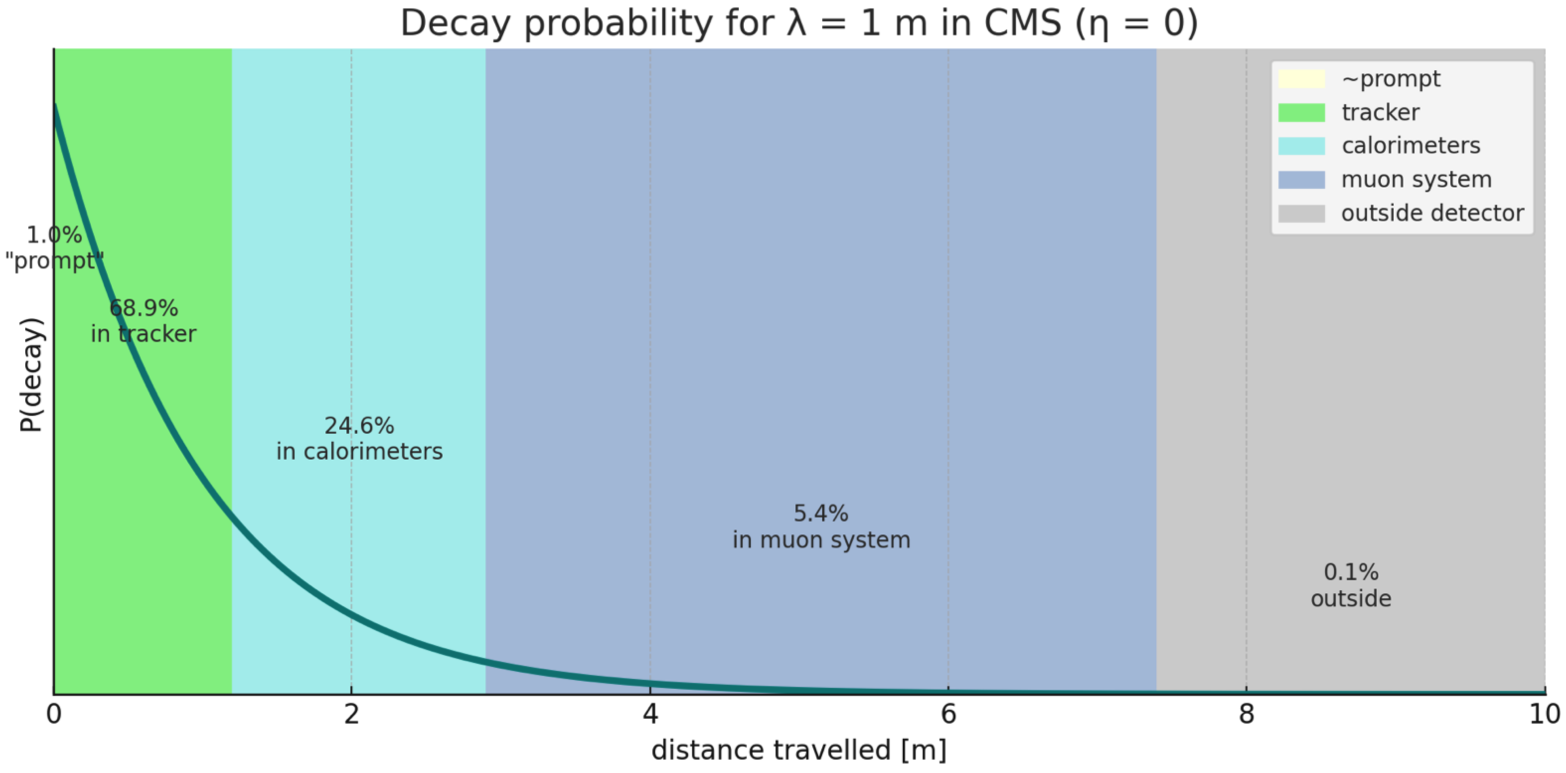
Searches in CMS for long-lived particles and non-conventional signatures

Eric Chabert, on behalf of the CMS collaboration

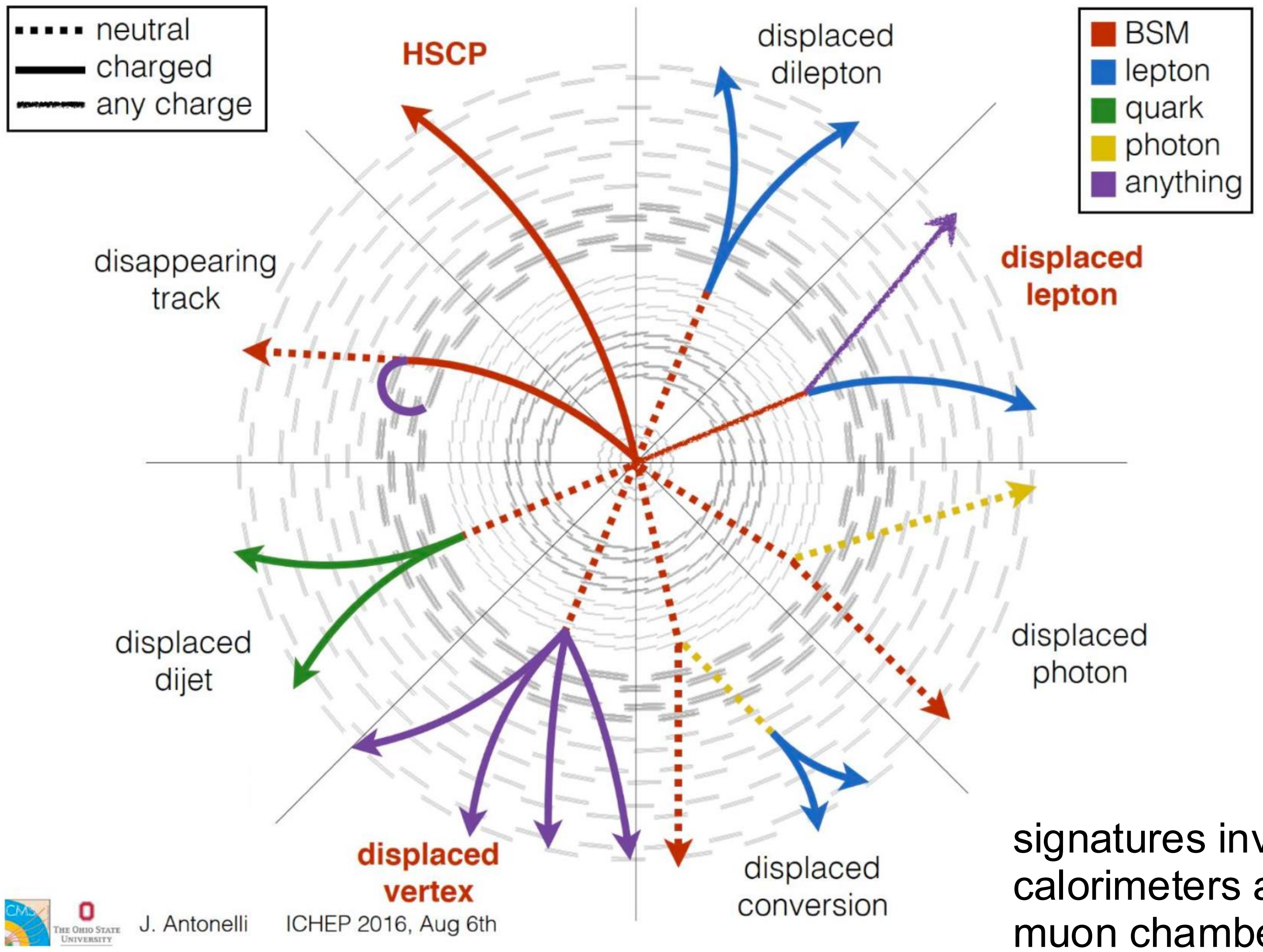
Long-lived particles (LLP)

- **Particle lifetime** can be large enough to enhance the probability to travel **measurable distances** before decaying.
- In SM, we have LLP such as kaon, pions and muons !
- In BSM, long lifetime could be generated by:
  - Nearly **mass-degenerate spectra** (ex: compressed SUSY)
  - Heavy virtual **mediators** (ex: heavy neutral lepton)
  - Small **couplings** (ex: hidden sector models)
- The probabilities depends on $\gamma c\tau$



LLP signatures

Different LLP properties ($c\tau$, mass, decay modes, …) lead to a **wide range of experimental signatures** that often require dedicated searches



signatures involving calorimeters and muon chambers

Today's menu:

4 **new** CMS results

- ✓ Soft displaced vertex
- ✓ Pair of displaced taus
- ✓ Displaced $\mu^+\mu^-$ & h^+h^-
- ✓ LLP Trigger @ run 3

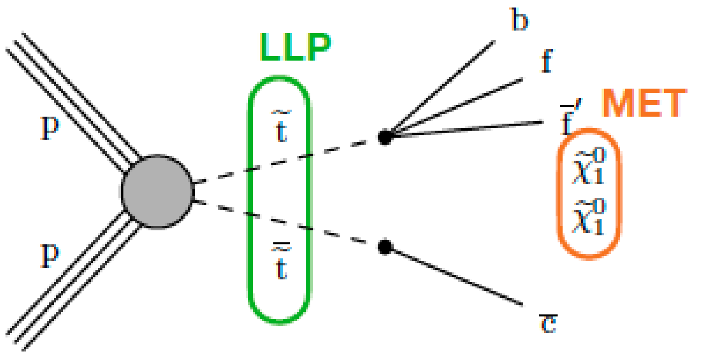
More covered in Celia Fernández Madrazo's presentation (11.07)

LLP with soft displaced vertex & MET

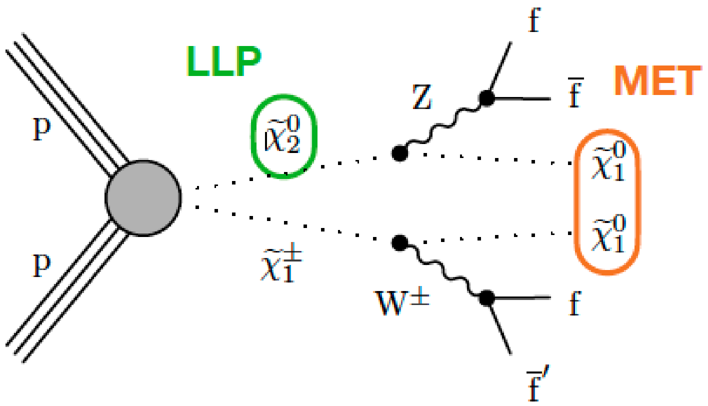
EXO-24-033

- Previous SUSY searches limited at **low mass splitting** between LLP & WIMP
- New analysis targetting
  - LLP decay into ≥ 2 charged particles → **Soft** (pT>0.5 GeV) **D**isplaced **V**ertex
  - Weaking interacting particles → MET
  - **I**nitial **S**tate **R**adiation jet → boost the decay

Top squark coannihilation

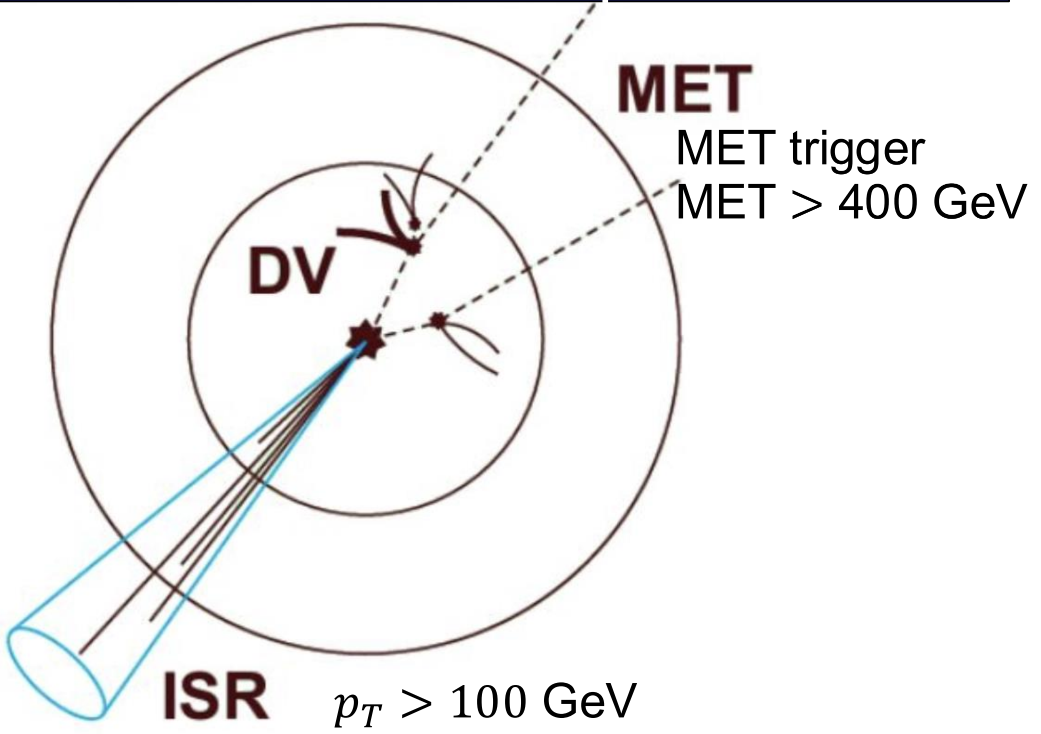


Bino-wino coannihilation



Free parameters: *Δm, m_{LLP}, cτ (only for bino-wino*)*
Consider **Δm ∈ [12-25] GeV**

ISR + MET + Soft Displaced Vertex



DV: ≥ 2 tr (pT > 0.5 GeV)

Veto on selected e,μ, γ, τ

LLP with soft displaced vertex & MET

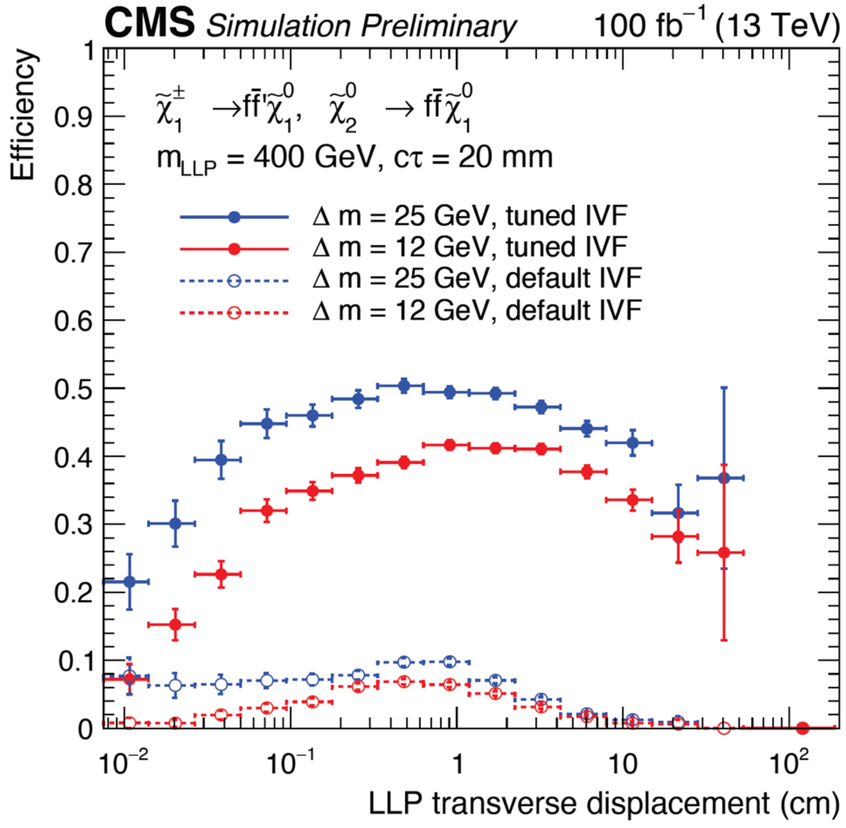
EXO-24-033

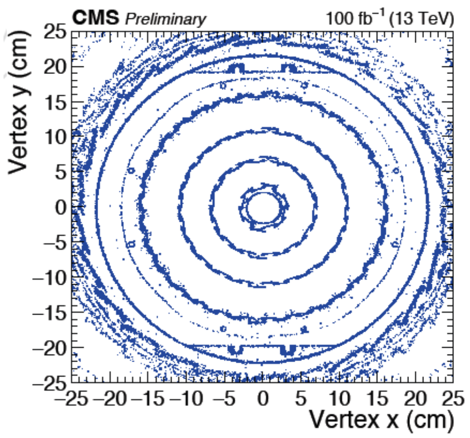
Soft Displaced Vertex

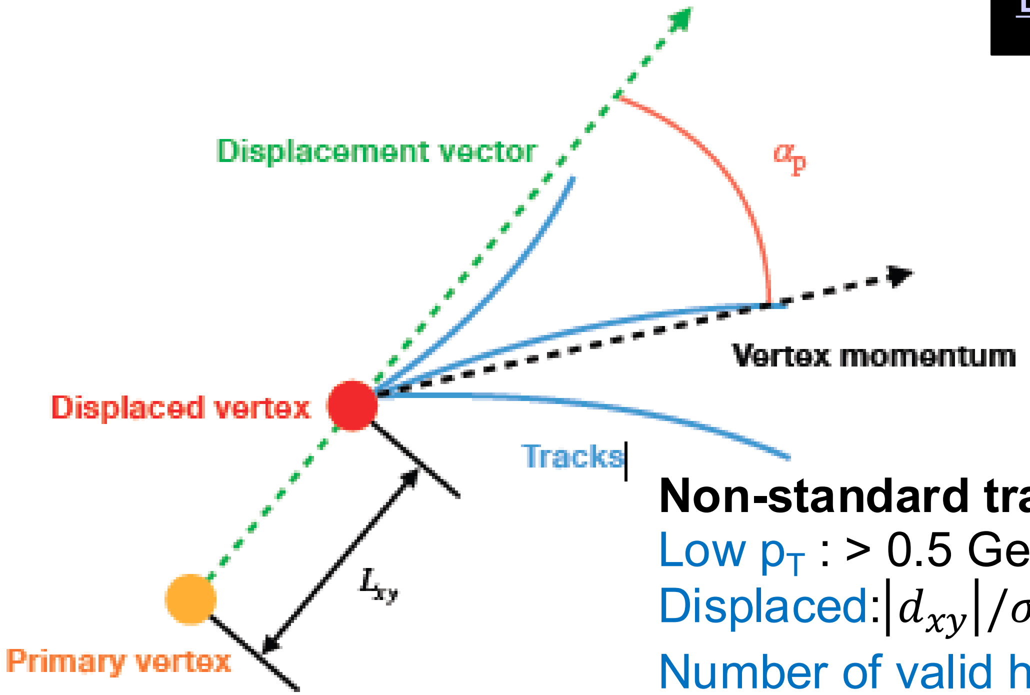
Inclusive Vertex Finder tuned for LLP

- Large opening angle
- Vertex momentum not pointing to primary vertex

Veto on tracker material region:
→ nuclear interaction is a source of background vertices







Non-standard track (pre)selection

Low p_T : > 0.5 GeV

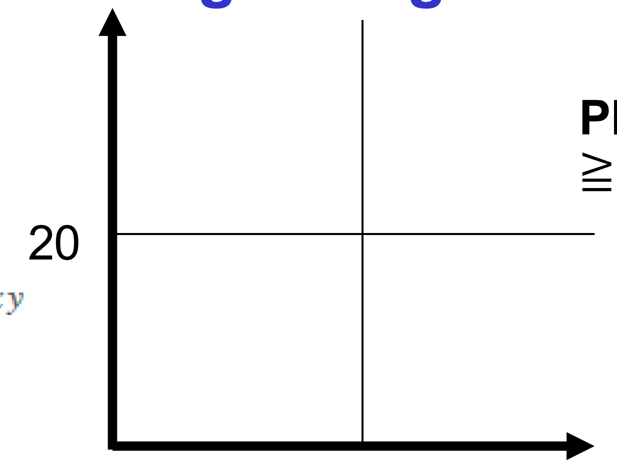
Displaced: $|d_{xy}|/\sigma_{d_{xy}}$ > (2) 4

Number of valid hits: > (6)13

Signal regions

Displacement:

$$S_{xy}^{vtx} \equiv |L_{xy}|/\sigma_{L_{xy}}$$



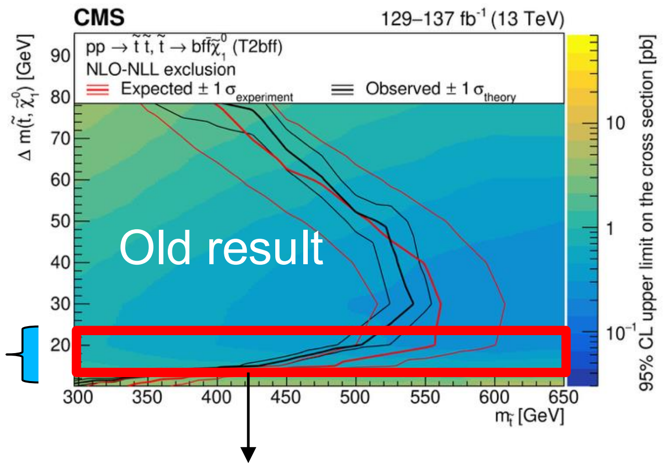
Plans for 1,2, ≧ 3 good tracks / DV

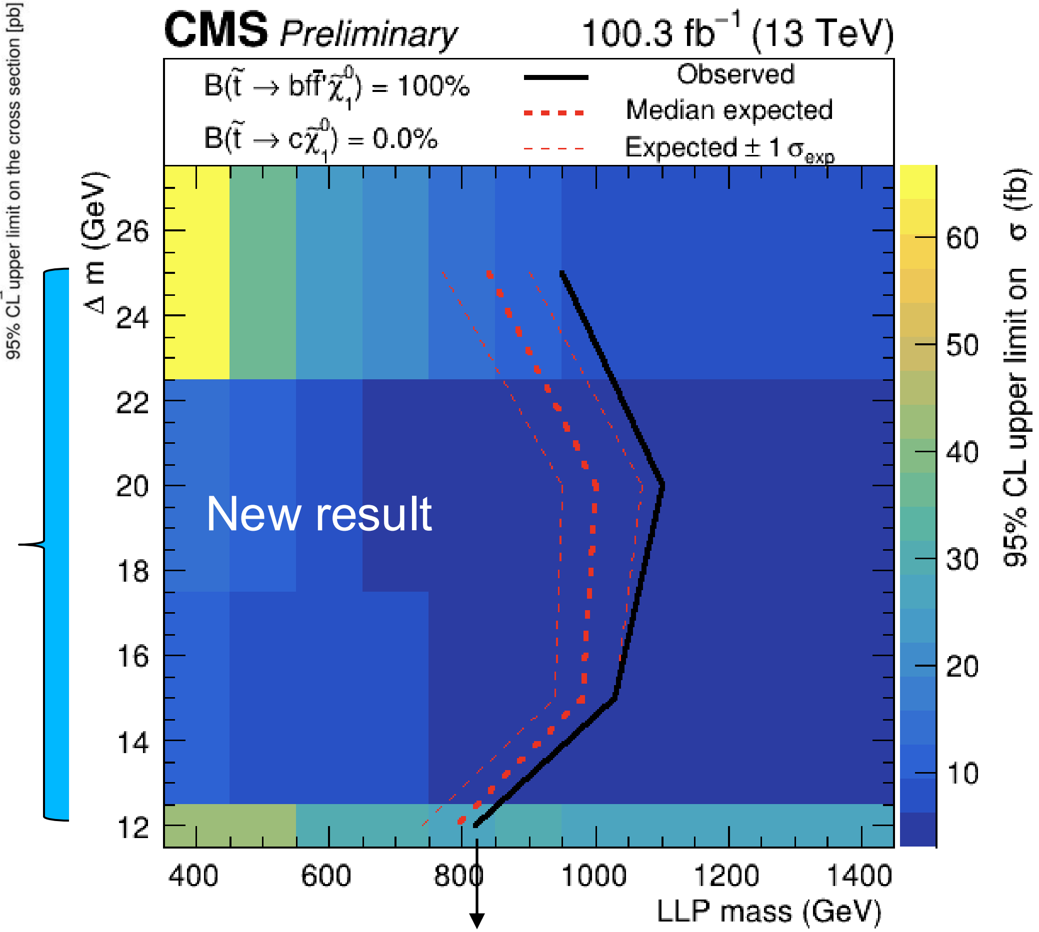
LLP with soft displaced vertex & MET

EXO-24-033

Top squark coannihilation

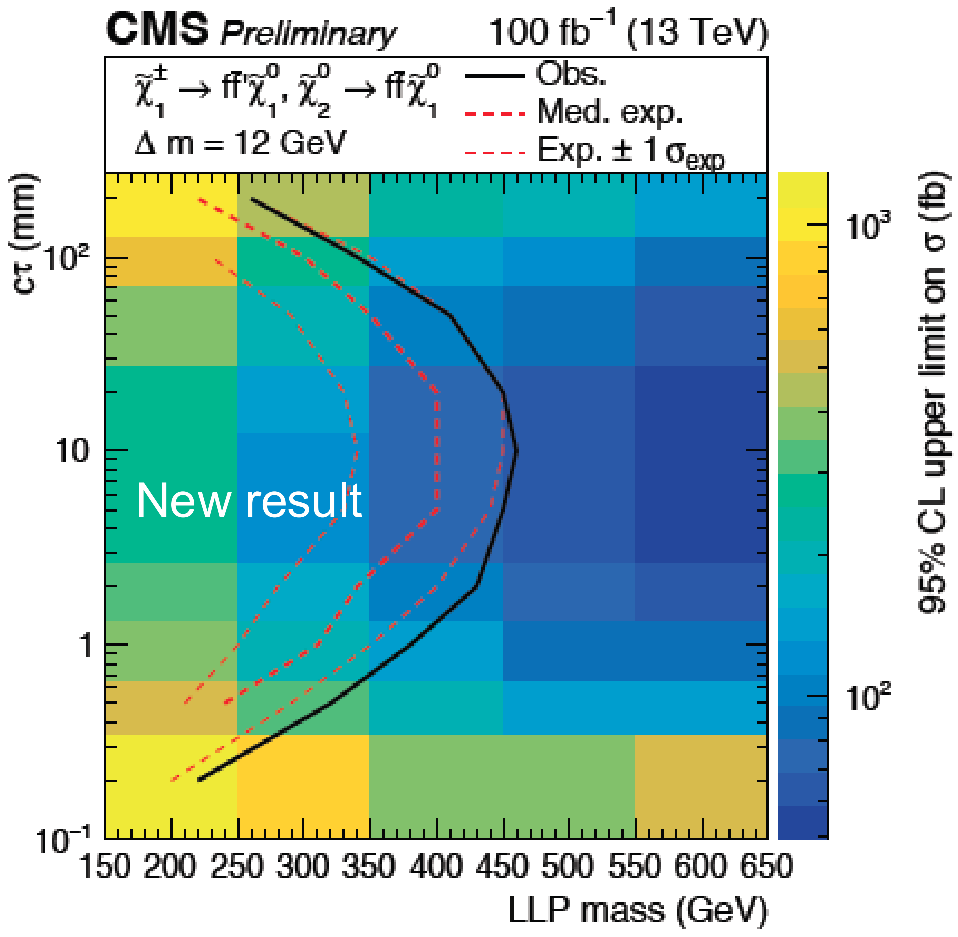
SUS-18-004: covers a broad range **Δ*m***
but limited sensitivity* at Δ*m





Bino-wino coannihilation:

Good sensitivity in o(1)-o(100) mm
→ Sensitivity up to 450 GeV

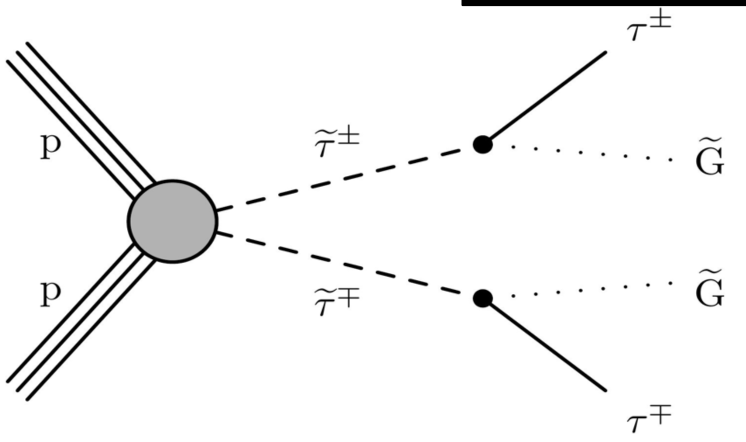


SVD lead to large improvement in the compressed spectra

Long-lived stau: use of NN displaced tagger

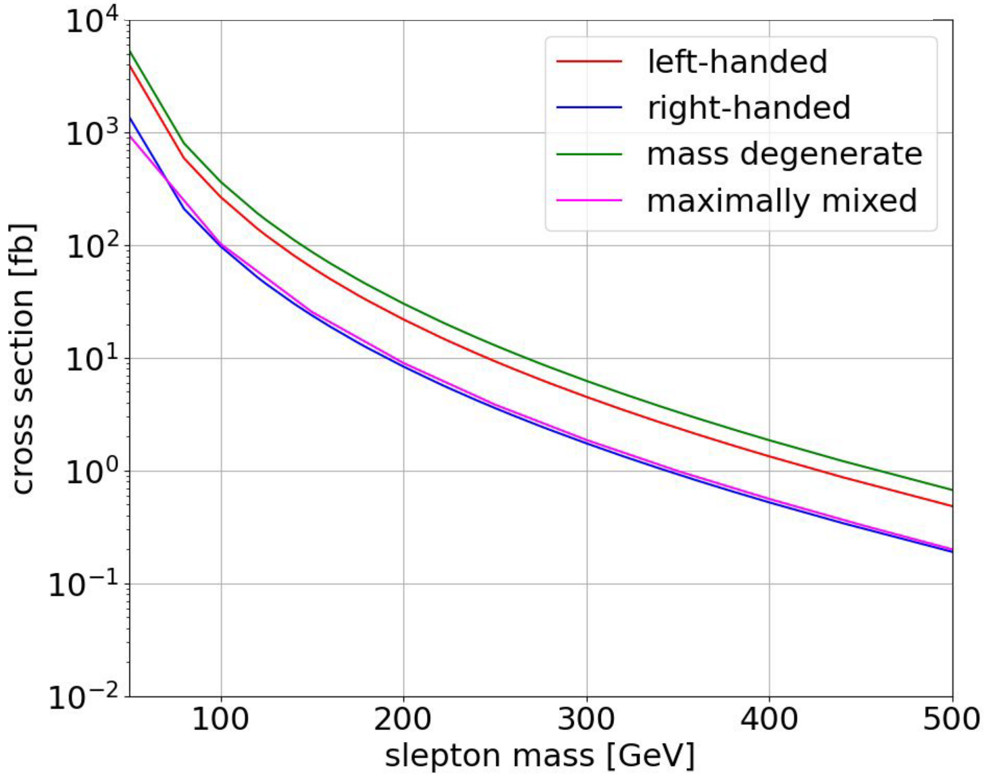
EXO-24-020

- Motivation GMSB models with gravitino being the LSP



- Previous publications
  - **Low $c\tau$** :
    - SUS-21-002: 2 hadronically decaying taus τ_{had}:
    - cover prompt decay using the default tau algorithm
  - **High $c\tau$:**
    - EXO-18-002: highly ionizing track – sensitive to $c\tau$ >>1m
  - **Intermediate $c\tau$:**
    - EXO-18-003: displaced electrons/muons (no τ_{had})

- **New strategy:**
  - Search with 2 τ_{had} (largest BR)
  - Developped a dedicated tagger for displaced tau
  - Improved sensitivity



Long-lived stau: use of NN displaced tagger

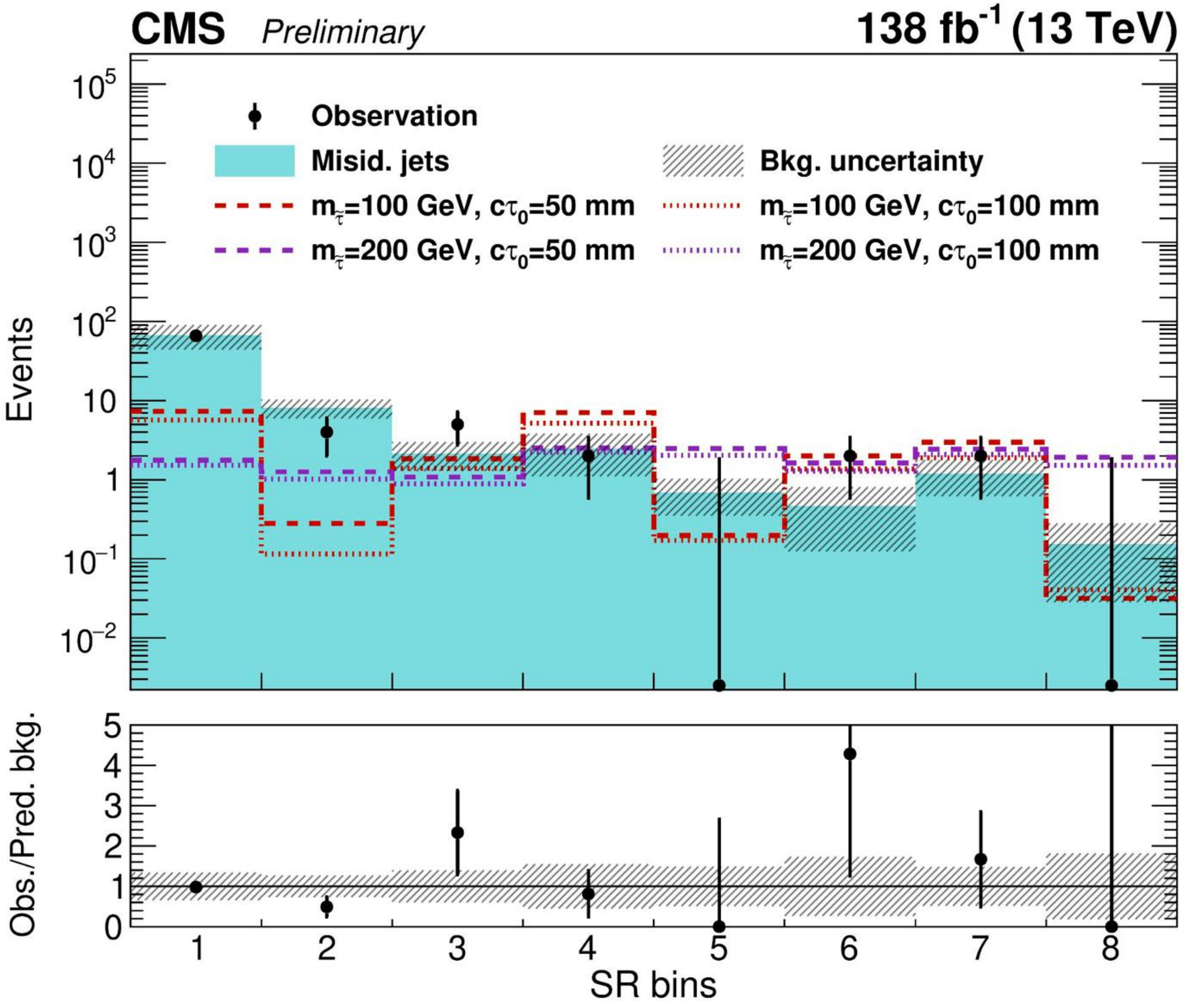
EXO-24-020

- New tagger: DisTau
  - Use AK4 jets with loose constraints to vertex
  - ParticleNet-like architecture - Inputs: jet daugher features

- Event selection
  - MET trigger – MET > 120 GeV
  - Veto on electrons, muons & b-jets
  - **Exacty 2 jets with DisTau ID**

- Signal Region (SR) bins

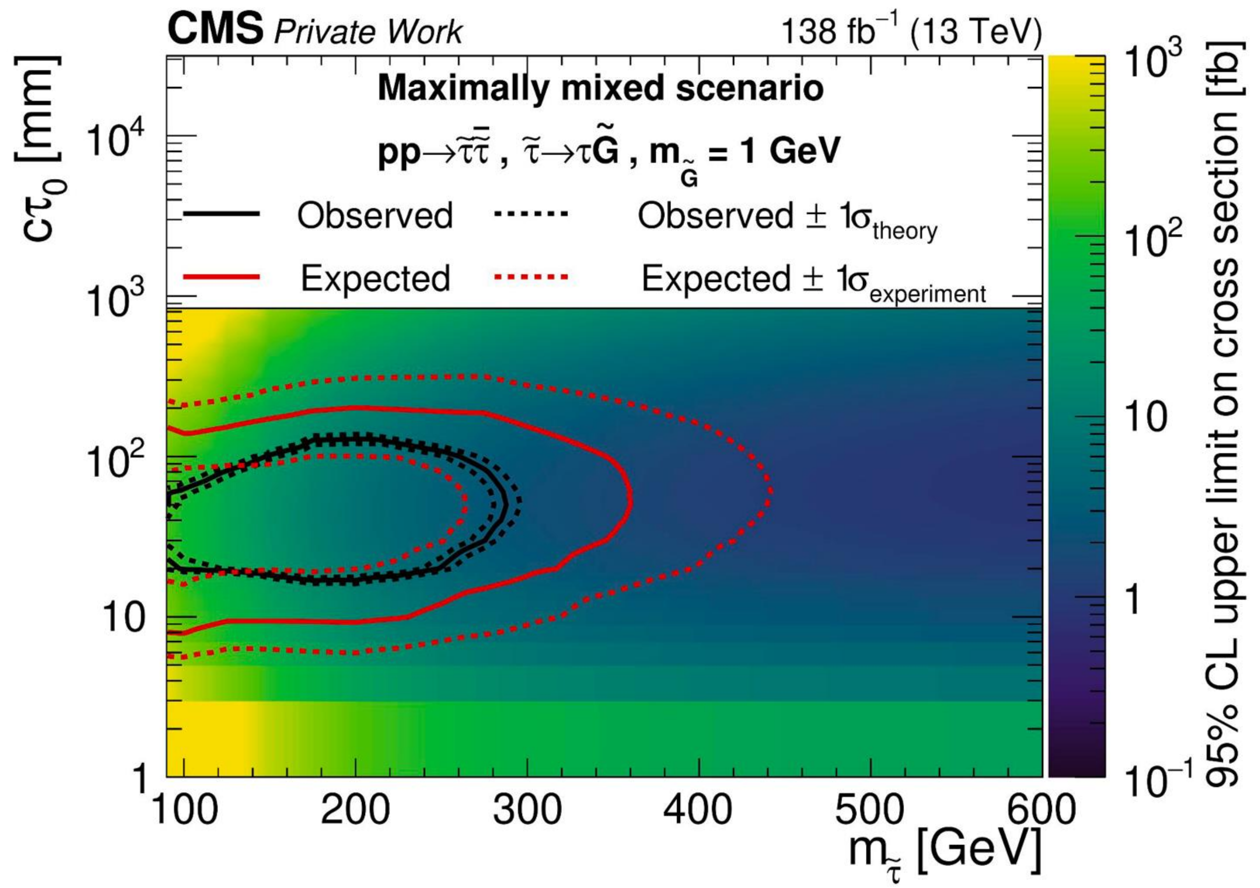
defined by $p_{T,j2}$, MET and m_{T2} variables

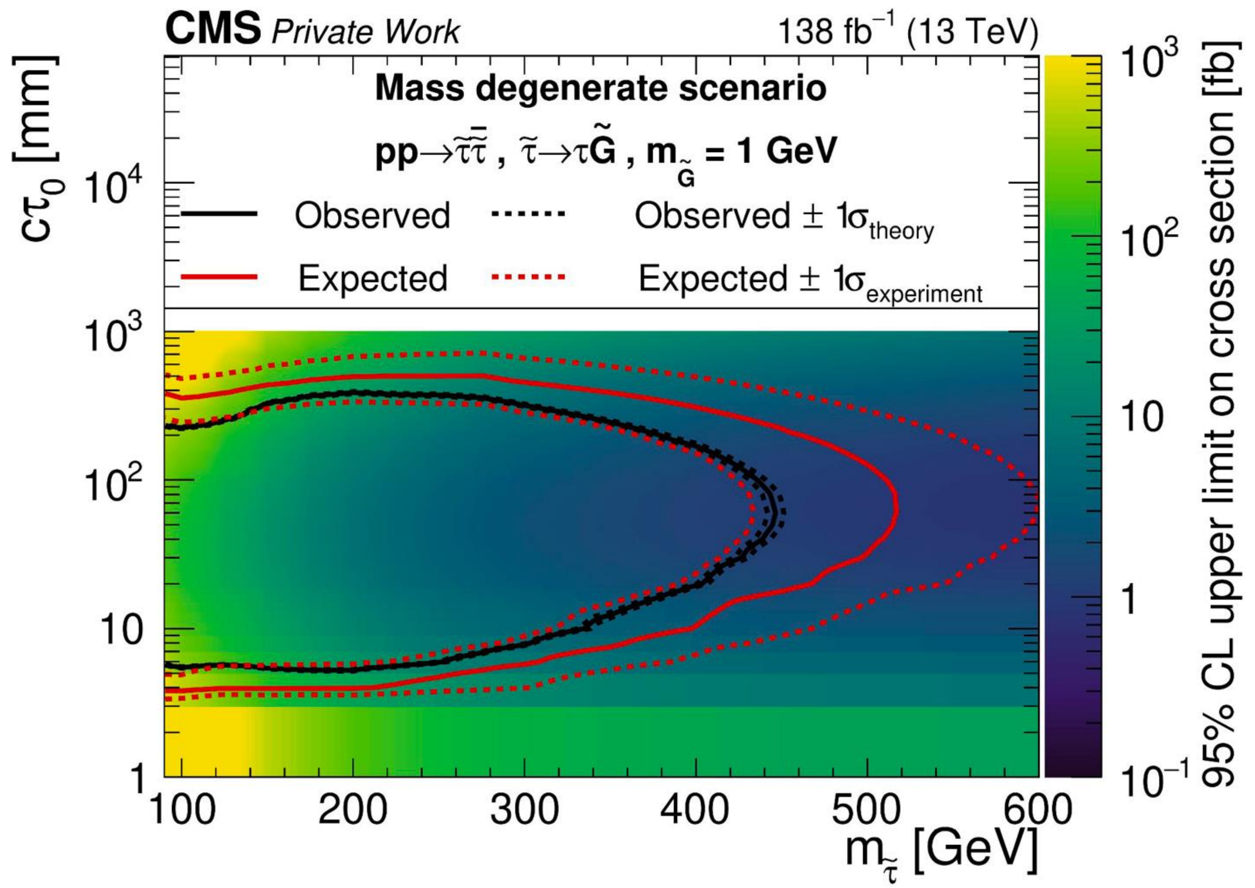


Long-lived stau: use of NN displaced tagger

EXO-24-020

Strongly pushed the limits from about 5 up to 40 mm depending on mass and scenario

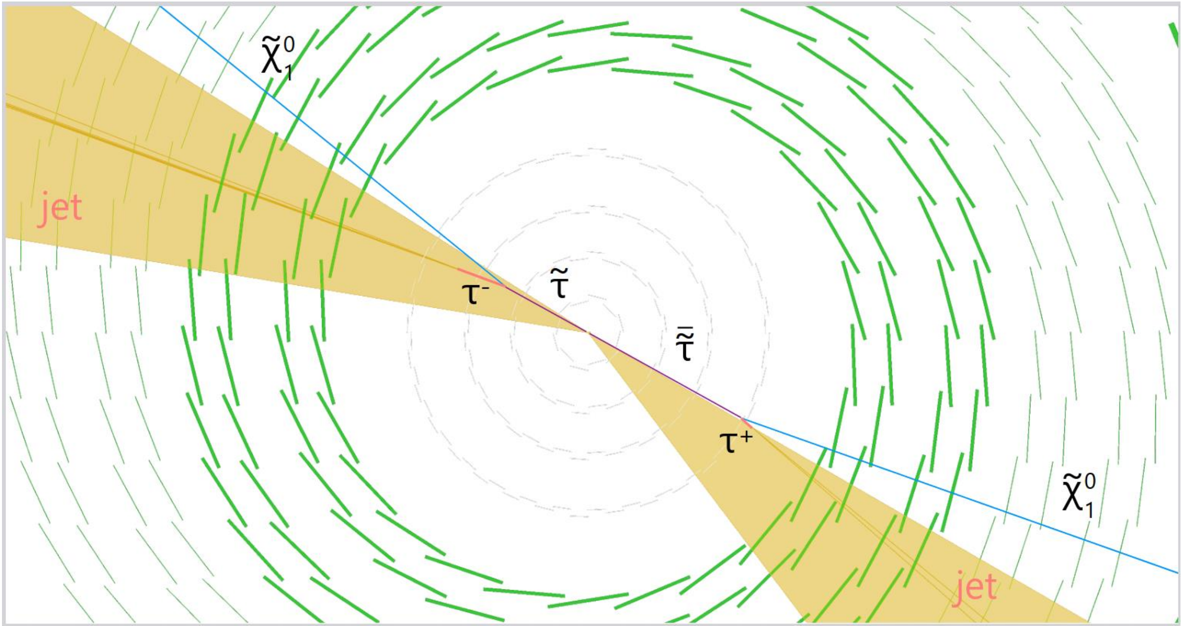


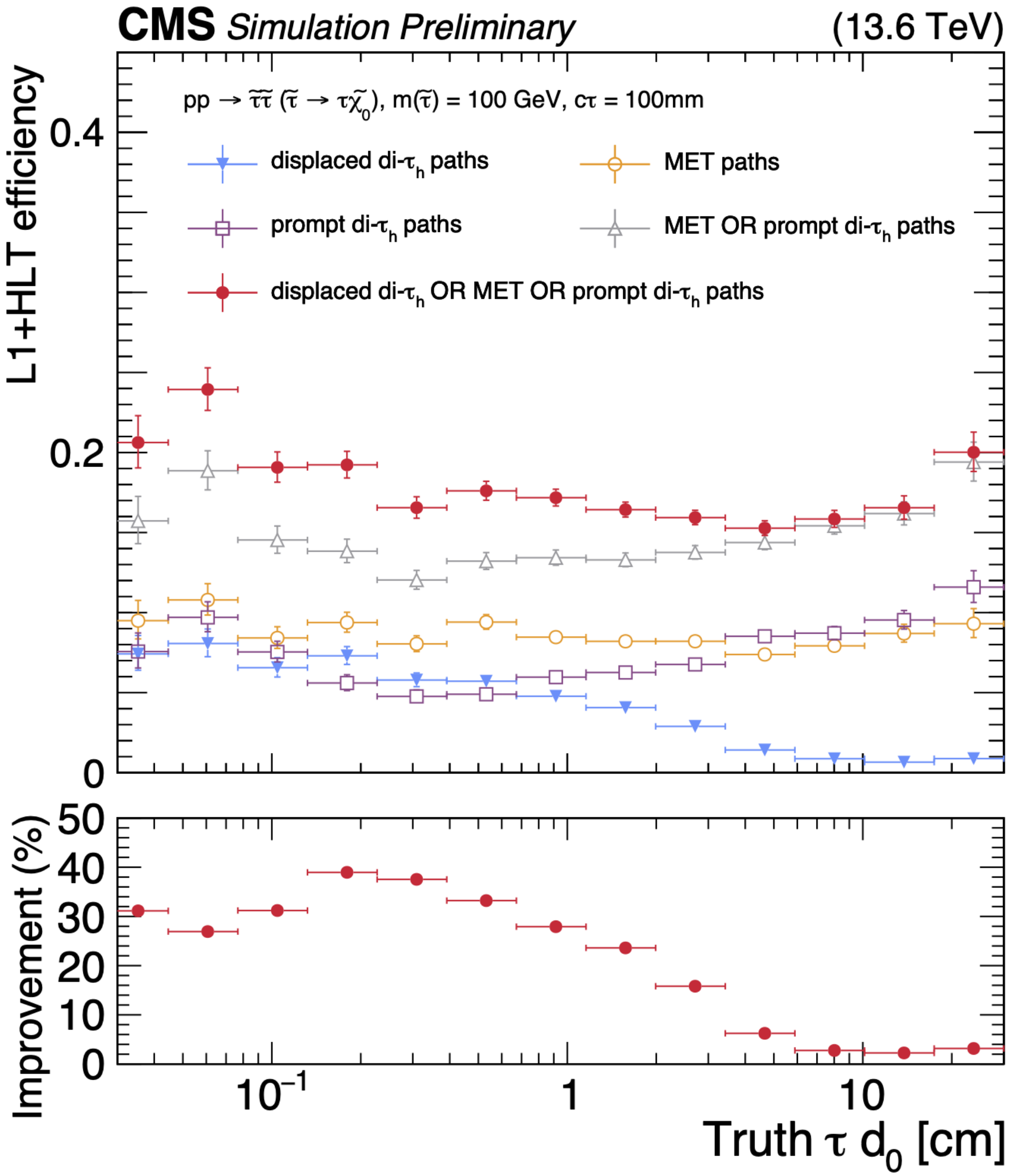


Long-lived stau: run 3 perspectives

EXO-23-016

- **New trigger introduced in Run 3**:
  - Dedicated to triggering on displaced taus at the HLT
  - Improves the trigger efficiency for tau $d_0 < 5$ cm and $p_T^{miss} < 300$ GeV

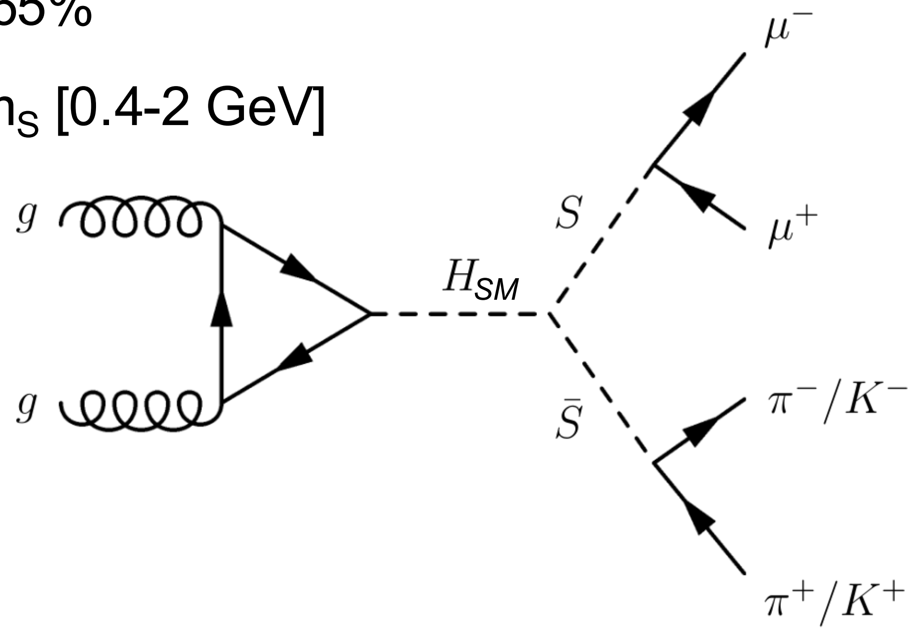


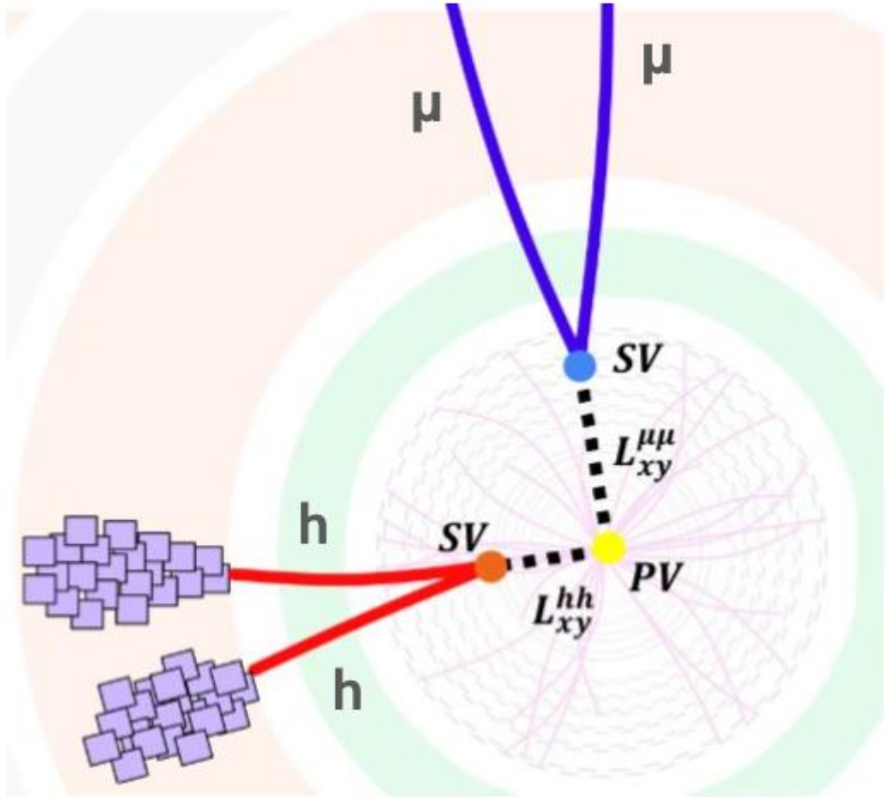


Long-lived light scalar from Higgs decay

EXO-24-034

- Light scalars o(GeV) appear in several BSM theories (SUSY, DM, cosmic inflation, ..)
- Small mixing parameter with H_{SM}
  → prompt/displaced decays
- For $0.4<m_S<2$ GeV: $S \rightarrow \pi^+\pi^-$ or $k^+ k^-$
  are the dominant decay modes
  - BR($\pi^+\pi^-$ or $k^+ k^-$) within 30 to 65%
  - BR($\mu^+\mu^-$) within 3 to 24% for m_S [0.4-2 GeV]
- Signal searched





Long-lived light scalar from Higgs decay

EXO-24-034

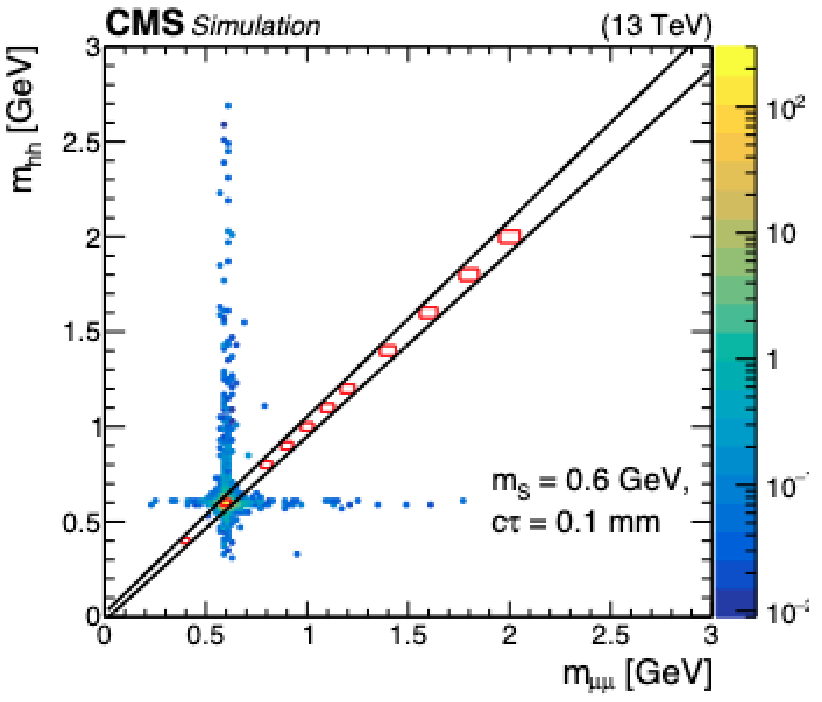
- Event selection

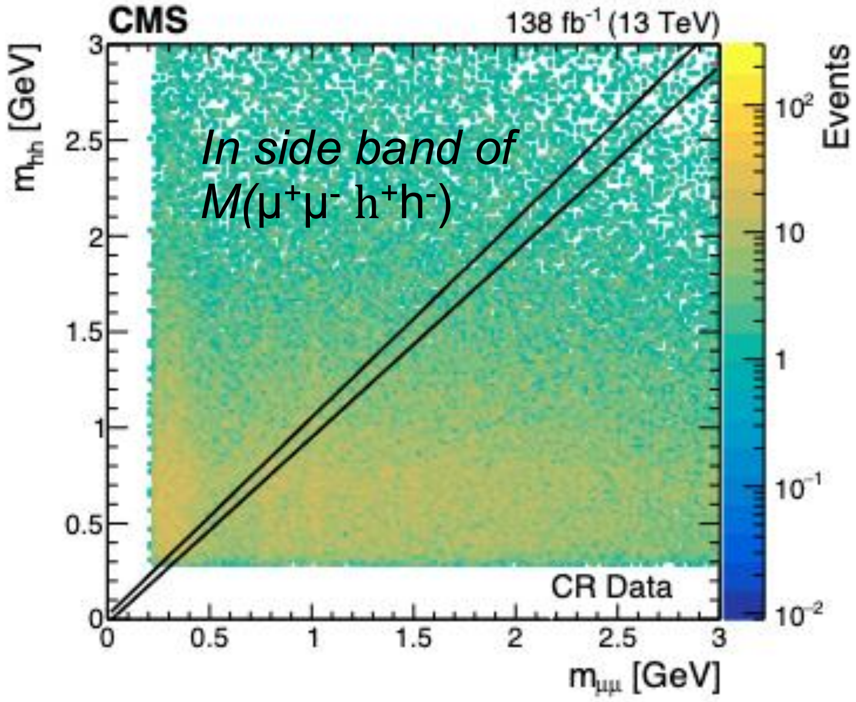
  - Muon trigger - Muon: p_T>5, 26/29 (trigger) GeV
  - Hadrons (π or k): p_T>5 GeV
  - Mass window on $M(\mu^+\mu^-)$ & $M(h^+h^-)$ depending on resolution at different m_S
  - Constraint on $M(\mu^+\mu^- h^+h^-)$ compatible with $M(H_{SM})$

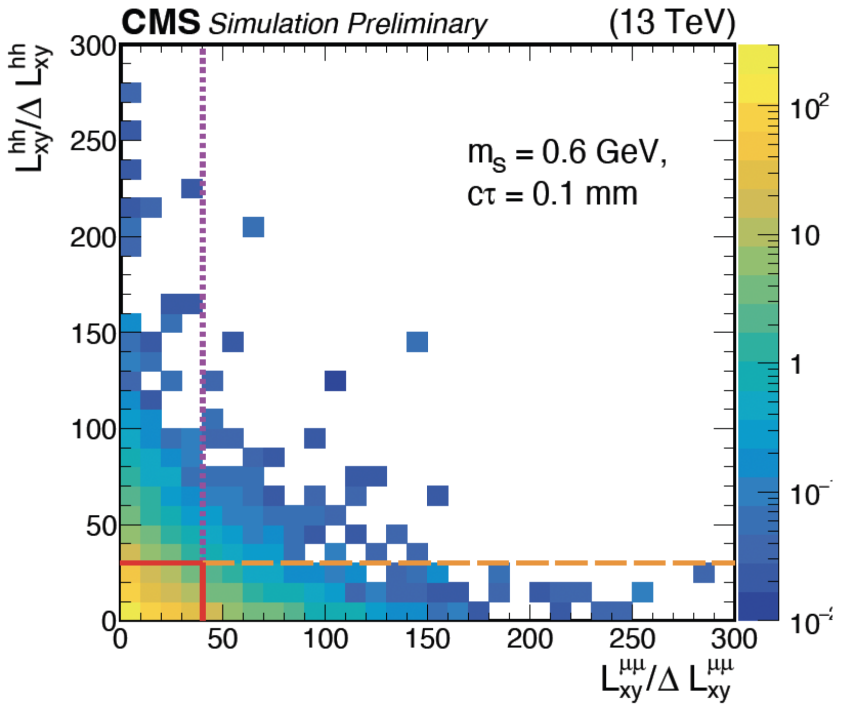
Selection region – 4 categories

(based on L_{xy} significance)

- Prompt
- Displaced $\mu^+\mu^-$
- Displaced $h^+ h^-$
- Both displaced

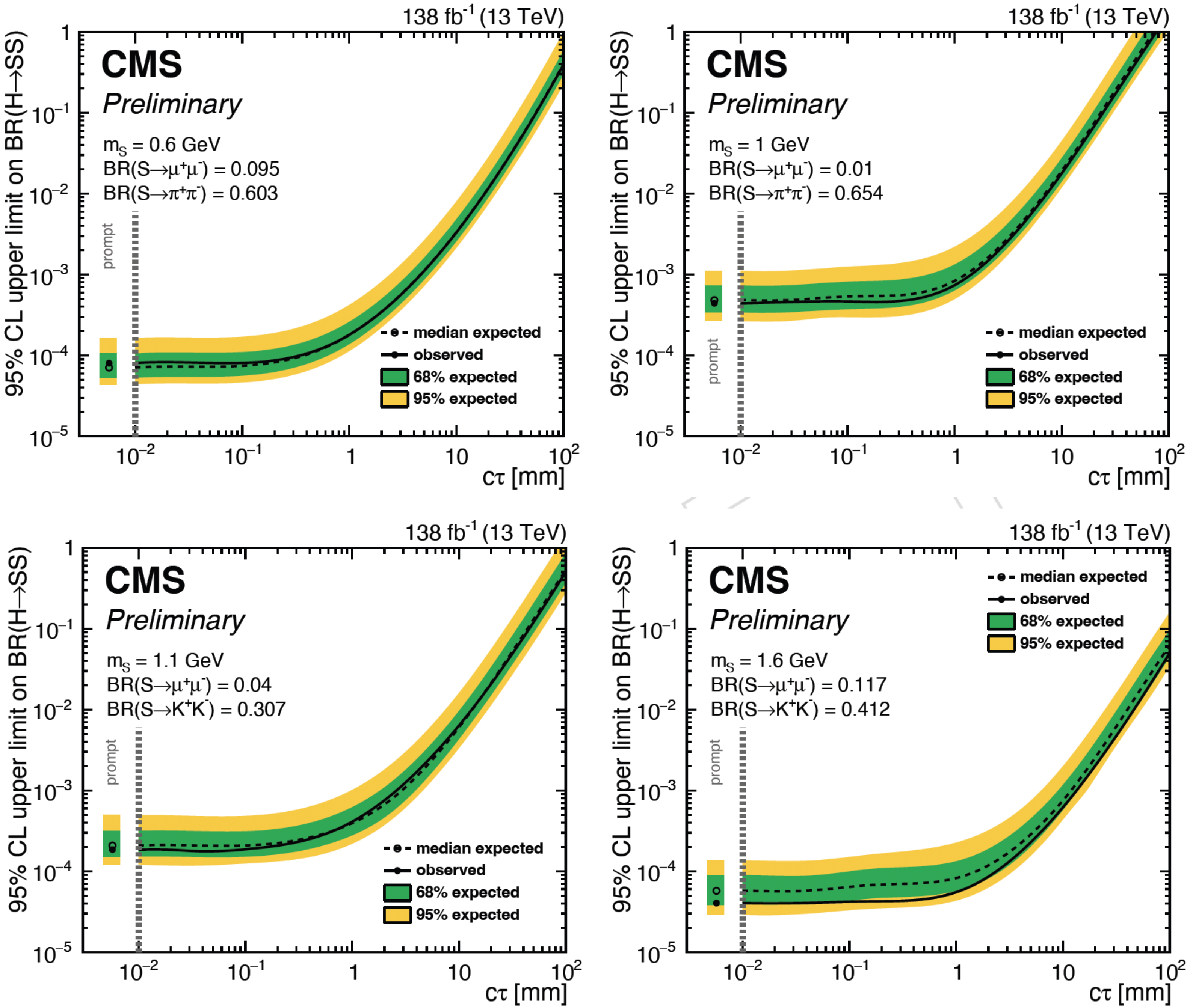






Long-lived light scalar from Higgs decay

EXO-24-034



Limits combining the 4 categories

Kaons decay opens for m(S)>2m(K)

Good sensitivity for m_S in 0.4-2 GeV dominated by the prompt category for $c\tau$<1 mm

LLP triggers at run 3

EXO-23-016

- Long-lived particles could leave **unique signatures** that may not captured by standard triggers
- **Dedicated triggers targeting LLPs** enable increased sensitivity to wide variety of signal models
- During Run 3, variety of such triggers were introduced and/or improved compared to Run 2
- The performance of these triggers in 2022-2024 data and their powerful complementarity is reported
- **In 2024**

(typical run with PU of 63)

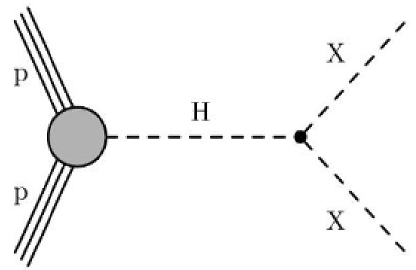
Data	Total rate [Hz]	Pure rate [Hz]
Standard	393	311
Parking	234	182
Scouting	4200	3800
Full reconstruction: standard or parking	586	389

- **LLP triggers**
  - **Displaced objects**: jets, tau, photon+H_T, single and dimuon, muon+photon
  - **Timing:** ECAL-based delayed jet, delayed photon, HCAL-based displ & delayed jet
  - **Other**: Muon Detector Shower, Jet or no-BPTX
  - **Scouting**: dimuon

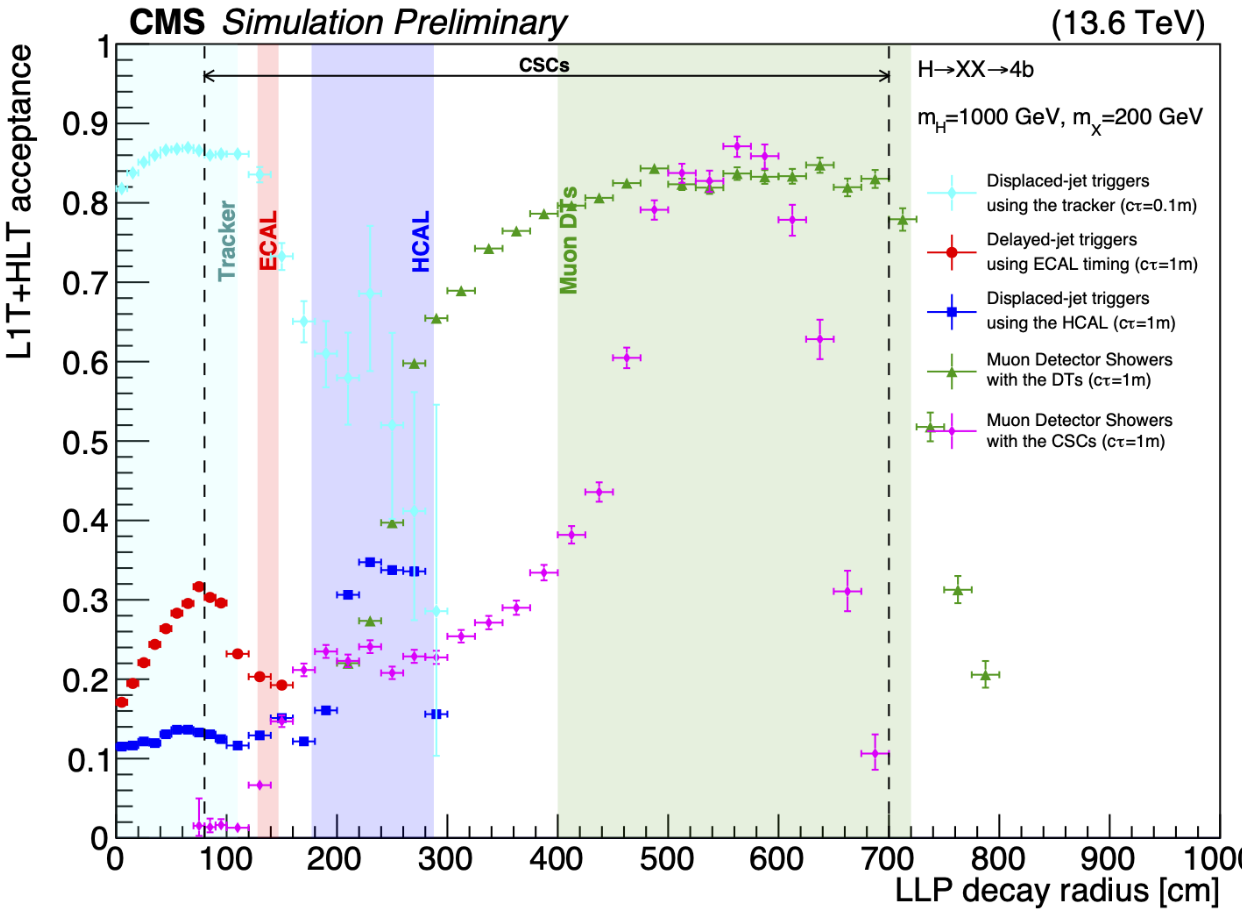
LLP triggers

EXO-23-016

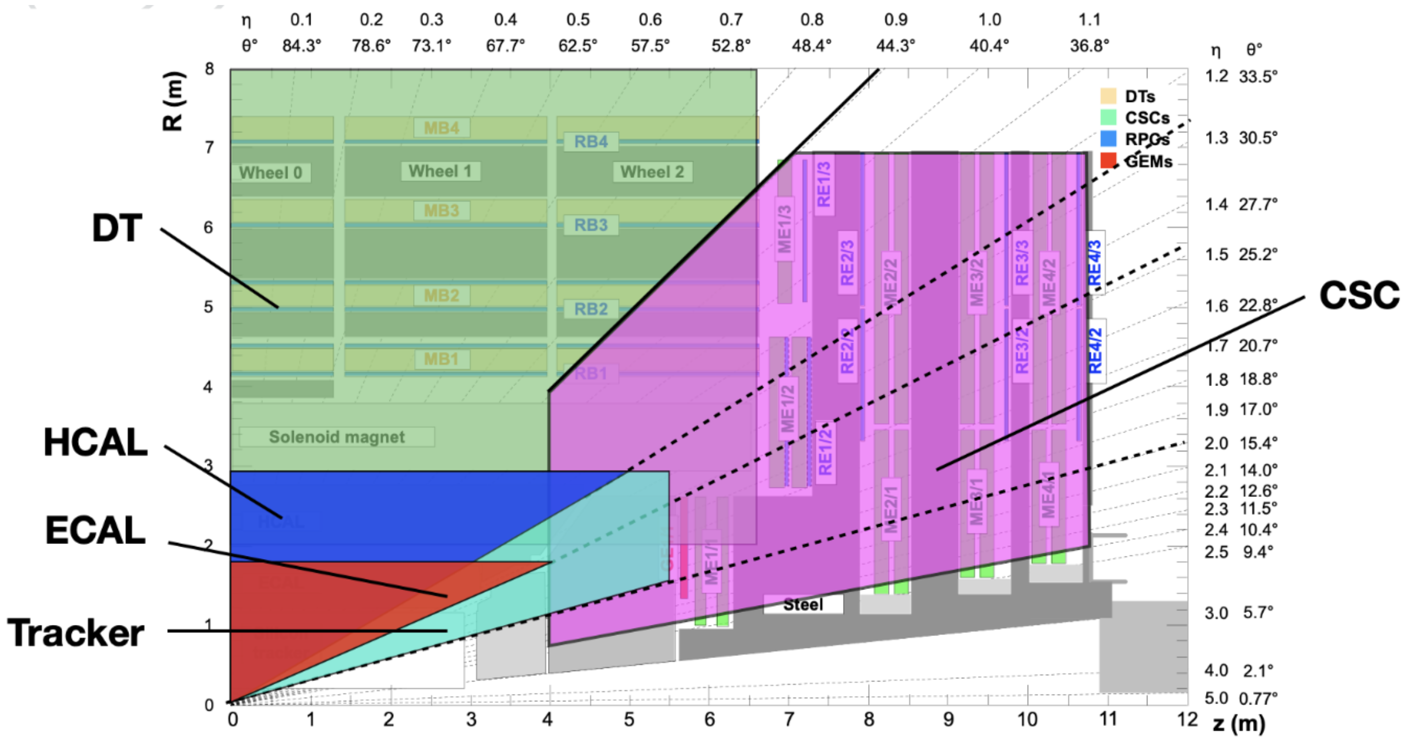
- LLP triggers capitalize on **different CMS subdetectors**, hence **can target different phase space**
- The powerful **complementarity** of the program is shown using Twin Higgs model as a benchmark



Complementarity of dedicated hadronic LLP triggers, for H→XX→4b signal



The fiducial regions used for trigger acceptance calculation



Conclusions

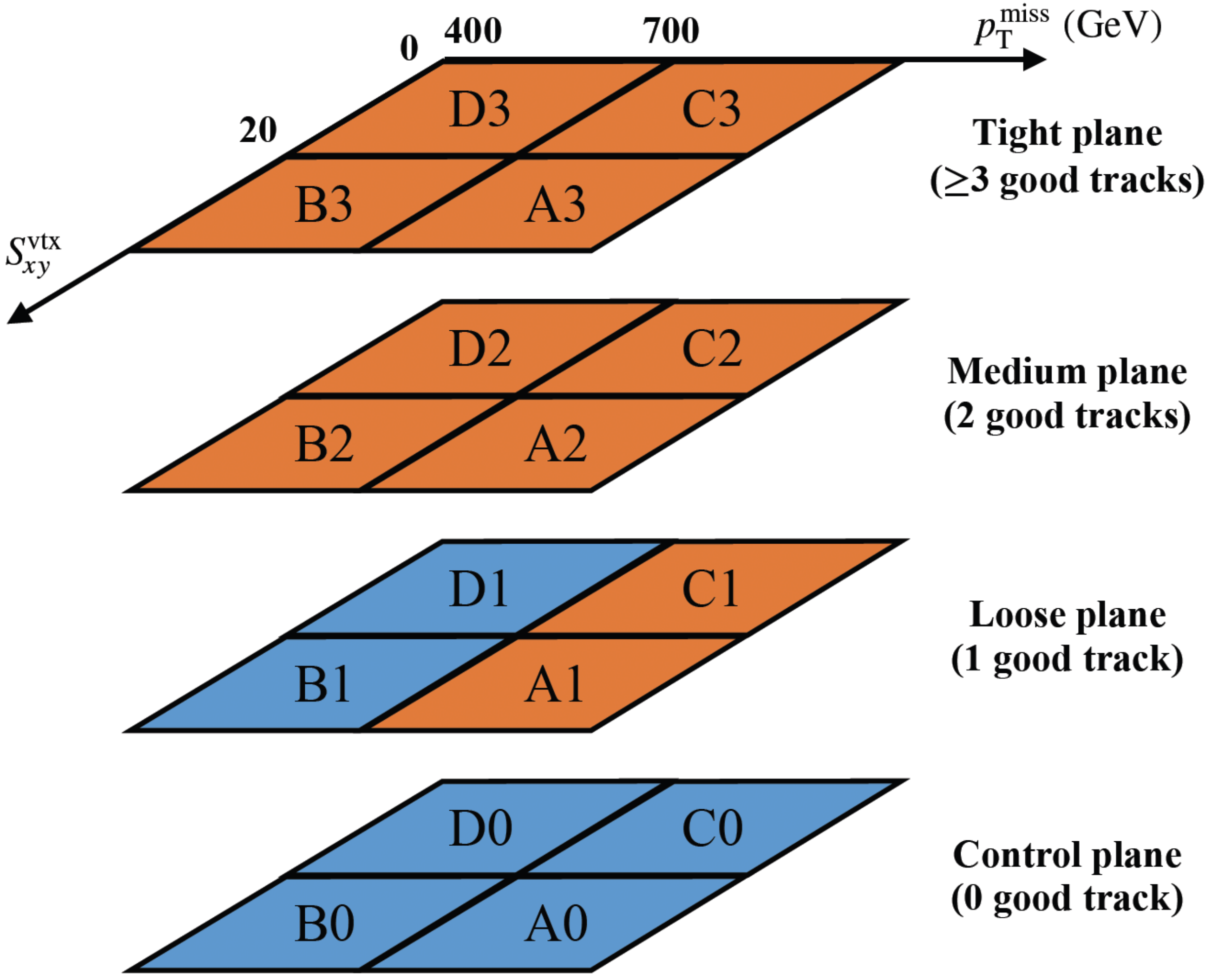
- CMS has released new results on long-lived particles
  - Soft Displaced Vertex + MET that probes compressed spectrum of SUSY
  - Long-lived staus with the used of a dedicated tau ID algorithm
  - Search for $H_{sm} \rightarrow SS$, S being a long-lived low mass scalar with 2 displaced pairs (muons and hadrons)
  - No excess observed but limits have been pushed further

- CMS continues to expands its BSM searches at lower coupling, lower mass and for a broad range of lifetime

- New triggers introduced during Run 3 will significantly improve our discovery potential → stay tuned !

LLP with soft displaced vertex & MET

EXO-24-033



signal and control regions

$$f_{i\to i+1} = \frac{f_{0\to 1}}{f_{0\to 1}^{lowMET}} f_{i\to i+1}^{lowMET}$$

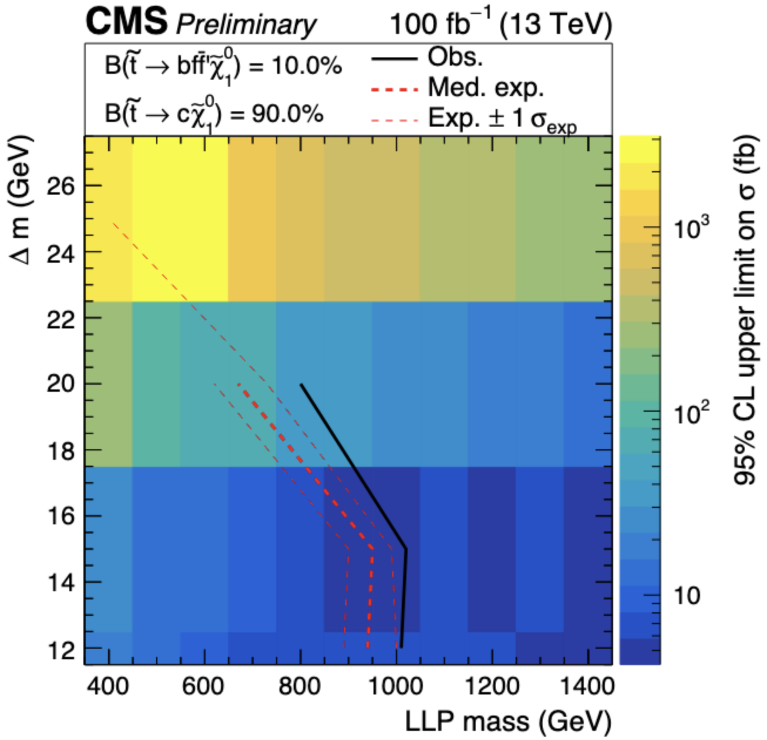
$$f_{0\to 1} = \frac{N_{bkg}^{B1+D1}}{N_{bkg}^{B0+D0}} \qquad N_{bkg}^{A1+C1} = N_{bkg}^{A0+C0} f_{0\to 1}$$

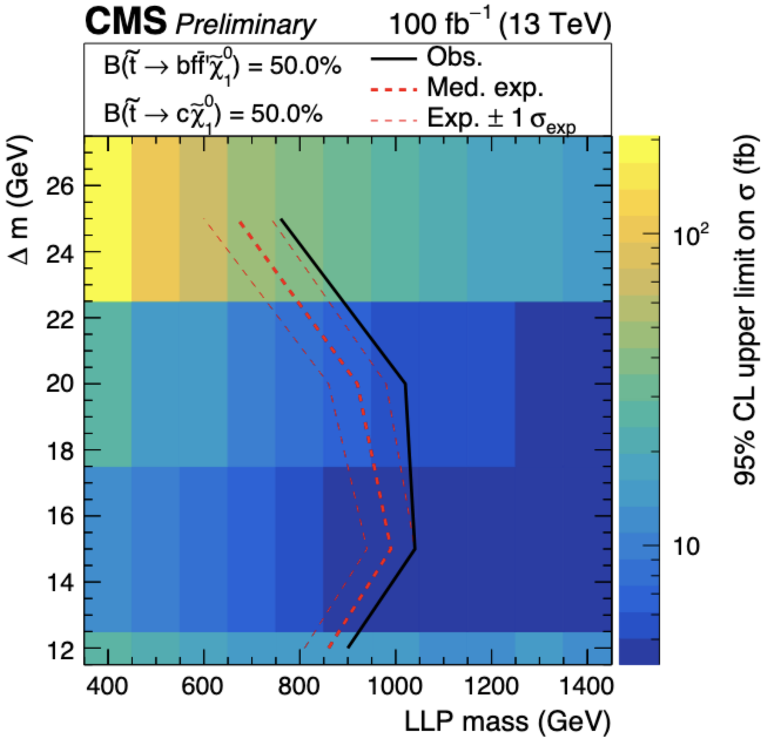
Search plane	A	B	C	D
Tight plane ($N_{track}^{good} \geq 3$)	0	3	0	5
Prediction	0.4 ± 0.1	7.9 ± 0.7	0.5 ± 0.1	9.4 ± 0.8
Signal	1.8 ± 0.1	3.8 ± 0.2	0.4 ± 0.1	1.1 ± 0.1
Medium plane ($N_{track}^{good} = 2$)	5	98	5	117
Prediction	4.1 ± 0.3	78.7 ± 4.0	6.1 ± 0.5	115.7 ± 5.9
Signal	1.3 ± 0.1	2.9 ± 0.2	0.9 ± 0.1	1.9 ± 0.1
Loose plane ($N_{track}^{good} = 1$)	22	563	57	1224
Prediction	28.3 ± 1.6	–	65.1 ± 3.6	–
Signal	1.2 ± 0.1	3.0 ± 0.2	0.9 ± 0.1	2.8 ± 0.2
Control plane ($N_{track}^{good} = 0$)	63	1318	353	6638
Prediction	–	–	–	–
Signal	0.4 ± 0.1	1.4 ± 0.1	0.9 ± 0.1	2.8 ± 0.1

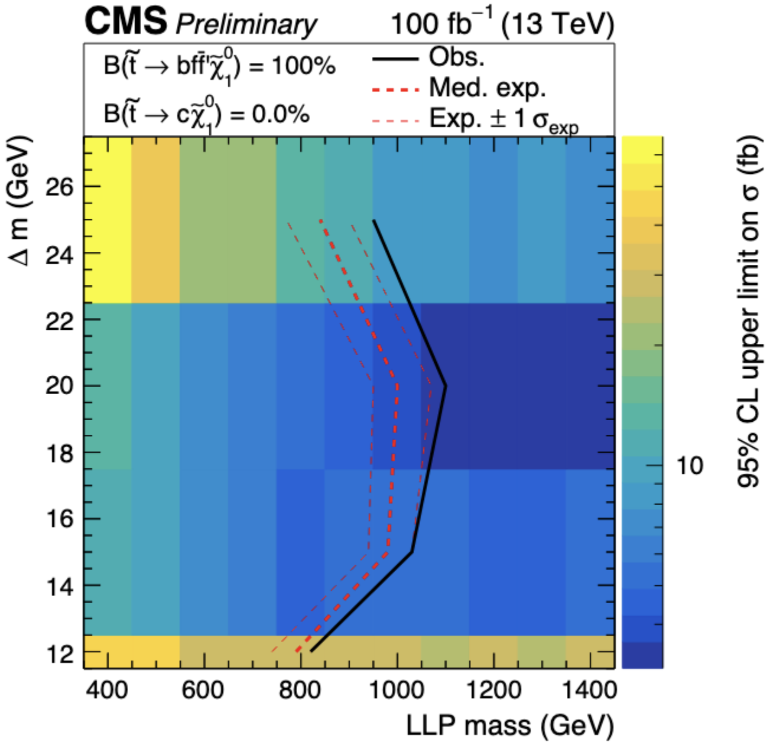
LLP with soft displaced vertex & MET

EXO-24-033

BR 4 body decay: 10 – 50 – 100%



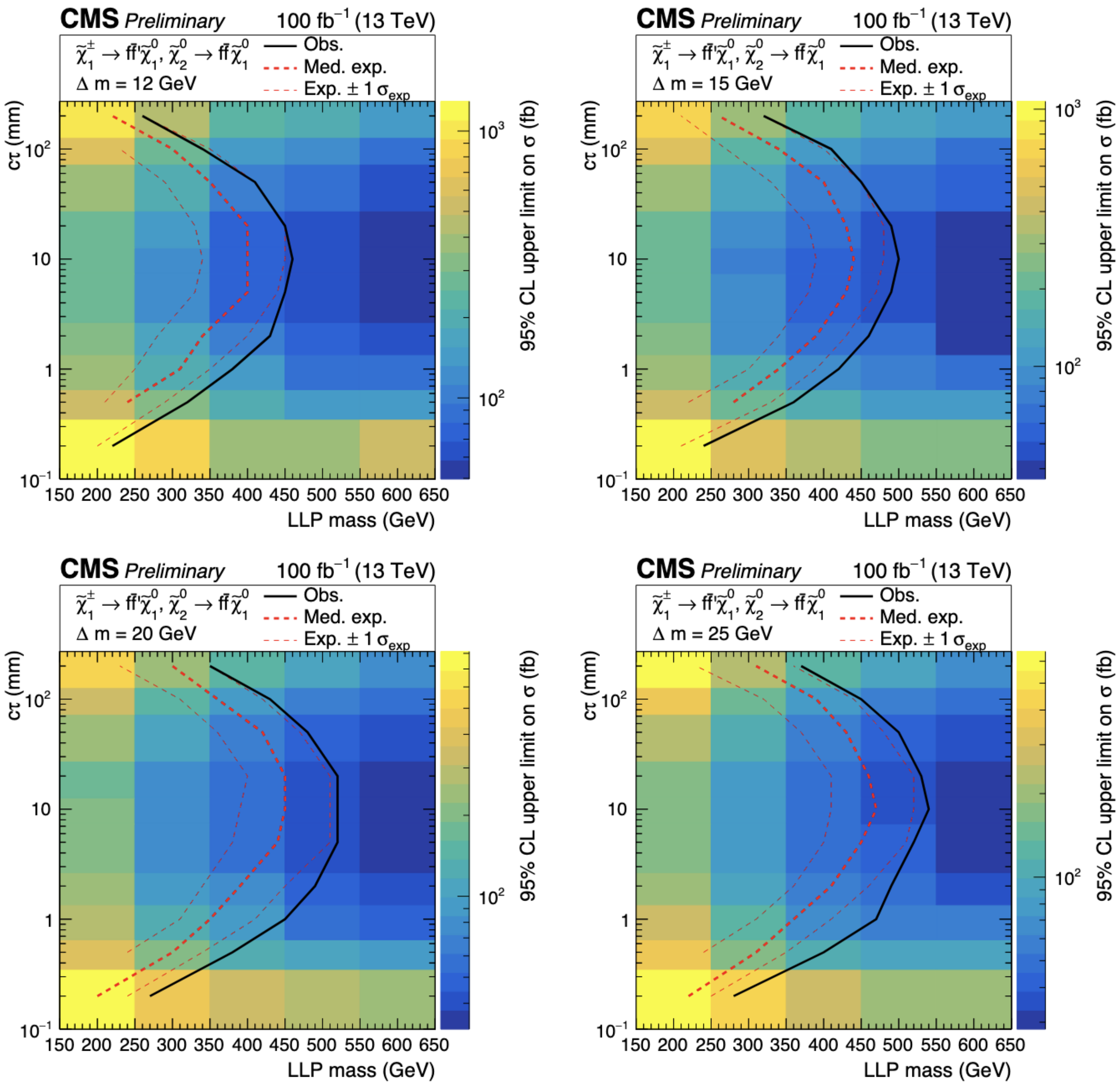




LLP with soft displaced vertex & MET

EXO-24-033

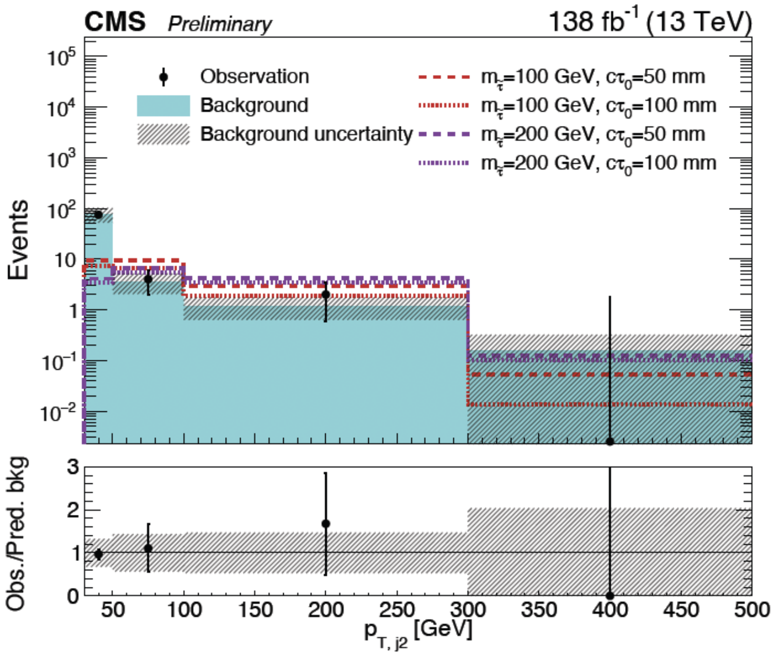
Δm varies from 12 to 25 GeV



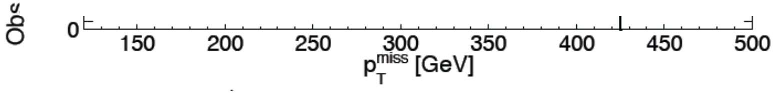
Long-lived stau: use of NN displaced tagger

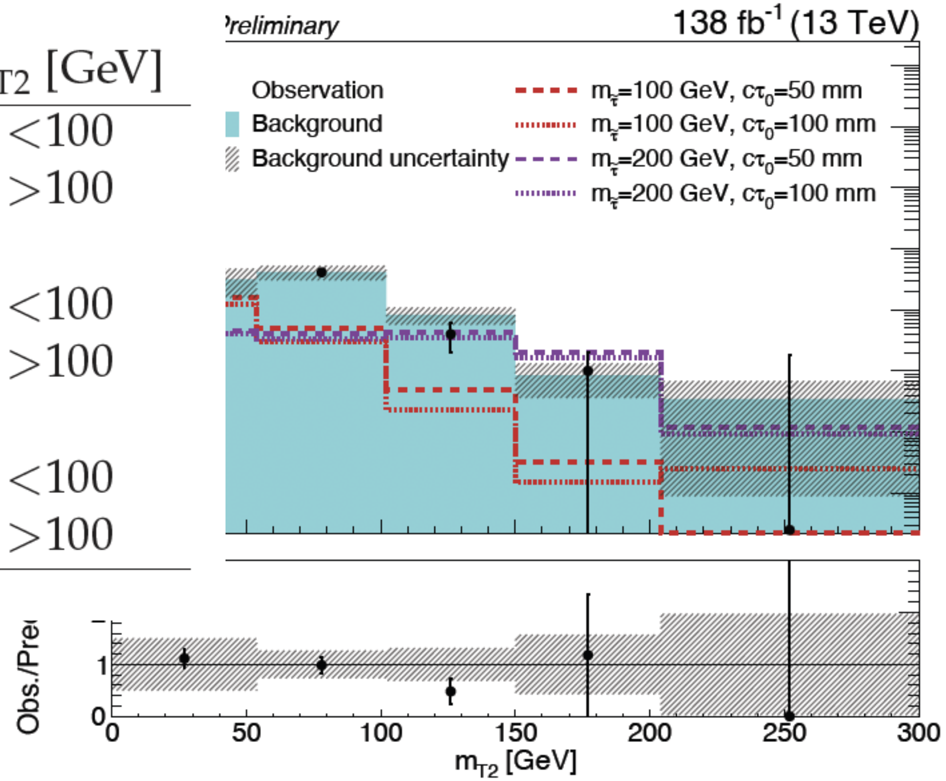
EXO-24-020

$$m_{T2}^2(\text{vis1},\text{vis2},p_T^{miss}) = \min_{\vec{p}_T^{\,inv1}+\vec{p}_T^{\,inv2}=\vec{p}_T^{\,miss}} [\max\{m_T^2(\vec{p}_T^{\,vis1},\vec{p}_T^{\,inv1}), m_T^2(\vec{p}_T^{\,vis2},\vec{p}_T^{\,in}$$



Bin no.	$p_{T,\,j2}$ [GeV]	p_T^{miss} [GeV]	m_{T2} [GeV]
1	30–50	120–250	<100
2	30–50	120–250	>100
3	30–50	>250	
4	50–100	120–250	<100
5	50–100	120–250	>100
6	50–100	>250	
7	>100		<100
8	>100		>100





Long-lived stau: use of NN displaced tagger

EXO-24-020

Bin no.	$p_{T,\,j2}$ [GeV]	p_T^{miss} [GeV]	m_{T2} [GeV]
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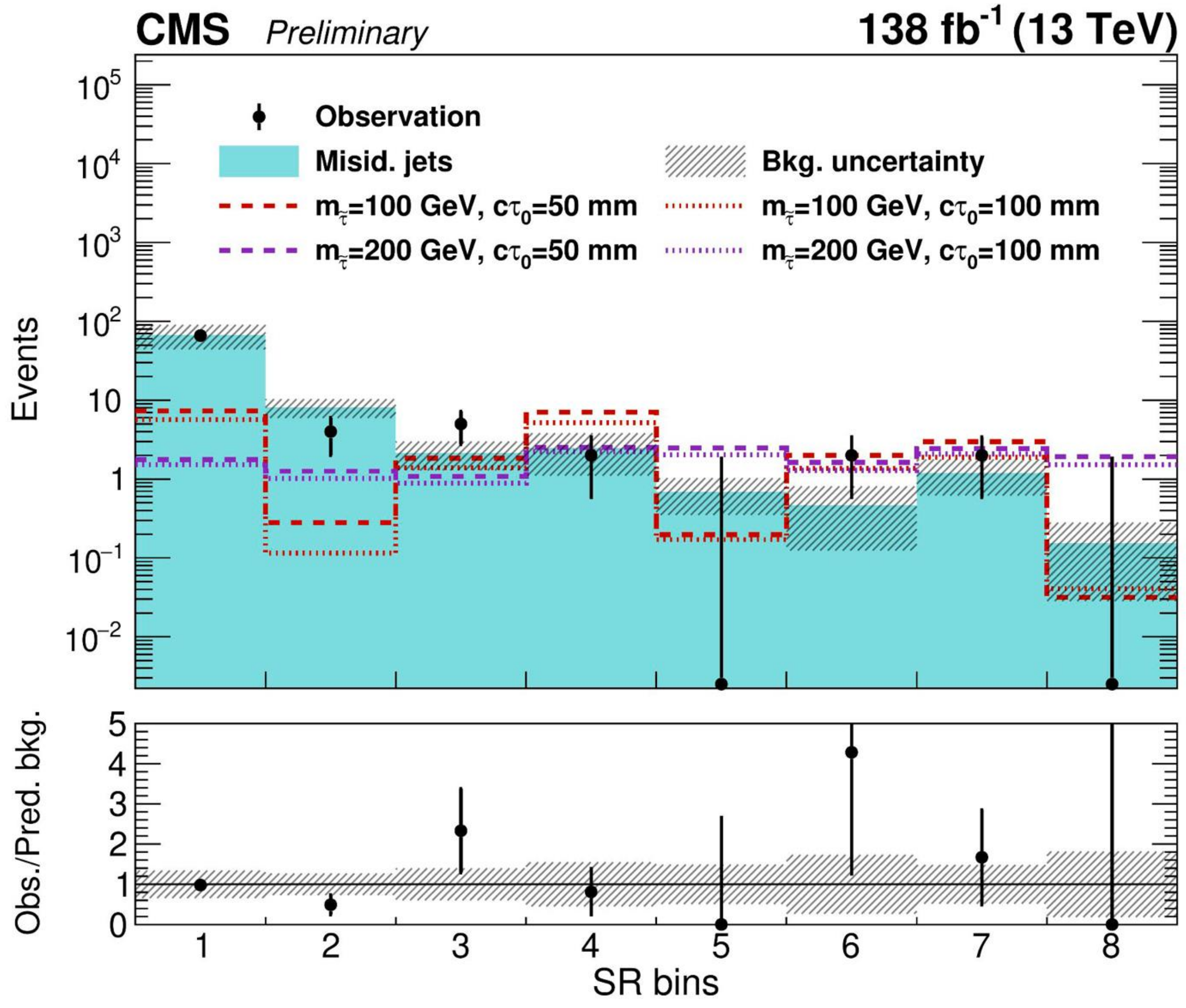
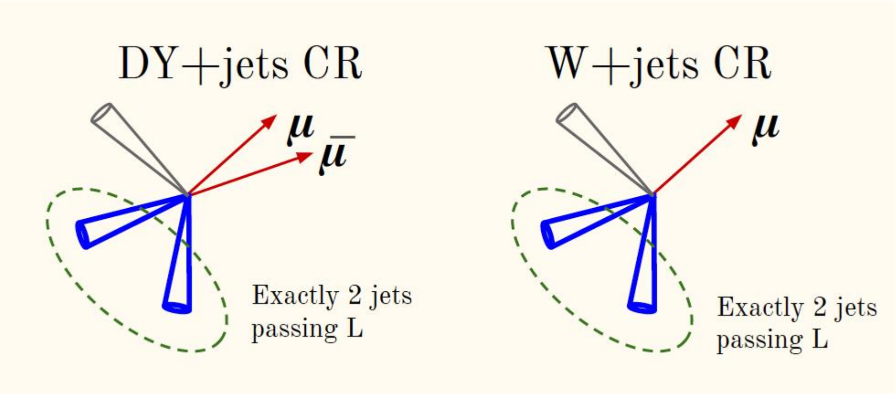
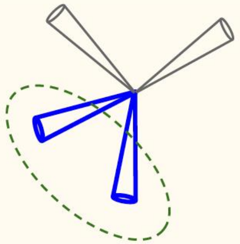
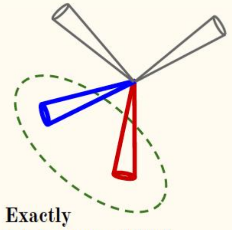
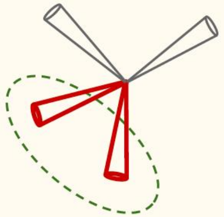
3	30–50	>250	
4	50–100	120–250	<100
5	50–100	120–250	>100
6	50–100	>250	
7	>100		<100
8	>100		>100



Long-lived stau: use of NN displaced tagger

EXO-24-020

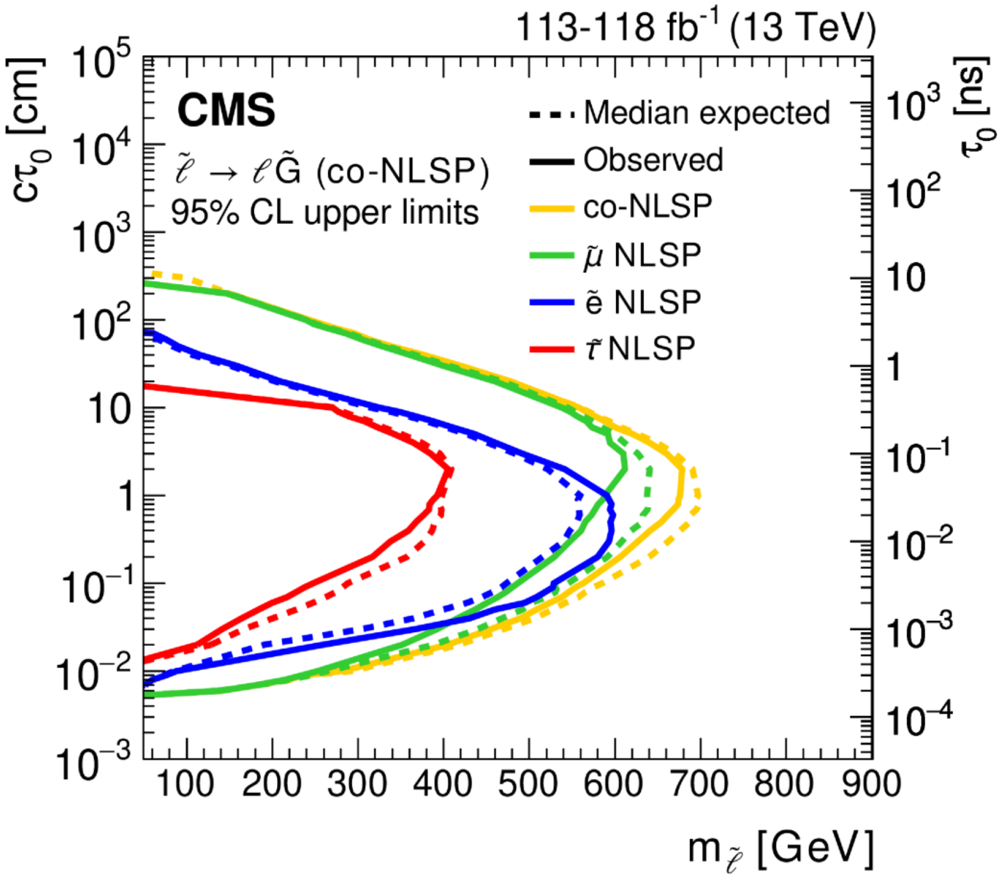


	T0	T1	T2
	 Exactly 2 jets passing L but not T	 Exactly 1 jet passing WPT 1 jet passing L but not T	 Exactly 2 jets passing T
Baseline region selections	BRT0	**BRT1** **(primary validation region)**	**BRT2 (SR)**
DY+jets CR selections	DYCRT0	DYCRT1	DYCRT2
W+jets CR selections	WCRT0	WCRT1	WCRT2

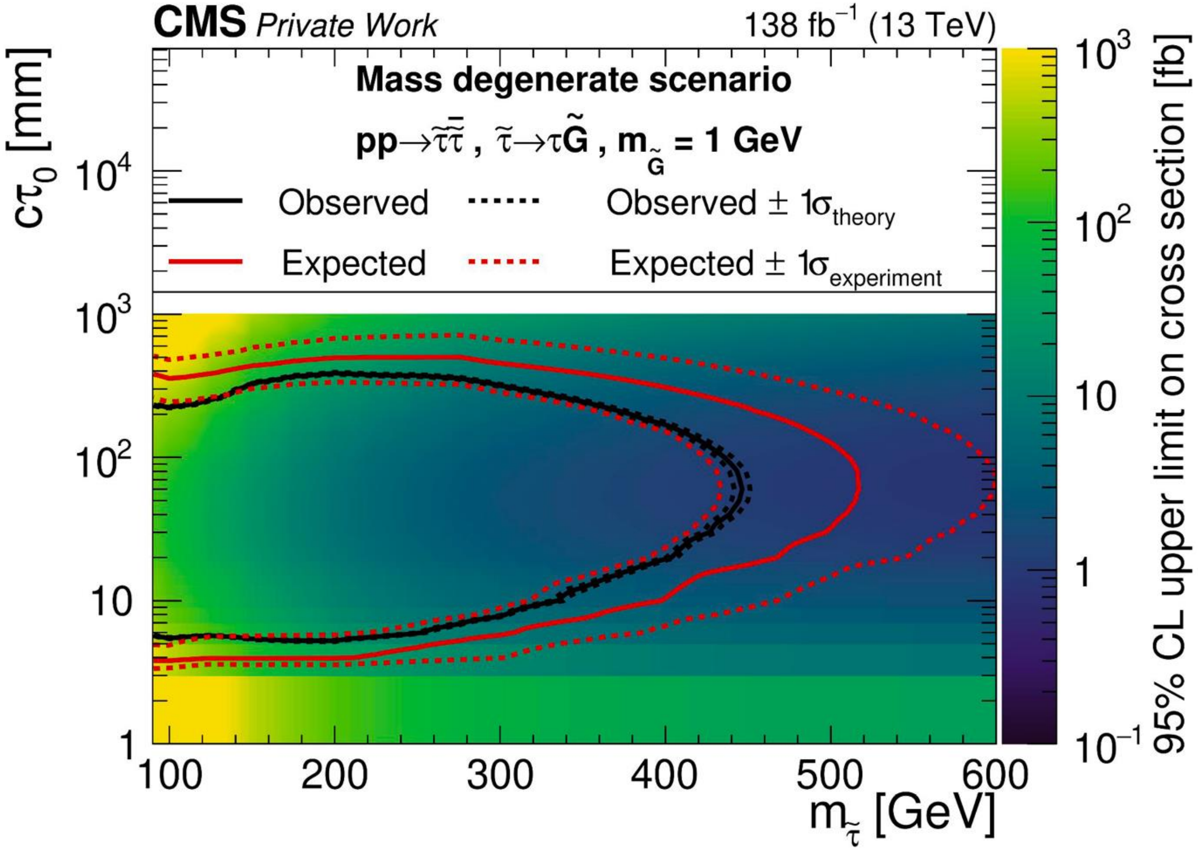
Long-lived stau: use of NN displaced tagger

EXO-24-020

Old (based on displaced e/mu)

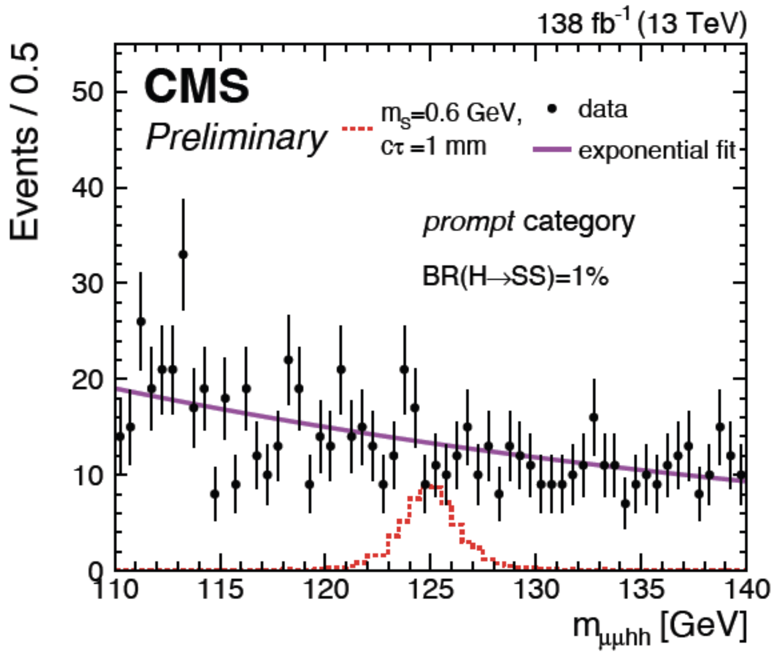


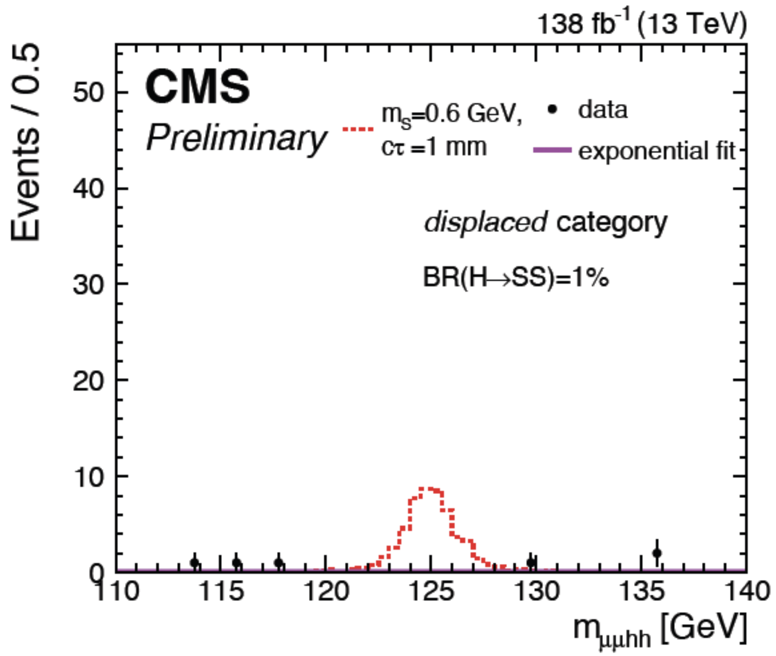
New (based on DisTau)

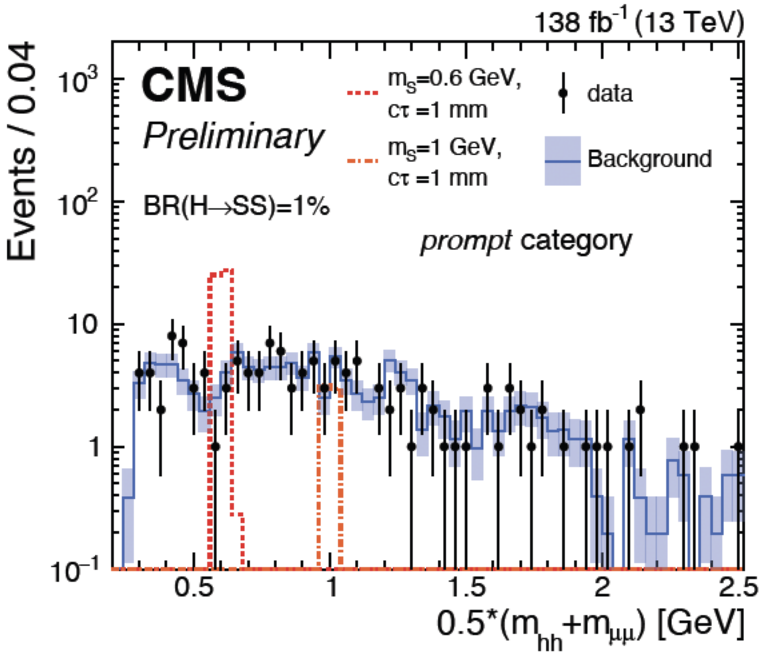


Long-lived light scalar from Higgs decay

EXO-24-034







Long-lived light scalar from Higgs decay

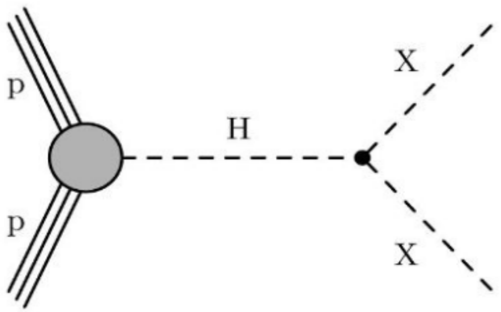
EXO-24-034

Selection	Requirements		Additional Information
Muons	$n_\mu \geq 2$, $p_T^{\mu_1} \geq 26$ GeV, $p_T^\mu > 5$ GeV, $\lvert\eta_\mu\rvert < 2.4$		$p_T^{\mu_1} \geq 29$ GeV (2017), $p_T^\mu > 26$ GeV (2018 diμ trigger)
Hadrons	$n_h \geq 2$, $p_T^h > 5$ GeV, $\lvert\eta_h\rvert < 2.4$, $h = \pi^\pm$ ($h = K^\pm$ for $m_S \geq 1.1$ GeV)		
Dimuon	$\Delta R_{\mu\mu} < 0.4$, valid vertex		
Dihadron	$\Delta R_{hh} < 0.4$, valid vertex, $p_T^{hh} > 20$ GeV		
Loose invariant mass	$m_{\mu\mu} < 5$ GeV, $m_{hh} < 5$ GeV, $m_{\mu\mu hh} \in [110, 140]$ GeV		SR and CR in $m_{\mu\mu hh}$
Di-object invariant mass	$m_{\mu\mu} \sim m_{hh}$		
Categories	*prompt* ($L_{xy}^{\mu\mu}/\sigma_{xy}^{\mu\mu} < 40$, $L_{xy}^{hh}/\sigma_{xy}^{hh} < 30$), *displaced* $\mu\mu$, *displaced* hh, *displaced*		Non-*prompt* categories made by inverting L_{xy}/σ_{xy} alternatively
	prompt	non-*prompt*	category-wise cuts
Relative isolation	$I_{rel}^{\mu_1} \leq 0.3$, $I_{rel}^{\mu_2} \leq 0.6$, $I_{rel}^{h_1} \leq 0.6$, $I_{rel}^{h_2} \leq 0.8$	$I_{rel}^{\mu_1} \leq 0.5$, $I_{rel}^{\mu_2} \leq 0.8$, $I_{rel}^{h_1} \leq 1$, $I_{rel}^{h_2} \leq 1.6$	μ_1, μ_2 = leading, subleading μ; h_1, h_2 = leading, subleading h

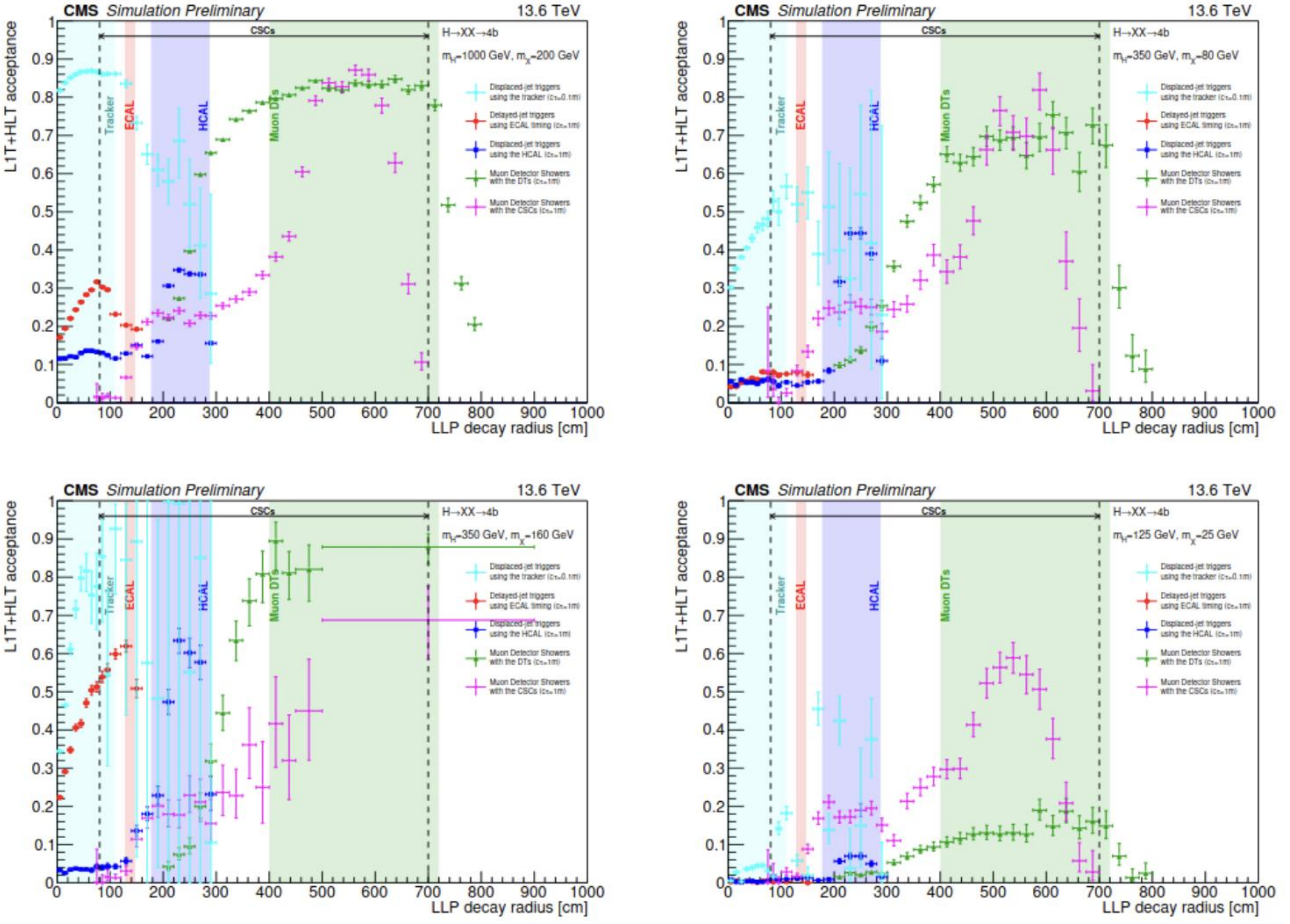
LLP triggers at run 3

Results for different masses

H to XX twin Higgs model



cτ = 0.1 m for the displaced-jet triggers using the tracker
cτ = 1 m for the other triggers.



LLP triggers at run 3

EXO-23-016

Triggered signature	Trigger description	HLT rate [Hz]
Disappearing track	$p_T^{miss} > 105\,GeV$ + $\geq$1 isolated track ($p_T > 50\,GeV$)	4
Disp. tau	$\geq$2 disp. τ_h ($p_T > 32\,GeV$, $d_0 > 0.005\,cm$)† $\geq$1 disp. τ_h ($p_T > 24\,GeV$) + $\geq$1 μ ($p_T > 24\,GeV$)† $\geq$1 disp. τ_h ($p_T > 34\,GeV$) + $\geq$1 e ($p_T > 34\,GeV$)†	36
Disp. jet	$\geq$2 jet ($p_T > 40\,GeV$, inclusive tagging req.) + $H_T > 430\,GeV$ $\geq$2 jet ($p_T > 40\,GeV$, disp. tagging req.) + $H_T > 240\,GeV$ + $\geq$1 L1 μ ($p_T > 6\,GeV$)	53 (163)
HCAL-based disp. and delayed jet	$\geq$2 jet ($p_T > 40\,GeV$, displ. tagging req.) + $H_T > 170\,GeV^{\dagger}$ $\geq$2 jet ($p_T > 40\,GeV$, inclusive. tagging req.) + $H_T > 200\,GeV^{\dagger}$ $\geq$1 jet ($p_T > 60\,GeV$, neutral hadron energy fraction >0.7) + $H_T > 200\,GeV^{\dagger}$	35
ECAL-based delayed jet	$\geq$1 inclusive and trackless jet†	37 (77)
Delayed diphoton	$\geq$2 ECAL superclusters (time >1 ns)†	15
Disp. photon + H_T	$\geq$1 γ ($p_T > 60\,GeV$) + PF $H_T > 350\,GeV$	12
Disp. single and dimuon	$\geq$2 L2 μ ($p_T > 10\,GeV$, $d_0 > 1\,cm$)† $\geq$2 L3 μ ($p_T > 16, 10\,GeV$, $d_0 > 0.01\,cm$)† $\geq$2 L2 μ ($p_T > 23\,GeV$) $\geq$1 L2 μ ($p_T > 50\,GeV$, $d_0 > 1\,cm$)† $\geq$1 L3 μ ($p_T > 30\,GeV$, $d_0 > 0.01\,cm$)†	165
Double disp. L3 muon	$\geq$2 L3 μ ($p_T > 43\,GeV$)	2

Triggered signature	Trigger description	HLT rate [Hz]
Disp. L3 muon+photon	$\geq$1 L3 μ ($p_T > 43\,GeV$) + γ ($p_T > 43\,GeV$) $\geq$1 L3 μ ($p_T > 38\,GeV$, $d_0 > 1\,cm$) + γ ($p_T > 38\,GeV$)	5
Dimuon scouting	$\geq$2 scouting μ ($p_T > 3\,GeV$)	4200
MDS in CSCs	$\geq$1 CSC cluster ($\geq$200/500 hits in outer/inner rings)† $\geq$2 CSC clusters ($\geq$75 hits)†	14
MDS in CSCs + X	$\geq$1 CSC cluster ($\geq$100 hits) + $\geq$1 e ($p_T > 5\,GeV$)† $\geq$1 CSC cluster ($\geq$100 hits) + $\geq$1 L3 μ ($p_T > 5\,GeV$)† $\geq$1 CSC cluster ($\geq$100 hits) + $\geq$1 τ_h ($p_T > 10\,GeV$)† $\geq$1 CSC cluster ($\geq$50 hits) + $\geq$1 γ ($p_T > 20\,GeV$)†	14
MDS in DTs	L1 $p_T^{miss} > 150\,GeV$ + $\geq$1 DT cluster ($\geq$50 hits)† $\geq$1 L1 CSC cluster + $\geq$1 DT cluster ($\geq$50 hits)†	9
Jet No-BPTX	$\geq$1 out-of-time jet ($E > 60\,GeV$)	1
Muon No-BPTX	$\geq$1 out-of-time L2 μ ($p_T > 40\,GeV$)	7