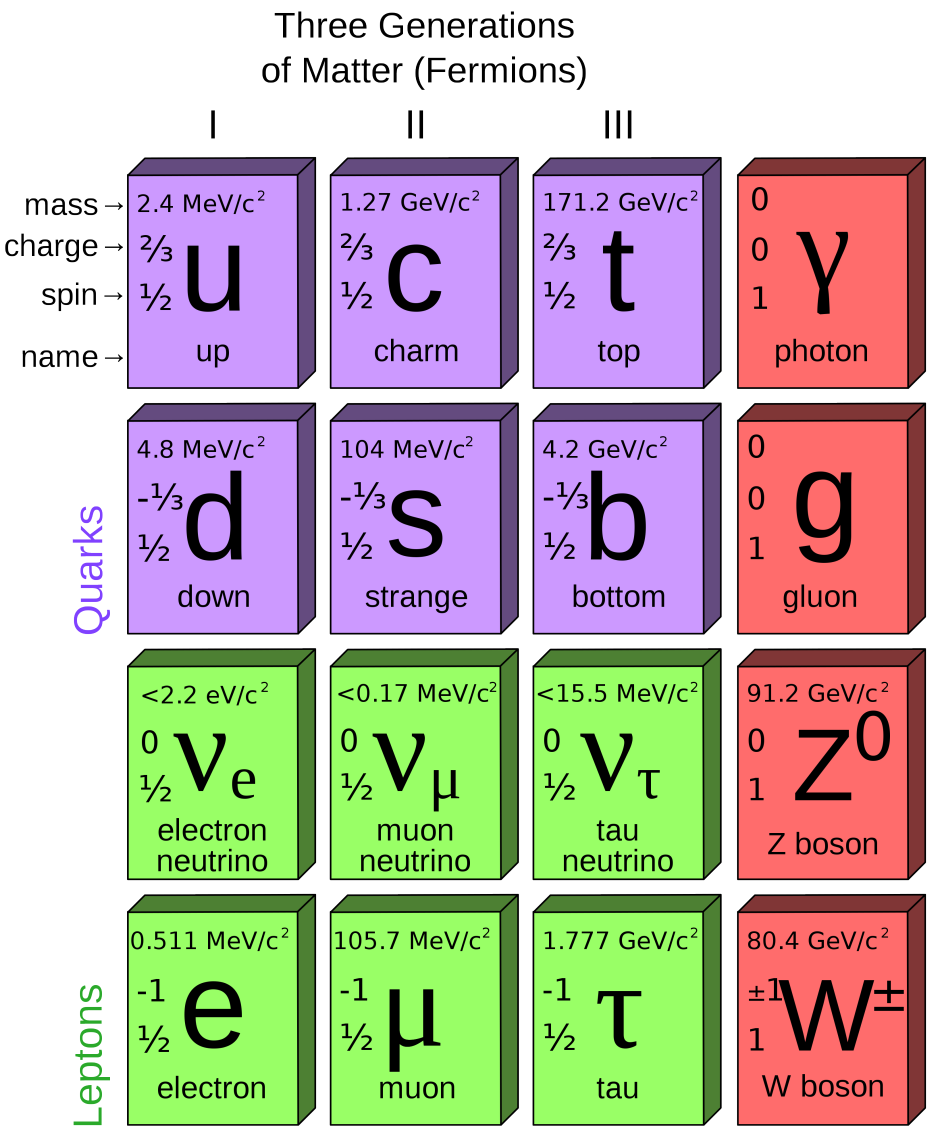
Exotic Physics and SUSY in ATLAS

Caterina Doglioni
on behalf of the ATLAS UniGe group

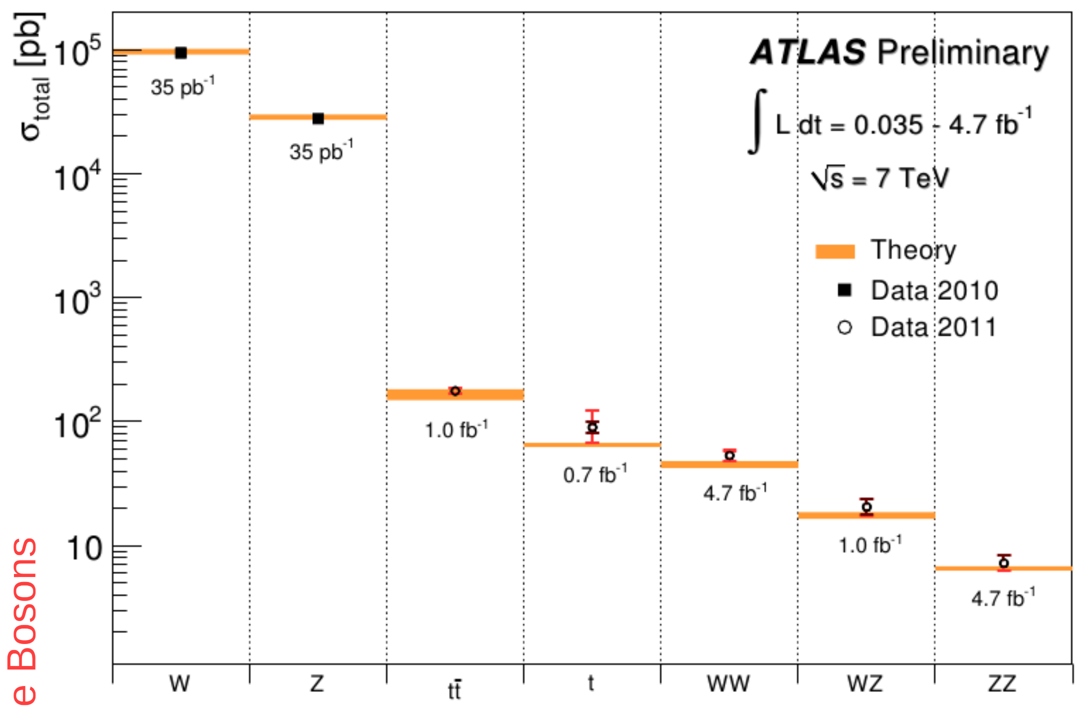
showing contributions by:
Attilio Picazio, Francesco Guescini, Moritz Backes, Philippe Mermod, Ashkay Katre, Ahmed Abdelalim, Gauthier Alexandre, Bertrand Martin, Xin Wu, Johanna Gramling

DPNC Journée de Réflexion – 18/06/2012

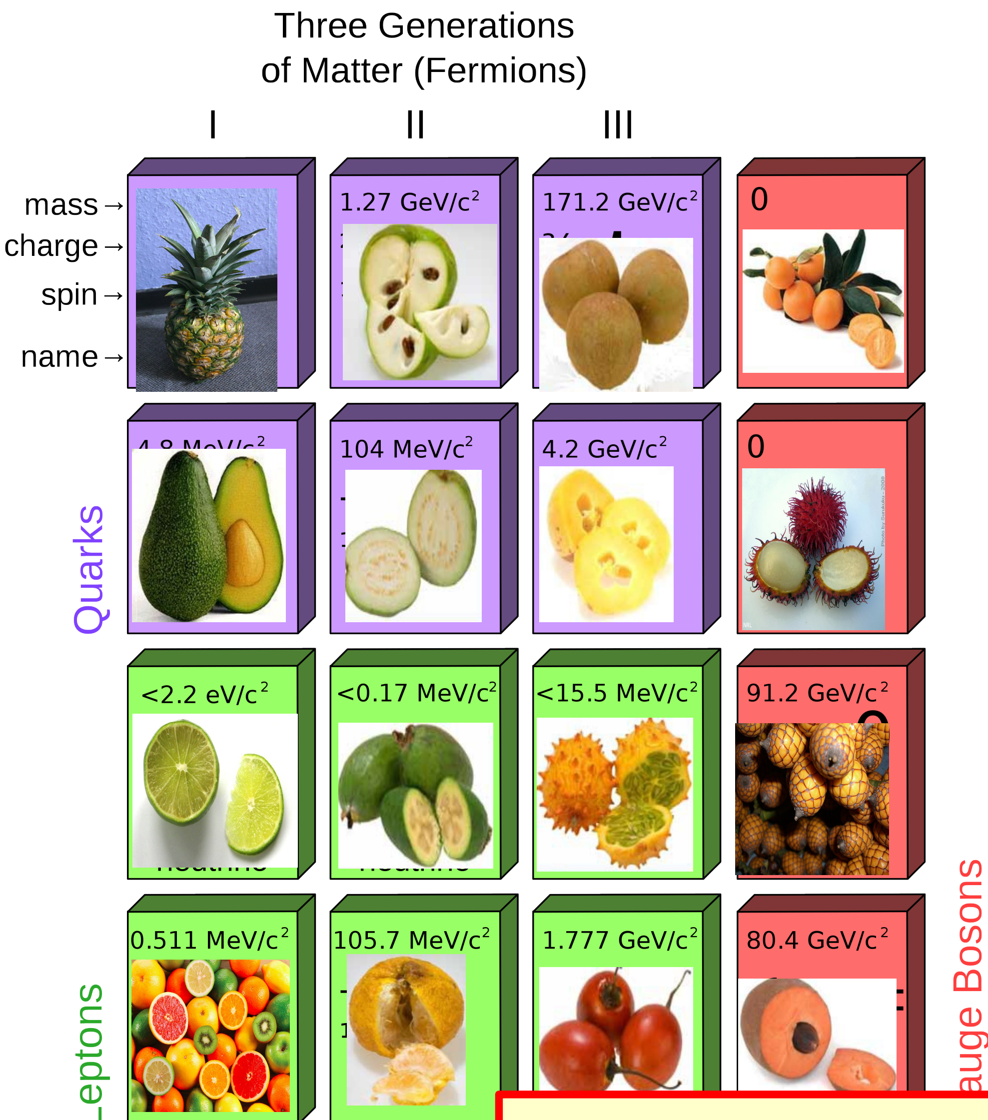
ATLAS has rediscovered the expected...



Summary plot of SM cross sections
vs theory expectations



...but what about the unexpected?



Looking **beyond** the Standard Model

Exotic physics:

- **Dijet searches:** look for new phenomena in dijet final states
- **Dark matter:** look for escaping particles (missing mass)
- Look for **magnetic monopoles**
- **Excited leptons:** look for signs of lepton compositeness

Supersymmetry:

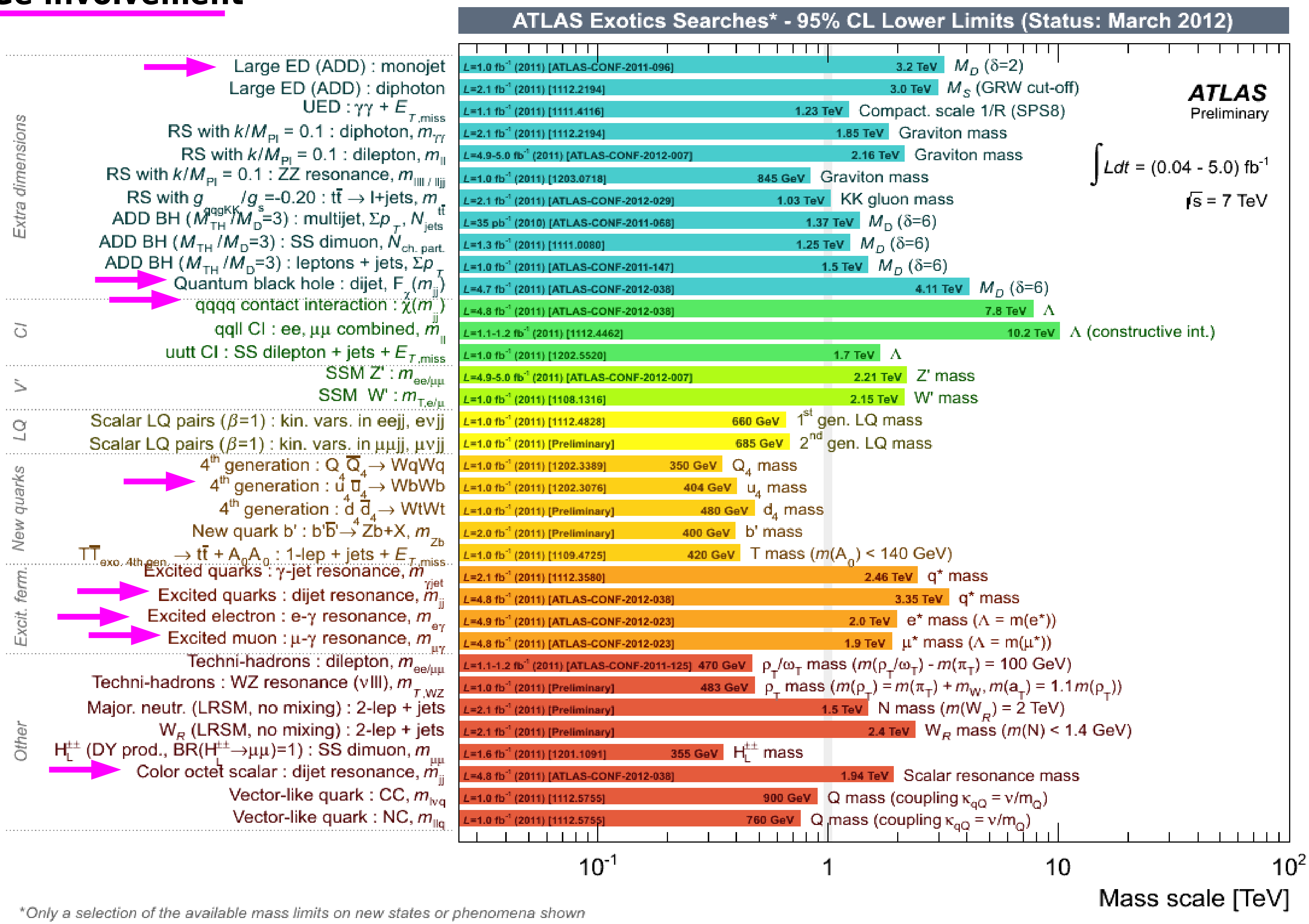
- **Compressed SUSY:** look for SM partner particles manifesting as missing energy

This talk: (short) selection of ATLAS results with DPNC involvement

UNIVERSITÉ DE GENÈVE

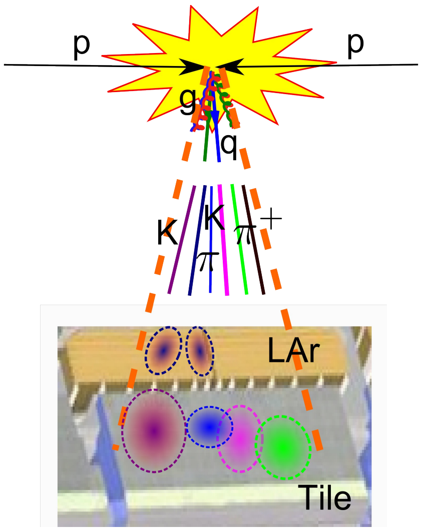
Non-SUSY, beyond the Standard Model

UniGe involvement



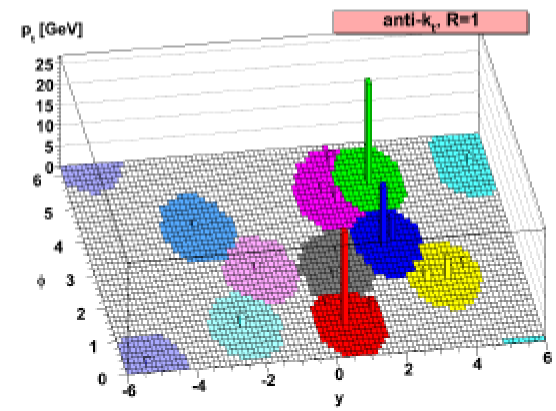
Input to dijet searches: jet performance

CD, Francesco Guescini, Attilio Picazio

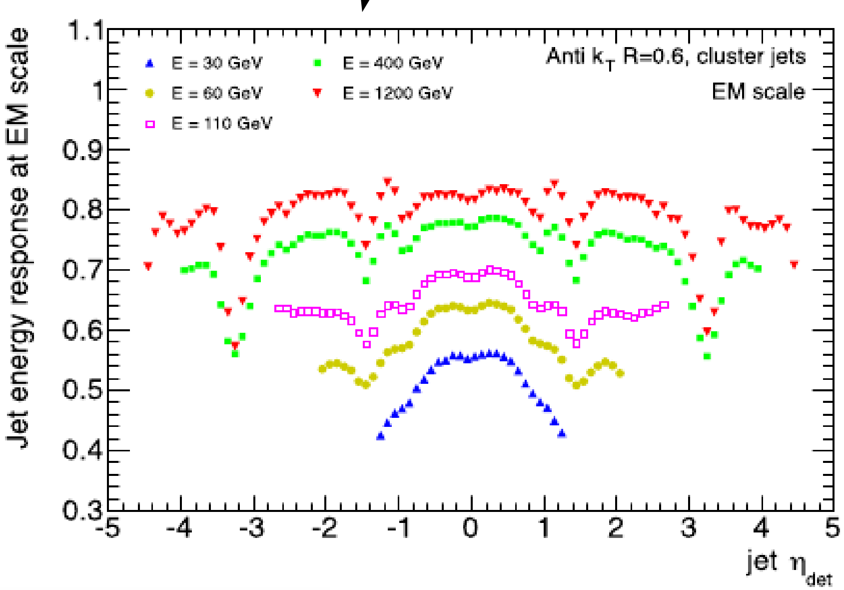


From calorimeter **energy deposits** to **hadronic jets:**
DPNC input to

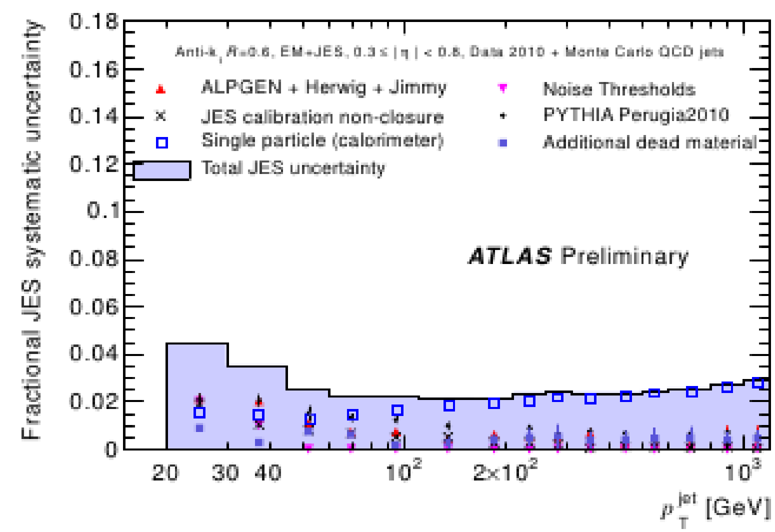
- Jet reconstruction and calibration
  - Jet energy scale uncertainty (dominant systematic for many LHC measurements)



[Cacciari, Salam, Soyez JHEP 0804:063,2008]



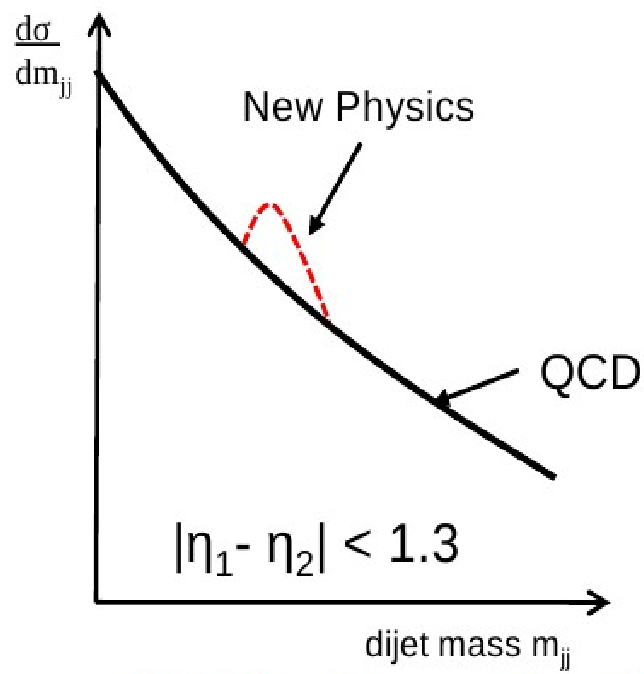
$<$2.5% for central jets, p_T =100 GeV
$<$9 (14)% for endcap (forward) jets



Beyond the SM with dijets: 2011

CD, Francesco Guescini

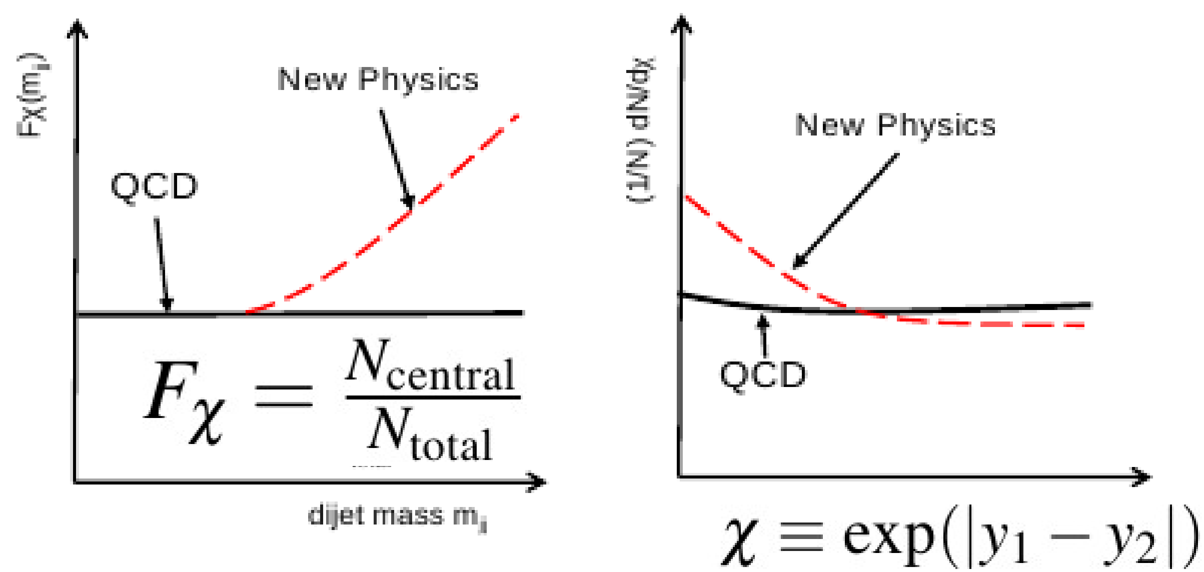
Search in the **mjj mass spectrum**



[F. Ruehr, LPCC Workshop on Higgs/BSM]

Sensitive to invariant mass **'bumps'**: signs of i.e. excited quarks (→ parton substructure)

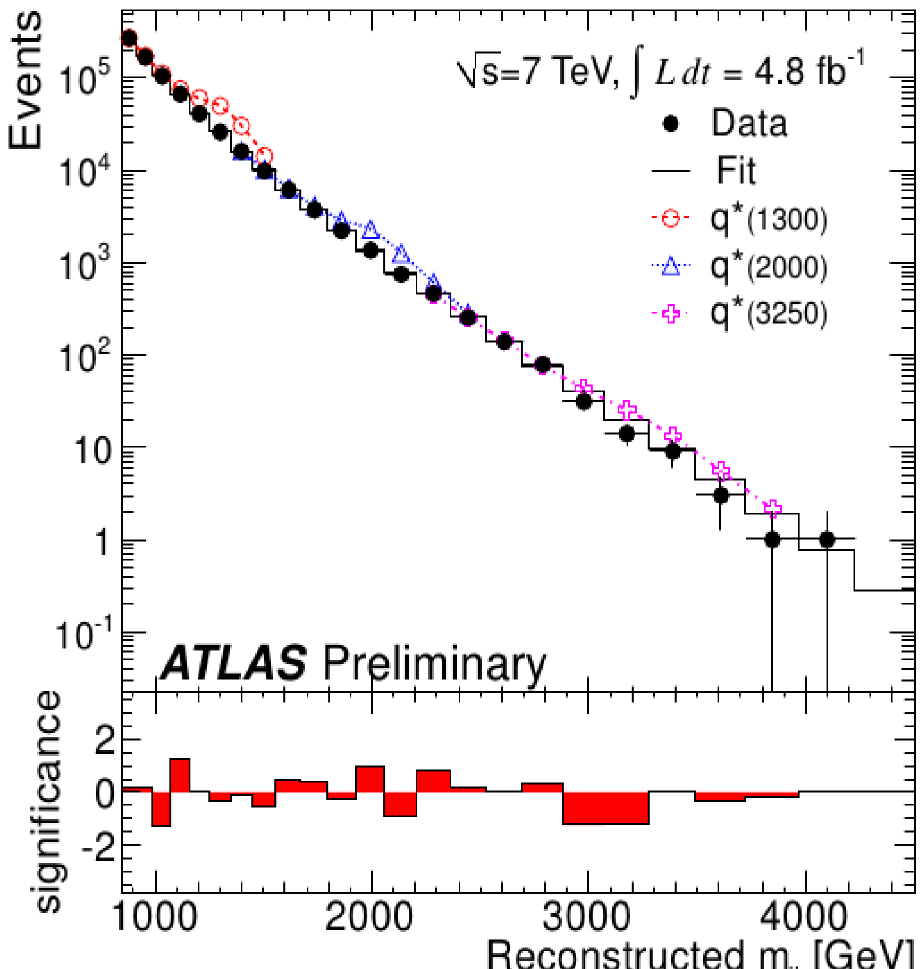
Search in **dijet angular distributions**



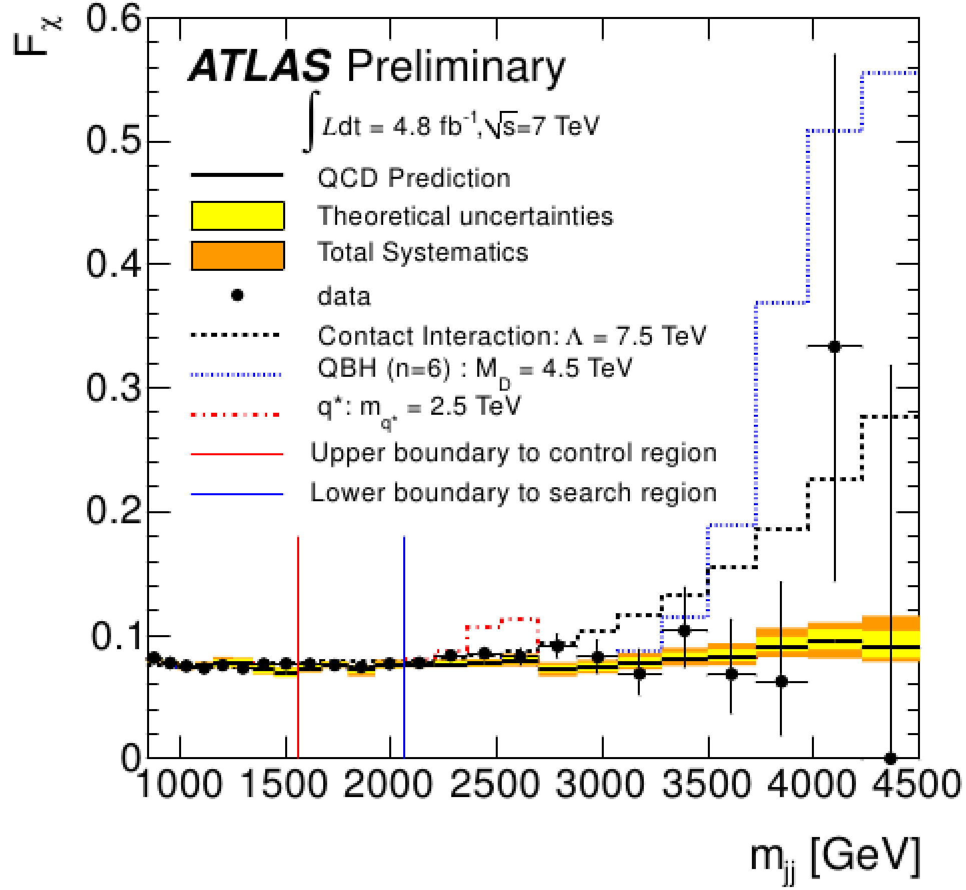
Sensitive to slow **deviations from QCD** (excesses at high scattering angles): signs of i.e. micro-black-holes, contact interactions...

Beyond the SM with dijets: 2011

Search in the **mjj mass spectrum**



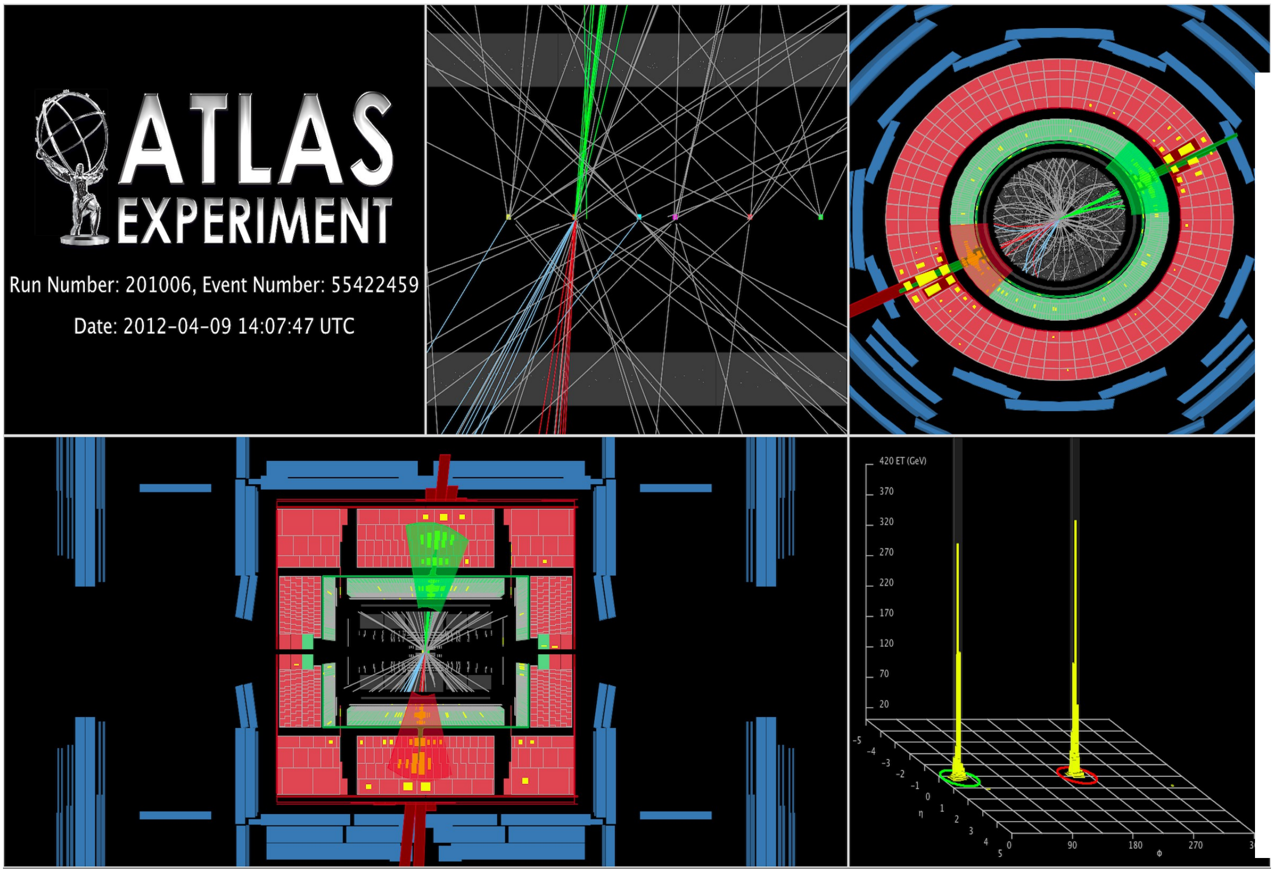
Search in **dijet angular distributions**

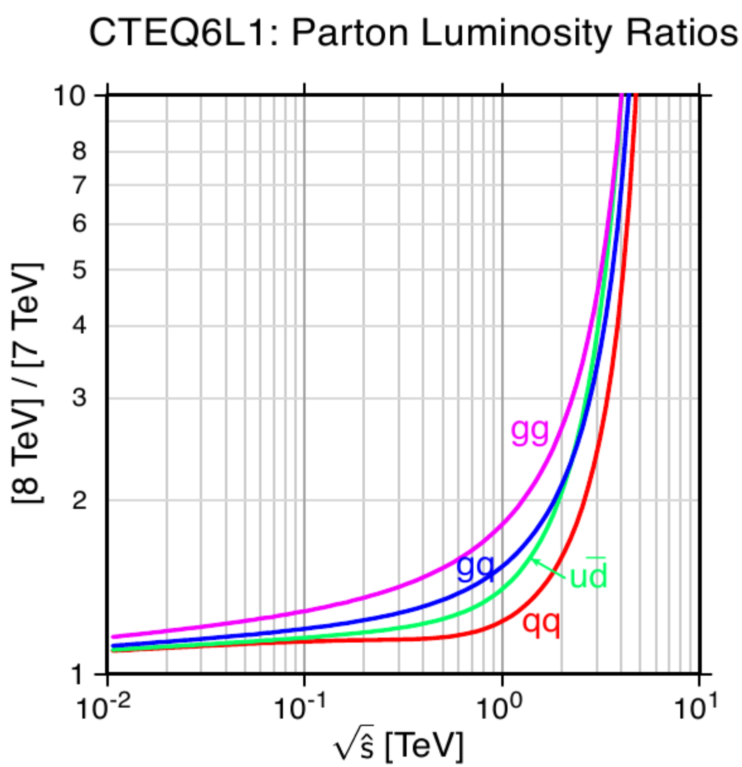


Beyond the SM with dijets: 2012

CD, Francesco Guescini, Attilio Picazio

Highest dijet mass event recorded up to end of April 2011: mjj ~ 3.6 TeV



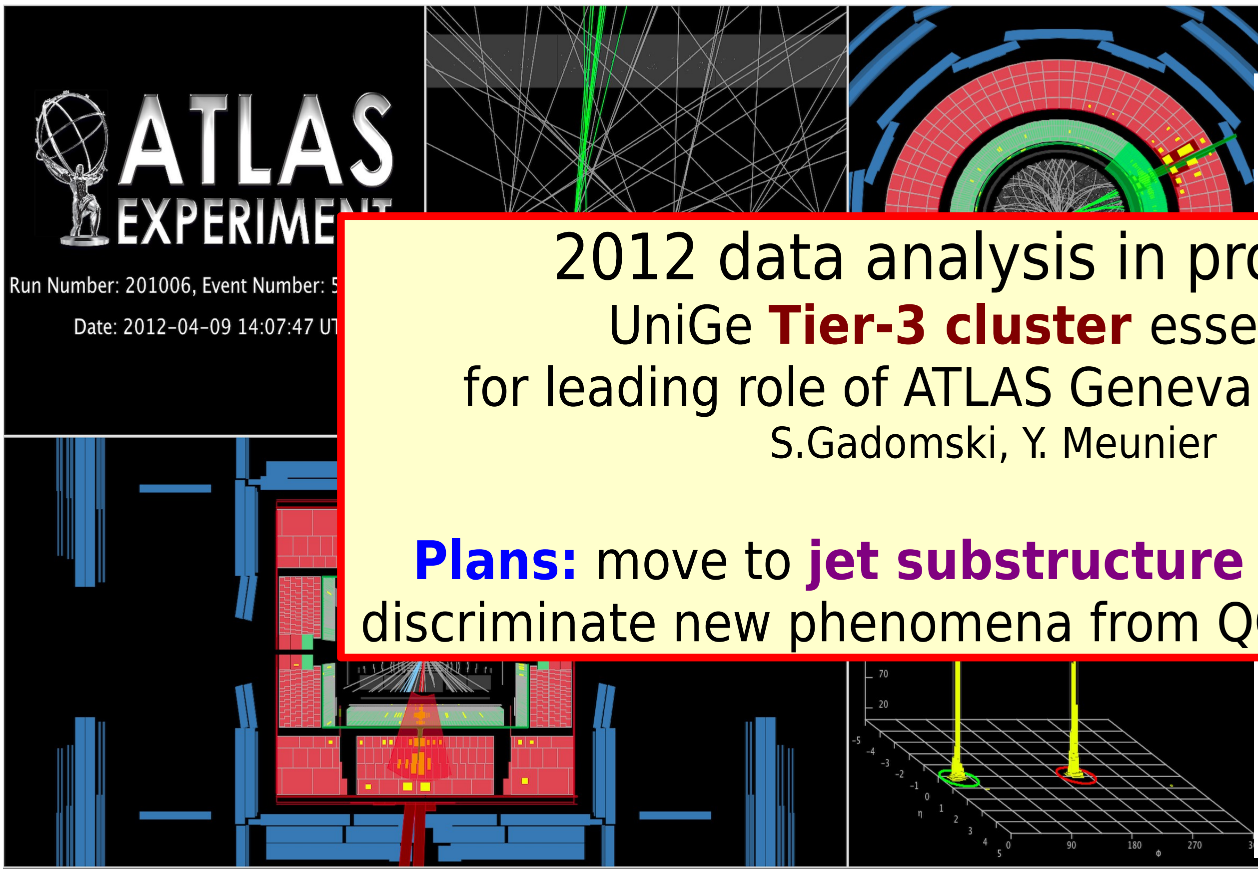


LHC: √s=7 TeV → √s=8 TeV: increase in cross sections (→ sensitivity)

Beyond the SM with dijets: 2012

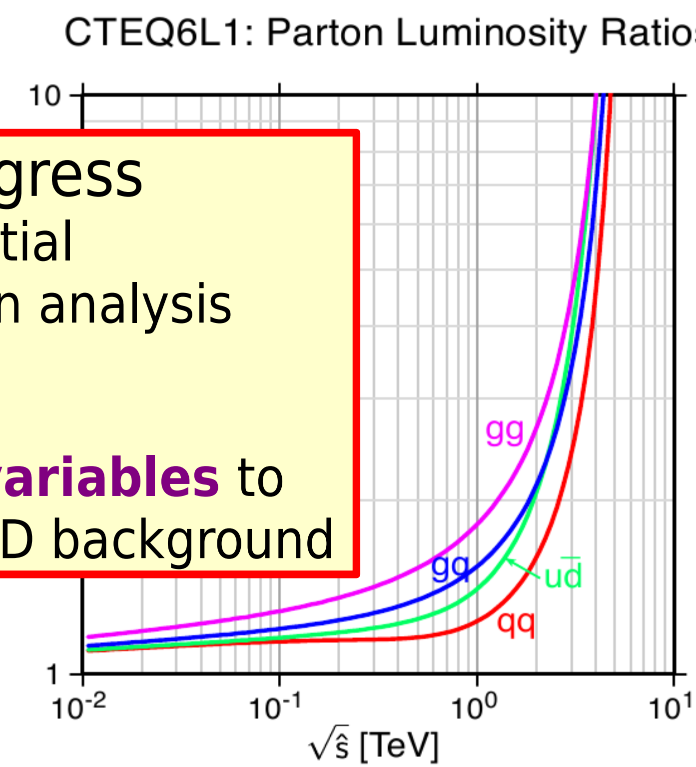
CD, Francesco Guescini, Attilio Picazio

Highest dijet mass event recorded up to end of April 2011: mjj ~ 3.6 TeV



2012 data analysis in progress
UniGe **Tier-3 cluster** essential
for leading role of ATLAS Geneva in analysis
S.Gadomski, Y. Meunier

Plans: move to **jet substructure variables** to discriminate new phenomena from QCD background

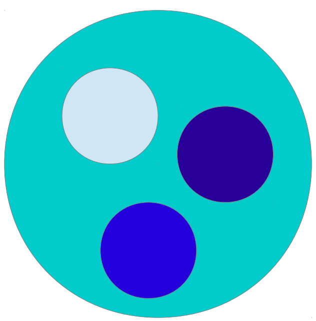


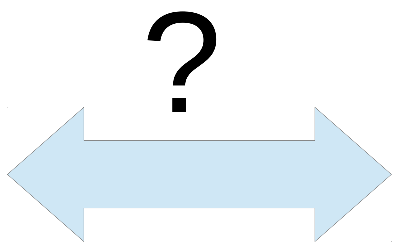
LHC: √s=7 TeV → √s=8 TeV: increase in cross sections (→ sensitivity)

Excited leptons

Ahmed Abdelalim, Gauthier Alexandre, Bertrand Martin

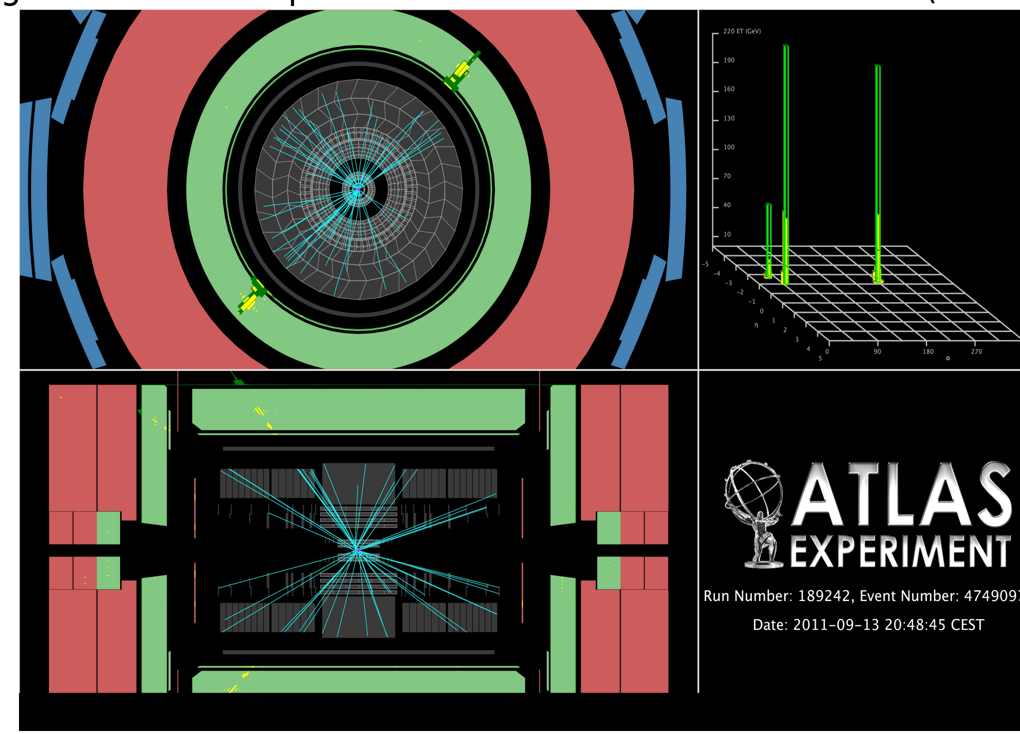
Composite leptons:
can be excited
and emit radiation





$$\ell^{*\pm} \rightarrow \ell^{\pm}\gamma$$

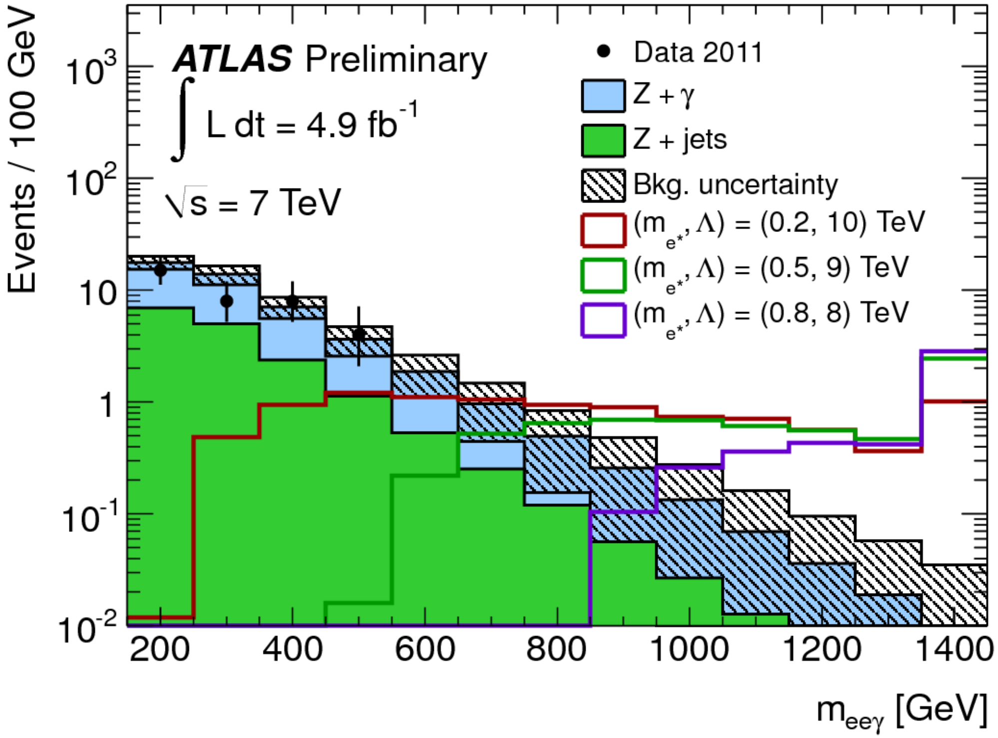
Highest dielectron-photon invariant mass event in 2011 (550 GeV)



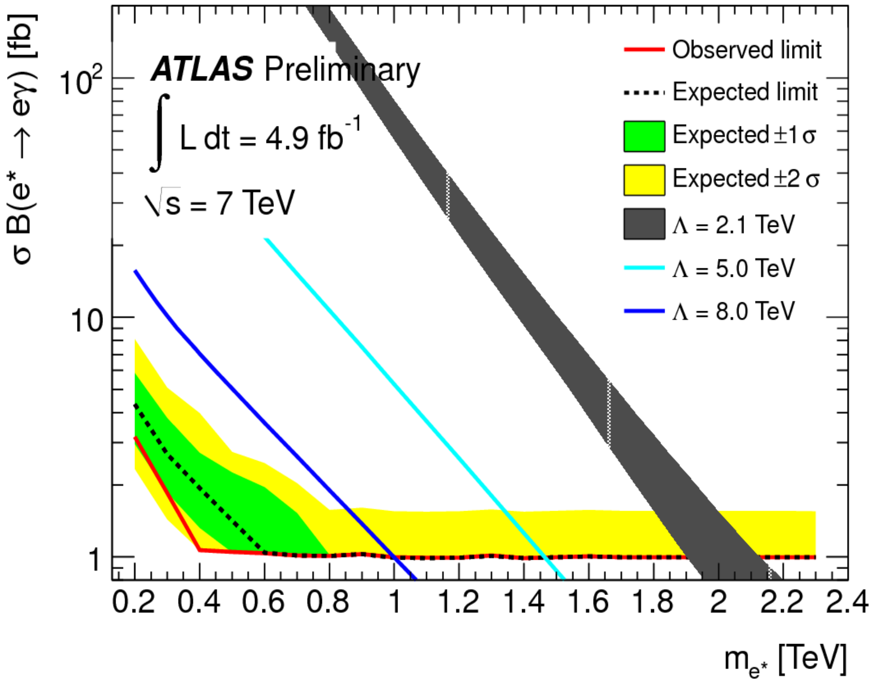
Idea for this analysis:

Search for excesses in tails of *llγ* distribution
Evaluate backgrounds by extrapolation from control to signal region

Excited leptons



Dielectron-photon invariant mass



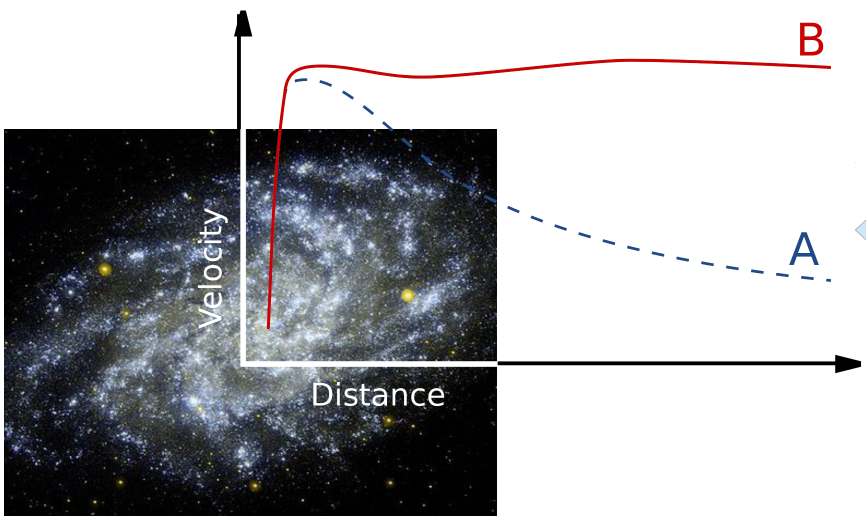
95% CL exclusion limits for excited electrons

Plans: join starting 2012 effort, add decay channel $\mathbf{l^* \rightarrow l l l' l'}$
(4-lepton final state → lower backgrounds,
more favourable branching ratio for high l* masses)

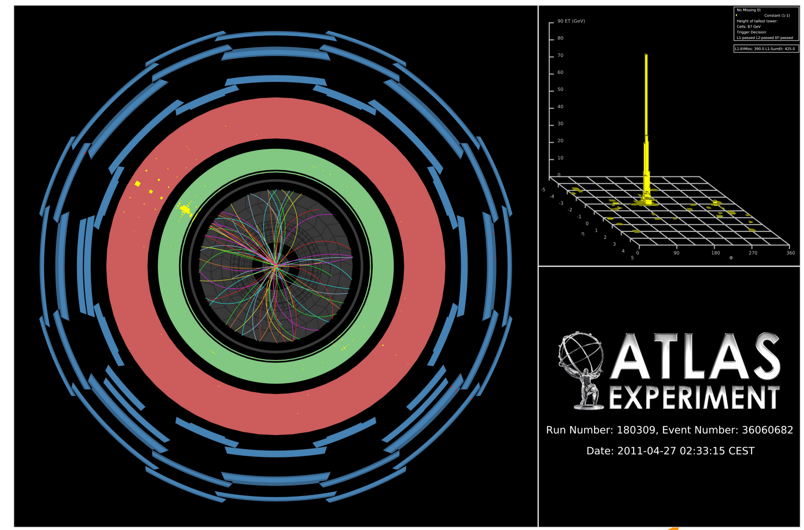
Dark Matter Search at LHC: jets + MET

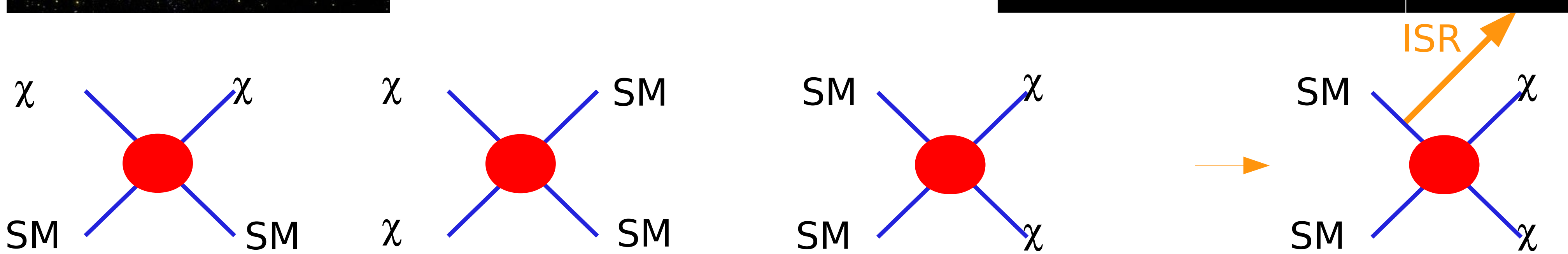
Johanna Gramling, Xin Wu

- Evidence for Dark Matter: Mass determined by light emission ≠ mass determined by motion ⇒ **Dark “Mass”!**



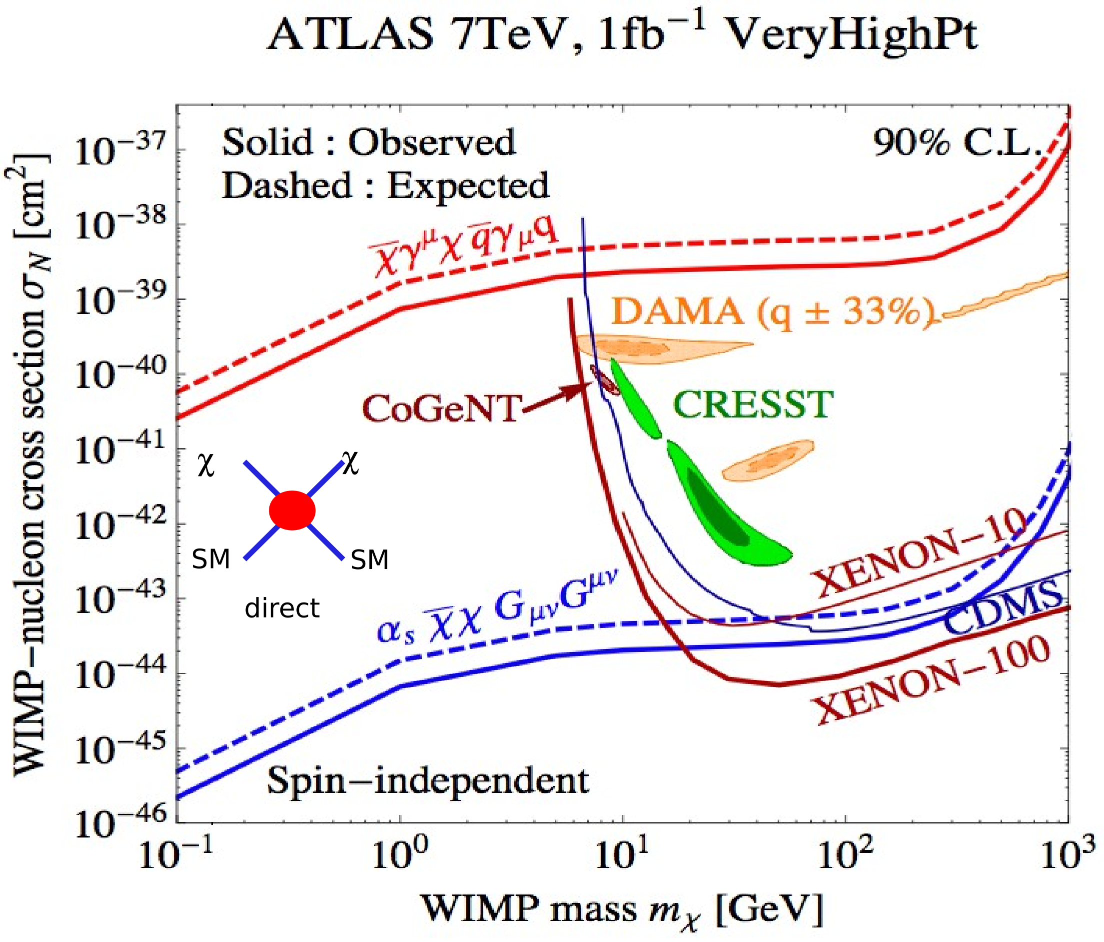
?





direct	indirect	collider: invisible →	visible
hadronic recoil: deep underground, cryogenic	cosmic rays: ground-based or space observatories	missing transverse energy in particle collisions →	**Monojets** Monophotons

WIMP limits from Monojets



arXiv:1109.4398

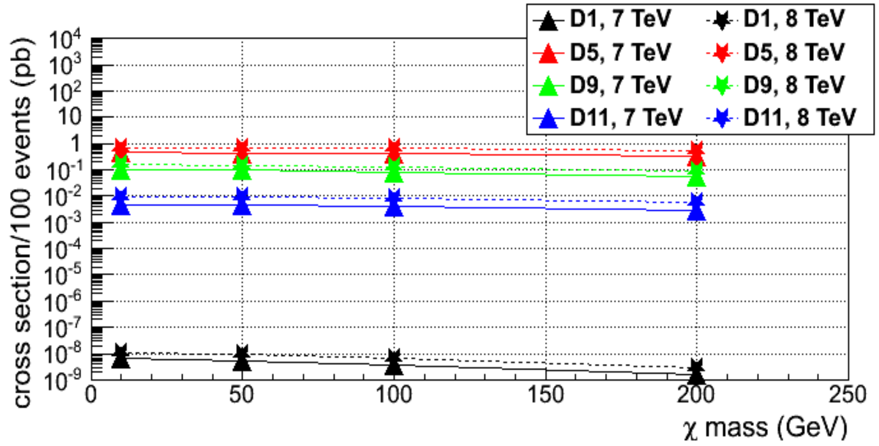
- LHC limits do not suffer from astrophysical uncertainties
- LHC limits reach to low WIMP masses → complementary to direct detection!
- Reach of LHC limits comparable to other experiments

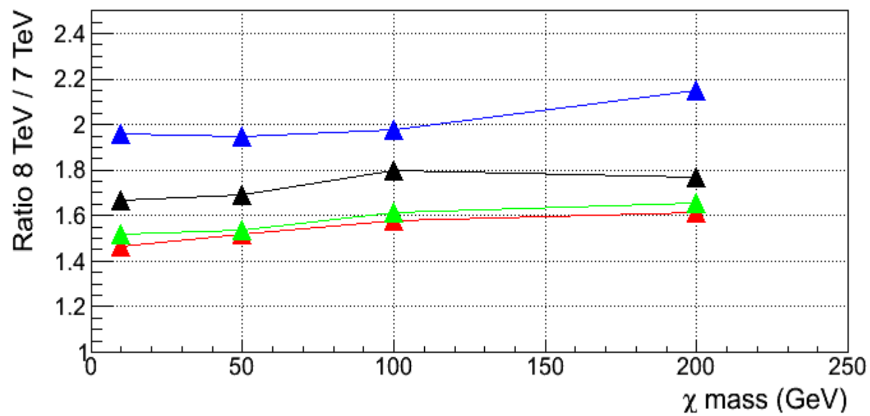
Outlook for WIMPs @ LHC

- Finalising analysis of 2011 dataset (4.7 fb^{-1})
- 2012 data: pp collisions @ 8 TeV:
  DPNC involvement

  → x-sections: 1.5 – 2 times higher wrt 7 TeV!

  – Focus on cut optimization for WIMP signals
  – Further studies of background/performance
  – MC generation and validation ongoing
- “Take over” interpretation of ATLAS results: direct & indirect detection results
  – Better knowledge of systematic effects
  – Profit from close exchange with theorists





DPNC-wide collaboration planned

Monopole Searches at LHC & beyond

Akshay Katre, Philippe Mermod

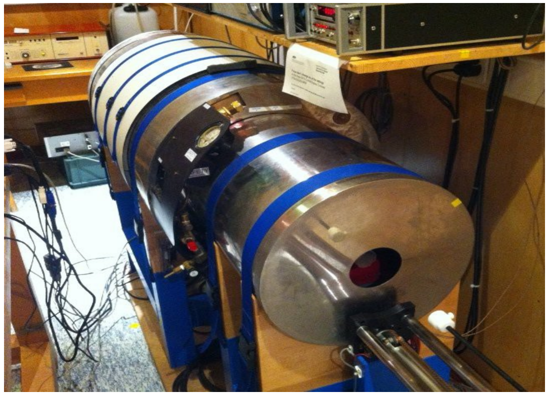
Dirac argument (1931)

- Pole of magnetic charge would explain electric charge quantisation: $g/e = 68.5n$
- Large coupling to the photon → very high **dE/dx**

Large Hadron Collider

Strong **DPNC involvement** in several **complementary** monopole searches:

- Flying through ATLAS
- Trapped in LHC accelerator material
- Trapped inside the Earth



SQUID magnetometer

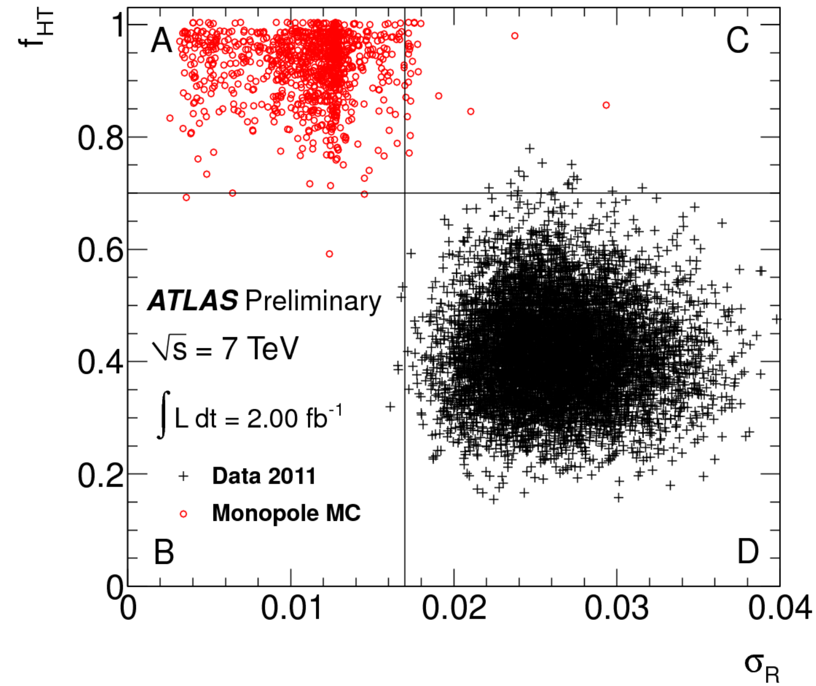
Monopoles in ATLAS

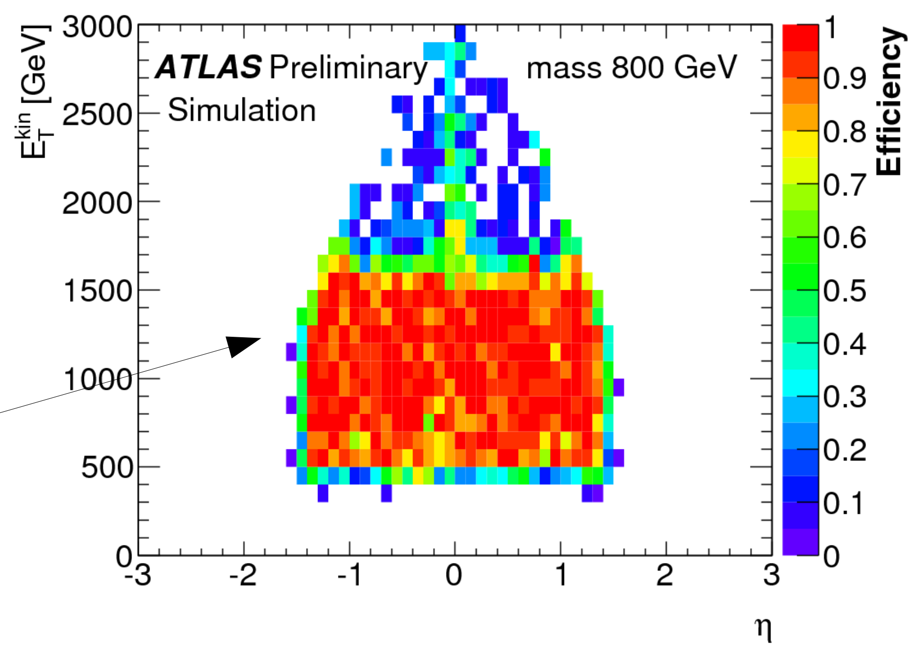
First ATLAS monopole search (almost) published: [insert reference here]

- Signature: high ionisation in TRT and narrow cluster
- Uses standard EM triggers → **sensitive only to high energy or low charge (1g_D)**

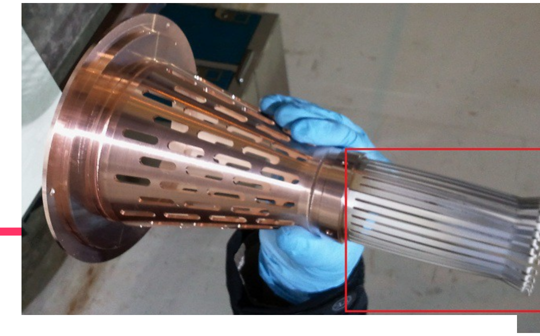
New high-level trigger algorithm under development in our group

- Based on TRT HT hit fraction
- Recover low-energy monopoles → **large acceptance increase**
- Validation ongoing, expected to run for second half of 2012

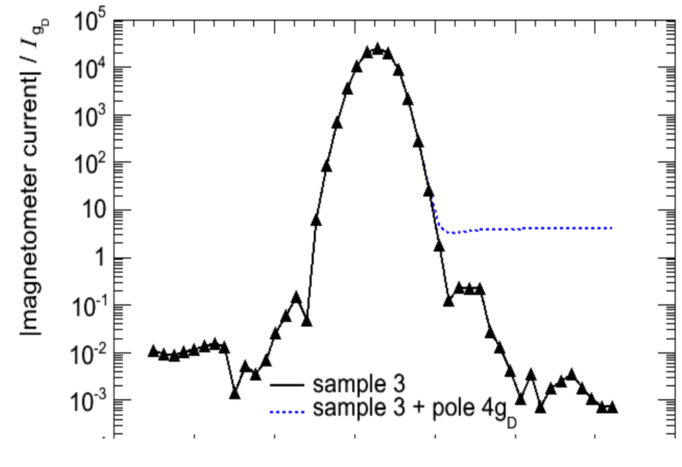




Trapped monopoles



SQUID magnetometer measurements
performed at ETH Zürich



- Using accelerator material in full view of CMS collisions
- **Proof of principle – article under publication**

Future proposals

1) **ATLAS and CMS beam pipes** to be replaced next year

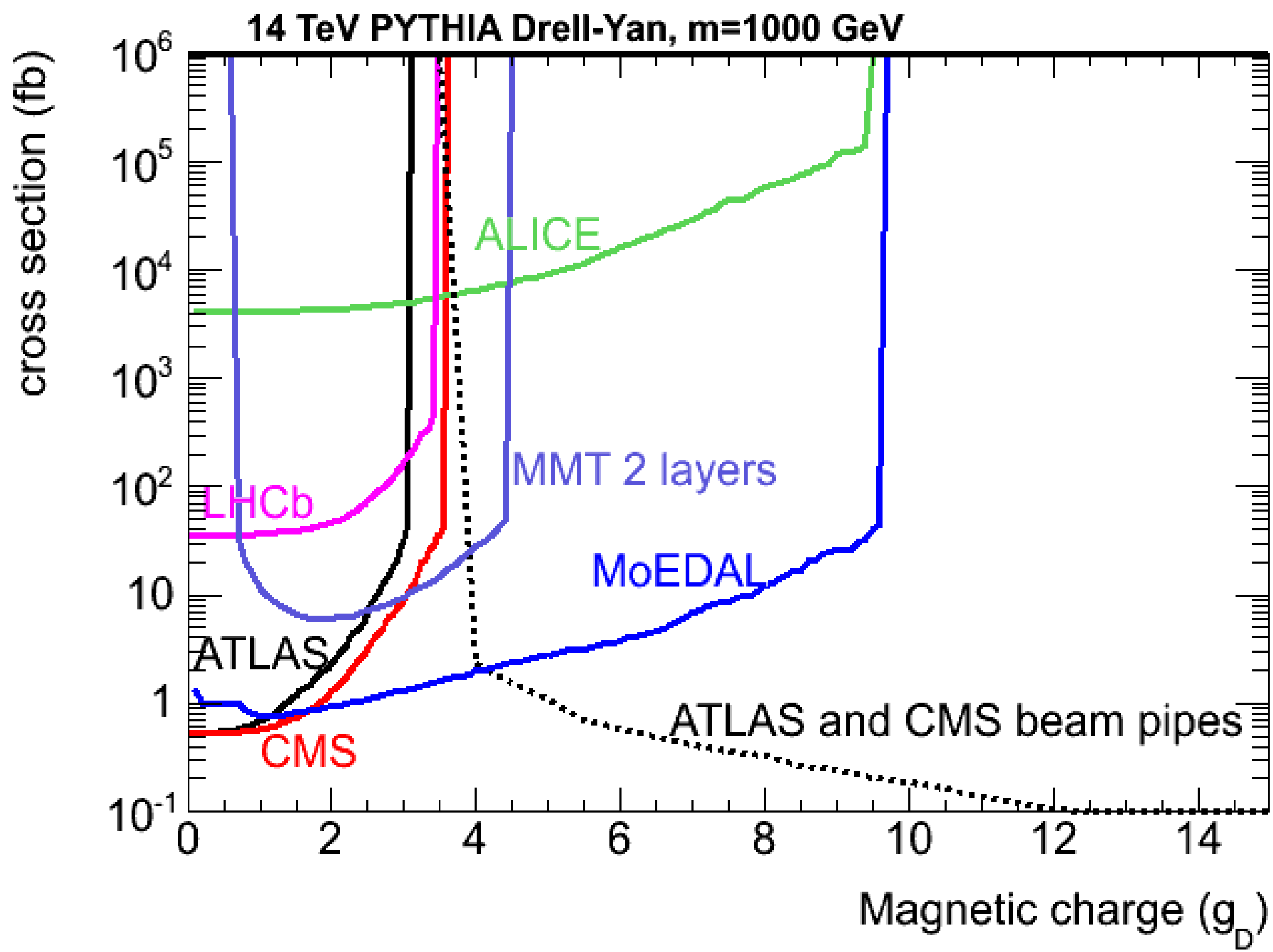
- Sensitivity to very high magnetic charges

2) **MoEDAL monopole trap** (MMT) near LHCb

- **DPNC is joining the MoEDAL experiment!**
- Complementary MoEDAL **subdetector**: array of Aluminium modules on the floor of th VELO cavern
- Analysis is QUICK → first 14 TeV monopole results

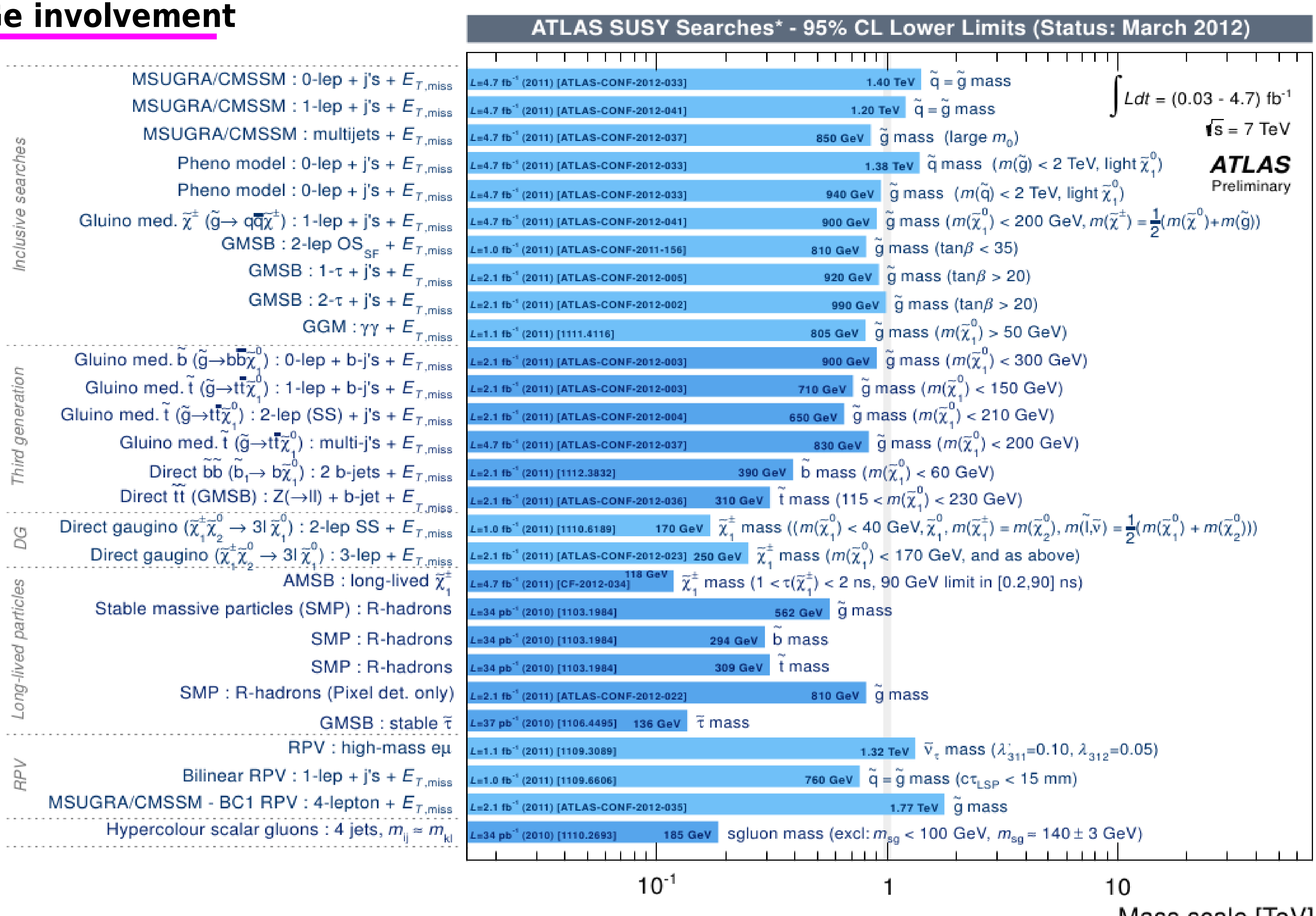
Monopoles at the LHC: summary

Cross-section needed for discovery



SUperSYmmetric extensions to the SM

UniGe involvement

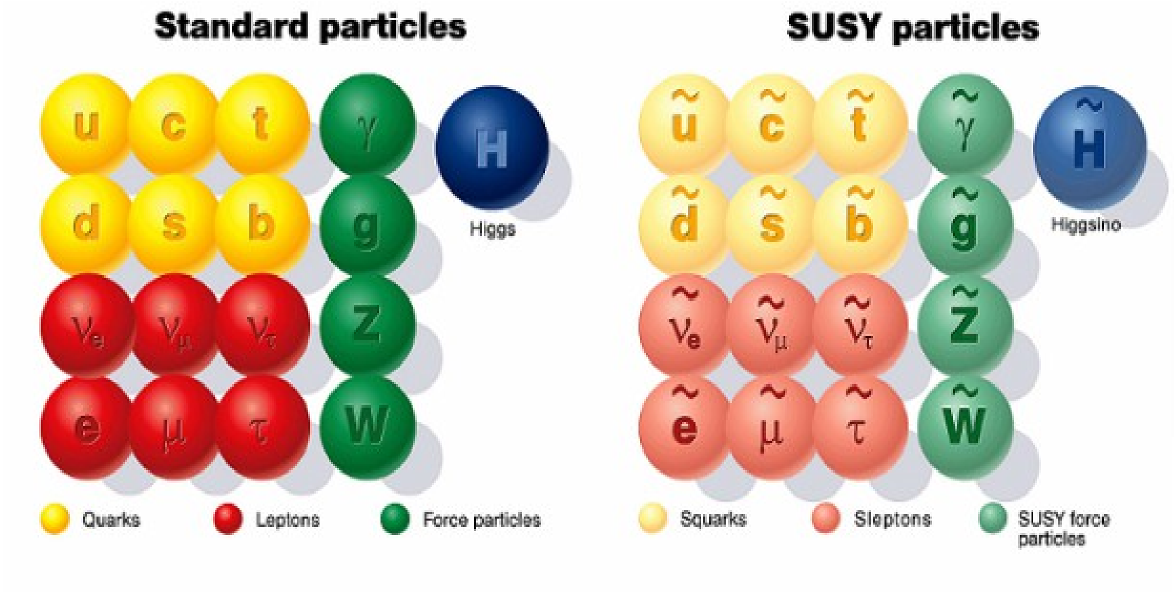


*Only a selection of the available mass limits on new states or phenomena shown

→ *Compressed SUSY*

Compressed SUSY analysis

Moritz Backes



ATLAS SUSY searches to date:

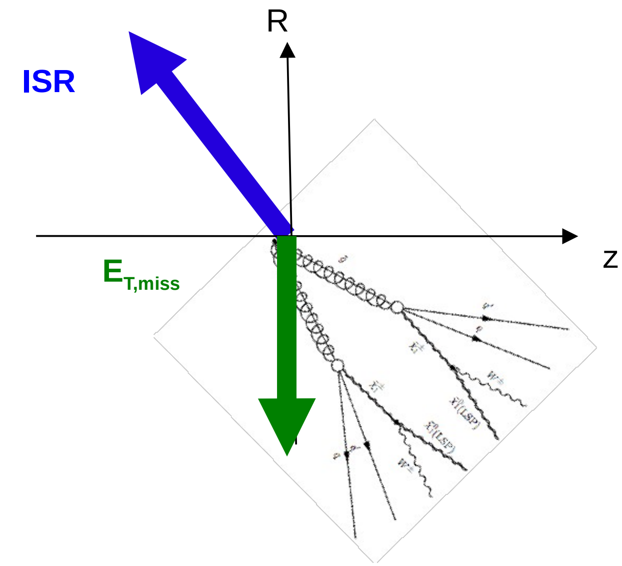
Final states with **jets**, **missing transverse energy** ($E_{T,miss}$)
and ≥ 0 **isolated high p_T leptons** in the final state

→ stringent limits on scenarios (cMSSM/mSUGRA) where **mass differences** between pair-produced superparticles and lightest supersymmetric particles (LSP) are **large**.

...what if mass differences are small (compressed SUSY)? DPNC analysis

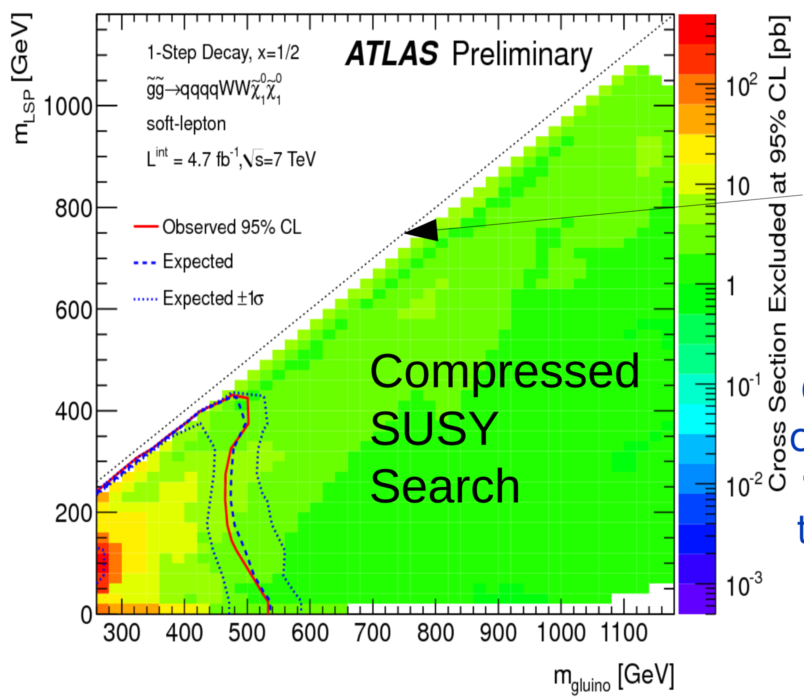
Compressed SUSY analysis results

Select events with:
Exploit ISR of jet recoiling against SUSY particle
Low p_T electrons, High p_T jets, High $E_{T,miss}$



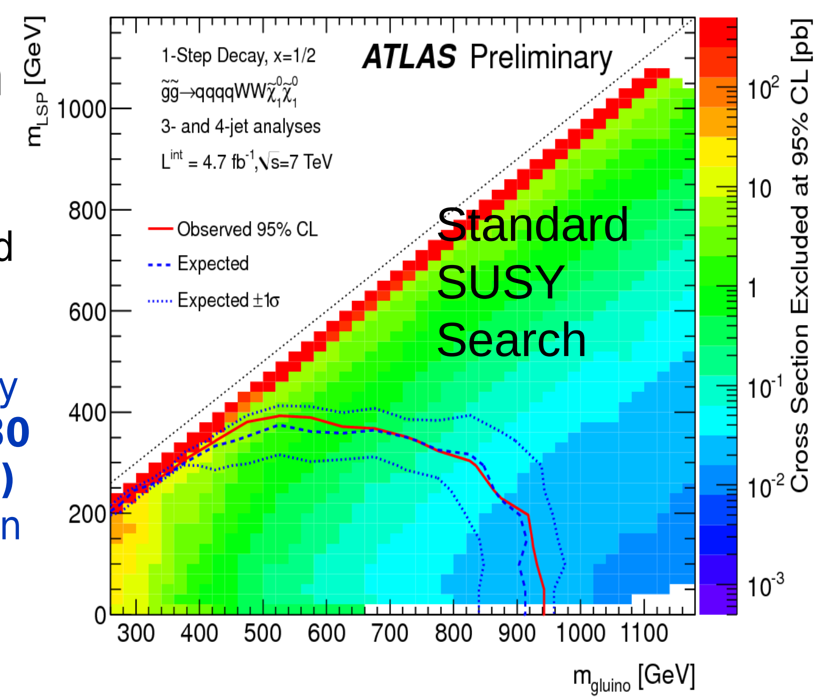
Backgrounds:
take from control regions, data-driven method, MC simulation (small contributions)

Use **Simultaneous Global Likelihood Fit**
to constrain/extrapolate dominant backgrounds



Improvement in exclusion limits
near diagonal region interesting for compressed SUSY

Cross-section **excluded** by compressed search is **20-30 times lower (i.e. better)** than the standard search in this region.



Conclusions

Looking **beyond** the Standard Model → **no** new physics yet!
DPNC ATLAS group **keeps on looking** and contributing to:

Supersymmetry

Compressed SUSY models: *new paper will be published soon*

Exotic physics

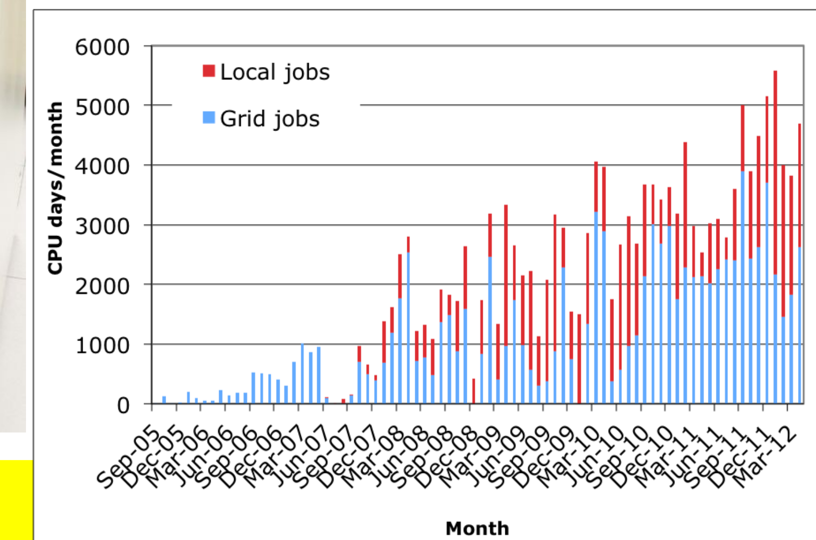
Dijet searches: *2011 paper in final stages, 2012 analysis ongoing*
Dark matter: *2012 monojet analysis ongoing*
Magnetic monopoles: *2011 paper in final stages, work for 2012 (within and beyond ATLAS) started*
Excited leptons: *2011 paper in final stages*

We're just at the **beginning** of searches at the LHC!

Backup slides

The ATLAS Tier-3 at the Uni of Geneva

- **368 CPU cores**
- **466 TB net**
  - **284 in a grid SE (DPM)**
  - **129 NFS, 54 reserve**
- **10 Gb/s direct to CERN IT**
  - **now also to Swiss academic network**
- **used for ATLAS, T2K et FAST**
- **ATLAS grid jobs using spare CPU cycles**
- **managed in collaboration with the Dinf**



Use by month since 2005

Compressed SUSY searches - Introduction

Inclusive Supersymmetry searches published to date by ATLAS:

•Searches with jets, missing transverse energy ($E_{T,miss}$) and ≥ 0 isolated high p_T leptons in the final state.

•Stringent limits on cMSSM / mSUGRA scenarios and simplified models, where the mass differences (ΔM) between the pair-produced super-particles and the lightest supersymmetric particle (LSP) are large.

Idea of this analysis:

•Search for models where the mass splittings between SUSY particles are small ('compressed' models).

Challenge:

•Small acceptance due to soft decay products (leptons, jets) and small missing transverse energy ($E_{T,miss}$) due oppositely aligned LSPs.

→Select events with an additional hard jet from initial state radiation (ISR)which recoils against the SUSY particles leading to more collinear LSPs and thus increased $E_{T,miss}$.

→Select events with additional soft jets and one isolated low p_T lepton form the SUSY decay in the final state.

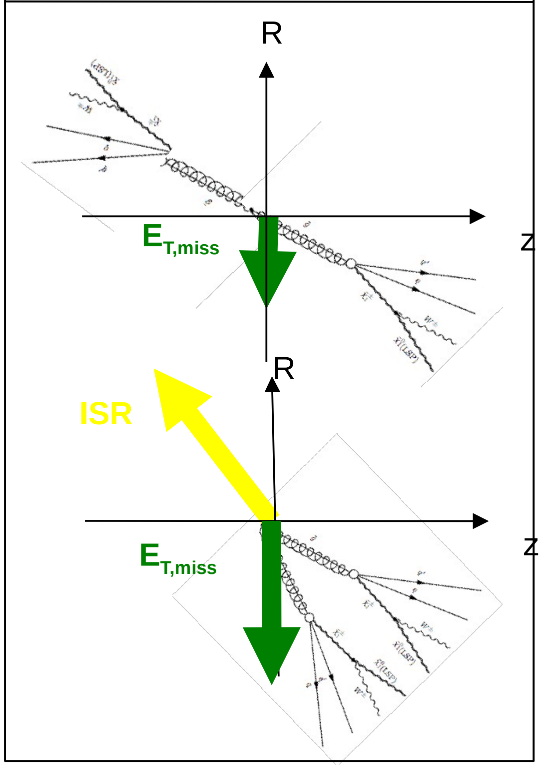
Interpretation of results in Simplified Models:

•Simple decay chains with a limited spectrum of SUSY particles.

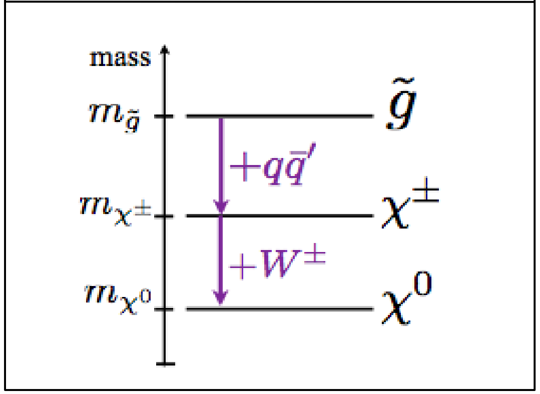
•Parameterization in terms of SUSY production cross-section, masses, decay branching ratios.

→ Cover models with small and large ΔM

Effect of ISR



1-step Simplified Model



Compressed SUSY searches – Analysis Overview

Event Selection:

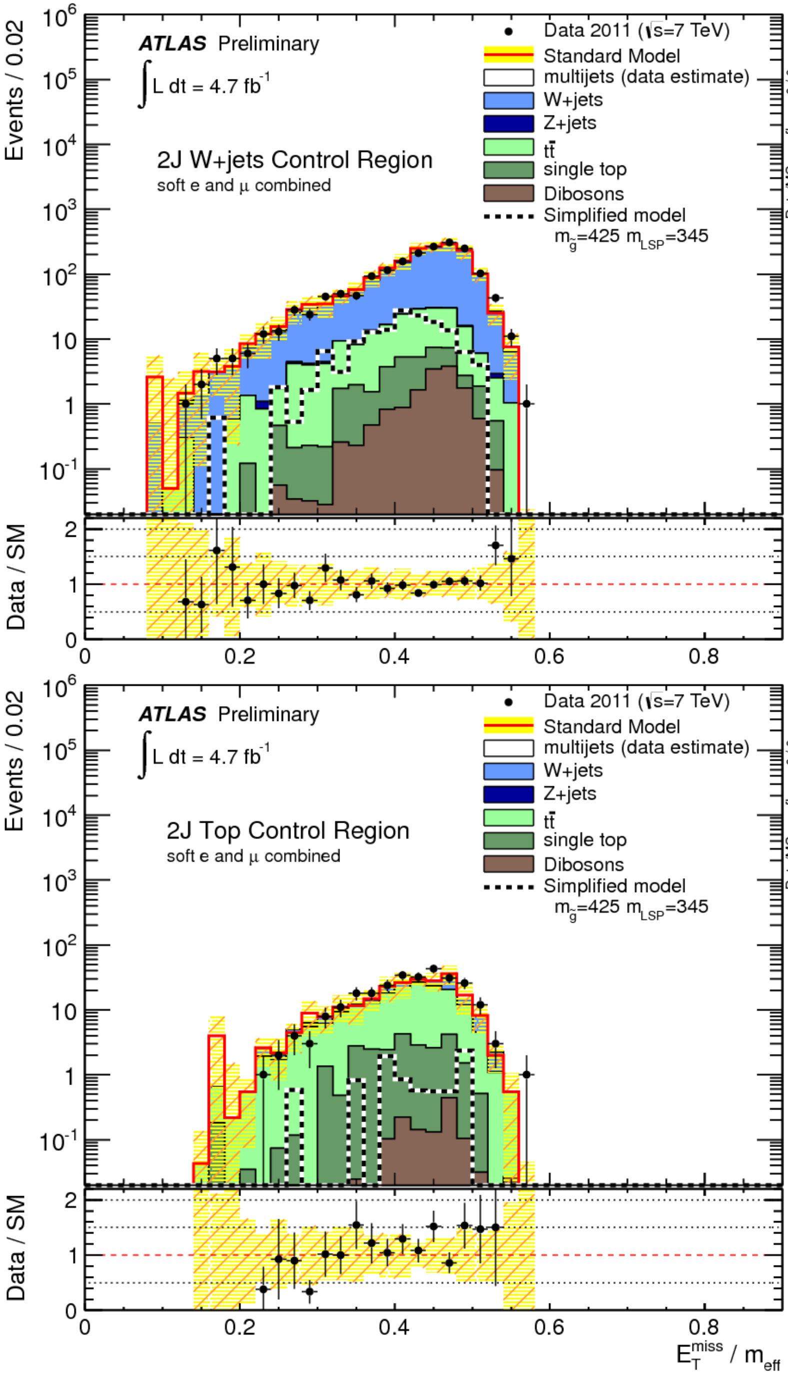
- $E_{T,miss}$ triggers
- One lepton with 7(6) GeV < p_T < 25 (20) GeV for electrons (muons)
- Leading jet p_T > 130 GeV, subleading jet p_T > 25 GeV
- $E_{T,miss}$ > 250 GeV
- m_T > 100 GeV
- $E_{T,miss}$ / M_{eff} > 0.3, where $M_{eff} = \Sigma\, p_T(\text{jets}) + p_T(\text{lepton}) + E_{T,miss}$

Backgrounds:

- Dominant contribution from W+jets, ttbar – estimated from dedicated control regions
- Small contribution from QCD (estimated with a data-driven method)
- Small contribution from remaining backgrounds taken from simulation (single top, diboson)

Simultaneous Fit:

- All information is combined into a global likelihood fit.
- Dominant backgrounds are constrained in the control regions and extrapolated to the signal regions using simulation.
- Validation regions in between the control and signal regions are used to test the validity of the method.



Compressed SUSY searches – Results and Outlook

Results:

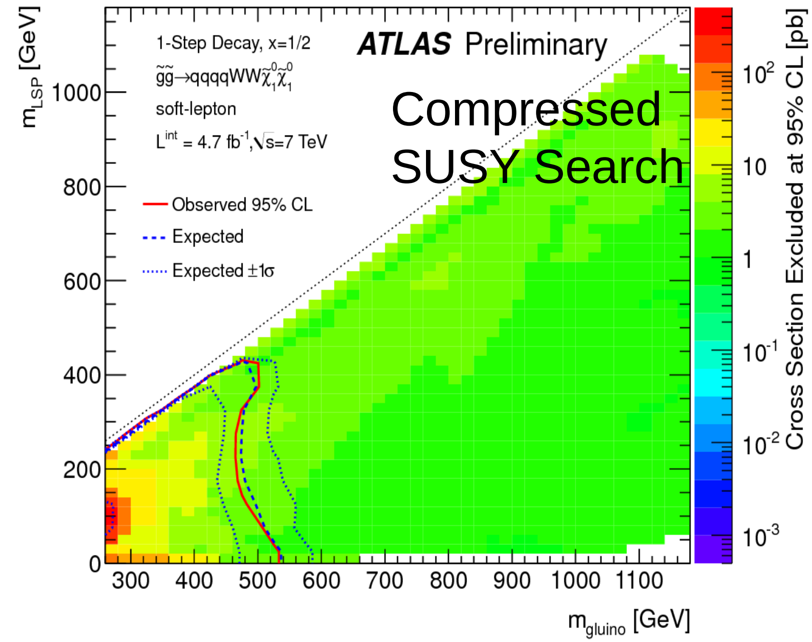
•No excess observed over the Standard Model expectation in 4.7 fb^{-1} (full 2011 ATLAS dataset)

•Derived limits in terms of a 1-step simplified model with gluino-gluino production and decay to the LSP via an intermediate chargino (see bottom Fig. page 1)

→Clear improvement of the compressed search (top) over the existing standard search (bottom) in the compressed region with low ΔM close to the diagonal.

→Cross-section excluded by the compressed search is 20-30 times lower (i.e. better) than the standard search in this region.

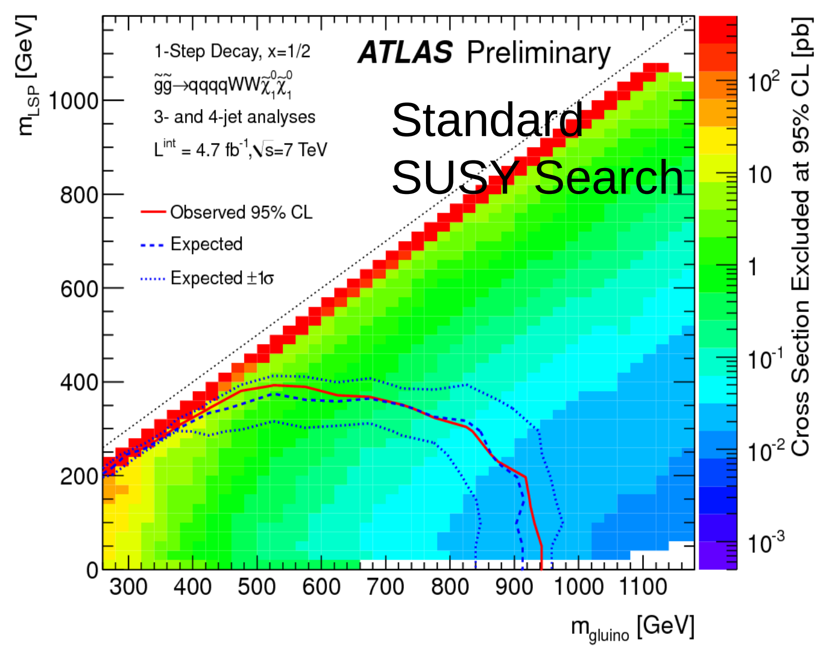
→Results public as conference note in ATLAS-COM-CONF-2012-038, https://cdsweb.cern.ch/record/1426982, March 2012.



Outlook:

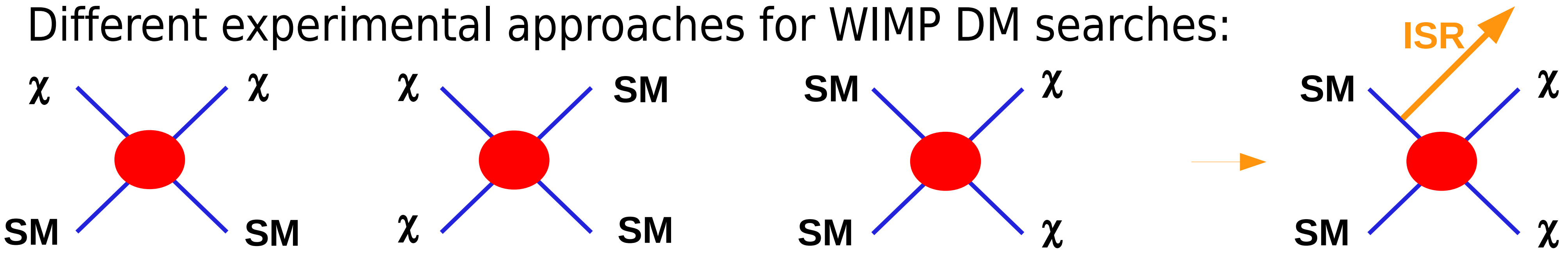
•A combined paper of all inclusive analysis with jets, $E_{T,miss}$ and ≥ 1 isolated lepton is undergoing ATLAS review at the moment and will be published in July.

•The analysis was carried out in close collaboration with the CERN SUSY group. Future involvement of the ATLAS Geneva group in SUSY searches to be determined.



Dark Matter Search at LHC: jets + MET

- Evidence for Dark Matter: Mass determined by light emission ≠ mass determined by motion ⇒ **Dark “Mass”!**
- Different experimental approaches for WIMP DM searches:



direct | **indirect** | **collider: invisible** → **visible**

hadronic recoil: deep underground, cryogenic

cosmic rays: ground-based or space observatories

missing transverse energy in particle collisions → **Monojets** Monophotons

- To predict signals and to “translate” and interpret different searches: Assumption about “red Bubble” needed -> **Contact interaction!**
  - Only χ in reach of LHC -> EFT
  - Coupling to SM set by m_χ and cutoff-scale M_* -> constrained by thermal relic density
  - χ is Dirac-Fermion

14 operators possible! Pick characteristic set:

$\frac{m_q}{M_*^3}\bar{\chi}\chi\bar{q}q$	**(D1)**	$\frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	**(D9)**
$\frac{1}{M_*^2}\bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q$	**(D5)**	$\frac{1}{4M_*^3}\bar{\chi}\chi\alpha_s\left(G^a_{\mu\nu}\right)^2$	**(D11)**

Full List of Interaction Operators

$$\frac{m_q}{M_*^3}\bar{\chi}\chi\bar{q}q \quad \text{(D1)}$$

$$\frac{m_q}{M_*^3}\bar{\chi}\gamma^5\chi\bar{q}q \quad \text{(D2)}$$

$$\frac{m_q}{M_*^3}\bar{\chi}\chi\bar{q}\gamma^5 q \quad \text{(D3)}$$

$$\frac{m_q}{M_*^3}\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q \quad \text{(D4)}$$

$$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q \quad \text{(D5)}$$

$$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q \quad \text{(D6)}$$

$$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_m u\gamma^5 q \quad \text{(D7)}$$

$$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q \quad \text{(D8)}$$

$$\frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q \quad \text{(D9)}$$

$$\frac{1}{M_*^2}\epsilon^{\mu\nu\alpha\beta}\bar{\chi}\sigma_{\mu\nu}\chi\bar{q}\sigma_{\alpha\beta}q \quad \text{(D10)}$$

$$\frac{1}{4M_*^3}\bar{\chi}\chi\alpha_s\left(G^a_{\mu\nu}\right)^2 \quad \text{(D11)}$$

$$\frac{1}{4M_*^3}\bar{\chi}\gamma^5\chi\alpha_s\left(G^a_{\mu\nu}\right)^2 \quad \text{(D12)}$$

$$\frac{1}{4M_*^3}\bar{\chi}\chi G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} \quad \text{(D13)}$$

$$\frac{1}{4M_*^3}\bar{\chi}\gamma^5\chi G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} \quad \text{(D14)}$$

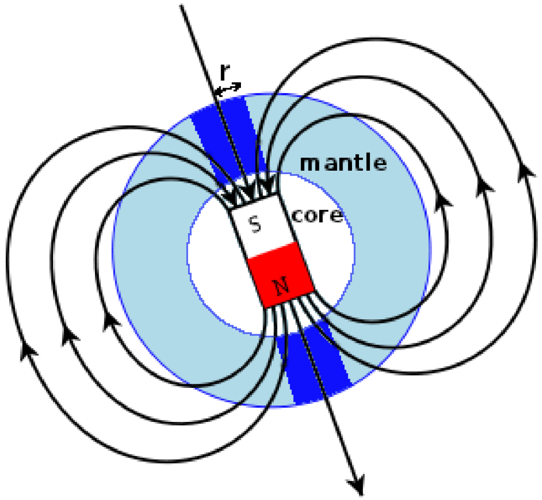
Analysis Cuts for 2011 analysis

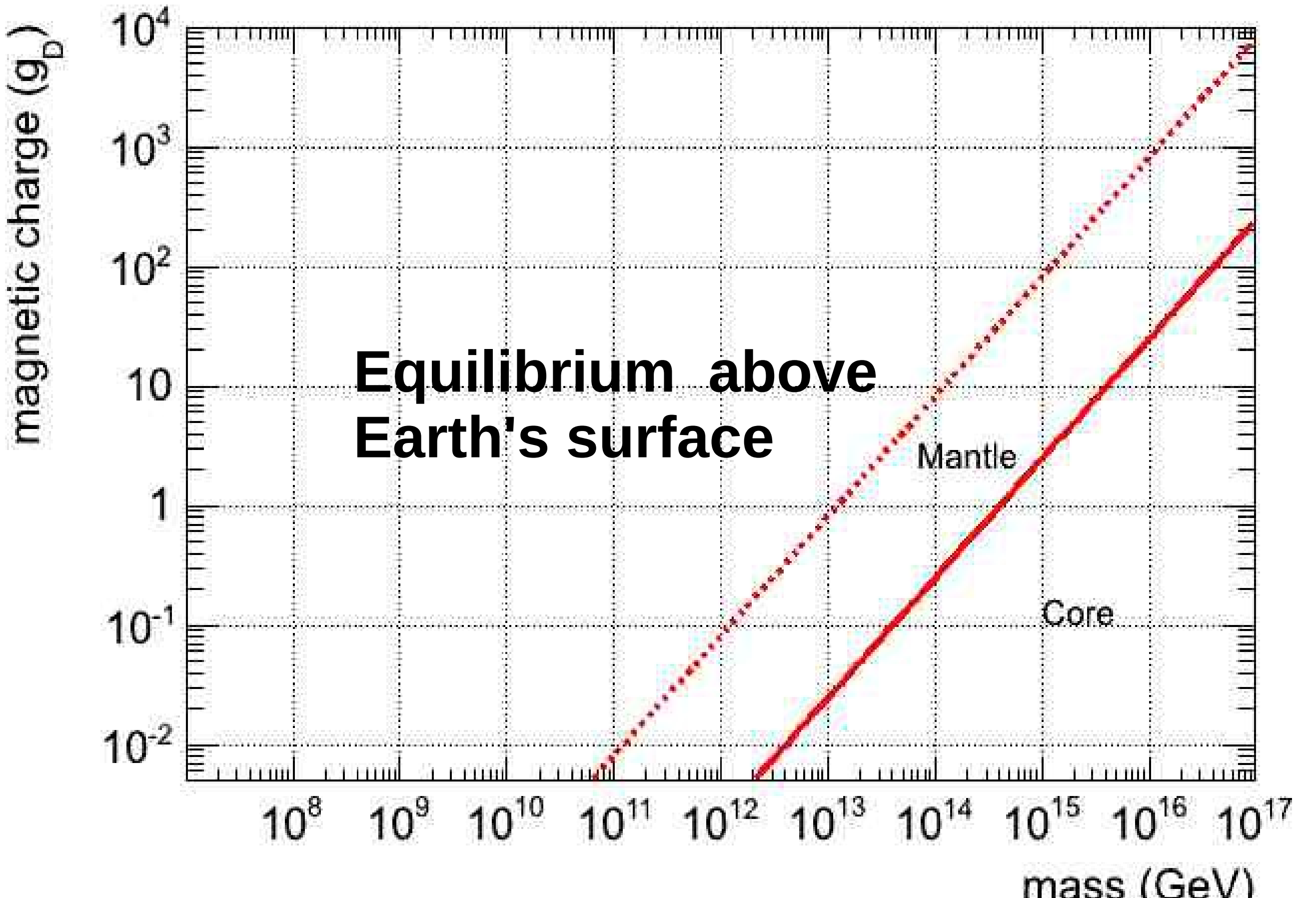
- Trigger on E_T^{miss} at 60 GeV
- $\Delta\phi(E_T^{miss}$, jet2) > 0.5
- Not more than two jets with a transverse momentum above 30 GeV
- Events that contain at least one electron or muon passing loose quality cuts are vetoed
- 3 signal regions almost symmetric in E_t^{miss} and p_T^{jet1}:

SR1	SR2	SR3
p_T^{jet1} > 120 GeV	p_T^{jet1} > 250 GeV	p_T^{jet1} > 350 GeV
E_T^{miss} > 120 GeV	E_T^{miss} > 220 GeV	E_T^{miss} > 300 GeV

Side project: polar volcanic rocks

- **Primordial monopoles inside Earth** would migrate along the Earth's magnetic field
  - ➔ Position with all forces in equilibrium
  - ➔ May be found in polar volcanoes!



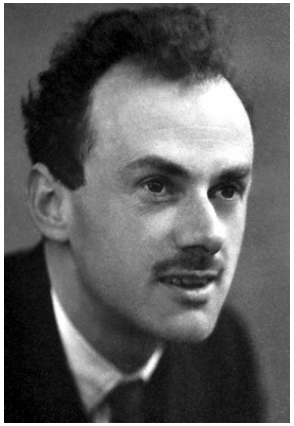


Measurements next week and early july

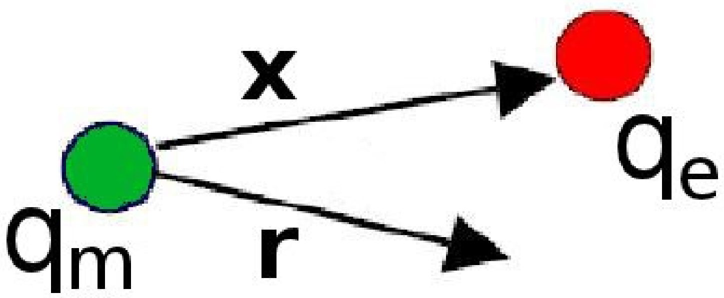
~10 kg of samples from Antarctica, Greenland, Jan Mayen and Gakkel Ridge

Dirac's argument

Proc. Roy. Soc. A 133, 60 (1931)



- Field angular momentum of electron-monopole system is quantised:



$$\mathbf{L} = \int \mathbf{r} \times \mathbf{E} \times \mathbf{B} \, \mathrm{d}\mathbf{r} = \frac{\mu_0 q_e q_m}{4\pi} \hat{\mathbf{x}}$$

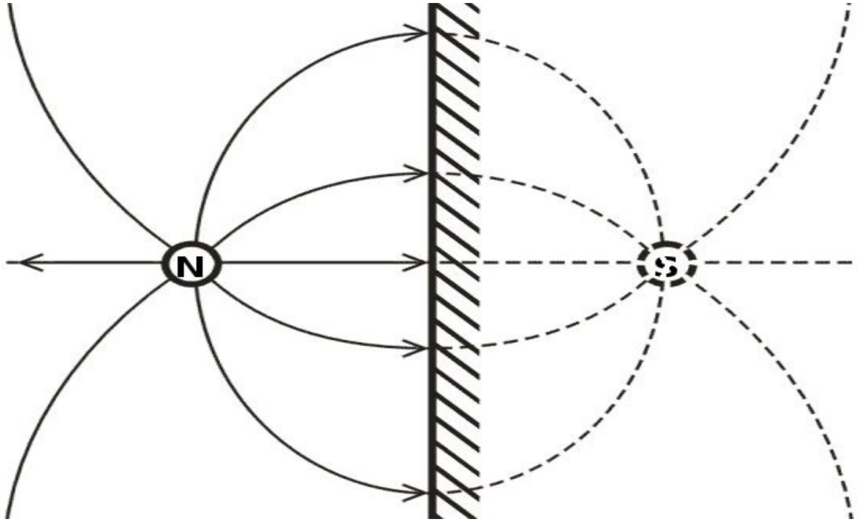
$$\Rightarrow q_e q_m = n \frac{h}{\mu_0} \; (n \text{ integer number})$$

- Explains quantisation of electric charge!
  - Fundamental magnetic charge (*n*=1):

$$g_D = \frac{1}{2\alpha} = 68.5 \; (\text{with } q_m = gec \text{ and } q_e = e)$$

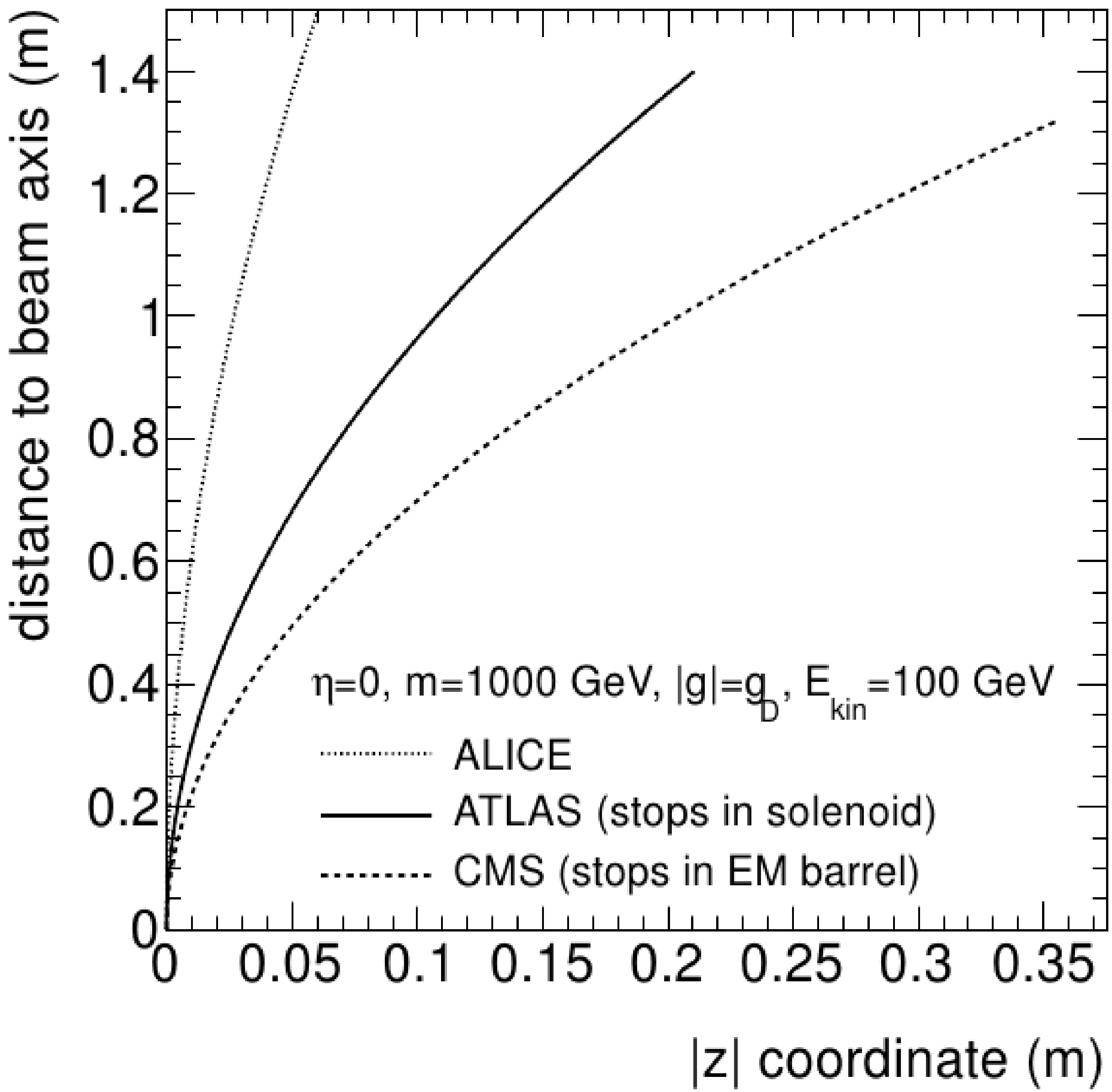
Monopole binding in matter

- **To atoms**
  - Binding energies of the order of a few eV
- **To nuclei with non-zero magnetic moments**
  - Binding energies of the order of 200 keV
- **At the surface of a ferromagnetic**
  - Image force of the order of 10 eV/Å
  - **Robust prediction** (classical)



Monopole bending

arXiv:1112.2999



Acceleration along magnetic field:

$$F_m = q_m \cdot B$$

- Straight line in *xy* plane
- Parabola in *rz* plane

Monopole ionisation energy loss

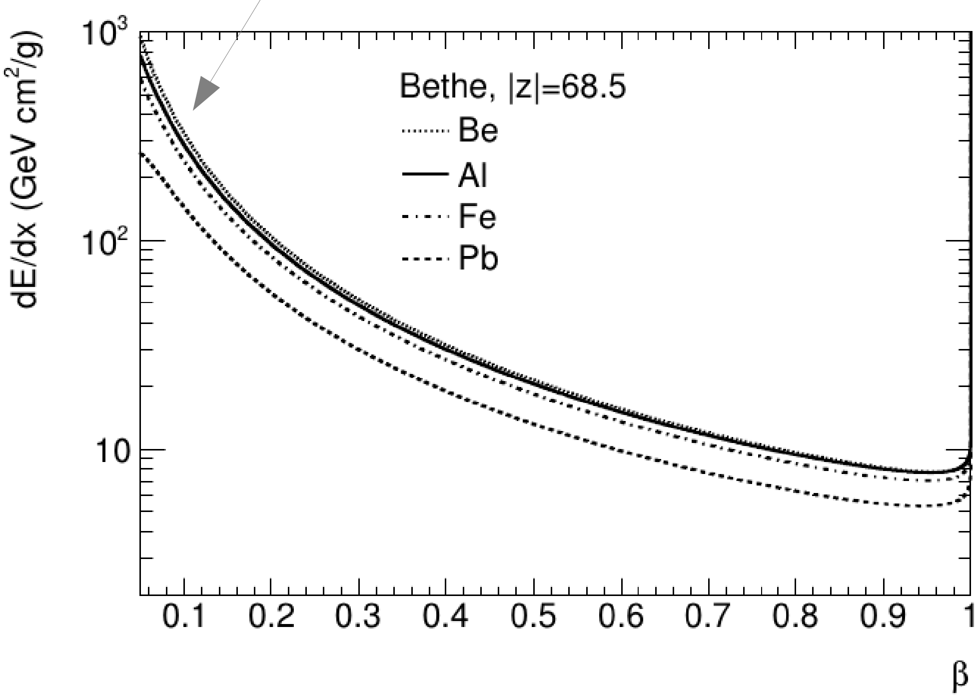
Electric

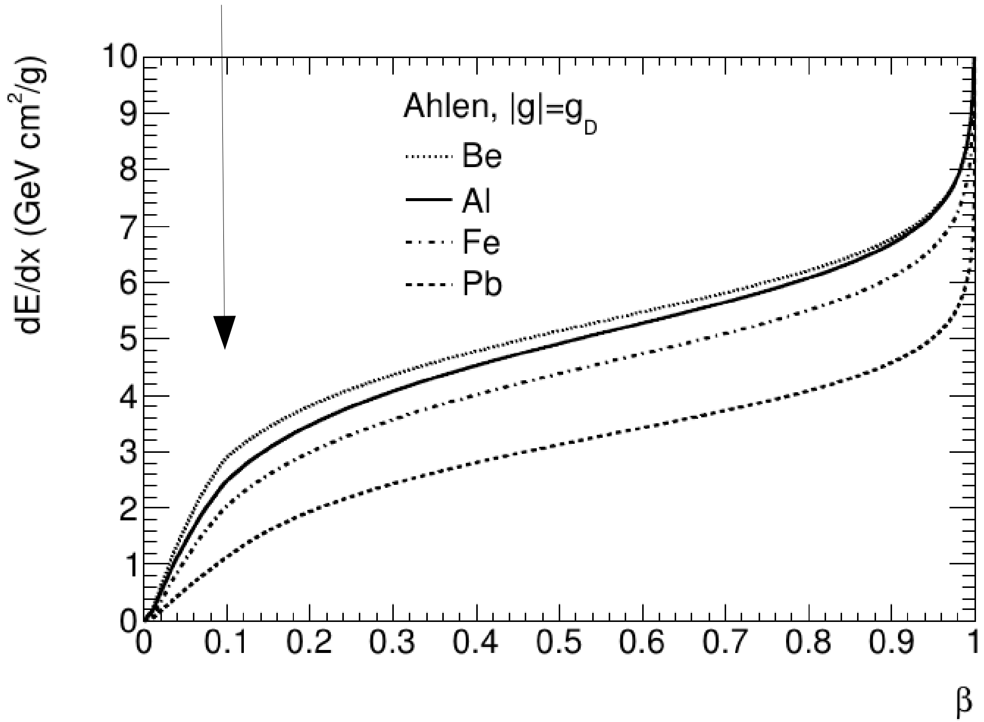
$$-\frac{\mathrm{d}E}{\mathrm{d}x} = K\frac{Z}{A} \left[\ln\frac{2m_e c^2\beta^2\gamma^2}{I} - \beta^2\right]$$

Magnetic

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

No Bragg peak!

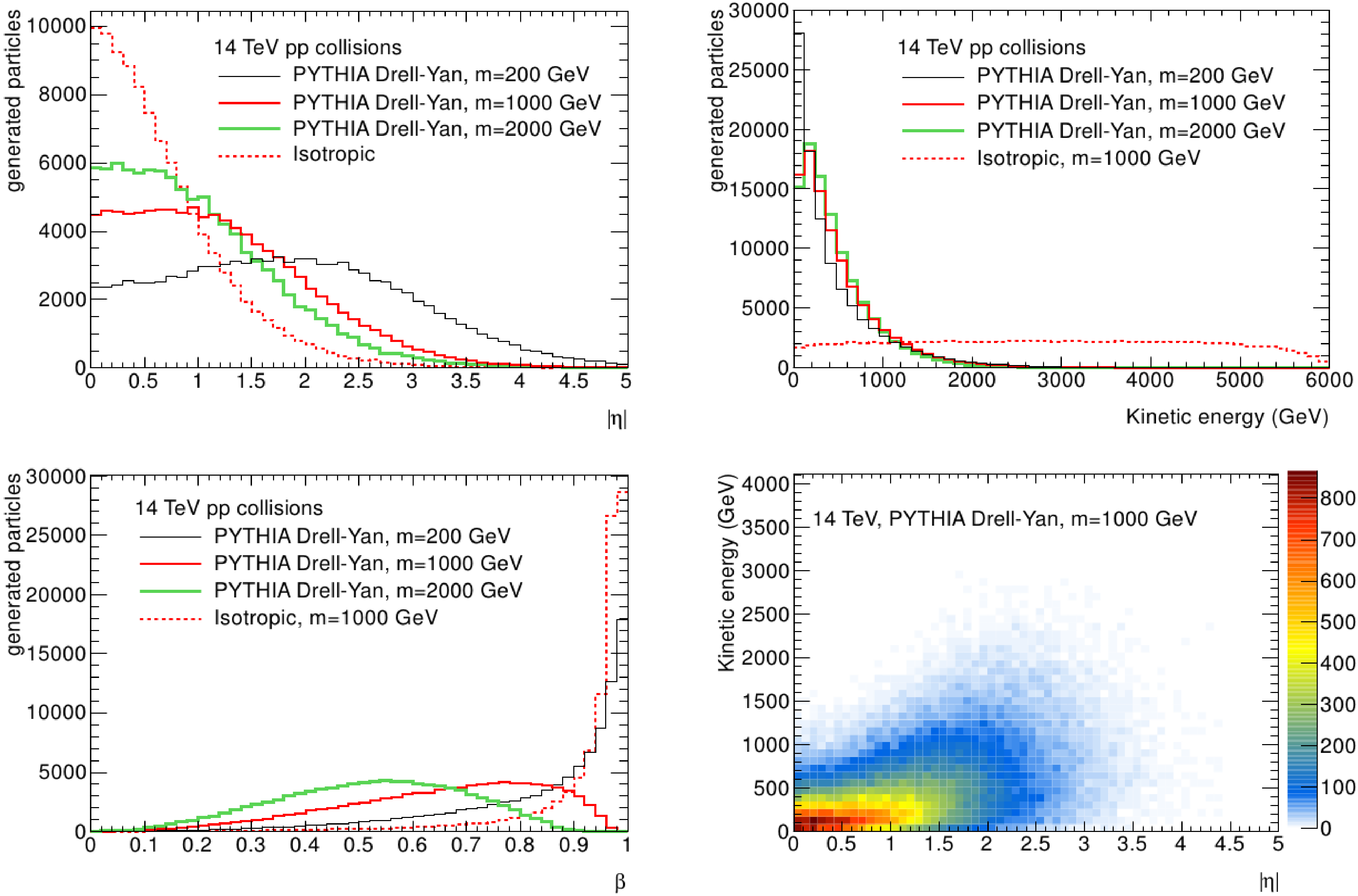




Dirac monopole: $|g_D| = 68.5$ → several thousand times greater d*E*/d*x* than a minimum-ionising |z|=1 particle

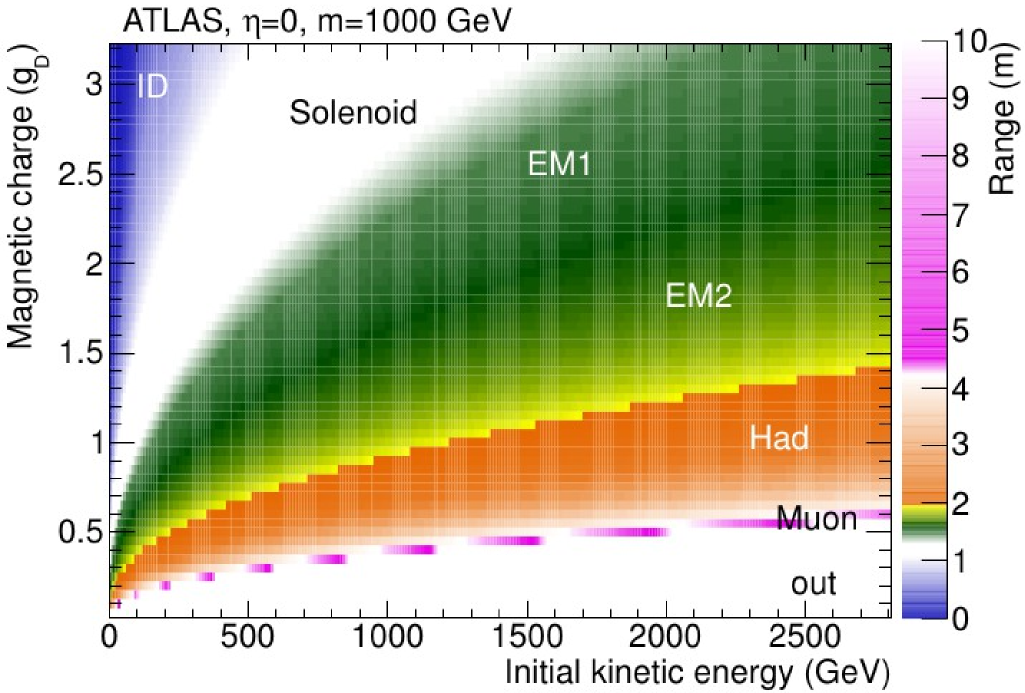
Monopole production kinematics

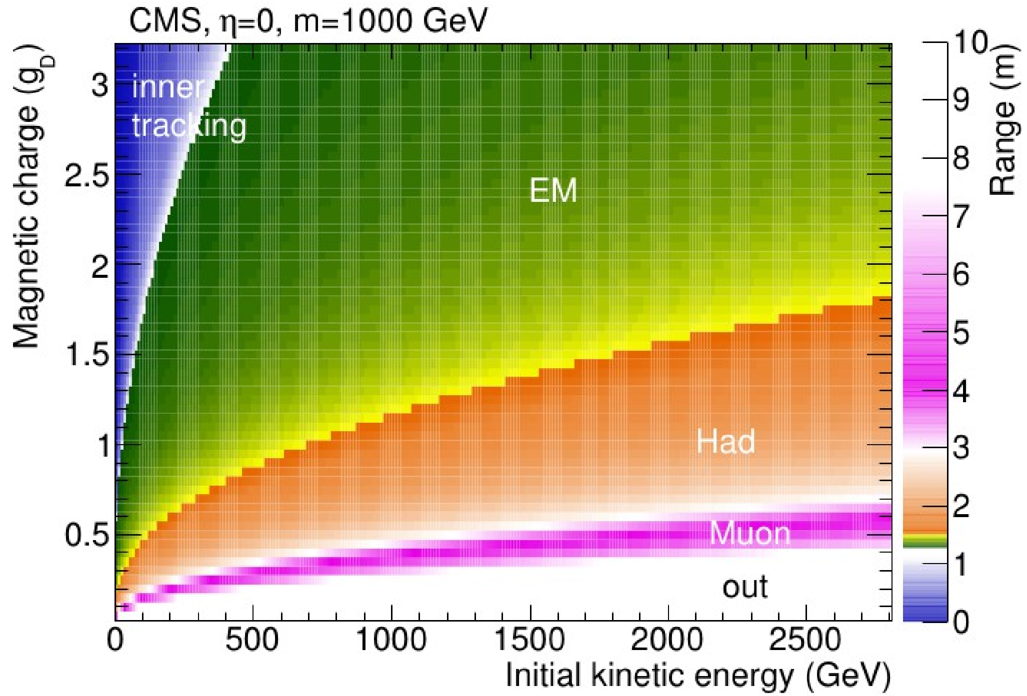
arXiv:1112.2999



Range of monopoles in ATLAS and CMS

arXiv:1112.2999 (2012)



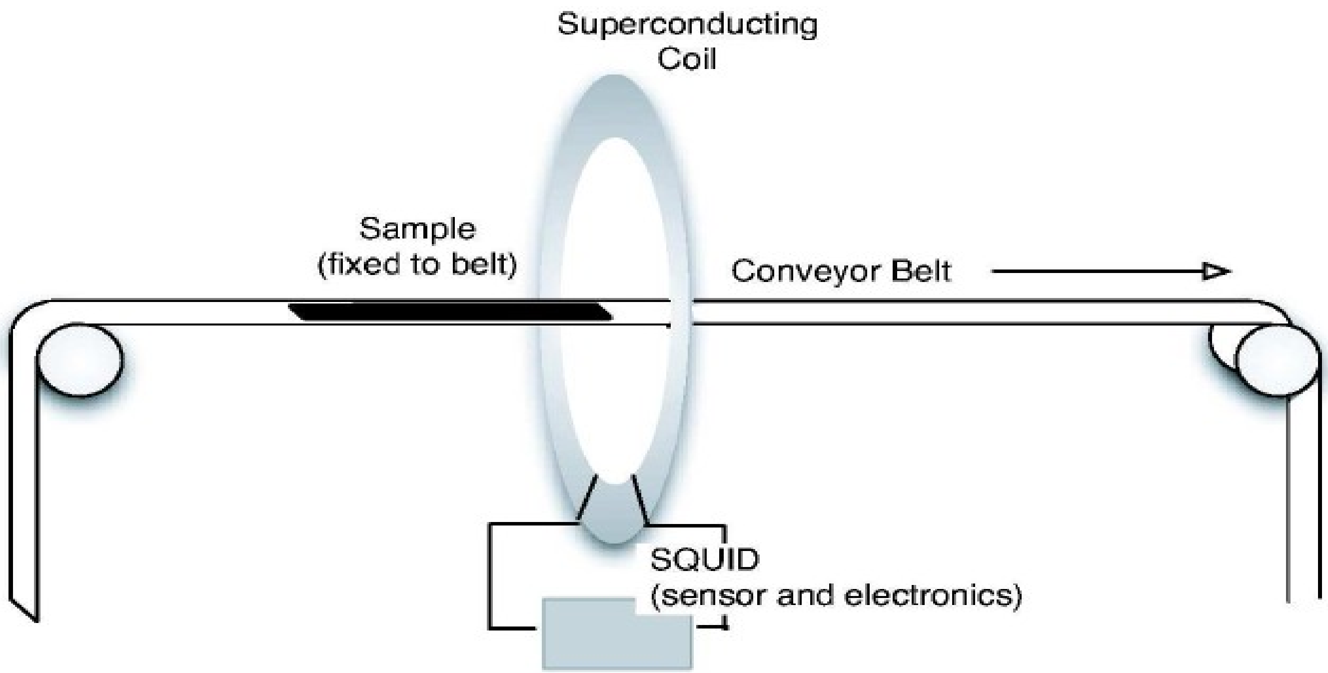


Induction technique

Principle: moving magnetic charge induces electric field

Tiny permanent current measured after passage of sample through superconducting coil

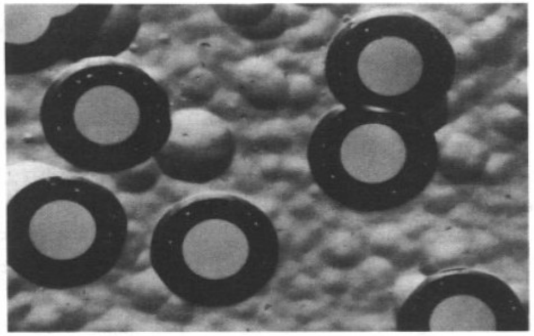
- Directly proportional to magnetic charge
- No mass dependence

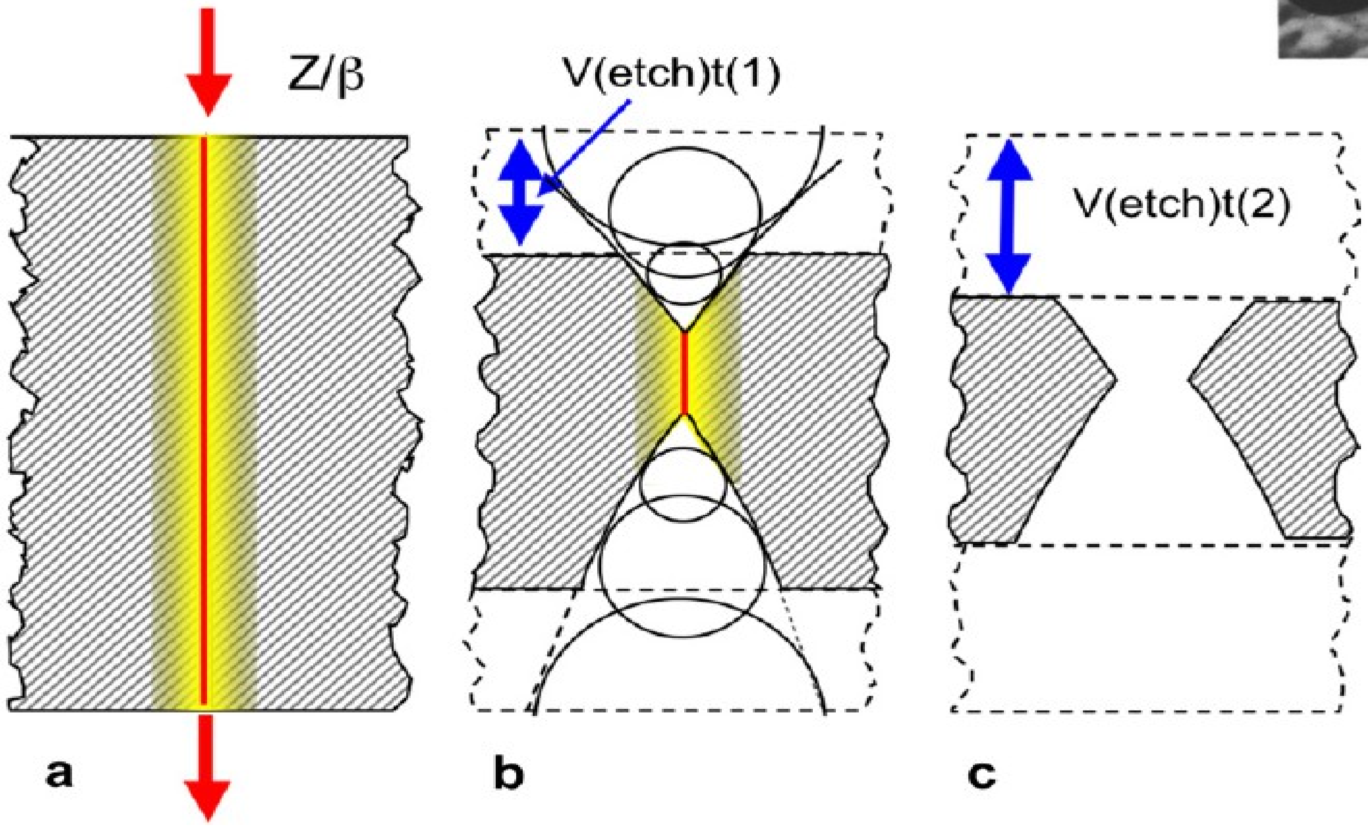


Track-etch technique

Principle: passage of highly ionising particle causes permanent damage in plastic foils

- Etching reveals the etch-pit cones
- Easily tested with ion beams



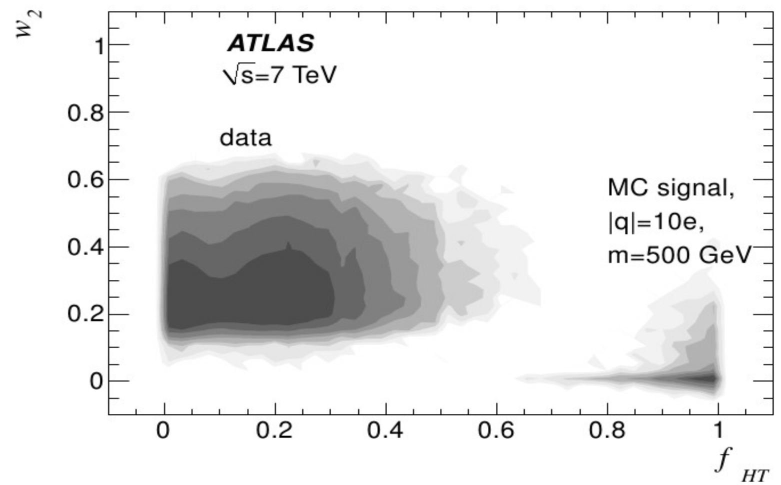


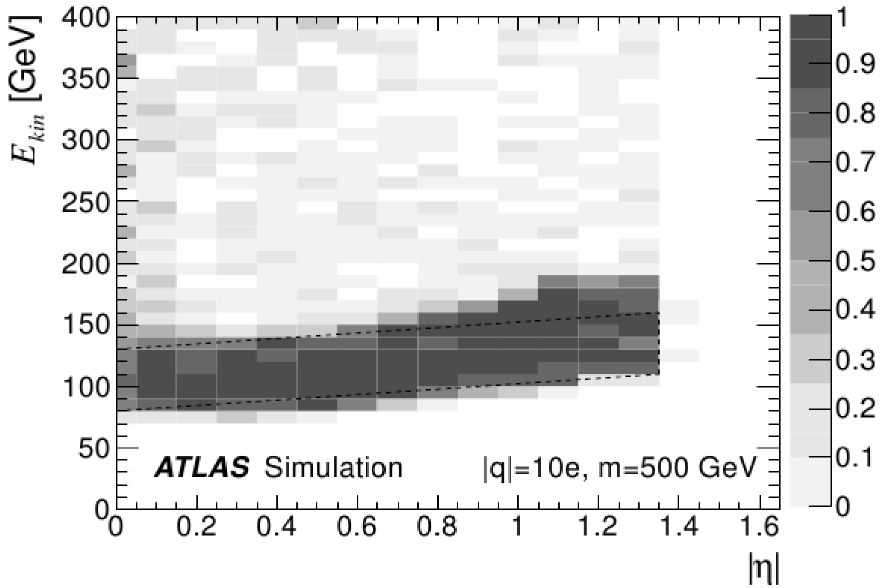
ATLAS search multiply-charged particles

arXiv:1102.0459 (2011)

First HIP search at the LHC

- Very first data (summer 2010)
- Standard EM trigger and reco
- Interpretation 6e < $|q_e|$ < 17e



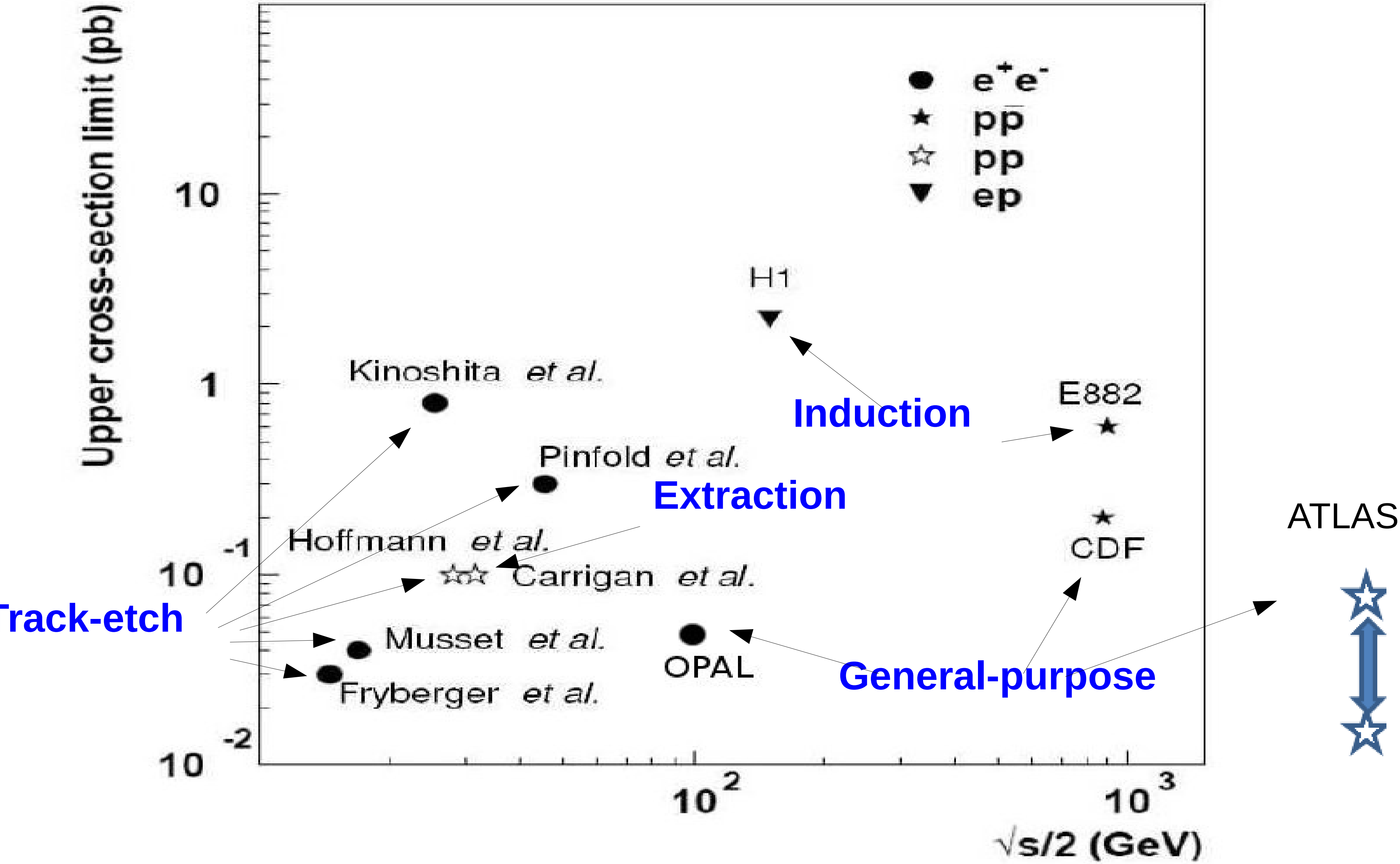


Major source of inefficiency comes from acceptance (punch through)
→ **Model-independent approach:**
1-2 pb limits set in well-defined kinematic ranges

Sequel: monopole search with 2011 data with dedicated reconstruction and simulation

Current collider cross section limits for a Dirac monopole

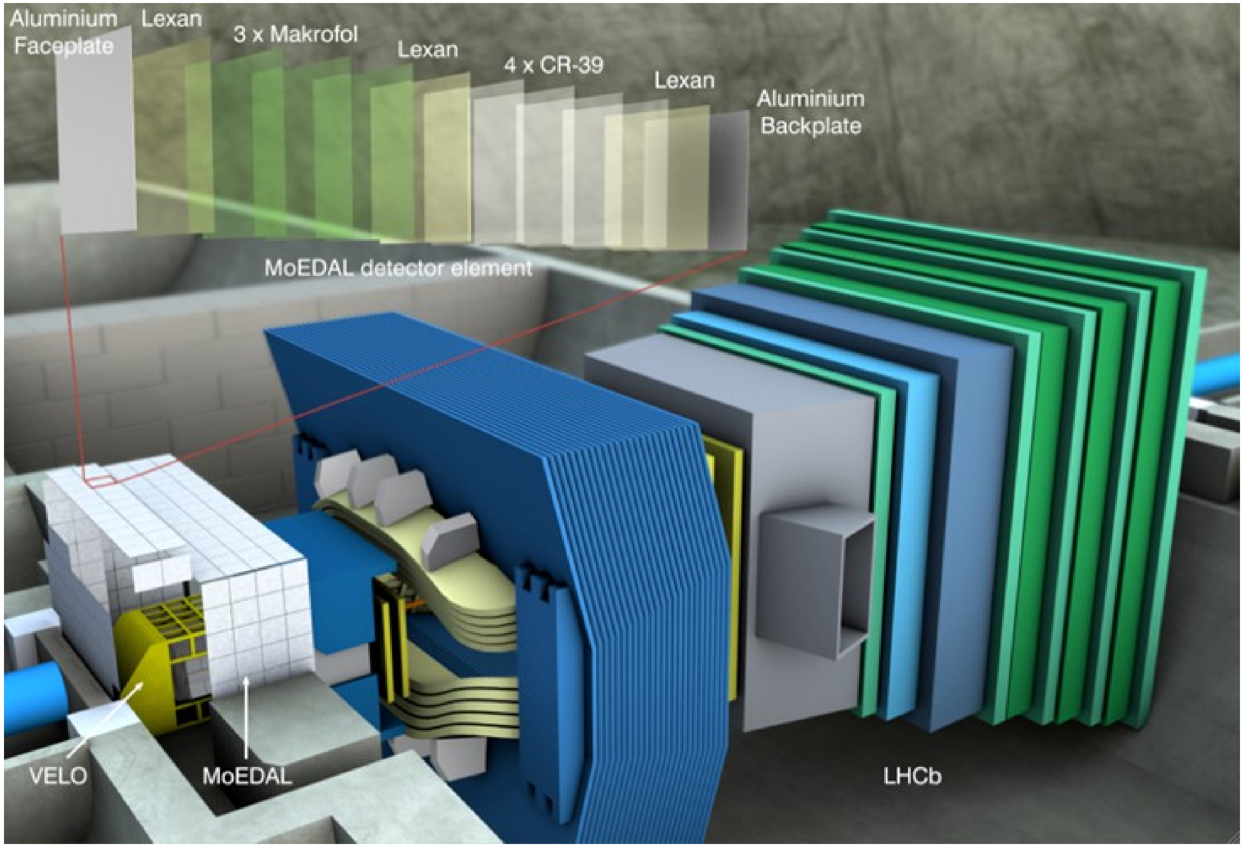
(generally assuming Drell-Yan-like kinematics)



MoEDAL

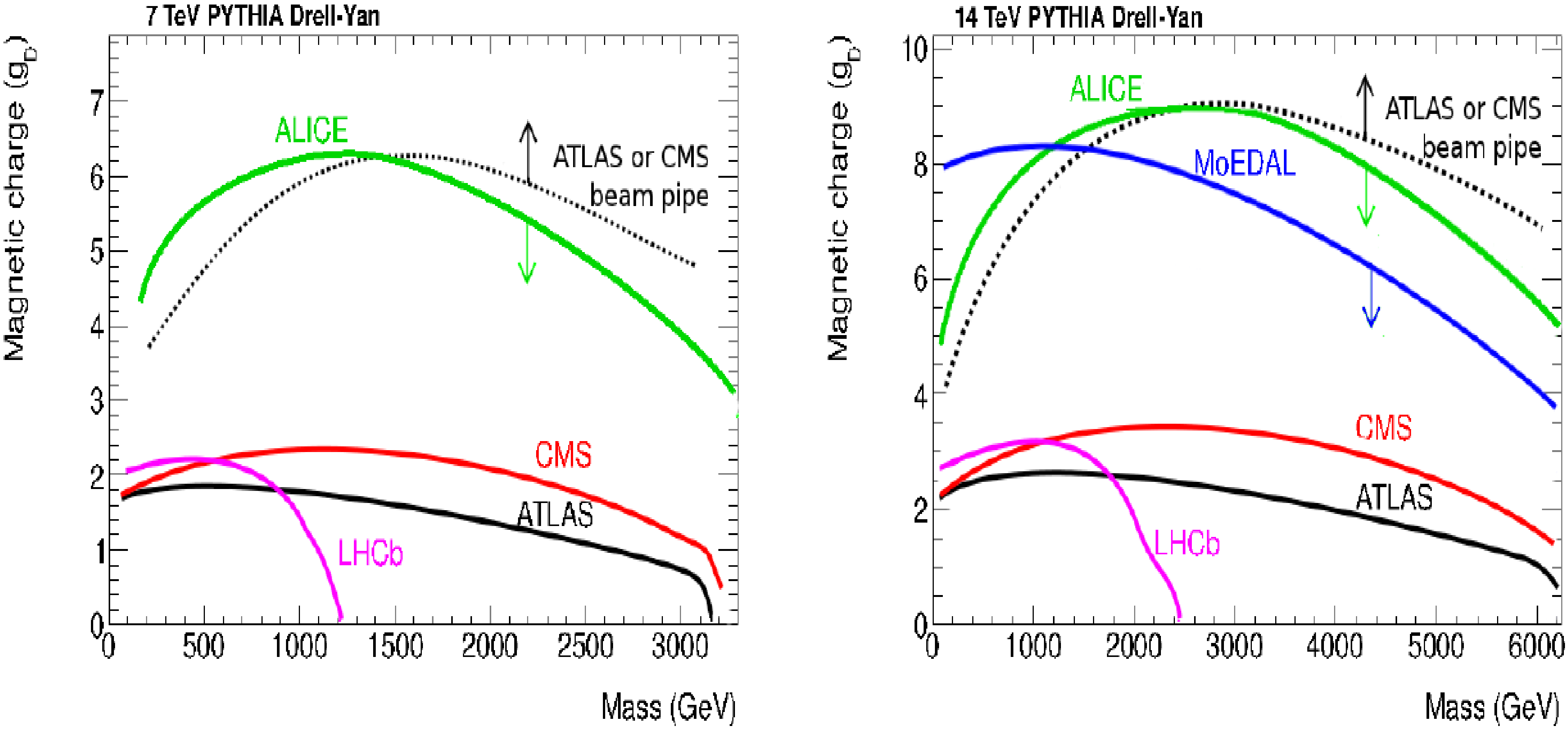
The seventh LHC experiment, dedicated to highly ionising particle detection

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



Test array already deployed around LHCb interaction point
Main run planned for 2014-2015

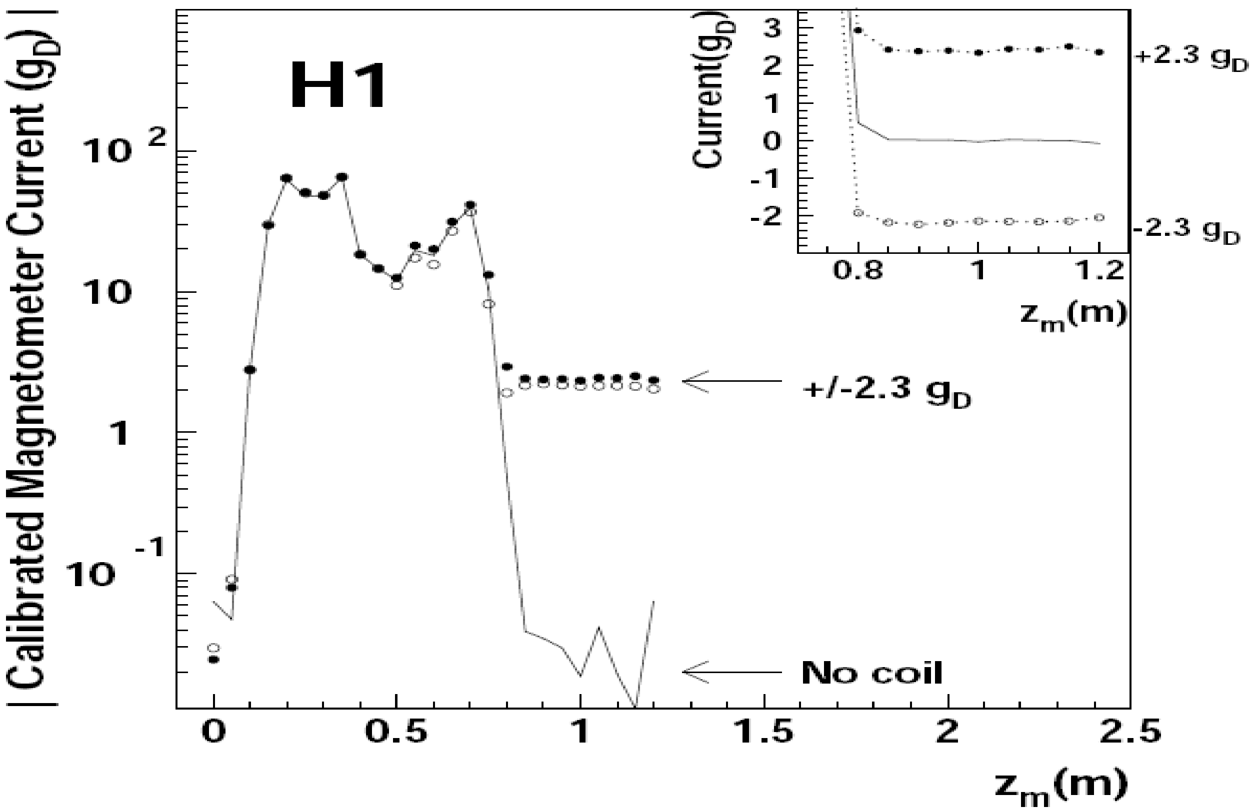
LHC reach in mass and charge



H1 beam pipe (HERA, induction)

- Monopoles and dyons with very high magnetic charges would stop in the Al beam pipe!
- 0.1 – 1 pb limit (up to 140 GeV monopole with $g \geq g_D$)

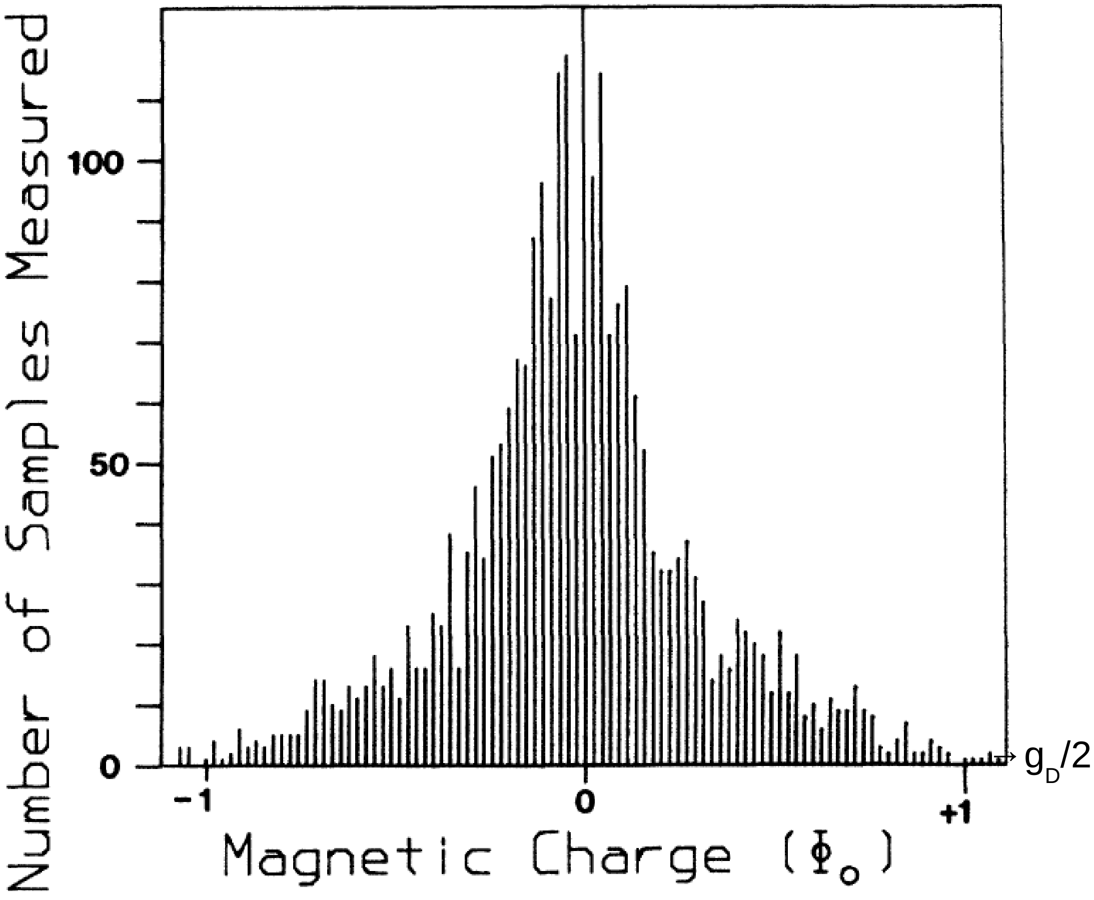
arXiv:hep-ex/0501039 (2005)



Deeply buried rocks and seawater
(induction – cosmic)

PRA 33, 1183 (1986)

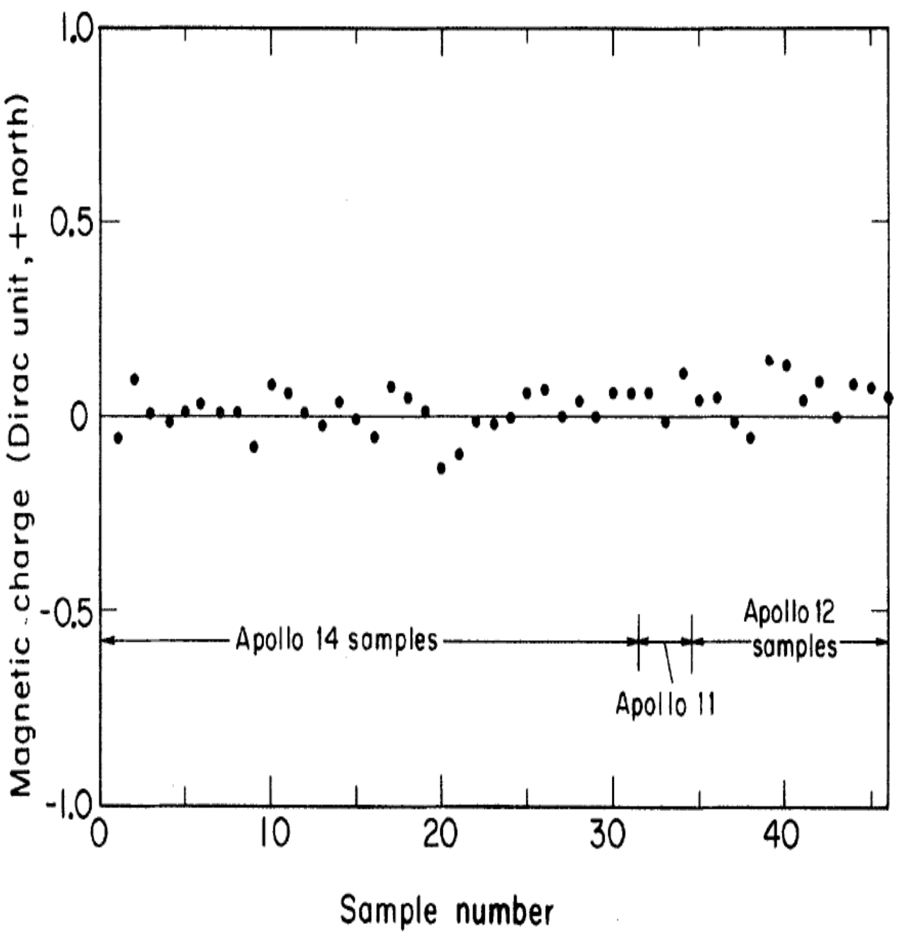
- Hundreds of kilograms of material analysed with large superconducting detector
- Depths of up to 25 km → stop higher-energy monopoles
- $\rho < 5 \cdot 10^{-30}$ mon./nucleon

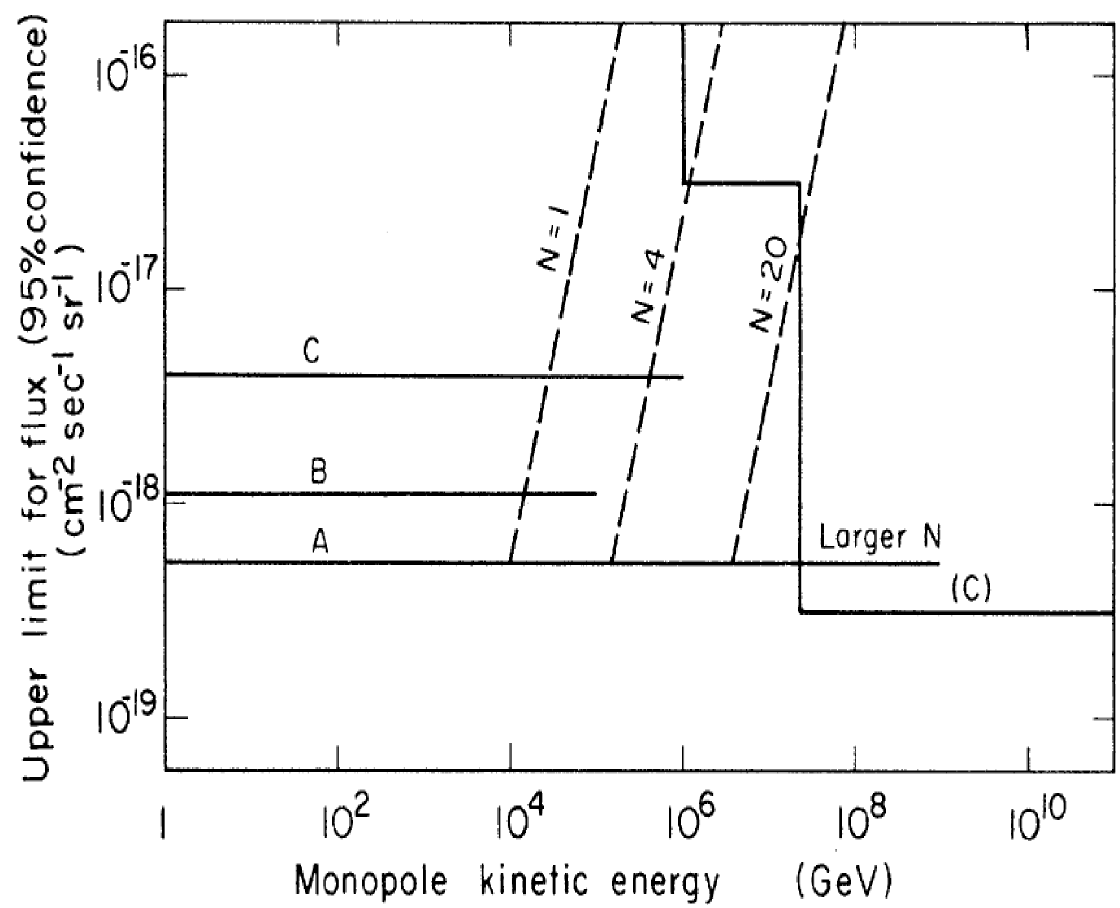


Moon rocks (induction – cosmic)

- Exposure: 4 billion years!
  - No movement (few meters depth)
- No atmosphere and no magnetic field
  - Robust assessment of monopole fate after stopping

PRD 4, 3260 (1971)
PRD 8, 698 (1973)





Meteorites (induction – stellar)

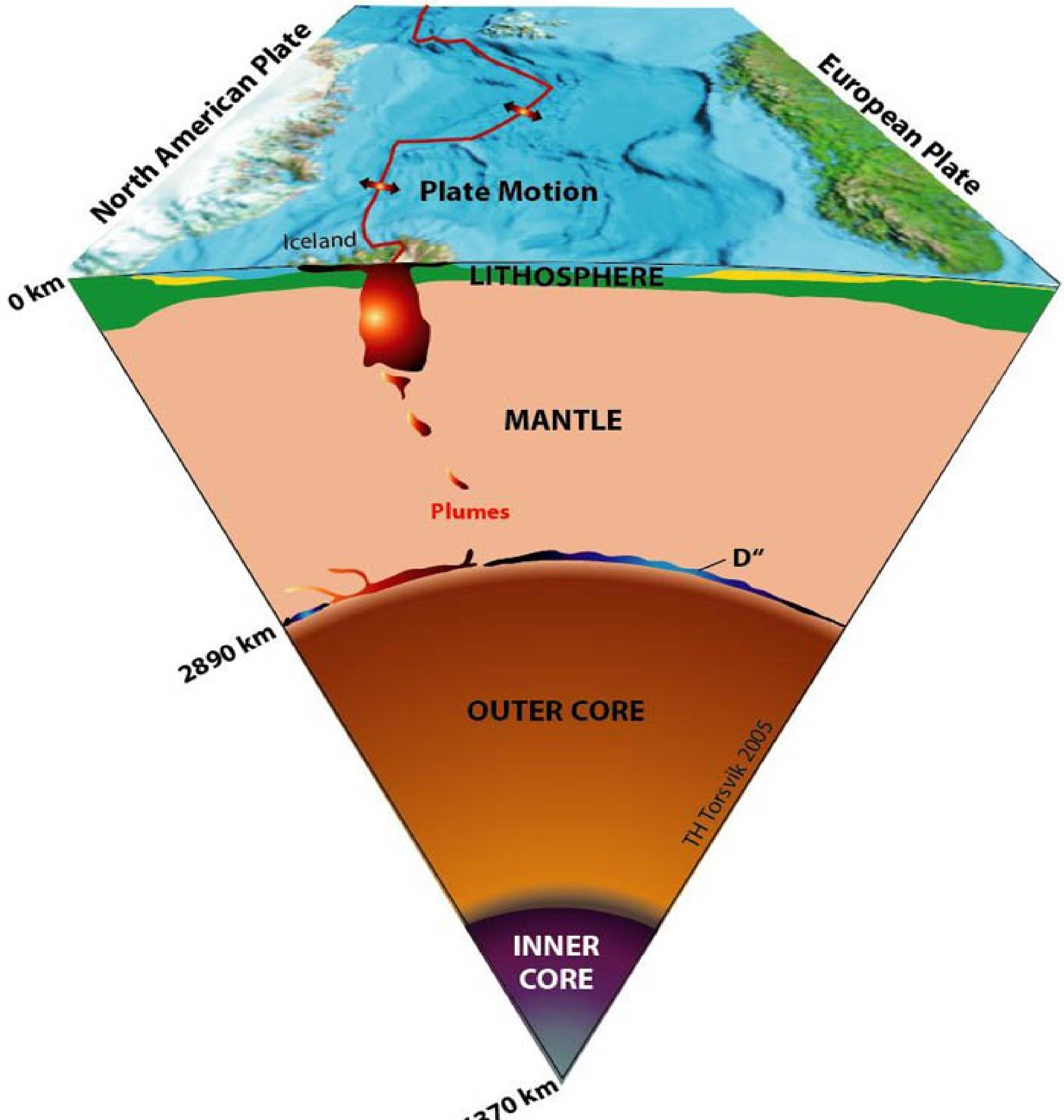
- **Stellar monopoles** heavier than the heaviest nuclei
  - ➔ Sank to the Earth's interior during Earth's formation
  - ➔ Crust depleted today
- Motivates searching in meteorites, assuming:
  - Impact did not dislodge monopole
  - Meteoroid does not originate from planetary crust
- 112 kg of meteorites analysed
- $\rho < 3 \cdot 10^{-29}$ mon./nucleon

PRL 75, 1443 (1995)

Possible future search: comets

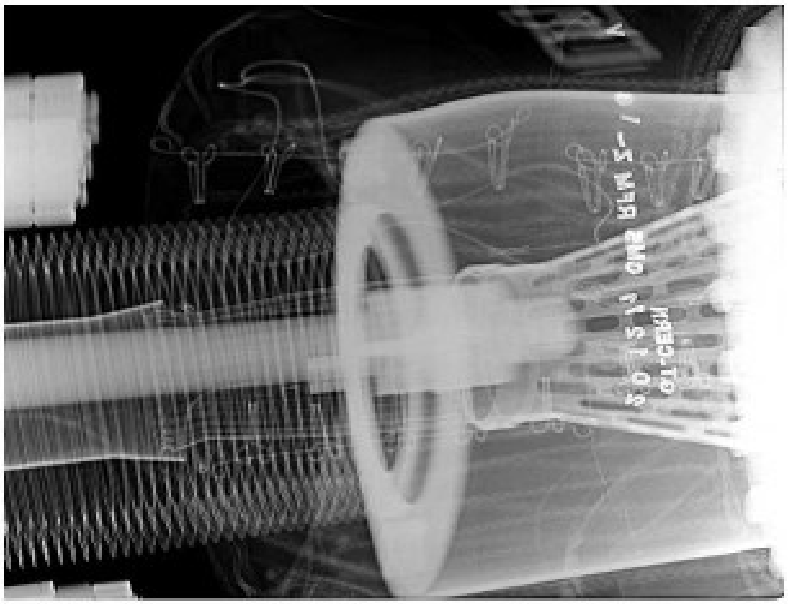
→ Contain materials that the solar system formed from

“Hot spot” plume in the Earth's mantle



LHC plugin module
(18 m from CMS interaction point)

BEFORE



AFTER

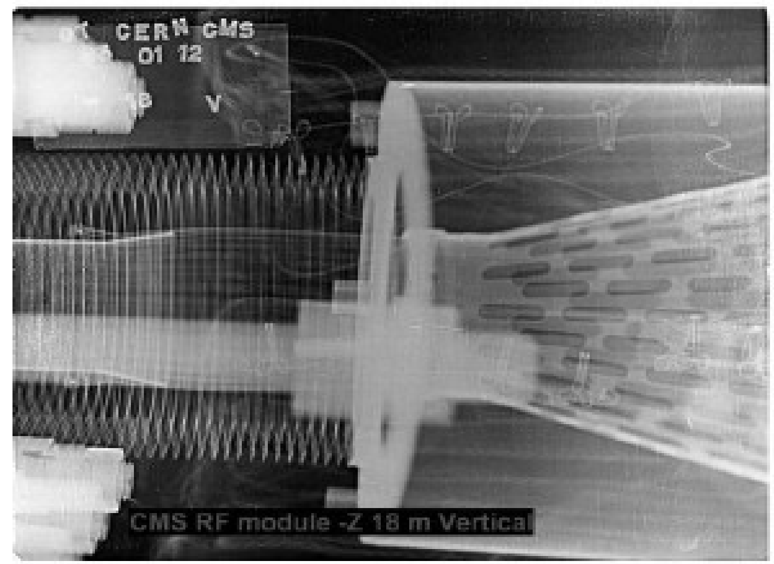
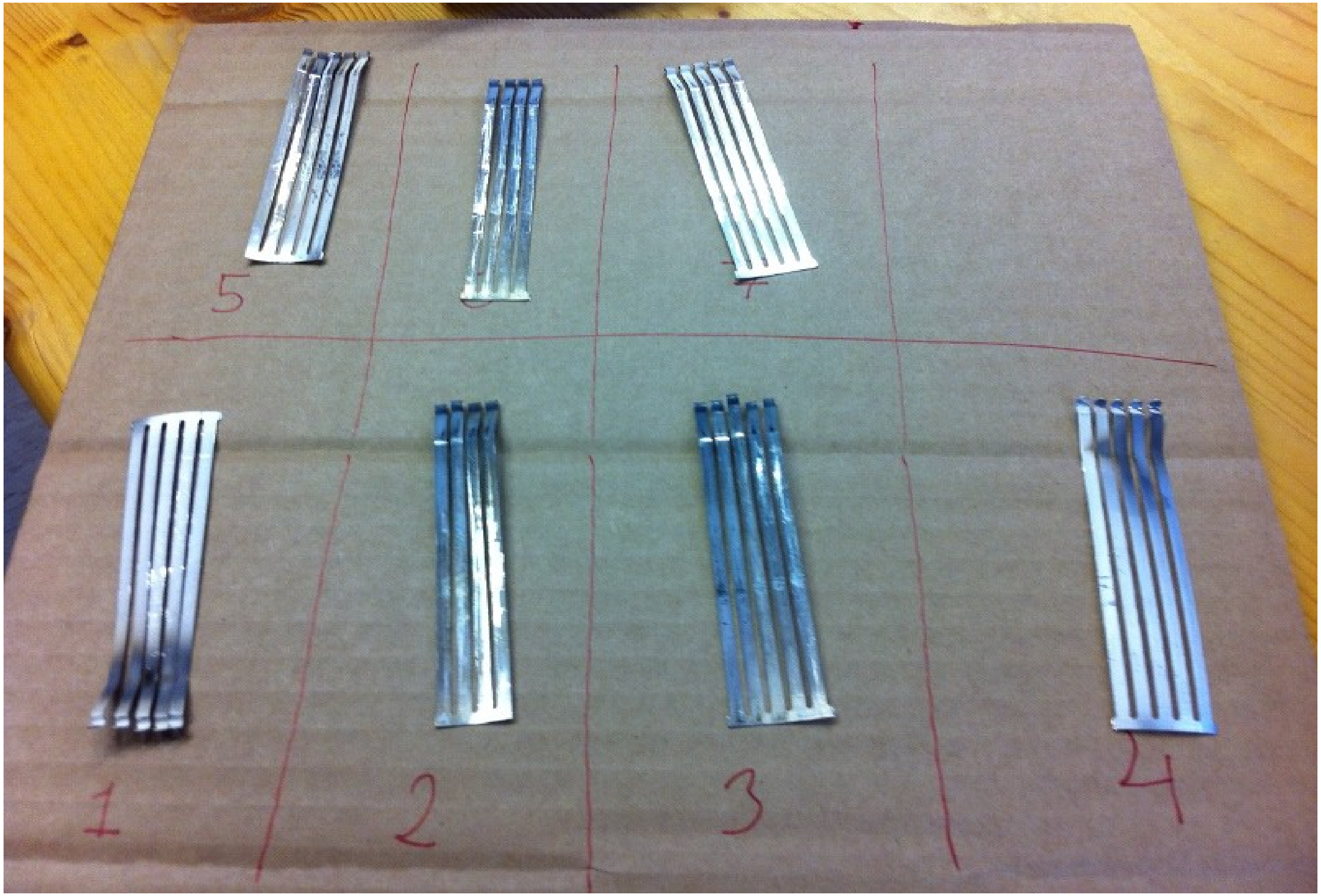


Figure 1: X-ray pictures (from above) of the plugin module with buckled fingers (left) and the new one after replacement with fingers around the beampipe (right). The sample used in this search corresponds to the fingers of the plugin module in the left picture, which reach to a position nearer the beam than the beampipe (36 mm diameter, to be compared to 40 mm diameter for the beampipe).

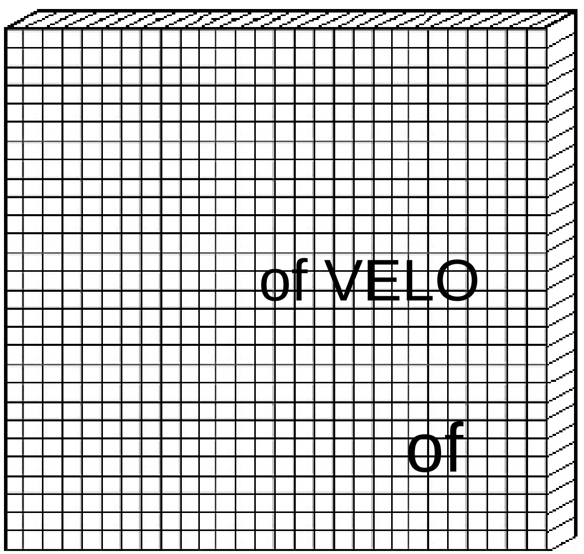
LHC plugin module fingers after cutting



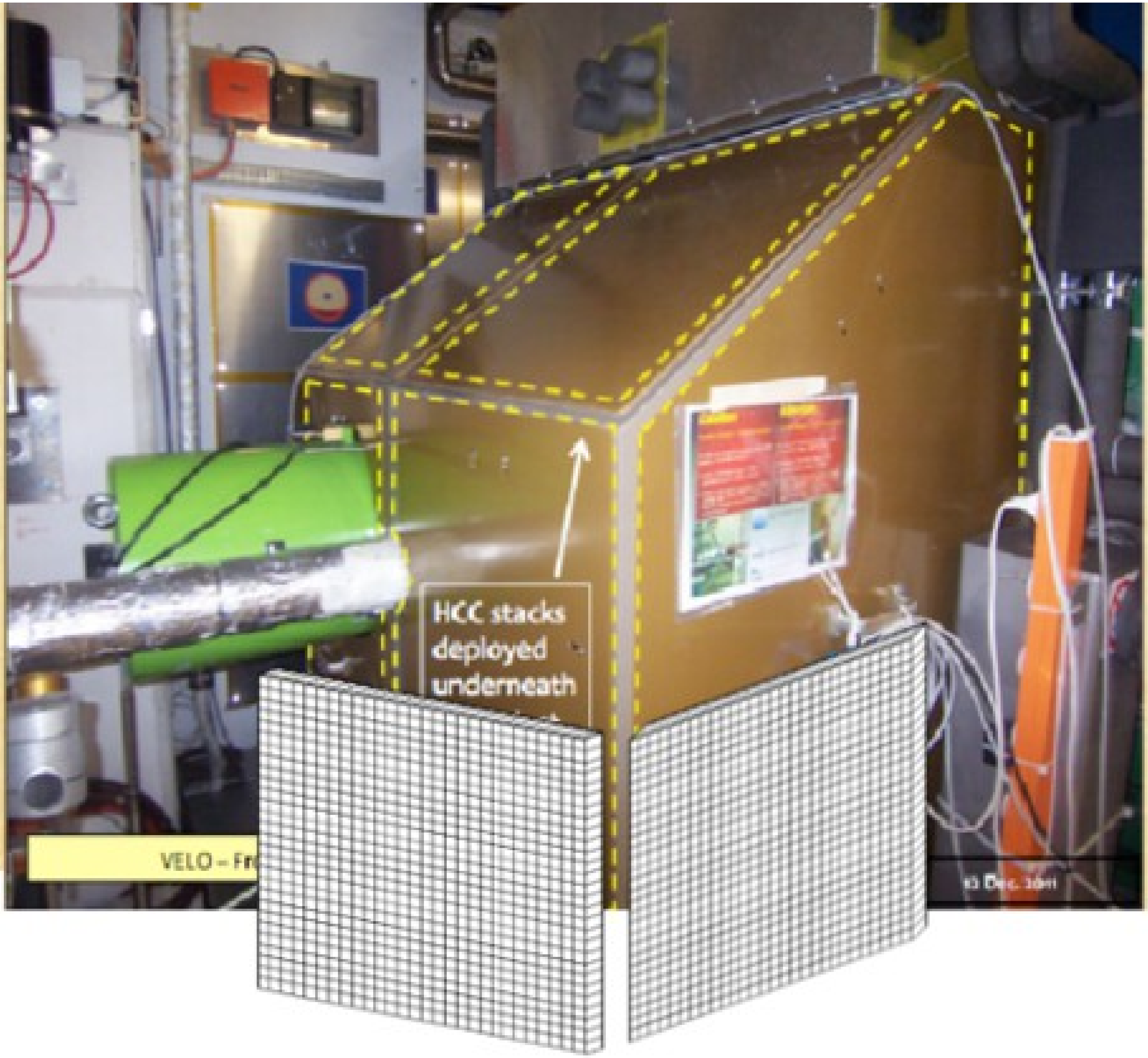
MMT preliminary design

- Material: Aluminium
  - Large nuclear dipole moment (spin 5/2) → likely to bind to monopoles
  - Cheap
- Module: parallelepiped 1.75 x 1.75 x 5 cm
  - Nicely fits magnetometer sample holder

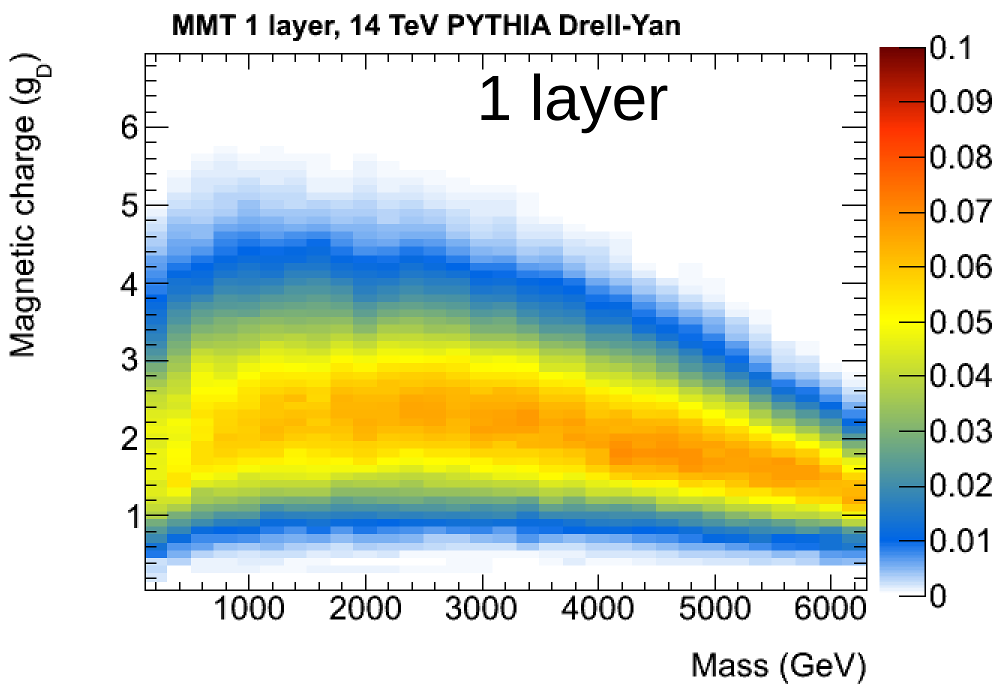
- Array: 49 x 49 cm
  - 1 layer: 784 modules, 32.4 kg, depth 5 cm
  - 2 layers: 1568 modules, 64.8 kg, 10 cm
- Two arrays
  - one in front and one on the side vacuum chamber
- MoEDAL track-etch module in front each array

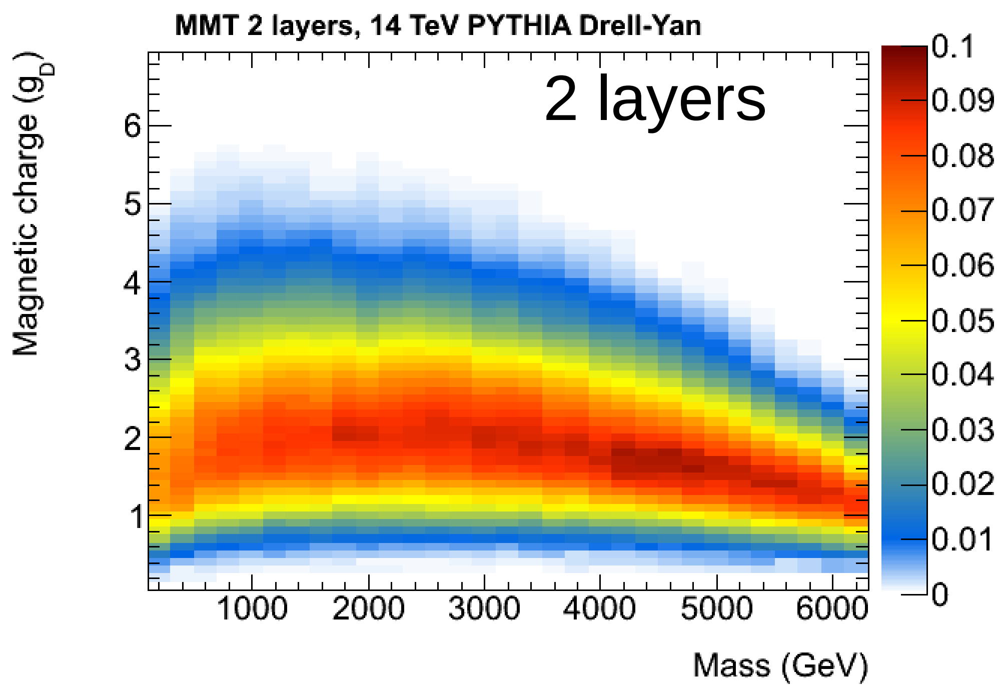


A view of MMT in the VELO chamber



MMT acceptance estimates
(assuming Drell-Yan pair production mechanism)





2–10 % acceptance for monopoles in the range 1–4 g_D

- Higher charge → stops in VELO chamber
- Lower charge → punches through the MMT