Searches for Long-lived Particles at CMS

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June 28, 2023

What are long-lived particles?

- For our purposes today:

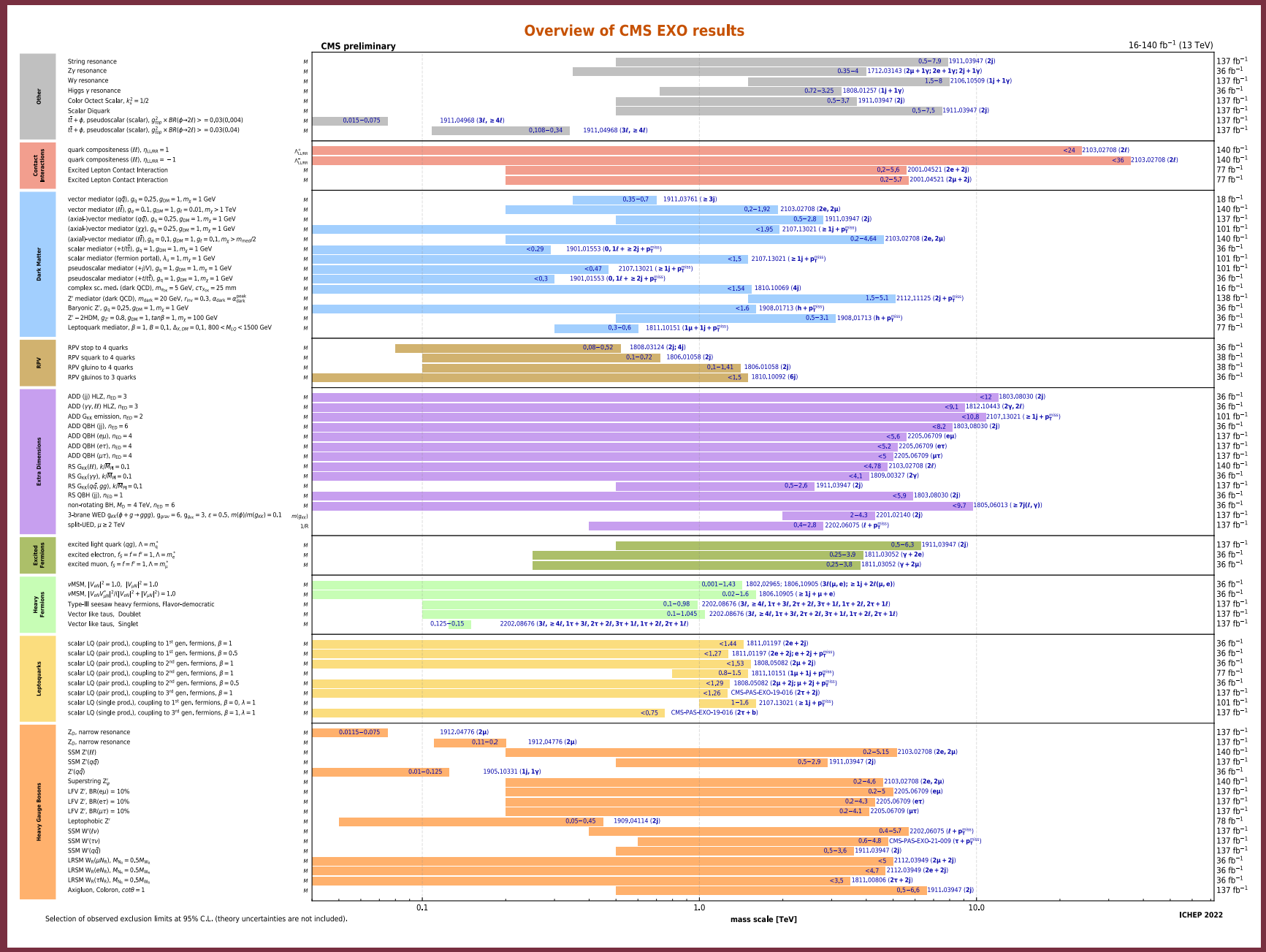
- Long-lived particles:
  - live long enough to travel measurable distance within detector
  - lifetime longer than b-quark
  - (generally) unstable
  - can detect particle or decay products within detector

- We exclude neutral particles that escape completely without being directly observed
  - generally part of missing transverse energy searches

Searches for New Physics

- We know the standard model (SM) of particle physics does not answer all of our questions
  - it does an amazing job
- Theorists have come up with MANY ideas that extend the standard model
- But what matches reality?
  - data must point the way
- In my opinion, discovery of new physics not described by the standard model is the most important physics result particle physics can achieve

We have searched many, many times

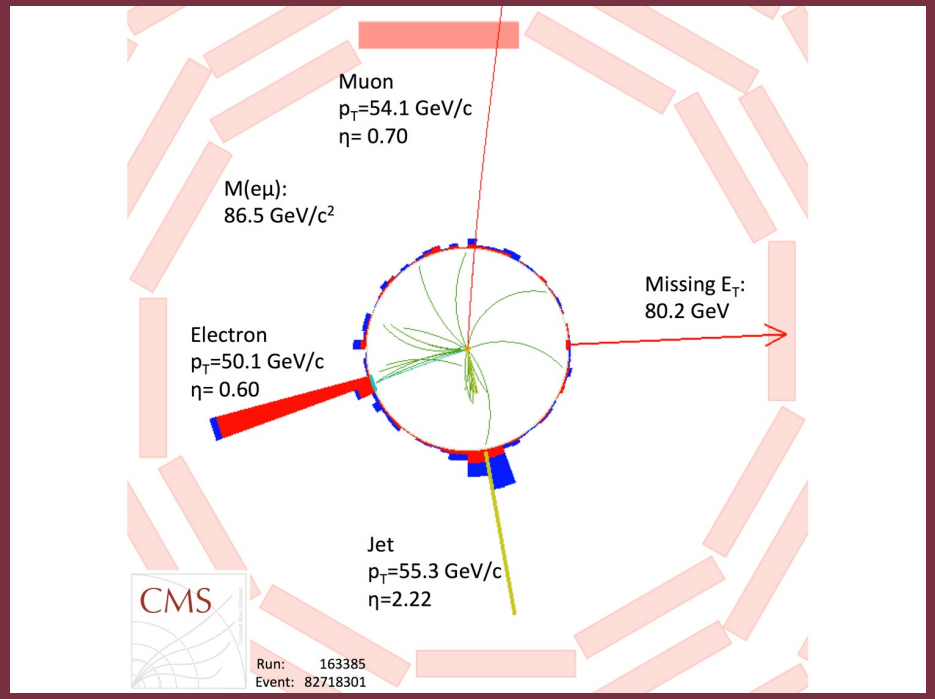


Why Long-lived Particles?

- Standard model has many long-lived particles
  - muon, pion, kaon, neutron, etc.
- Why not?
- We haven’t found evidence in the obvious places
  - we started with the easy searches

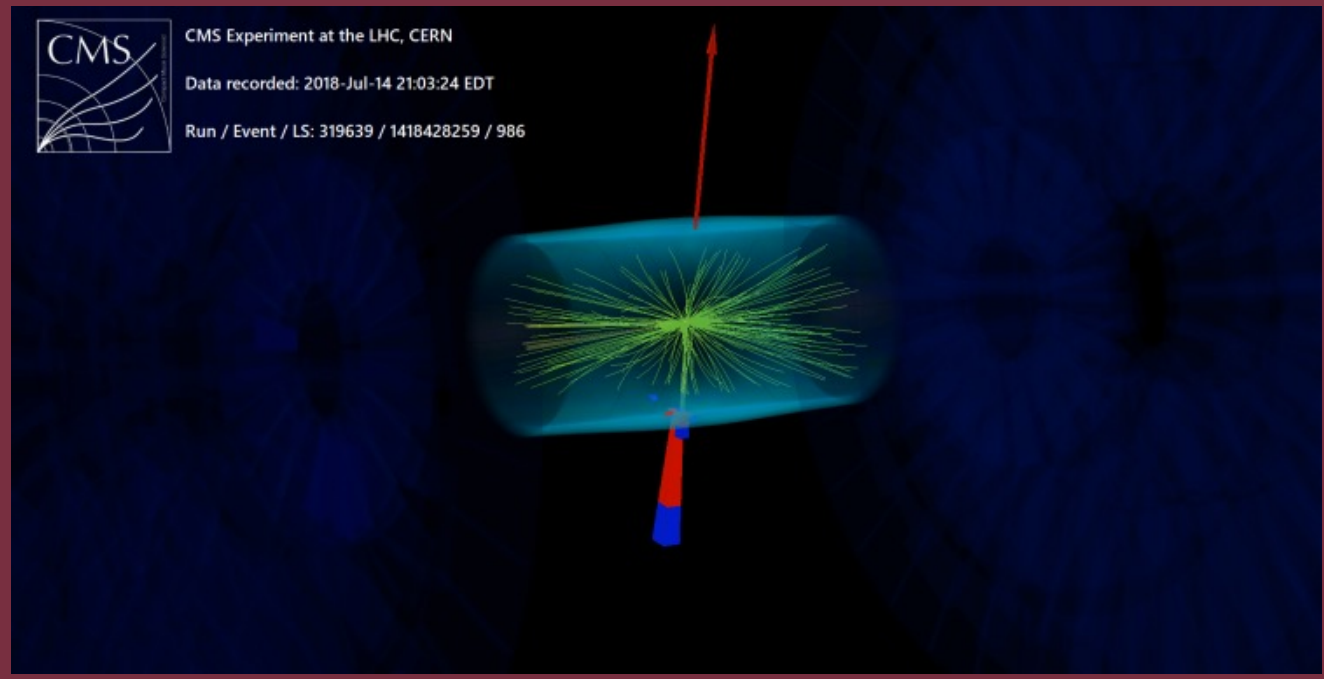
Assumptions

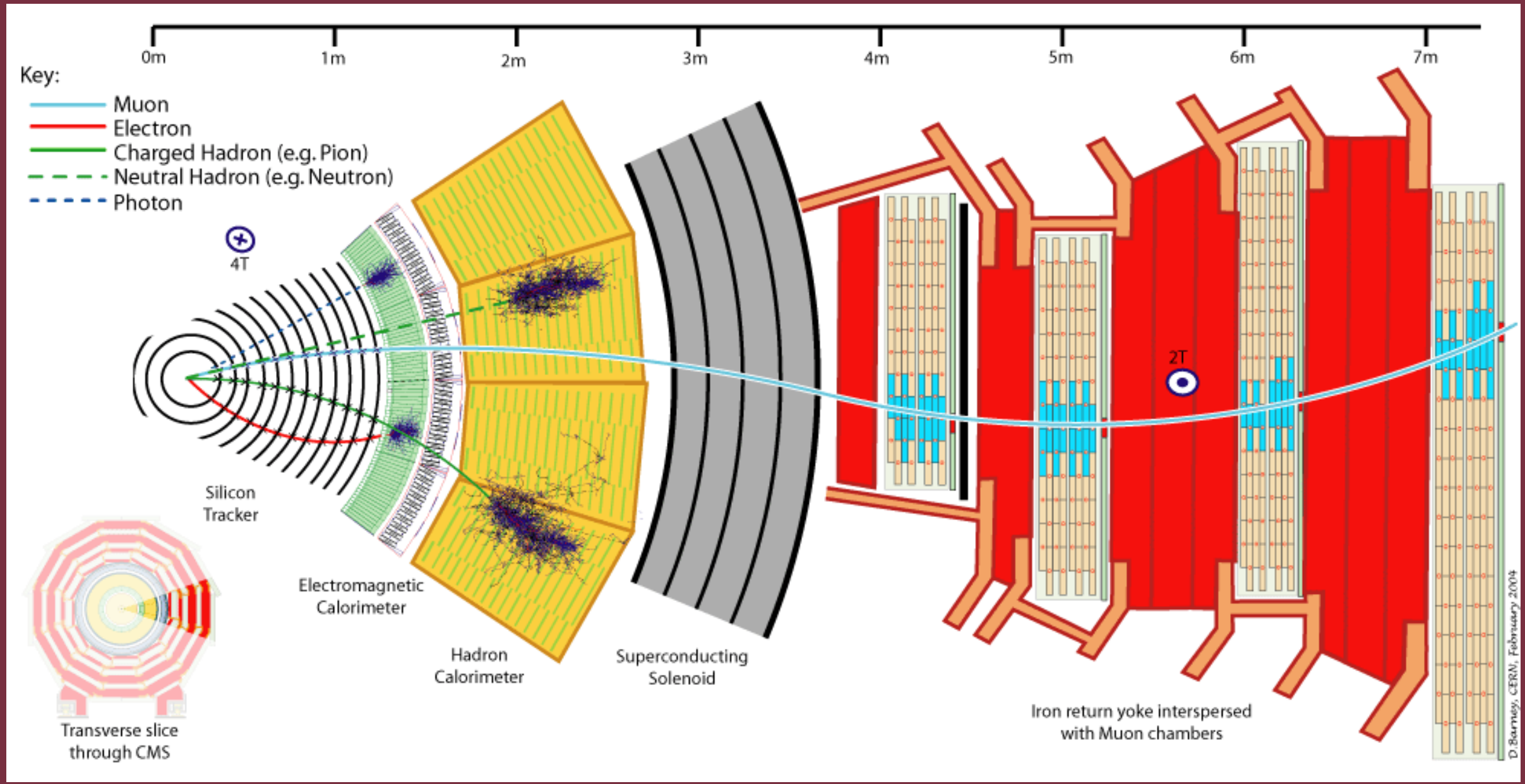
- **Most physicists expected new particles would:**
  - **decay immediately into standard model particles**

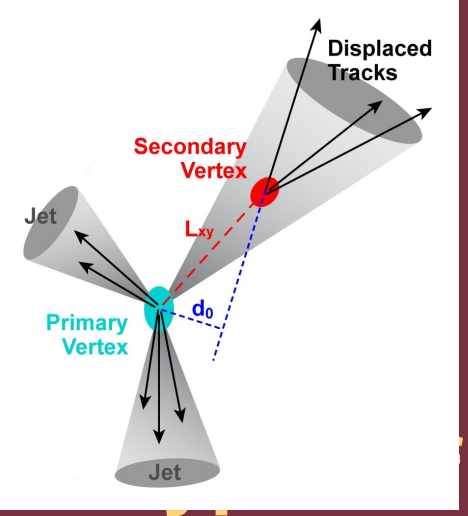


or

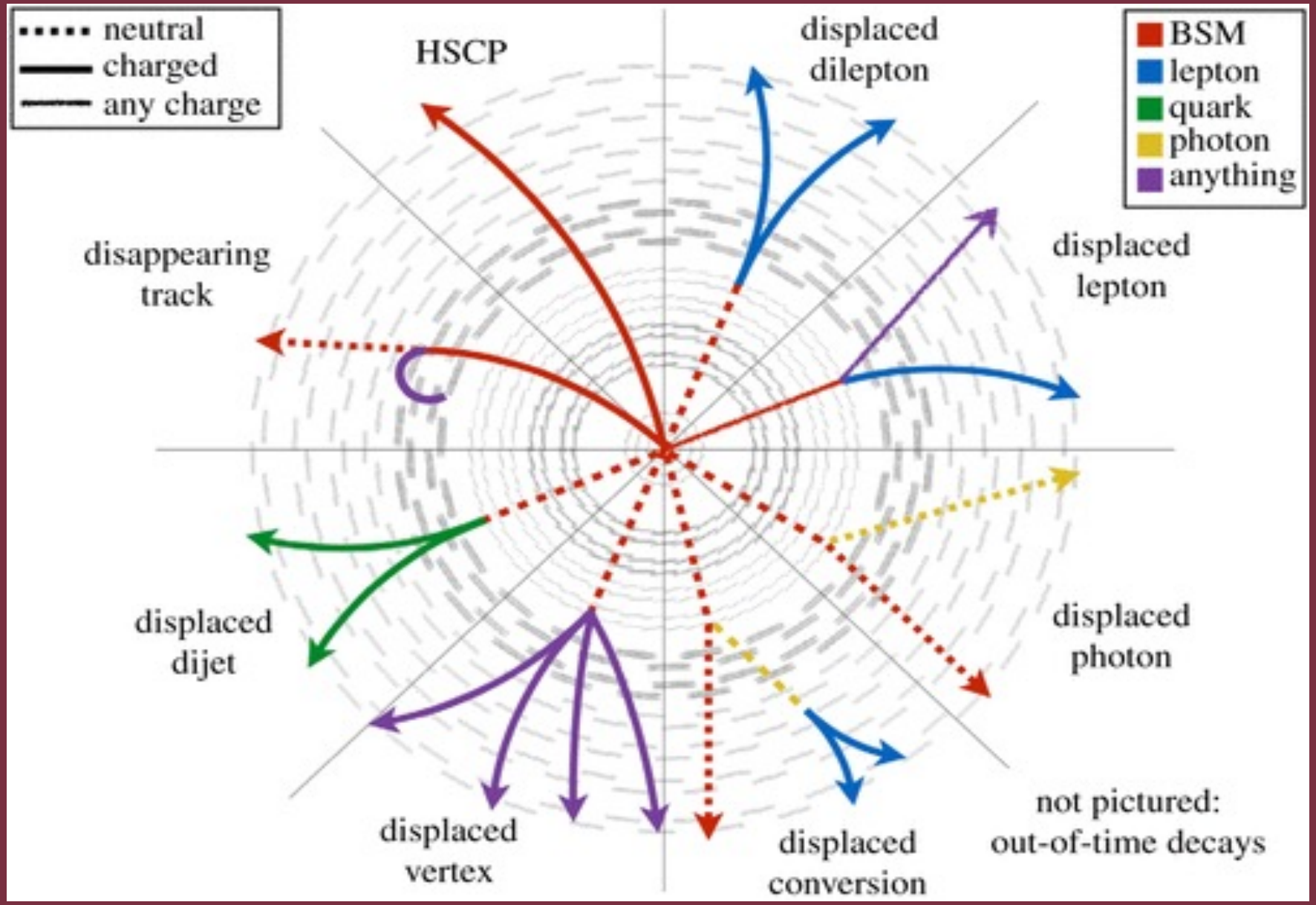
  - **be stable and neutral → escape undetected**




0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004



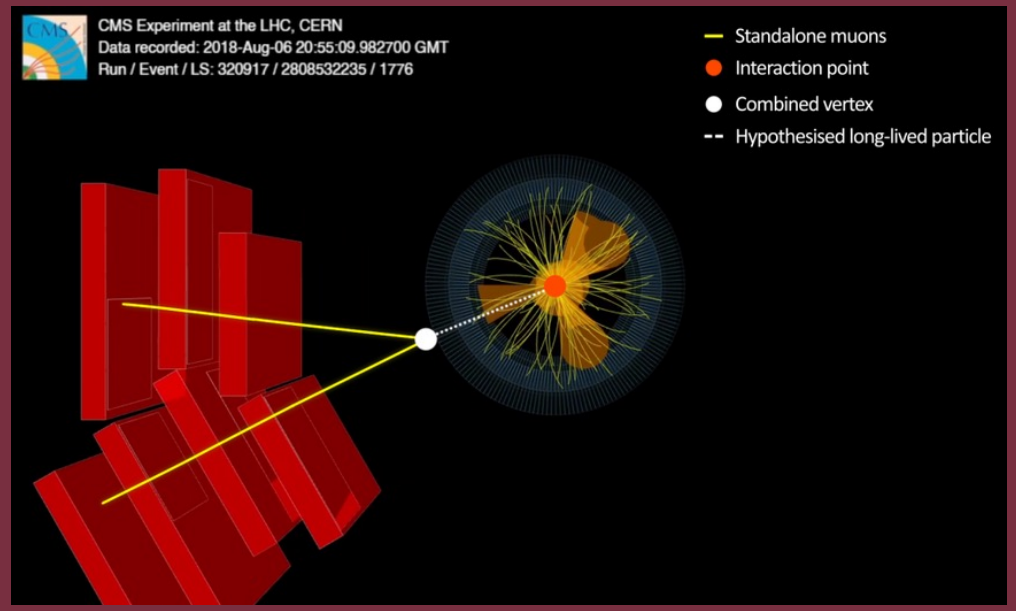
long-lived particle searches

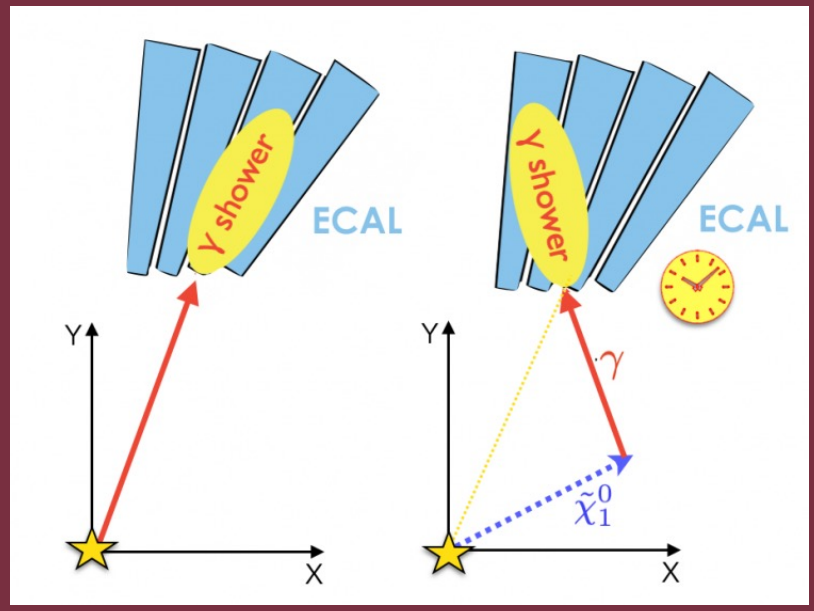


From "Searching for long-lived particles at the Large Hadron Collider and beyond, Volume: 377, Issue: 2161, DOI: (10.1098/rsta.2019.0047)"

Unique Signatures

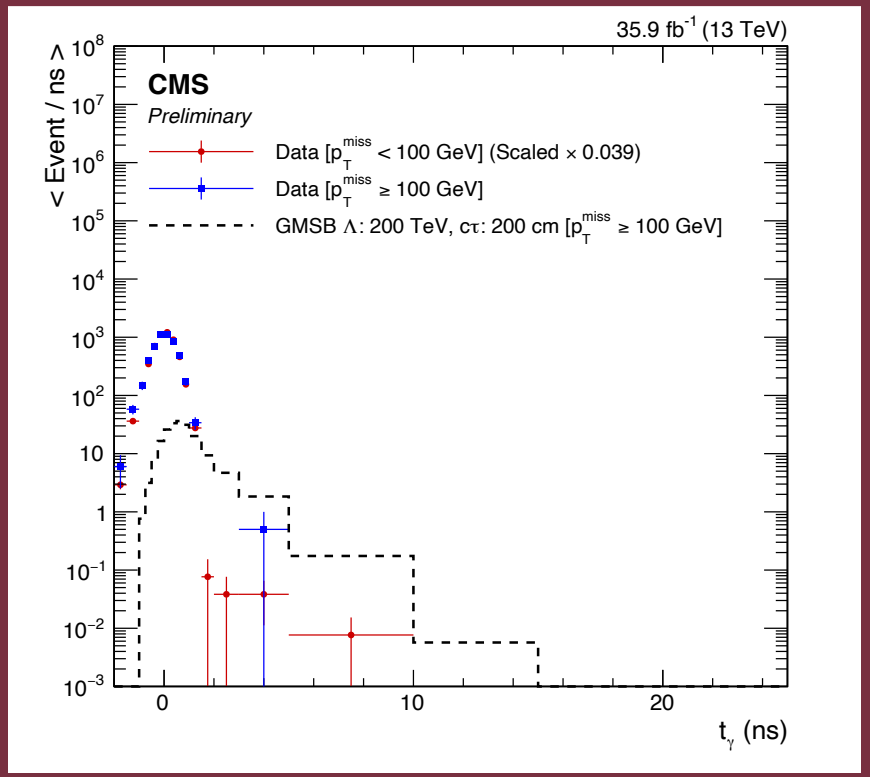
- Displaced decays – particles that decay far from where they were produced
  - observe decay products
  - displaced reconstructed vertex
  - observed particles don't point back to center of detector
- Slow moving particles
  - delayed signature in detector
- Unique detector interactions
  - bend in a different direction in magnetic field
  - too much/too little ionization





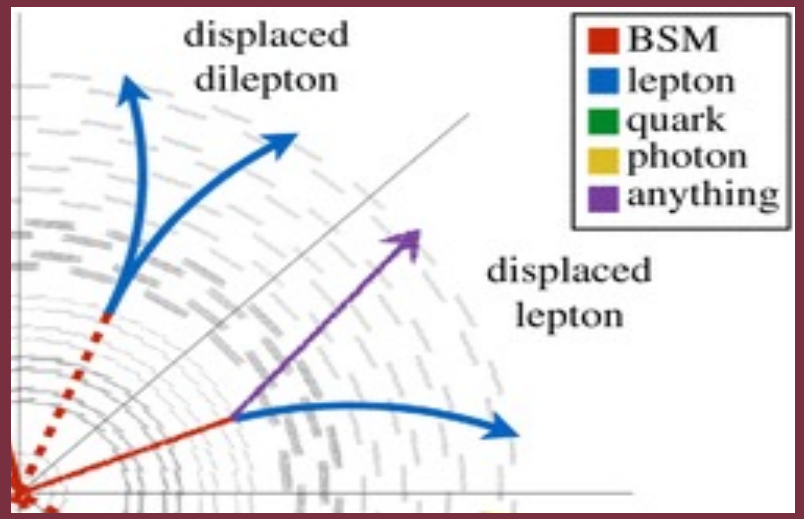
Detector Capabilities

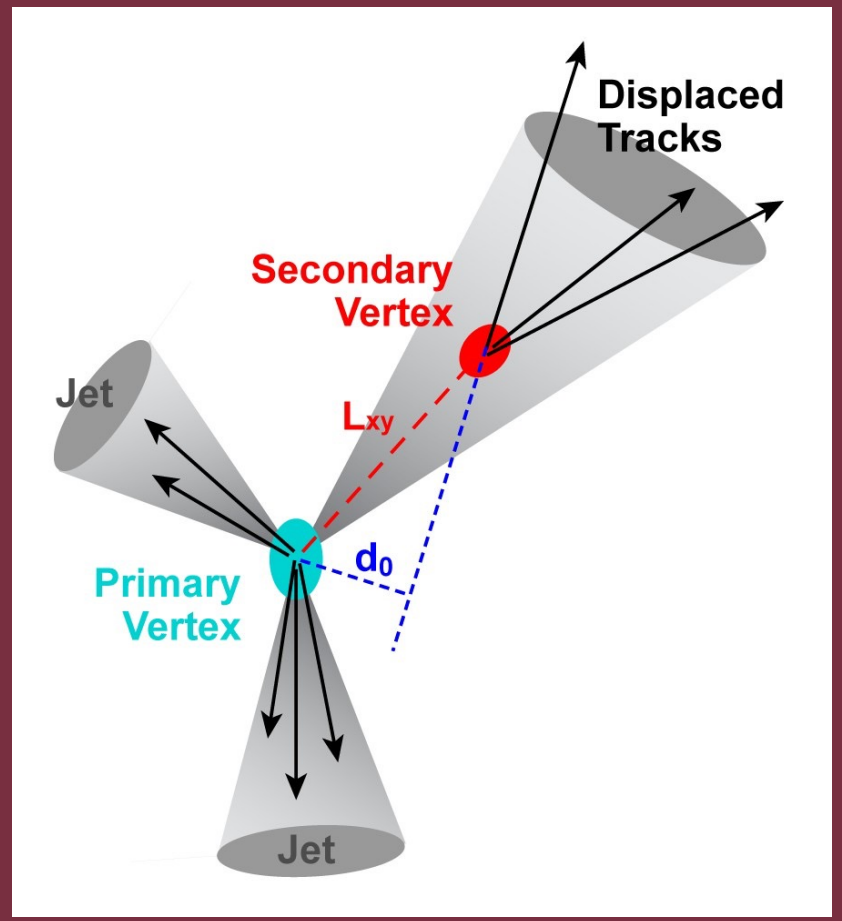
- LHC experiments were designed with assumptions in mind
- But sometimes detector capabilities can be used in new ways
- ECAL timing
  - electromagnetic calorimeter measures the arrival time
  - Possible scenario
    - massive, long-lived particle – slow moving
    - decay involves a photon
- Silicon tracker energy deposit
  - can look for anomalous energy deposition
  - Possible scenarios
    - charge >1e (or <1e)
    - slow moving means higher ionization



Software Capabilities

- Sometimes software can be re-engineered to do more than originally planned
- Displaced tracks
  - expand range of tracks that can be found
    - break assumption that track comes from interaction region



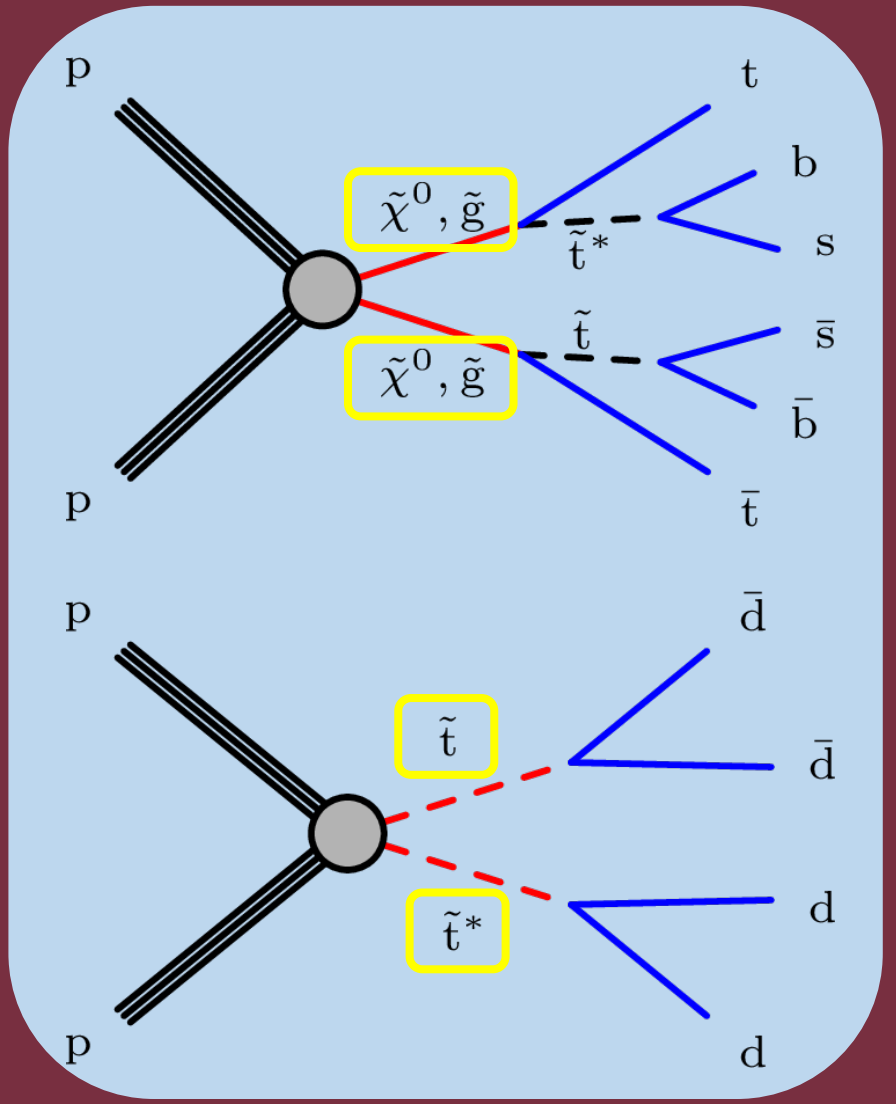


Some Example Searches

Displaced Vertices - Jets

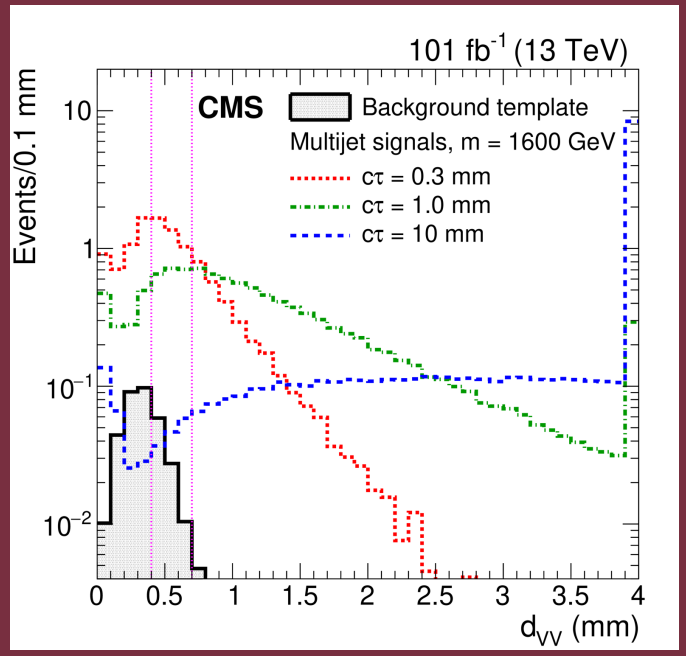
Phys. Rev. D 104 (2021) 052011

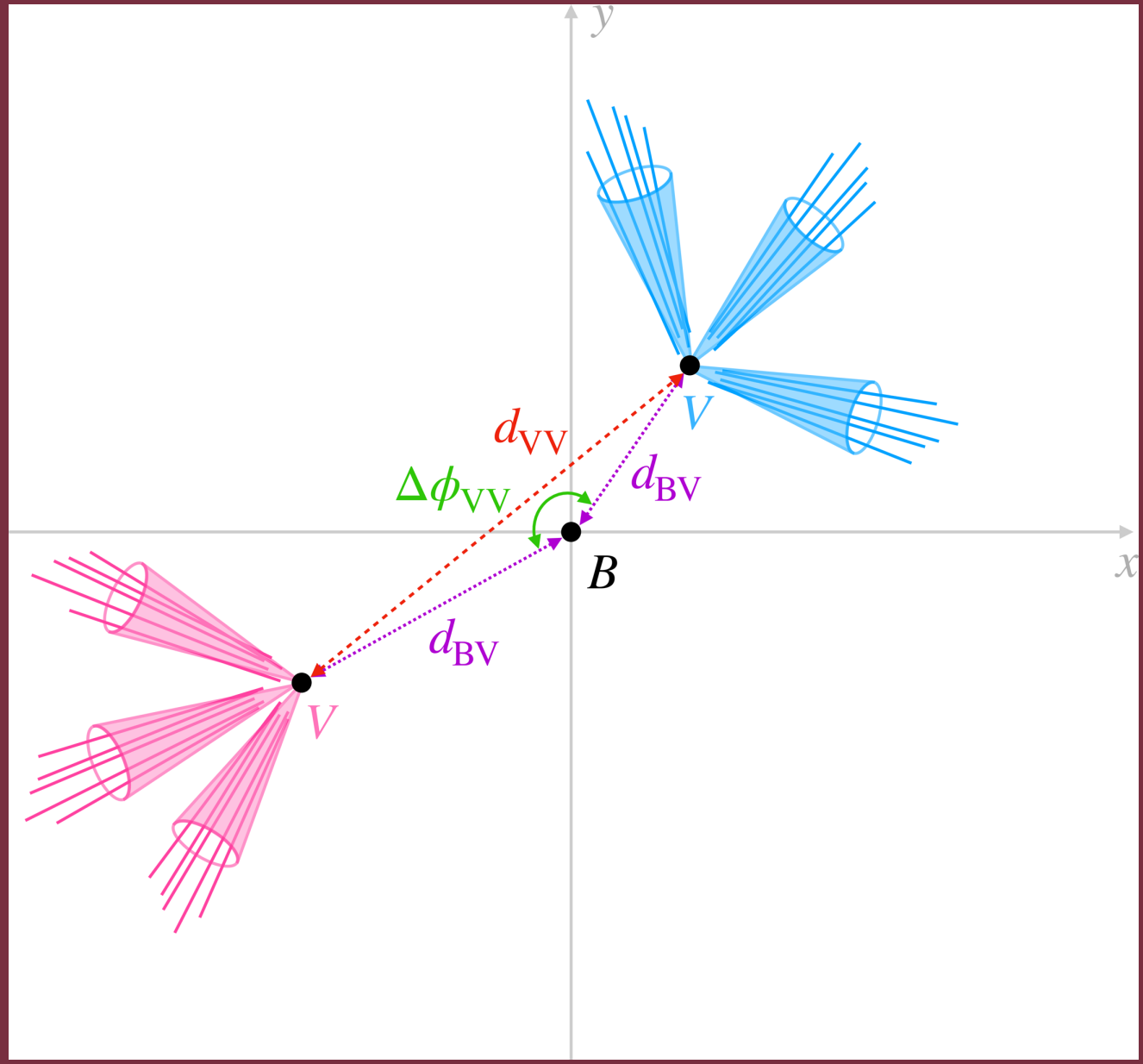
- Search for neutral, long-lived particle (LLP) decaying to jets
- Produce them in pairs
- Signature:
  - jets arises from two vertices well away from collision point



V → jets

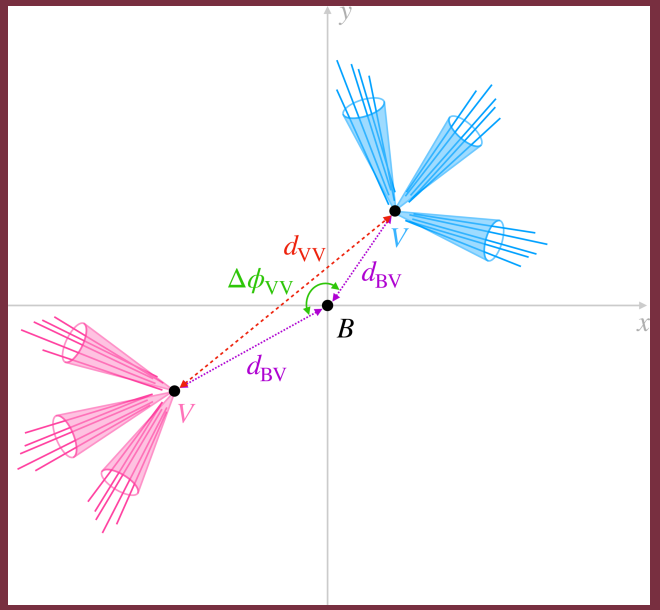
- Each cone represents a jet from the decay
- Note, most particles don't point back to the origin

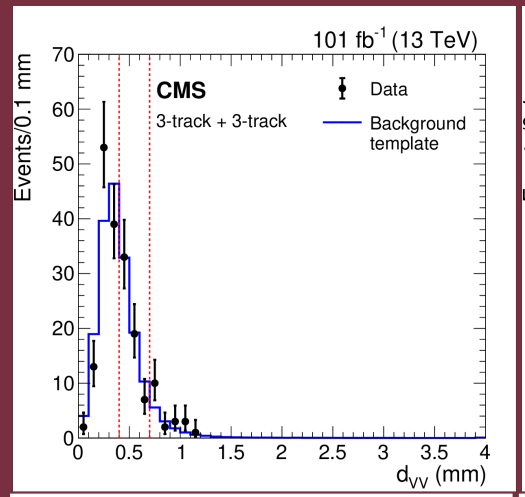


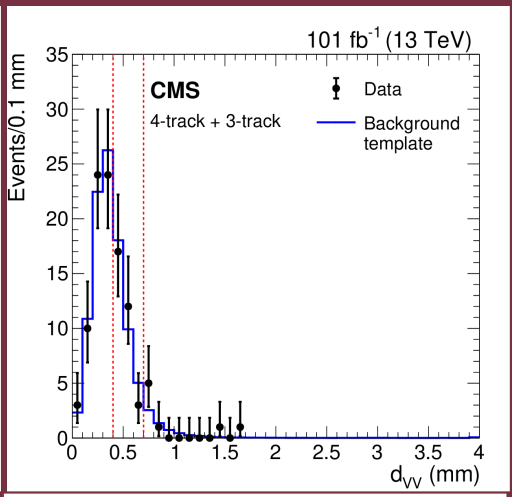


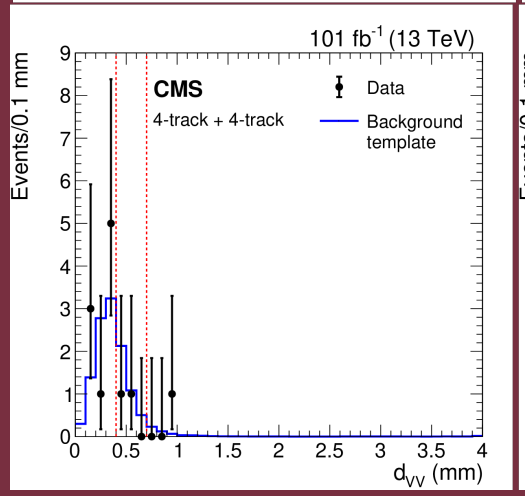
Results

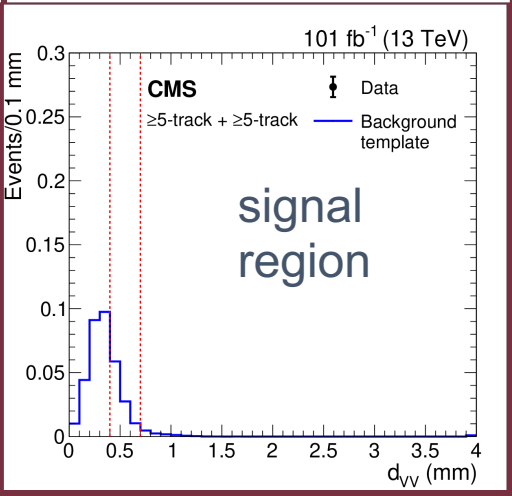
- Require ≥2 jets with ≥5 tracks
- Predict background and signal in d_{VV} regions











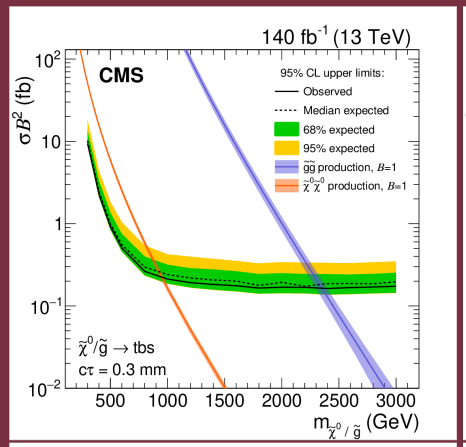
No events observed in signal region

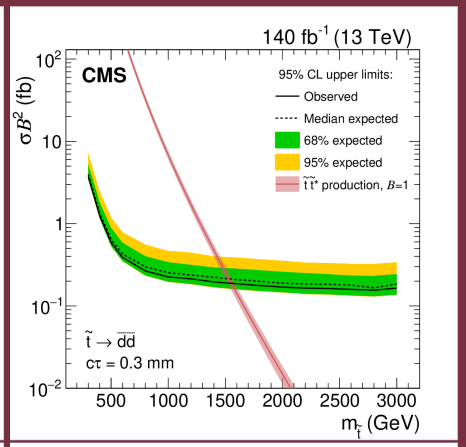
d_{VV} range	Predicted background yield	Predicted multijet signal yields 0.3 mm	1.0 mm	10 mm	Observed
0–0.4 mm	0.243 ± 0.003 (stat) ± 0.061 (syst)	4.4 ± 0.5	1.5 ± 0.1	0.26 ± 0.02	0
0.4–0.7 mm	0.097 ± 0.003 (stat) ± 0.032 (syst)	4.1 ± 0.5	2.1 ± 0.2	0.14 ± 0.01	0
0.7–40 mm	0.012 ± 0.001 (stat) ± 0.006 (syst)	3.0 ± 0.3	7.6 ± 0.7	12 ± 1	0

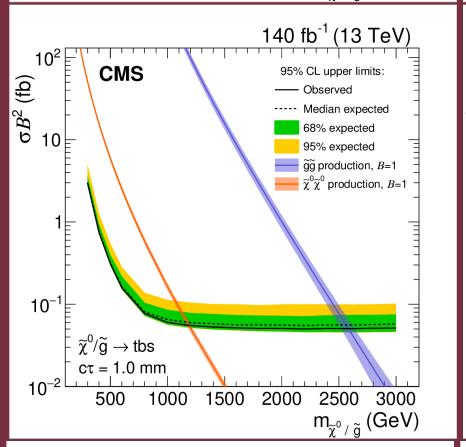
Limits

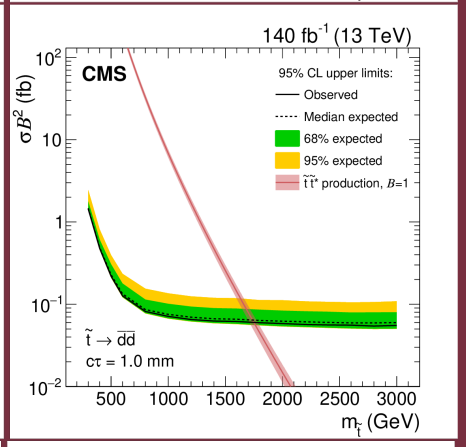
as function of mass

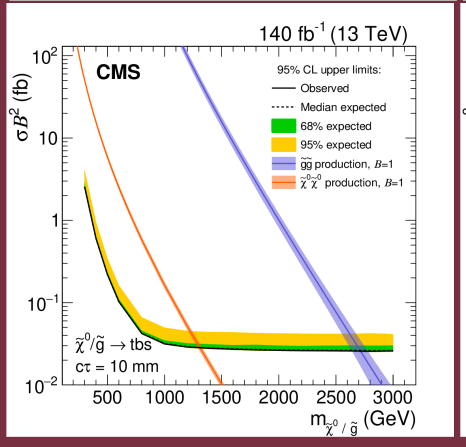
as function of lifetime

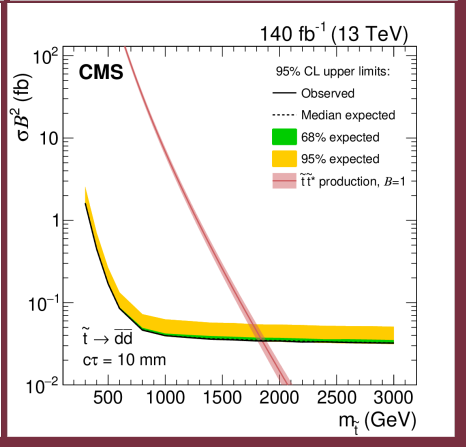


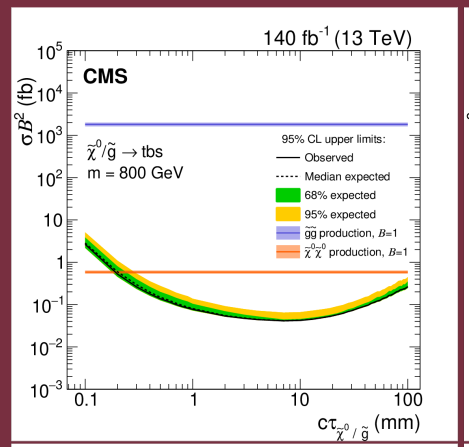


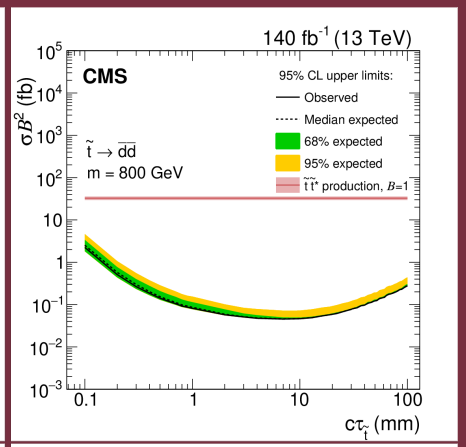


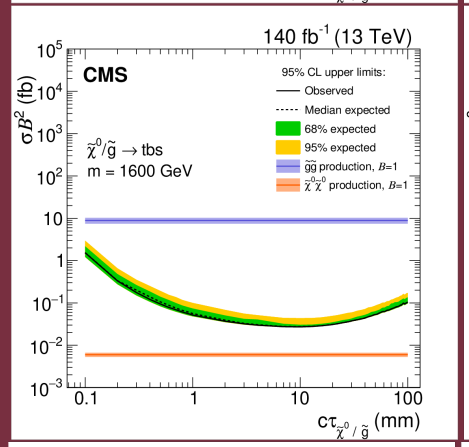


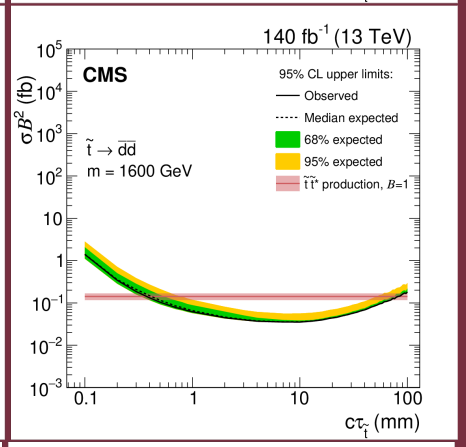


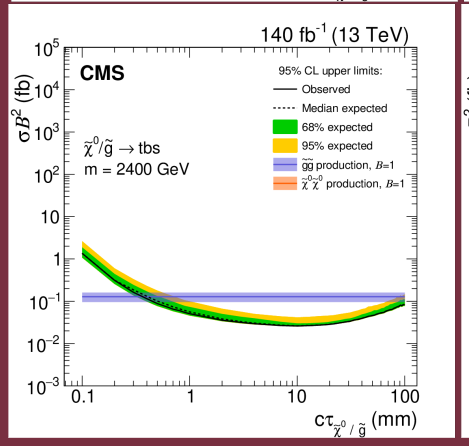


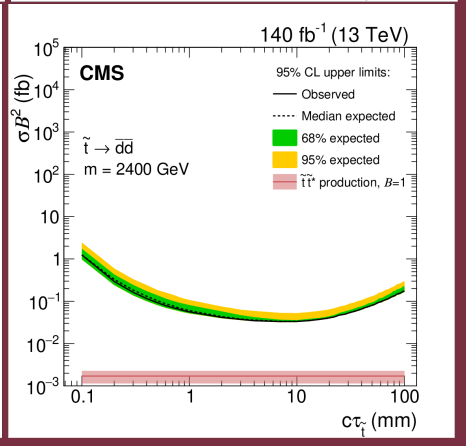






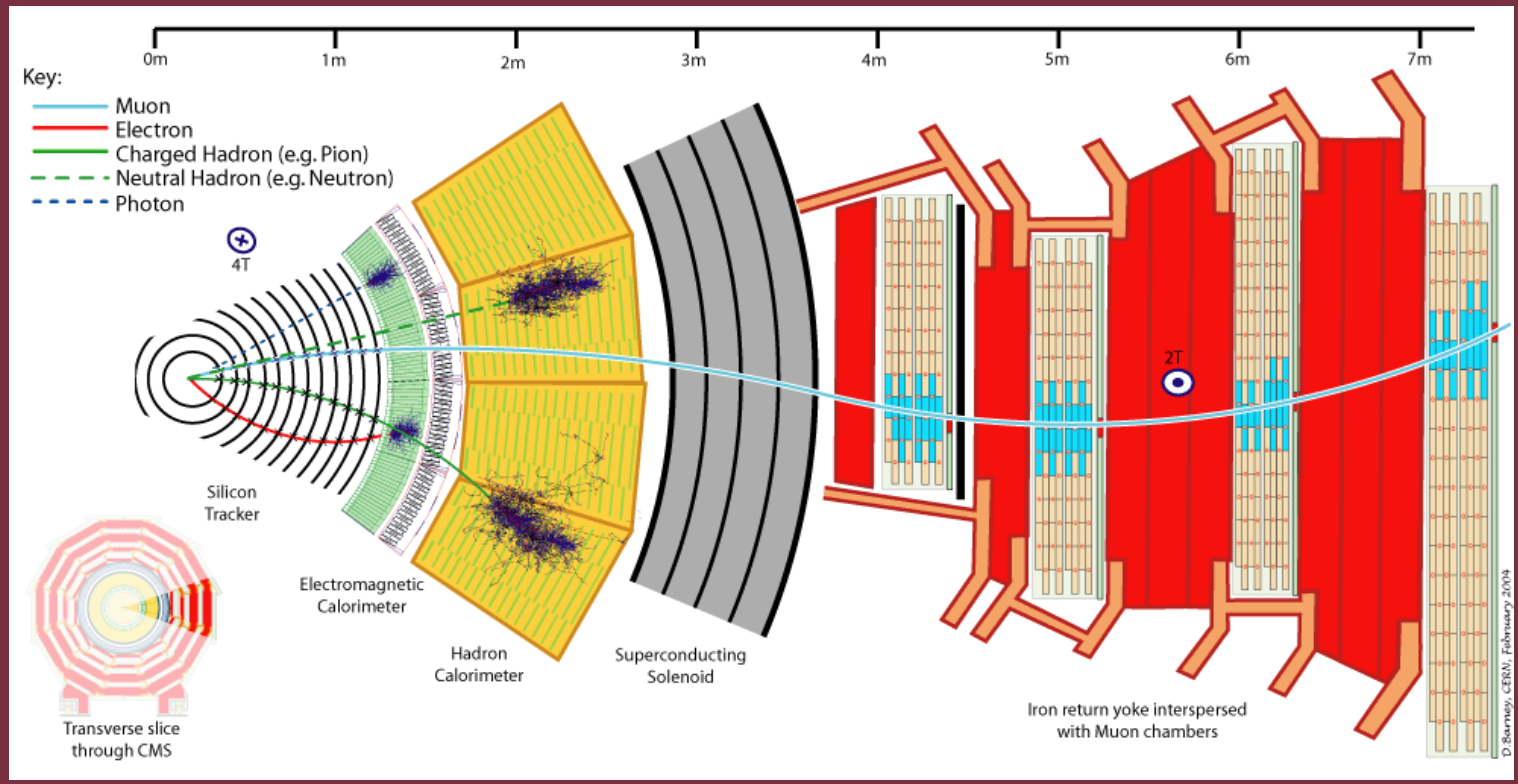




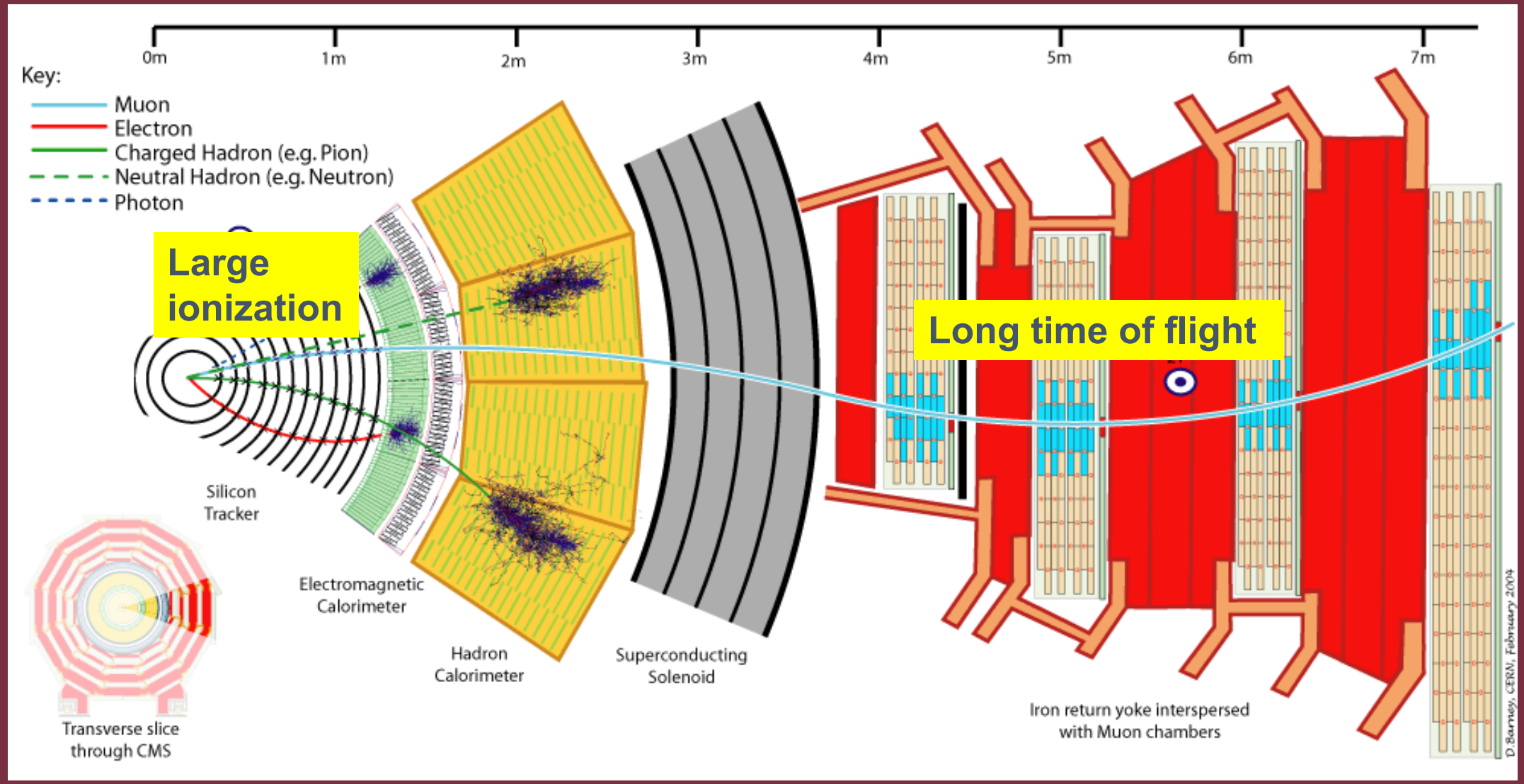


Heavy Stable Charged Particles (HSCPs)

- Heavy: mass > 100 GeV/c^2
- "Stable": lifetime long enough to pass through detector before decaying
- Charged: Q ≠ 0e
- like a muon (sometimes)

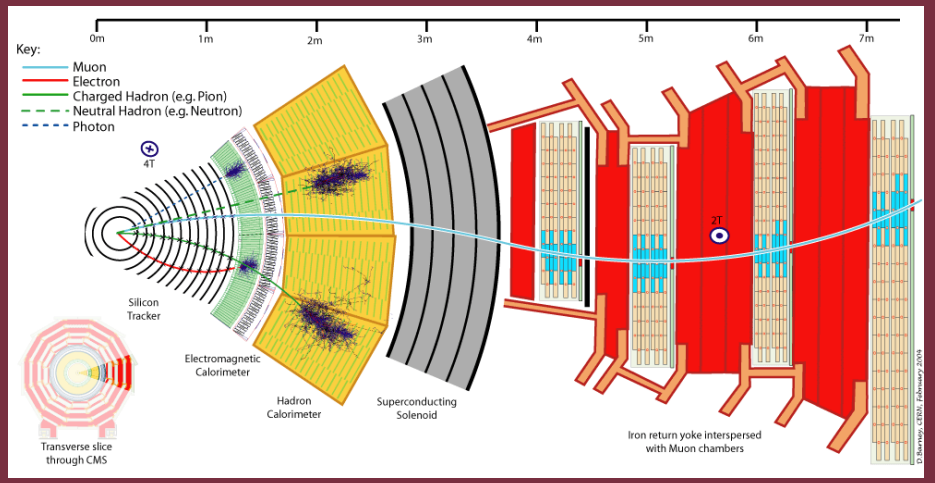


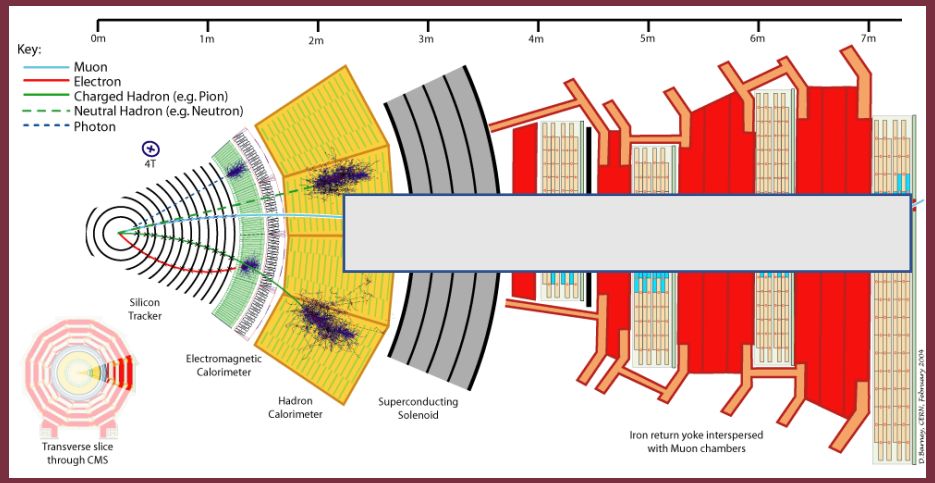
Slow Moving → Unique Signatures



HSCP Models

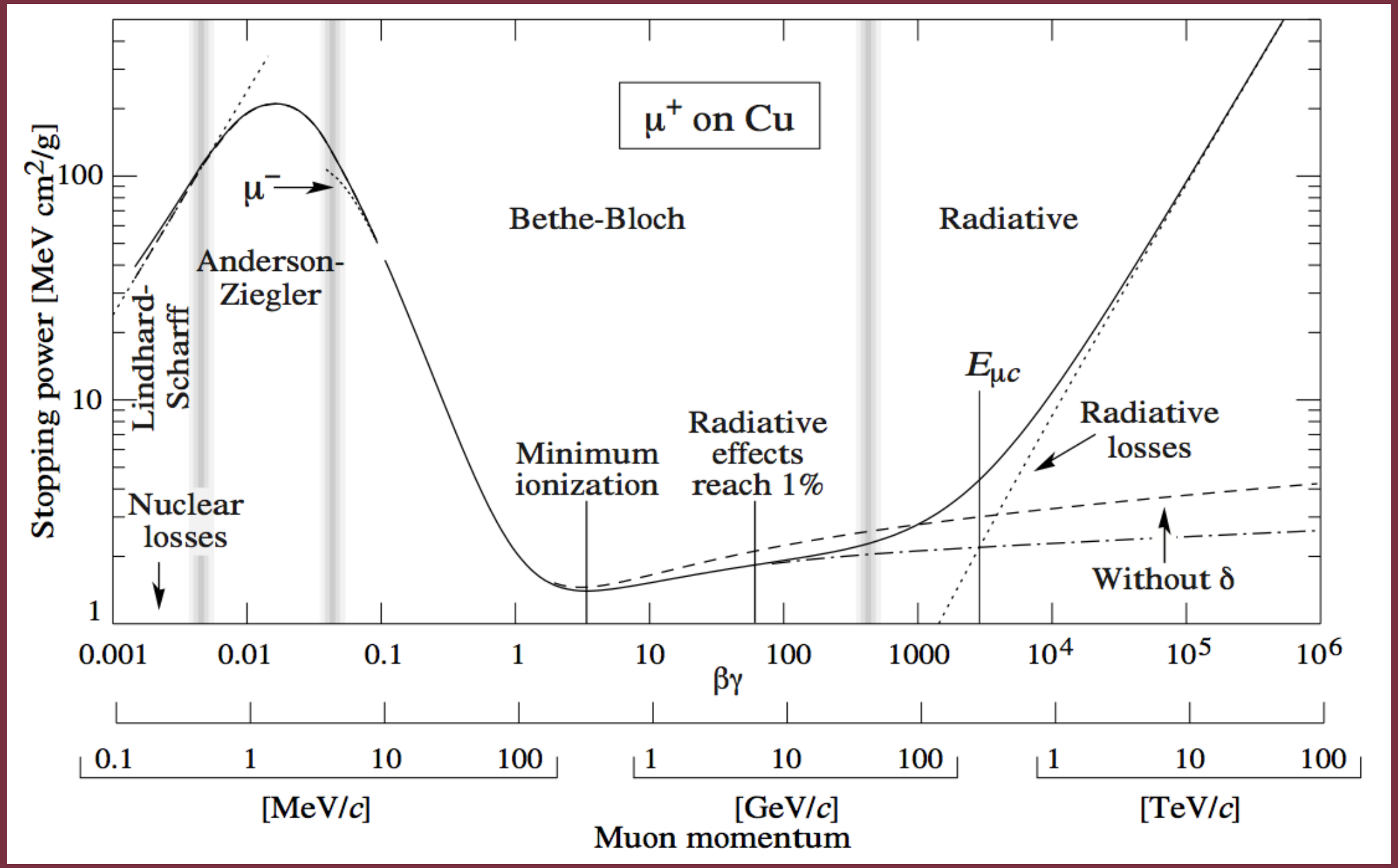
- Lepton-like
  - interacts electromagnetically
  - acts like a muon traversing detector
  - ex. supersymmetry - stau
- R-hadron
  - interacts electromagnetically and strongly
  - binds together with quarks and gluons (R-hadron)
  - ex. supersymmetry – stop or gluino
  - complication - R-hadrons can exchange quarks with detector material
    - charge exchange – charged ⇔ neutral



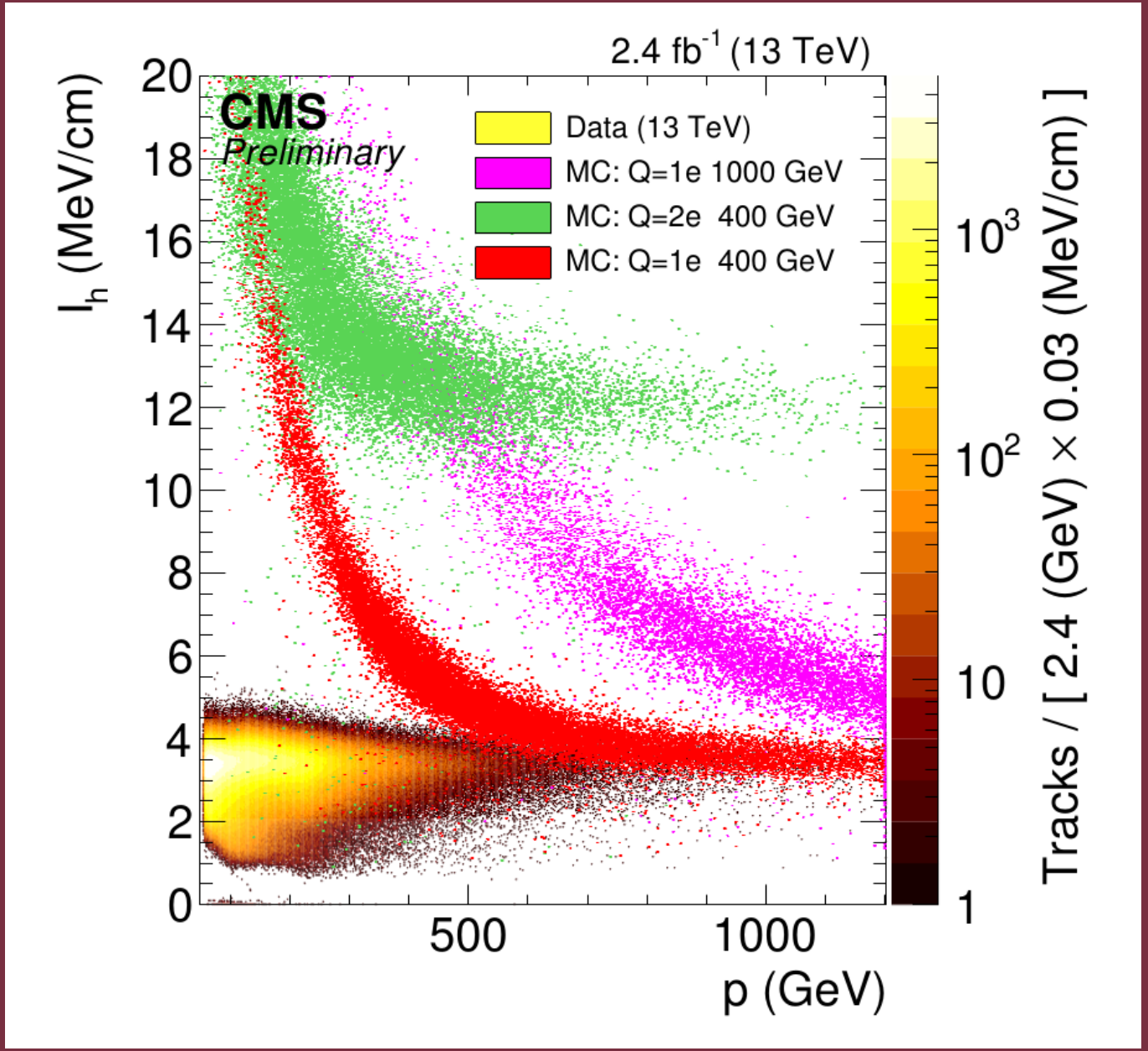


HSCP Analysis Channels

- Tracker + time-of-flight
  - use dE/dx in silicon + time-of-flight to muon system
- Tracker-only
  - use dE/dx in silicon (no requirement on muon system)
- Muon-only
  - use time-of-flight to muon system (no track required)
- Fractionally-charged (|Q| < 1e)
  - use small dE/dx in silicon + muon track
- Multiply-charged (|Q| > 1e)
  - use very large dE/dx in silicon + muon track


μ+ on Cu
Stopping power [MeV cm2/g]
100
10
1
μ−
Anderson-
Ziegler
Lindhard-
Scharff
Nuclear
losses
Bethe-Bloch
Minimum
ionization
Radiative
effects
reach 1%
Radiative
Eμc
Radiative
losses
Without δ
0.001
0.01
0.1
1
10
100
1000
10^4
10^5
10^6
βγ
0.1
1
10
100
[MeV/c]
1
10
100
[GeV/c]
1
10
100
[TeV/c]
Muon momentum

Ionization

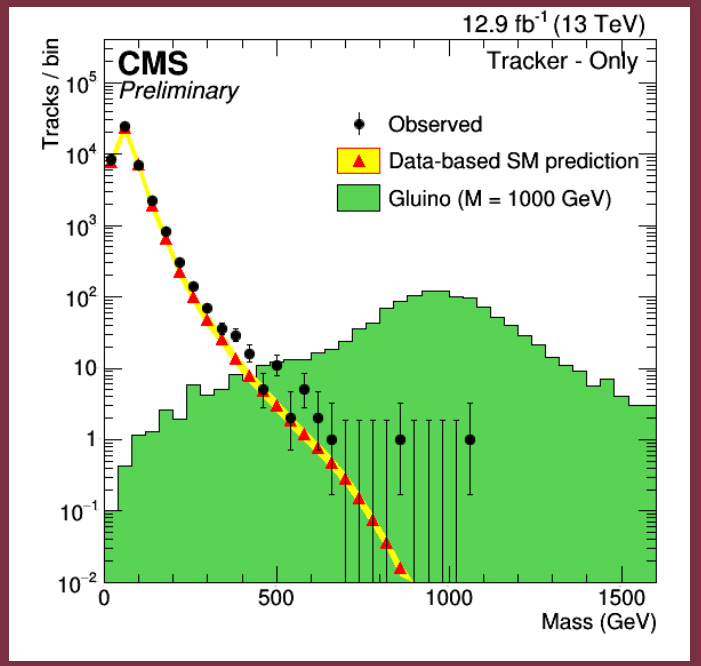

2.4 fb^{-1} (13 TeV)
CMS
Preliminary
Data (13 TeV)
MC: Q=1e 1000 GeV
MC: Q=2e 400 GeV
MC: Q=1e 400 GeV
I_h (MeV/cm)
p (GeV)
Tracks / [2.4 (GeV) × 0.03 (MeV/cm)]

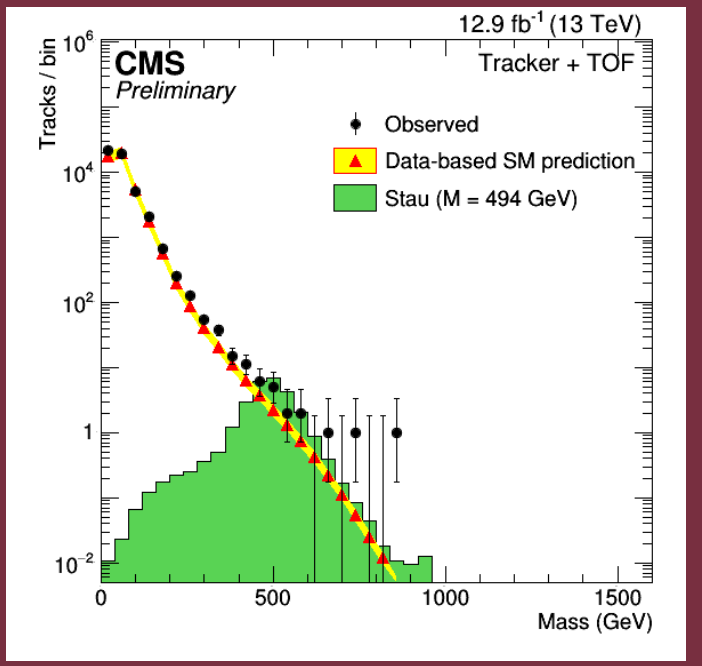
Mass Extraction

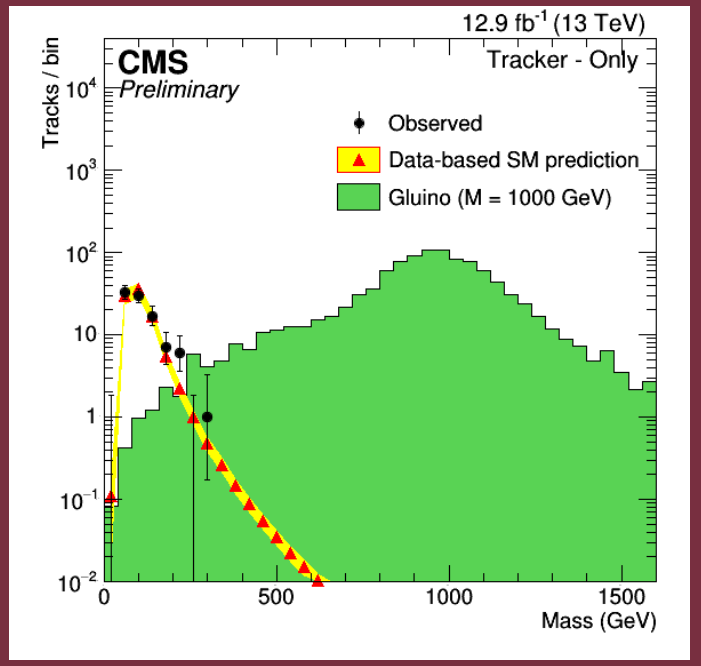
- Use dE/dx and momentum to calculate mass

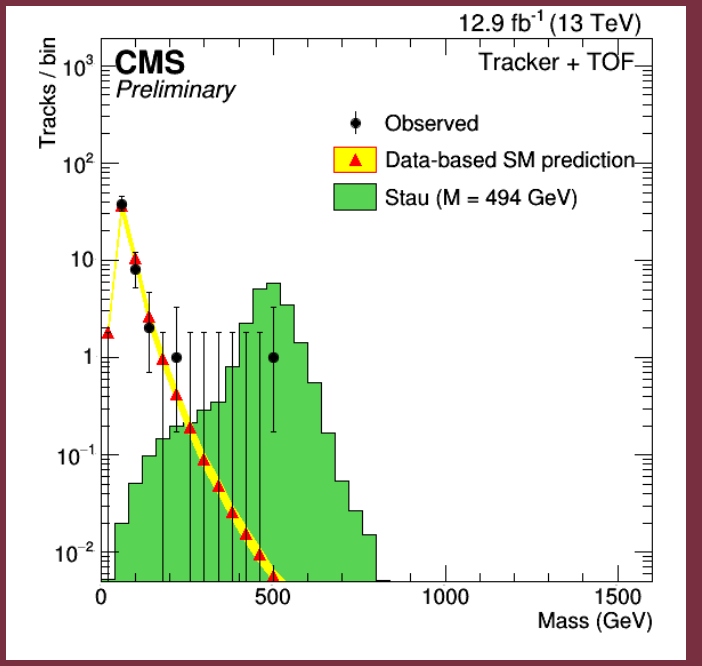
$$\left\langle \frac{dE}{dx} \right\rangle = K\frac{m^2}{p^2} + C$$

- "Loose" selection
  - verify technique
- "Tight" selection
  - signal region

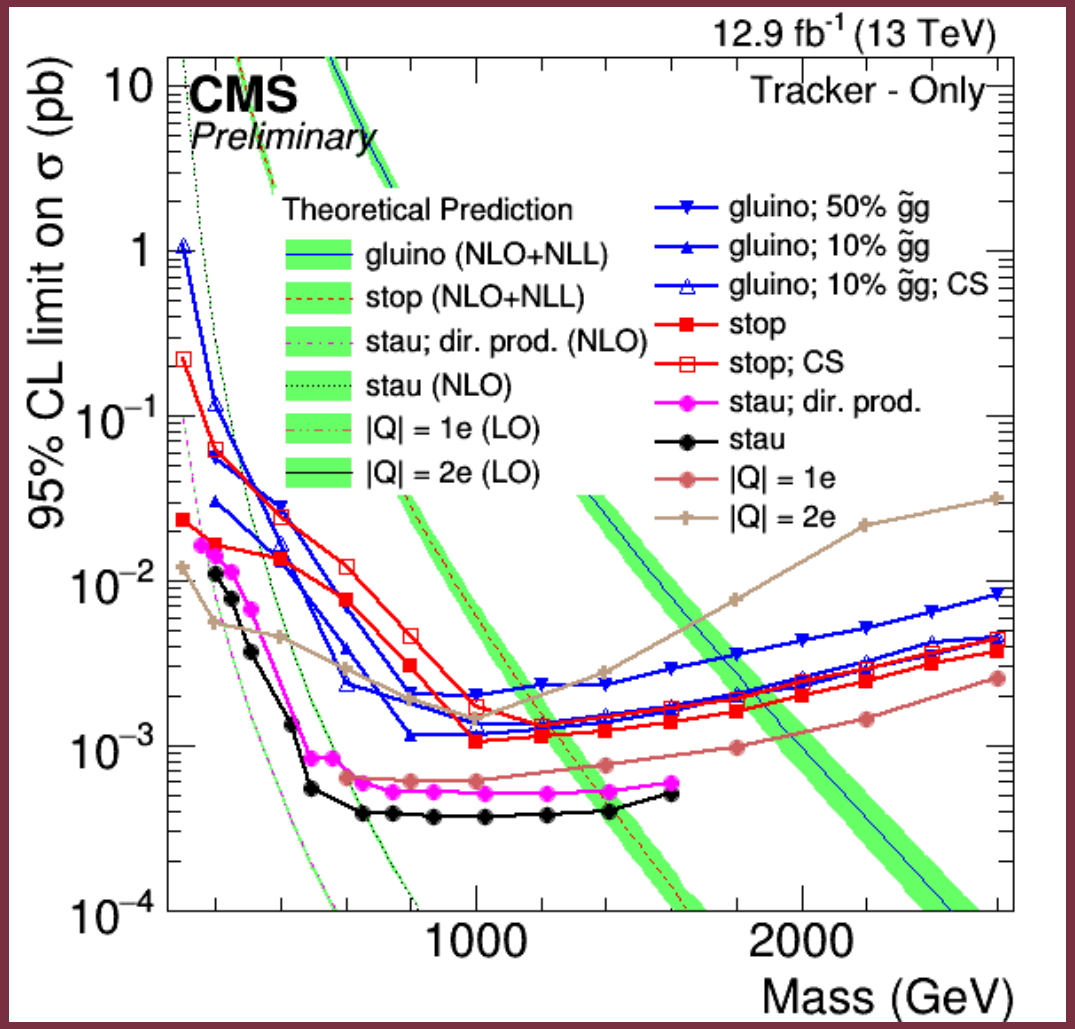


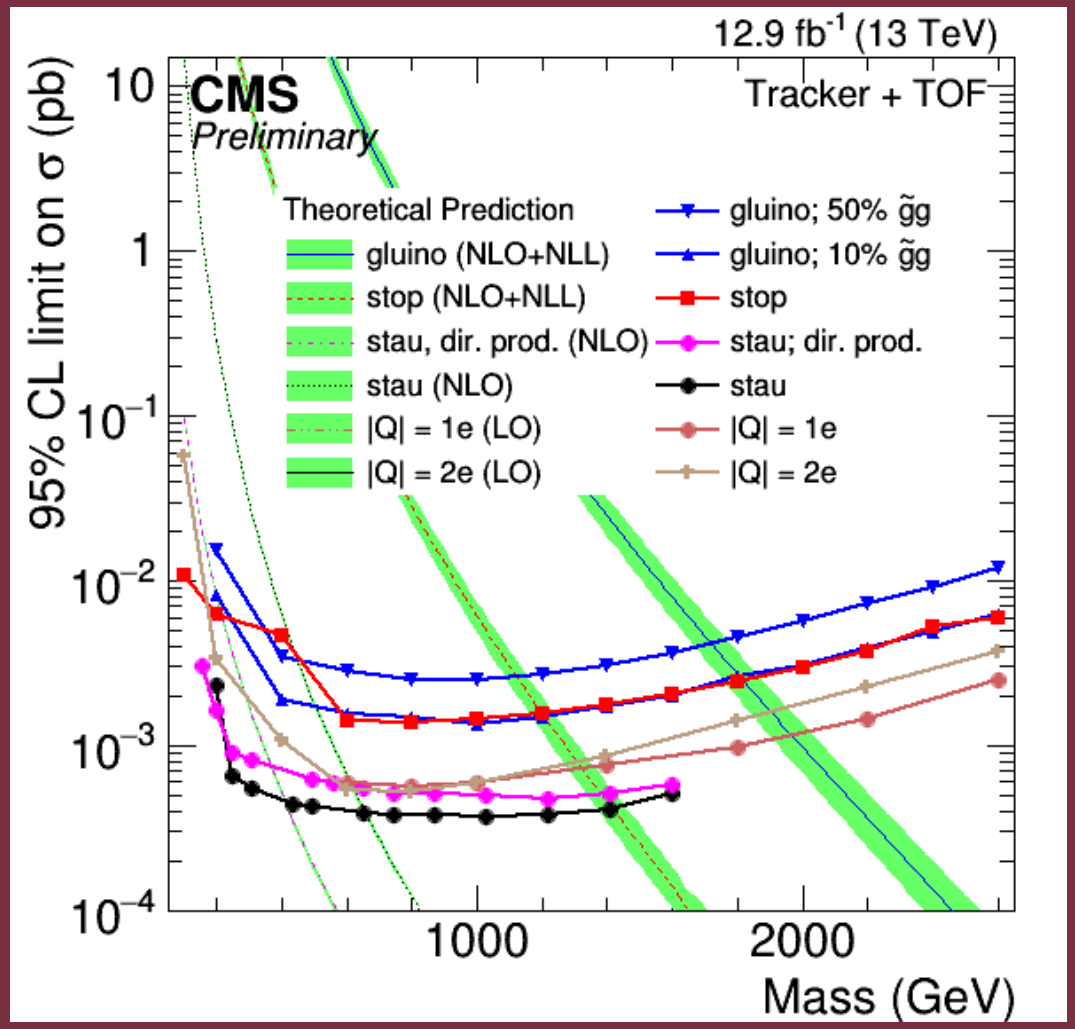




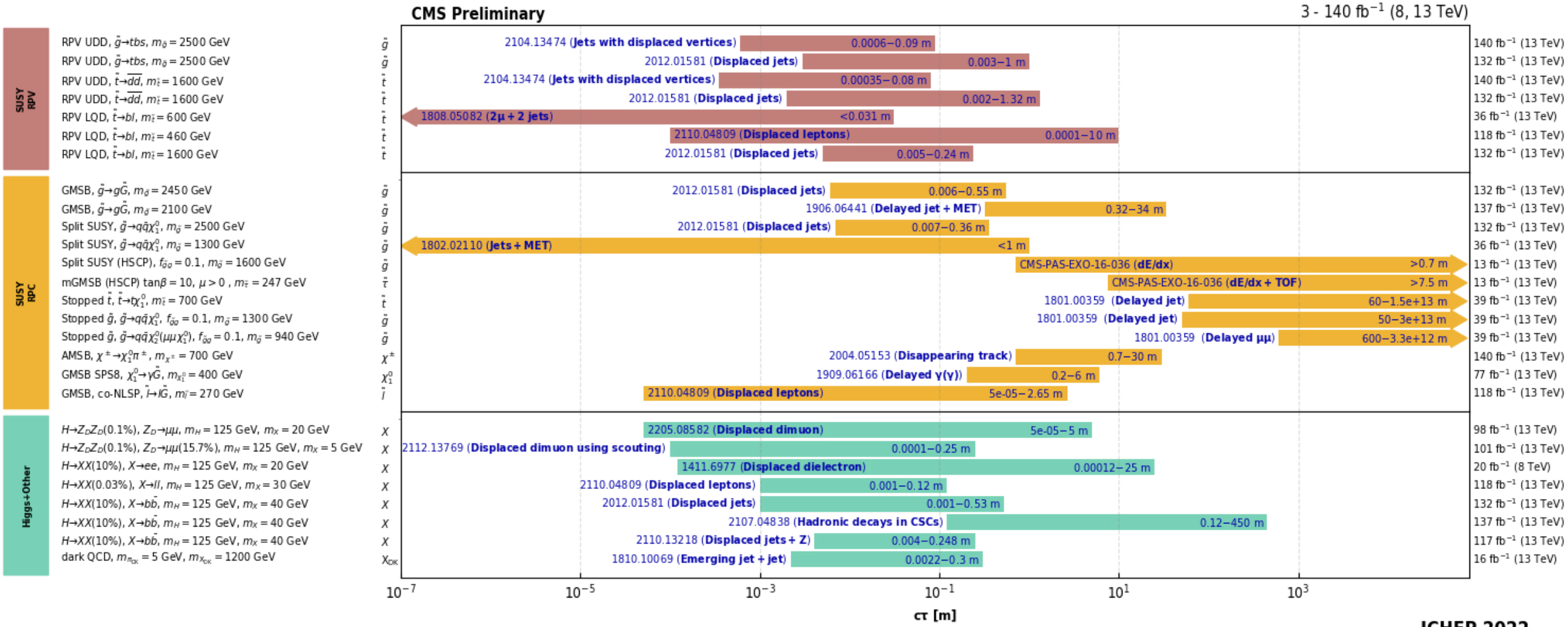


Cross-section Limits





Overview of CMS long-lived particle searches

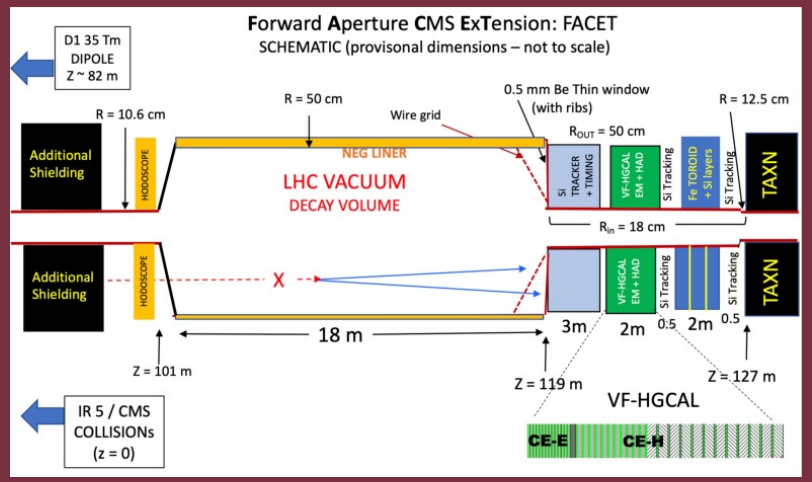


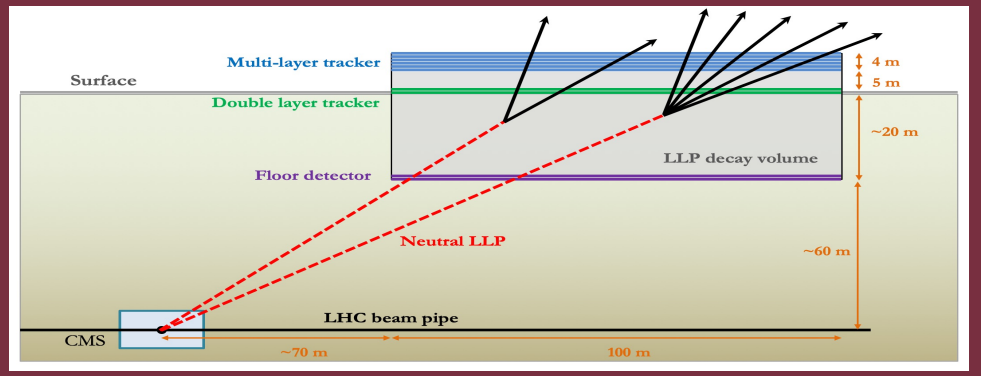
ICHEP 2022

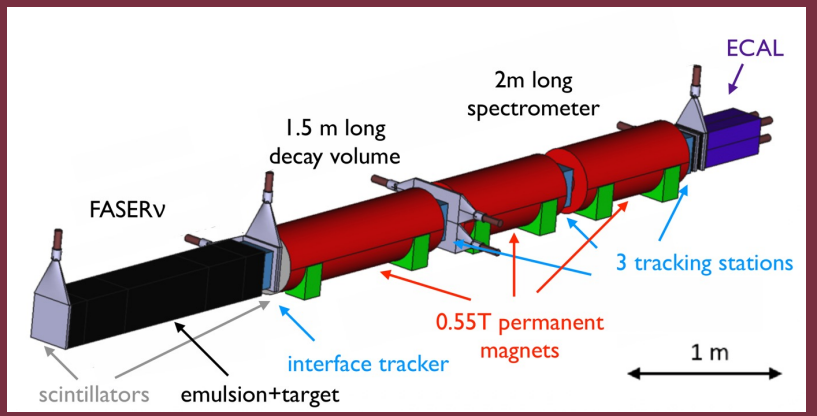
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

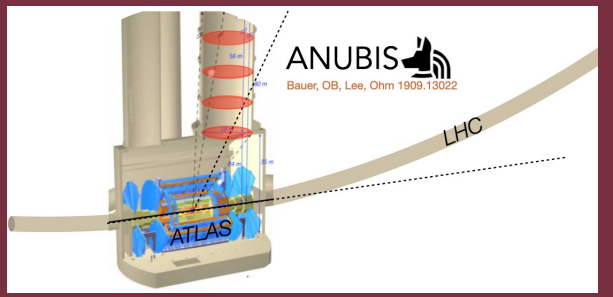
New Dedicated Experiments

- MoEDAL
- FASER
- SHiP
- MATHUSLA
- FACET
- millaQan
- FORMOSA
- ANUBIS
- SND@LHC
- CODEX-b



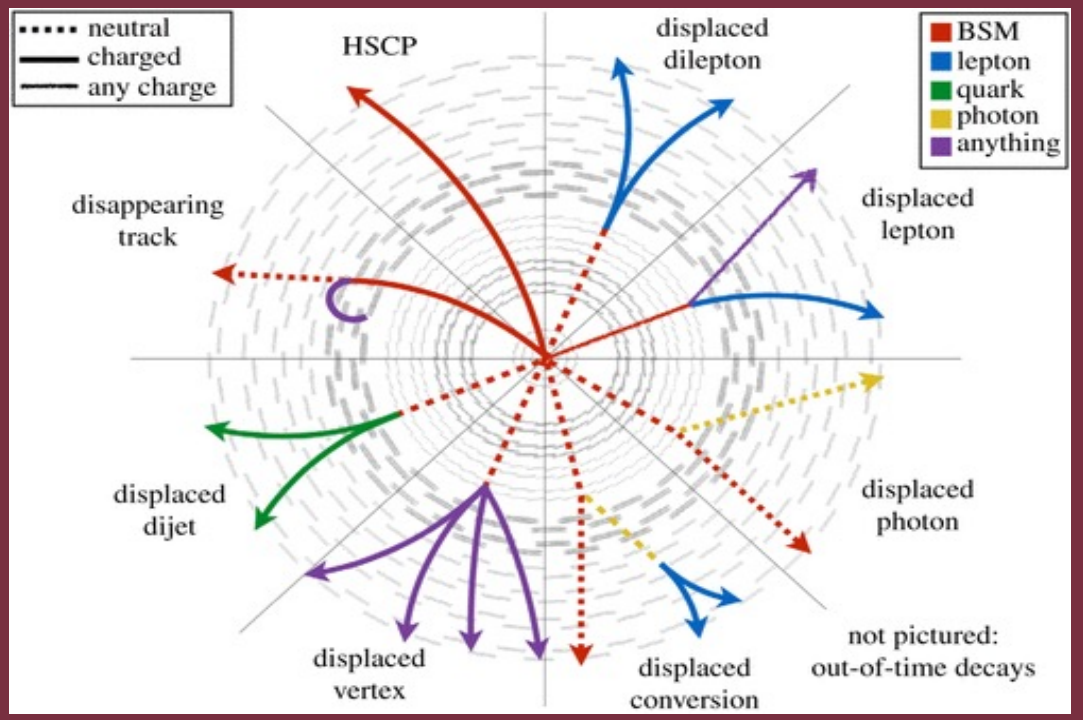






Review

- Many reasons to look for long-lived particles
- Challenges
  - need to adapt detectors and software to different signatures
- Many searches done and ongoing
- Dedicated experiments proposed and running
- There is a lot of interest in LLPs at the LHC
  - may be the window on new physics



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