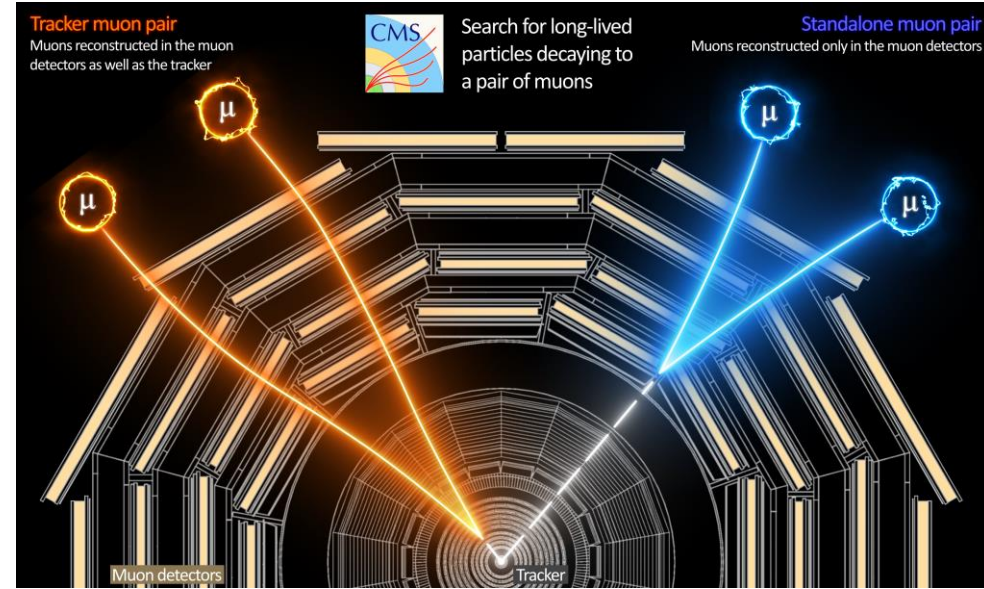
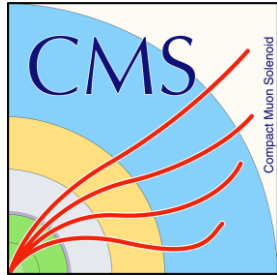




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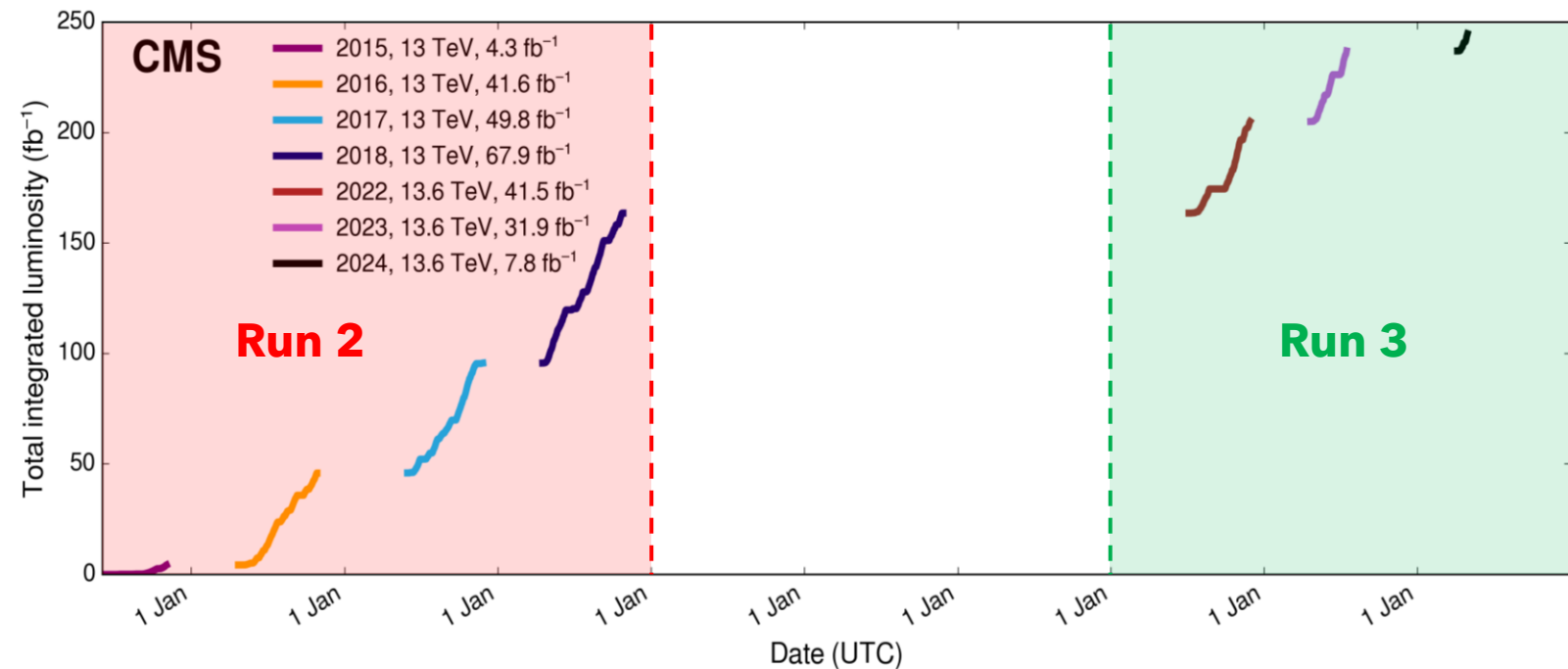
Search for long-lived particles at CMS

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Introduction

- After the **Higgs** discovery we have no clear guiding principle for **BSM** searches.
- As experimentalist, no preferred BSM theory:
 - We have an unprecedented amount of data from the LHC.
 - Exploit all details of this data looking for anything that looks different than SM.
 - Many possibilities, in this presentation we will cover the search for **long-lived particles**.
- We are currently in the middle of the **Run 3** data taking.
 - Highest CM energy ever reached **13.6 TeV**.
- We have used all the knowledge acquired during Run 2 to improve the current Run 3 analysis.

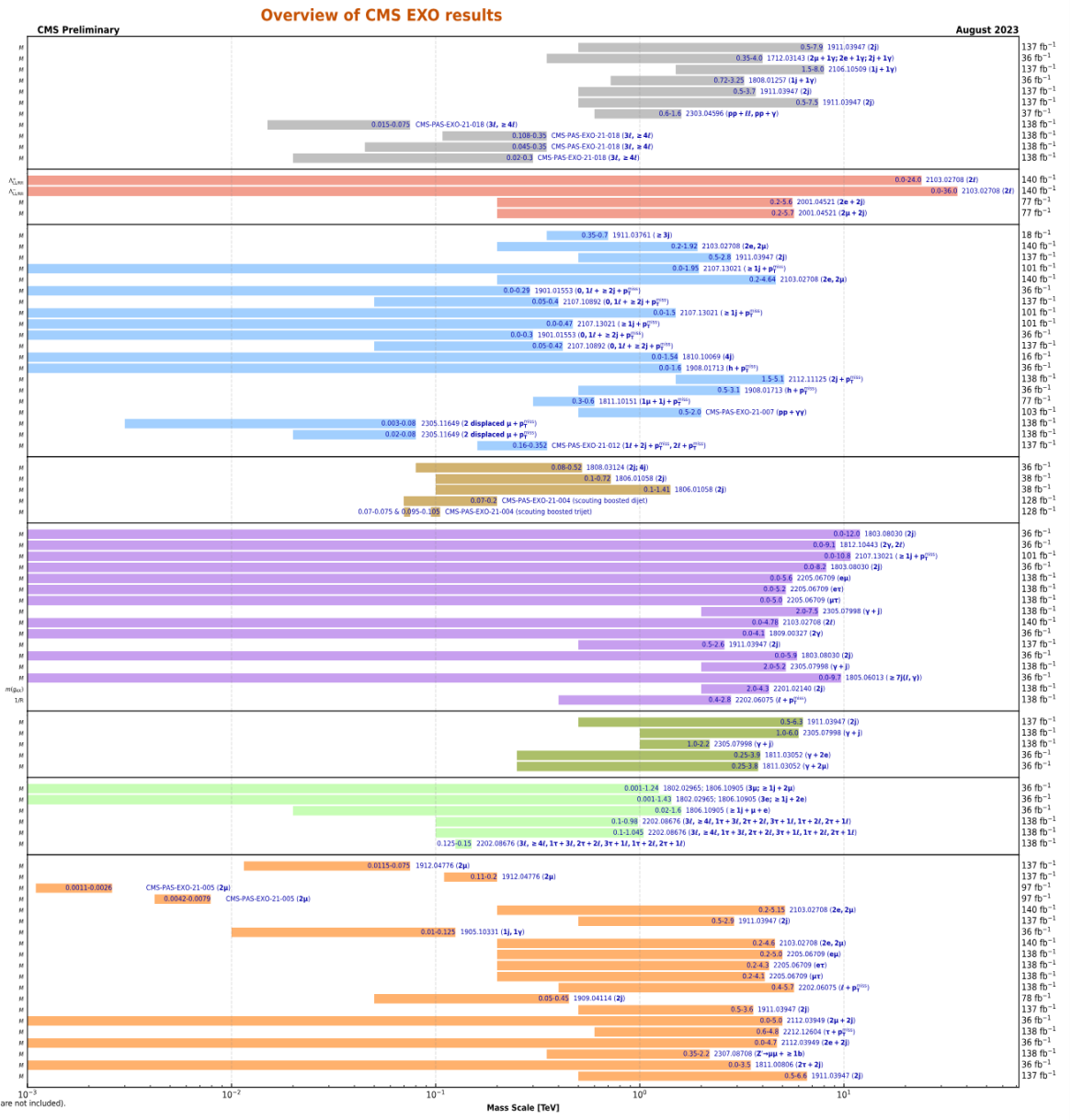


Introduction

Current searches performed in CMS (each line is a paper):

- Theory serves as a guidance to not leave any corner of the phase space unexplored.
- We unfortunately did not detect BSM physics...
 - but not for lack of trying.
- However, many fundamental questions are still open:
 - Nature of dark matter.
 - How neutrinos acquire mass.
 - Matter-antimatter asymmetry.
- Strong motivation** to keep searching at the LHC.

Other	Spring resonance Zγ resonance Wγ resonance Higgs γ resonance Color Octet Scalar, $k_1^2 = 1/2$ Scalar Dipole $pp \rightarrow Z\gamma + X$ $f\bar{f} + \phi$, pseudoscalar (scalar), $g_{\phi qq}^2 \times BR(\phi \rightarrow ee) \geq 0.01(0.003)$ $f\bar{f} + \phi$, pseudoscalar (scalar), $g_{\phi qq}^2 \times BR(\phi \rightarrow ee) \geq 0.03(0.04)$ $f\bar{f} + \phi$, pseudoscalar, $g_{\phi qq}^2 \times BR(\phi \rightarrow \tau\tau) \geq 0.2$ $f\bar{f} + \phi$, scalar, $g_{\phi qq}^2 \times BR(\phi \rightarrow \tau\tau) \geq 0.2$
Contact Interactions	quark compositeness (ff), $\Lambda_{UV} = 1$ quark compositeness (ff), $\Lambda_{UV} = -1$ Excited Lepton Contact Interaction Excited Lepton Contact Interaction
Dark Matter	vector mediator (v), $g_v = 0.25, g_{\mu\nu} = 1, m_\nu = 1$ GeV vector mediator (ff), $g_v = 0.1, g_{\mu\nu} = 1, g_1 = 0.01, m_\nu > 1$ TeV (axial-)vector mediator (qq), $g_v = 0.25, g_{\mu\nu} = 1, m_\nu = 1$ GeV (axial-)vector mediator (ff), $g_v = 0.1, g_{\mu\nu} = 1, g_1 = 0.1, m_\nu > m_{had} Z$ scalar mediator (+ff), $g_s = 1, g_{\mu\nu} = 1, m_\nu = 1$ GeV scalar mediator (+ff), $g_s = 1, g_{\mu\nu} = 1, m_\nu = 1$ GeV scalar mediator (hermion portal), $\lambda_s = 1, m_\nu = 1$ GeV pseudoscalar mediator (+ff), $g_p = 1, g_{\mu\nu} = 1, m_\nu = 1$ GeV pseudoscalar mediator (+ff), $g_p = 1, g_{\mu\nu} = 1, m_\nu = 1$ GeV pseudoscalar mediator (+ff), $g_p = 1, g_{\mu\nu} = 1, m_\nu = 1$ GeV complex sc. med. (dark QCD), $m_{\mu\nu} = 5$ GeV, $c_{\mu\nu} = 25$ mm Baryonic Z, $g_z = 0.25, g_{\mu\nu} = 1, m_z = 1$ GeV Z' mediator (dark QCD), $m_{\mu\nu} = 20$ GeV, $f_{\mu\nu} = 0.3, g_{\mu\nu} = g_{\mu\nu}^{SM}$ Z' - ZHDM, $g_z = 0.8, g_{\mu\nu} = 1, \tan\beta = 1, m_z = 300$ GeV Leptoquark mediator, $\beta = 1, g = 0.1, \delta_{\mu\nu} = 0.1, 800 < M_{LQ} < 1500$ GeV axion-like particle, $f' = 1.2$ TeV ⁻¹ inelastic dark matter model, $y = 10^{-1}, \alpha_D = 0.1$ inelastic dark matter model, $y = 10^{-1}, \alpha_D = 0.1$ dark Higgs, $g_h = 0.25, g_{\mu\nu} = 1, \theta = 0.01, m_h = 200$ GeV, $m_Z = 700$ GeV
RPV	RPV stop to 4 quarks RPV squark to 4 quarks RPV gluino to 4 quarks RPV stop-squaring boosted RPV mass degenerated higgsinos to trijet boosted squaring
Extra Dimensions	ADD (g) HLZ, $n_{DD} = 3$ ADD (γγ) HLZ, $n_{DD} = 3$ ADD $G_{\mu\nu}$ emission, $n_{DD} = 2$ ADD QBH (g), $n_{DD} = 6$ ADD QBH (ff), $n_{DD} = 4$ ADD QBH (ff), $n_{DD} = 4$ ADD QBH (ff), $n_{DD} = 4$ ADD QBH (ff), $n_{DD} = 4$ ADD QBH (ff), $n_{DD} = 6$ RS $G_{\mu\nu}(ff)$, $k/M_{\text{pl}} = 0.1$ RS $G_{\mu\nu}(ff)$, $k/M_{\text{pl}} = 0.1$ RS $G_{\mu\nu}(ff)$, $k/M_{\text{pl}} = 0.1$ RS QBH (g), $n_{DD} = 1$ RS QBH (ff), $n_{DD} = 1$ non-rotating BH, $M_{\text{BH}} = 4$ TeV, $n_{DD} = 6$ 3-brane WED $g_{\mu\nu}(g + g + g + g)$, $g_{\mu\nu} = 6, g_{\mu\nu} = 3, c = 0.5, m(\phi)/m(g_{\mu\nu}) = 0.1$ split-UED, $\mu \geq 2$ TeV
Excited Fermions	excited light quark (q), $A = m_q^*$ excited light quark (q), $f_1 = f = F = 1, A = m_q^*$ excited b quark, $f_1 = f = F = 1, A = m_b^*$ excited electron, $f_1 = f = F = 1, A = m_e^*$ excited muon, $f_1 = f = F = 1, A = m_\mu^*$
Heavy Fermions	vMSM, $ V_{cb} ^2 = 1.0, V_{ub} ^2 = 1.0$ vMSM, $ V_{cb} ^2 = 1.0, V_{ub} ^2 = 1.0$ vMSM, $ V_{cb} ^2 = V_{ub} ^2 = V_{td} ^2 = V_{ud} ^2 = 1.0$ Type-II seesaw heavy fermions, Flavor-democratic Vector like taus, Doublet Vector like taus, Singlet
Heavy Gauge Bosons	Z _μ narrow resonance, $\epsilon^2 = 8 \times 10^{-3}$ (90% C.L.) Z _μ narrow resonance, $\epsilon^2 = 4 \times 10^{-3}$ (90% C.L.) Z _μ narrow resonance, $\epsilon^2 = 7 \times 10^{-3}$ (90% C.L.) Z _μ narrow resonance, $\epsilon^2 = 3 \times 10^{-3}$ (90% C.L.) SSM Z'(q) SSM Z'(q) Z'(q) Superspinning Z' _μ LFV Z', BR(eμ) = 10% LFV Z', BR(eτ) = 10% LFV Z', BR(μτ) = 10% SSM W'(q) Leptoquark Z' SSM W'(q) LRSM W _{μ}(q), M_W = 0.5M_W SSM W'(q) LRSM W_{μ}(q), M_W = 0.5M_W LRSM W_{μ}(q), M_W = 0.5M_W β₁ - β₂ Z', g_Z × [1 TeV/m]₁ = 0.08, β₂ = 0 LRSM W_{μ}(q), M_W = 0.5M_W Axivision, Coloron, color = 1}}}}



Physics Beyond the Standard Model

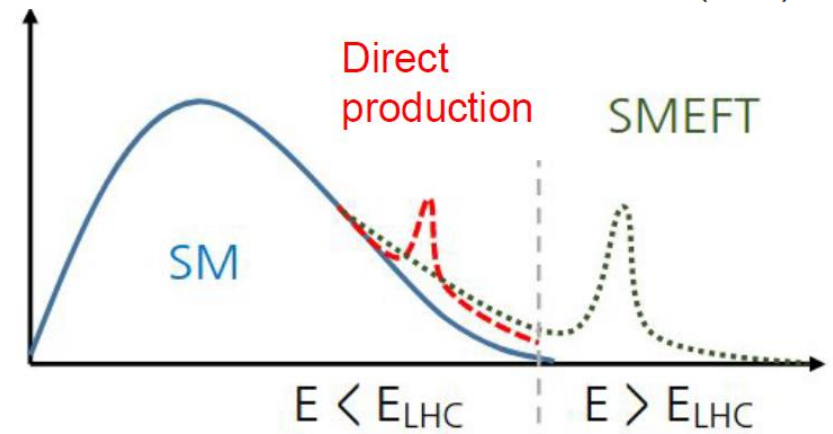
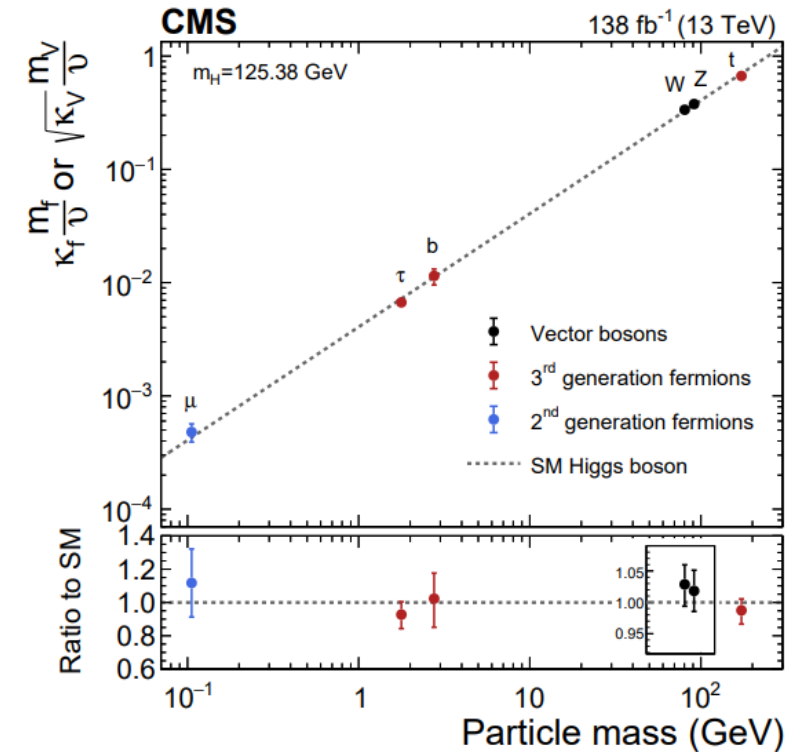
- Where are we searching for BSM physics?
- Improve the precision of SM tests (e.g. m_W , yukawa couplings).
- Target unobserved SM processes (diHiggs production).
- Search for deviations at the tails of distributions: effective field theories (EFT).

Wilson coefficient

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{C_i}{\Lambda^2} O_i^{(6)}$$

UV scale EFT operator

- **Probe new phase space (e.g. long lived particles).**



Long lived particles

- **What are displaced muons?**

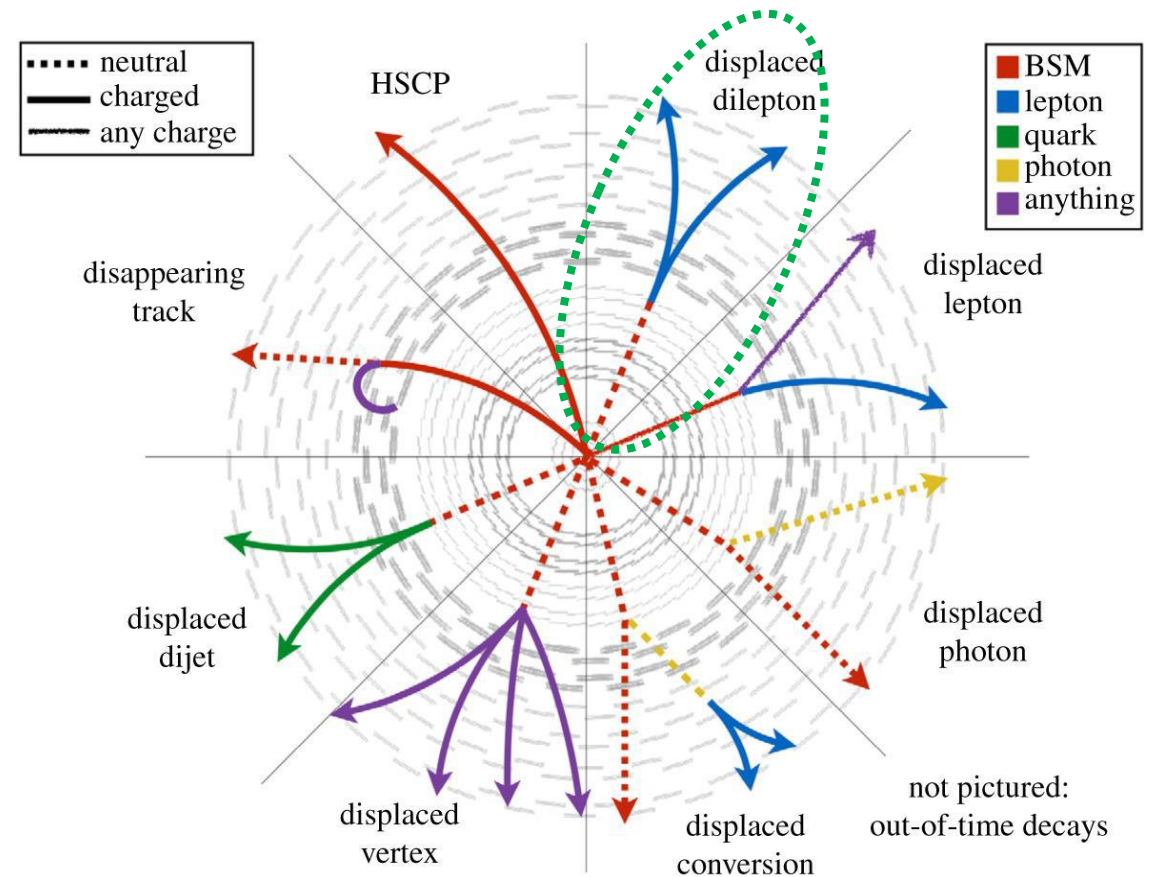
- Muons that are not produced in the primary vertex (PV).
- They can be produced through the decay of a **long-lived particle** (LLP).
- Therefore, they do not have to point to the PV.

- **Why are they interesting:**

- Signature of new physics.
- Many exotic models can produce displaced muons:
 - RPV, Exotic Higgs models, dark photon, ...

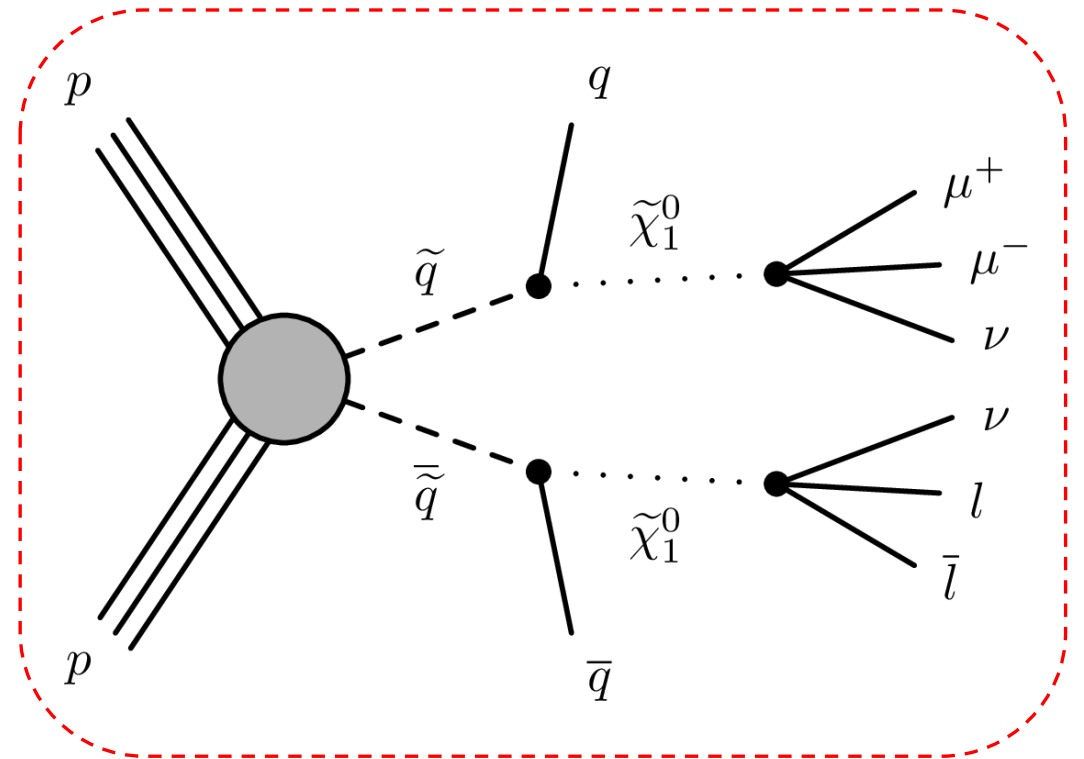
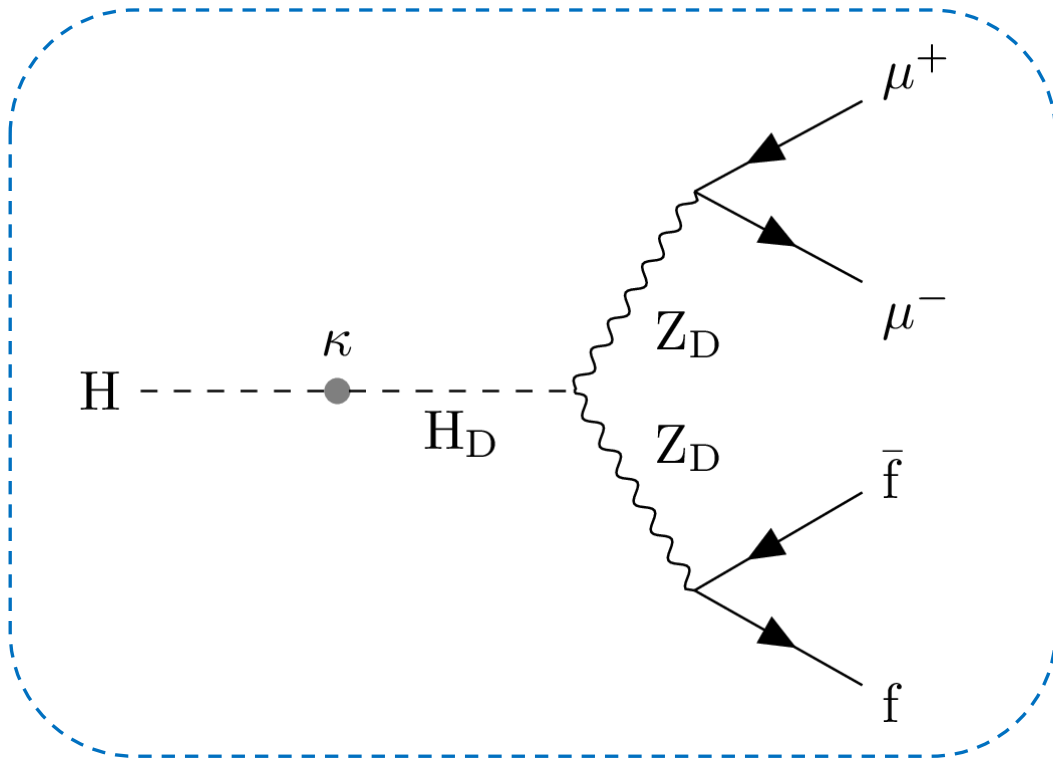
- **Challenges:**

- They need a special reconstruction.
- Highly displaced muons can be misidentified with low p_T non-displaced muons.



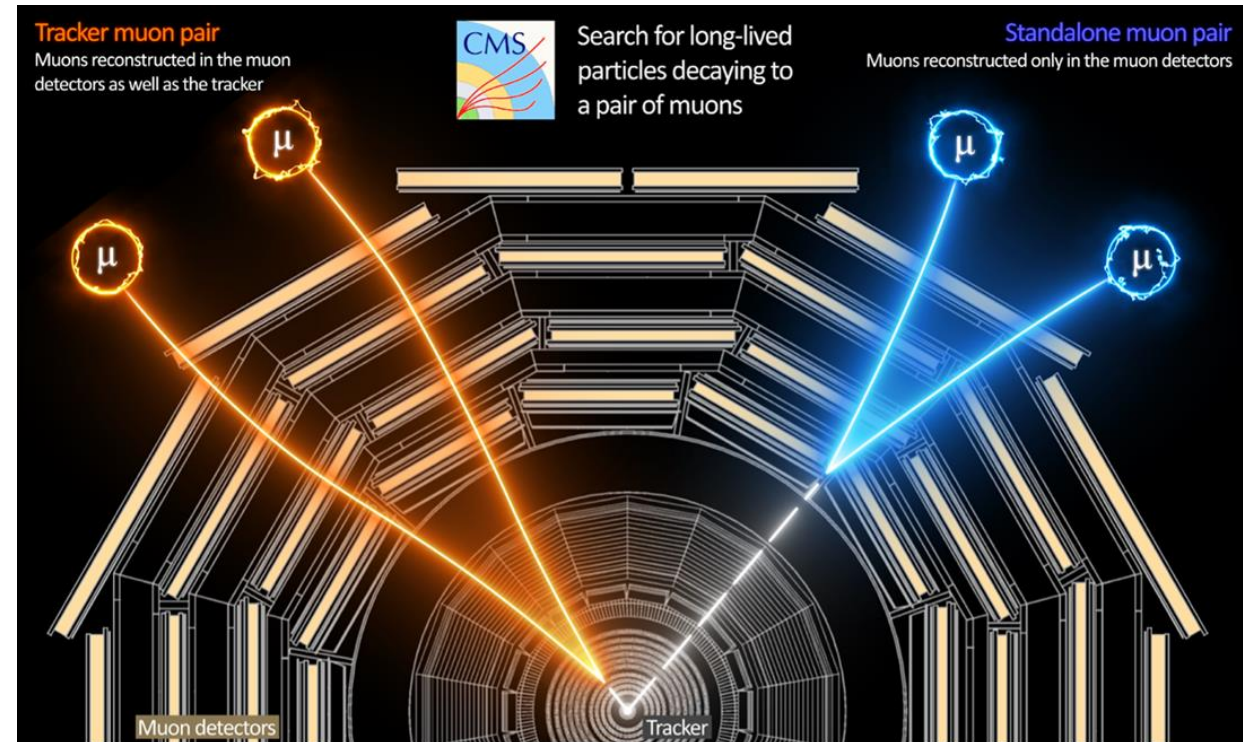
Theory models featuring LLPs

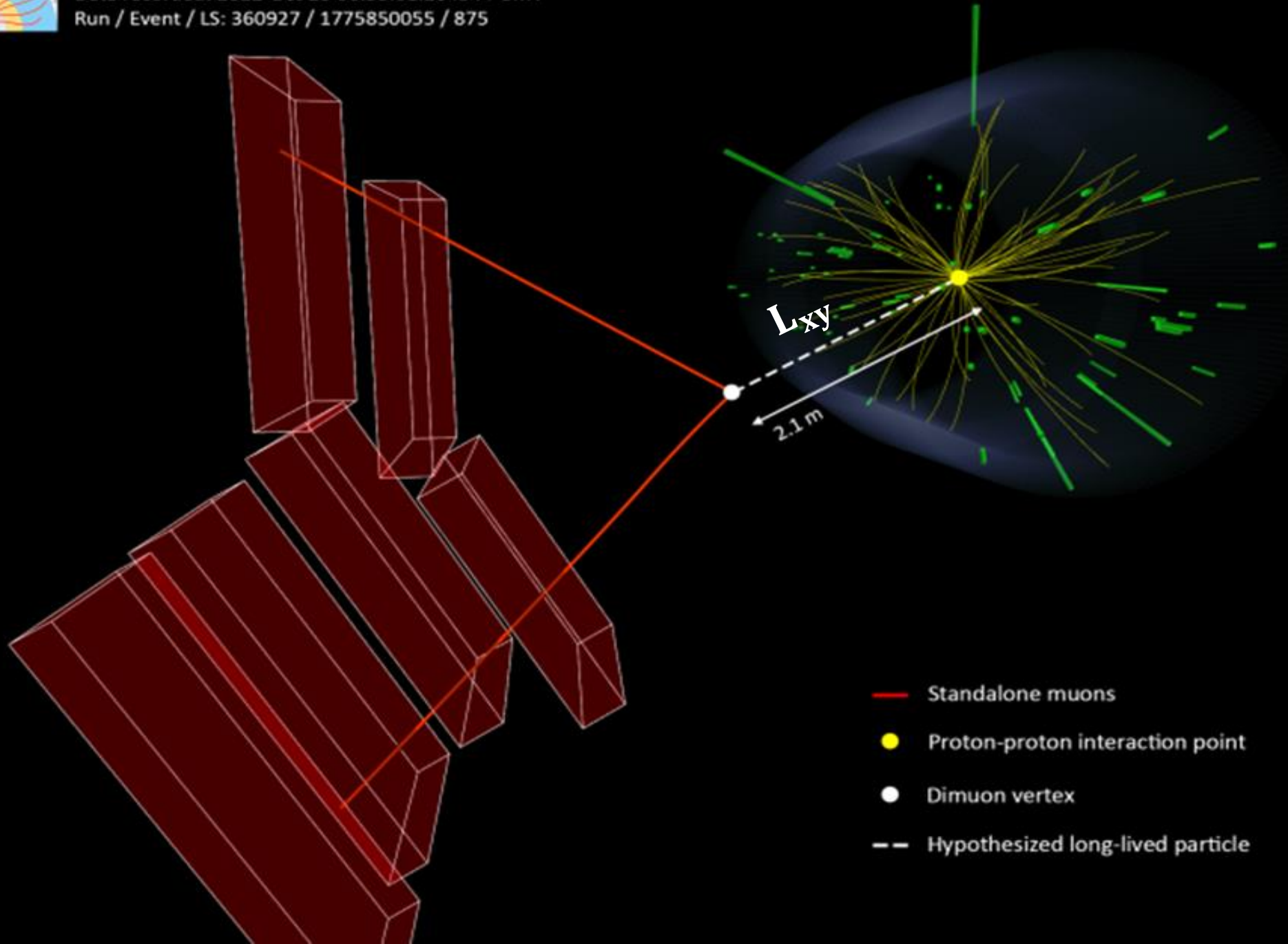
- **Dark photon** production in the decay of Higgs bosons.
 - Dark photons would travel a certain distance in the detector before decaying into 'displaced muons'.
- **Simplified SUSY model**, in which long-lived neutralinos decay to a pair of muons and a neutrino as a result of R-parity violation (RPV).



Displaced dimuon search at 13.6 TeV

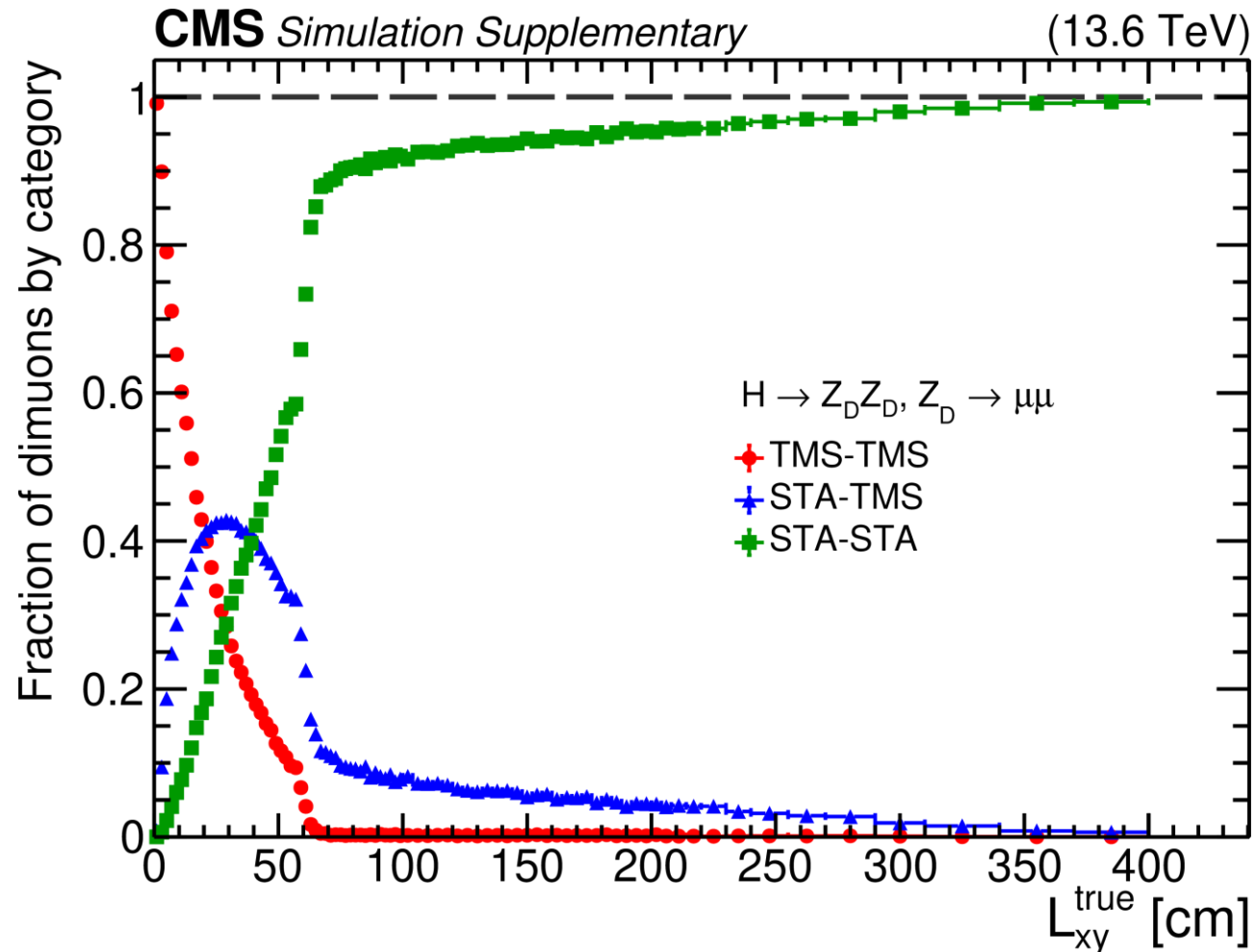
- Generic, inclusive search for long-lived particles decaying into pairs of oppositely-charged muons (**displaced dimuons**) within the tracker and beyond.
- Analyzed **data collected in 2022 at 13.6 TeV** (36.6 fb^{-1}).
- **Two types of muons considered:**
 - **DSA:** displaced standalone muons (muon system only).
 - **TMS:** global + tracker muons (muon system + tracker).
- **Vertex fit:**
 - Dimuon candidates are formed from pairs of muons passing the muon identification criteria.
 - Each pair of selected muon tracks is fit to a common vertex.



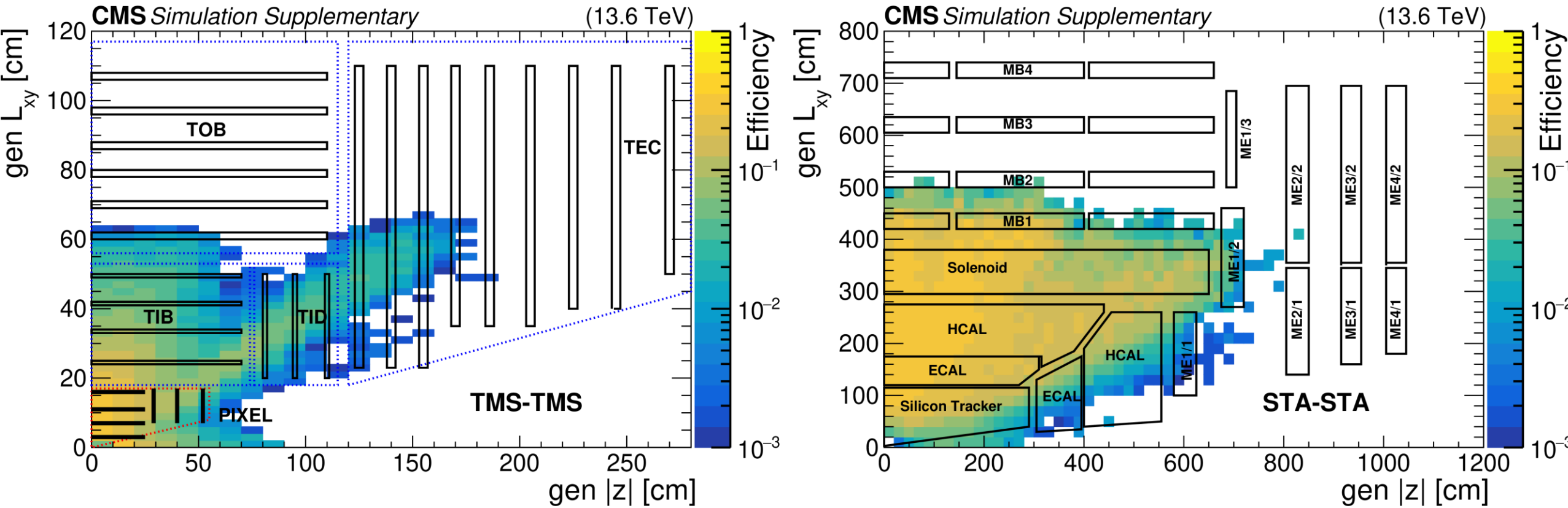


Displaced dimuon search at 13.6 TeV

- Search uses 3 dimuon categories, STA-STA, STA-TMS, TMS-TMS..



Displaced dimuon search at 13.6 TeV

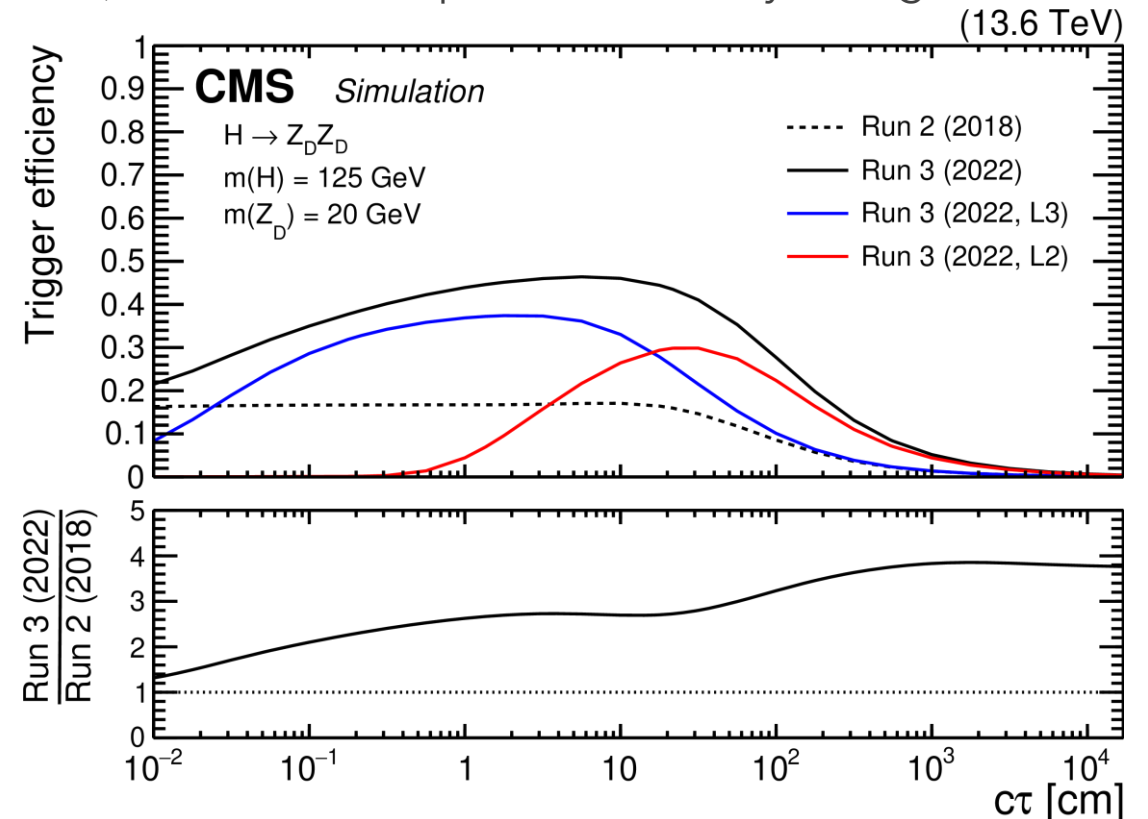


Displaced dimuon search at 13.6 TeV

- Not all collisions can be recorded. If an event is not recorded it is lost forever.
 - The **trigger** is the system that takes the decision to save an event.
 - Two systems conform the CMS trigger: **L1** (hardware based) and **HLT** (software based).
- For an LLP search it is crucial to develop good triggers to record the collisions.
- Run 2 search was limited by: high p_T thresholds (23 GeV) at HLT; and drop of L1 efficiency at large **displacement** due to beam spot constrained p_T .

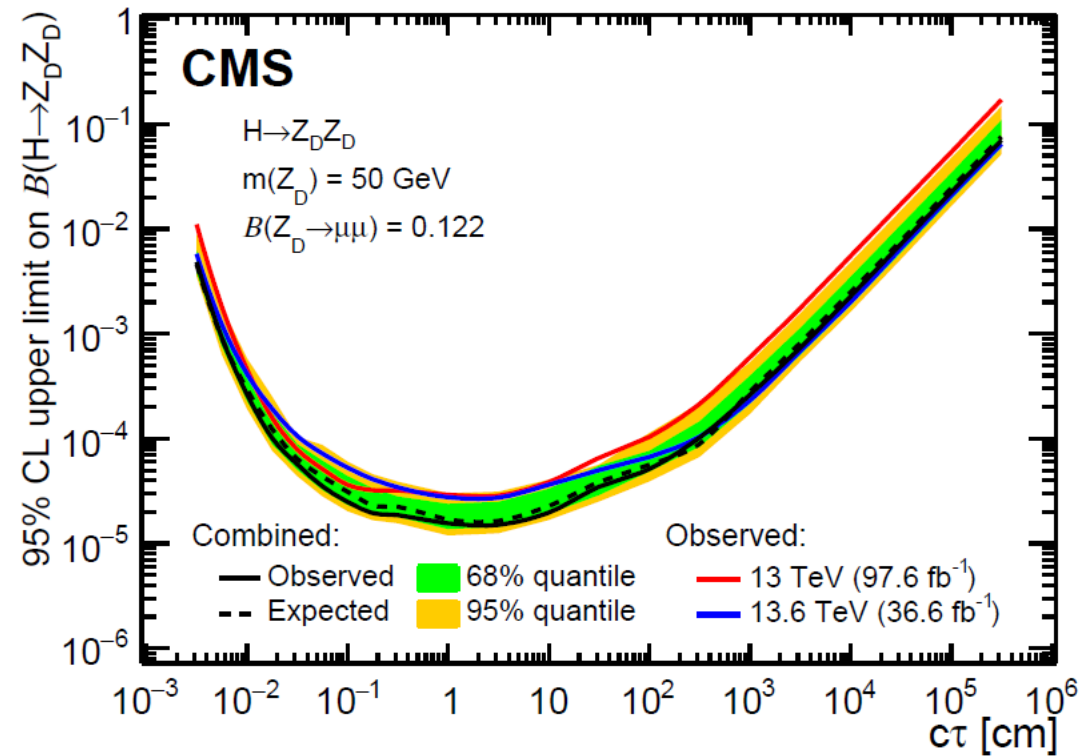
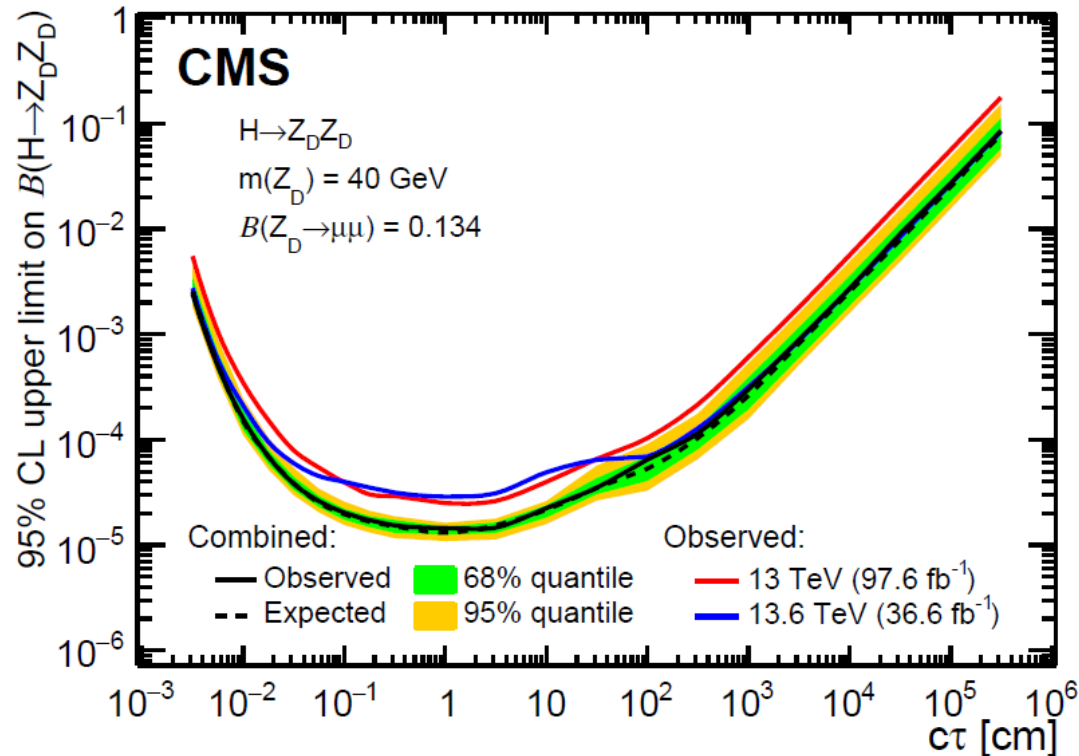
- **Improvements for Run 3:**

- **New L1 seeds** lowering p_T thresholds and including unconstrained p_T .
- **New HLT paths** lowering p_T thresholds for muons passing loose displacement cuts.
- Substantial **improvement** in efficiency, up to a **factor of 4**, at masses of a few tens of GeV and large $c\tau$.



Displaced dimuon search at 13.6 TeV

- Comparable or better sensitivity than Run 2 with only 38% of the data.
- Improvement coming from trigger developments for Run 3.



Summary

- BSM particles could have different lifetimes, charges, masses, and/or interactions compared to known SM particles.
- **We don't know if they exist, data will tell.**
 - The phase space is broad and still largely unexplored.
- Growing field in active R&D.
 - Plenty of lessons learned during Run 2.
 - New triggers for Run 3.

Thanks!