# Experimental Coverage WG: Report


José Francisco Zurita

Institut für Kernphysik (IKP) and Institute für Theoretische Teilchen Physik (TTP),
Karlsruher Institut für Technologie (KIT).

Institut für Theoretische Teilchenphysik

Karlsruhe Institute of Technology

WG: Xabier Cid Vidal, Heather Russell, Albert de Roeck, Jared Evans, David Curtin, JZ


**Searches for long-lived particles at the LHC, ICTP Trieste 20.10.2017**

# WG goals

- This working group originally aims at identifying the most obvious gaps in coverage of the current studies.
- Byproduct: provide a concise summary of searches, inviting to challenge the shortcomings and caveats (some already in the lightning round!).
- By definition: we exclude Hidden Valley signatures and dedicated experiments such as MoEDAL, MilliQan (they get their own section!).
- Status: Internal note (almost) finished, a 1st "public" draft is expected after the workshop (so we can add <u>your</u> feedback).
- Should we transform the summary above in a library / webpage / catalog with all LLP studies linked? (à la HXSWG)

# Classification

- Any classification attempt is arbitrary, but within the options we concentrate in the final state products: hadronic, leptonic, semi-leptonic, photonic.
- Whatever does not fall in the categories above goes into the "non-standard"* track section (/dev/null).
- Backgrounds are (fairly well) understood, I won't cover them. The main limitations in coverage arise from:
  - triggers (recycling prompt ones vs dedicated strategies).
  - object properties (pT thresholds, location in the detector, etc).
  - targeted topology (e.g: 1 vs 2 LLPs).

* Includes all sorts of unconventional signatures: quirks, monopoles, disappearing tracks, etc…

# Fully hadronic decays: landscape

- ATLAS:
  - two DVs decaying in:
    - HCAL: ATLAS-CONF-2016-103
    - MS and ID: CERN-PH-EP-2015-071
    - ID (+ MET): ATLAS-CONF-2017-026
  - DV + X (X=muon, electron, jet, MET): CERN-PH-2015-065
- CMS:
  - inclusive displaced jets and leptons: CMS PAS-EXO-16-003
  - displaced jets: CMS PAS-EXO 2013-037
- LHCb: looks for SM Higgs / scalar decaying into LLPs:
  - 1 LLP: LHCb-PAPER-2016-065 (the other LLP lost in acceptance).
  - 2 LLP: LHCb-PAPER-2016-014

# Fully hadronic decays@ATLAS+CMS

- ATLAS:
  - Large radius tracking (LRT): Left-overs hits from normal tracks give *displaced tracks*. (see M.Lutz's talk)
  - Dedicated triggers in HCAL (*CalRatio*)/MS (*MuonRoI*). FTK can improve these! (see T. Holmes and L. Horyn talks)
  - DV+X: use standard "X" triggers.
  - $c\tau \sim [0.1\text{-}10]$ m constrained for rates of ~ 50fb$^{-1}$.
- CMS:
  - Dedicated off-line *displaced jet (DJ)* tagger triggering on large $H_T > 350\text{-}500$ GeV.
  - Fails for $c\tau < 3$ mm (> 1m) due to SM B-physics backgrounds (no decays on tracker).
  - 2 DJs are kept (1 DJ used as control sample, no coverage for single LLP.)
  - Theory recast of this search for SM Higgs [arXiv:1508.01522]
- Most searches require pairs of DVs.
- Sensitivity degrades for low masses: CMS, $c\tau$=30 mm, efficiency of 2 (41)% for 50 (100) GeV.

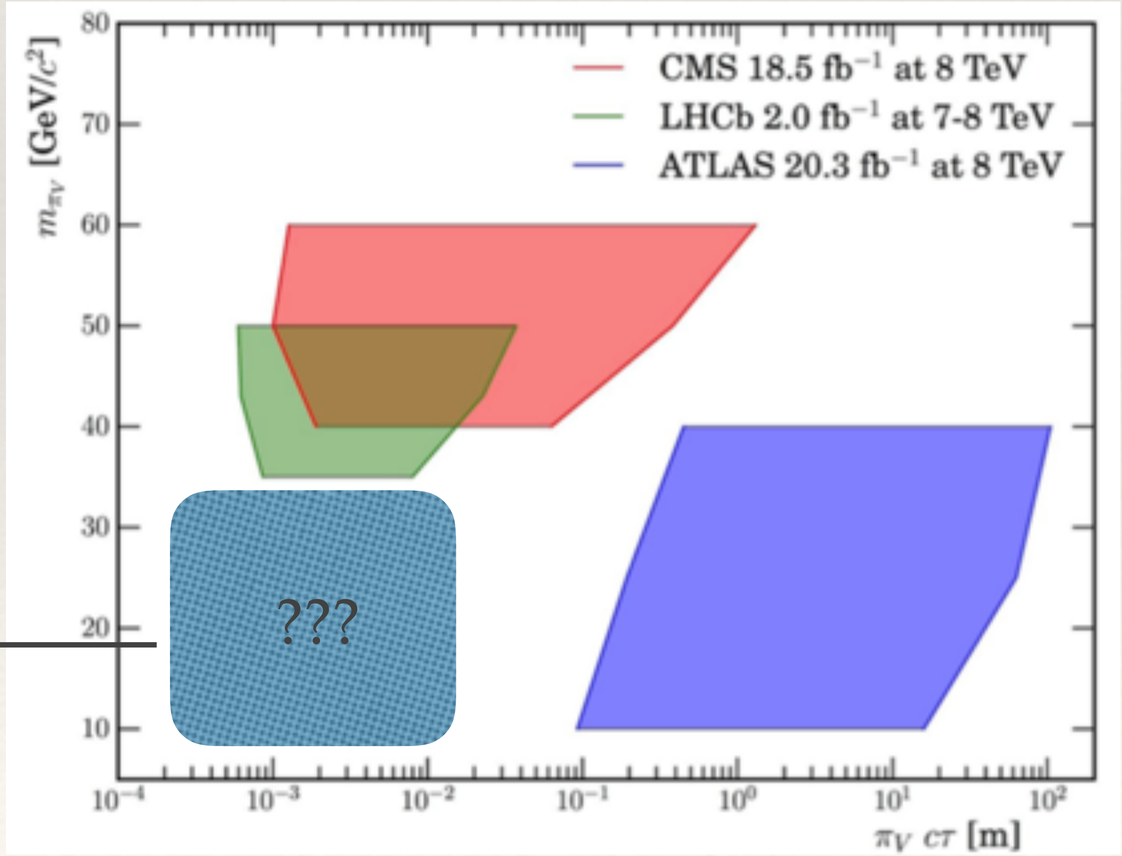
# Fully hadronic decays@LHCb

- Focuses on scalars decaying into pairs of dark pions ($\pi_V$)
- Trigger on DVs ($d_T > 4$ mm) with 4+ tracks.
- Improvements: shorter cτ (understanding detector) and lower masses (higher boosts using jet-substructure). See C.Vasquez Sierras's talk yesterday

H(125) -> $\pi_V \pi_V$

BR(H -> $\pi_V \pi_V$) < 50%

Do we give-up on this region?




CMS-EXO-12-038
LHCB-PAPER-2016-065
CERN-PH-2015-065

Borrowed / stolen from M. Borsato

# Leptonic decays

- ATLAS:
  - 2 displaced OS lepton pairs: CERN-PH-2015-065
  - displaced lepton-jets: ATLAS-CONF-2016-042 (also prompt in CERN-PH-2015-242)
- CMS:
  - 2 displaced OS lepton pairs: CMS PAS EXO 12-037, only MS: CMS PAS EXO 14-012.
  - displaced lepton jets: CMS-HIG-13-010
  - 1 e + 1 μ with large impact parameter (0.2-20 mm) CMS-EXO-16-022
    Nothing else is required (the tracks do not even point to a common vertex!)
- LHCb: light neutral LLPs going into $\mu^+\mu^-$ from B->K decays.
  - neutral B: LHCb-PAPER-2015-036.
  - charged B: LHCb-PAPER-2016-052.

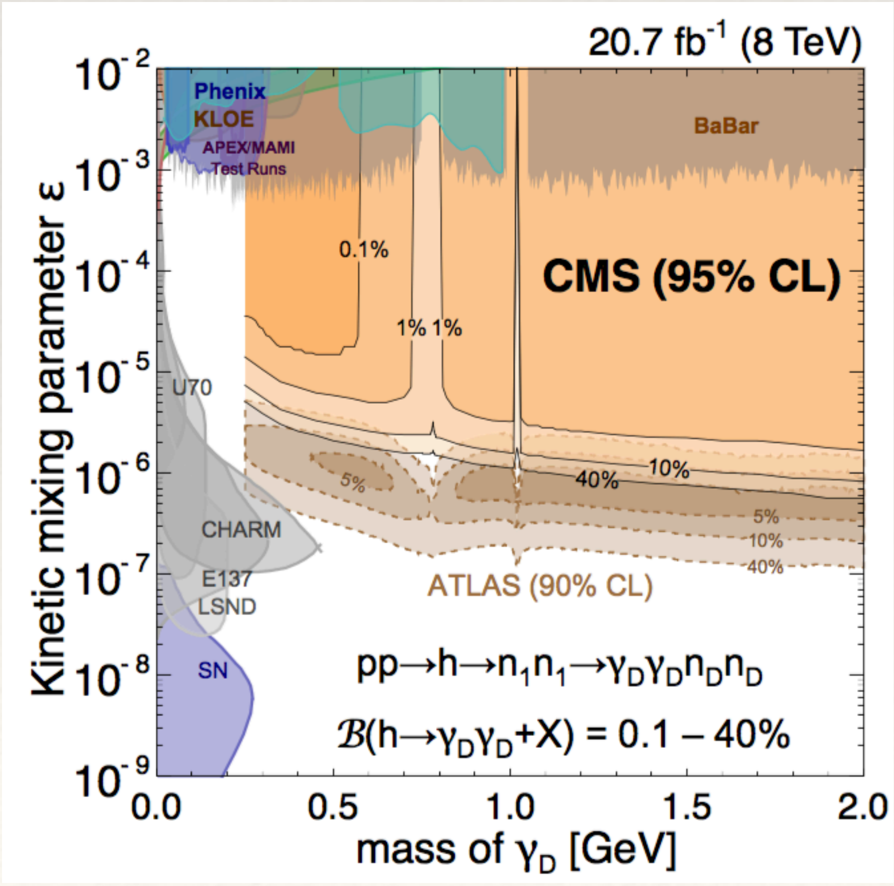
* Lepton-jet is a highly collimated lepton, decaying from O(GeV) parent particles.

# Leptonic decays@ATLAS+CMS

- ATLAS:
  - Trigger on $\mu,\gamma$ (large impact e more difficult to reconstruct)
  - Form DV (> 4 mm from PIP) with OS leptons (no flavor bias) and outside of dense material regions (to avoid photon conversion).
- CMS:
  - Standard lepton triggers.
  - PIP with 4+ tracks and $\mu$ displaced < 24 (2) cm along (transverse) to the beam.
  - DV with two OS leptons and pT cut (26,36,21) for ($\mu$,$e_1$,$e_2$).
- CMS high impact electron+muon:
  - Dedicated trigger for displaced e-$\mu$ pairs, using only pT information (no tracking!) (see Keller's talk)
  - $|d_0|$ / $\mu$m defines "prompt" (<100), "control" (100-200) and "signal" (> 200) region (*SM lepton-free*).
- These searches do not include: $e^+ e^-$, $\mu^+ \mu^-$ not from same vertex, SS leptons, prompt 3rd lepton, hadronic $\tau$s.

# Displaced lepton-jets@ATLAS+CMS

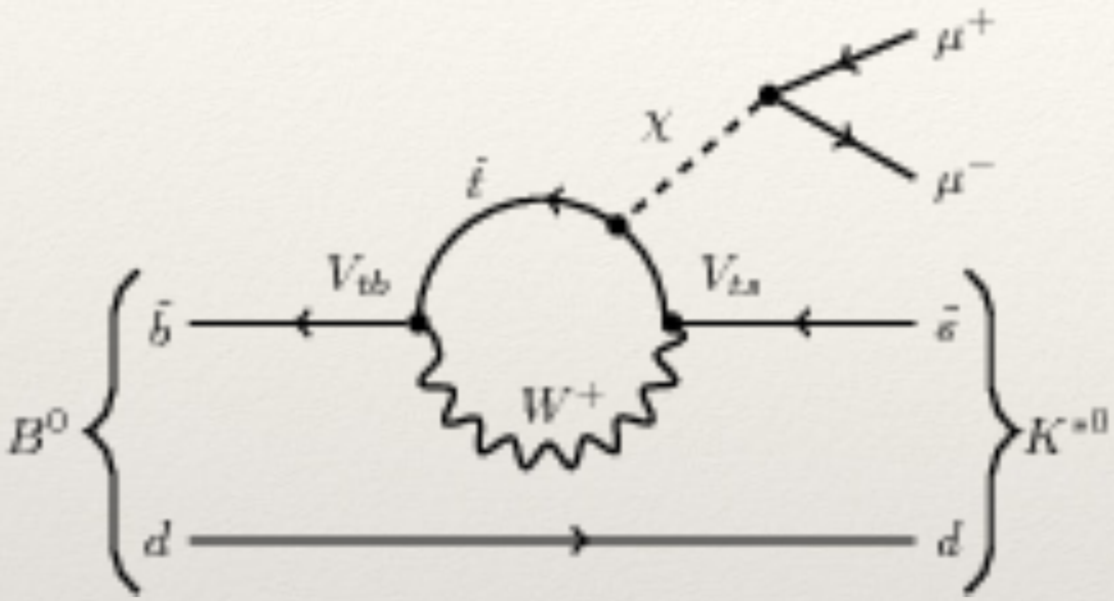
- CMS: Trigger on $\mu$'s with standard isolation requirements.
  Request 4$\mu$ only, using 2 pairs of 2 OS (electrons, taus are lacking!)
- ATLAS: Dedicated triggers *CalRatio, MuonRoI.*
  Cluster lepton-jets (fixed-cone size) and tag them by (μ,jet) content.

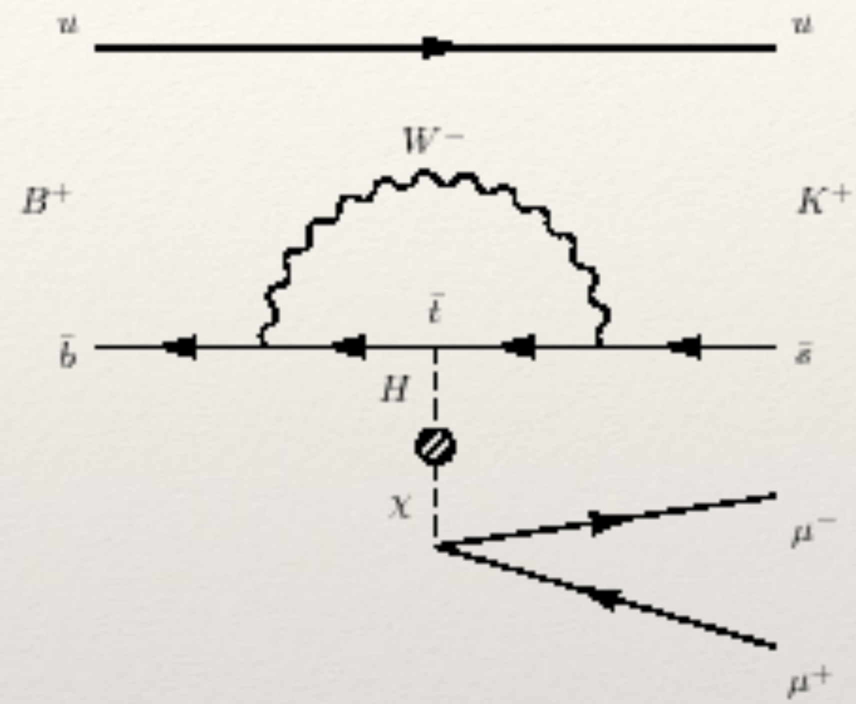



- Interpretation done in terms of light scalars going to $\mu$, dark photons ($\gamma_D$).
- How smooth is the transition from displaced leptons-jets to 'standard displaced" leptons? Are we covering intermediate masses?

Results from LHCb-PAPER-2017-038 not included.

# Leptonic decays@LHCb




- Uses LHCb capabilities to identify the B-mesons, Kaons.
- Scan on $m(\mu^+\mu^-)$. $X \to \mu^+\mu^-$ is not necessarily displaced (prompt X.
- Reach limited due to the kinematics of the event (What if $m_X > 5$ GeV?)

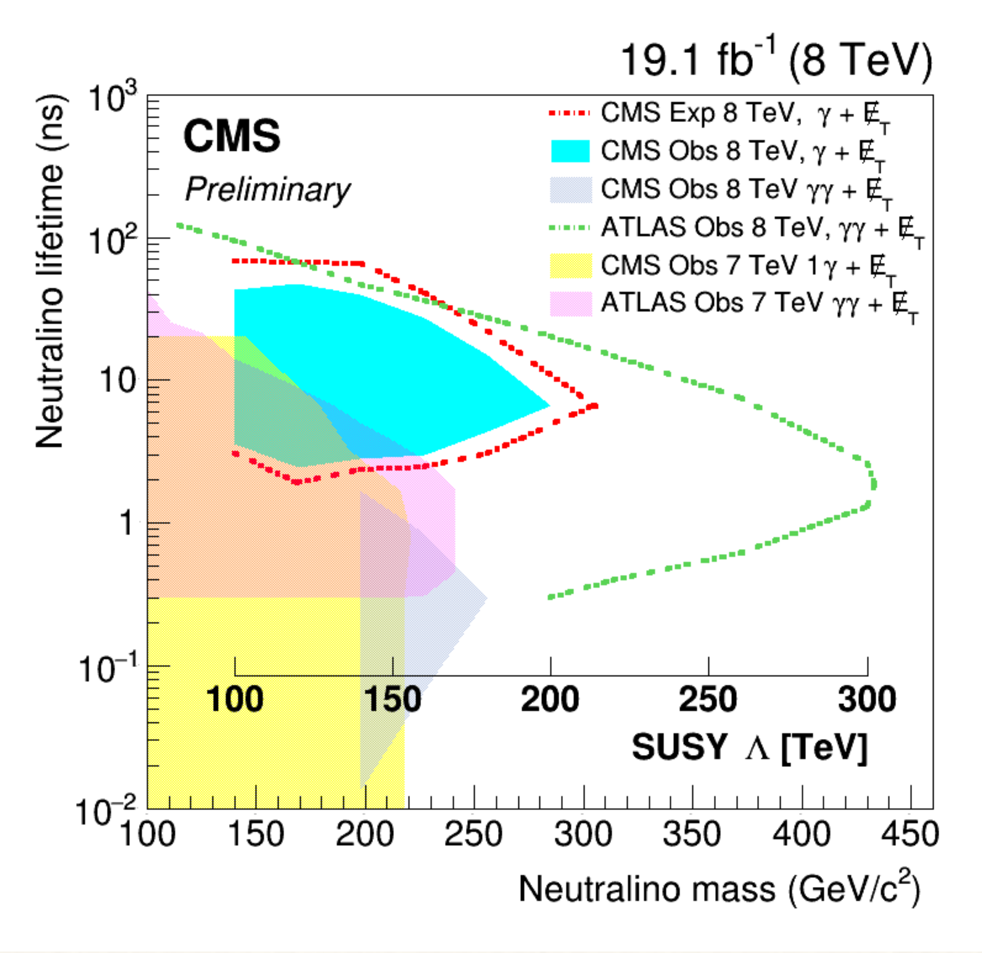
# Semi-Leptonic decays

- Many leptonic and hadronic searches partially cover this case: ATLAS e,μ + tracks (CERN-PH-2015-065), CMS inclusive DV search (CMS PAS-EXO-16-003), CMS large impact e,μ (CMS-EXO-16-022)
- LHCb-PAPER-2016-047: dedicated search for semi-lep decaying LLPs. Triggers on $\mu$, selects offline a DV and does MVA on pT($\mu$) and $d_0$ ($\mu$). Optimisation on LLP mass and muon isolation. Covers cτ between 1.5 and 30 mm.
- How does the simultaneous presence of jets and leptons affect the selection / analysis? For instance: prompt jet searches veto non-standard jets. Lepton isolation will miss highly-boosted LLP decaying to e+j, μ+j?

See J.Evans's talk yesterday for more examples.

# Photonics decays

- Non-standard γs: not coming from PV (*non-pointing*) and/or arrive late at ECAL (*delayed*).
- ATLAS all-in-one: CERN-PH-EP-2014-215.
  CMS: delayed CMS-PAS-EXO-012-35, non-pointing CMS-PAS-EXO-14-017.
- ATLAS triggers on two loose γs, CMS on γ + 2j. Veto on standard γ.




- <u>Gaps</u>:

  1) prompt-γ (they are vetoed!)

  2) no-MET final states (*γγ,γl,γj*)

  3) single γ

  4) … (BYOG)

# Non-standard tracks

- The signatures that failed the “final state” categorisation attempted before is mostly due to unusual tracks appearing in the detector.
- In more detail, I will briefly go over:
  - Heavy Stable Charged Particles (HSCP)
  - Stopped Particles (SP)
  - Magnetic Monopoles (MM)
  - Quirks (Q)
  - Strongly Interacting Massive Particles (SIMP)
  - Disappearing tracks (DT)

# Heavy Stable Charged Particles (HSCP)

CMS-EXO-12-026, CMS PAS EXO-16-036, CERN-PH-EP-2014-252, CERN-EP-2016-131

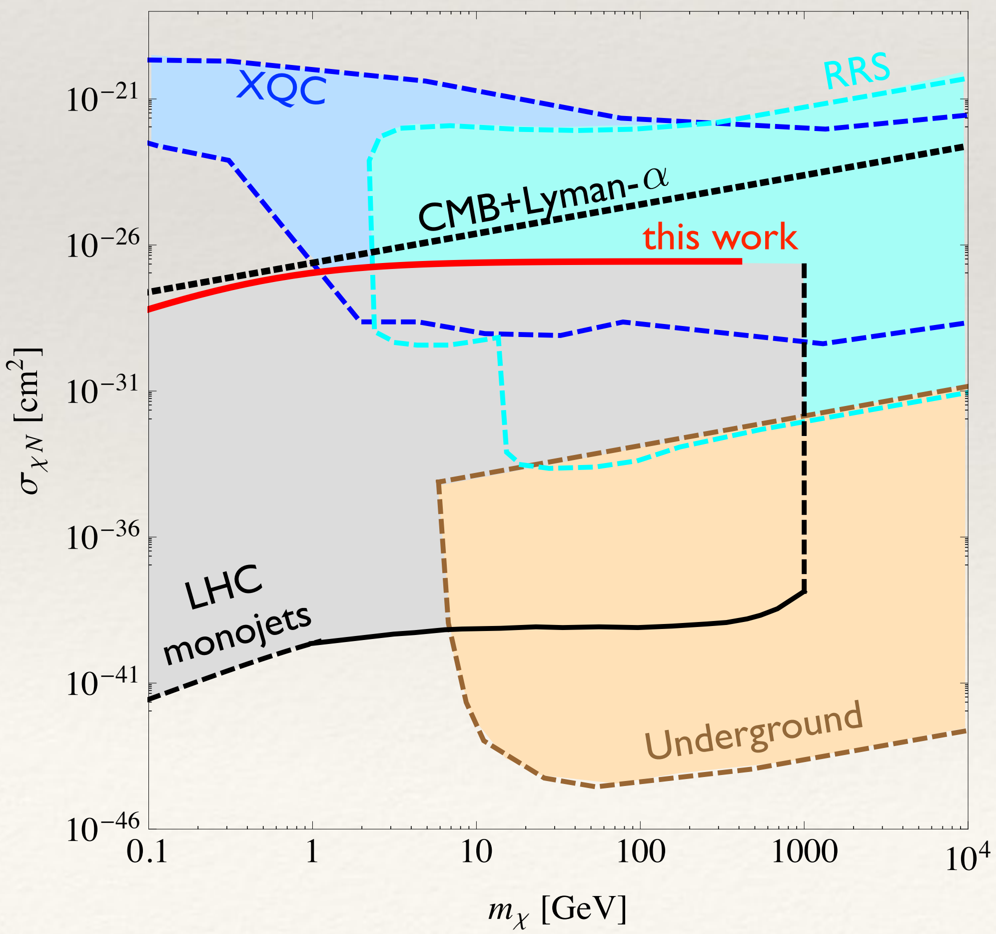
- HSCP searches @ ATLAS, CMS rely on two key properties:
  - $|q| \neq e$: ionization loss (dE/dx) different than SM particles.
  - Large mass -> $\beta = v/c < 1$: longer time-of-flight (TOF) to calorimeters.
    TOF information used optionally (partonic exchange can change q).
- Trigger on single muon or MET + offline "good track" selection.
- Common benchmarks: colored (weak) HSCPs: R-hadrons (sleptons)
- LHCb: no radiation in the ring imaging Cherenkov detector (RICH).
  Requests two OS $\mu$ with $m(\mu\mu) > 100$ GeV, $\beta > 0.8$ (muon chamber rec.) + ANN.
- No obvious weak points found. Improvements?

# Stopped particles (SP)

- HSCP with very low kinetic energy gets stopped (most likely in the dense calorimeters) and decays when no collisions take place (out-of-time decays).
- Refs: CERN-PH-EP-2013-061, CMS PAS EXO-16-004, CMS PAS EXO-17-004.
- Dedicated trigger selecting crossings without nearby bunches + hard jet. ATLAS also requests $|h|<1.3$ and MET > 50 GeV.
- The action happens in the muon systems, as the Stopped Particles make themselves cozy in the calorimeter.
- Main bgds: cosmic muons, beam halos (protons interacting with beampipe).
- No obvious weak points found. Improvements?

# Strongly Interacting Massive Particles (SIMPs)

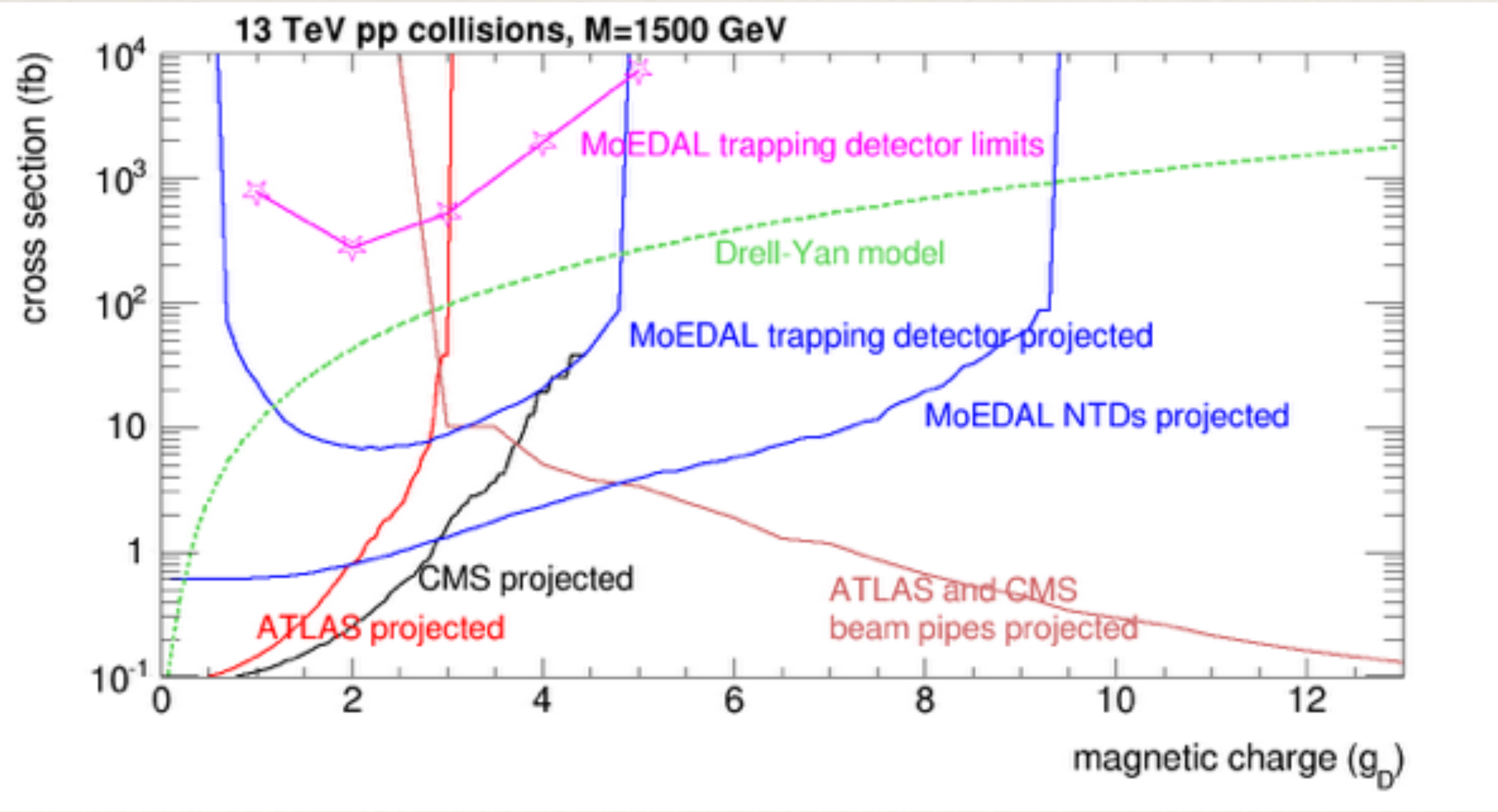
- Based on: Daci, de Bruyn, Lowette, Tytgat, Zaldivar, 1503.05505.
- Motivated by self-interacting DM (missing satellites, core-cusp).
- $\chi$ colored, simplified model with $q\bar{q}$ -> M -> $\chi$ $\chi$ , M ~ 1 GeV.




- Signature: HCAL deposit without associated track (2 trackless jets!). Pheno similar to emerging jets.
- Trick: small charged energy fraction.
- Analysis underway by CMS! (see talks by S. Lowette @ April's workshop and A. de Roeck yesterday.)

# Magnetic Monopoles (MM)

- ATLAS [CERN-PH-EP-2015-174] looks for highly-ionising particles (HIPs). HIPs encompass a variety of BSM scenarios: magnetic monopoles, stable microscopic black holes, dyons, etc.
Focus on MM for the sake of the argument, results are recastable.




- Magnetic charge quantized in units of $g_D \approx 68.5$.
  - Behaves as a particle with $q/e = n\ 68.5$, ionisation power 4700 $n^2$ times the electron.
  - HUGE coupling constant, forbids any reasonable/possible perturbative calculation beyond LO.

Taken from P. Mermod's talk (tomorrow)

# Quirks (Q)

- Quirks are particles charged under both SM and a new confining gauge group SU(N), such that the quirk masses are above the confinement scale $\Lambda$ (no hadronization).
- Quirk-antiquirk pair can form a bound state while being separated by a distance $l$ (string scale). This generates a tension in the pair, leading to a trajectory different from the SM helix.
- Contrary to popular lore, quirks are not HV exclusive!
- Only existing search… D0! (FERMILAB-PUB-10-324-E)
- No spoilers! Details in the forthcoming talks by M. Farina and S. Knapen

M. Farina and M. Low [arXiv:1703.00912].

S. Knapen, H. K. Lou, M. Papucci, and J. Setford [arXiv:1708.02243]


15:30 → 17:20 Experimental coverage -- Part 2

Quirks -- Part 1

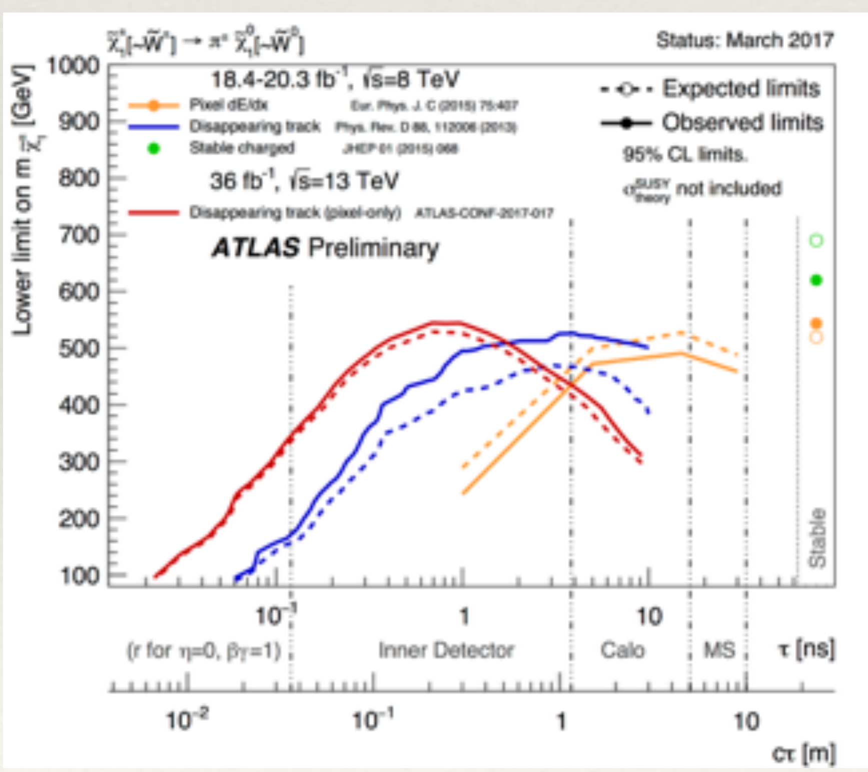
Speakers: Marco Farina (Sezione di Pisa (IT)) , Marco Farina (Cornell University)

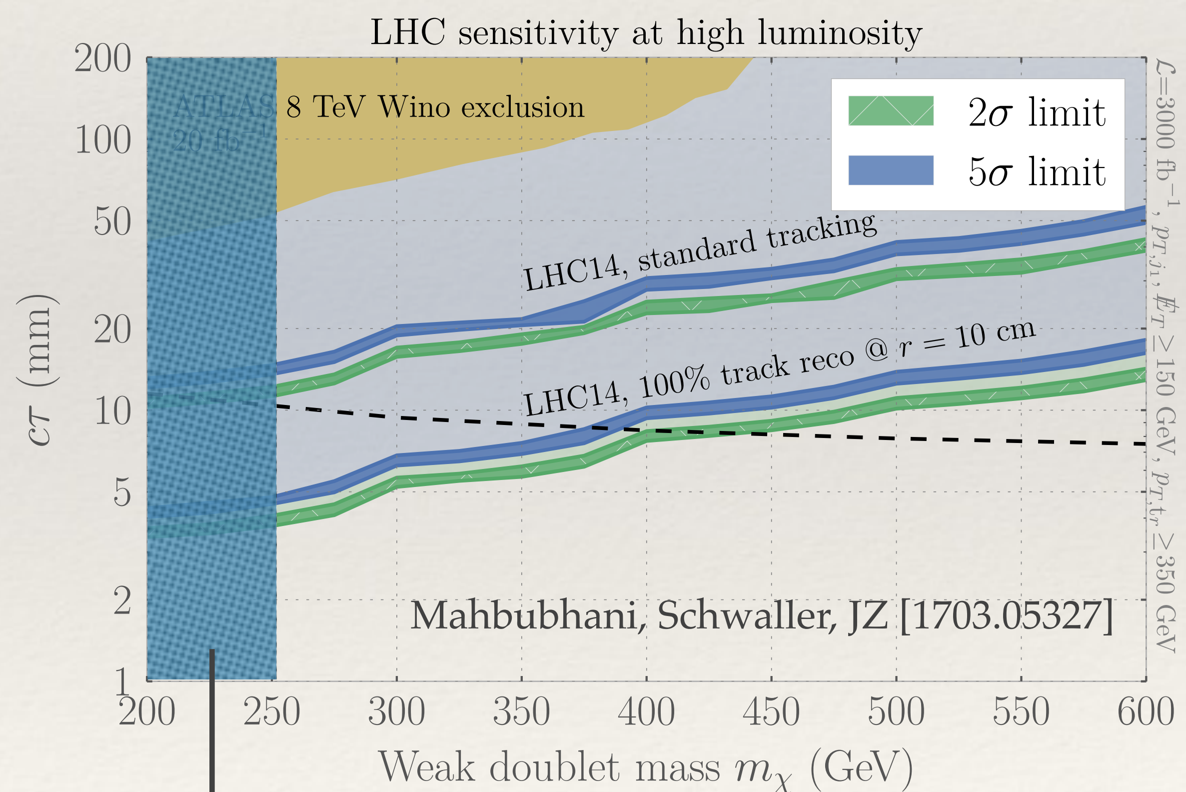
Quirks -- Part 2

Speaker: Simon Knapen (Lawrence Berkeley National Lab)

# Disappearing track (DT)

- Charged particle decays into neutral particle plus a soft charged one (e.g: $X^+ \to X^0 + \pi^+,\mu^+$). Track vanishes in thin air. Trigger on hard jet + MET.
- cτ: ATLAS went from 30 to 12 cm with 4th layer. CMS pixel detector upgrade?
- Wino (Higgsino) cτ = 55 (6.6) mm. Scalar models have no preferred value!




Mono jet + soft-leptons:
Schwaller, JZ [1312.7350], Low and L.-T. Wang,[1404.0682], Barducci, Belyaev, Bharucha, Porod, Sanz [1504.02472].

- How low can we go in cτ?

# Conclusions

- Broad overview of existing searches presented here.
- The goal is to provide all essential information for the non-expert reader, and refer the avid one to the original publications.
- Need to discriminate between intrinsic limitations and possible improvements: EXP feedback needed!
- Need to have comparisons of the EXP capabilities in a few BSM scenarios: common benchmark(s) appreciated.
- Not the whole landscape covered here: heavy neutral leptons, magnetrons, kinked tracks, fractionally(milli) charged particles, emerging jets,…
- This chapter should motivate improvements and wild ideas (stay tuned for the forthcoming lightning round)
- If you wanna join or contribute, just ping us!