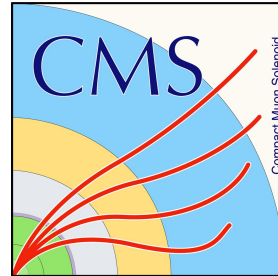# Search for long-lived particles at the LHC
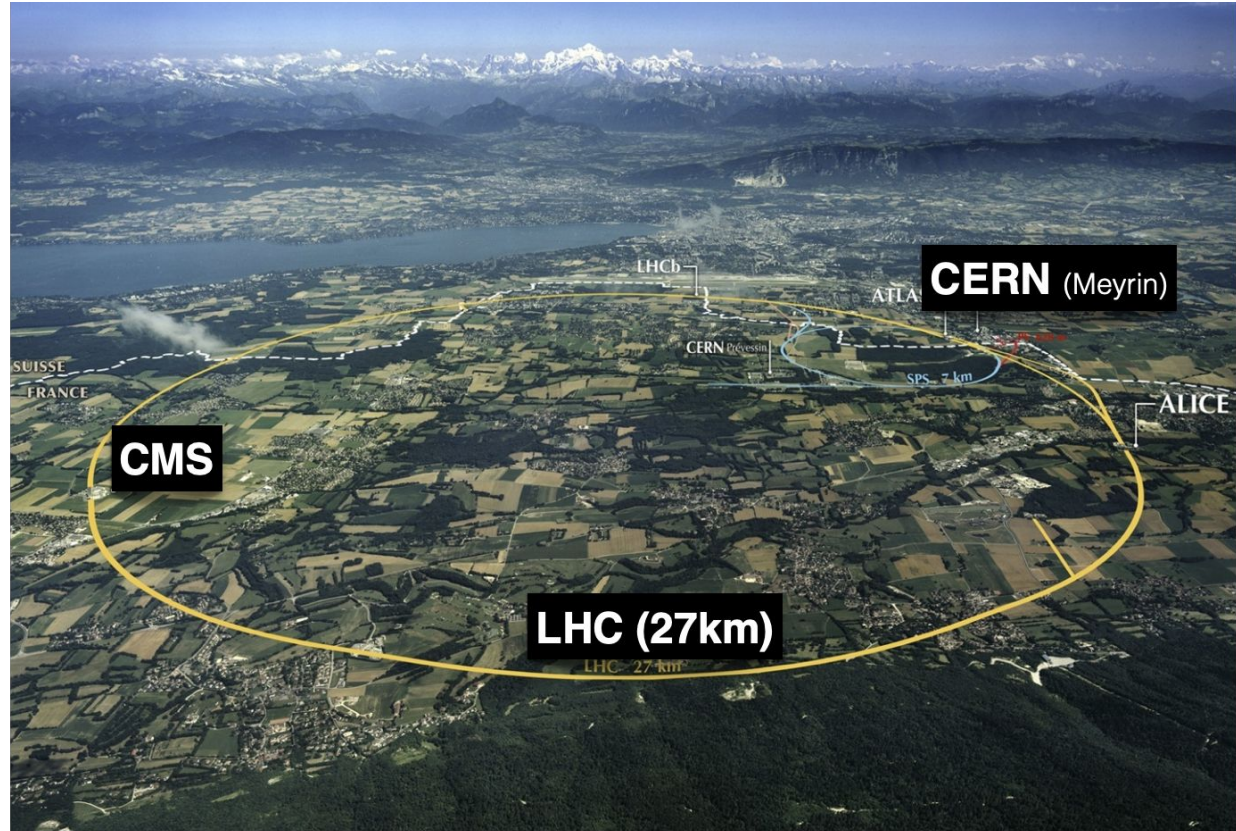
Saranya Ghosh

భారతీయ సాంకేతిక విజ్ఞాన సంస్థ హైదరాబాద్
भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

Introduction : Large Hadron Collider (LHC)

- Most powerful particle accelerator in the world

- Collides proton bunches at c.o.m. energy of 13.6 TeV (design: 14 TeV)

- Diverse physics program,
  - Prominently featuring search for new particles beyond the Standard Model (BSM)

Introduction : Search for long-lived particles

- Extensive search programs for new physics @ ATLAS, CMS & LHCb experiments at LHC

- Typically focused on prompt SM particles
  - prompt : particles that decay very close to p-p interaction vertex -> short lifetimes

- Open questions but no discoveries
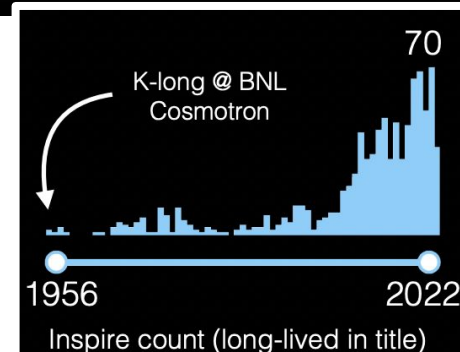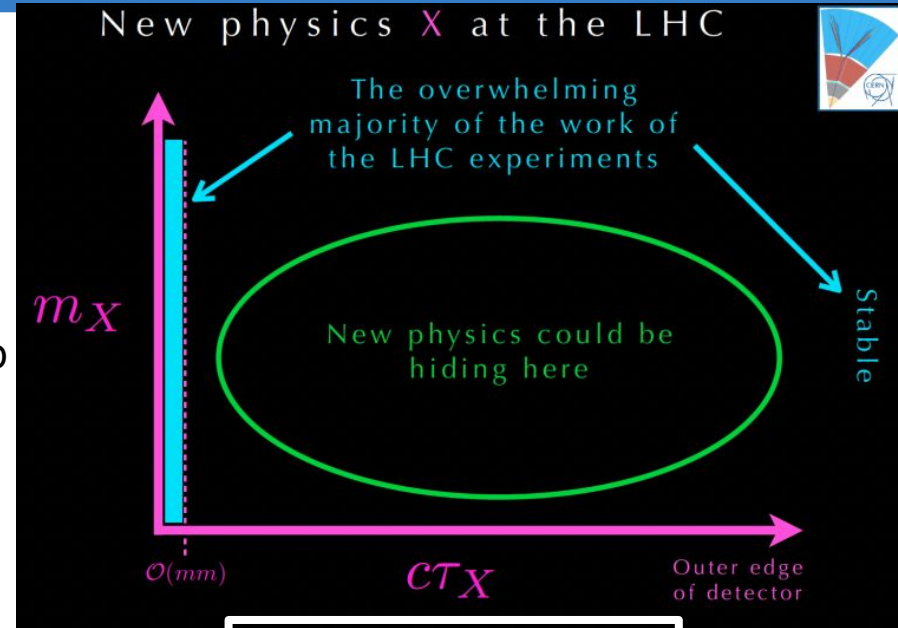 - requires re-imagination of searches
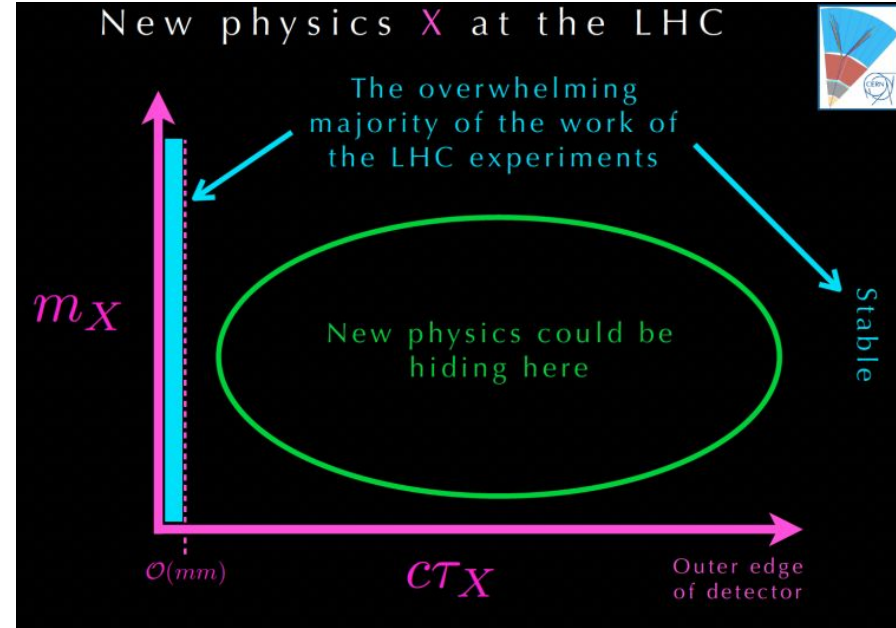
Introduction : Search for long-lived particles

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- Open questions but no discoveries
  - requires re-imagination of searches

- LHC provides excellent opportunity to search for long-lived particles
  - Interest in searches for LLPs is gaining momentum -> "hot topic"

New physics X at the LHC

The overwhelming majority of the work of the LHC experiments

m_X

New physics could be hiding here

Stable

$\mathcal{O}(mm)$ $c\tau_X$ Outer edge of detector

70

K-long @ BNL Cosmotron

1956   2022

Inspire count (long-lived in title)

LLPs : Standard Model (SM)

- Searches for LLPs : not a far stretch
  - several SM particles are long-lived

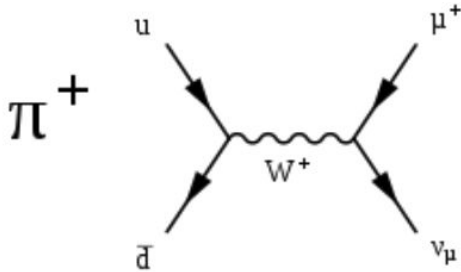- Phase space of lifetimes for search limited by detector dimensions
  - more on that later…
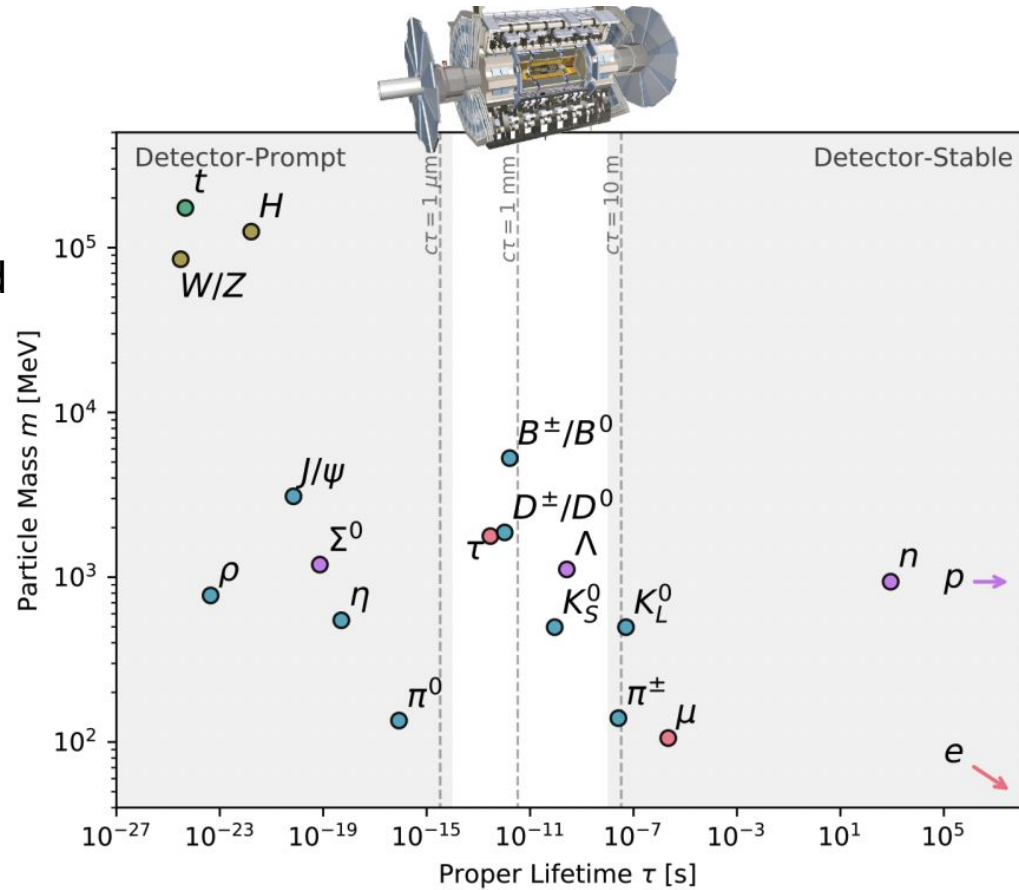
LLPs : What leads to SM LLPs?

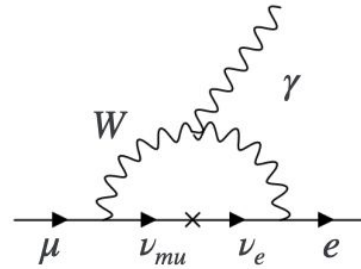$$\frac{1}{\tau} = \Gamma \propto g^2 |\mathcal{M}|^2 \Phi$$

$$\downarrow$$

$$\left(\frac{m}{\Lambda}\right)^n$$

Small couplings

Heavy intermediary

Limited phase space

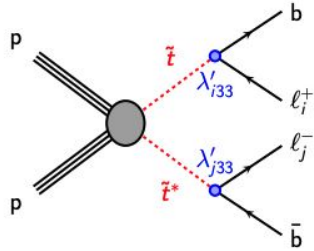$$K_L \rightarrow \pi^+ \pi^- \pi^0$$

$$m(K) - 3m(\pi) \approx 70 \text{ MeV}$$

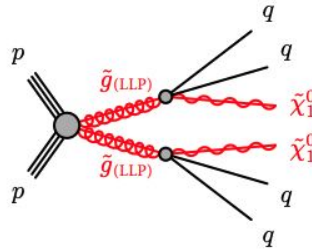- Such characteristics can be there for BSM particle too!

LLPs : BSM

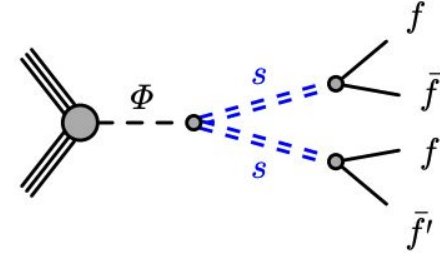**R-Parity violating SUSY**
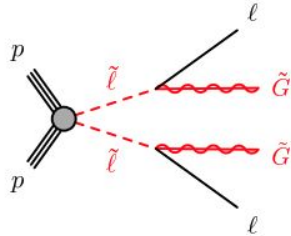- Small decay couplings

Split-SUSY
- gluino forms R-hadron

Hidden Sector
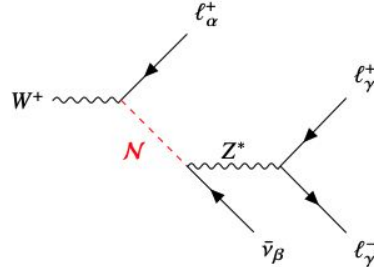- Heavy scalar (Higgs or Φ) decay to long lived scalars

Gauge-Mediated SUSY Breaking
- Small gravitational coupling to lightest gravitino

Heavy Neutral Leptons
- Small left-handed neutrino mixture → rare weak interactions

Compressed SUSY
- Small mass splittings

- Multiple other models as well can have LLP signatures…

LLPs : BSM -> experimental signatures

R-Parity violating SUSY
- Small decay couplings

Split-SUSY
- gluino forms R-hadron

Hidden Sector
- Heavy scalar (Higgs or Φ) decay to long lived scalars
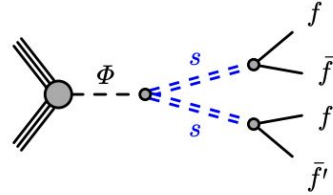
Gauge-Mediated SUSY Breaking
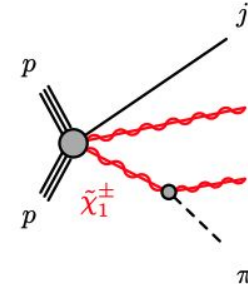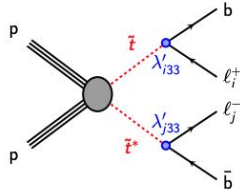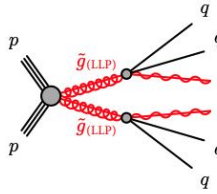- Small gravitational coupling to lightest gravitino
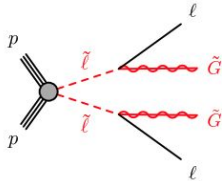
Heavy Neutral Leptons
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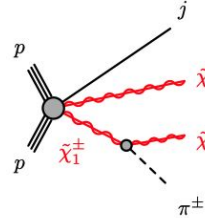
- Different experimental signatures
  - Displaced vertices
  - Displaced jets
  - Displaced leptons / photons
  - Disappearing tracks

LLPs : Experimental signatures

Courtesy: J. Antonelli
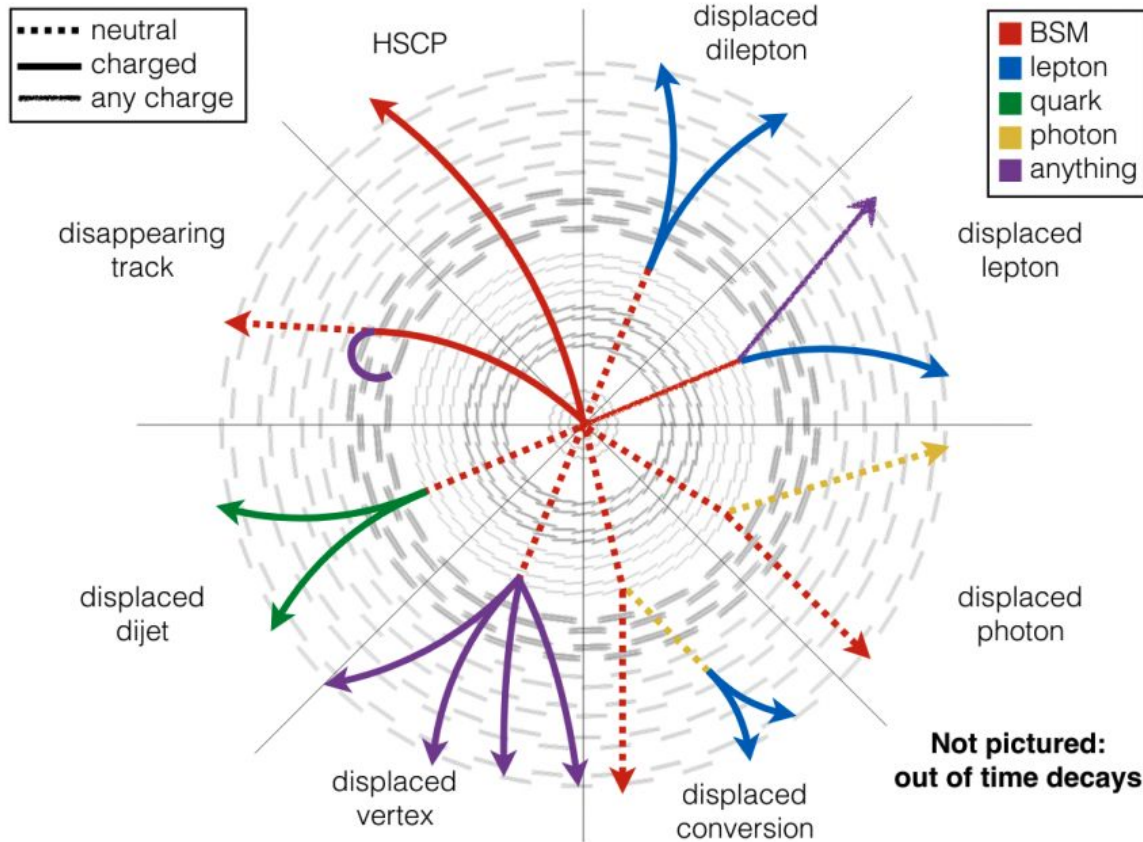
LLPs : Experimental signatures

- Phase space of lifetimes for search limited by detector dimensions
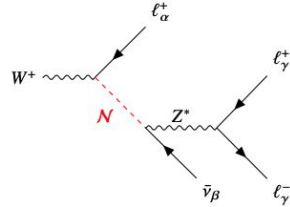
- General experiments, techniques not designed for LLPs

- LLP signatures are experimentally challenging
  - Require special reconstruction techniques
  - Innovative triggering
  - Specific background estimation techniques

Courtesy: J. Antonelli
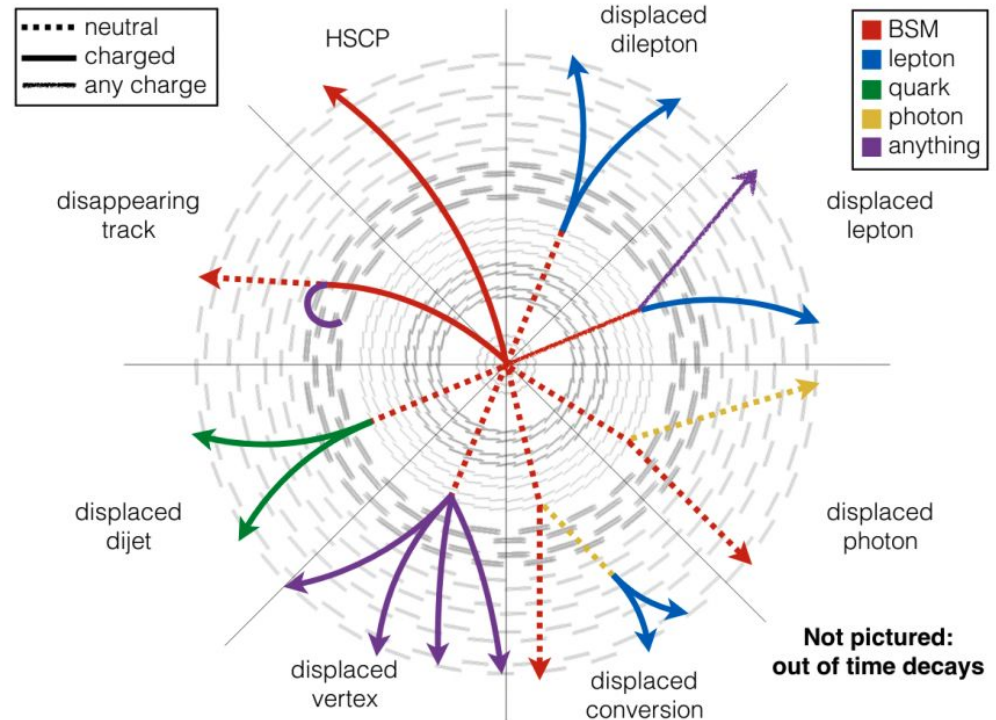
Detectors : ATLAS detector
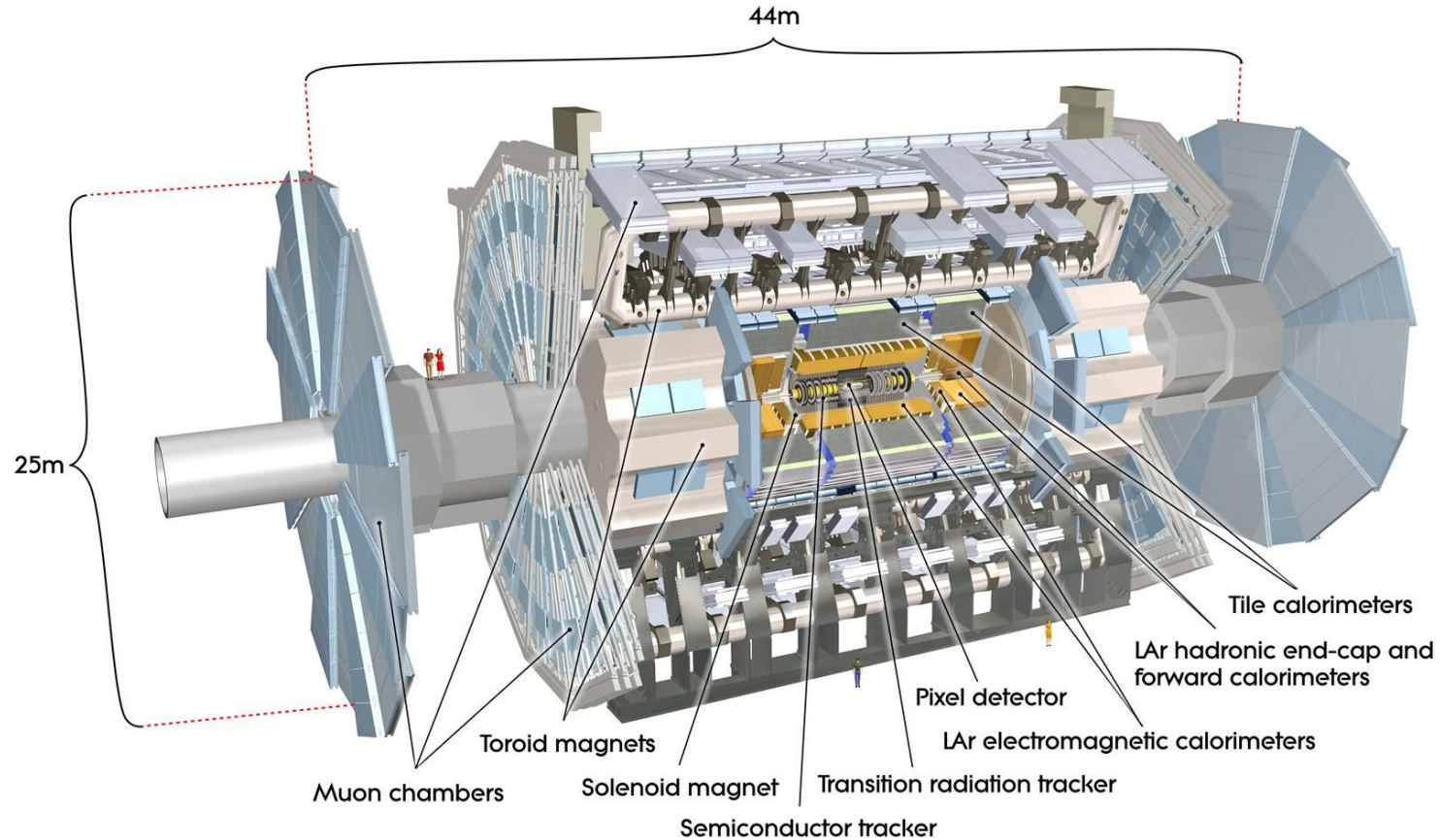
Detectors : LHCb detector
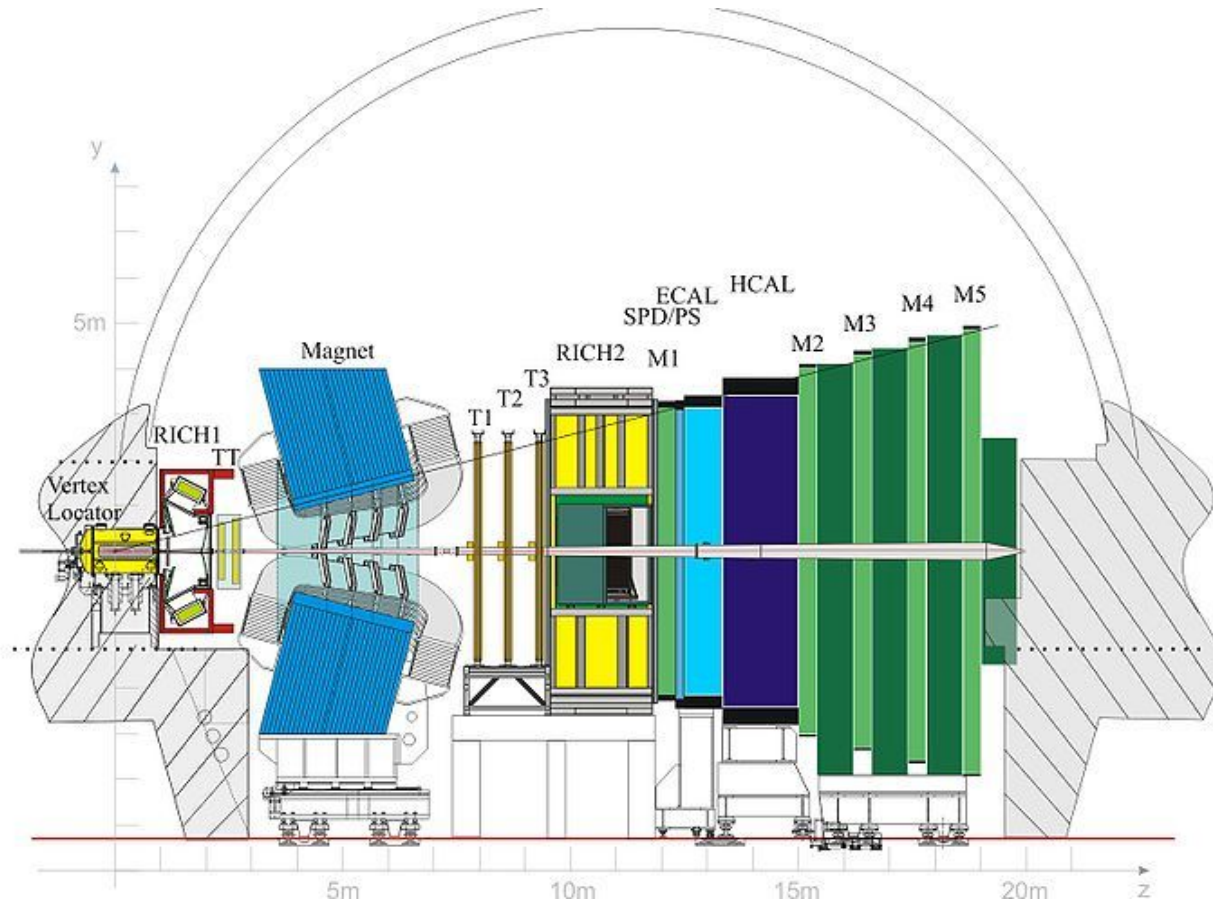
Detectors : Dedicated LLP detectors (new, proposed)
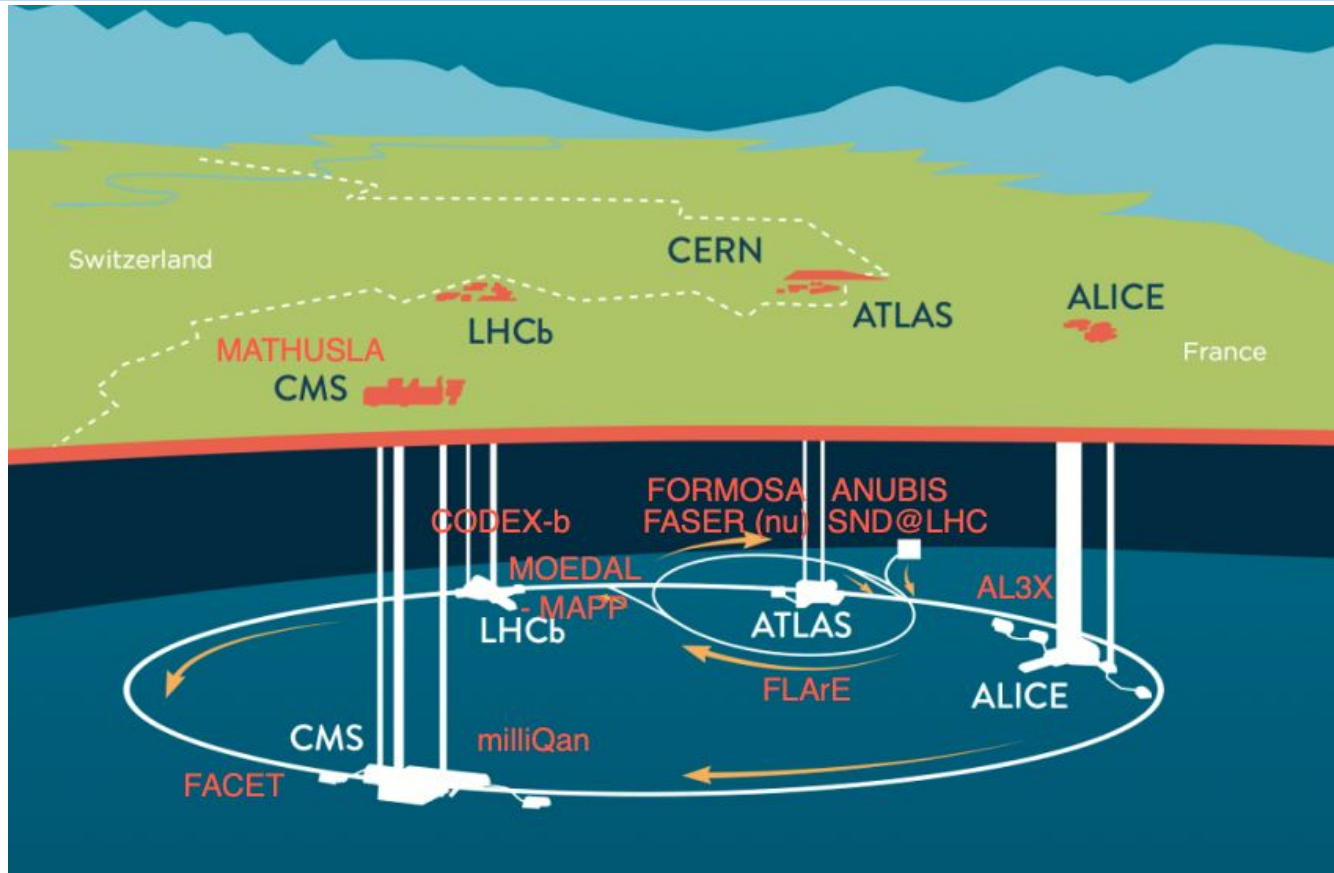
- These are new / upcoming / proposed ; will not be featured much in this talk

Detectors : CMS detector

CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A

MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
Silicon strips ~16m² ~137,000 channels

FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO$_4$ crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

- Experiment of focus in this talk

Detectors : CMS detector

- Experiment of focus in this talk : special reconstruction techniques used for LLP searches

Search for LLPs using displaced vertices

- Focus on intermediate lifetimes from 100 μm to 100 mm

- Trigger on events with large jet activity

- Use tracks satisfying special selection requirements to reconstruct displaced vertices
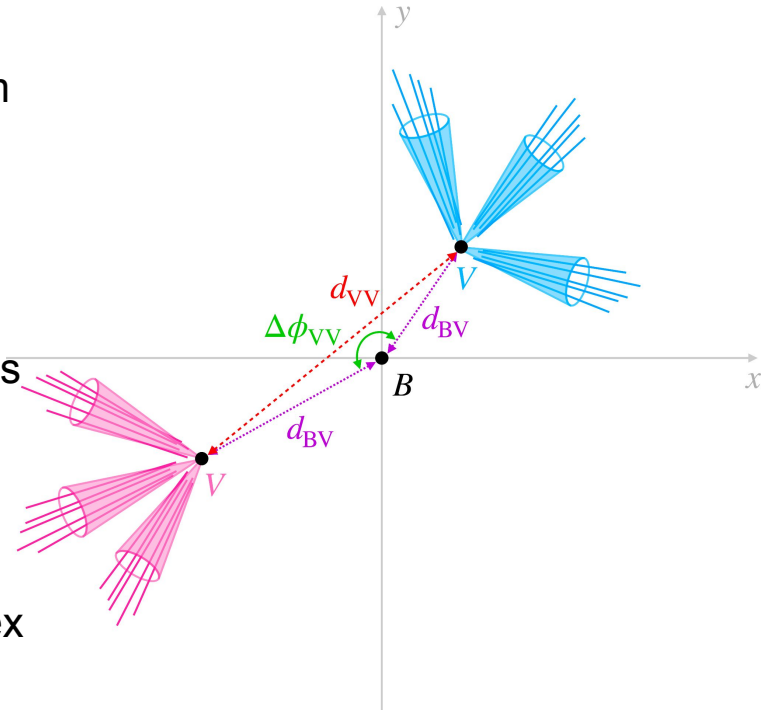
- Iteratively merge tracks into vertices and require vertices to satisfy quality requirements

- x-y distance of vertex from detector origin < 20.9 mm

- Require two vertices and distinguish signal from tiny background using x-y distance between displaced vertex pairs dVV

Search for LLPs using displaced vertices

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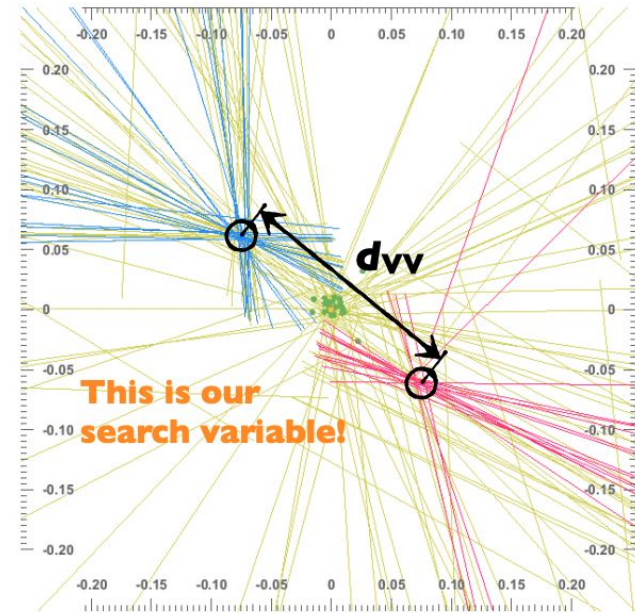
- Background from misreconstructed tracks : data driven estimation

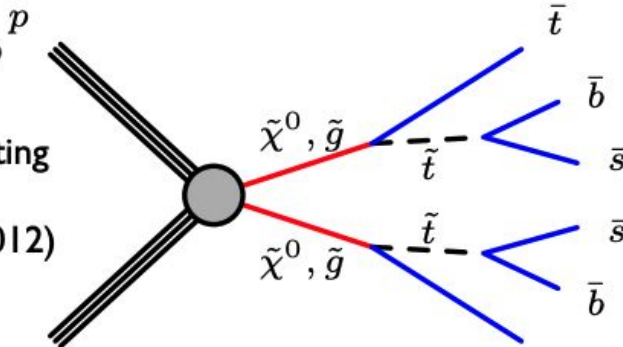# Search for LLPs using displaced vertices

Benchmark signal models

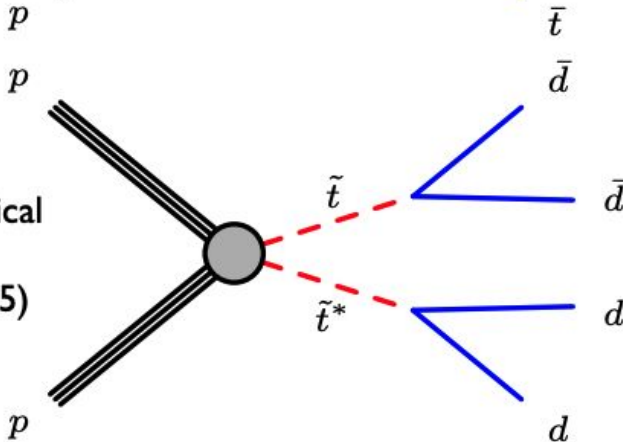"Multijet"

Minimal flavor violating RPV SUSY, PRD **85**, 095009 (2012)

"Dijet"

Standard or dynamical RPV SUSY, JHEP **08**, 016 (2015)

● No signal found, limits set:
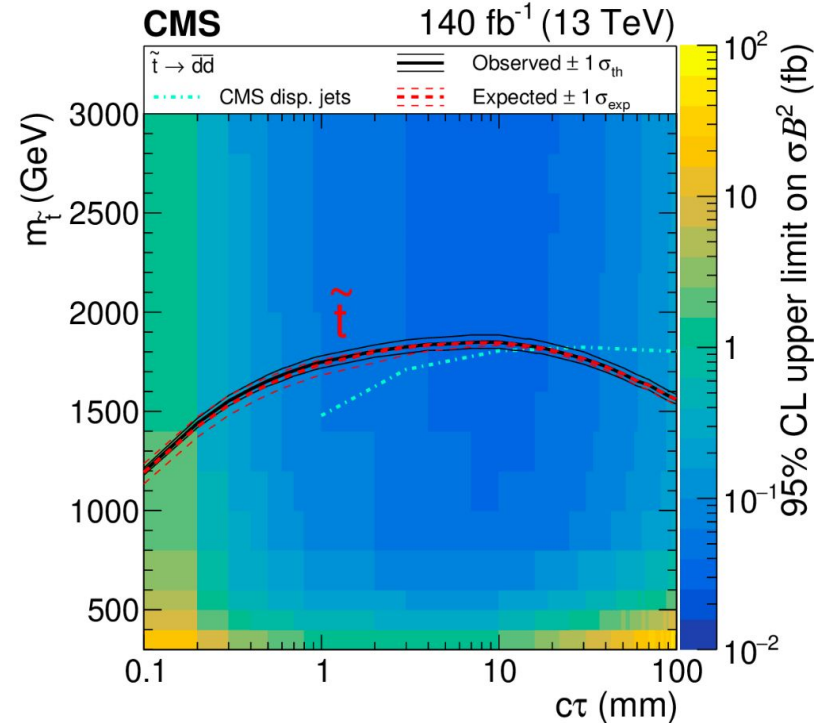
Search for LLPs using displaced jets

- Search for LLPs with displaced jets - benchmark model: split SUSY scenario

  - Lifetimes cτ = 10μm to 10m

- A novel neural network based approach used to identify displaced jets
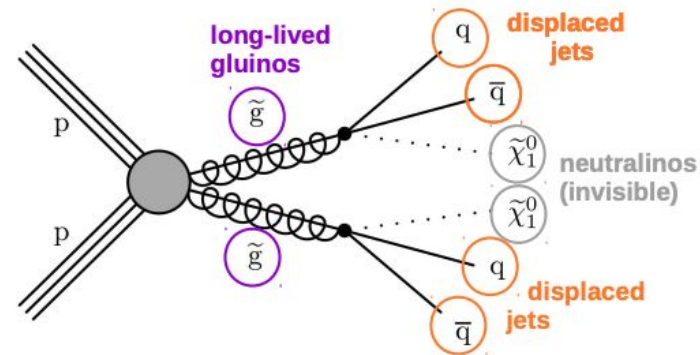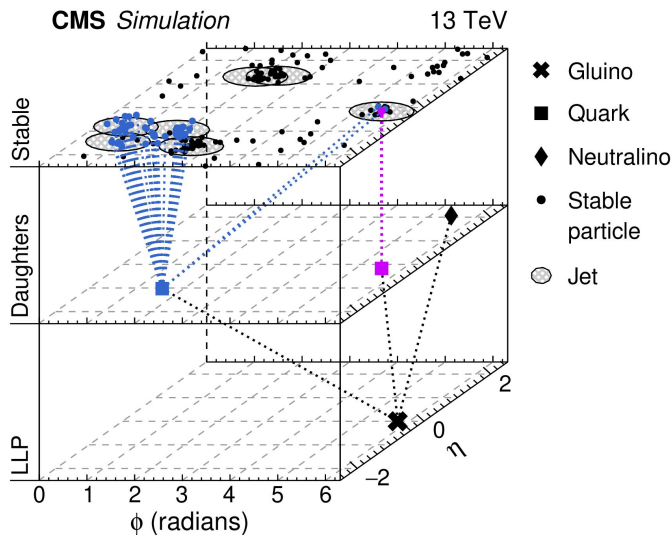
Search for LLPs using displaced jets

- LLP jet tagging efficiency:
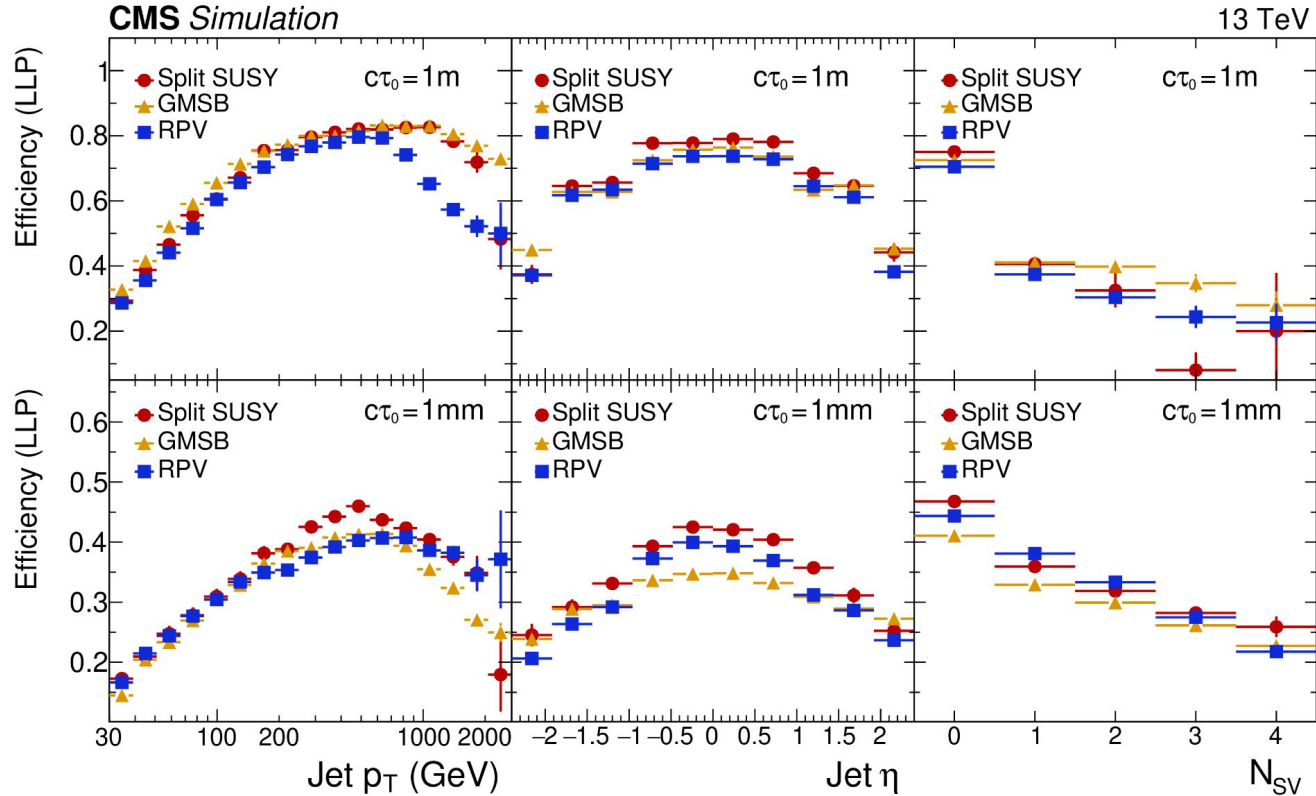
Search for LLPs using displaced jets

- Search results and comparison with non-ML jet-tag based results

Search for LLPs using delayed photons

- Signature of delayed photons using the ECAL timing information

- Benchmark BSM model: GMSB scenarios

- Photons emerging from neutral LLP arriving late in time relative to expectation from prompt photons

- Requires special reconstruction to include photons that might arrive late in time

- Dedicated trigger used for photon + hadronic activity in event

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- Special measurements of timing resolution of CMS electromagnetic calorimeters used

- Data driven background estimation performed.

Figure details (as shown):
- 13 TeV
- $\sigma(\Delta t)$ (ns)
- **CMS**
- 2016 (35.9 fb^{-1})
- 2017 (41.5 fb^{-1})
- $\sigma(\Delta t) = \dfrac{N}{A_{eff}/\sigma_N} \oplus \sqrt{2}C$
- $N_{2016} = 31.6 \pm 1.2$ ns
- $C_{2016} = 0.077 \pm 0.001$ ns
- $N_{2017} = 30.4 \pm 1.2$ ns
- $C_{2017} = 0.095 \pm 0.001$ ns
- A_{eff}/σ_N

Search for LLPs using delayed photons

- Signature of delayed photons using the ECAL timing information

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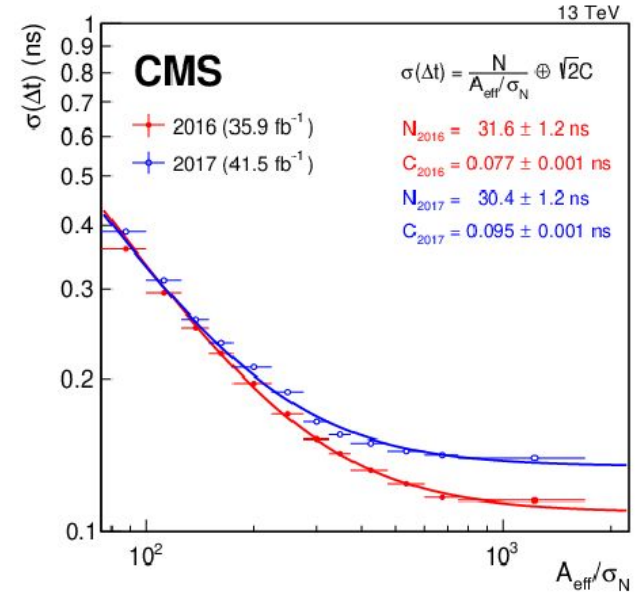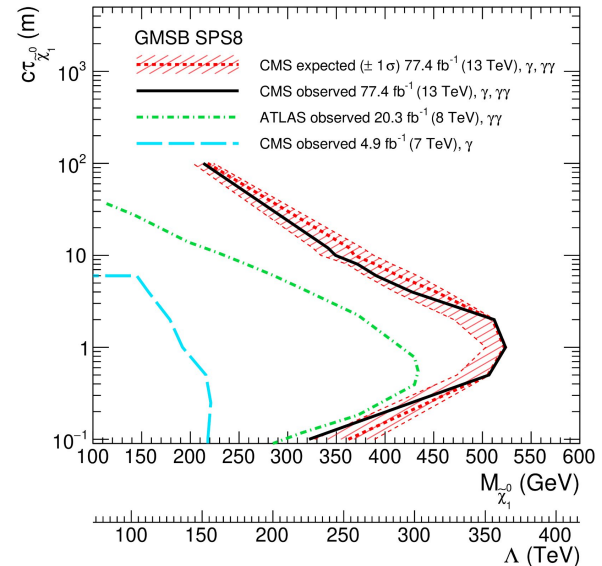- Dedicated trigger used for photon + hadronic activity in event

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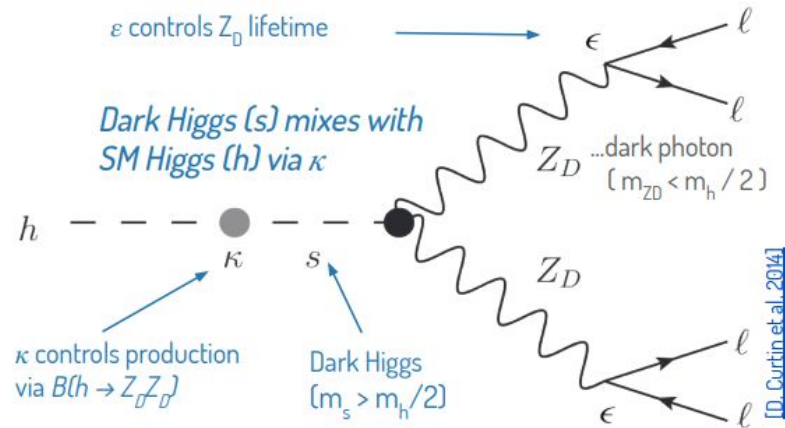- Limits set in terms of neutralino mass / SUSY breaking scale

Search for LLPs using displaced muons

- Inclusive search for long-lived exotic particles decaying to a pair of muons
- Benchmark BSM model: Dark photon model
  - proper decay length cτ(ZD) from a few tens of μm to ≈100 m

Dark photon model: $h \to Z_D Z_D$, $Z_D \to \mu^+\mu^-$.

ε controls Z_D lifetime

Dark Higgs (s) mixes with SM Higgs (h) via κ

Z_D ...dark photon $(m_{ZD} < m_h/2)$

h κ s Z_D

κ controls production via $B(h \to Z_D Z_D)$
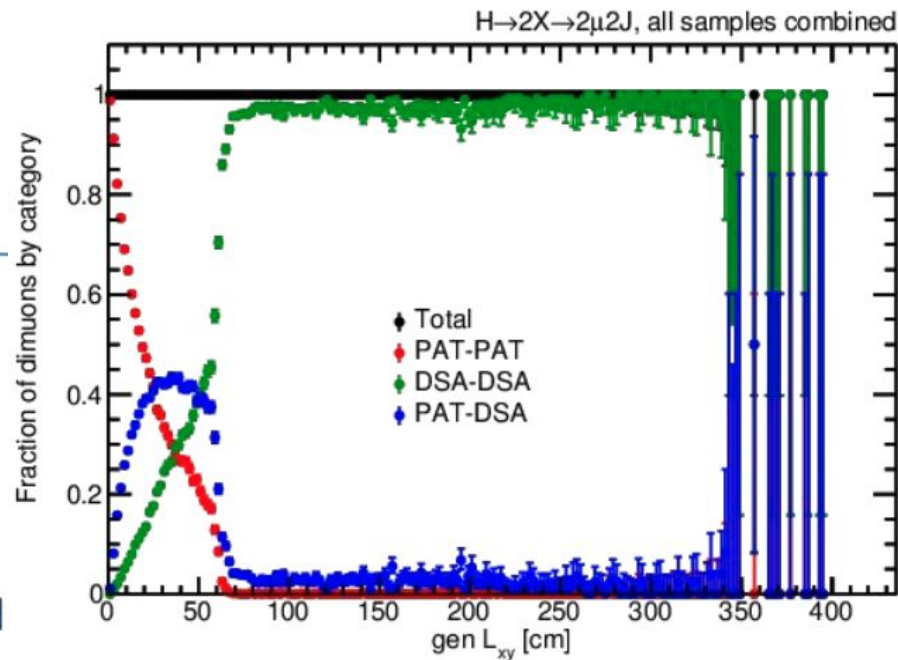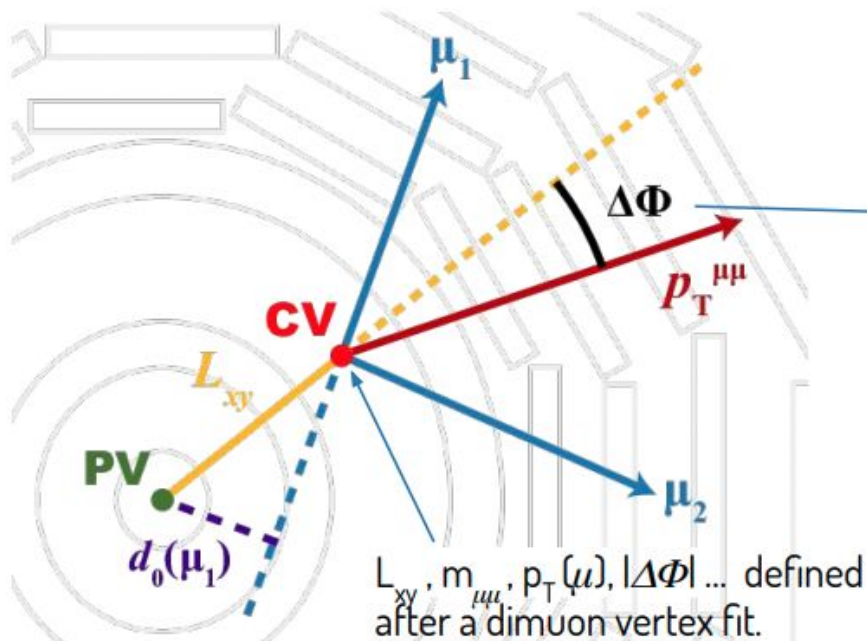
Dark Higgs $(m_s > m_h/2)$

[D. Curtin et al. 2014]

- Special muon reconstruction used to extend probed phase space

Search for LLPs using displaced muons

- Special muon reconstruction using only outer muon stations
- Muon tracks reconstructed under assumption of displaced vertex

L_{xy}, $m_{\mu\mu}$, $p_T(\mu)$, $|\Delta\Phi|$ ... defined after a dimuon vertex fit.

Search for LLPs using displaced muons

arXiv:2205.08582

- Prompt muon reconstruction used in complementarity to extend phase space probed

- Special selections to remove background from cosmic muons, misreconstruction

- Data driven background estimate

- Limits set on signal model
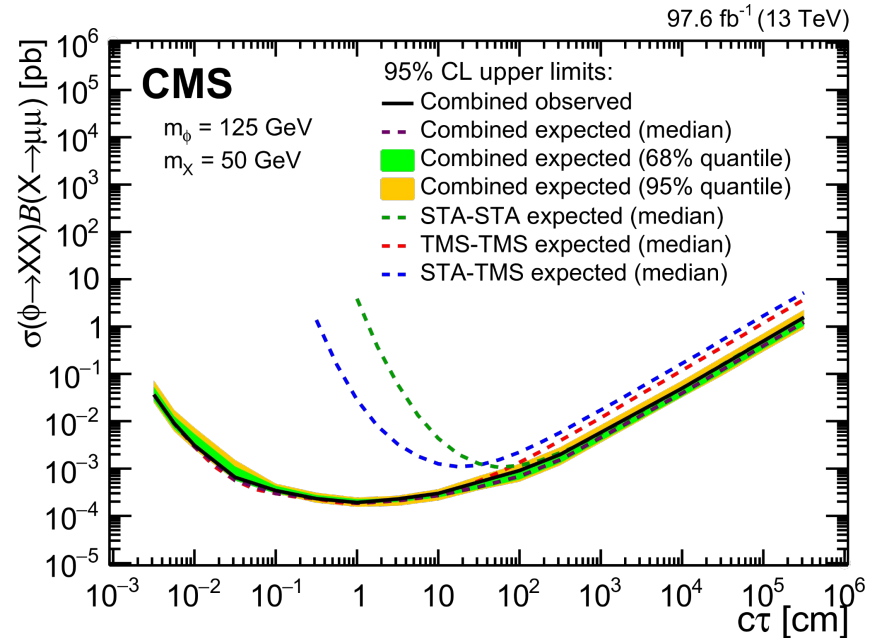
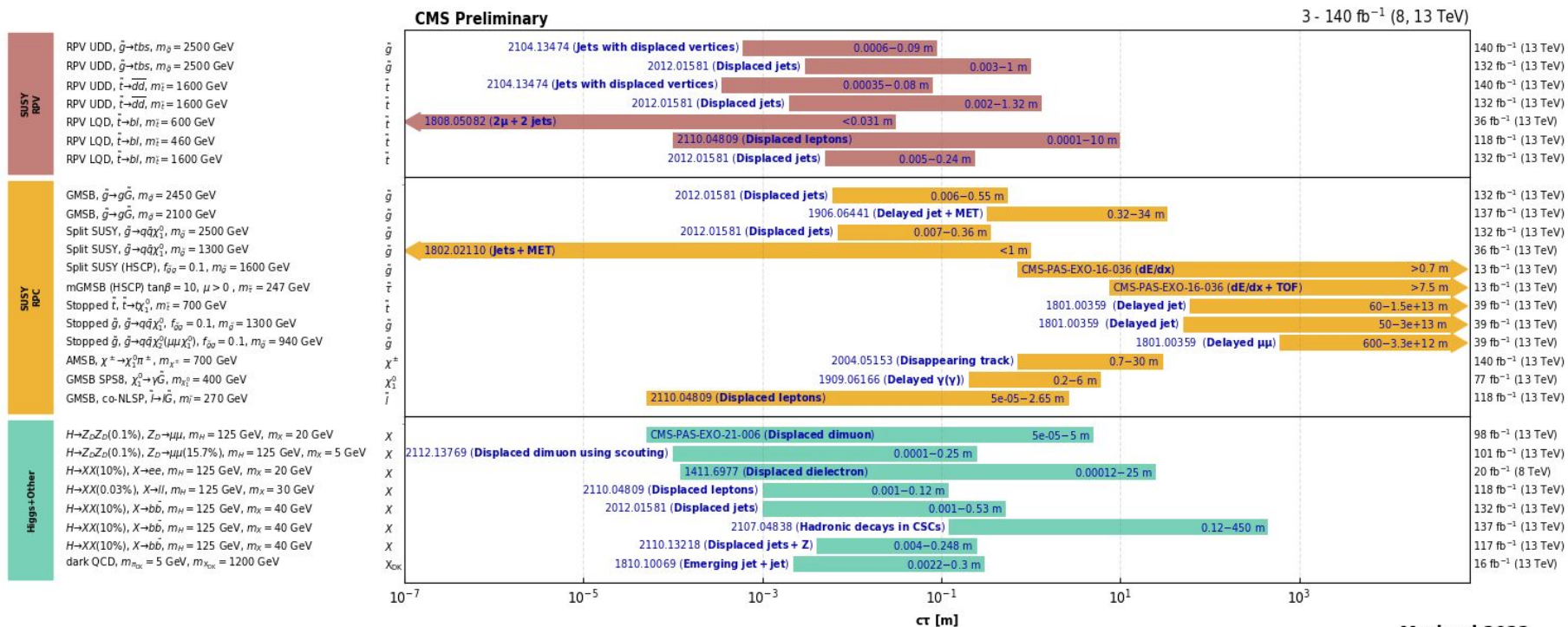# LLPs : BSM -> experimental signatures

Overview of CMS long-lived particle searches

CMS Preliminary

3 - 140 fb^{-1} (8, 13 TeV)

Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.
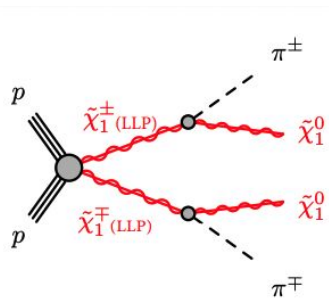
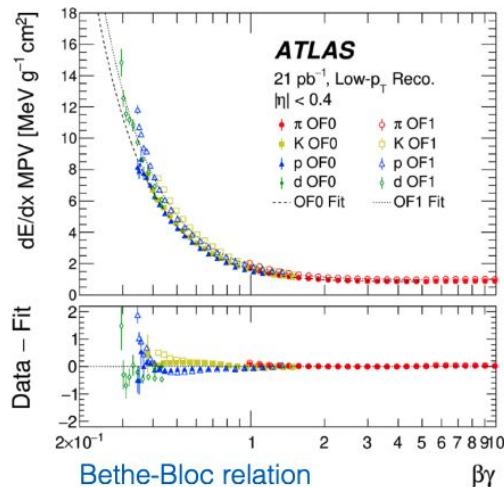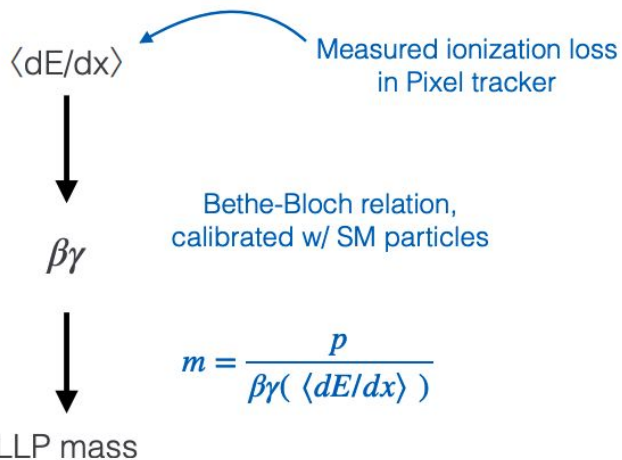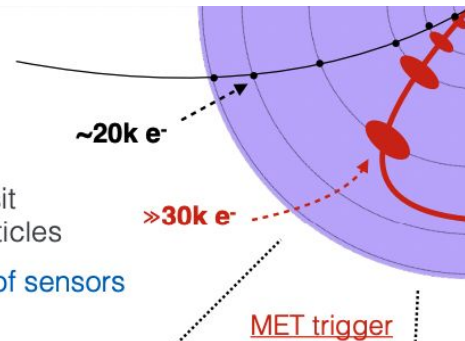**Moriond 2022**

- **Several other searches performed / underway**

ATLAS search using ionisation loss information

arXiv:2205.06013

Target
$\Delta D > 55$ cm
$m \sim [100 - 3000]$ GeV

- Slow, heavy charged particles deposit more energy in trackers than SM particles
  - Large & long signals from clusters of sensors

~20k e⁻

»30k e⁻

MET trigger

$\langle dE/dx \rangle$

Measured ionization loss in Pixel tracker

$\beta\gamma$

Bethe-Bloch relation, calibrated w/ SM particles

$$m = \frac{p}{\beta\gamma(\ \langle dE/dx \rangle\ )}$$

LLP mass

Bethe-Bloc relation

- CMS results upcoming

ATLAS search using ionisation loss information

arXiv:2205.06013

3.3 σ global excess
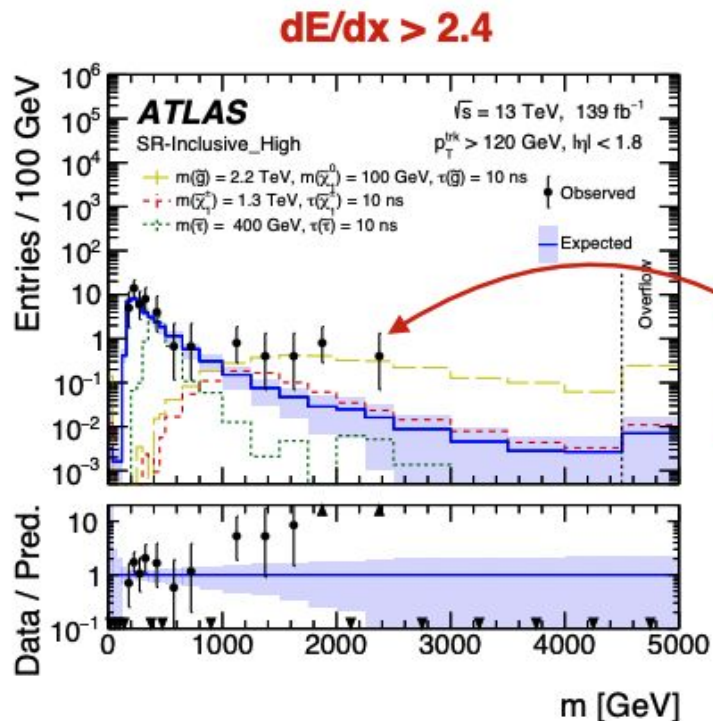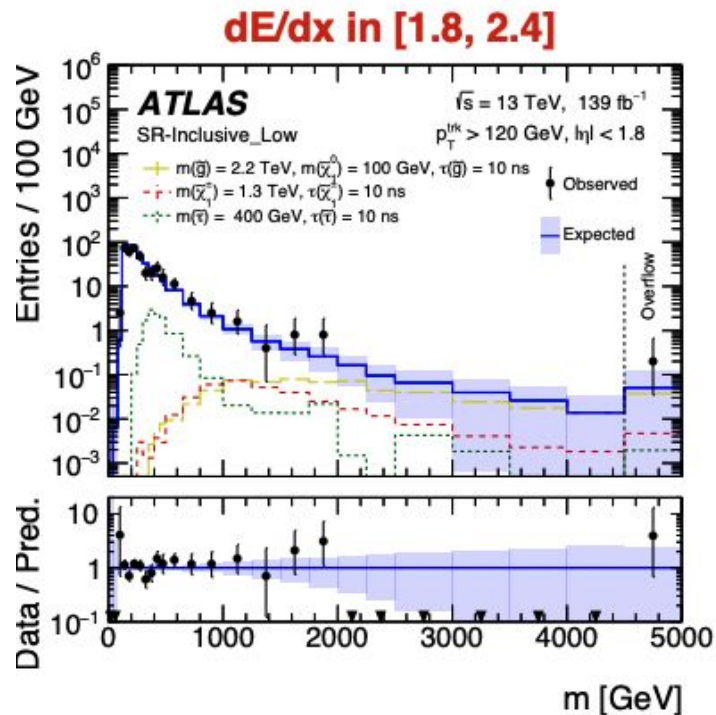
- CMS results upcoming

Summary

- LHC provides an excellent opportunity to search for BSM LLPs

- LLPs have become an important part of the BSM search program of the LHC based experiments

- New and dedicated reconstructions techniques are being developed and used to target LLPs at the LHC
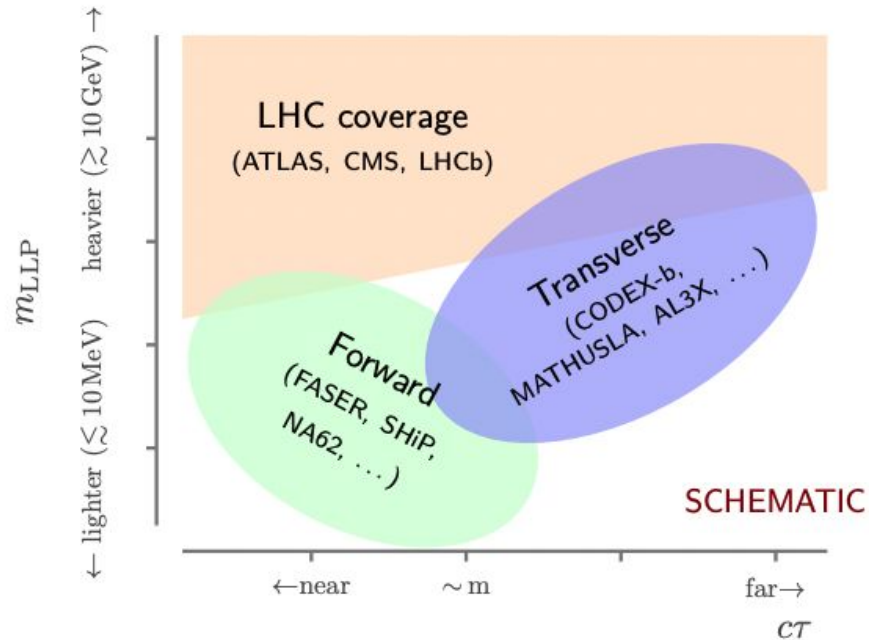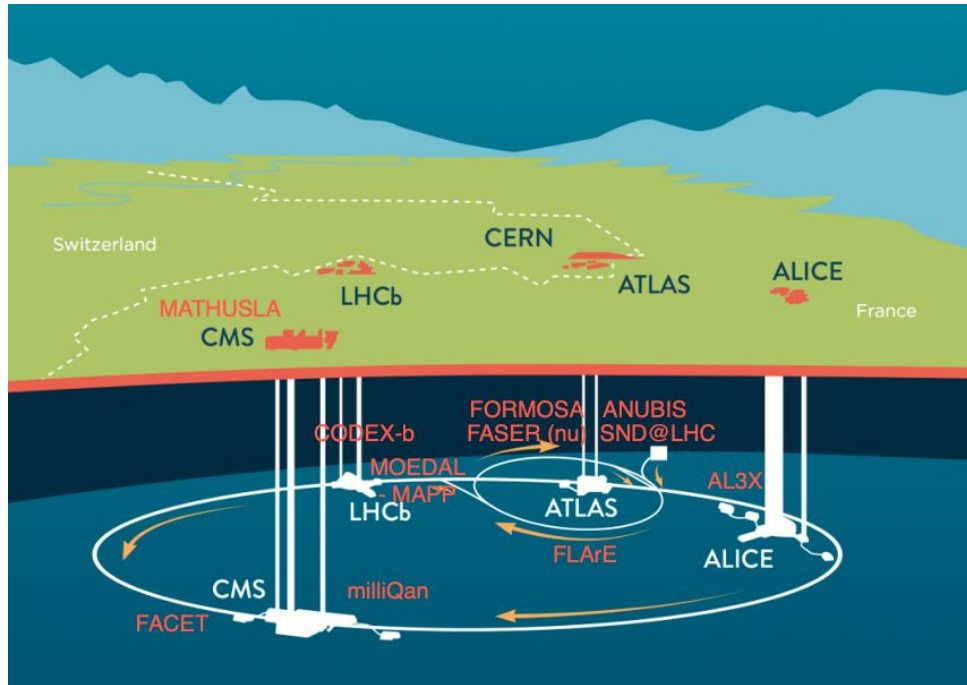
Outlook

- LHC Run-3 has just begun -> provides exciting opportunity to further probe LLP phase space

- Dedicated triggers, data taking techniques, reconstruction methods are being developed that will be used for the first time with the Run-3 data
  - New dedicated triggers
  - CMS using HCAL segmentation
  - ATLAS using optimised Large Radius Tracking
  - LHCb with new trackers

- Expect important new results to come in the next years

- There remains much more scope for HL-LHC with upgraded detectors and special detectors

Thank you!

Backup

LLP signatures

Graphic credit: Heather Russell

disappearing tracks

displaced multi-track vertices in ID + MET, jets, leptons

non-prompt photons

displaced leptons, lepton jets, or lepton pairs

emerging j

stable or meta-s charged partic

trackless jets with low EMfrac

displaced multi-track vertices in Muon Spectrometer