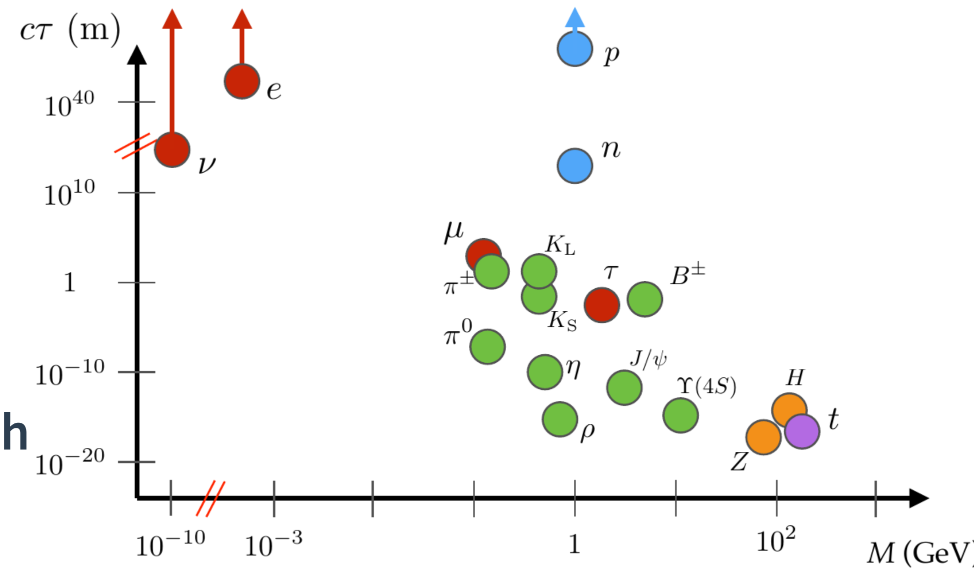
Search for new physics with long-lived and unconventional signatures (in CMS)

Soham Bhattacharya (DESY)
on behalf of the CMS Collaboration

34th Rencontres de Blois
2023

Long-lived particles

- **Mechanism of macroscopic lifetimes:**
  - Small coupling
  - Reduced phase space
    small mass difference with final state particle(s)
  - Heavy off-shell mediator
- **The Standard Model has several particles with macroscopic lifetimes**



[from Brian Shuve: source]

$$\Gamma \sim \frac{\epsilon^2}{(8\pi)^{a-1}} \frac{m^n}{M^{n-1}}$$

(e.g. neutrons)

(e.g. pions, muons, kaons)

[Knappen, Lowette, 2022 (2212.03883)]

The **C**ompact **M**uon **S**olenoid
(CMS)

"Ah, it's the one other than ATLAS?"

– from a conversation at Blois

Let me try to convince you that

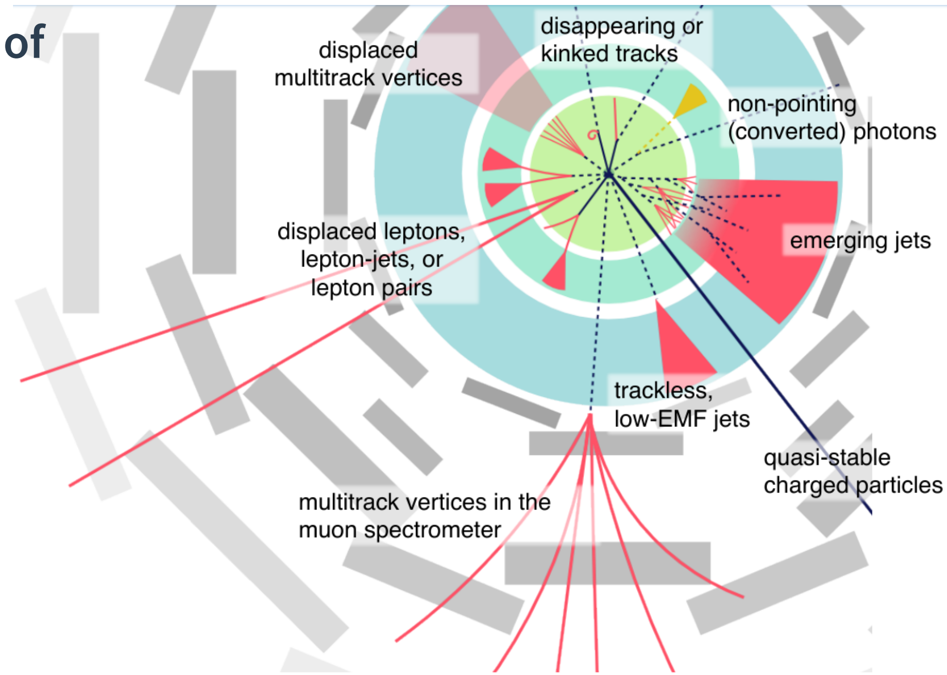
even ***CMS*** has a *very mature and diverse search program*

for long-lived and non-conventional signatures

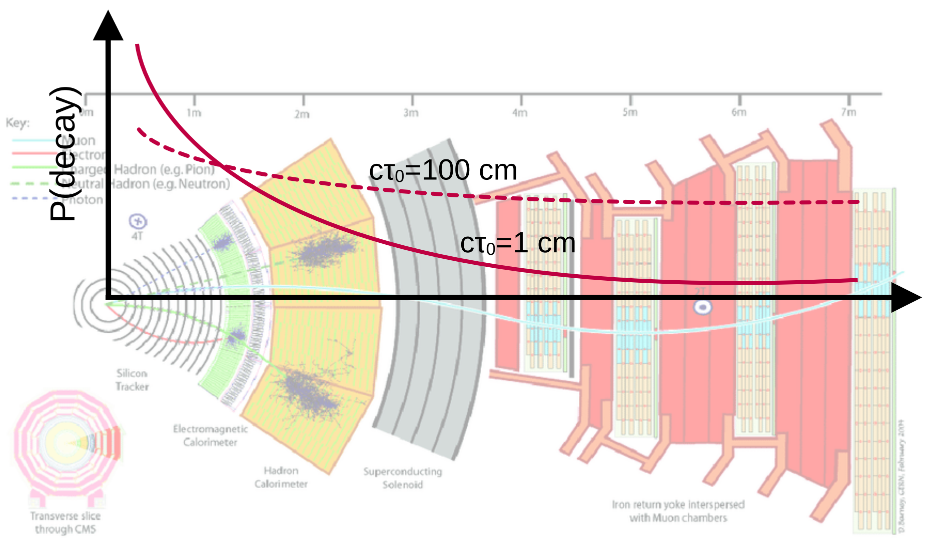
:)

Long-lived particle (LLP) signatures

- Long-lived BSM particles can produce a wide range of unconventional signatures
- Non-standard backgrounds
- Traditional techniques may be inefficient
- May need:
  - Dedicated triggers
  - Special reconstruction



[from Heather Russell: source]



- **Different sub-detectors relevant for different lifetimes**
- **Need a wide variety of searches to explore different scenarios**

Searches with unconventional signatures

Unconventional: not only long-lived!

Number	Title	Status	Date
PAS-EXO-21-013 **NEW!**	**Search for long-lived heavy neutral leptons with lepton flavour conserving or violating decays to a jet and an electron, muon, or tau lepton**	**PAS (Preliminary)**	**18 March 2023**
EXO-19-009 **NEW!**	**A search for new physics in central exclusive production using the missing mass technique with the CMS detector and the CMS-TOTEM precision proton spectrometer**	**Submitted to EPJC**	**8 March 2023**
PAS-EXO-20-010 **NEW!**	**Search for inelastic dark matter in events with two displaced muons and missing transverse momentum in proton-proton collisions at √s=13 TeV**	**PAS (Preliminary)**	**3 March 2023**
EXO-21-014	**Search for long-lived particles using out-of-time trackless jets in proton-proton collisions at √s=13 TeV**	**Accepted by JHEP**	**13 December 2022**
PAS-EXO-19-006	**Search for fractionally charged particles in pp collisions at √s=13 TeV**	**PAS (Preliminary)**	**29 November 2022**
EXO-21-006	**Search for long-lived particles decaying to a pair of muons in proton-proton collisions at √s=13 TeV**	**Accepted by JHEP**	**17 May 2022**
EXO-20-014	**Search for long-lived particles decaying into muon pairs in proton-proton collisions at √s= 13 TeV collected with a dedicated high-rate data stream**	**JHEP 04 (2022) 062 27**	**27 December 2021**
EXO-20-003	Search for long-lived particles produced in association with a Z boson in proton-proton collisions at √s=13 TeV	JHEP 03 (2022) 160	25 October 2021
EXO-18-003	Search for long-lived particles decaying to leptons with large impact parameter in proton-proton collisions at √s=13 TeV	EPJC 82 (2022) 153	10 October 2021
EXO-20-015	Search for long-lived particles decaying in the CMS endcap muon detectors in proton-proton collisions at √s=13 TeV	PRL 127 (2021) 261804	10 July 2021
EXO-19-013	**Search for long-lived particles decaying to jets with displaced vertices in proton-proton collisions at √s=13 TeV**	**PRD 104 (2021) 052011**	**28 April 2021**

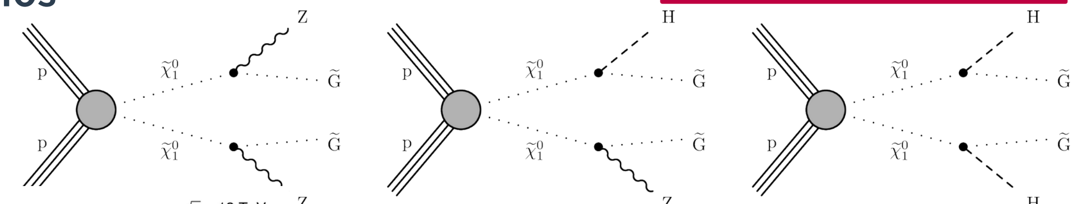
... and many more: http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/index.html

- Several very interesting results
- Will only show results from a (biased) selection (in bold)

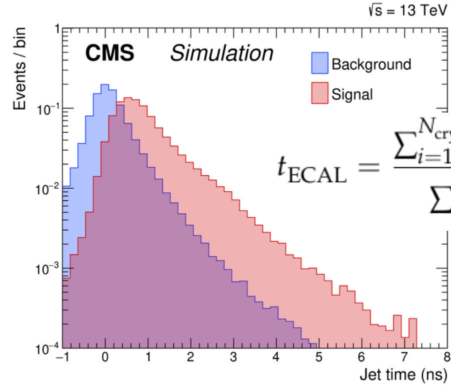
Trackless and out-of-time jets

EXO-21-014 (2212.06695)

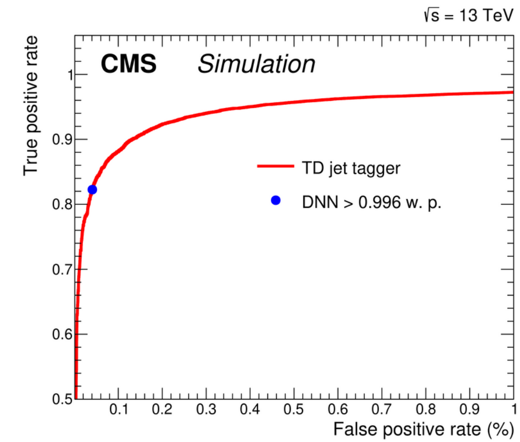
- **Nearly mass-degenerate charginos and neutralinos**
- **Production:** $\tilde{\chi}^0_1\tilde{\chi}^0_2,\ \tilde{\chi}^0_1\tilde{\chi}^\pm_1,\ \tilde{\chi}^0_2\tilde{\chi}^\pm_1,\ \tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$
- **They decay to** $\tilde{\chi}^0_1$**: effective** $\tilde{\chi}^0_1$**-pair production**

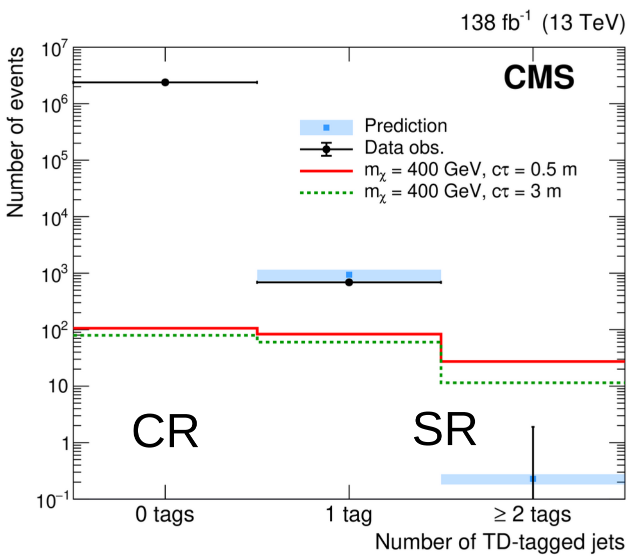


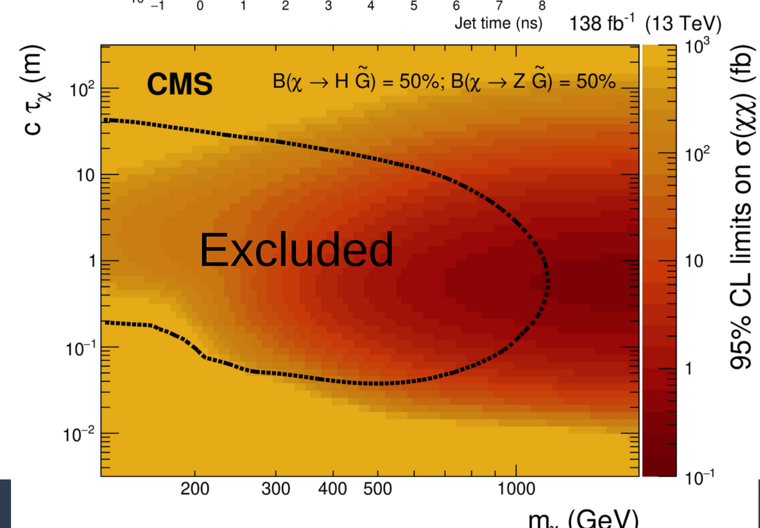
- **Signal jets arrive at ECAL 1-10 ns later.**
  Effective jet time resolution 400-600 ps
- **Dedicated delayed jet DNN tagger**
  - Bin in terms of # tagged jets



$$t_{\mathrm{ECAL}} = \frac{\sum_{i=1}^{N_{\mathrm{crystal}}} t^i_{\mathrm{ECAL}} E^i_{\mathrm{ECAL}}}{\sum_{i=1}^{N_{\mathrm{crystal}}} E^i_{\mathrm{ECAL}}}$$





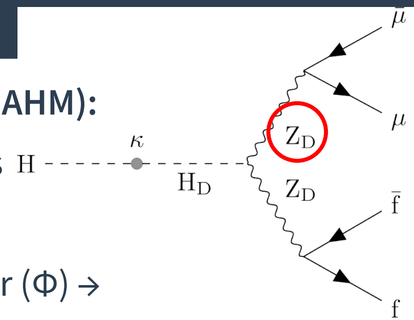


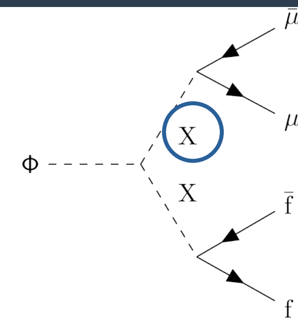
- No excess
- For 400 GeV $\tilde{\chi}^0_1$: excluded cτ up to ~20 m
- For cτ=0.5m: excluded $\tilde{\chi}^0_1$ up to 1.18 TeV

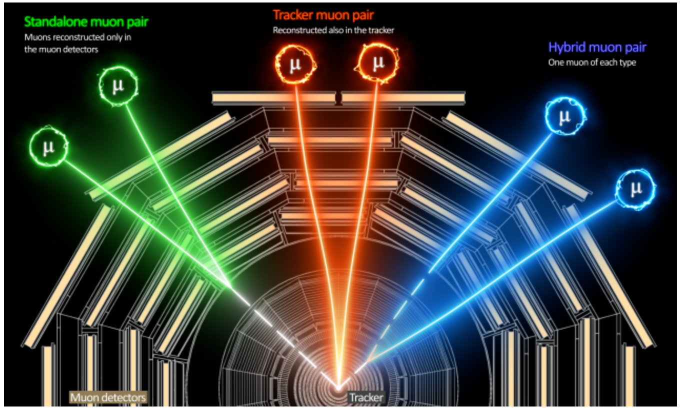
Displaced di-muon

EXO-21-006 (2205.08582)

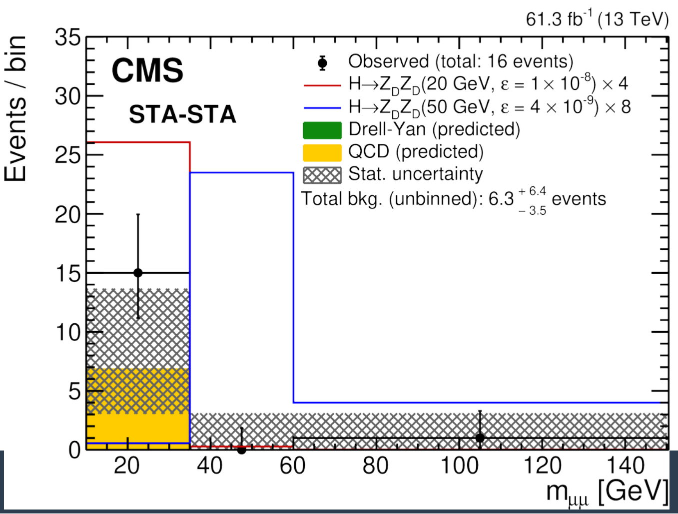
- **Hidden Abelian Higgs Model (HAHM):**
  - Dark photon (Z_D) → muons
- **Simplified model:**
  - Exotic heavy neutral scalar (Φ) → LL scalar (X) → muons
- **Dedicated di-muon triggers**
  - require 2 muons to be reconstructed in the muon system, without using tracker
- **Search categories defined based on the subdetector used to reconstruct the muon**
- **Bin in terms of di-muon mass (no excess)**

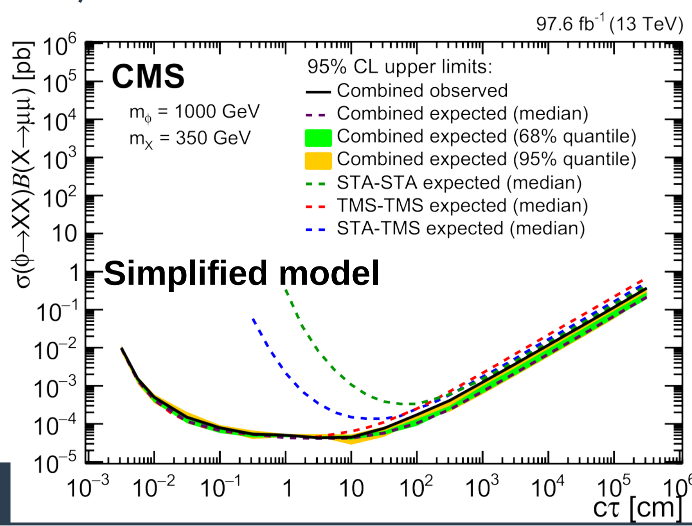


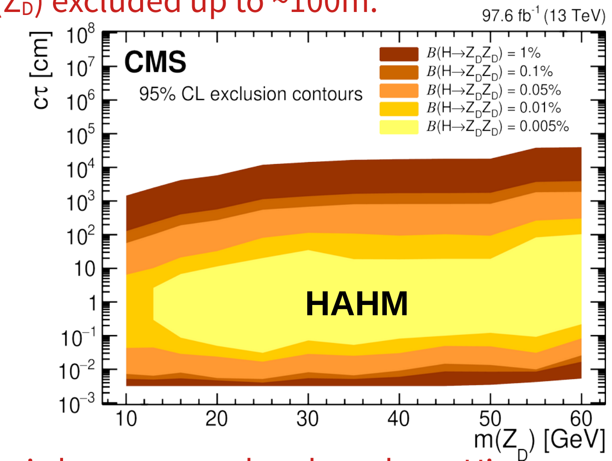




For 20<m(Z_D)<60 GeV and B(H→ $Z_D Z_D$=1%): cτ(Z_D) excluded up to ~100m.



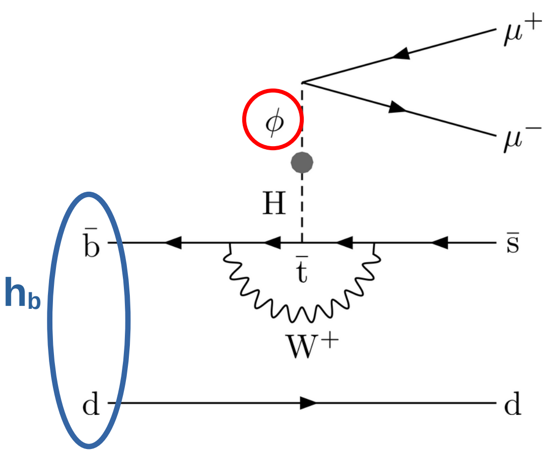


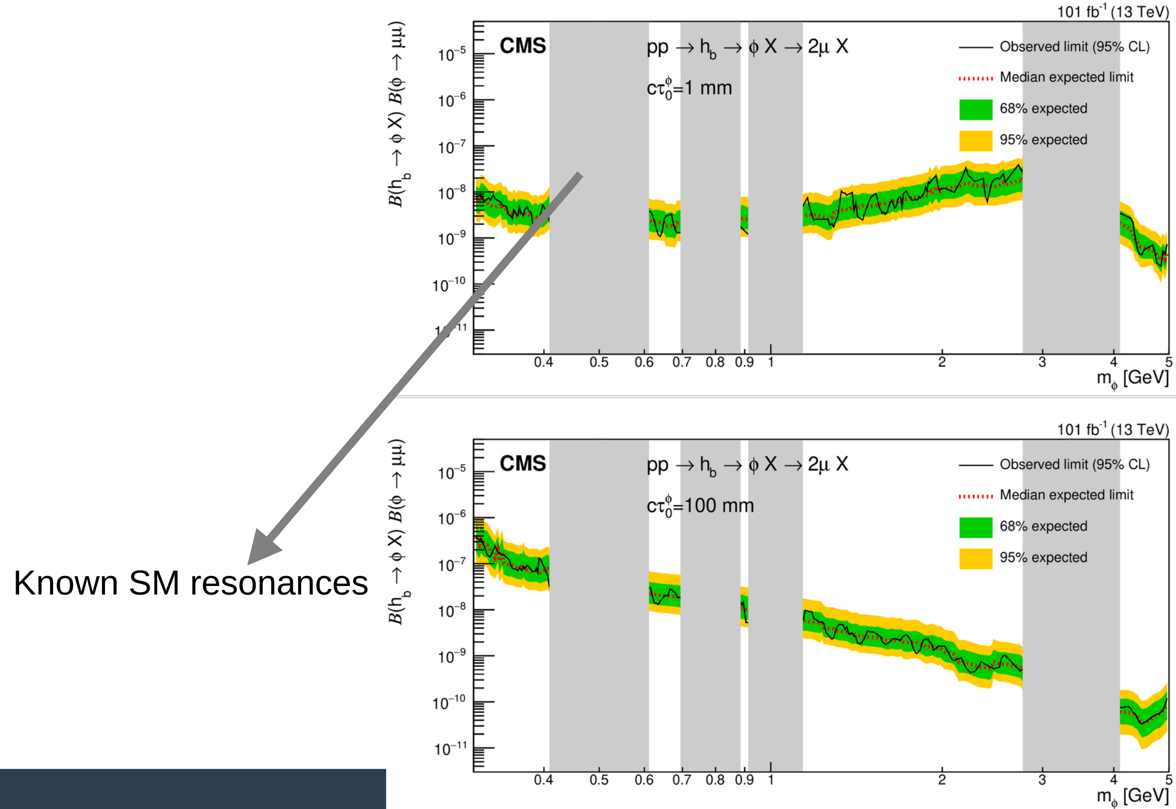


For exotic heavy neutral scalars above Higgs mass: best constrains on cτ(X)

Displaced di-muon

- **Lower m(Z_D) covered in previous search: EXO-20-014 (2112.13769)**
- **This also includes scalar resonance in b hadron (h_b) decay:**
  - Singlet scalar field ϕ mixes with H
  - Weak coupling of scalar ϕ with SM fermions – ϕ is long-lived

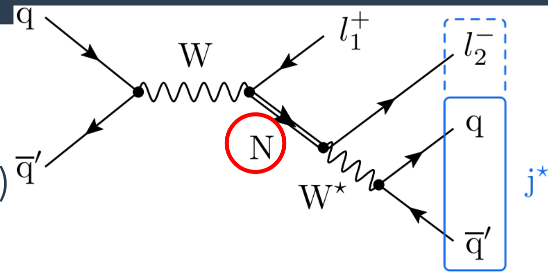




Heavy neutral leptons (HNLs)

- **See-saw mechanism – sterile HNLs**
  - HNL (N) is long-lived for small coupling strength with e, μ, τ (f_e, f_μ, f_τ)
  - Dirac HNL: (l_1, l_2) have OS
    Majorana HNL: (l_1, l_2) can have OS or SS
- **Dedicated displaced jet (neural network) tagger**
- **Events categorized based on:**
  - Lepton flavor
  - Lepton pair sign
  - Resolved or boosted (l_2, q and q' within a jet)
  - Bin in terms of d^{sig}_{xy} of l_2

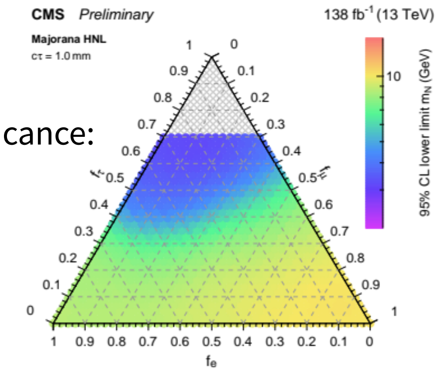
Transverse impact parameter significance:
$d^{sig}_{xy} = d_{xy}/\sigma(d_{xy})$

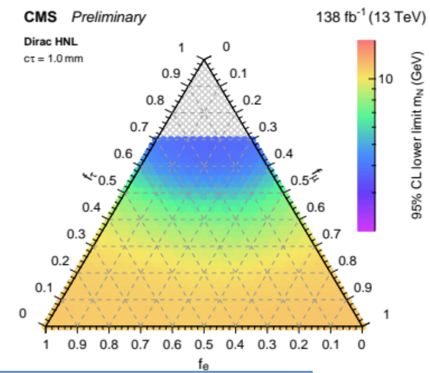


EXO-21-013

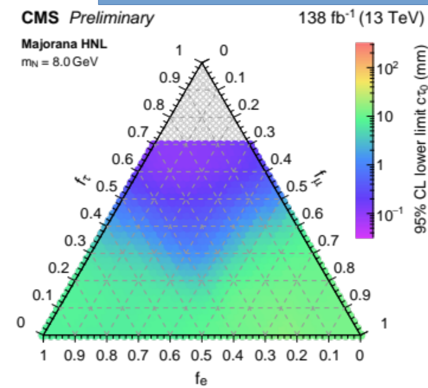
- No excess
- Strongest limits for pure muon coupling: $|\text{coupling}|^2 > 5(4)\times10^{-7}$ excluded for Dirac (Majorana) HNL

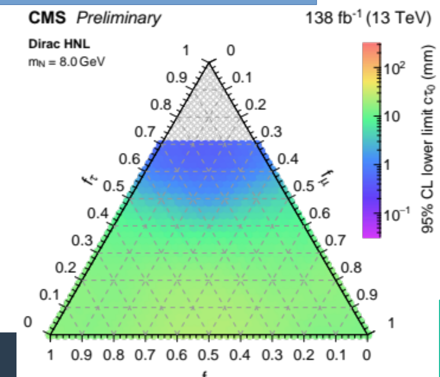
Lower limit on m(N) for cτ(N) = 1 mm

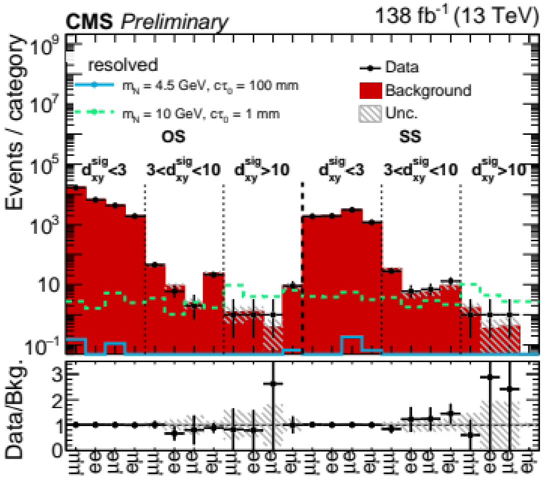


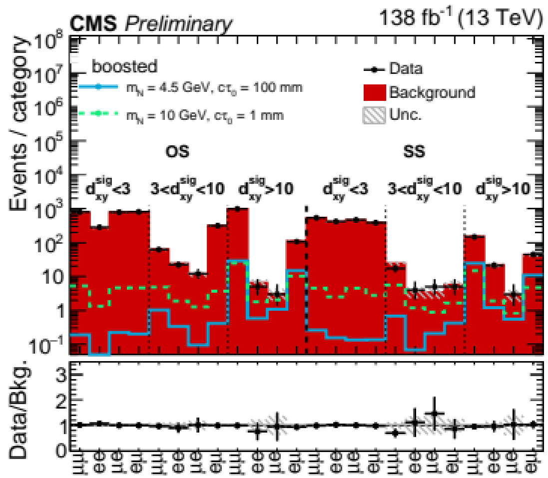


Lower limit on cτ(N) for m(N) = 8 GeV





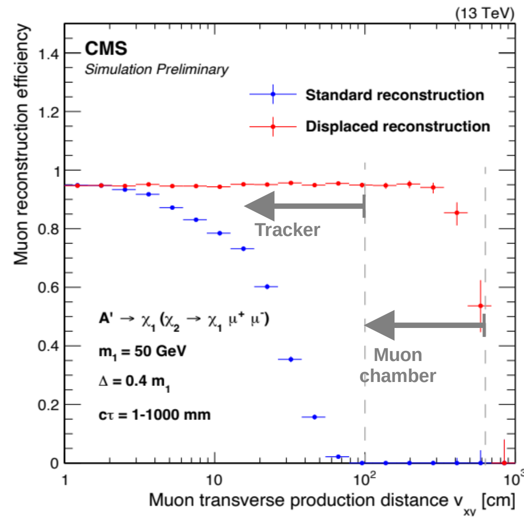


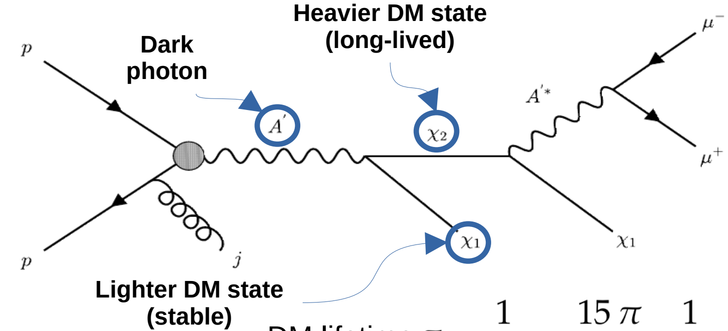


Inelastic dark matter

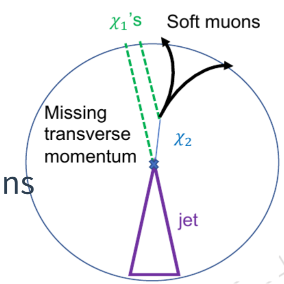
EXO-20-010

- **Two DM states X_1 and X_2**
  - Small mass gap ($\Delta = m_2 - m_1 = x m_1$; $x=0.1, 0.4$)
  - Inelastically coupled
  - X_2 is long-lived
- **Kinetically mixed heavy dark photon: $m(A') = 3m_1$**
- **Soft, collimated decay products**
  - X_1 collimated with muons
- **Dedicated displaced standalone (dSA) muon reconstruction algorithms**
- **Require #dSA muons ≥ 2**
  - Bin in terms of #dSA muons matched to standard muons (with tracker)
  - 0-match bin contains highly displaced muons
- **No excess**

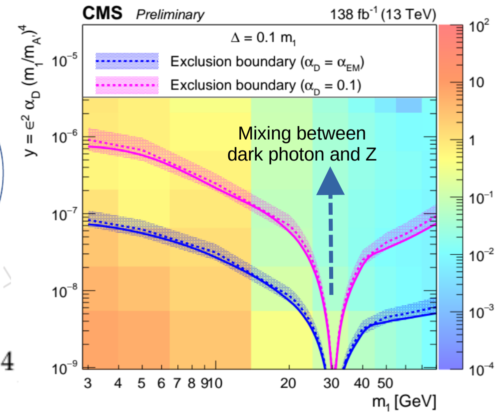


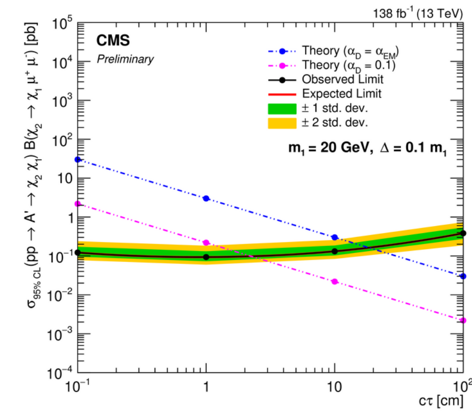


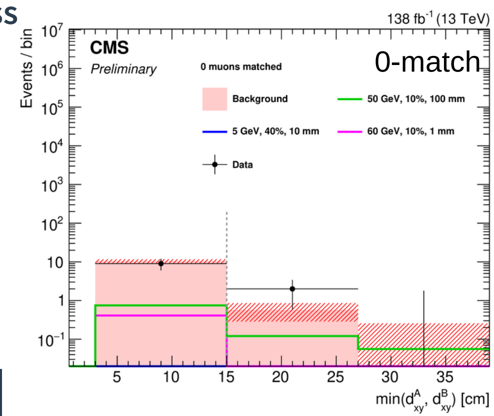
DM lifetime $\tau = \frac{1}{\Gamma} = \frac{15\,\pi}{4\,\alpha\,x^5}\frac{1}{y\,m_1}$



$$y \equiv \epsilon^2 \alpha_D (m_1/m_{A'})^4$$





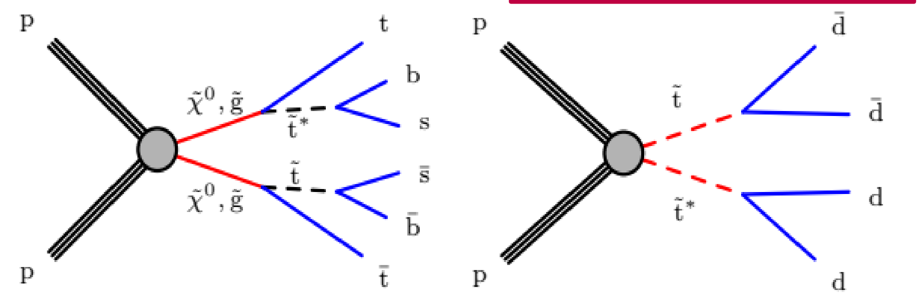


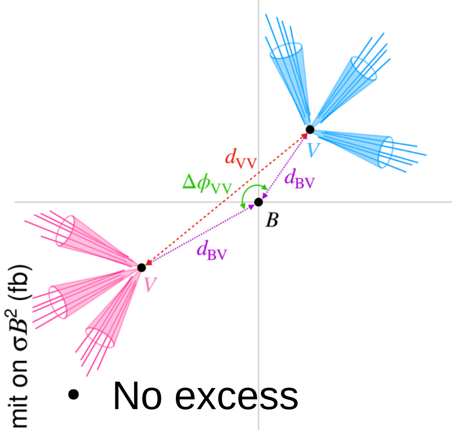
- For small Δ, DM annihilation rate largely depends on [1508.03050]: y (interaction strength) and m_1
- First ever search for inelastic dark matter (iDM) at hadron colliders

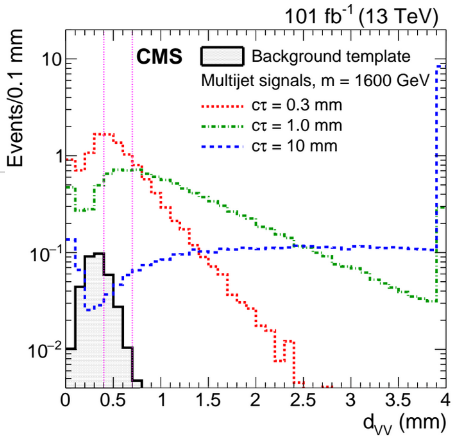
Displaced vertices

EXO-19-013 (2104.1347)

- **R-parity violating benchmark models**
  - Pair production of long-lived neutralinos, gluinos and top squarks
- **Multiple jets: use H_T triggers**
- **Dedicated Kalman-Filter based vertex reconstruction**
  - Using only tracks with large impact parameter significance ($d_{xy}/\sigma_{dxy} \geq 4$)
  - Signal vertices are required to have ≥5 tracks
- **3 search bins [0, 0.4, 0.7, 40 mm] in terms of d_{VV}**

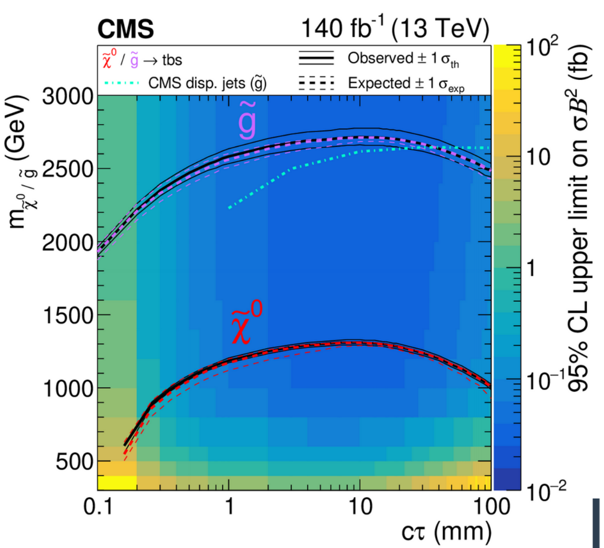


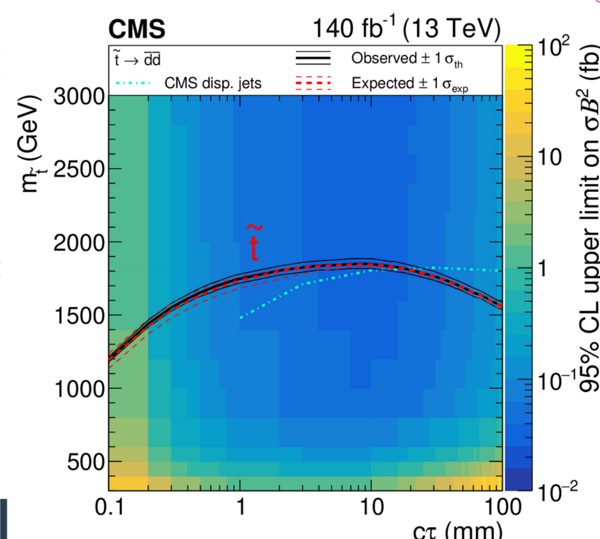




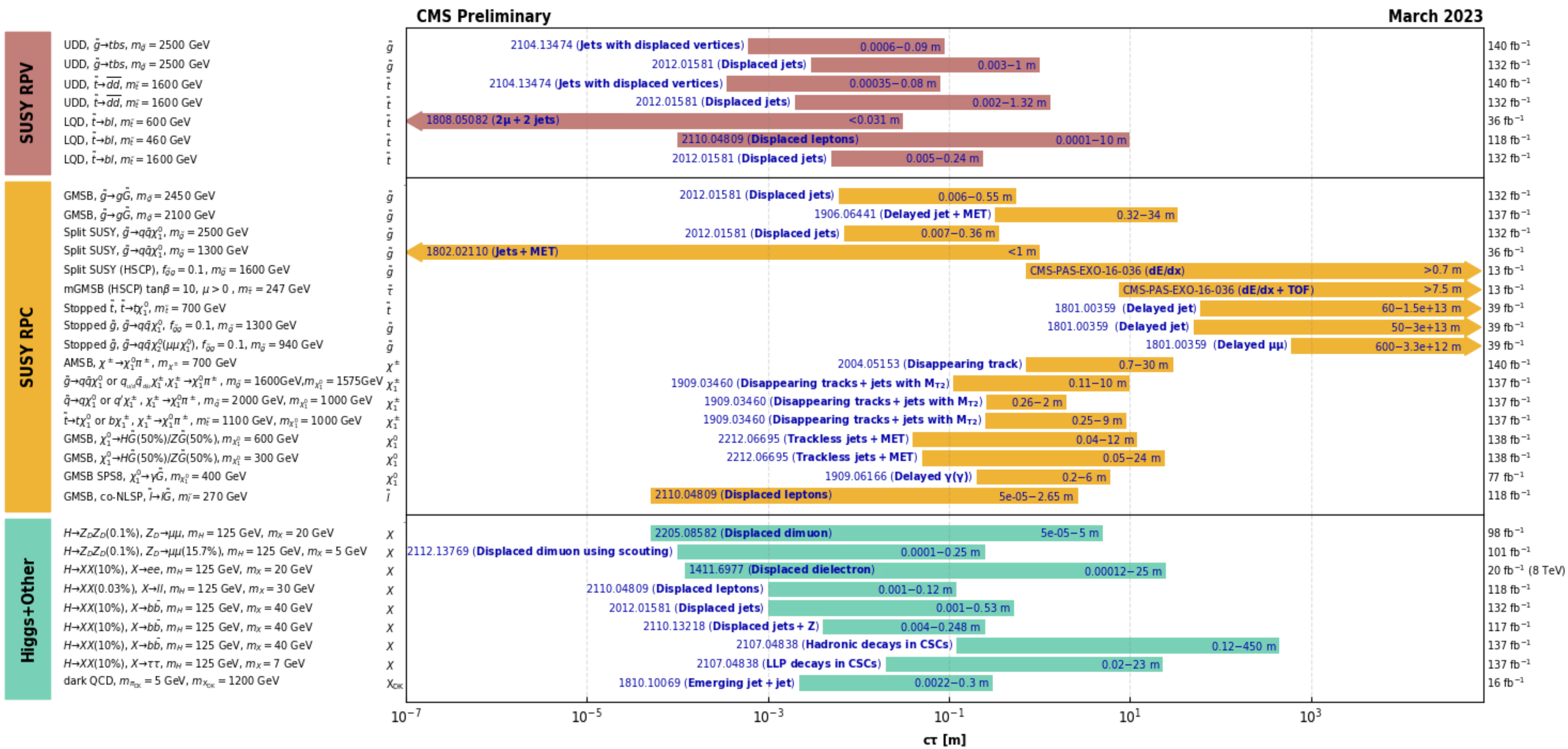
- No excess
- For the masses considered, most stringent limits for the cτ=0.1-15 mm

  (displaced jets has higher sensitivity above 15mm)





Overview of LLP searches at CMS



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.

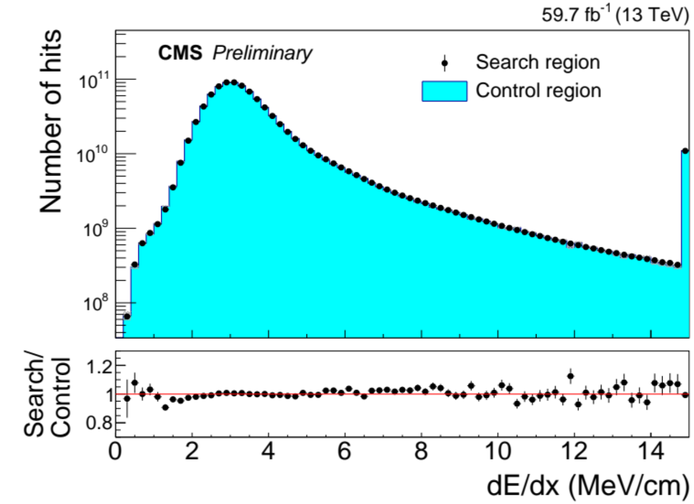
- Sensitivity to a lifetimes spanning several orders of magnitude (depending on the model)

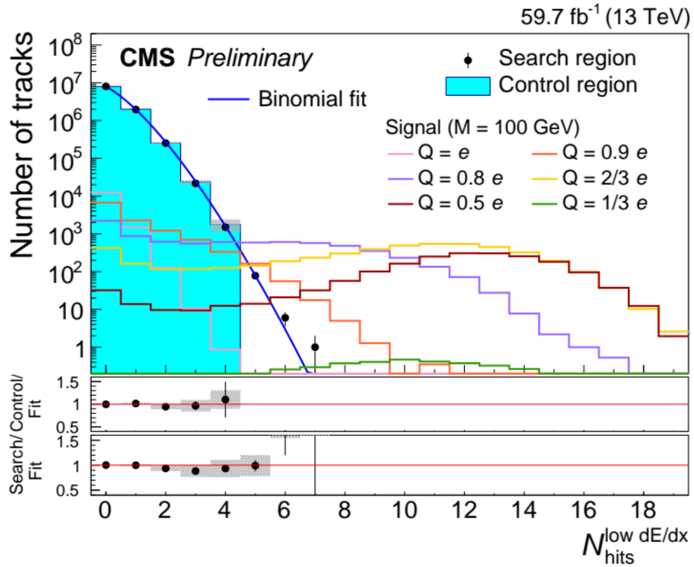
Other unconventional signatures

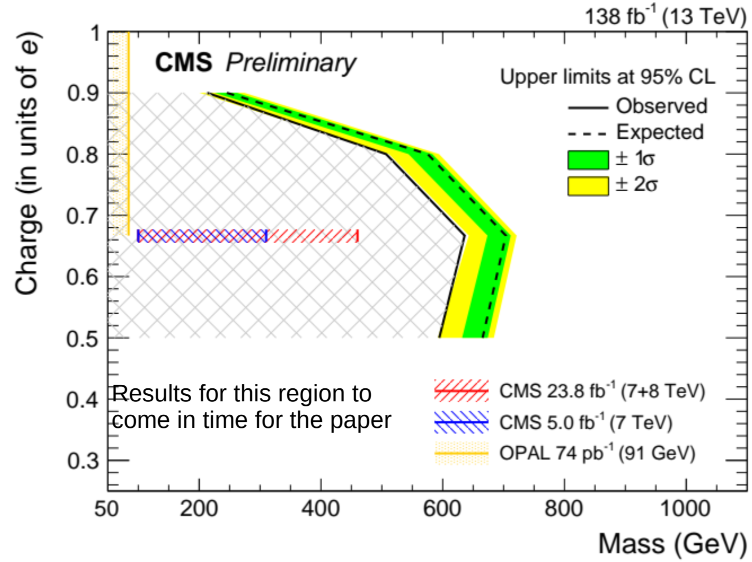
Fractionally charged particles (FCPs)

EXO-19-006

- **Charge Q lower than 1e:**
  - Ionization loss: $dE/dx \propto Q^2$: softer dE/dx spectrum
  - More hits with low dE/dx ($N^{\text{low dE/dx}}_{\text{hits}}$); threshold for “low” layer dependent
- **Account for radiation damage:**
  - Hits from pixel layer closest to the beam not counted
  - Signal dE/dx spectrum independently corrected for each layer
  - Period and layer dependent “low” dE/dx threshold (~1 to ~2.2 MeV/cm)
- **Search region – count $N^{\text{low dE/dx}}_{\text{hits}}$ in:**
  - Events with only 1 track
  - Events with 2 tracks with invariant mass <80 or >100 GeV





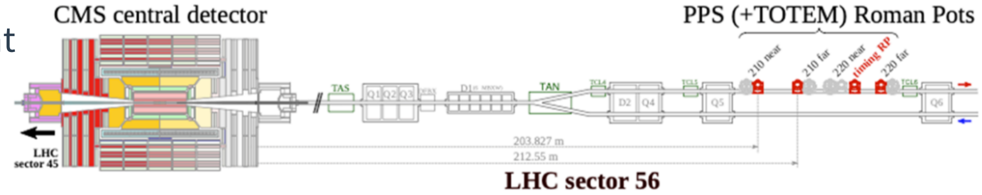


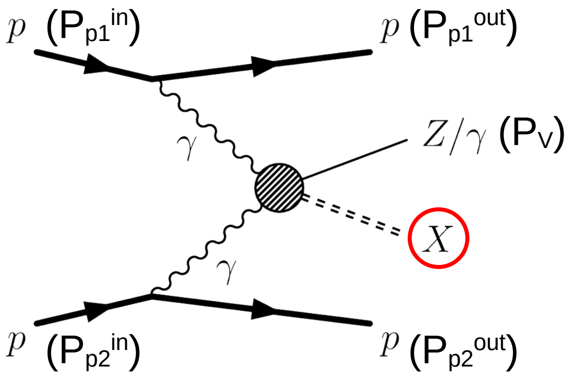
- No excess
- FCP of mass up to 636 GeV excluded for a charge Q=2/3e
- Best limits in this phase space

Search with the precision proton spectrometer

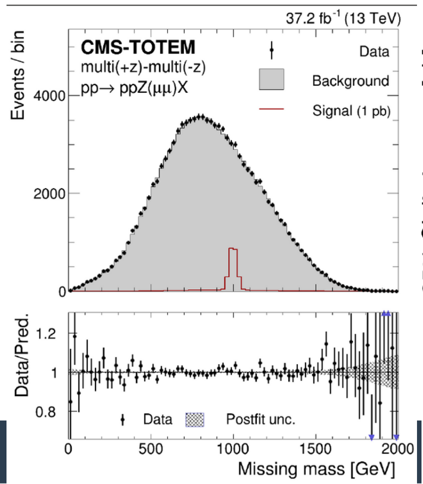
EXO-19-009

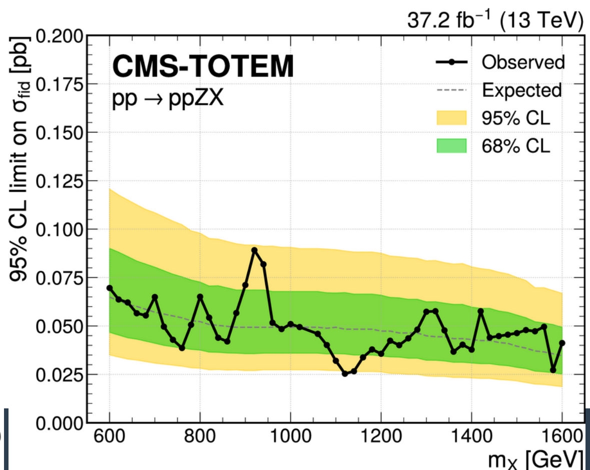
- **CMS TOTEM precision proton spectrometer (CT-PPS)**
  - Reconstruct flight path of protons from the interaction point
- **Generic search for massive heavy BSM particle X**
  - central exclusive production
- **Extract 4-momentum of X from the balance between:**
  - 2 forward protons and tagged SM particles
- **Missing mass (m_{miss}) approach (~2% CMS+CT-PPS mass resolution)**
  - No assumption about the decay properties of X
- **Dominant background from Z/γ+jets with 2 pileup protons:**
  - Fully data-driven

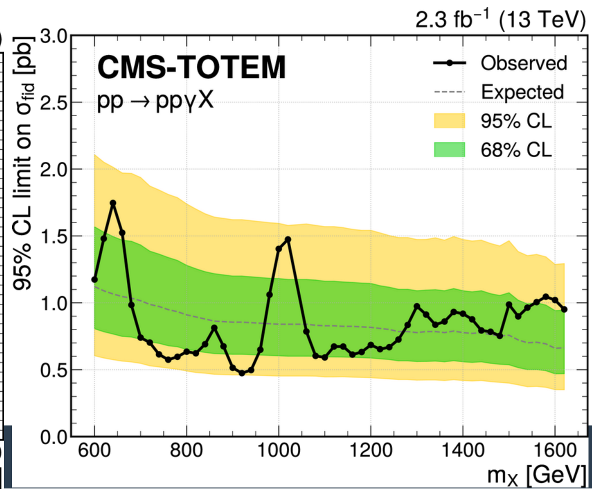




$$m^2_{\text{miss}} = \left[(P^{in}_{p_1} + P^{in}_{p_2}) - (P_V + P^{out}_{p_1} + P^{out}_{p_2}) \right]^2$$







- No excess
- Model independent limits on m_X
- Complements model specific searches

Summary

- **Significant progress in exploiting the full capability of the detector**
  - A wide variety of models and signatures explored
  - Presented only a small subset
  - Tremendous work in developing specialized triggers, reconstruction, etc.

What to look forward to


Unforunately
Duke Gaston
of Orléans
could not
complete his
Château

We are more optimistic about completing our upcoming search program

Unforunately Duke Gaston of Orléans could not complete his Château

Run-3

- Deploying more dedicated software level triggers

Phase-2 (HL-LHC)

- New sub-detectors with
  - Increased granularity
  - Improved timing capability
- Improved hardware level triggers (including tracks)
- More complex software level triggers (running on GPUs)


Long live the particles!
Thank you!

Backup

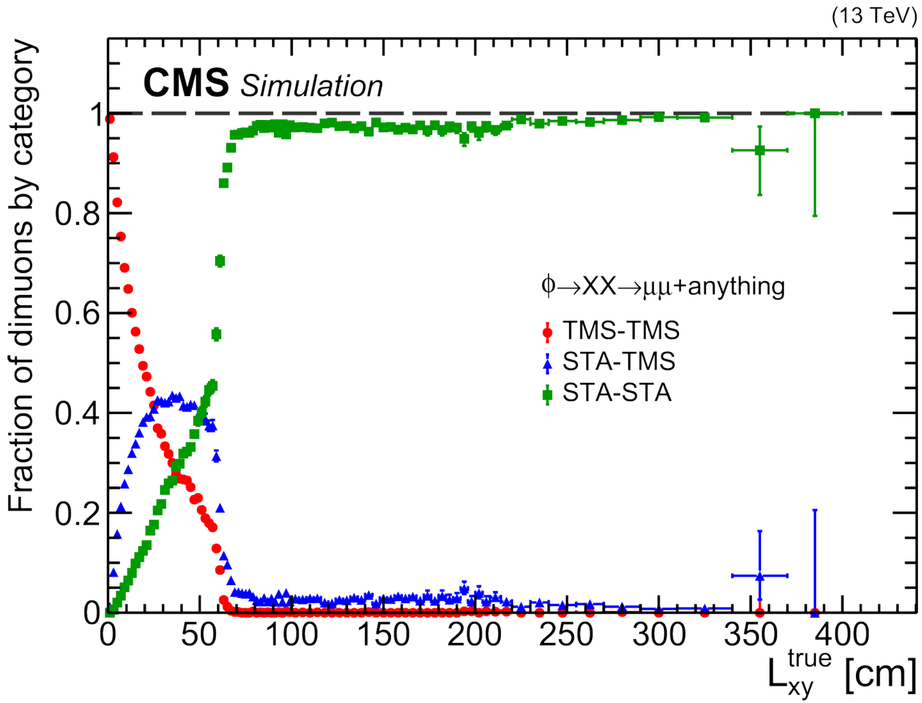
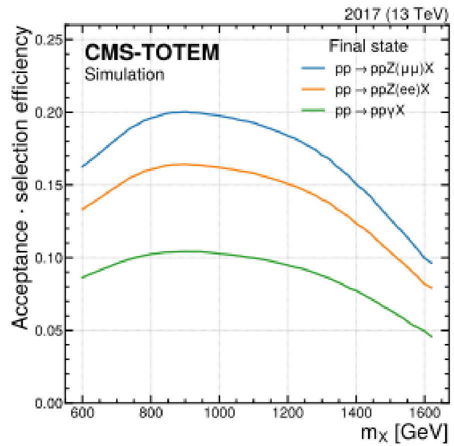
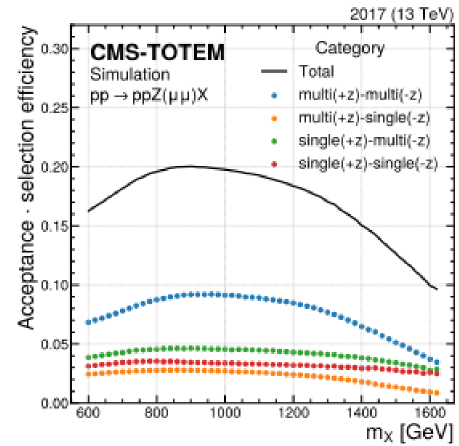

(13 TeV)
CMS Simulation
Fraction of dimuons by category
ϕ→XX→μμ+anything
TMS-TMS
STA-TMS
STA-STA
0
0.2
0.4
0.6
0.8
1
0
50
100
150
200
250
300
350
400
L_xy^true [cm]

Table 1: Number of tracks observed, expected for background events, and expected for signal events, in the highest $N_{\rm hits}^{\rm low\ dE/dx}$ bin, for each data set. The corresponding systematic uncertainties are also listed. The results for an FCP scenario at a mass of 100 GeV and a charge of $2/3\,e$ (i.e. the most sensitive scenario) is also shown.

	Early 2016	Late 2016	2017	2018
$N^{\rm observed}$	0	1	0	1
$N^{\rm expected}_{\rm Background}$	0.04	0.09	0.22	0.09
Fit function	±3771%	±159%	±231%	±19%
Fit range	±30%	±0.3%	±14%	±28%
$N^{\rm expected}_{\rm signal}$	602	988	2720	3622
L1 trigger inefficiency	5.0%	5.0%	5.0%	5.0%
Energy loss sim. in muon system	+3.8%-2.7%	+3.8%-2.7%	+3.8%-2.7%	+3.8%-2.7%
Muon detector inefficiency	3.0%	3.0%	3.0%	3.0%
Luminosity	2.5%	2.5%	2.3%	2.5%
Selection	2.0%	2.0%	2.0%	2.0%
dE/dx corrections	3.8%	1.1%	2.3%	1.7%
Limited signal sample	<1%	<1%	<1%	<1%

EXO-19-009


2017 (13 TeV)
CMS-TOTEM
Simulation
Final state
pp → ppZ(μμ)X
pp → ppZ(ee)X
pp → ppγX
Acceptance · selection efficiency
m_X [GeV]


2017 (13 TeV)
CMS-TOTEM
Simulation
pp → ppZ(μμ)X
Category
Total
multi(+z)-multi(-z)
multi(+z)-single(-z)
single(+z)-multi(-z)
single(+z)-single(-z)
Acceptance · selection efficiency
m_X [GeV]

EXO-19-013

Systematic effect	Dijet uncertainty (%)	Multijet uncertainty (%)
Vertex reconstruction	11–41	1–36
PDF and α_S uncertainty	1–8	1–8
Integrated luminosity	2–3	2–3
Jet energy scale	5	5
Jet energy resolution	2	2
Pileup	2	2
Trigger efficiency	1	1
Changes in run conditions	1	1
Total	13–42	7–36

	Systematic uncertainty (%)		
Systematic effect	0–0.4 mm	0.4–0.7 mm	0.7–40 mm
Closure in 3-track control sample	10	14	50
$\geq$5-track template normalization factor	24	24	24
Difference from 3-track vertices to $\geq$5-track vertices:			
Modeling of vertex pair survival efficiency	9	20	25
Modeling of $\Delta\phi_{VV}$	3	6	6
Variation of b quark fraction	1	3	6
Variation of b tagging correction factors	0.5	0.5	1
Total	28	35	61