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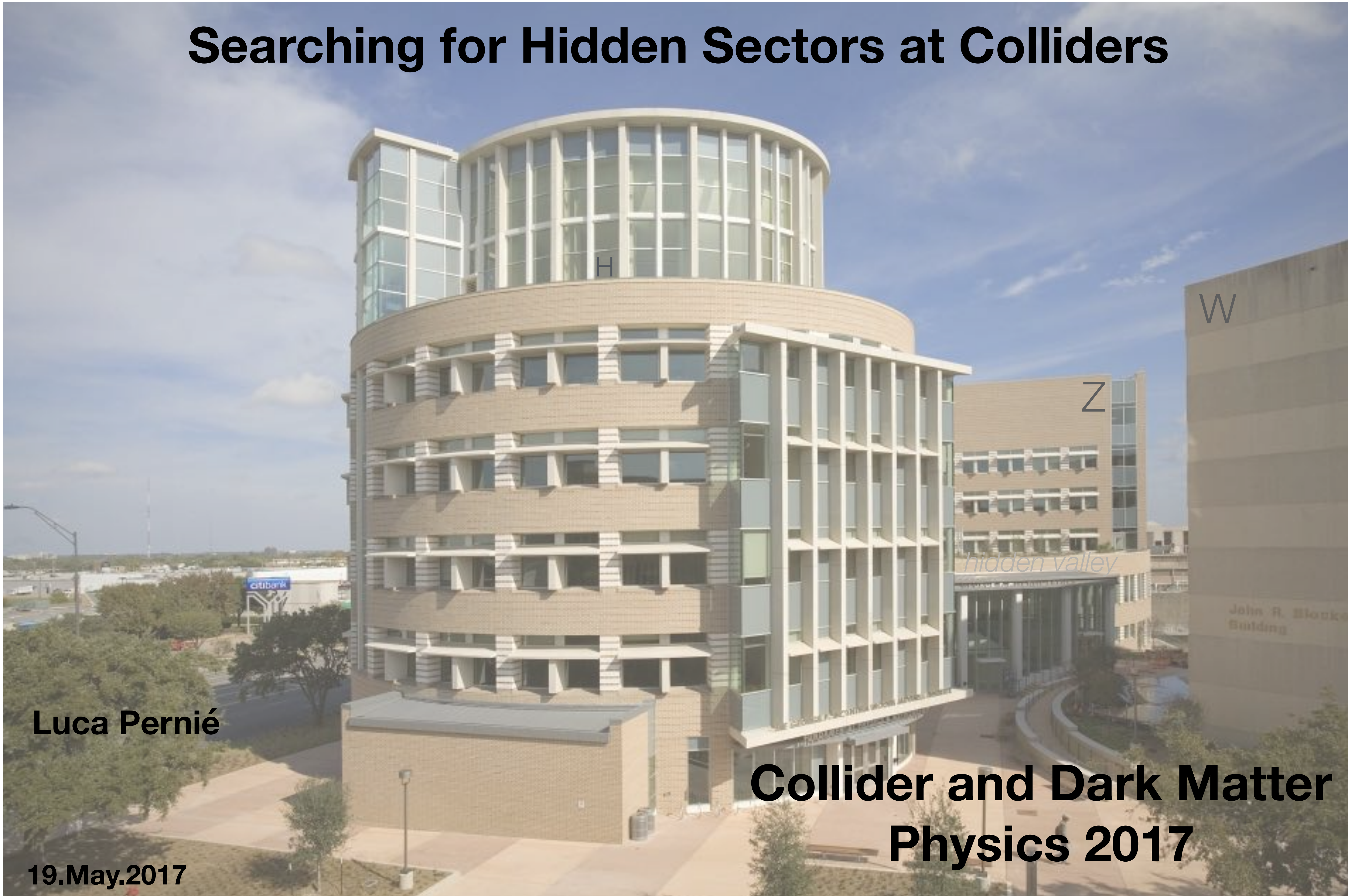
Searching for Hidden Sectors at Colliders



Luca Pernié

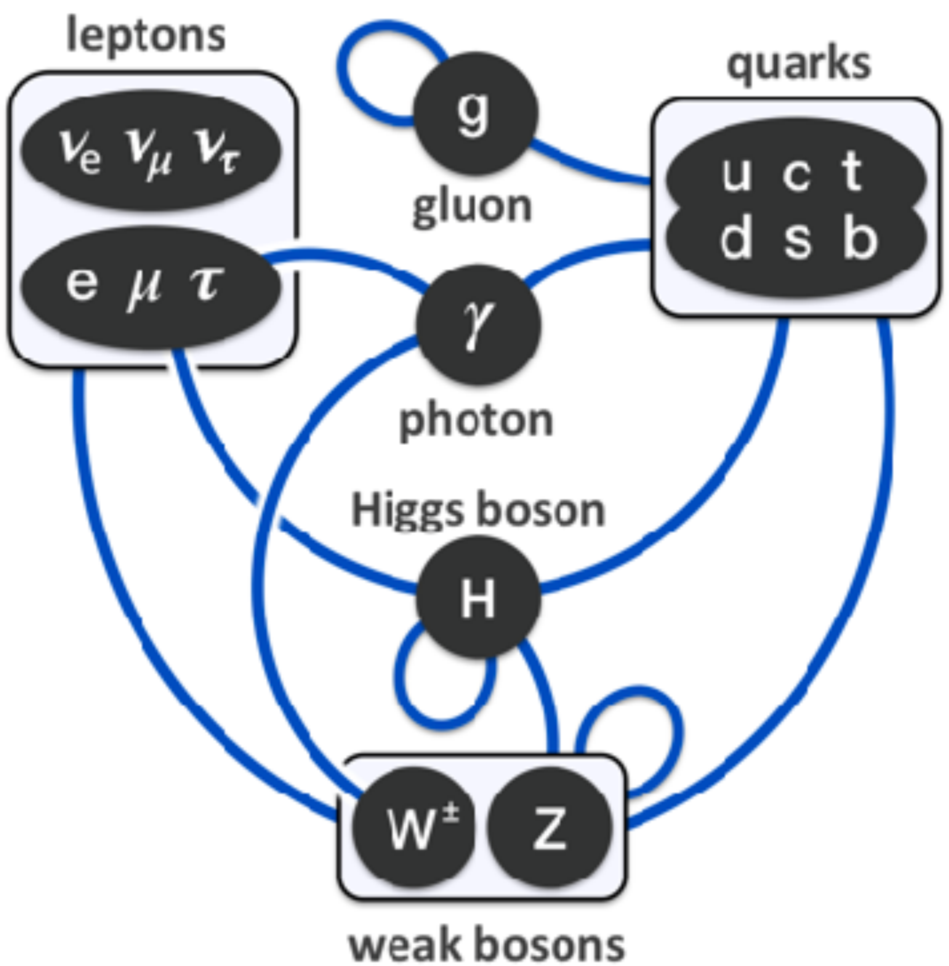
Collider and Dark Matter Physics 2017

19.May.2017

Are we looking into the right places?

- Standard Model (SM): our current theory of matter and interaction

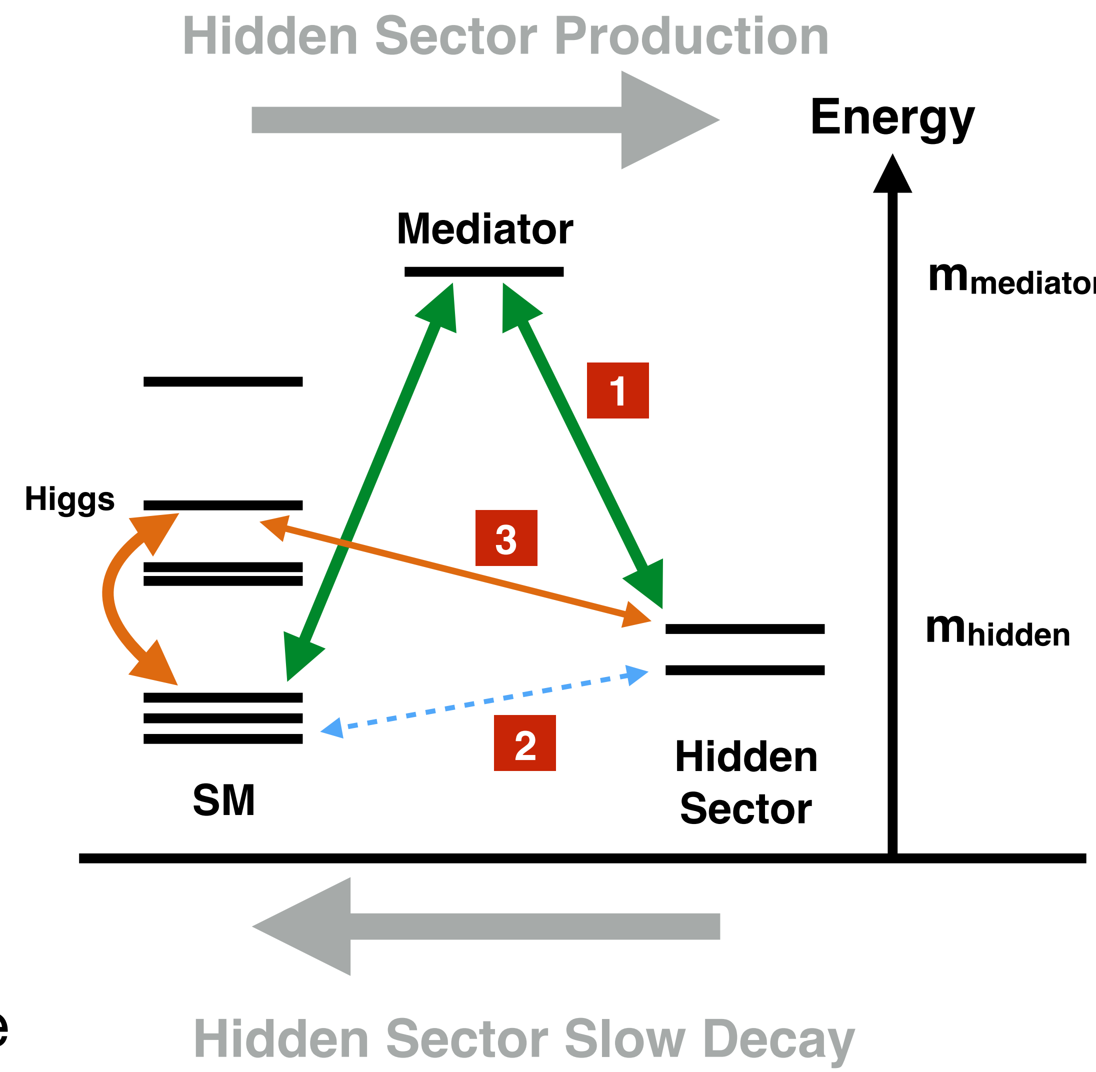
- Unfortunately, it cannot provide a complete description of the Universe:
  - → Higgs Mass is unprotected against quantum corrections in the SM: $m_h^2 \sim m_{h0}^2 - \alpha \lambda_f^2 \Lambda^2$
  - → Baryogenesis:
    $$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-9}$$
  - → Neutrino physics
  - → Dark Matter



- No hints of physics beyond the Standard Model:
  - → <u>Are we looking in the right place?</u>
  - → Null results may point us towards the true nature of the Universe
    - → Hidden sectors with only tiny interactions with the SM
    - → Signatures are subtle and can easily be missed: Long Lived Particles (LLPs)

Where hidden sectors can hide?

- Quest for new physics is not one-dimensional!
  - → New physics not necessarily at higher energies
  - → New physics could lie at m_{hidden} < TeV (hidden by small coupling to SM)



- Possible for a hidden sector to contain just 1 species of particles with no non-gravitational interactions but…
  - → BSM is motivated if the hidden sectors play a part in solving SM shortcoming
  - → Hidden sectors can be connected to the SM via small effective couplings (portals)

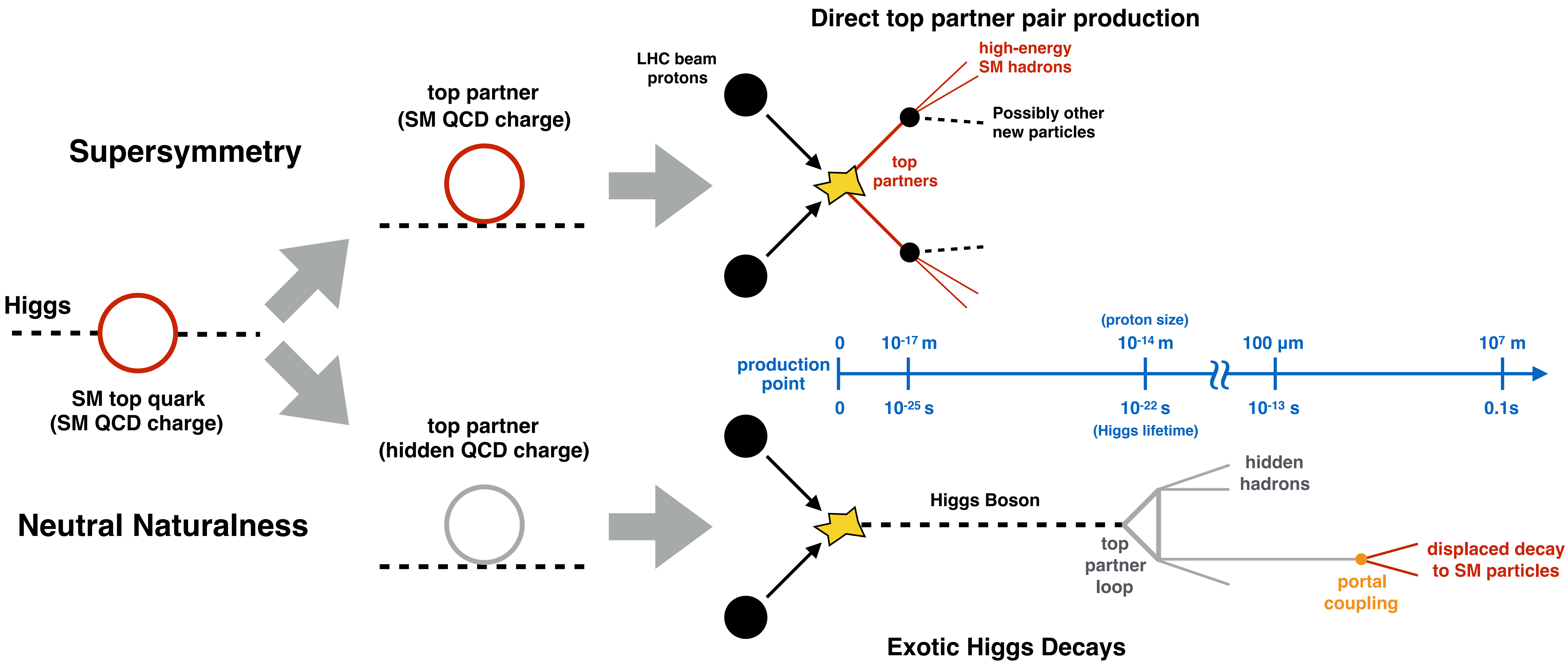
- Rich phenomenology depending on Mediator nature (Heavy mediator, photon-dark photon oscillation, etc…)

- Portal is a tiny keyhole: decay can take a long time (Long-Lived Particles, LLP)

Flashes of Hidden Worlds at Colliders, D. Curtin and R. Sundrum, Submitted to Physics Today, arXiv:1702.02524

Hidden states and the hierarchy problem

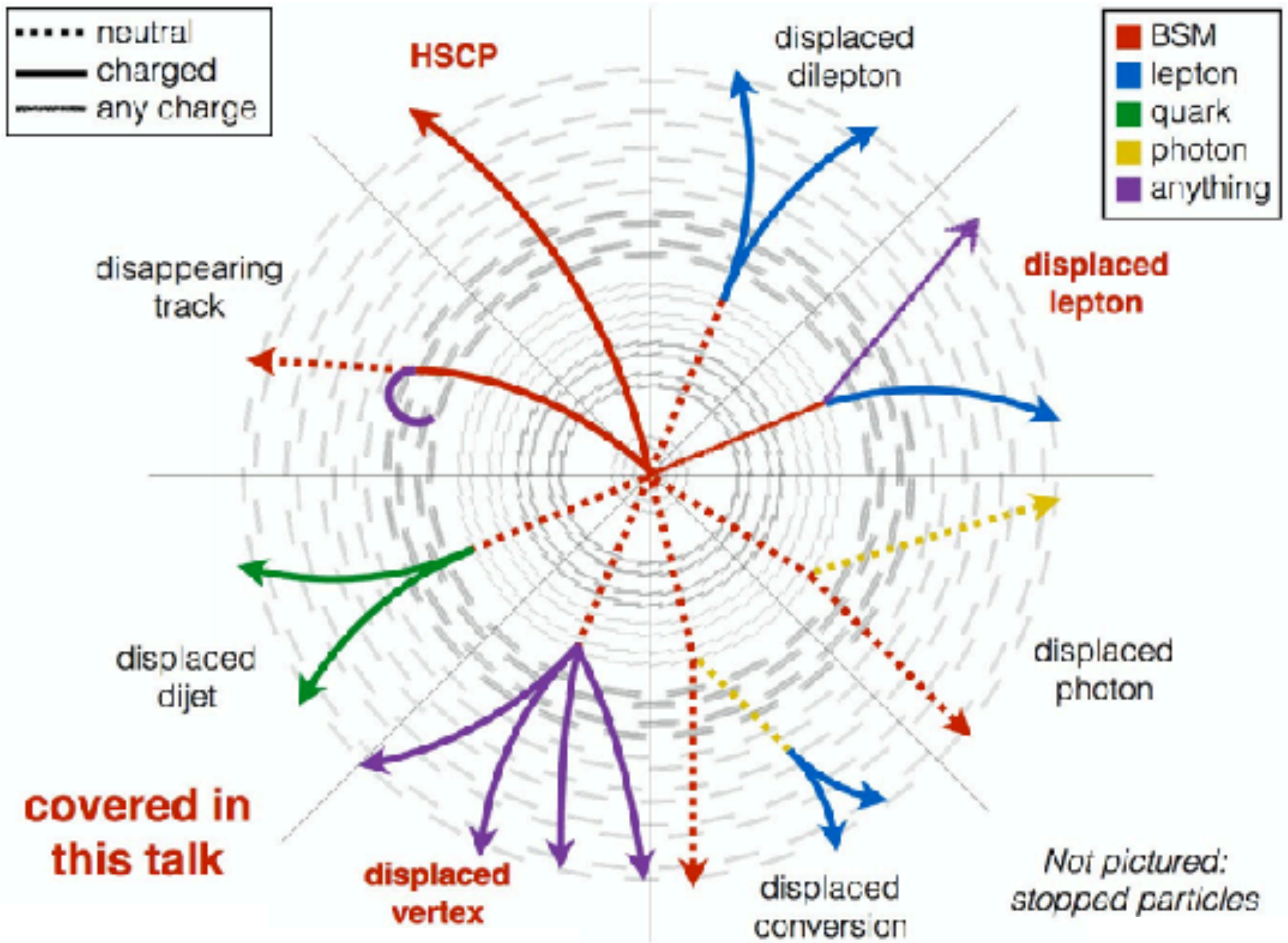
- Higgs Mass is not protected against large quantum corrections in the SM
  - → Most important contributions are top quark loops
  - → In SUSY top loop is cancelled by the presence of stops
  - → In Neutral Naturalness SM top is reflected by a top partner charged under hidden QCD
    - → Higgs boson acquires a new decay mode to the hidden QCD hadrons



Flashes of Hidden Worlds at Colliders, D. Curtin and R. Sundrum, Submitted to Physics Today, arXiv:1702.02524

Long Lived Particle at Colliders

- LHC allows to probe Hidden Sectors with $m_{mediator}$ or m_{hidden} at/above the EWK scale
- High-Luminosity (HL) LHC upgrade will increase the number of collisions by factor 10 (~1.5×10^8 Higgs bosons)
- LLP production typically occurs at low rates: each individual displaced decay is so spectacular that backgrounds are orders of magnitude lower

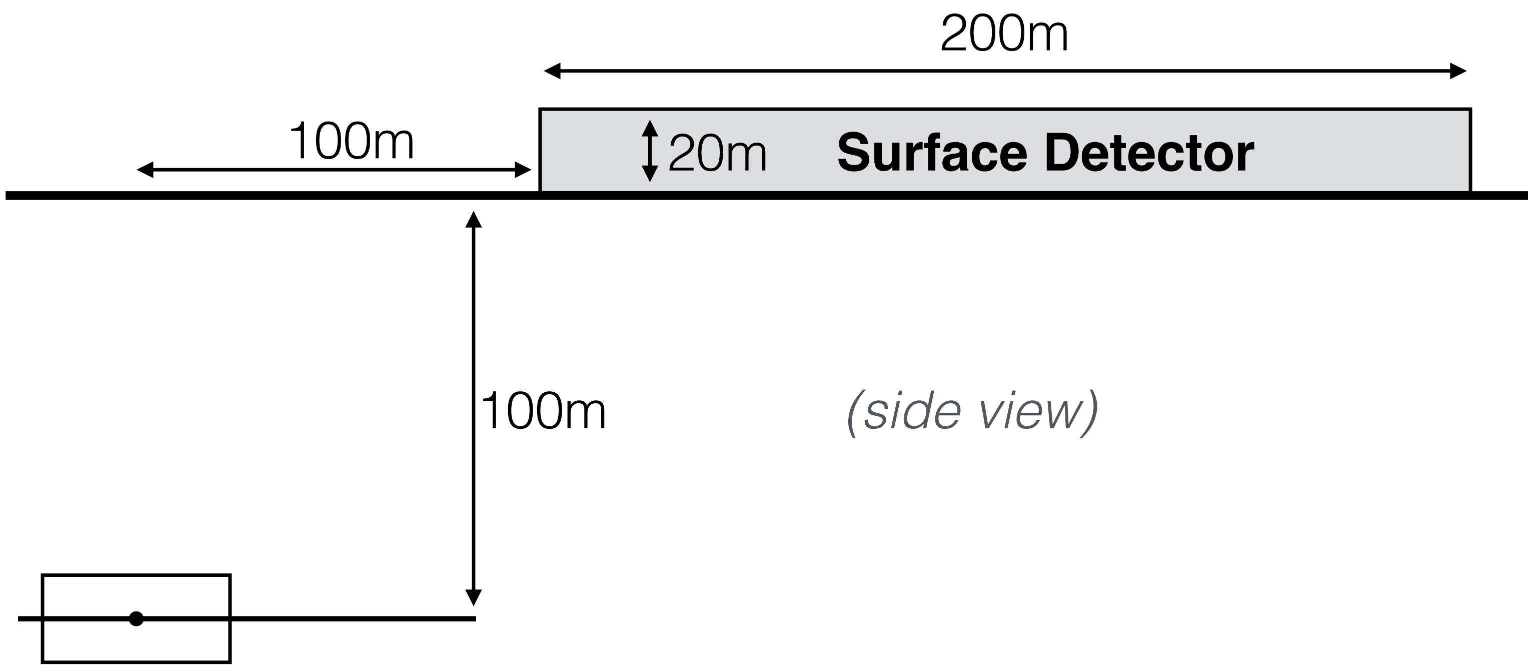


- LLP in thermal equilibrium with the SM plasma in early Universe
- As the universe cooled, first elements were formed (Big Bang Nucleosynthesis, BBN) took place
- With few exceptions, LLPs decaying during/after BBN would disrupt the process
  → LLP parameter space is finite!

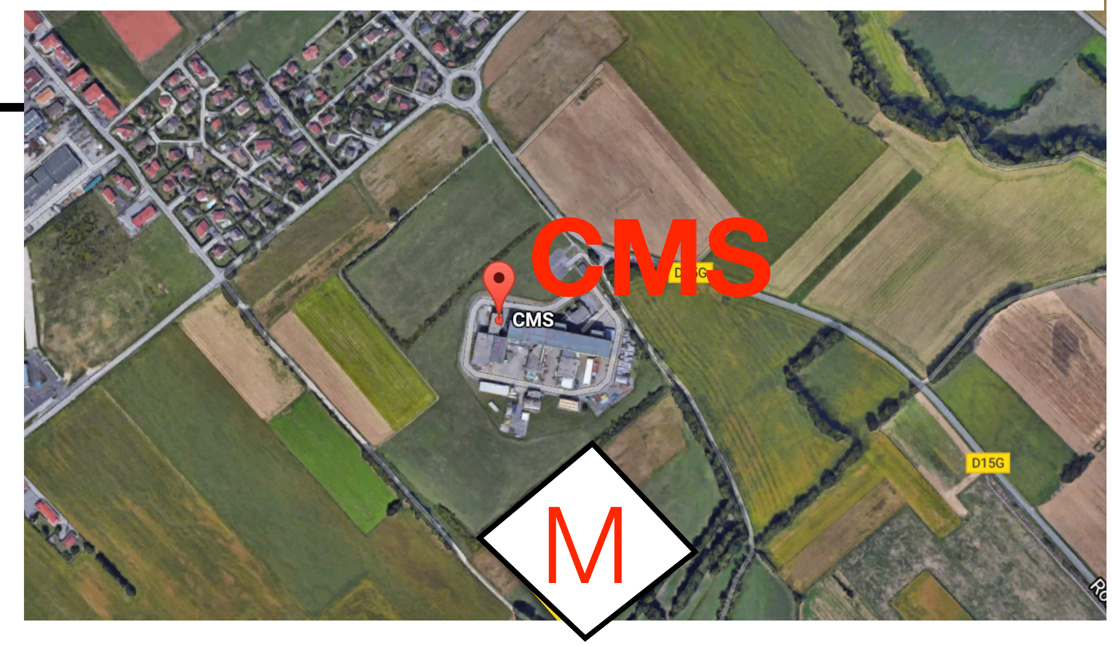
Karsten Jedamzik. Big bang nucleosynthesis constraints on hadronically and electromagnetically decaying relic neutral particles. Phys. Rev., D74:103509, 2006.

Example of dedicated experiment: Mathusla

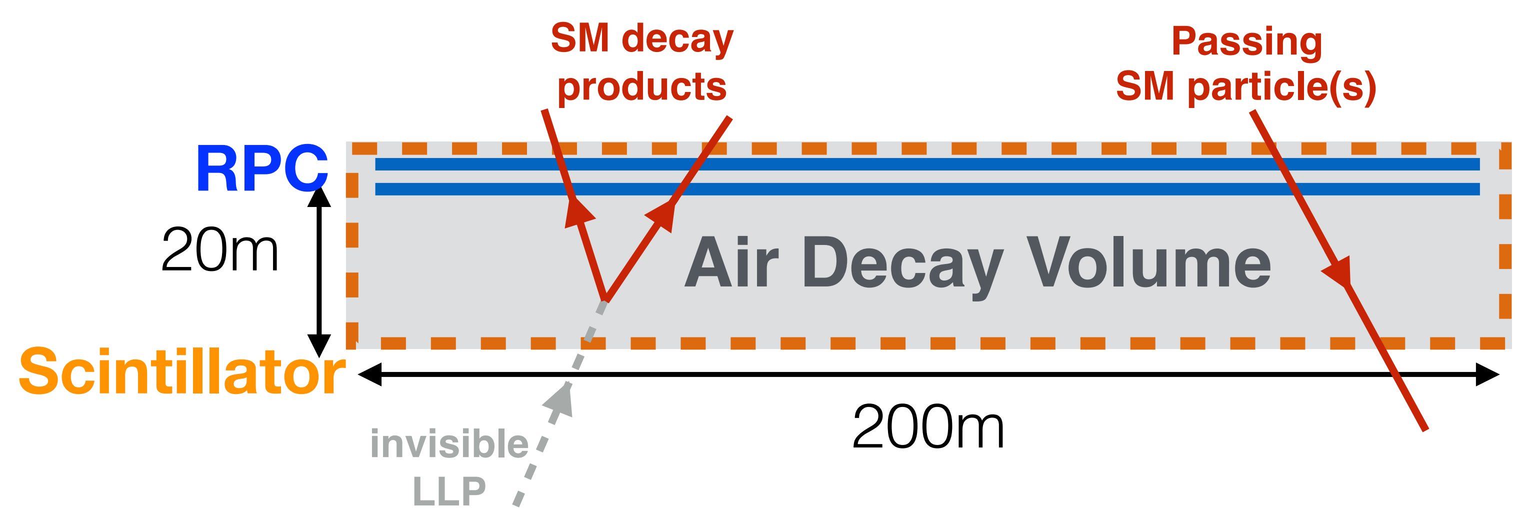
- MAssive Timing Hodoscope for Ultra-Stable NeutraL pArticle
  → Geometric coverage ~ 5%



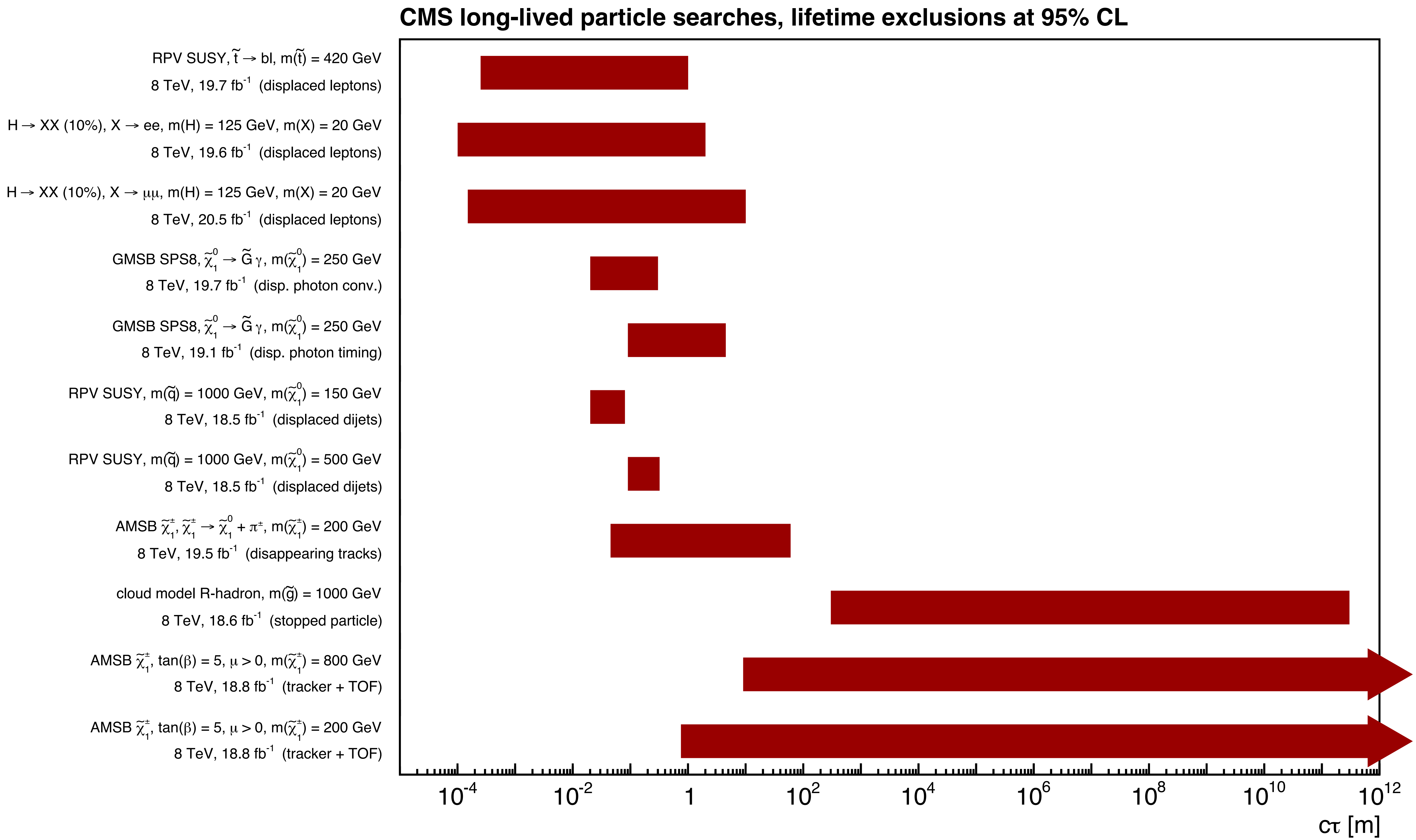
$$N_{\rm obs} \sim N_h \cdot {\rm Br}(h \to {\rm ULLP} \to {\rm SM}) \cdot \epsilon_{\rm geometric} \cdot \frac{L}{bc\tau}$$



- QCD induced fake backgrounds are a limiting factor in CMS/ATLAS
- Virtually background free
- Layers of RPCs in the roof: directional tracker
- Scintillators: additional veto
- ~ns →10 cm resolution
  (Vertex and TOF distinguishes LLP from cosmic rays, neutrino scattering)

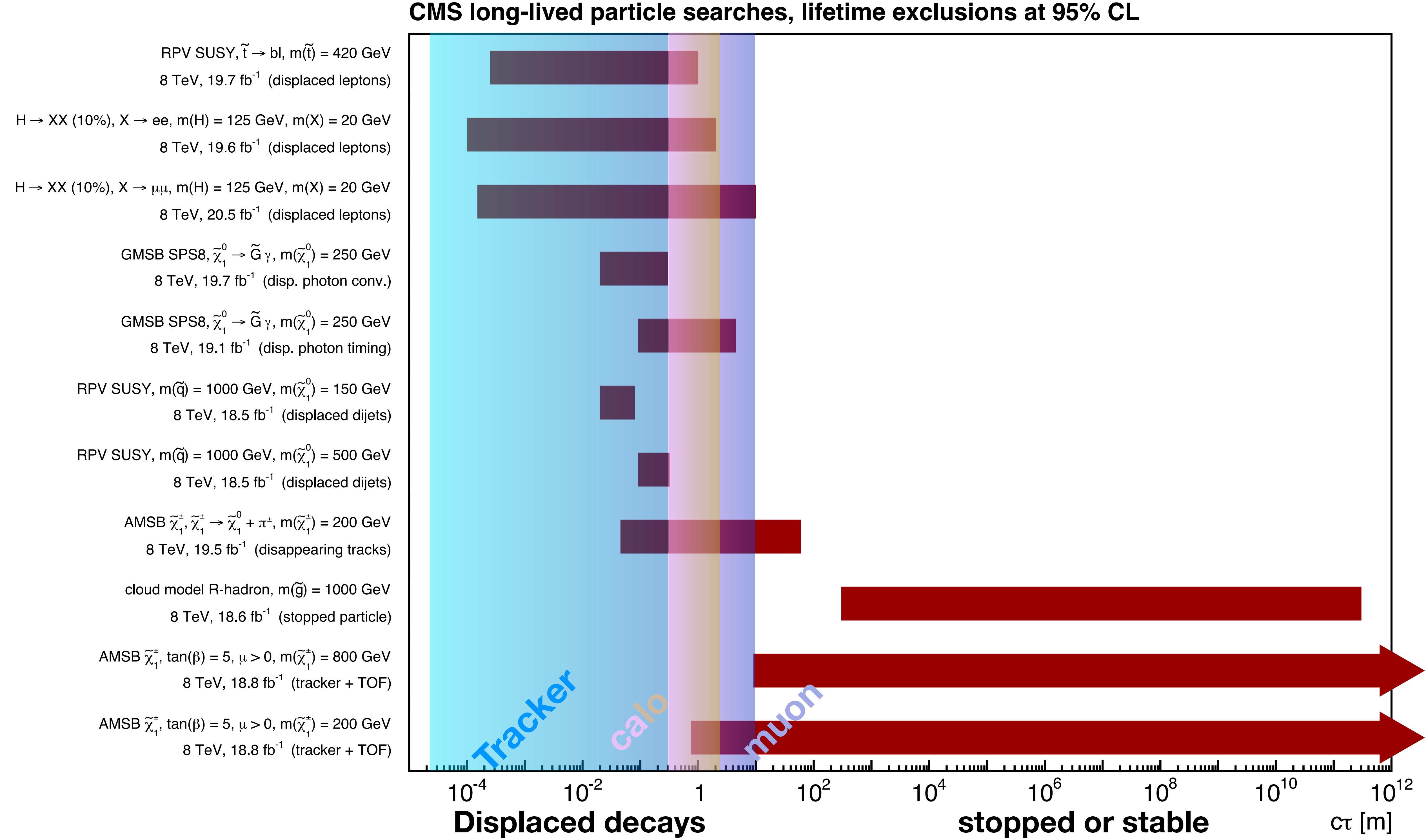


What about CMS?



- <u>About 16 order of magnitude in lifetime covered</u>

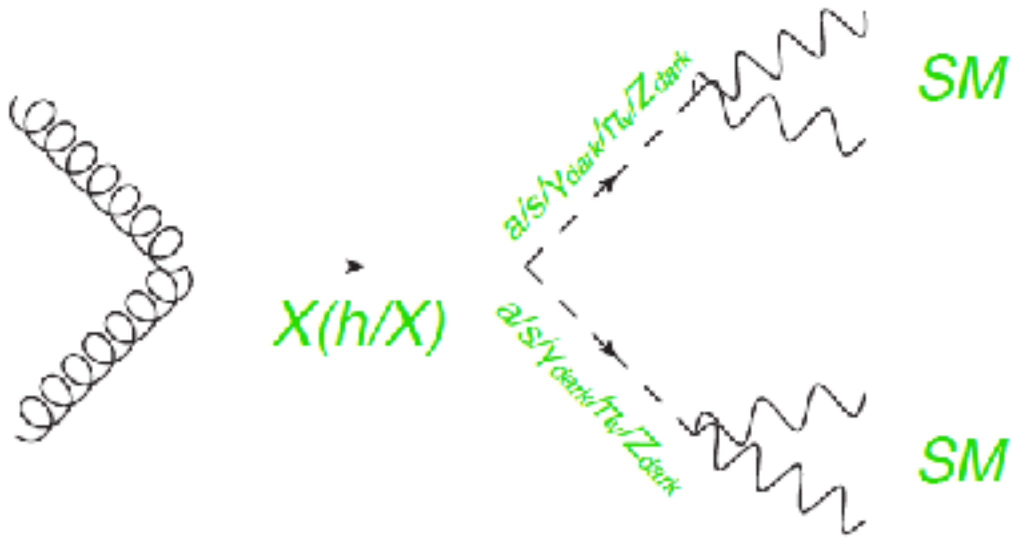
What about CMS?

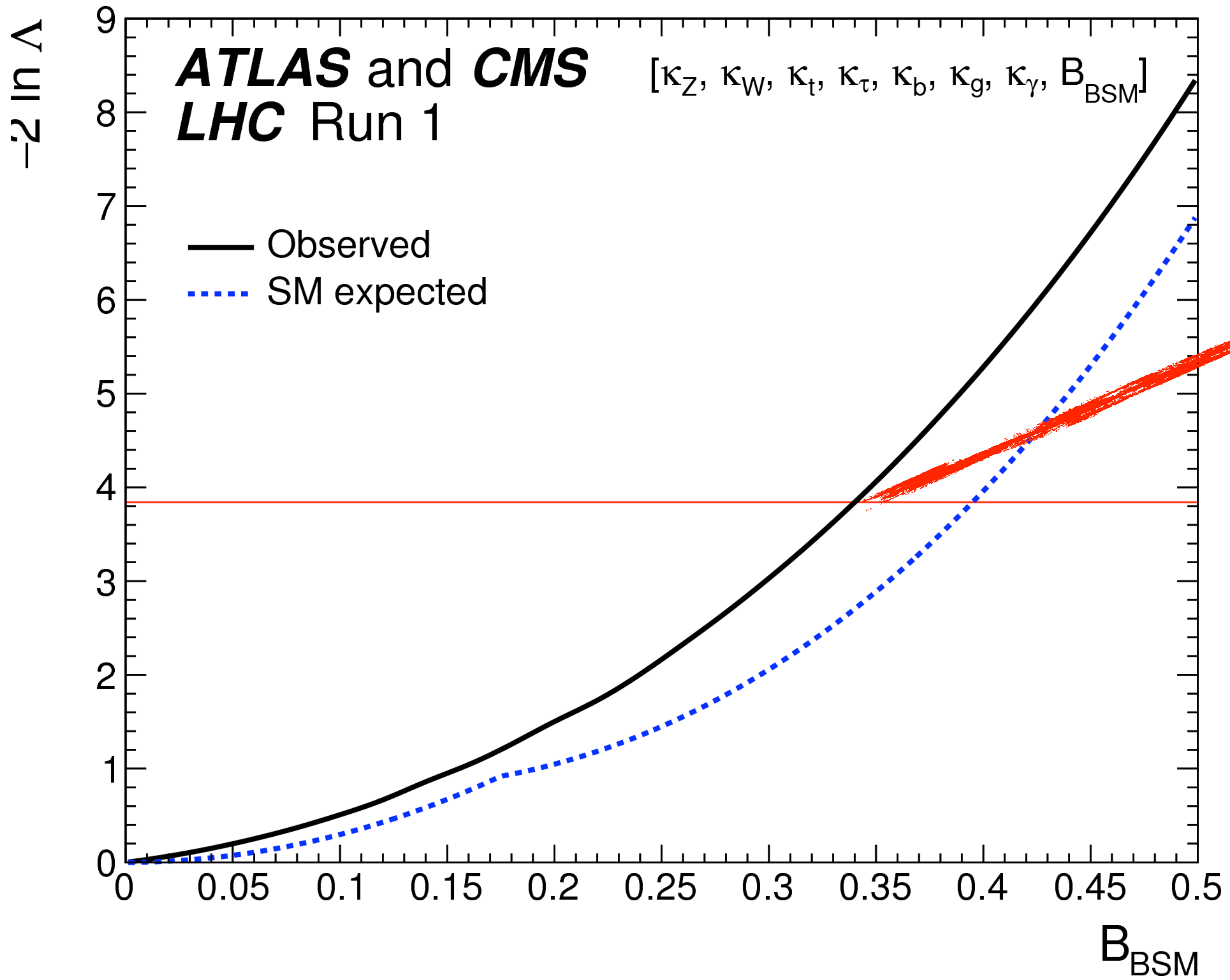


Decays to dark sector particles at CMS: long-lived signatures Ted Kolberg (Florida State University) Dark Interactions 2016, BNL

The Higgs and the dark sector

- Dark Interaction from Higgs decay:
  → Still plenty of space for Exotic decays





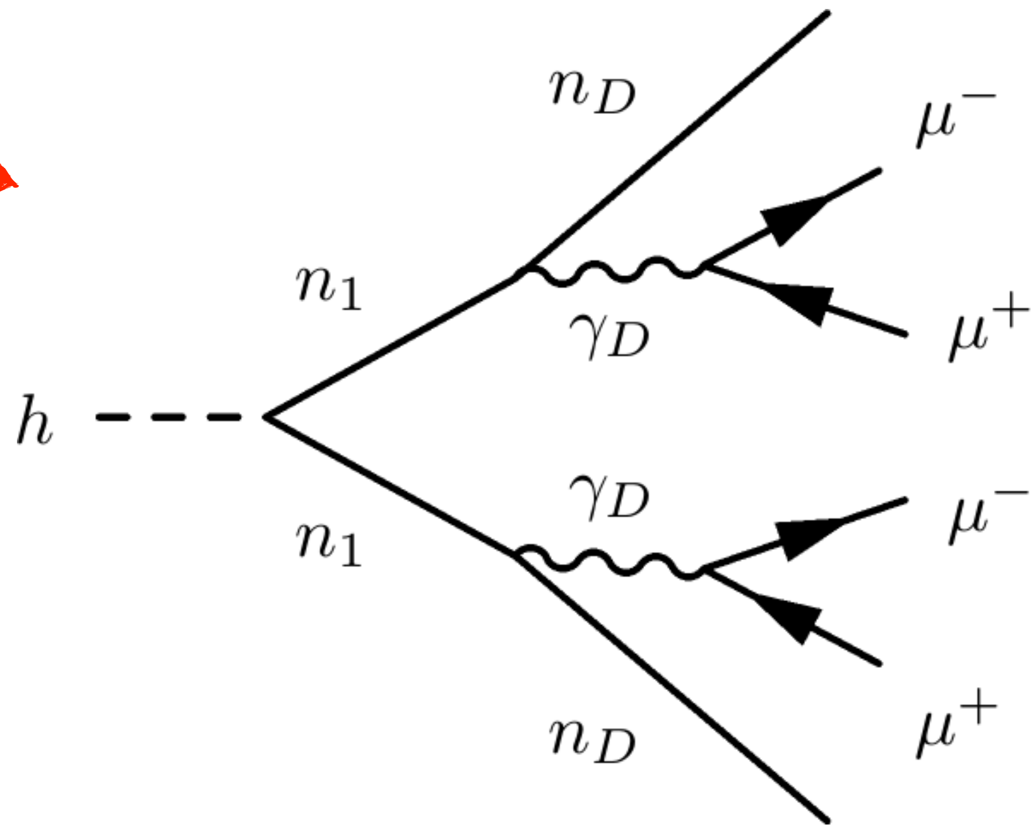
BR (h→BSM) < 34% at 95% CL

Negative log-likelihood scan of BBSM, (combination of ATLAS and CMS) when allowing additional BSM contributions to Higgs boson width. Assumptions:|κV| ≤ 1 and BBSM ≥ 0. All other parameters (in the legend) are also varied

https://arxiv.org/pdf/1606.02266.pdf

Variety of possible final states

- H→aa → fermions:
  → 4μ, 2b2τ, 2b2μ, 2μ2τ, 4τ, 4b
- H→aa →4γ
- H→aa →2b + MET
- H→Z_dZ_d→4l
  (Z_{dark}=Z_d)
- H→invisible
- H→lepton-jets
- H→Long-lived→Displaced hadronic jets
- …



Texas A&M and Rice University involved in displaced muons searches!

Triggering on displaced objects

- Search for displaced signatures start from here!
- Level-1 (L1): regional reconstruction of objects in calorimeters and muon chambers (target rate 100 kHz)
- Higher Level Trigger (HLT): specialized reconstruction sequences that include full detector information, target physics rate of 1kHz
- Challenges: No tracking at L1; Tracking at HLT targeted towards prompt objects; Delayed signals require special input for collecting signals outside of bunch crossings

- Examples:
  - → Displaced jets: pile-up will drive H_T requirements ever higher. Possible to use displaced seeds for online tracking to tighten association of jets to tracks
  - → Displaced photons: E_T thresholds on single photon triggers are very high, whereas signal models have a wide spectrum. In Run2 H_T cross trigger to lower threshold.
  - → Disappearing tracks: No tracking at Level-1, so trigger on MET from ISR. Run2: dedicated MET cross trigger with an isolated track at HLT (track requirements limit signal efficiency)

Displaced muons trigger

- Ad-hoc trigger for displaced muon signatures (introduced in Run-2):
  - → Primary dataset (PD): Double Muon
  - → HLT_TrkMu15_DoubleTrkMu5NoFiltersNoVtx
  - → 2 L1 muons with p_T>12 GeV and p_T>5 GeV (OR p_T>10 GeV and p_T>3.5 GeV)
  - → Global muons are reconstructed using dedicated algorithm for non-pointing muon

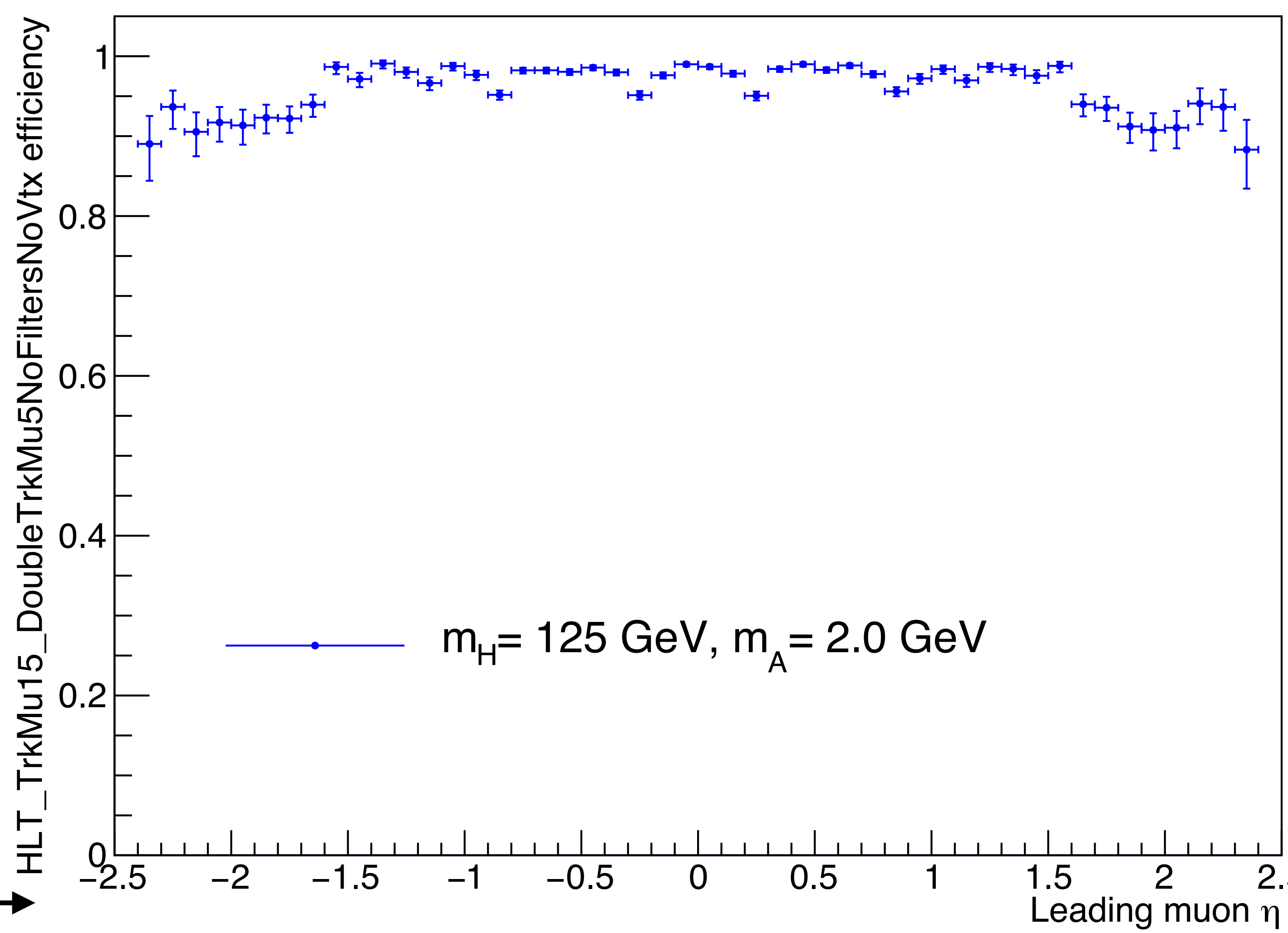
Trigger efficiency versus leading muon η

- Diminished trigger efficiency in the forward region

- At least one offline muon with: p_T>17 GeV, |η|<0.9 (to ensure high trigger efficiency)

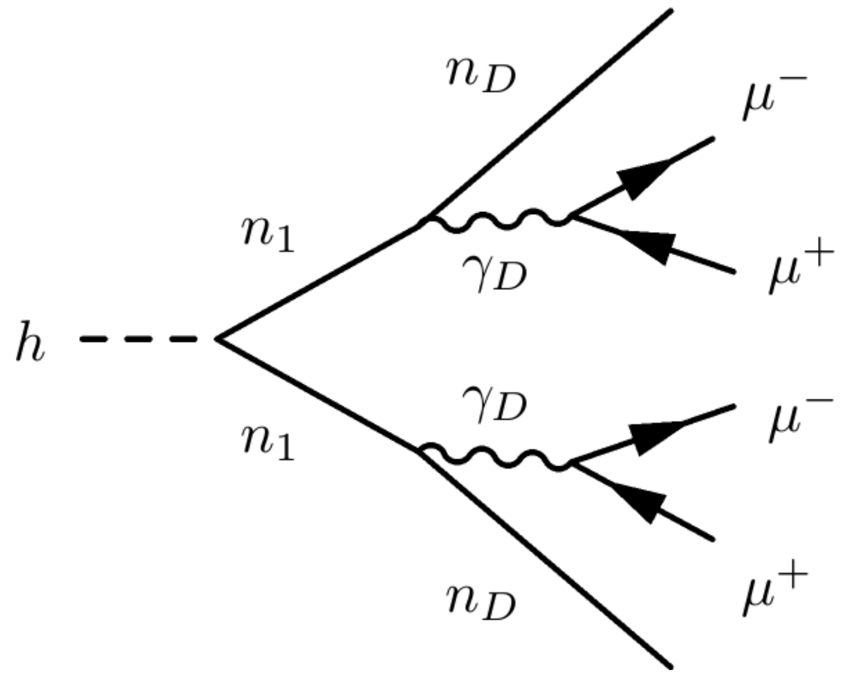
- Once this requirement is applied: trigger efficiency per event high (96-97%)

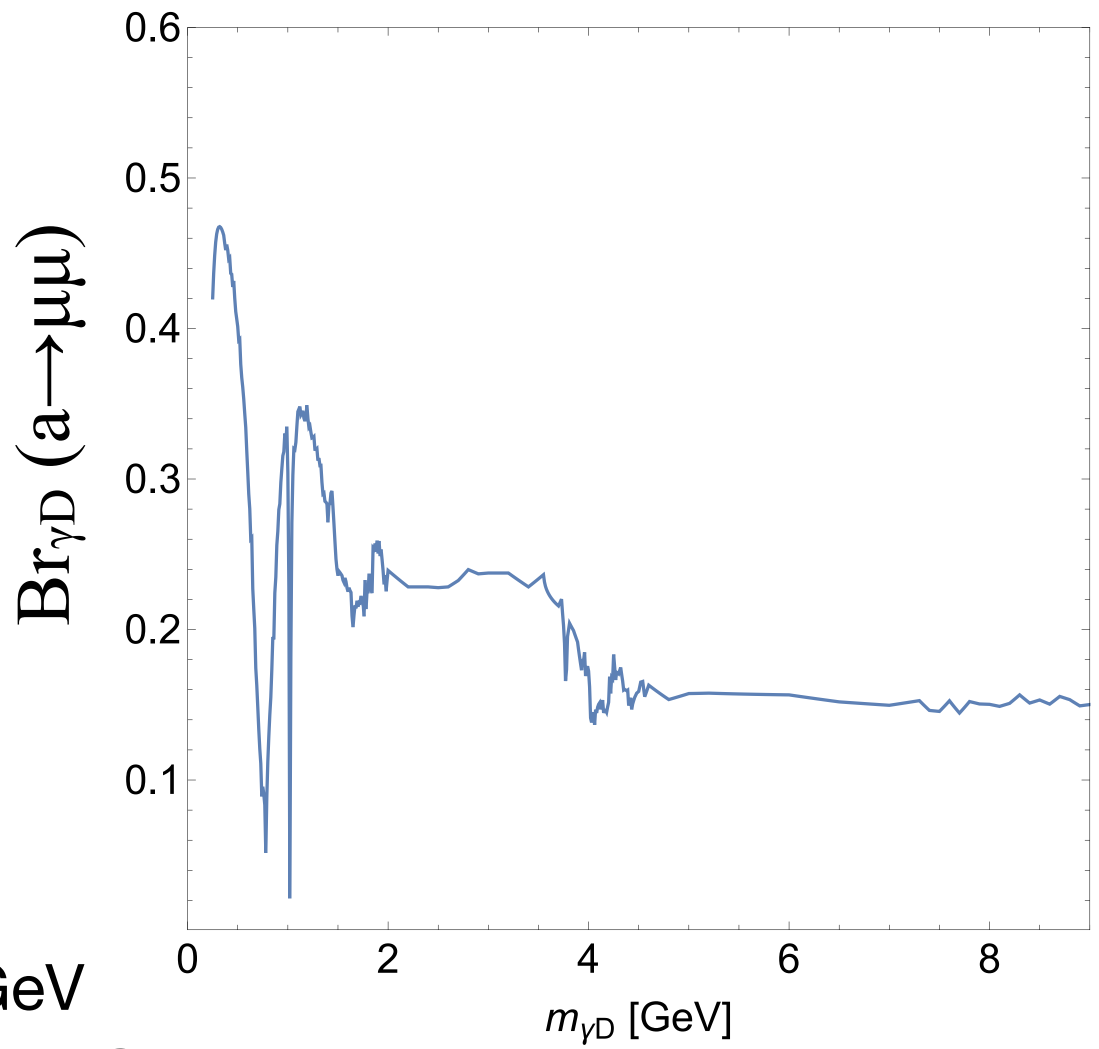
Asking leading μ to have p_T>17 GeV →



Dark SUSY @TAMU

- Dark SUSY:
  - → Predict cold dark matter at ~ TeV scale
  - → $U(1)_D$ is broken, giving rise to light dark photons (γ_D)
  - → γ_D weakly couples to SM particles via small kinetic mixing (ε)
  - → Lightest neutralino is no longer stable and can decay to a dark neutralino (which escapes detection) and a dark photon
  - → γ_D can have a non-negligible lifetime and can travel some distance prior decaying!





- Generating dark SUSY samples with:
  - $m(\gamma_D)$ from 0.25 to 8.5 GeV
  - $c\tau$ from 0 to 100 mm
  - Used $m(\gamma_{n1})$=10 GeV and $m(\gamma_{nD})$=1 GeV

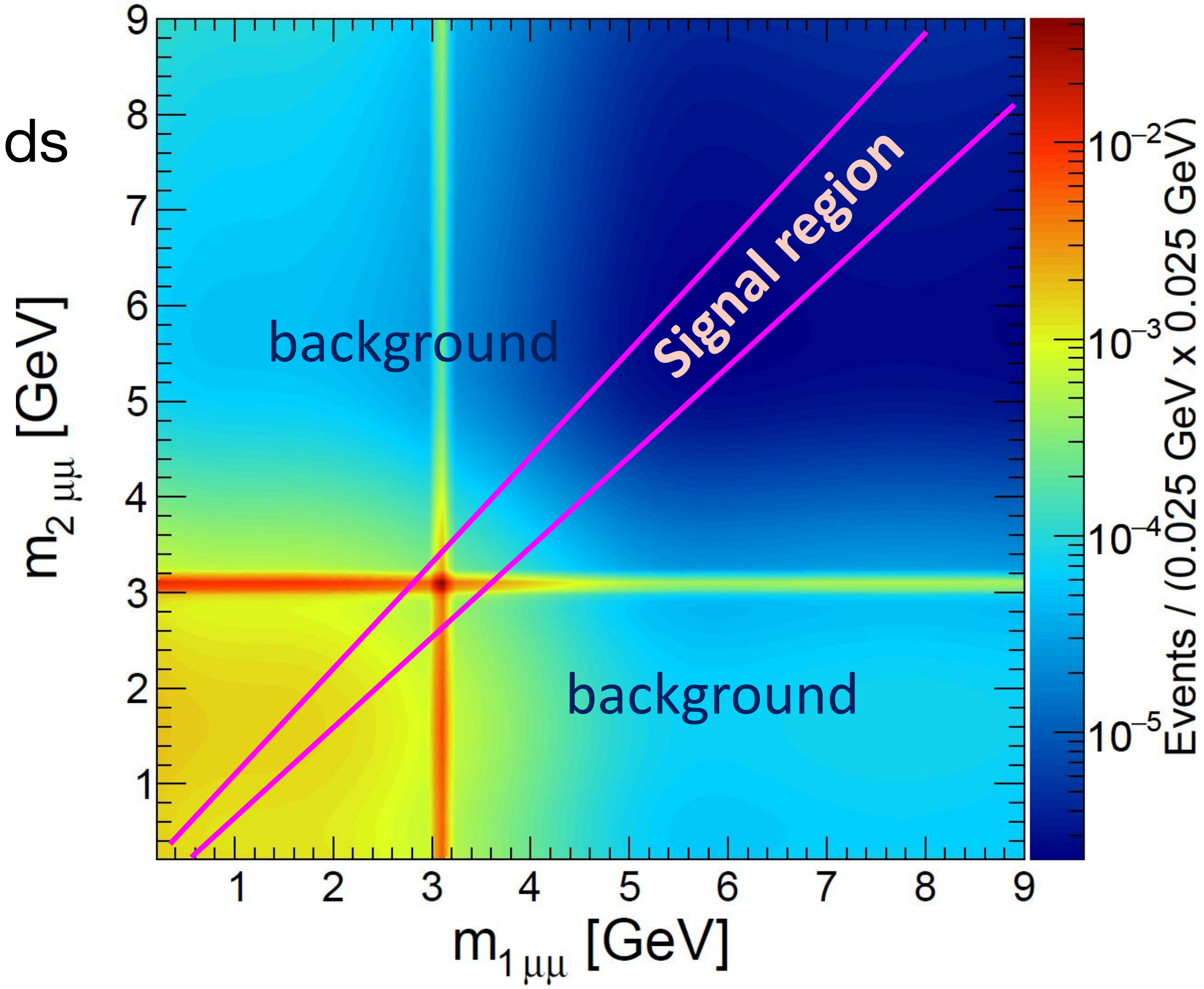
Analysis strategy

❖ Reconstructing 2 muon pairs

❖ Reconstruction and efficiencies:
→ Ad-hoc trigger for displaced muon signatures
→ Constrain the decay of the light boson within a fiducial volume (flat efficiency needed in order to be model independent)

❖ Estimate the contribution of SM backgrounds in signal region

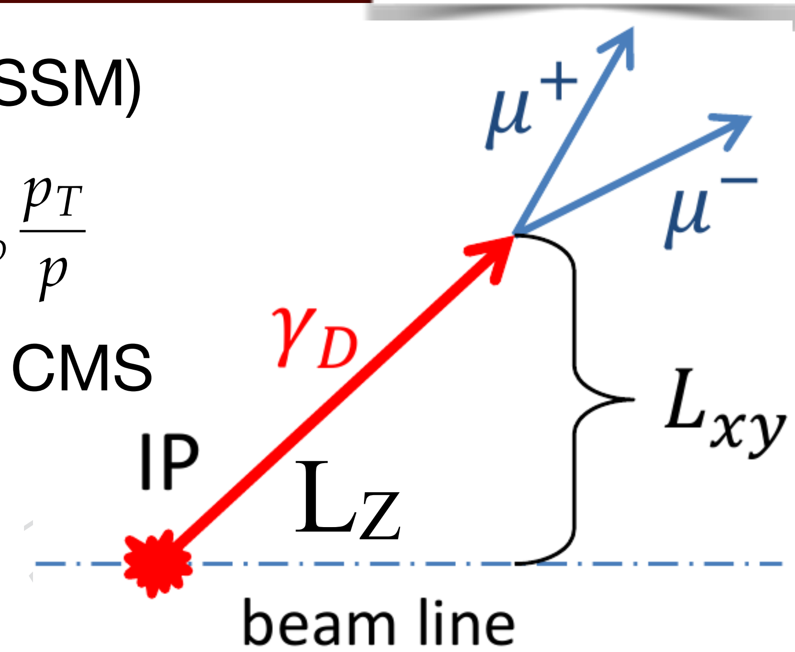
❖ Search for new physics:
→ Signal region: corridor in the 2D space of muon-jets masses
→ Corridor has a width that represent 5 σ of mass resolution



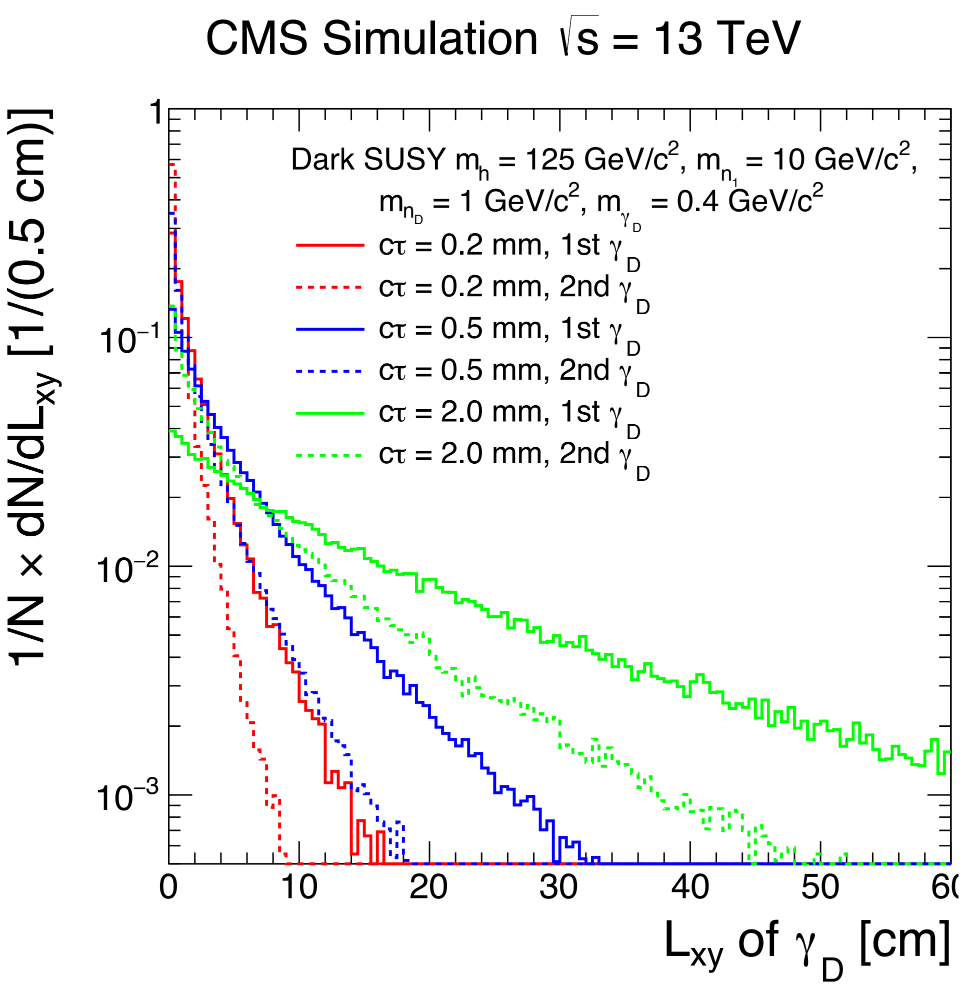
Fiducial region

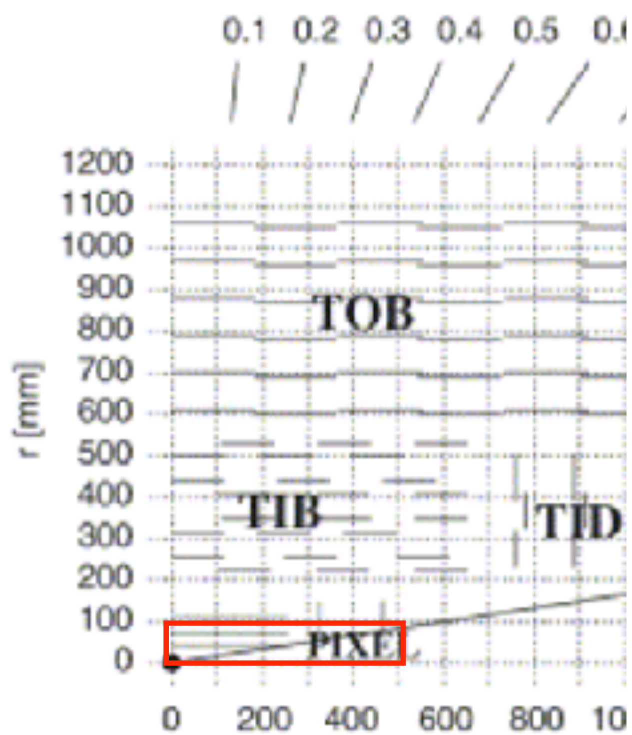
- We test the reconstruction efficiency for dark SUSY (and NMSSM)
  → Reconstruction vs cτ (lifetime)

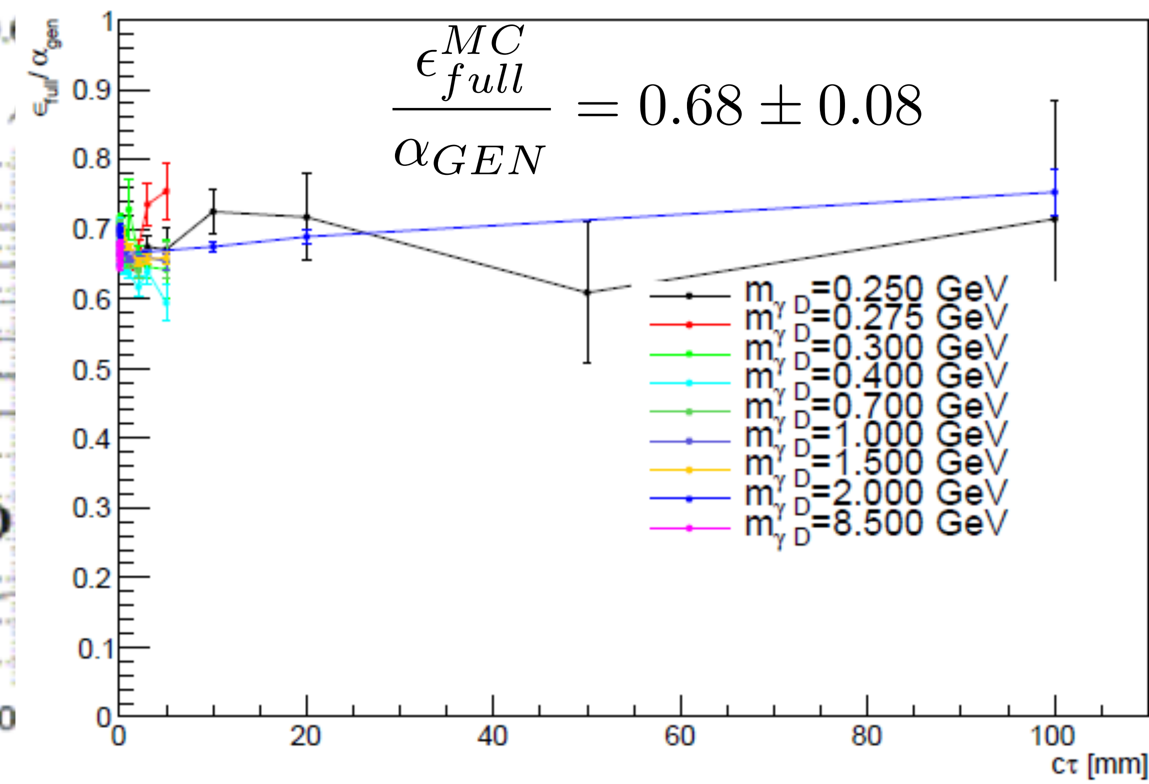
$$L_{xy} = \gamma c\tau_{\gamma_D}\frac{p_T}{p} = \frac{E}{m_{\gamma_D}} c\tau_{\gamma_D}\frac{p_T}{p}$$



- Efficiency is measured inside a fiducial volume defined by the CMS pixel system (Lxy < 9.8 cm and Lz < 48.5 cm)

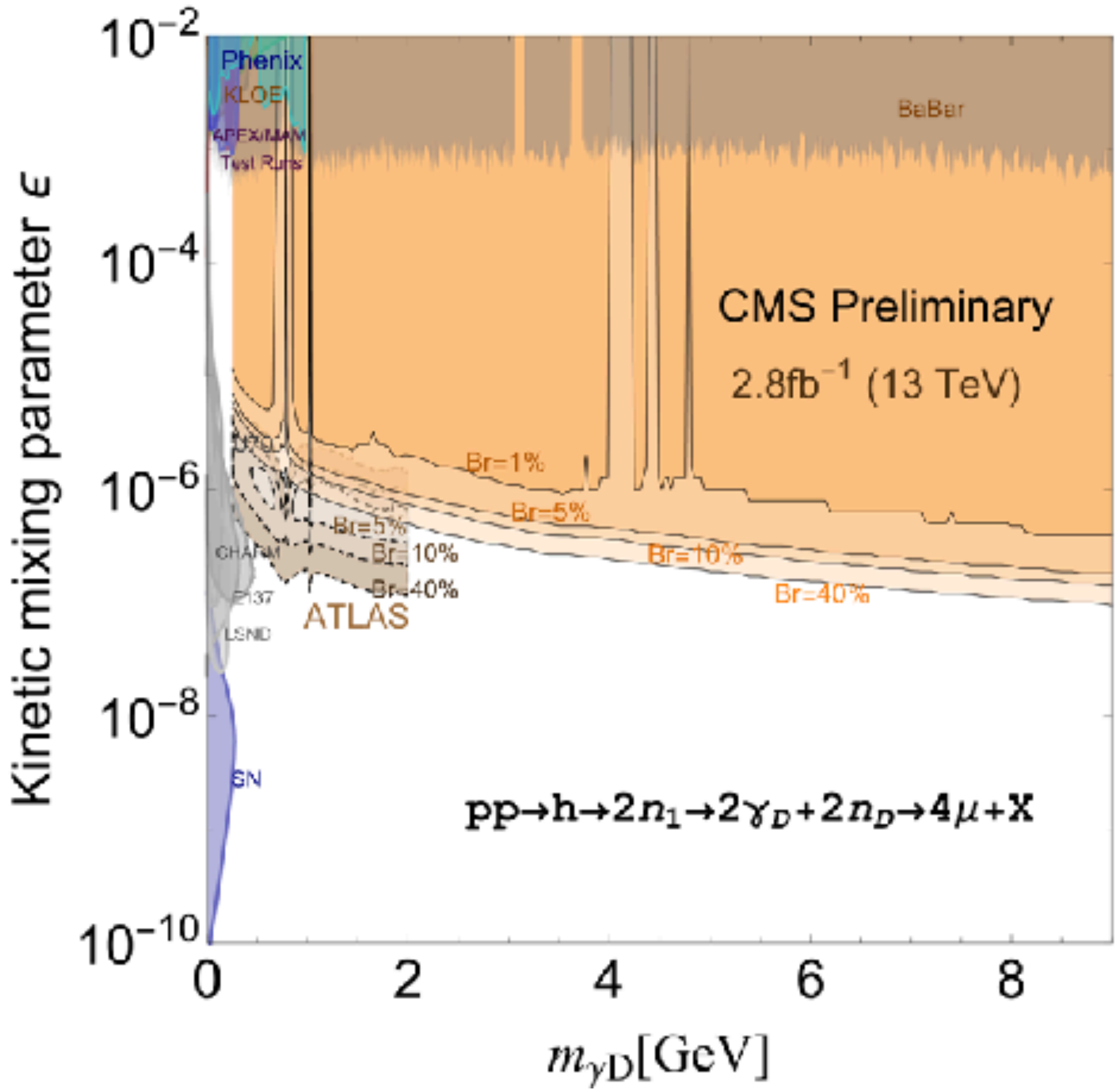






Searches at CMS:

- Final exclusion plots shows CMS + other experiments
  - → Limits in the 2D plane: mass vs kinematic mixing parameter
  - → Colored contours represent different values of Br($h \to 2\gamma_D + X$) in the range 1-40%
  - → Assumed m_{n1} = 10 GeV, m_{nD} = 1GeV



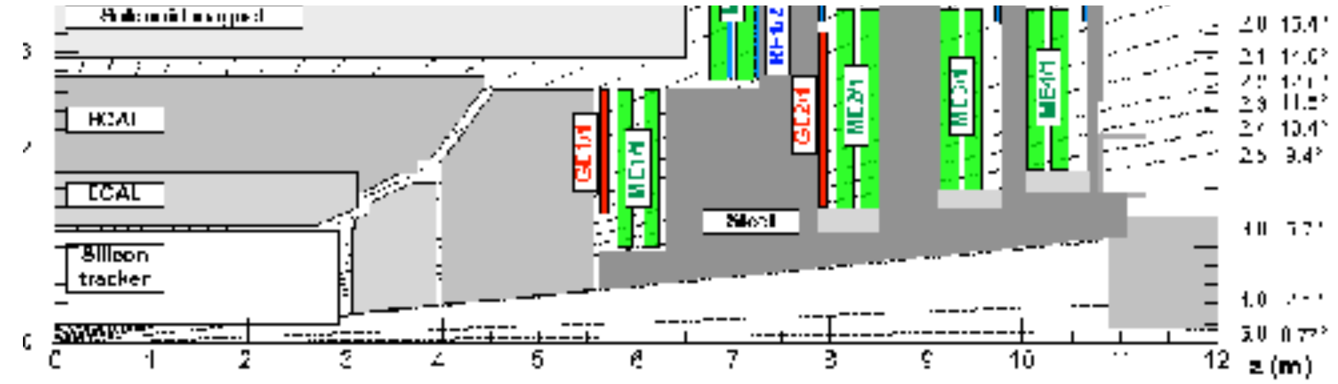
- Exclusion limits orthogonal to ATLAS one
  - → ATLAS looks for di-muon final state
  - → Able to trigger using only muon system
  - → Ask explicitly displaced signature to remove DY background (reason why they exclude only high ϵ)

Looking at the future:

- Especially in the case new physics delay into be found… preparing to turn every stone
  → Planning a displaced muons trigger

- A daunting task:
  → L1 Track Trigger will not be able to reconstruct displaced tracks (lower p_T resolution)
  → L1 muon reconstruction assumes muons coming from the interaction point

- Still potential for designing a displaced muon trigger:
  → Muon direction within a single station: underutilized in CMS L1 Muon trigger
    → Especially for Endcap (help from GEM!!)
  → True energetic displaced muons will have a consistent bending angle in different stations
  → Veto Tracker tracks to reduce rate (propagate L1 track to second muon station, veto L1Mu if L1 track is in a cone of ΔR=0.12)



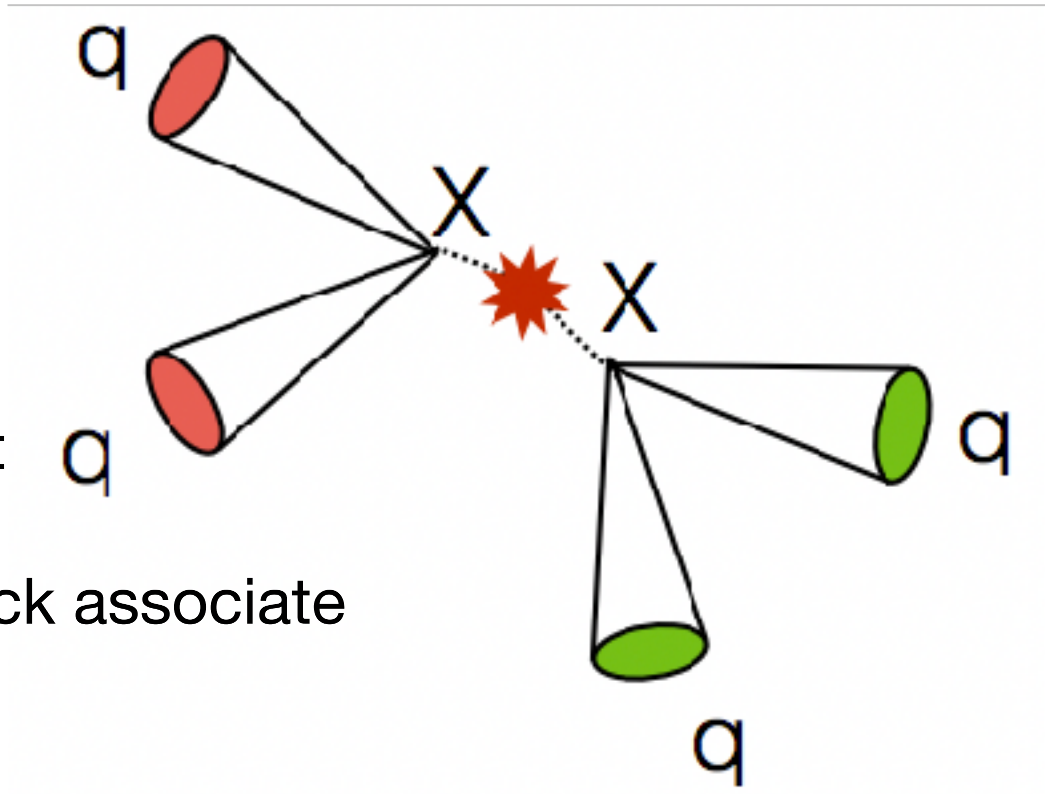
Conclusions

- Quest for new physics is not uni-dimensional
  → Absence of new physics could point us toward the new nature of the Universe
- Dedicated LLP experiments could probe intermediate cτ regions
- Displaced at CMS/ATLAS start from triggering
  → Triggering on LLPs involves either dedicated triggers or generic triggers
  → Generic triggers can provide sufficient signal acceptance, as some signals otherwise limited by options at L1/HLT for a more specific trigger
  → Trends from Run1 to Run2 have mostly been to either raise thresholds in order to cope with pileup or design a more signal-specific trigger
- Upgrades to CMS will yield more opportunities to target more challenging signals with dedicated triggers

BACKUP

Displaced jets

- Signal: pair-produced long-lived neutral particle decaying to jet pairs



- Dedicated displaced jet triggers
  - → First:
    - → Jet H_T, thresholds bumped up from Run1
    - → At least two jets, $p_T > 40$, $|\eta| < 2.0$
    - → No more than 2 prompt tracks associated to a jet
  - → Second:
    - → Lower HT threshold, now include at least one track associate with $IP^{2D} = 5^{*}\sigma_{IP}{}^{2D}$

- **Challenges**: pile-up will drive H_T requirements ever higher, but would like to stay as low in H_T and p_T as possible

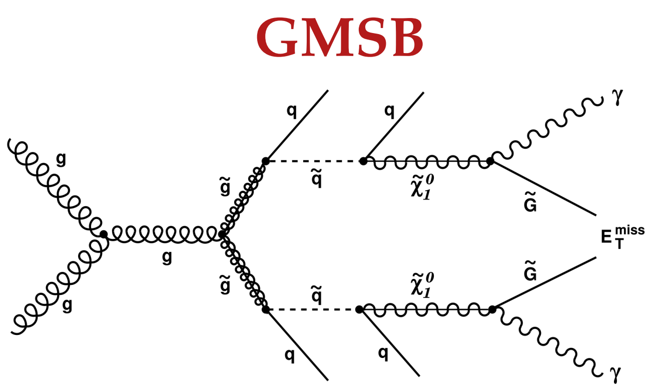
- **Possible improvements**: use displaced seeds for online tracking to tighten association of jets to tracks so p_T thresholds could be made lower

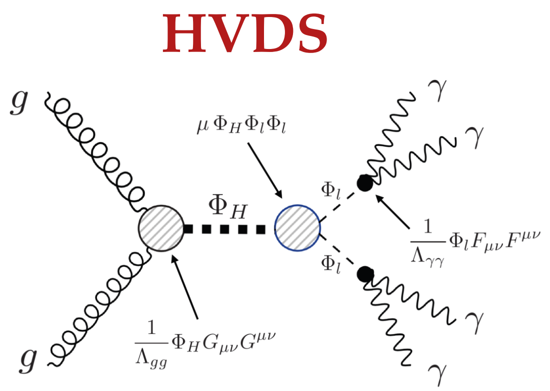
https://cds.cern.ch/record/2256654/files/EXO-16-003-pas.pdf

Displaced photons

Signal: singly, doubly, or many photons out-of-time with respect to prompt collisions

(can include some MET and jet activity)
→ Motivated by GMSB, Hidden Valley Dark Shower, inelastic Dark Matter





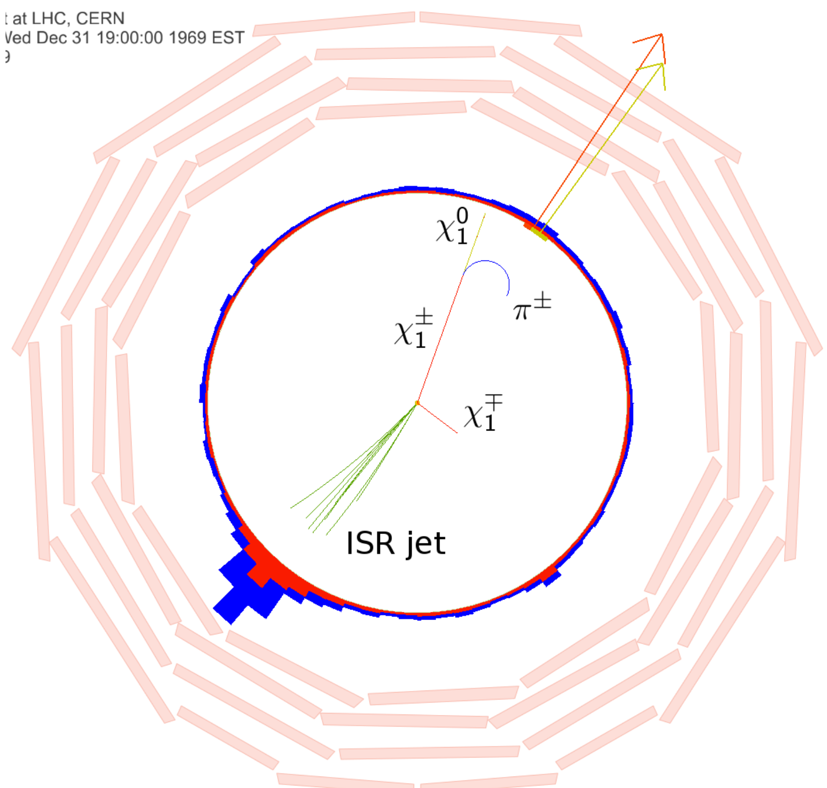
- **Challenges**: E_T thresholds on single photon triggers are very high, whereas signal models have a wide spectrum

- Trigger Strategy
  → Run1: Use of dedicated triggers: well isolated photon, taking advantage of shower shape, with MET or multijet cross-triggers
  → Present: Replace with H_T cross trigger to incorporate new models
  → Additionally, use double photon triggers with lower E_T thresholds and invariant mass to recover events in dark shower

https://cds.cern.ch/record/2063495/files/EXO-12-035-pas.pdf

Disappearing tracks

- Signal: Charged BSM particle that decays to soft product + weakly interacting particle
  - → When pair produced MET nearly cancels
  - → Primary benchmark: Anomaly Mediated SUSY Breaking



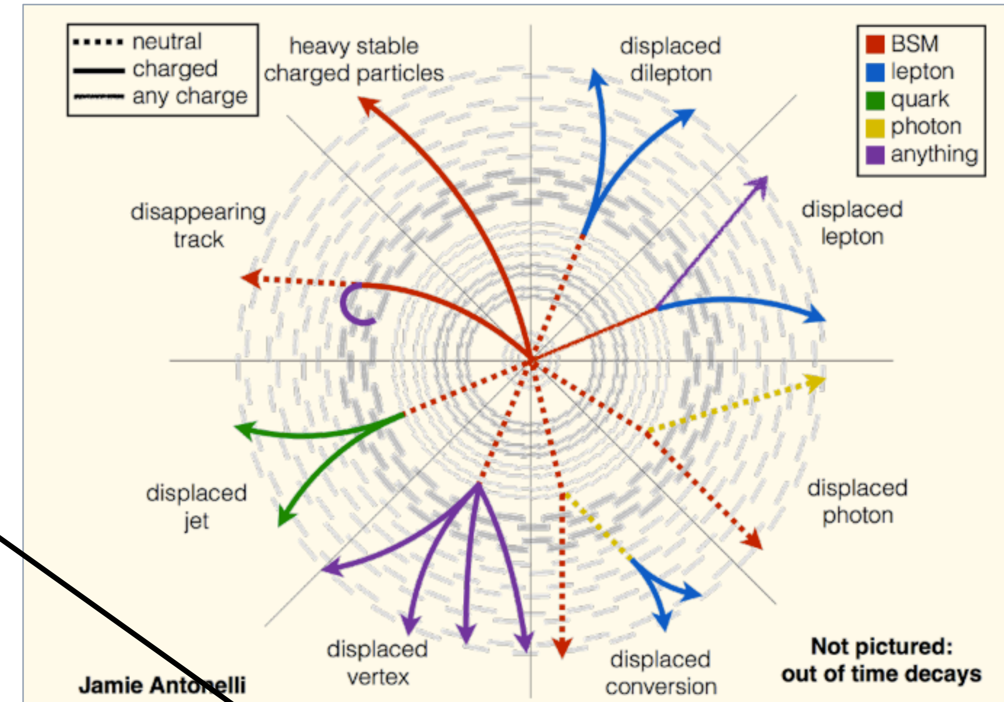
- Challenges: No tracking at Level-1, so trigger on MET from ISR jet recoiling off of $\chi_1^\pm\chi_1^\mp$

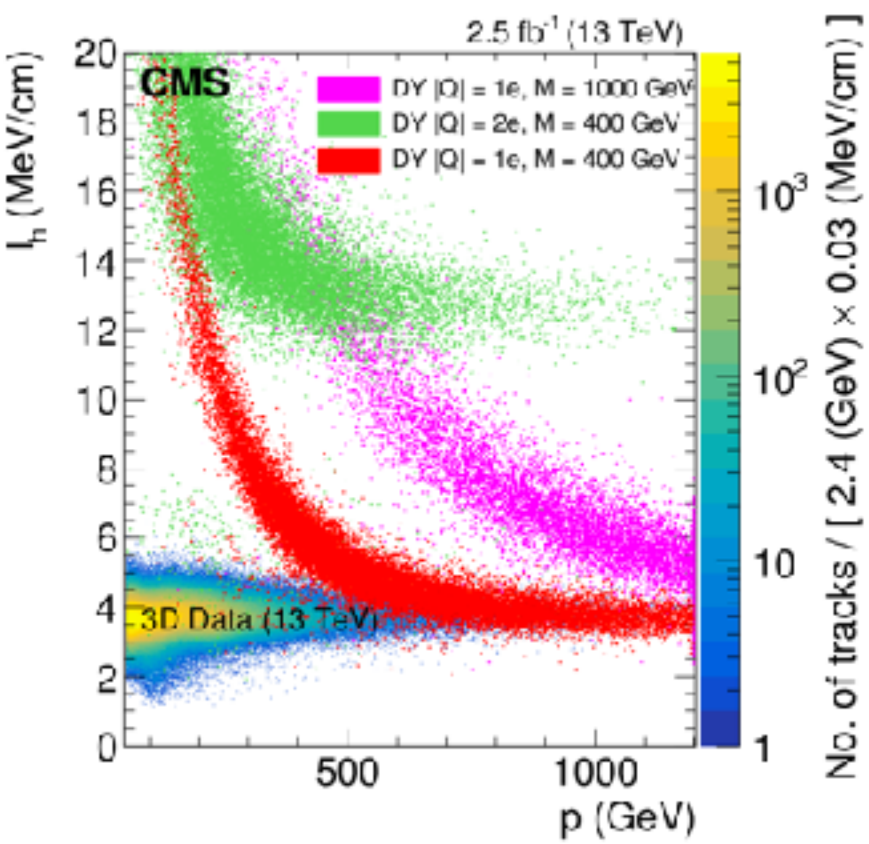
- Trigger Strategy:
  - → Run1: generic pure MET, and Jet + MET triggers
  - → Run2: dedicated MET cross trigger with an isolated track at HLT (track requirements limit signal efficiency)
  - → Extra pixel layers for 2017 to benefit track requirements (loosening isolation) + extended reach for shorter lifetime

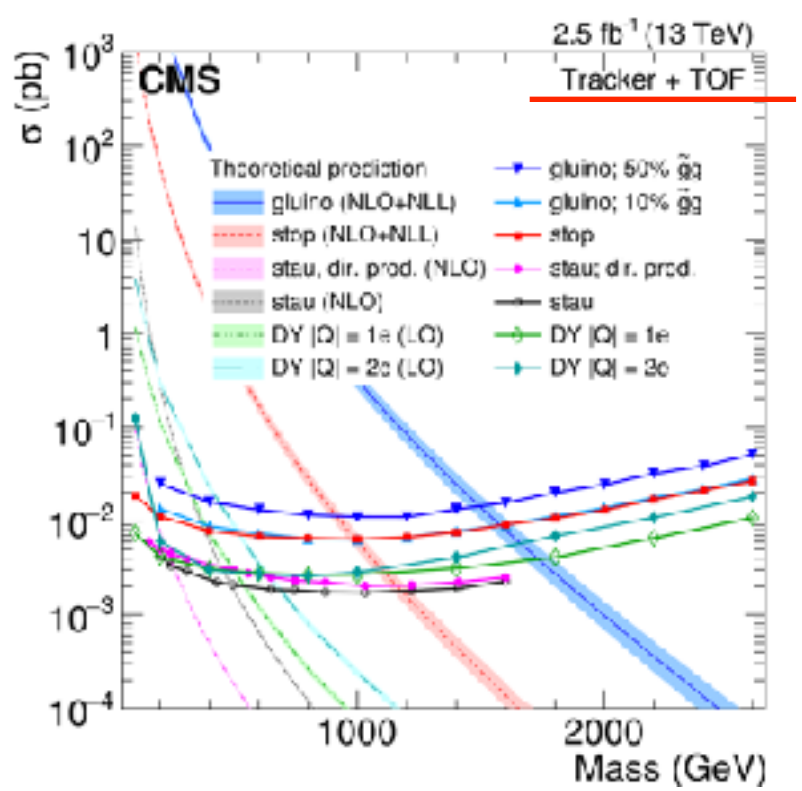
- Future: L1 tracking in Phase-II will grant a much wider range for triggering: no longer have to rely on ISR to trigger on

Searches at CMS:

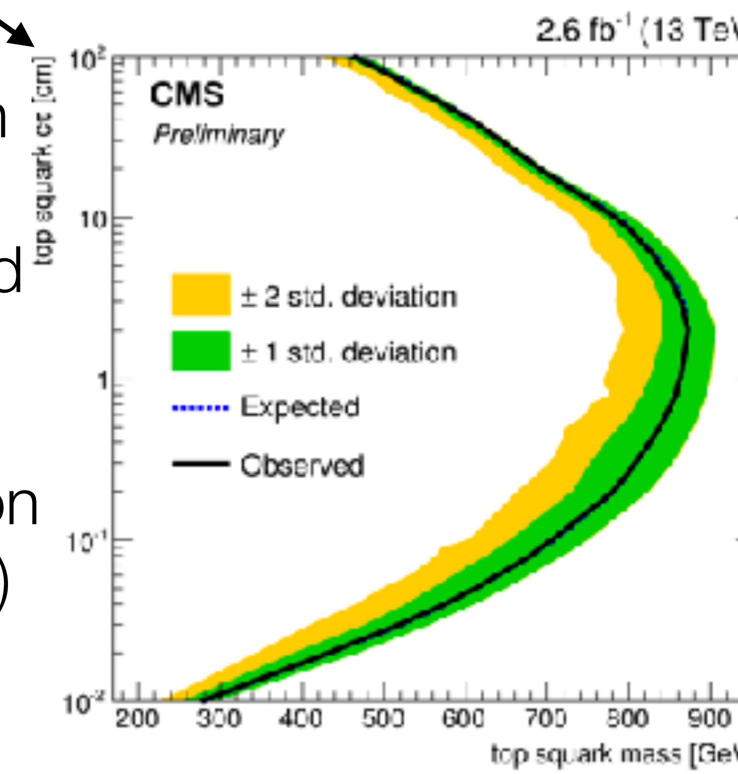
- Broad variety of final states:
  - → Long-lived charged particles
  - → Displaced leptons in the e-μ channel
    - →e/μ with transverse impact parameter ϵ[200μm-10cm]
- I_h discriminator based on dE/dx, from measurement of ionization deposited + time of flight information







Result in term on displaced SUSY (pair production of stops)

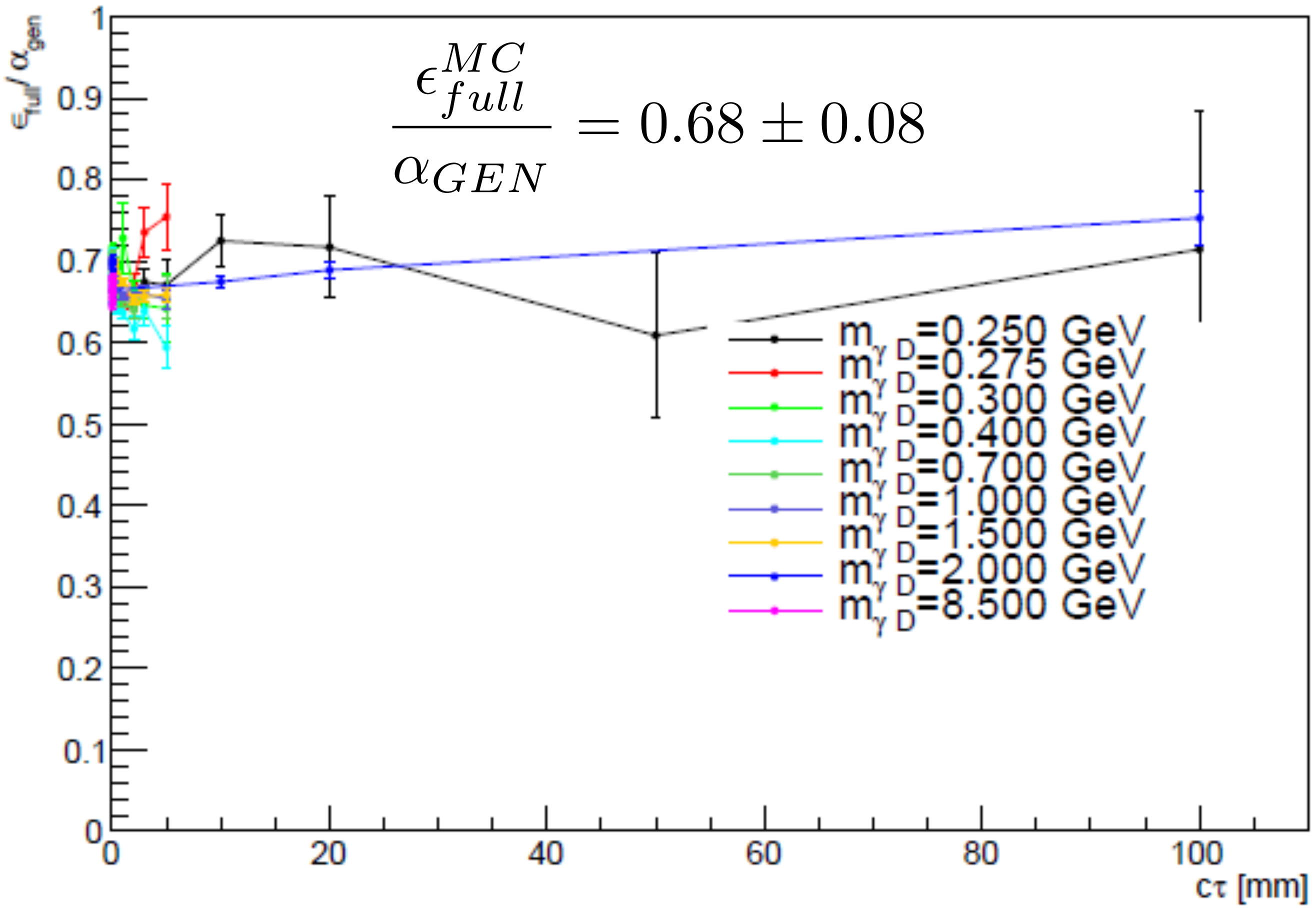


http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO-16-022/
http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO-15-010/

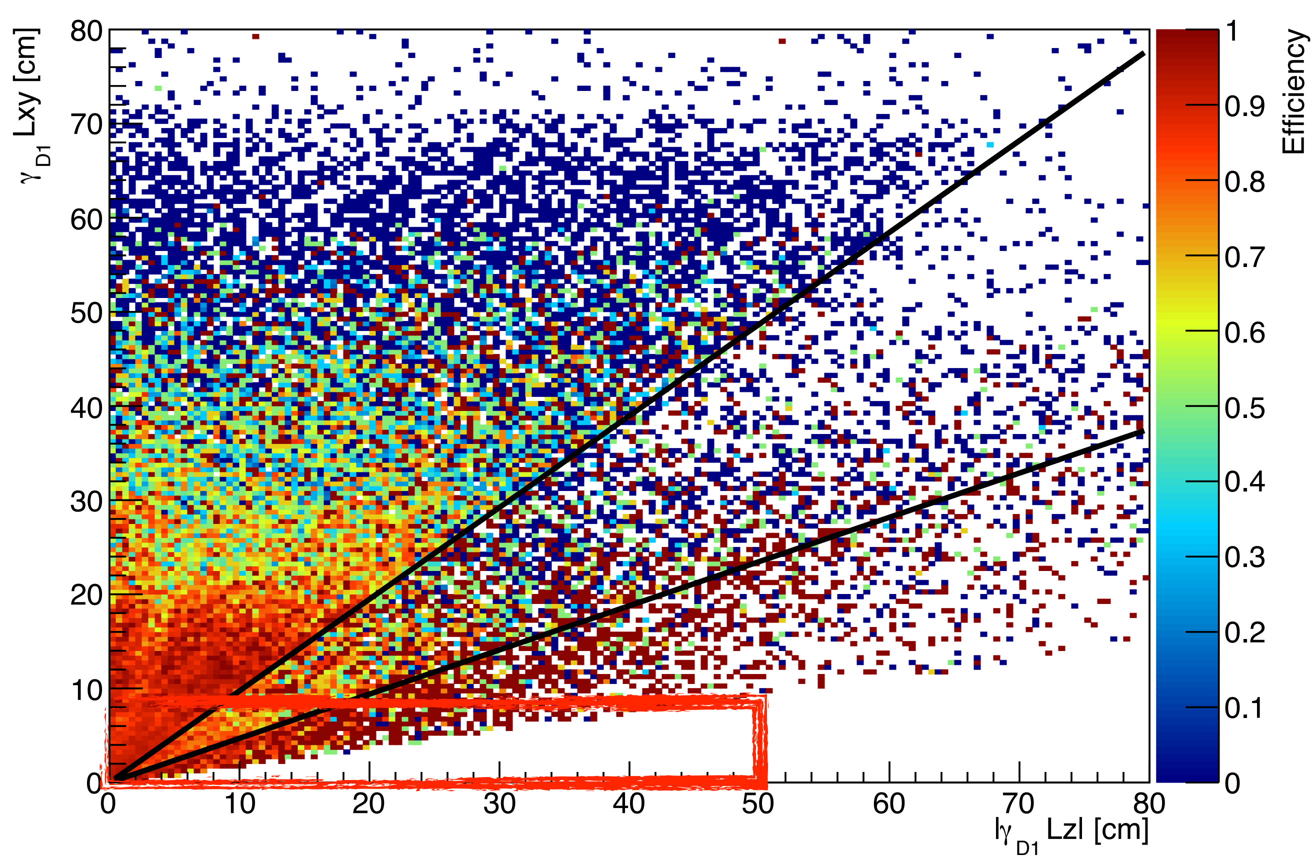
Analysis strategy

- Mean value for ϵ/α computed by considering all simulated points weighted by the statistic uncertainty

- Uncertainty is computed by looking at the larger deviation from the mean



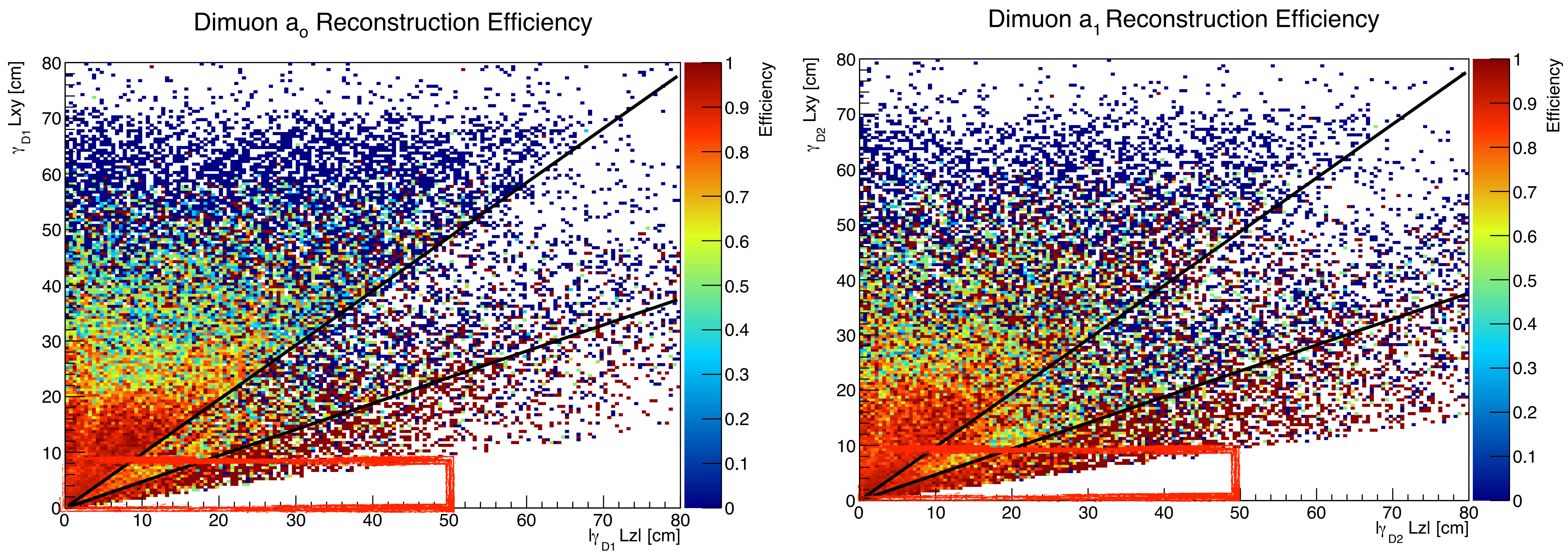
$$Eff = \frac{N_{GEN\mu\mu} - 2 \cdot RECO_{\mu}Match}{N_{GEN\mu\mu}}$$



Analysis strategy

- Efficiency map (as a function of Lxy and L_Z)
  - → Fiducial volume ensures high reconstruction efficiency
  - → Black line: beginning of overlap region (|η|<0.9) until beginning of ME1/1 (|η|<1.5)
  - → Plot shows $m_{\gamma D}$=0.25 GeV (all lifetimes together)

$$Eff = \frac{N_{GEN\mu\mu} - 2 \cdot RECO_{\mu}Match}{N_{GEN\mu\mu}}$$



- a_0 is the dark photon with the high p_T muon (if both have one the label is random)