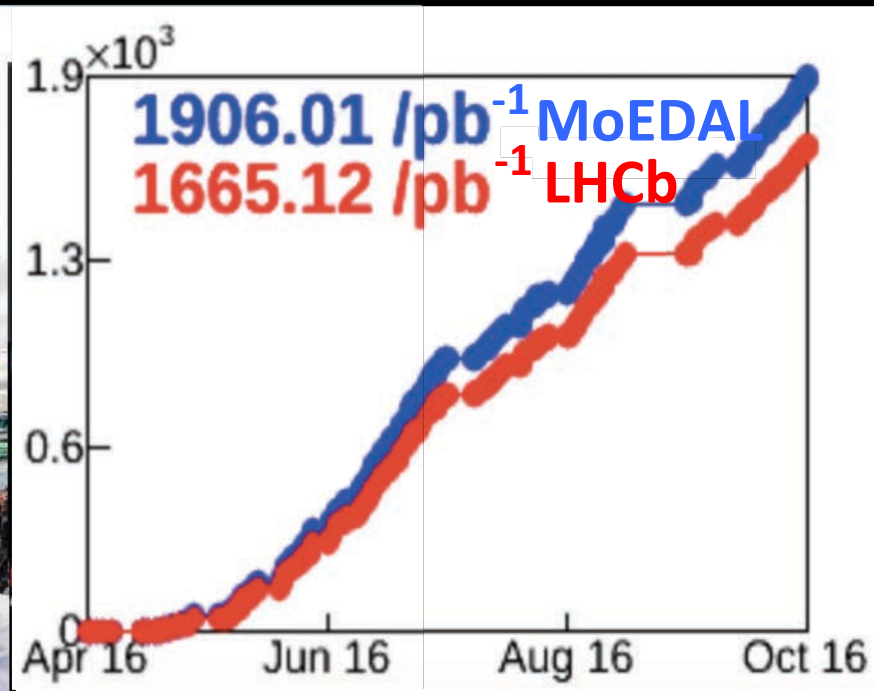
# MoEDAL in Run 2

LHC experiments are back in business at a new record energy 13 TeV

3rd June 2015

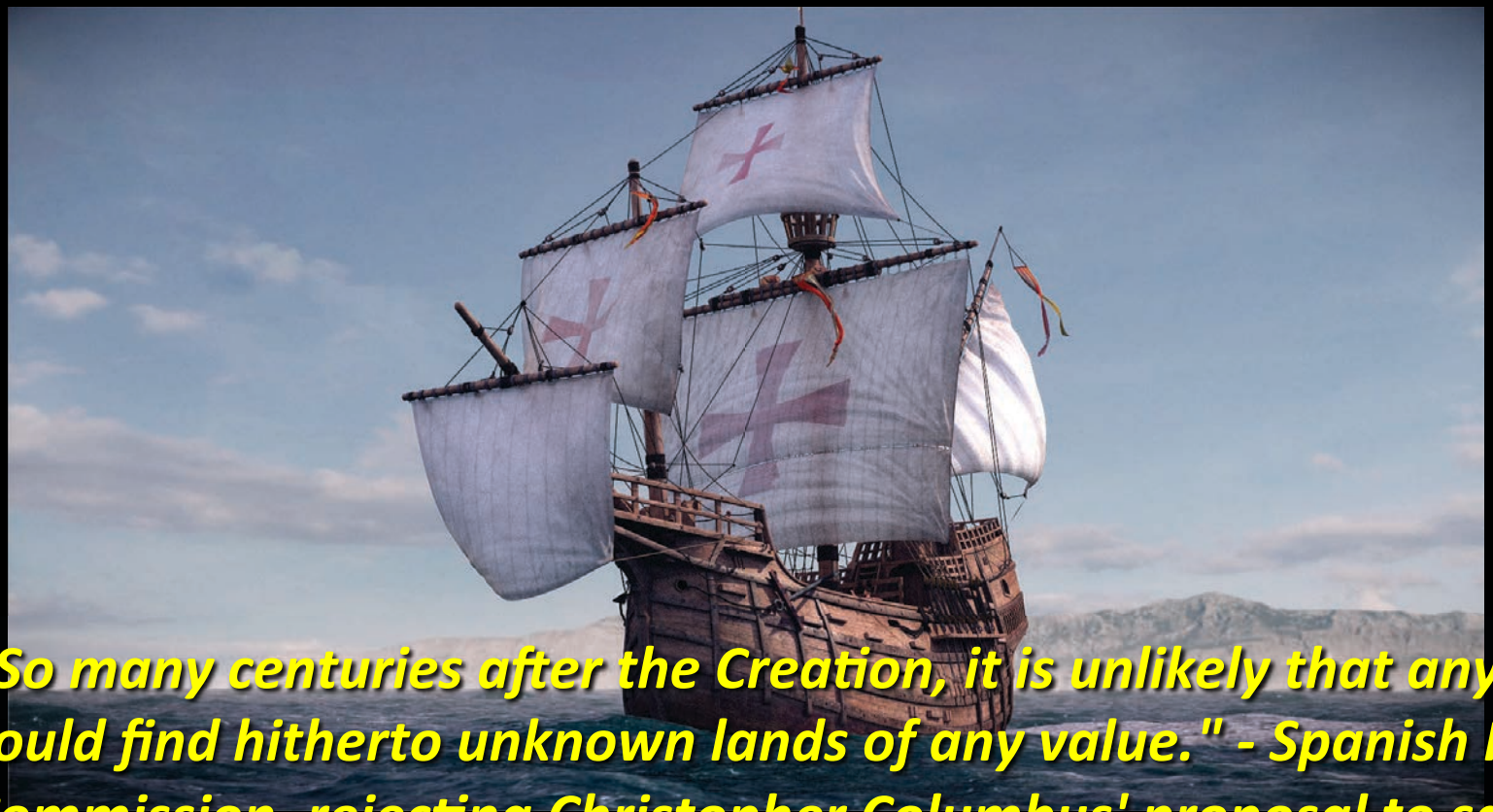



Recorded Luminosity

*The luminosity delivered to MoEDAL in 2015 was 366 $pb^{-1}$*

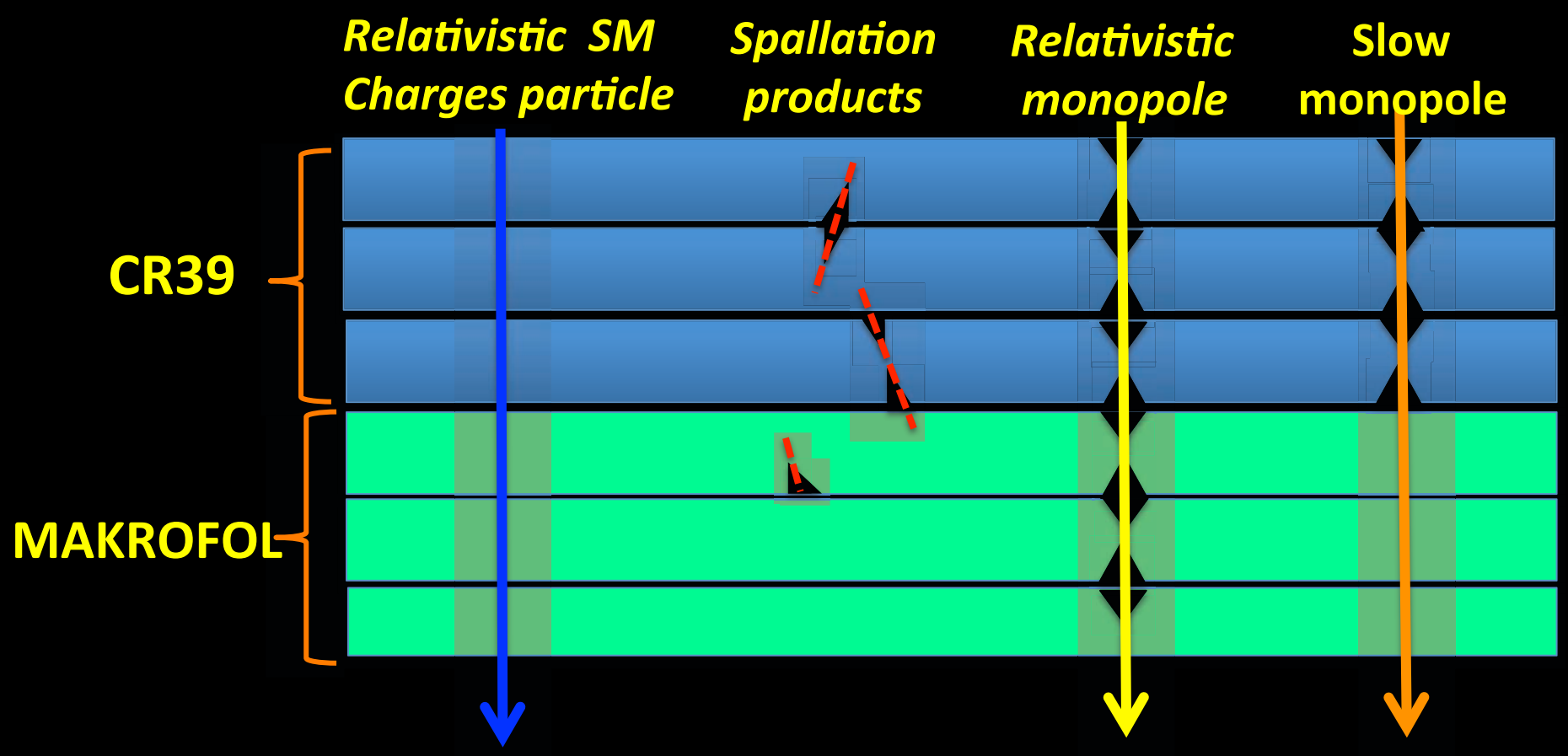
**Despite "Sparky" the Beech Marten – LHC is now on track**

# The LHC's Voyage of Discovery



***"So many centuries after the Creation, it is unlikely that anyone could find hitherto unknown lands of any value." - Spanish Royal Commission, rejecting Christopher Columbus' proposal to sail west.***

*In 2015 the LHC experiments – now including MoEDAL - set sail out on a voyage of discovery at the new LHC high energy frontier of 13TeV - **stay tuned for the report of new worlds***


Relativistic SM Charges particle
Spallation products
Relativistic monopole
Slow monopole
CR39
MAKROFOL