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 your 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
    - 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.
  - $c\tau \sim [0.1-10]$ m constrained for rates of $\sim 50fb^{-1}$.

- CMS:
  - Dedicated off-line displaced jet (DJ) tagger triggering on large $H_T > 350-500$ GeV.
  - Fails for $c\tau < 3$ mm ($> 1$m) 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 $c_\tau$ (understanding detector) and lower masses (higher boosts using jet-substructure). See C. Vasquez Sierras’s talk yesterday

$H(125) \rightarrow \pi_V \pi_V$

$\text{BR}(H \rightarrow \pi_V \pi_V) < 50\%$

Do we give-up on this region?

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 µ⁺µ⁻ from B→K decays.
  - 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 μ’s with standard isolation requirements. Request 4μ 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 μ, dark photons (γ_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 at LHCb

- Uses LHCb capabilities to identify the B-mesons, Kaons.
- Scan on $m(\mu^+\mu^-)$. $X \rightarrow \mu^+\mu^-$ is not necessarily displaced (prompt $X$).
- Reach limited due to the kinematics of the event (What if $m_X > 5 \text{ GeV}$?)
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 μ, selects offline a DV and does MVA on pT(μ) and d_0(μ). 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 $\gamma$s: not coming from PV (non-pointing) and/or arrive late at ECAL (delayed).


- ATLAS triggers on two loose $\gamma$s, CMS on $\gamma + 2j$. Veto on standard $\gamma$.

- **Gaps:**
  1) prompt-$\gamma$ (they are vetoed!)
  2) no-MET final states ($\gamma\gamma, \gamma l, \gamma j$)
  3) single $\gamma$
  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)


- HSCP searches @ ATLAS, CMS rely on two key properties:
  - $|q| \neq e$: ionization loss ($dE/dx$) different than SM particles.
  - Large mass $\Rightarrow \beta = v/c < 1$: 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).


- 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 $q\bar{q} \rightarrow M \rightarrow \chi \chi$, $M \sim 1$ 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 $q/e = n \times 68.5$, ionisation power $4700 \times n^2$ 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].

Disappearing track (DT)

- Charged particle decays into neutral particle plus a soft charged one (e.g: $X^+ \rightarrow X^0 + \pi^+, \mu^+$). Track vanishes in thin air. Trigger on hard jet + MET.

- $c\tau$: ATLAS went from 30 to 12 cm with 4th layer. CMS pixel detector upgrade?

- Wino (Higgsino) $c\tau = 55 \ (6.6)$ mm. Scalar models have no preferred value!

- How low can we go in $c\tau$?

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