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Searches in CMS for long-lived particles and other non-conventional signatures

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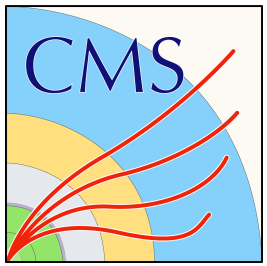
July 2022

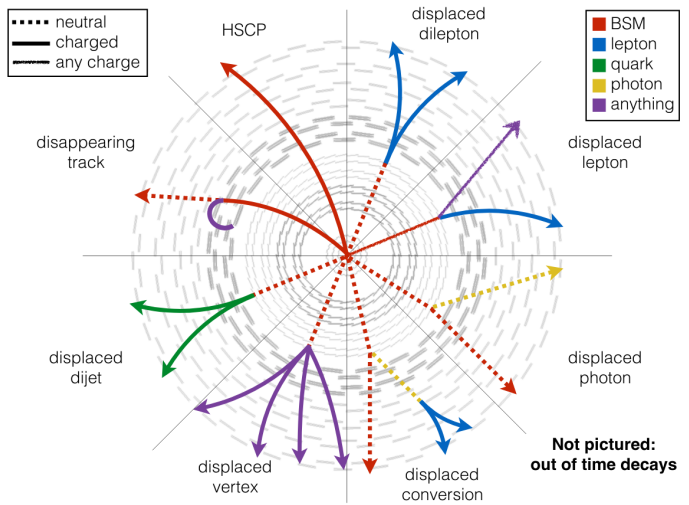


Non-conventional signatures and long-lived particles

New physics could be hiding in BSM models which predict the existence of particles that give rise to **non-conventional signatures**.

They are atypical topologies that offer **appealing and challenging searches** where we have to opportunity to improve:

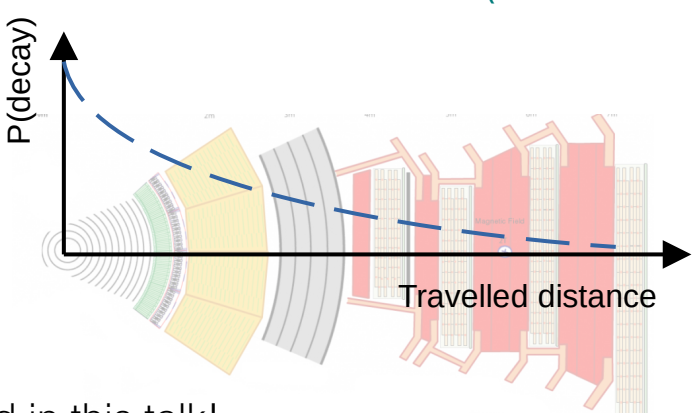
- The estimation of **non-standard backgrounds**
- Loss of efficiency in **reconstruction**
- Reduced **trigger** performance



(from J. Antonelli)

Long-lived particles LLP (high lifetimes) may decay away from the interaction point, so if we study their decay products:

→ Displaced particles

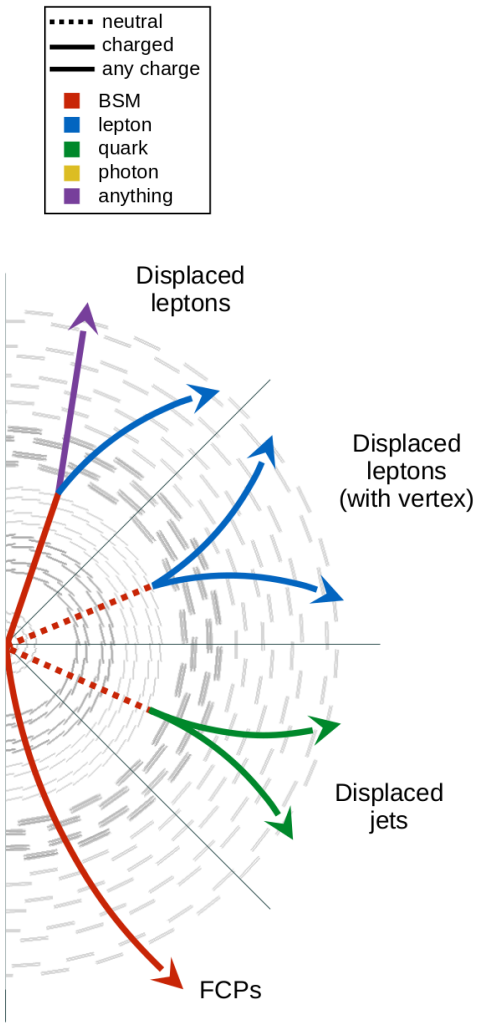


… if they are **Fractionally charged particles FCP** they are expected to leave less energy in the detector:

→ Low ionizing particles

… and many more that cannot be covered in this talk!

CMS searches by non-conventional signature



CMS has performed many searches that can be classified according to the non-conventional signature that is studied.

Challenges: Inclusivity, lower masses, momentum, high displacement (in case of LLPs)...

→ 5 of the most recent ones with **Run 2 data** are summarized in this talk:

Analysis	Signature	Displacement	Mass
CMS-EXO-18-003	Displaced (di)leptons	Within pixel tracker	> 30 GeV
CMS-EXO-20-014	Displaced dimuon (with vertex)	Within pixel tracker	> 200 MeV
CMS-EXO-21-006	Displaced dimuon (with vertex)	Tracker + muon system	> 10 GeV
CMS-EXO-20-003	Displaced jets + Z	Within tracker	> 15 GeV
CMS-EXO-19-006	Low ionizing particles	Outside of CMS	> 100 GeV

New result!

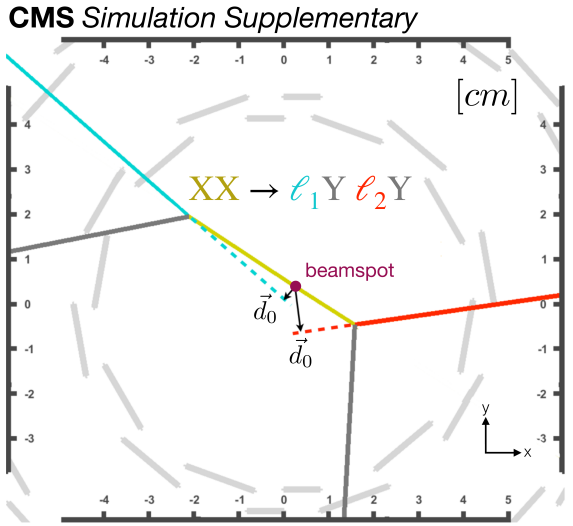
(Searches for Heavy Neutral Leptons (HNLs) not covered here but in the talk by Basile Vermassen today)

LLPs decaying to displaced leptons

CMS-EXO-18-003
2110.04809 (EPJC)

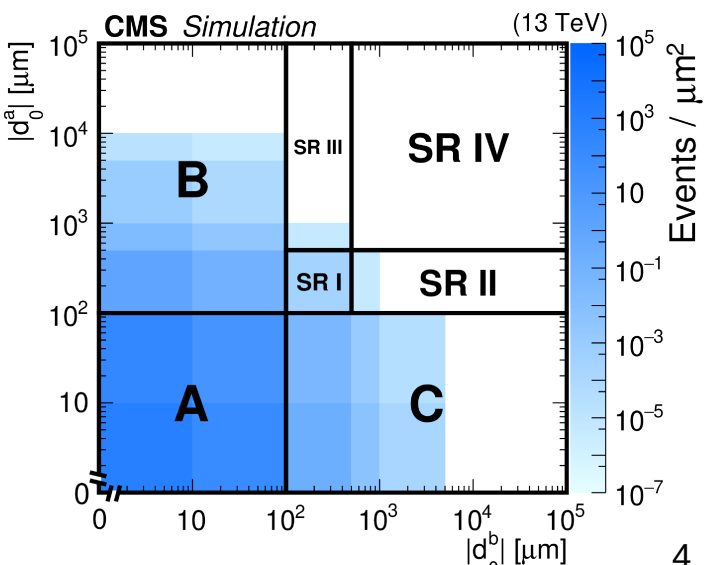
Inclusive search for long-lived particles decaying to displaced leptons

- Leptons not required to originate from a **common vertex**
- **μμ**, ee and e**μ final states**
- **Trigger** and **event selection** exclusively on displaced leptons
- Used leptons **$|d_0|$ as main discriminant** (up to 10 cm)



Background:

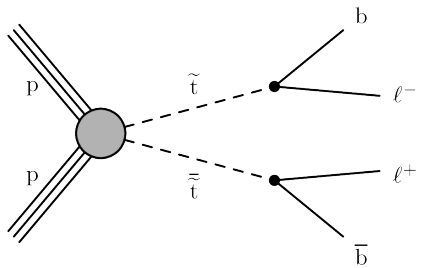
- ✗ Mismeasurements, leptonic tau decays, HF mesons estimated from **data-driven ABCD method** with both lepton $|d_0|$. Corrections applied to account for $|d_0|$ correlation.
- ✗ Cosmic muons, material interactions and LL SM hadrons largely **rejected by analysis selection**.

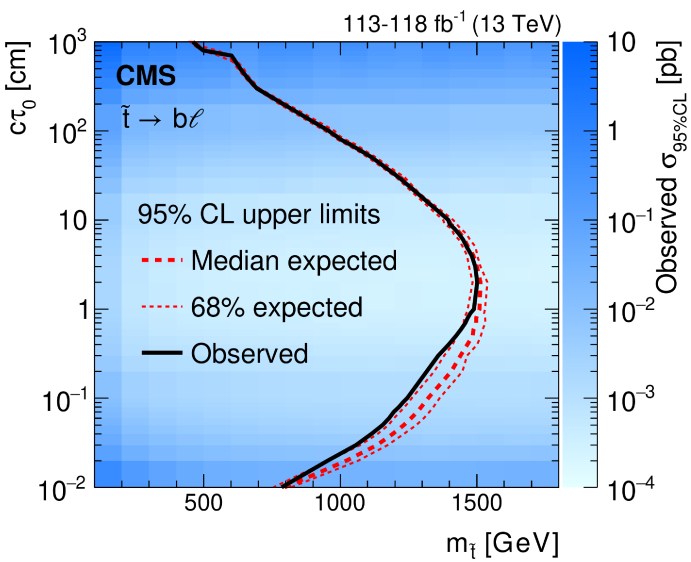


LLPs decaying to displaced leptons

CMS-EXO-18-003
2110.04809 (EPJC)

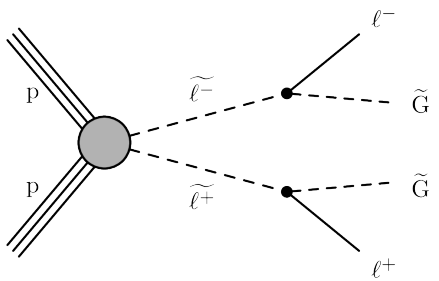
Exclusion limits set on RPV SUSY, GMSB SUSY and BSM Higgs models:

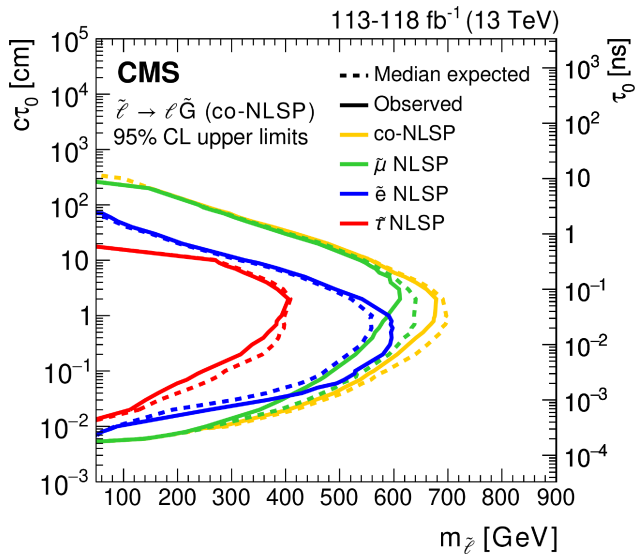




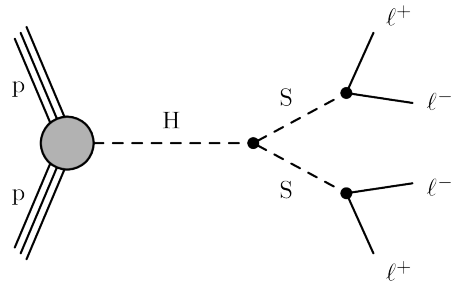
Max. sensitivity for $m_{\tilde{t}}$ =1500 GeV, cτ = 2 cm

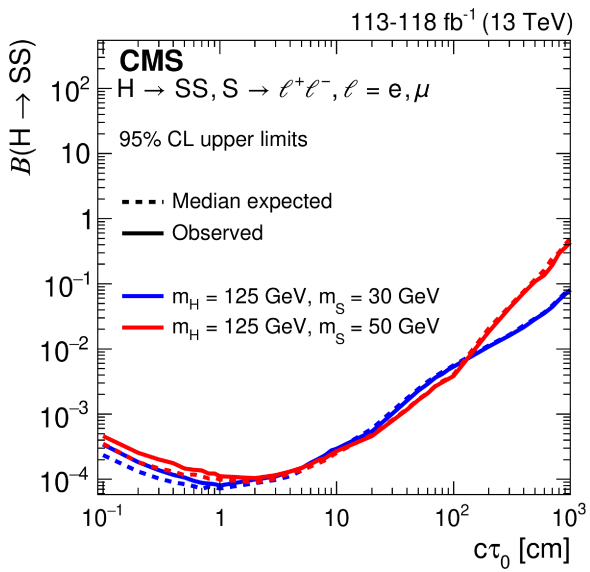
Similar limits than for t→dl (l = e, μ and τ)





Max. sensitivity for
$m_{\tilde{l}}$ =680 GeV, cτ = 2 cm





Max. sensitivity for
cτ = 1-2 cm

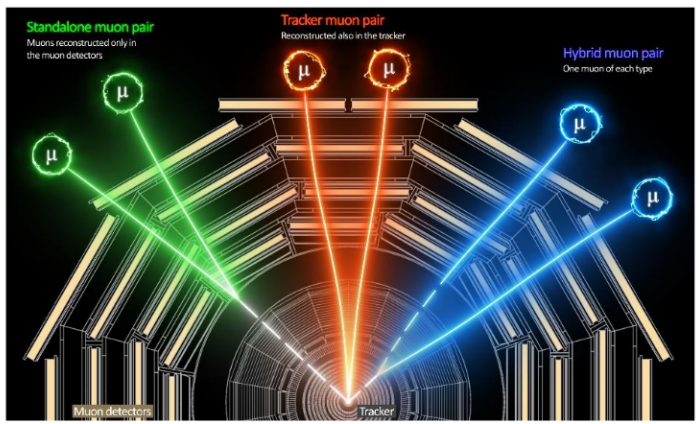
LLPs decaying to a pair of muons

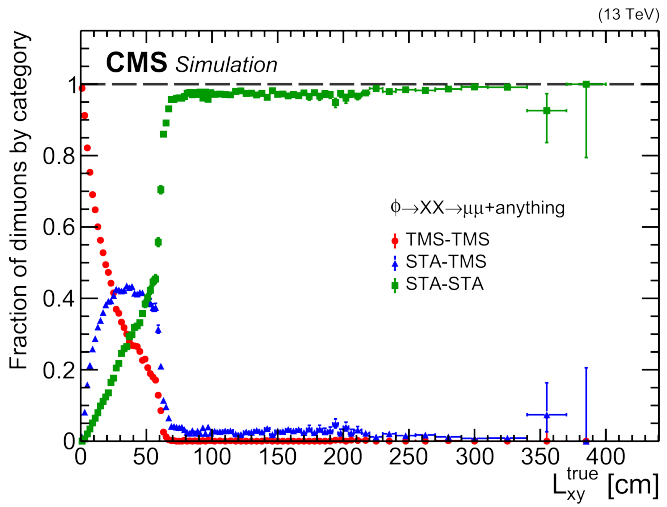
CMS-EXO-21-006
2205.08582 (JHEP)

Inclusive search for long-lived particles decaying to muons at distances ranging from few tens of μm to several meters

Topology: pair of OS charged muons originating from a common displaced vertex.

Splitted in three categories that are optimized separately





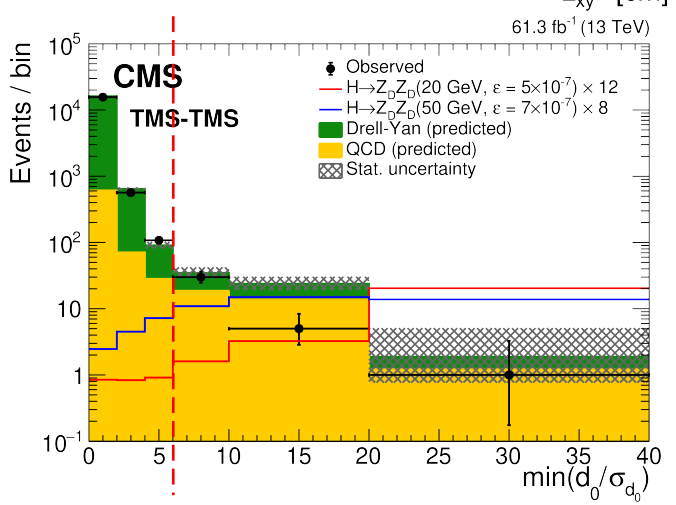
Triggered with muons only in muon chambers (No vertex constraint).

Background:

→ Cosmics, multijets, low-mass… suppressed with selection

→ Prompt misreconstruction estimated from control region with $|\Delta\Phi(p_T^{\mu\mu}, L_{xy})| > 3\pi/4$.

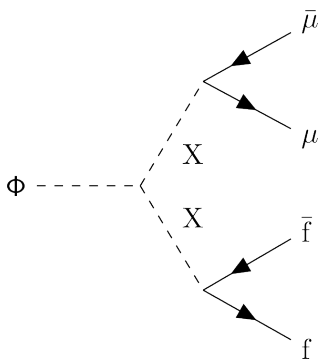
→ Nonprompt estimated from control region with SS dimuon vertices

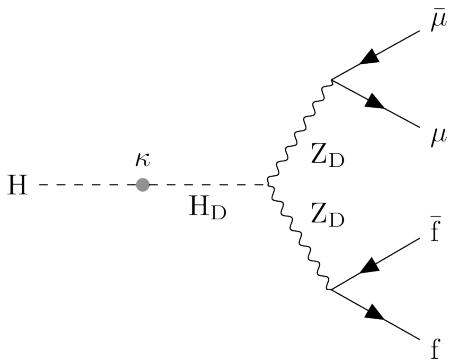


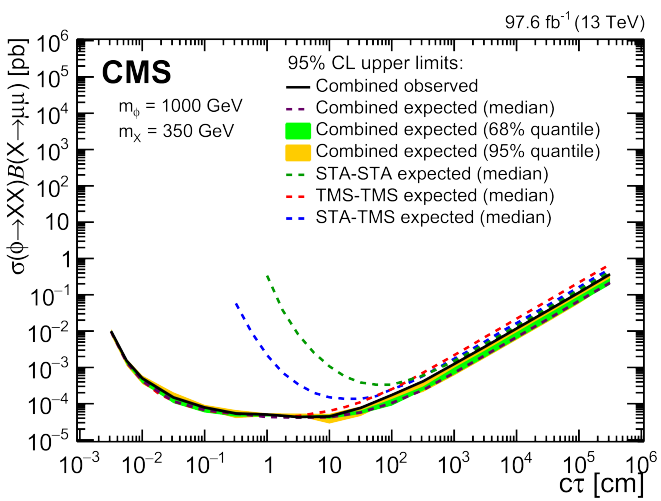
LLPs decaying to a pair of muons

CMS-EXO-21-006
2205.08582 (JHEP)

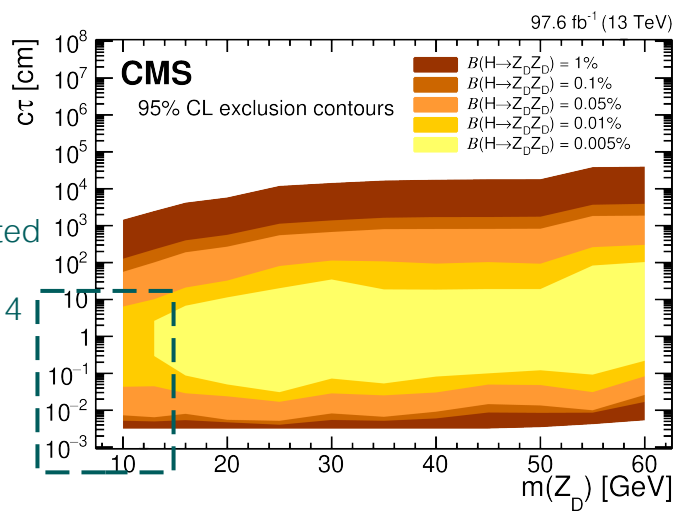
Exclusion limits set on a model with BSM heavy scalar decaying to LLPs and on a Hidden Abelian Higgs Model (HAHM) with dark photons Z_D:







Complemented by EXO-20-014



BR of Higgs to Z_D of 1% excluded for Z_D masses from 20 to 60 GeV and lifetimes from few tens of μm to 100 m

LLPs decaying to muons with high rate triggers

Search for long-lived particles decaying to muons with high rate triggers

Topology: pair of OS charged muons originating from a common vertex.

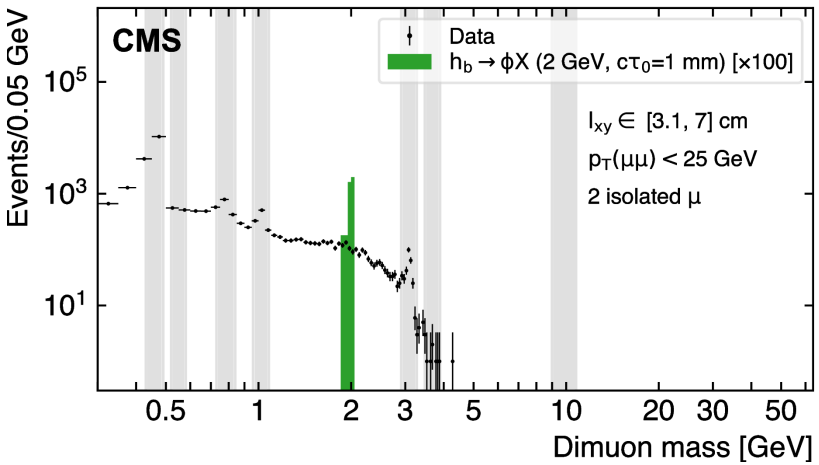
High rate triggers (2 OS muons):

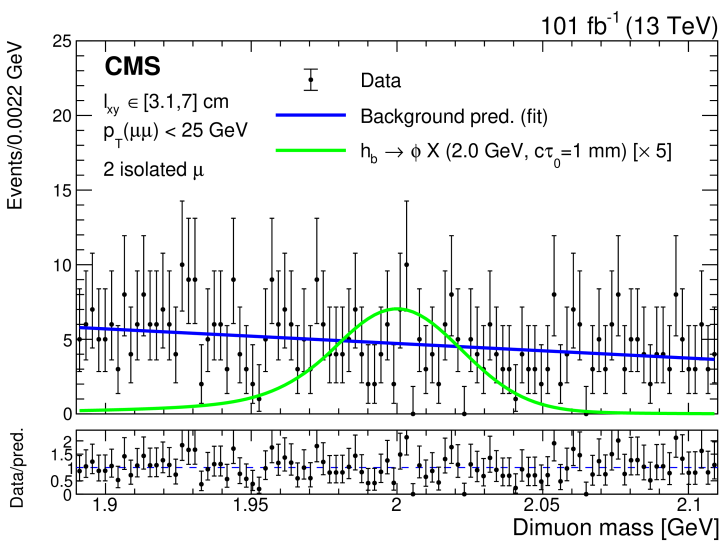
- ✔ Loose requirements, lower mass and muon p_T
- ✘ Limited information to be used
- ✘ Restricted to pixel tracker

Optimized selection to suppress background from cosmics, PU, QCD, misreconstruction, material interactions, B hadrons...

Event categorization as a function of transverse distance L_{xy}, dimuon $p_T^{\mu\mu}$ and isolation.

Simultaneous signal **+** background **fit** in mass windows where each contribution is parametrized by analytical functions.

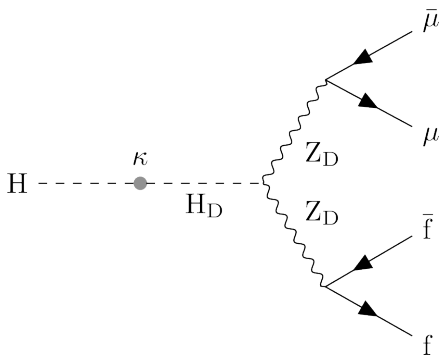


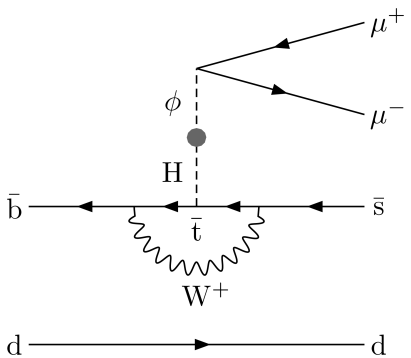


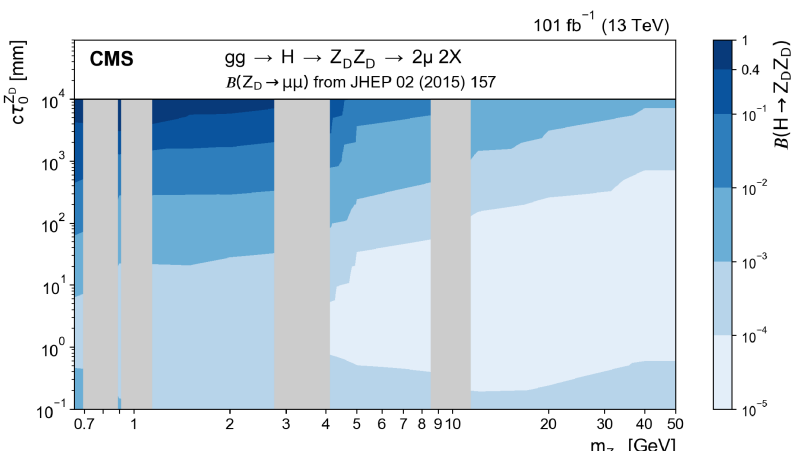
LLPs decaying to muons with high rate triggers

CMS-EXO-20-014
2112.13769 (JHEP)

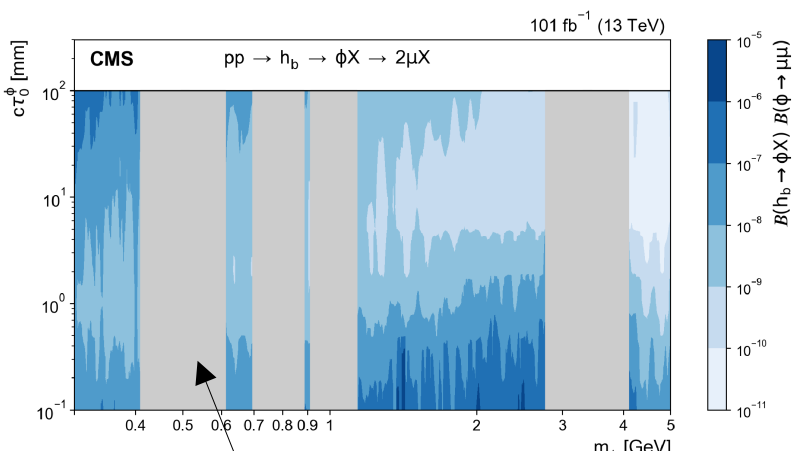
Upper limits set on a model with the Higgs boson decaying to dark photons Z_D and LL scalar resonances arising from b hadron decays ($h_b \rightarrow \Phi X$):







No B hadron background over ~5 GeV

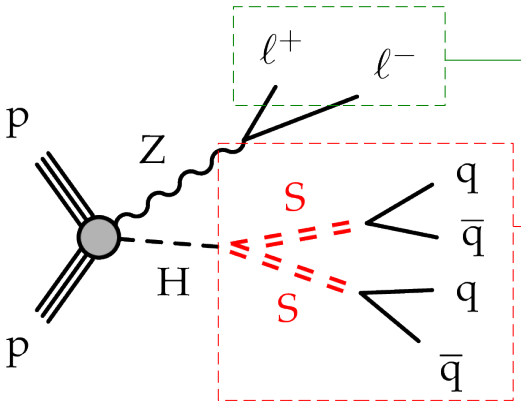


Low mass resonances are masked

Higgs decays into LLP with associated Z

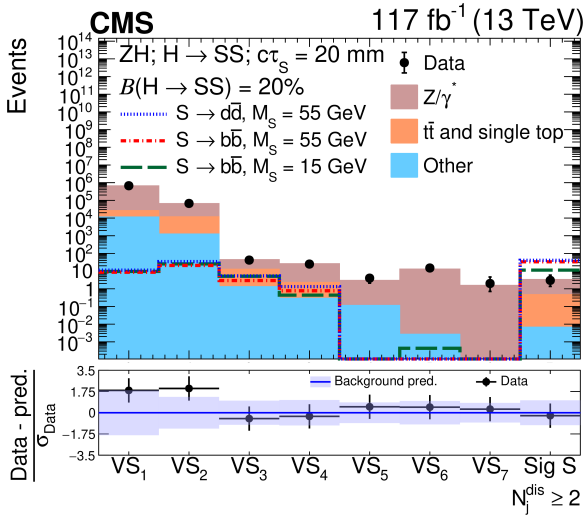
CMS-EXO-20-003
2110.13218 (JHEP)

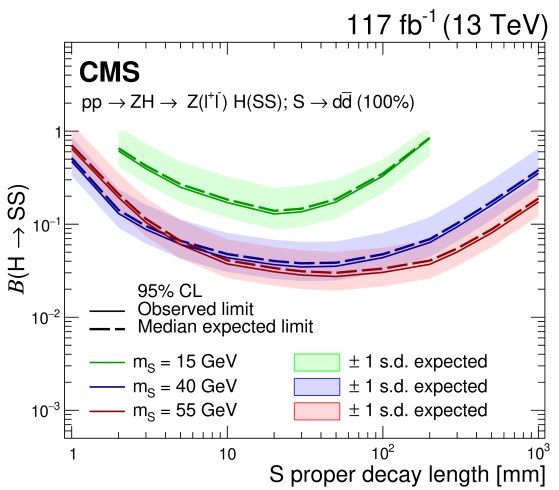
Search for Higgs boson decays into long-lived particles in associated Z boson production



Z boson is used to **trigger** the events

The number of displaced jets N^j_{dis} is used to **distinguish the signal from the backgrounds** (SM displaced decays, nuclear interactions, photon conversion and jet mis-identification)





Displaced jets are tagged with **track level information** variables.
(see CMS-EXO-16-003, 10.1016/j.physletb.2018.03.019)

- Drell-Yan and tt/single top are estimated from control regions while other bkgs from MC.

- **Validated in 7 VS$_i$ regions** by inverting jet tagging cuts

- **Signal region** defined as $N^j_{dis} \geq 2$

Search for fractionally charged particles

New result!

CMS-EXO-19-006

Search for fractionally charged particles

Energy deposited by a particle per unit length:

$$-\left\langle \frac{dE}{dx} \right\rangle = K Q^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \left(\frac{2 m_e (c\beta\gamma)^2 T_{max}}{I^2} \right) - \beta^2 \right]$$

Q < 1 → Low ionization power → Different dE/dx spectrum

Signature: High p_T track matched to a muon track:

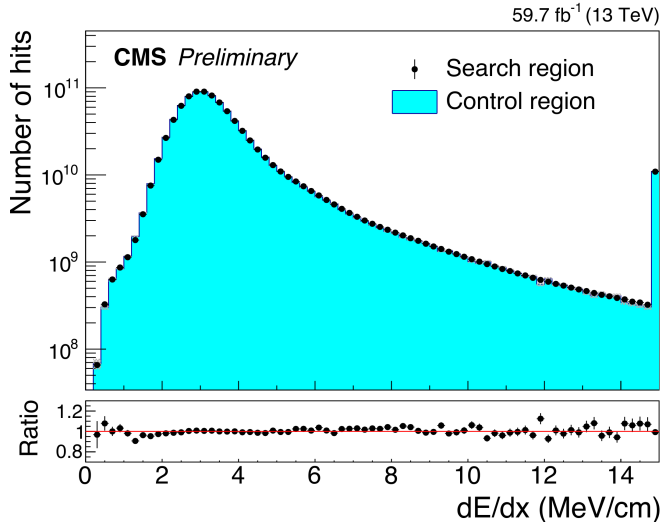
The number of tracker hits with low dE/dx $N_{hits}^{\text{low dE/dx}}$ is expected to be higher and it is used as main discriminant

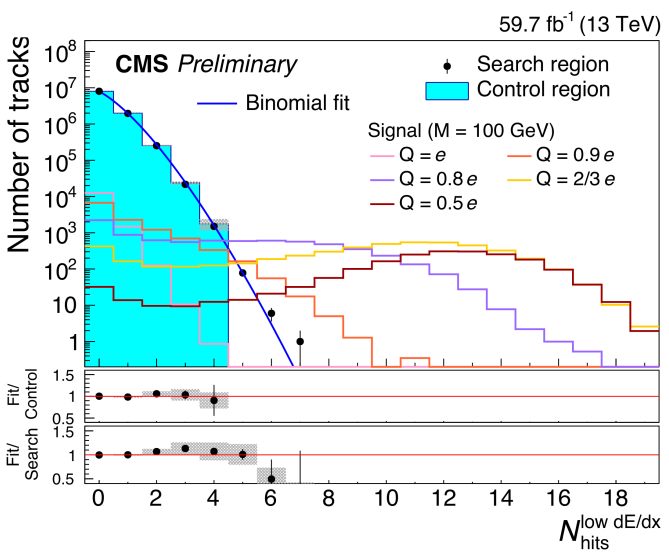
Background arises mainly from muons from W or Z decays:

→ Detector effects (radiation damage, pixel inefficiencies, edge hits…) mitigated with track/hit selection

→ Modelled with a fitted binomial distribution to extrapolate bkg from low to high $N_{hits}^{\text{low dE/dx}}$

Control Region: 80 GeV < $M_{\mu\mu}$ < 100 GeV



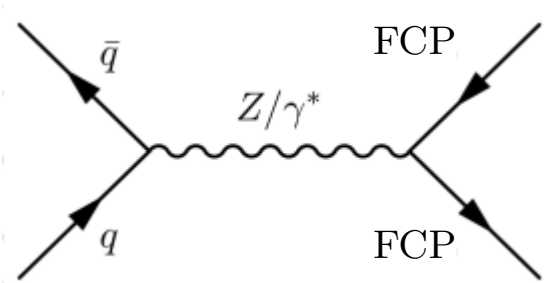


Search for fractionally charged particles

New result!

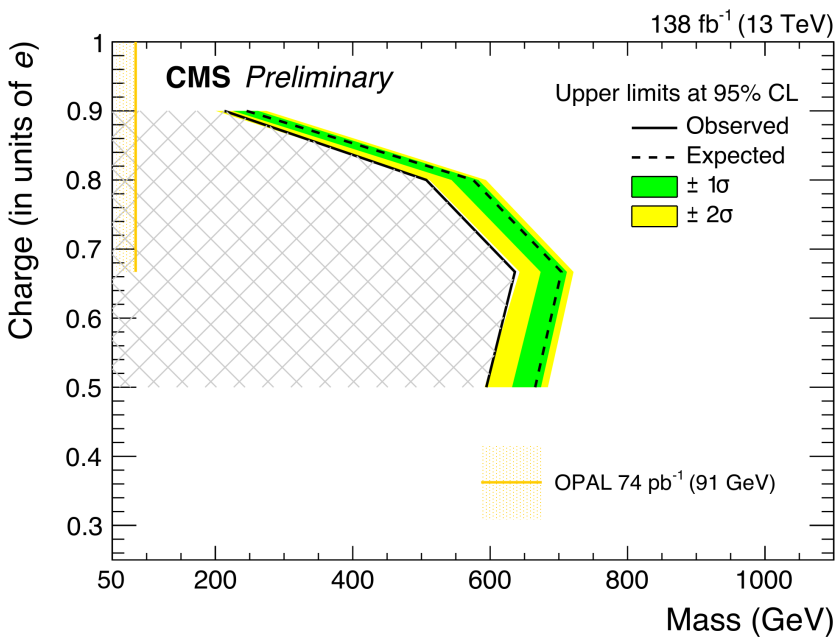
CMS-EXO-19-006

Exclusion limits set on the cross-section of FCPs production in Drell-Yan:



Best limits are obtained for intermediate charges

Excluded 2/3e for σ above 0.283 fb and masses of 636 GeV



Run 1 results from CMS for 2/3*e* and 1/3*e* FCPs not shown

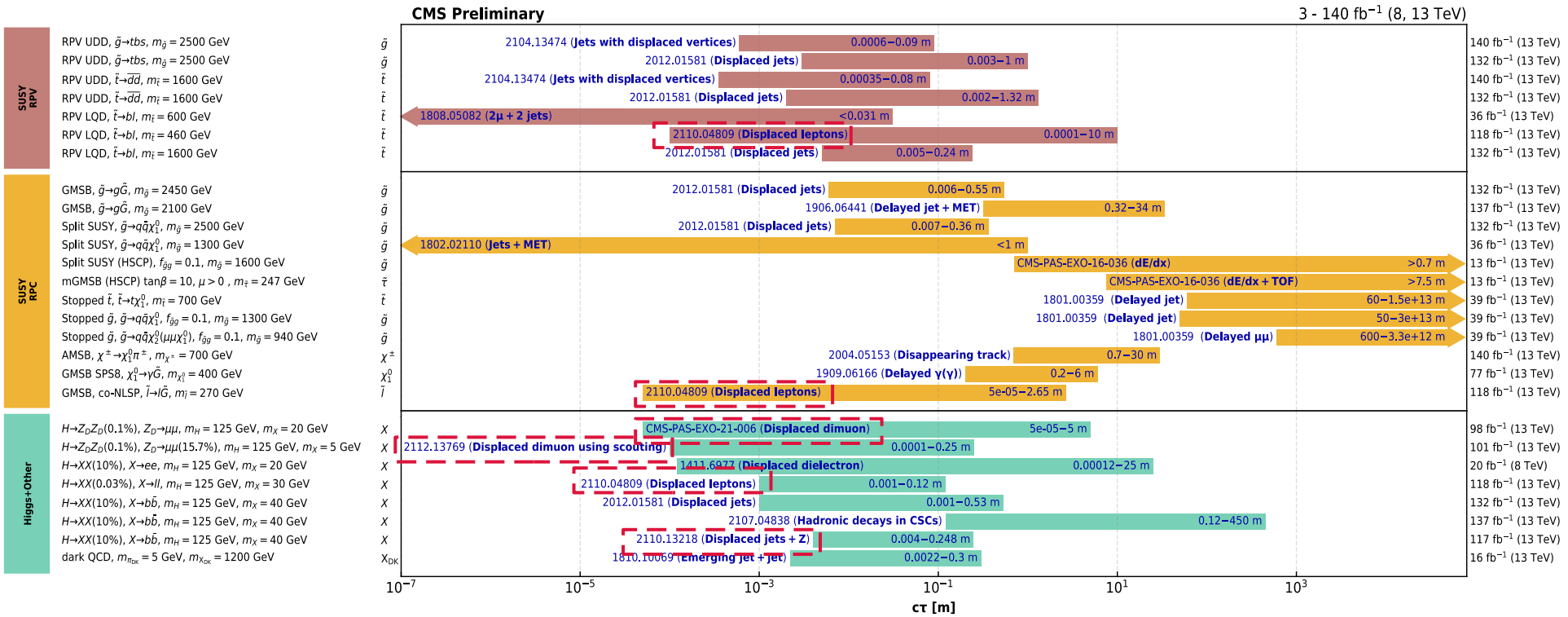
Results with Run 1* uncovered an issue with the FCPs simulation in the muon chambers, now corrected for Run 2.

- No impact on Sig vs Bkg method (from tracker)
- Affects selection efficiency in trigger/offline reconstruction for charges of 1/3*e*

→ Errata for Run 1 analysis are coming
→ Run 2 PAS will be held until errata is submitted

* PHYSICAL REVIEW D 87, 092008 and JHEP07 (2013) 122

Overview of CMS long-lived searches



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.

Summary

- **Non conventional signatures** offer the possibility to perform new appealing searches while looking at unexplored regions of the phase space
- They may provide a handle to **reduce background and gain sensitivity**

  … but at the same time are **challenging to detect and analyse**
- **Five of the latest non-conventional searches** were presented

  … and more exotic searches are still yet to come with Run 2 data
- Run 2 analyses have exploited all the tools available. There is room for **improvement towards Run 3** and a huge effort ongoing:
  - Improving triggers
  - Optimizing offline reconstructions
  - Designing new analyses techniques

More results available in
Public CMS Exotica results page

… thank you for your attention

Backup slides

EXO-18-003: Displaced lepton selection

Displaced lepton selection:

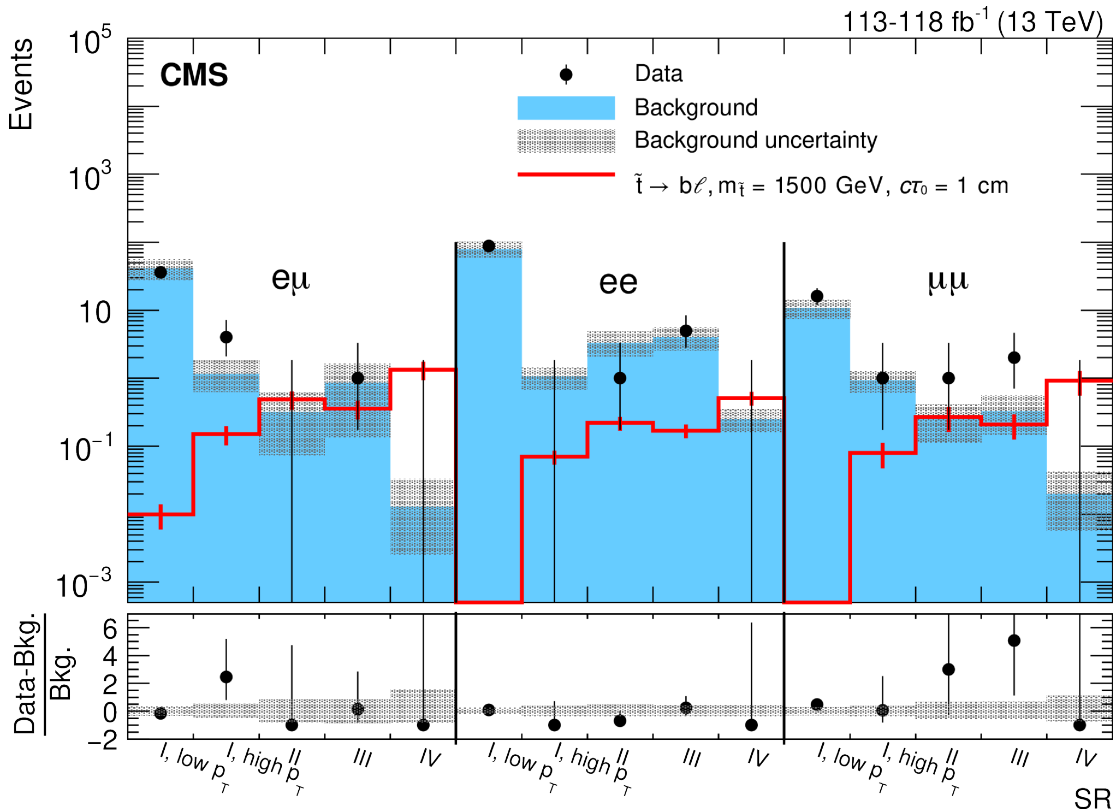
- ✗ Minimum p_T:
  - eμ: Electrons p_T > 42 (45) GeV and muons p_T > 40 (45) GeV in 2016 (2017 + 2018)
  - ee: p_T > 65 (75) GeV in 2016 (2017 + 2018)
  - μμ: p_T > 35 (45) GeV in 2016 (2017 + 2018)
- ✗ $|\eta| < 1.5$ (1.44) for muons (electrons)
- ✗ Removed η-Φ regions with no fully functional pixel layers
- ✗ Tight ID
- ✗ Isolation (PU corrected)
- ✗ Cosmic muon rejection:
  - $\cos(\alpha) > -0.99$
  - Δt(upper, lower) > - 20 ns
- ✗ $\Delta R > 0.2$
- ✗ Reject vertices in tracker material with $(\chi^2/\text{ndof})_{\text{vertex}} < 20$
- ✗ 100 μm < $|d_0|$ < 10 cm

Signal efficiency (m_t = 1500 GeV) over generated events

	200 GeV	1000 GeV	1800 GeV
	eμ SR		
0.1 cm	2.0%	4.5%	4.5%
1 cm	3.5%	7.8%	8.7%
10 cm	1.0%	2.6%	3.3%
100 cm	0.05%	0.12%	0.15%
	ee SR		
	200 GeV	1000 GeV	1800 GeV
0.1 cm	0.45%	2.1%	2.1%
1 cm	0.59%	2.8%	3.3%
10 cm	0.11%	0.59%	0.76%
100 cm	0.002%	0.01%	0.02%
	μμ SR		
	200 GeV	1000 GeV	1800 GeV
0.1 cm	1.4%	2.5%	2.5%
1 cm	3.0%	5.5%	5.8%
10 cm	1.4%	3.0%	3.6%
100 cm	0.10%	0.22%	0.31%

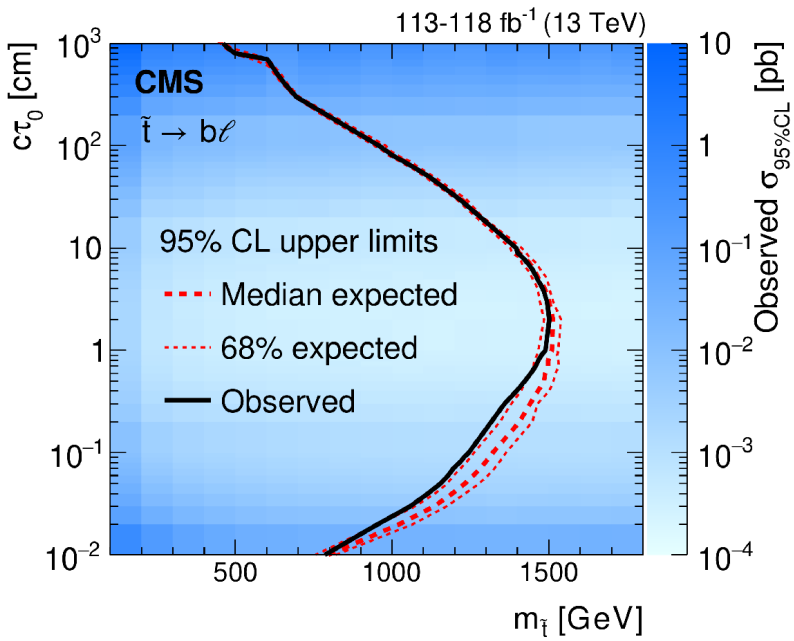
EXO-18-003: Signal region events

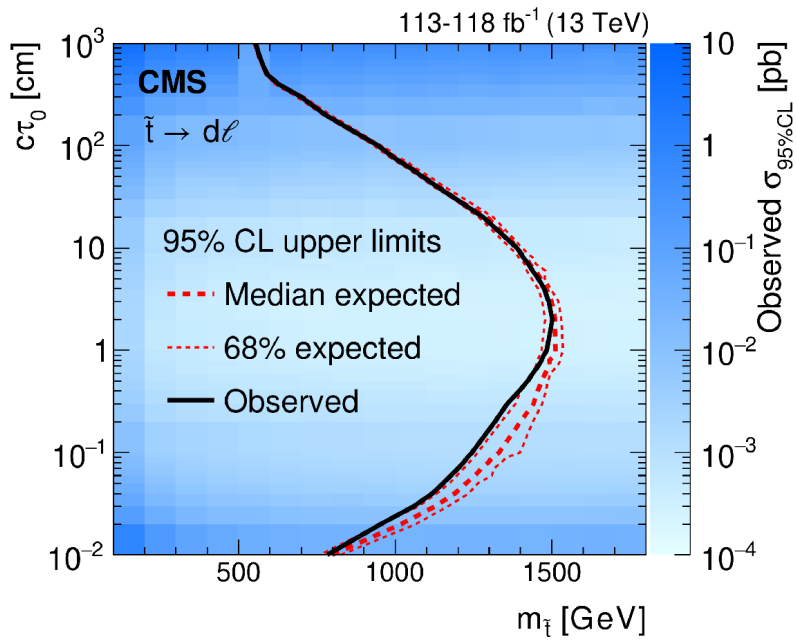
The number of observed and estimated background events in each channel and SR, with a representative signal overlaid is shown:



EXO-18-003: Additional results

Limits on RPV SUSY are set separately for top squarks decays into d and b quarks with very similar results:

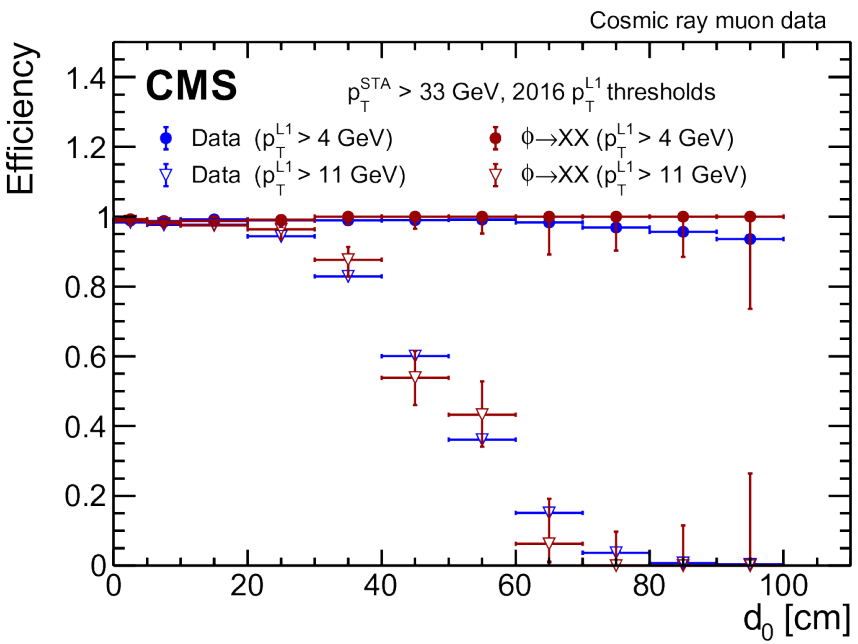


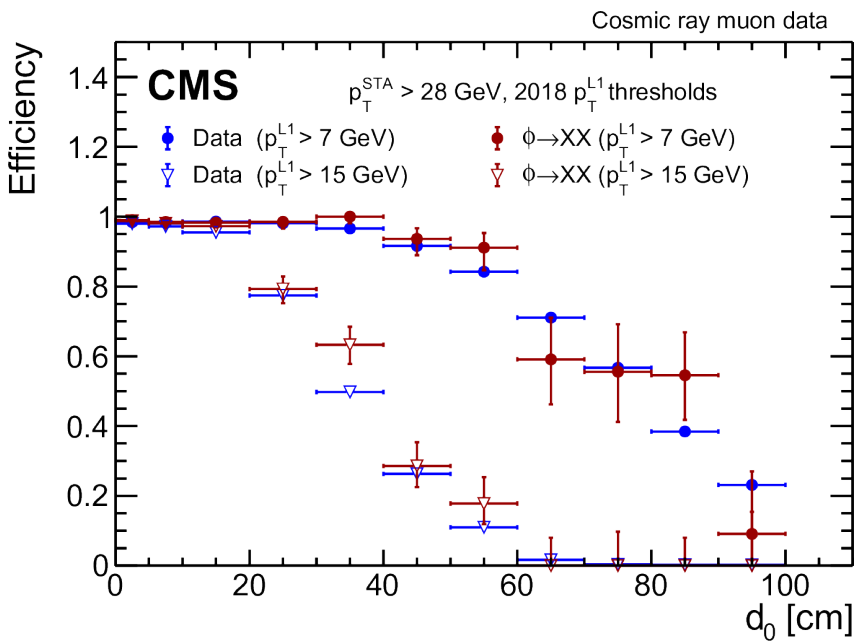


EXO-21-006: Trigger performance

High level triggers reconstruct the muons only in the muon chambers. Reconstruction is seeded by L1 dimuon triggers where the p_T assignment assumes that the muon was originated in the beamspot.

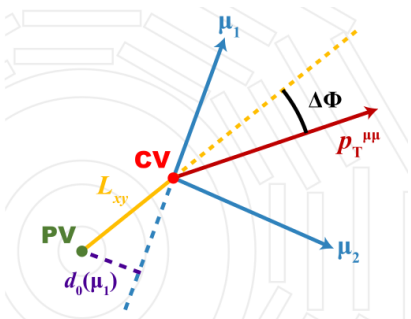
L1 thresholds were reached from 2016 to 2018.





EXO-21-006: Background studies

Misreconstruction estimated from $|\Delta\Phi(p_T^{\mu\mu}, L_{xy})| > 3\pi/4$ as it shows symmetric behavior in prompt background.

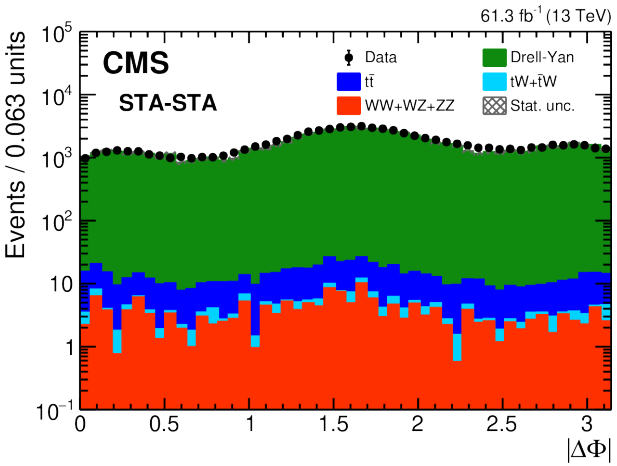


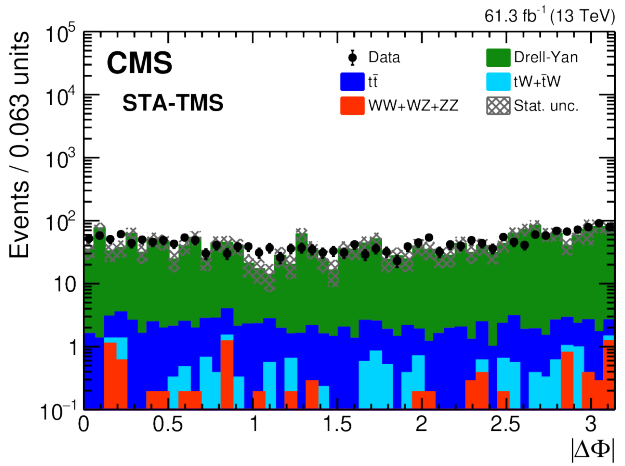
Non-prompt contribution (mainly QCD) is studied by inverting isolation cut.

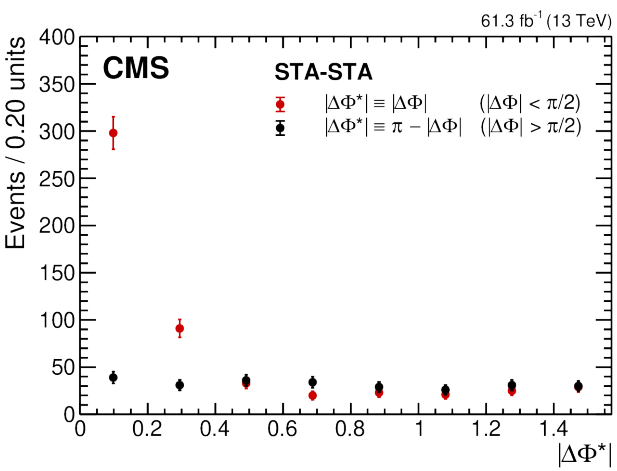
- $|\Delta\Phi(p_T^{\mu\mu}, L_{xy})|$ not symmetric

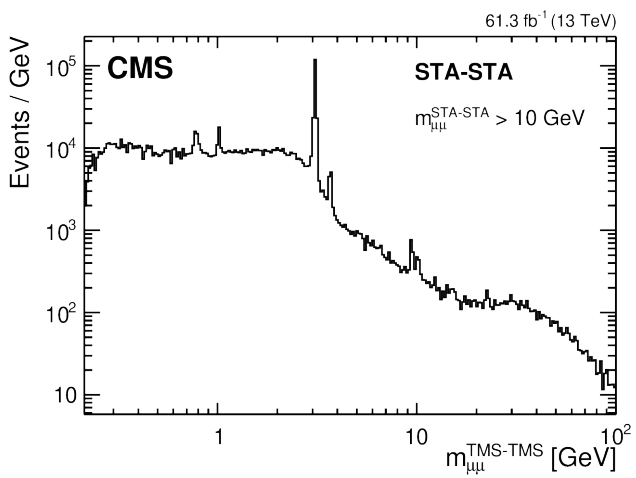
- Low mass for associated tracker muons

(Control regions with pairs inverting MuonSystem-to-Tracker association)



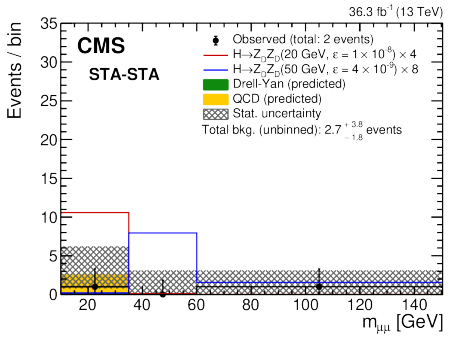


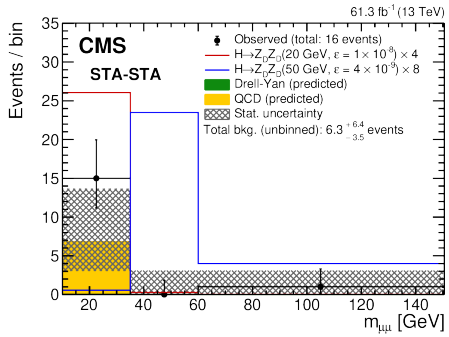




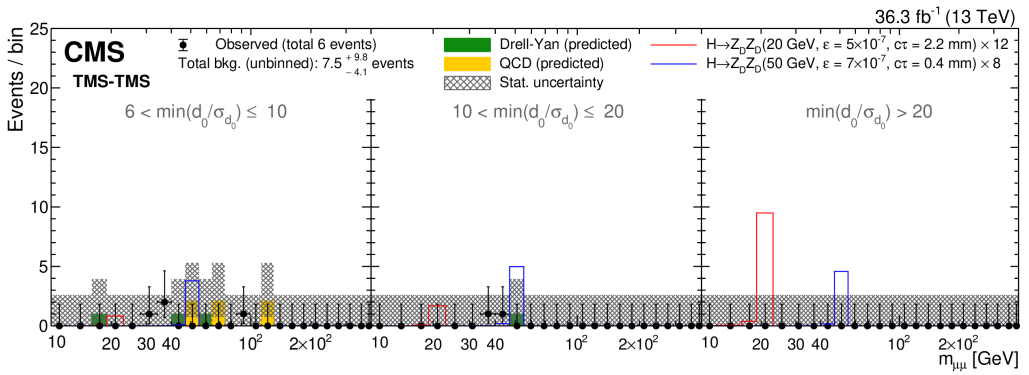
EXO-21-006: Observed events

Pairs reconstructed in only in muon chambers

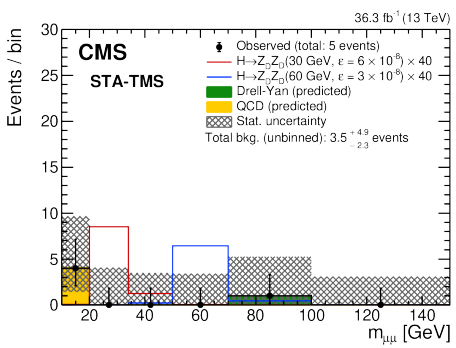


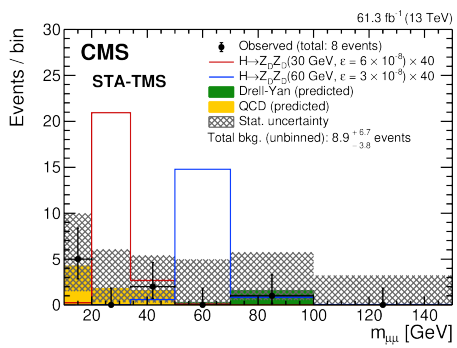


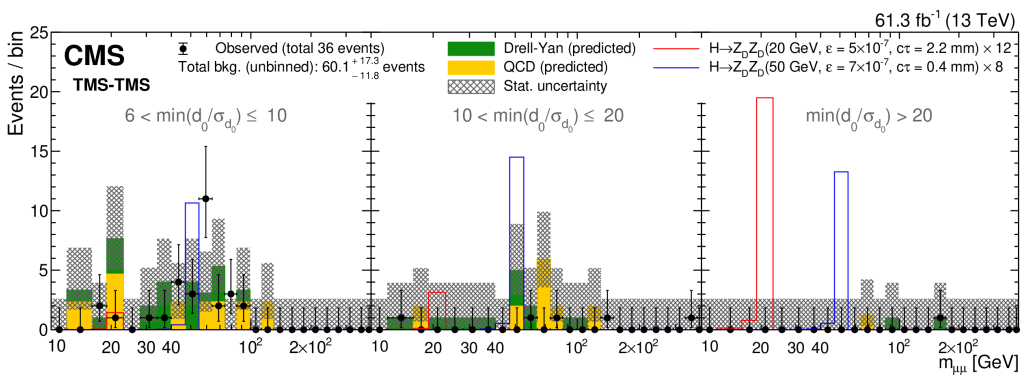
Pairs reconstructed in tracker + muon chambers



Hybrid pairs







EXO-20-014: High rate triggers and selection

→ Events ate **preselected at L1** and required to pass **at least one of 3 criteria**:

- ✗ Two L1 muons with opposite charges, p_T > 4 (4.5) GeV in 2017 (2018) and $\Delta R < 1.2$
- ✗ Two OS L1 muons with $|\eta| < 1.4$ and $\Delta R < 1.4$
- ✗ Two L1 muons with $p_T^{\mu 1} > 15$ GeV and $p_T^{\mu 1} > 7$ GeV

Only preselected events with muons with $p_T > 3$ GeV and $|\eta| < 2.4$ are **retained**.

→ **OS muon selection:**

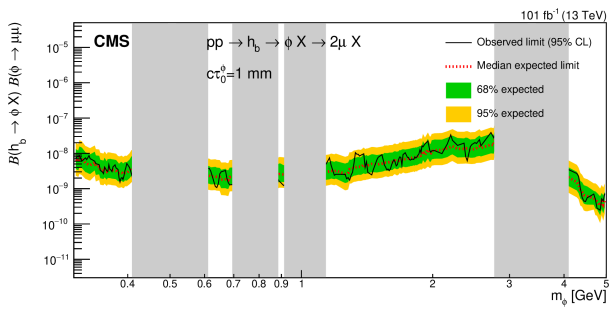
- ✗ Vertex with $L_{xy} < 11$ cm, $\Delta x < 0.05$ cm, $\Delta y < 0.05$ cm, $\Delta z < 0.1$ cm and $(\chi^2/\text{ndof})_{\text{vertex}} < 5$
- ✗ Muons with $(\chi^2/\text{ndof})_{\text{track}} < 3$ and $N_{\text{layers}} > 5$
- ✗ First (second) muon pair in the event:
  - Relative tracker isolation < 0.1 (0.2) and no jet within $\Delta R < 0.3$
  - $|\Delta\Phi(p_T^{\mu\mu}, \text{SV})| < 0.02$ (0.1)
  - $|\Delta\Phi(\mu_1, \mu_2)| < 2.8$
  - $\log_{10}(|\Delta\eta_{\mu\mu}|/|\Delta\Phi_{\mu\mu}|) < 1.25$
  - Consistent $N_{\text{pixel hits}}$ for $L_{xy} > 3$ cm
  - Veto to vertices within 0.5 cm of detector material
  - $|d_{xy}|/\sigma_{dxy} > 2$ (1)
  - $|d_{xy}|/(L_{xy}\, m_{\mu\mu} / p_T^{\mu\mu}) > 0.10$ (0.05)

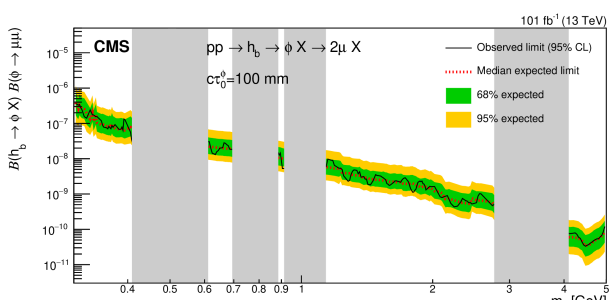
Total signal efficiency from 55% to 75%

EXO-20-014: Additional results

Limits on LL resonances in B hadron decays.

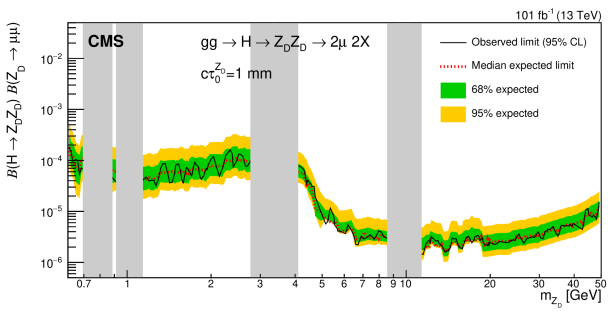
($c\tau$ = 1, 100 mm)

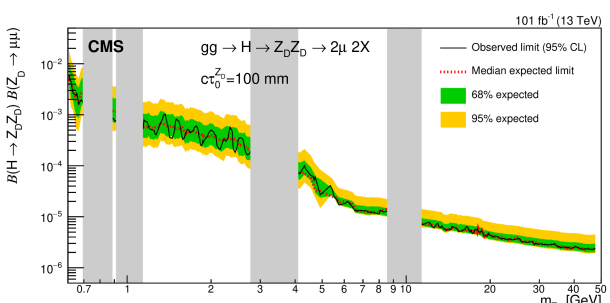




Limits on Higgs boson decays to dark photons.

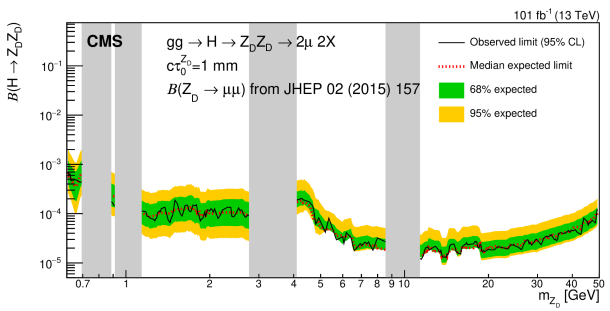
($c\tau$ = 1, 100 mm)

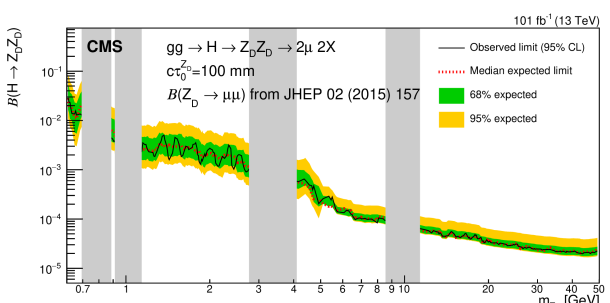




Limits on Higgs boson decays to dark photons with assumed $B(Z_D \to \mu\mu)$.

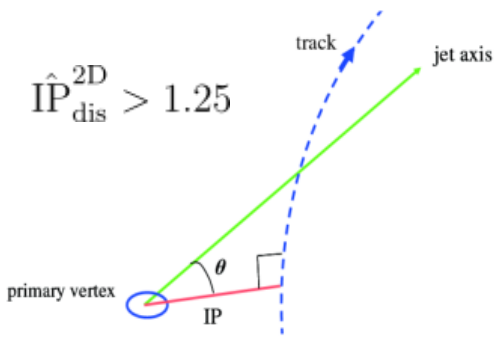
($c\tau$ = 1, 100 mm)

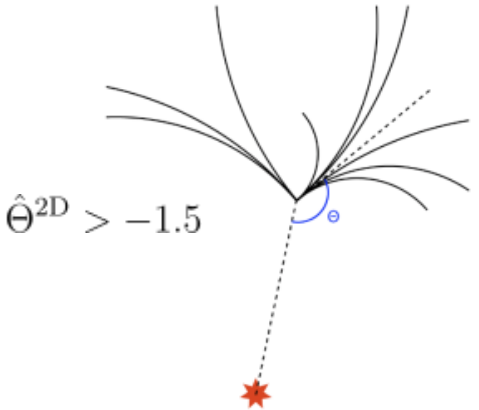




EXO-20-003: Displaced jet tagging variables

Displaced jet tagging variables:

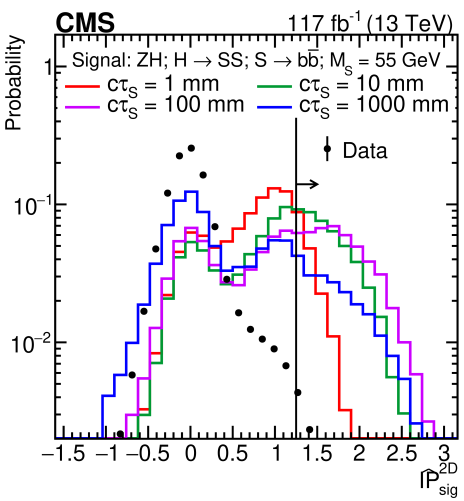


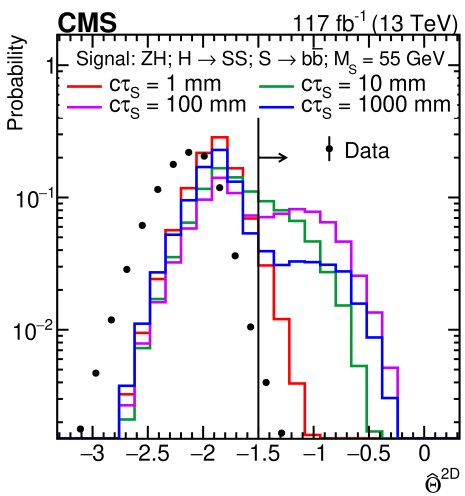


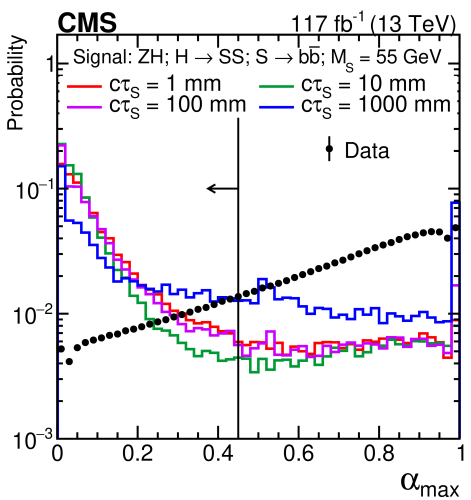
$$\alpha_{max} < 0.45$$

$$\alpha_{vtx_i} = \frac{\sum_{tracks \in vtx_i} p_T^{tracks}}{\sum_{tracks} p_T^{tracks}}$$

$$\alpha_{max} = MAX\{\alpha_{vtx_i}, \alpha_{vtx_j}, \ldots\}$$

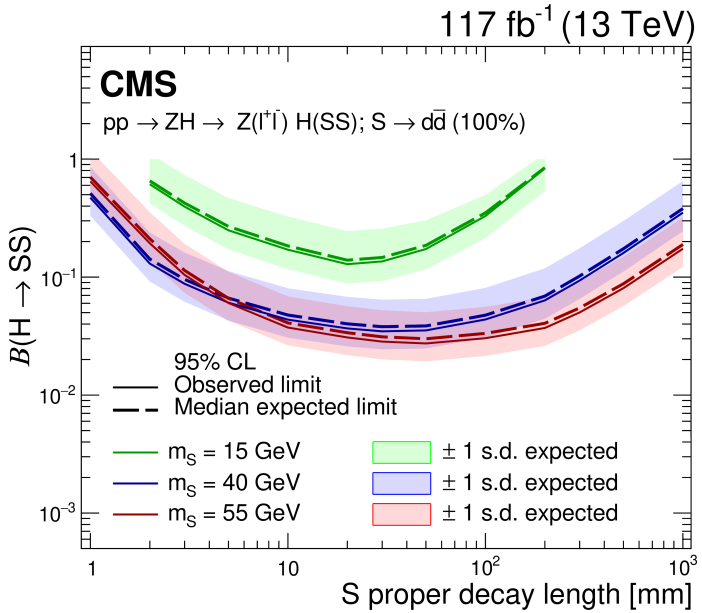


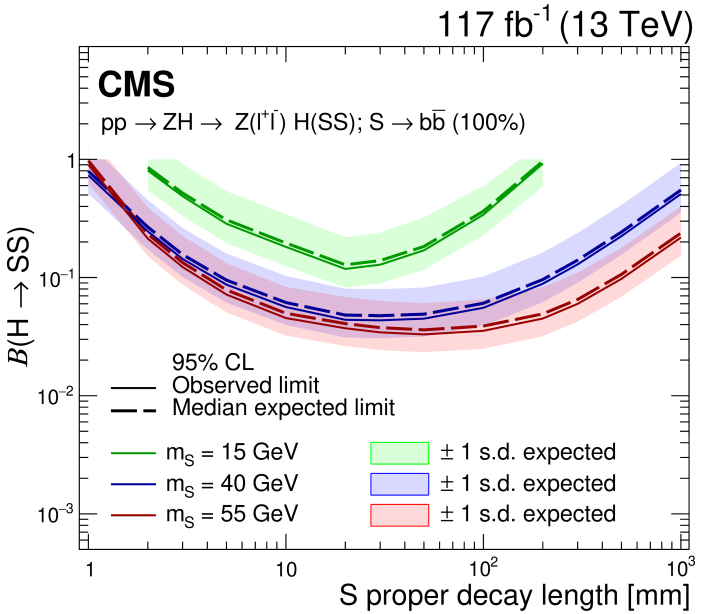




EXO-20-003: Additional results

Exclusion limits set on the Higgs boson branching fraction to a pair of LL scalars in two scenarios, S→dd and S→bb. Results do not have a strong dependence on quark flavor:





EXO-19-006: FCPs simulation in muon system

- ✗ Simulation in **tracker** is done with Geant 4 **which accounts for energy loss of FCPs**.
- ✗ For the **muon system** simulation, **charge was hardcoded as q=e**.

→ <u>Solution:</u> **Scaled the distance** between **two FCP interactions** by the **square of the charge**