Searches for physics beyond the standard model in CMS

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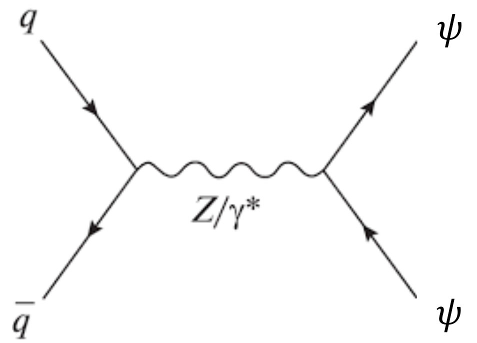
Bosons, fermions, and beyond

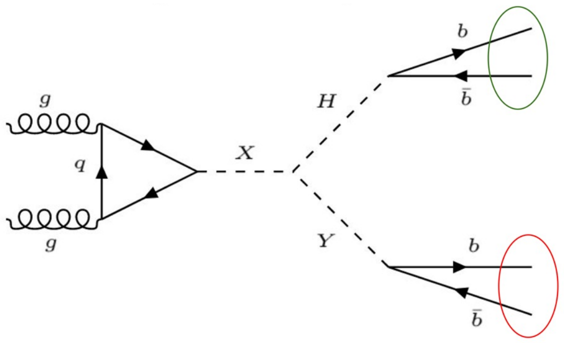
- Ample evidence of phenomena that the standard model (SM) in its current form cannot fully explain
  - Dark matter
  - Massive neutrinos
  - Light Higgs
  - [insert your favorite anomaly]
- In CMS, a robust program to find new physics beyond the SM is chugging away for 10+ years
- No direct evidence of new physics has yet been demonstrated, but certainly not for a lack of trying
- We will discuss some hot-off-the-press CMS BSM results, which add to the extensive existing body of searches for signs of SM deviations

Bosons, fermions, and beyond

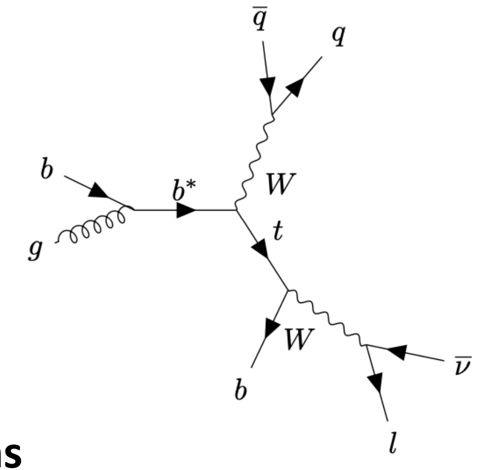
Fractionally charged fermions



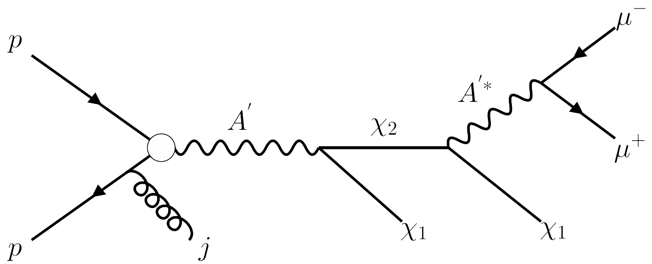
Supersymmetry



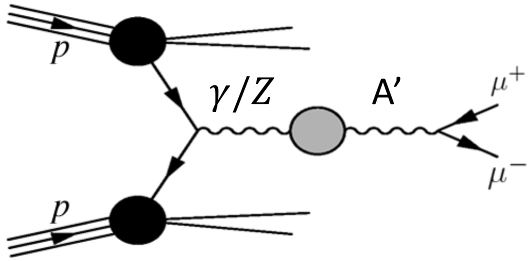
Compositeness models



Inelastic dark matter



Dark photons



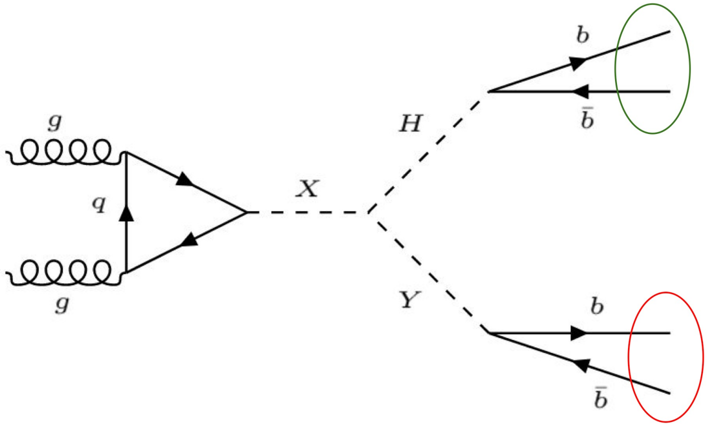
* Additional BSM Higgs and Top results shown by Harvey Newman and Prolay Mal

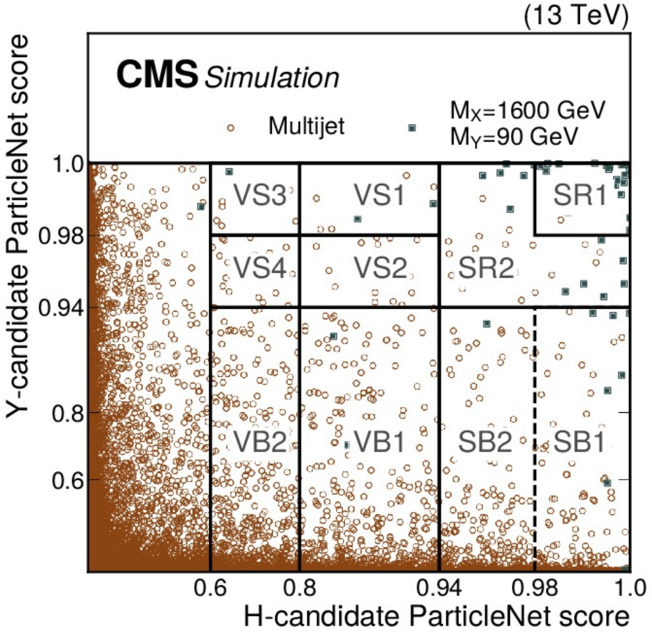
* Cannot cover all new CMS results (please check them out here!)

Search for heavy scalar resonances

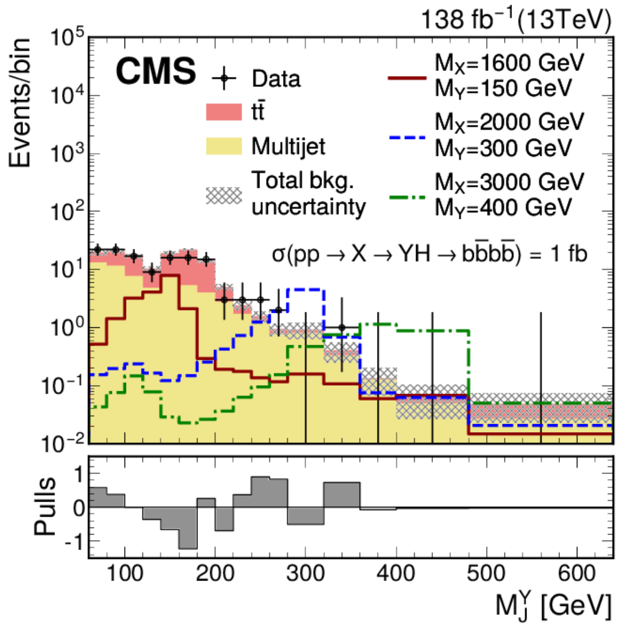
CMS-PAS-B2G-21-003

- Search for event topologies $X \to HY \to 4b$, where X is a heavy scalar and Y a lighter scalar, with $m_X \gg m_H, m_Y$
- Predicted by next-to-minimal supersymmetric model, among others
- Highly boosted H and Y, so look for **merged jets**





- Use a **GNN** (**ParticleNet**) to tell apart H and Y jets from light flavored jets
- Define signal and validation regions in 2D plane of GNN score
- Estimate multijet background in SR 1&2 from sidebands SB 1&2
- Validate approach with VS's and VB's

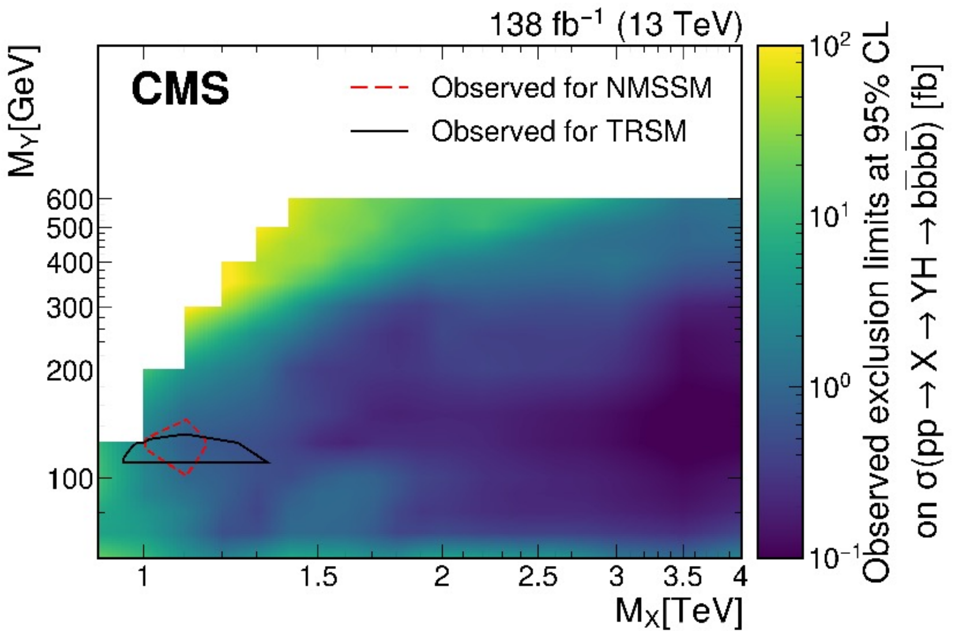


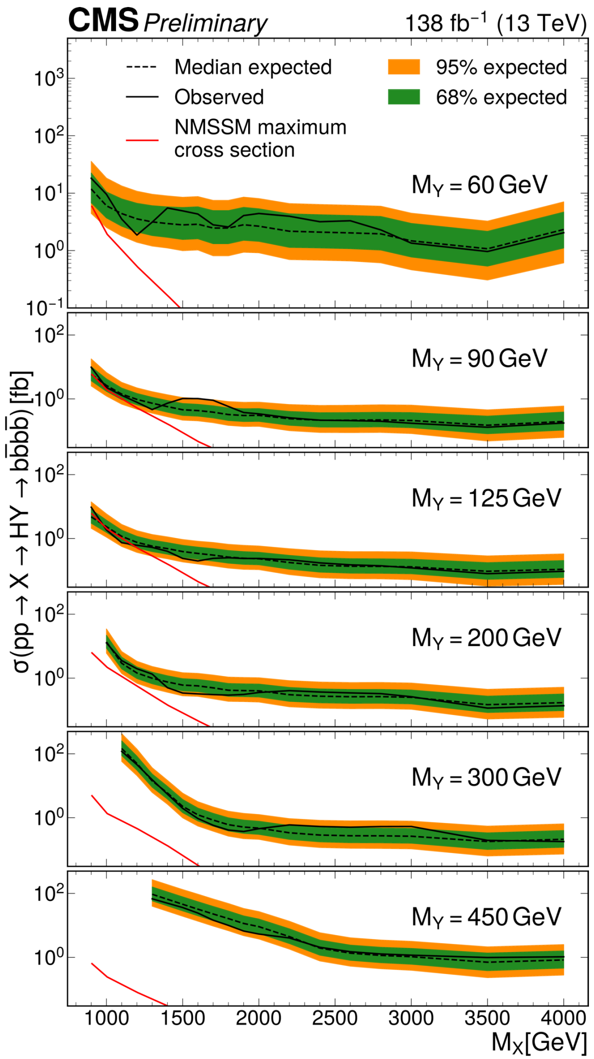
- Finally, search for bump signal in M_J^Y and M_J^H 2D plane

Search for heavy scalar resonances

CMS-PAS-B2G-21-003

- No excess over expected background observed
- Upper limits on $\sigma(pp \rightarrow X \rightarrow YH \rightarrow b\bar{b}b\bar{b})$ for various M_X and M_Y
- Factor of 4 improvement over similar searches from GNN and new mass decorrelation techniques
- Able to exclude parameter space from NMSSM

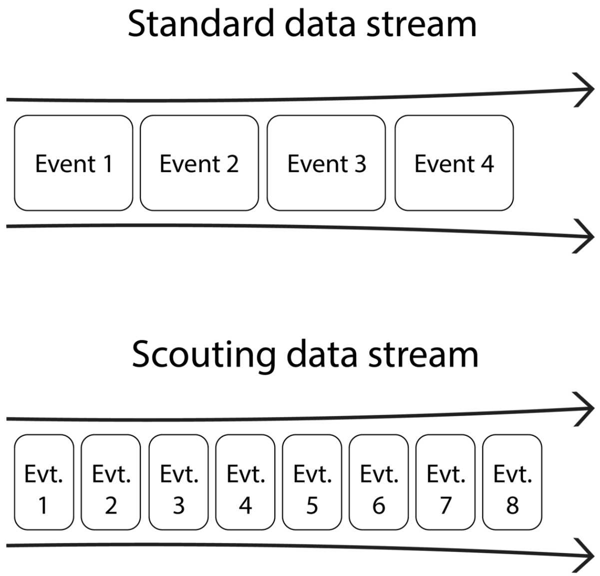


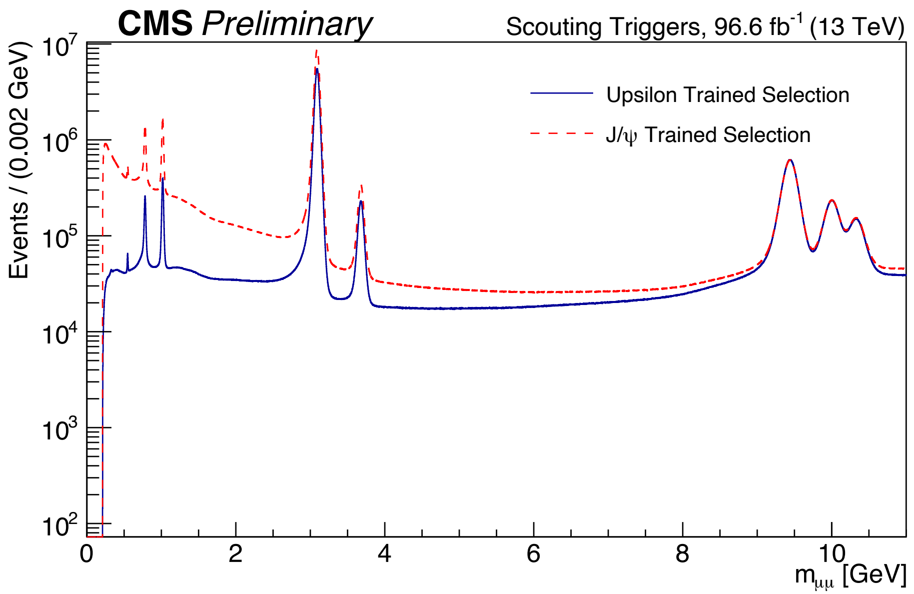


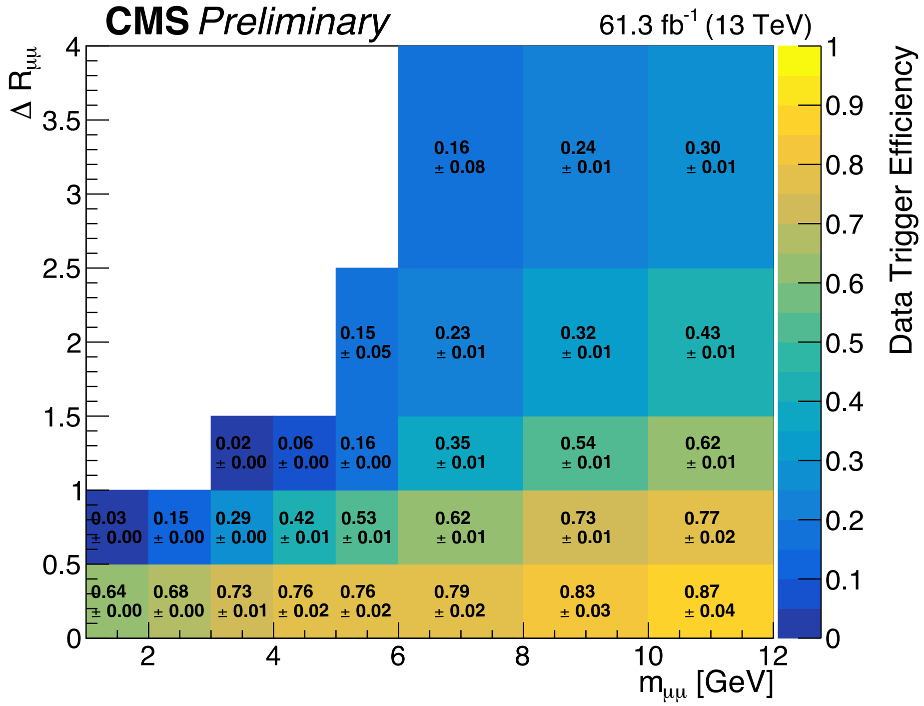
Search for light resonances with scouting

CMS-PAS-EXO-21-005

- **Data scouting** is a powerful technique that exchanges event size for number of events, keeping the data bandwidth constant
- Store only muon information → significantly reduce momentum thresholds in dimuon triggers (**from 17 to 3 GeV**)
- Enables probing of very low (GeV-scale) dimuon resonances





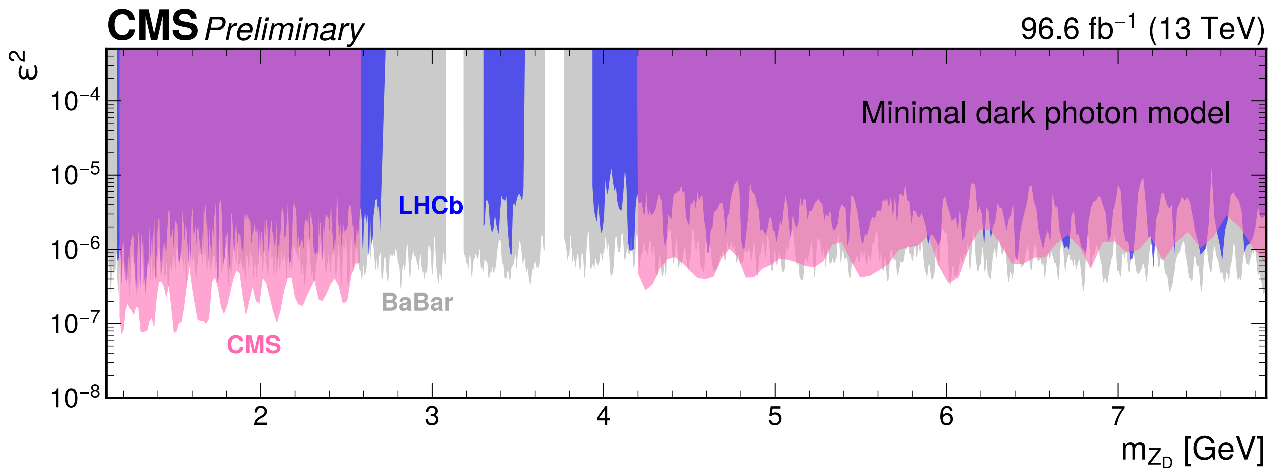


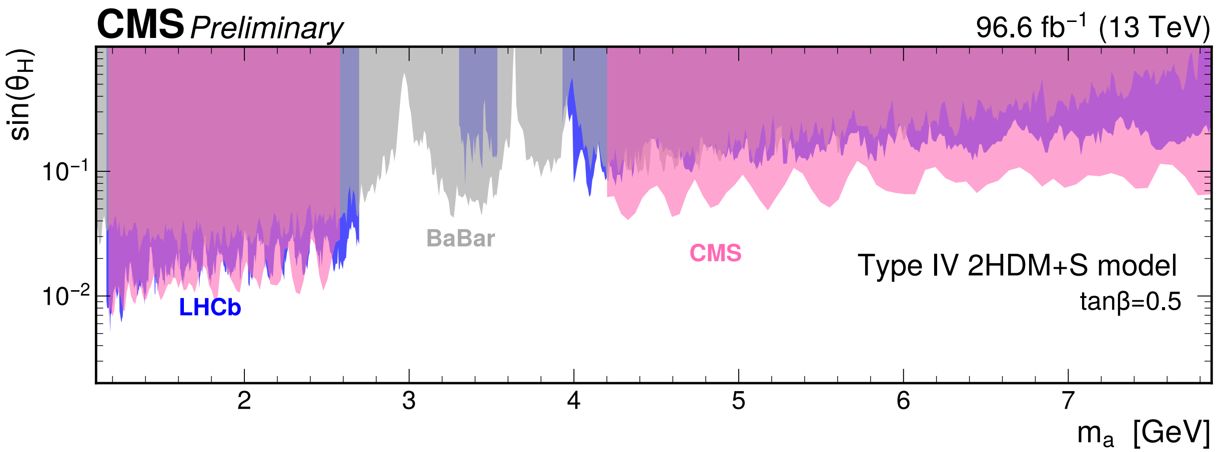
- High trigger efficiencies in data for $m_{\mu\mu}$ < 12 GeV
- Two MVA-based ID selections using Υ and J/ψ resonances for training

Search for light resonances with scouting

CMS-PAS-EXO-21-005

- No significant excess over expected background
- Exclusion limits set with two model interpretations
- Considerable improvement over LHCb limits for the **2HDM+S model with $m_a > 4$ GeV** and for the **dark photon model with $m_{Z_D} < 2.5$ GeV**



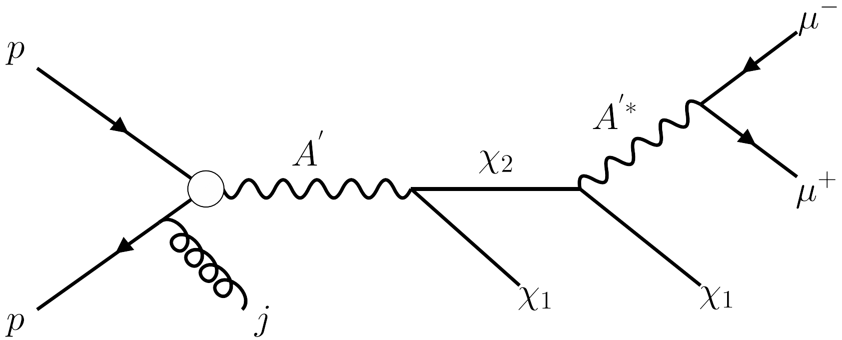


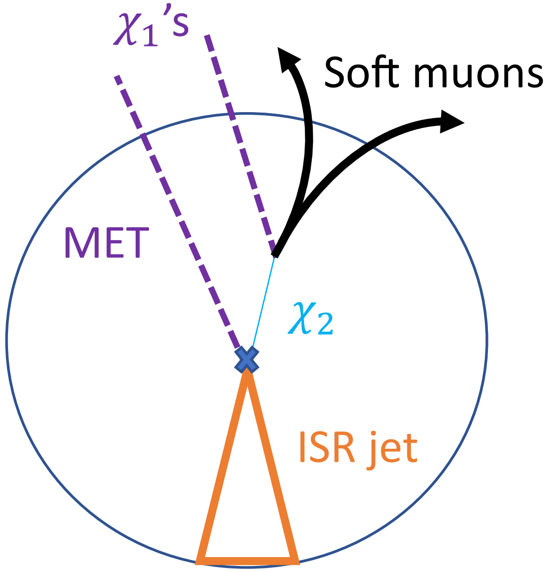
- Dark photon model:
  - Postulates an additional vector boson of a new $U(1)_D$ symmetry in the dark sector
  - Connected to the SM via kinetic mixing with kinetic mixing coefficient ϵ
- Two-Higgs-doublet + complex scalar model:
  - Predicts light CP-odd pseudoscalar boson a
  - Coupling to SM determined by its mixing with Higgs doublets (θ_H) and ratio of Higgs VEVs (β)

Search for inelastic dark matter

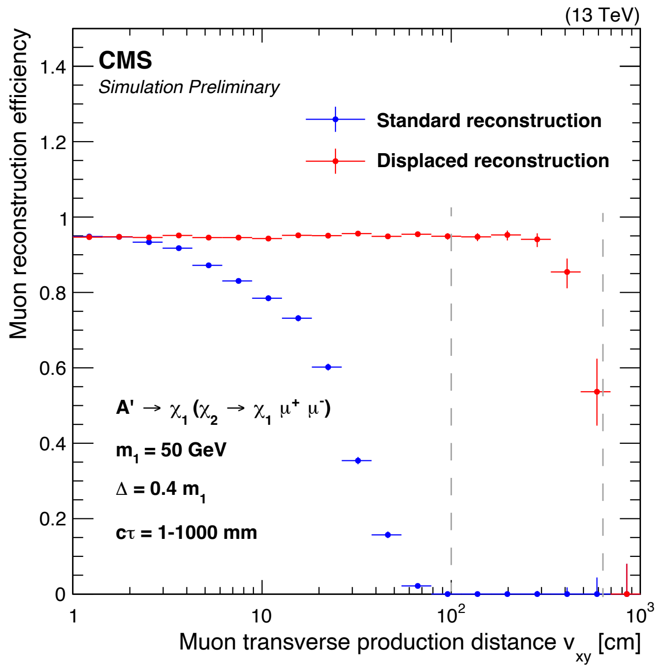
CMS-PAS-EXO-20-010

- Same dark photon, but now assume DM consists of two states χ_1 and χ_2
- Inelastic coupling between DM states favors χ_2 & χ_1 production via dark photon
- χ_2 is only slightly heavier than χ_1 (**compressed scenario**) → soft decay products
- χ_2 decay width proportional to mass splitting and kinetic mixing → **long-lived and displaced signatures**



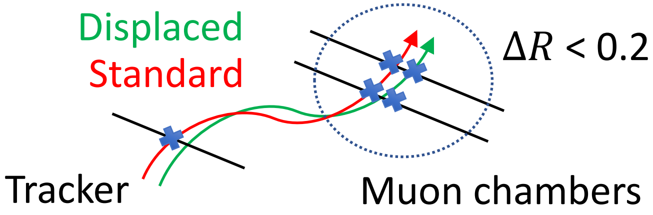


- Dedicated displaced muon reconstruction in CMS
- High efficiency to reconstruct muons up to ~ 400 cm from pp collision



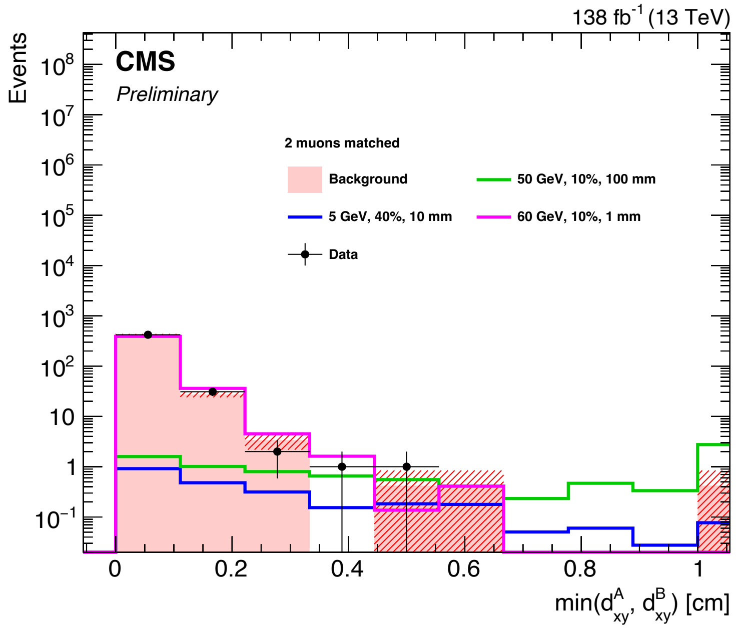
Search for inelastic dark matter

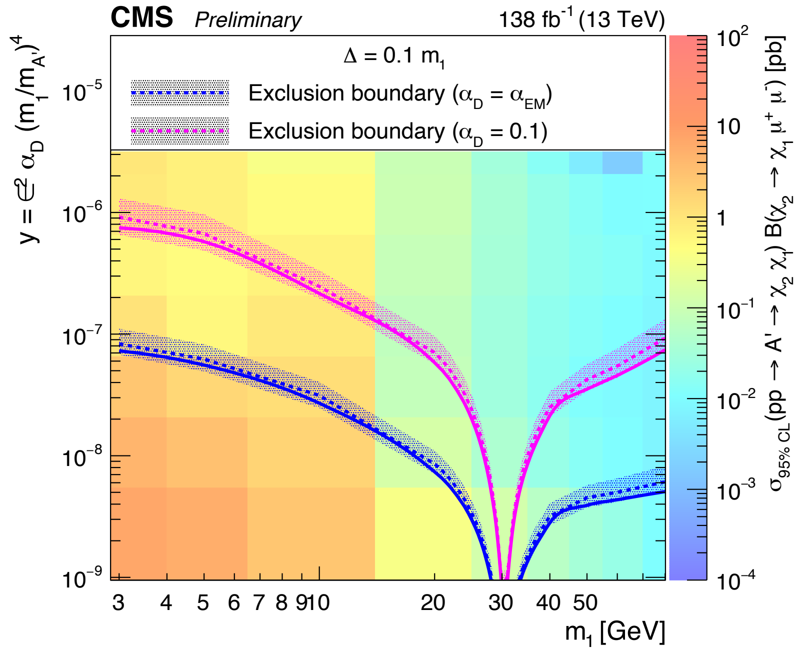
[CMS-PAS-EXO-20-010](CMS-PAS-EXO-20-010)

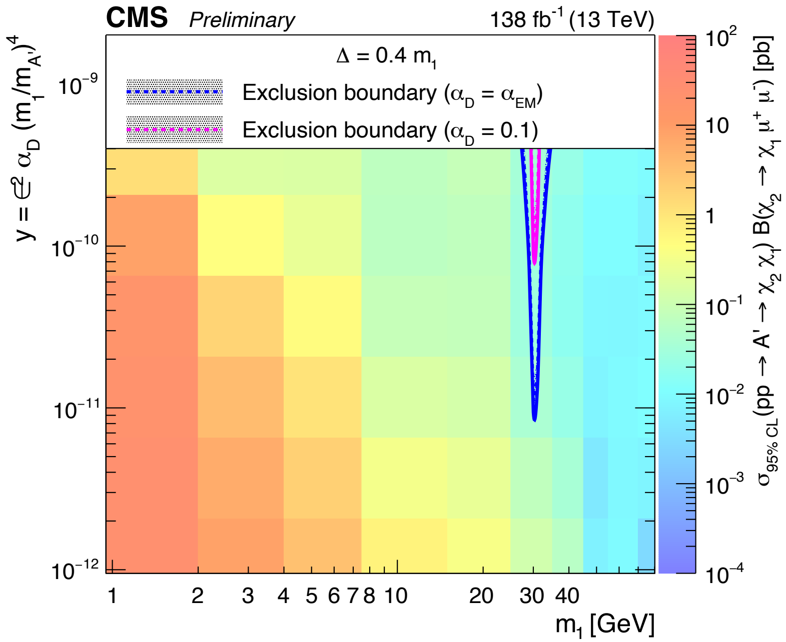


- Improved sensitivity by matching displaced and standard muon reconstruction when available
- Split signal region into 3 categories: 0, 1, or 2 muons matched
- Use displacement and isolation as discriminating variables against QCD multijets

First search for iDM at a hadron collider!



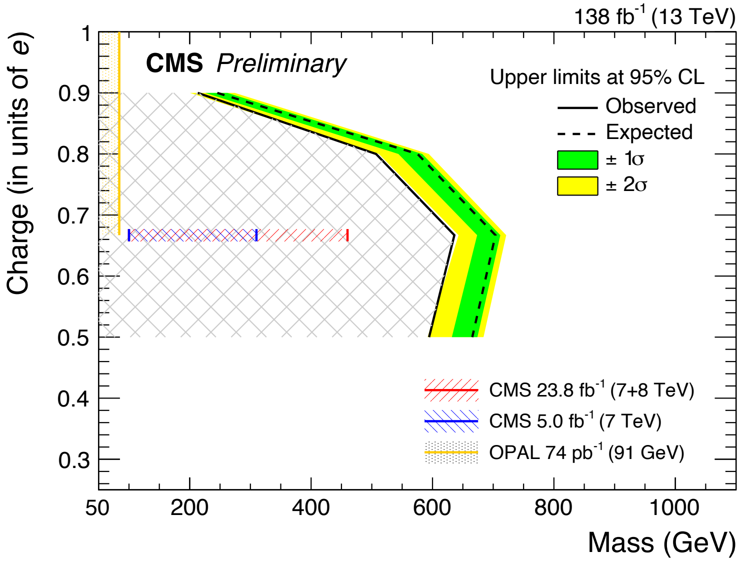


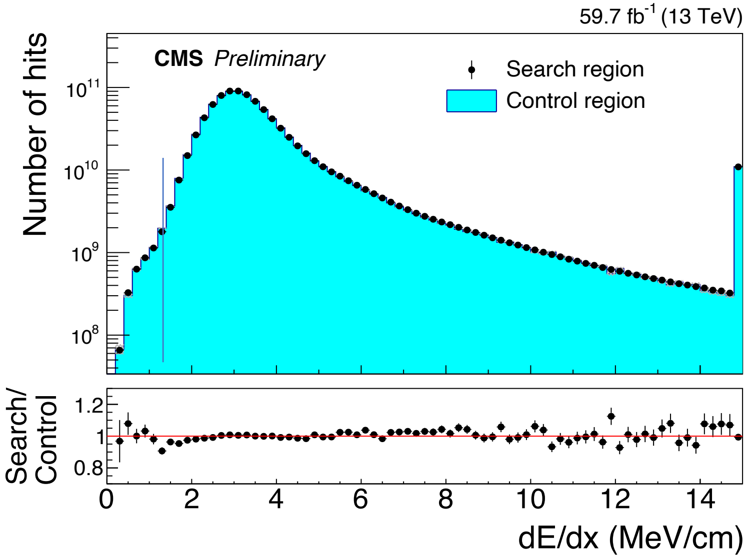


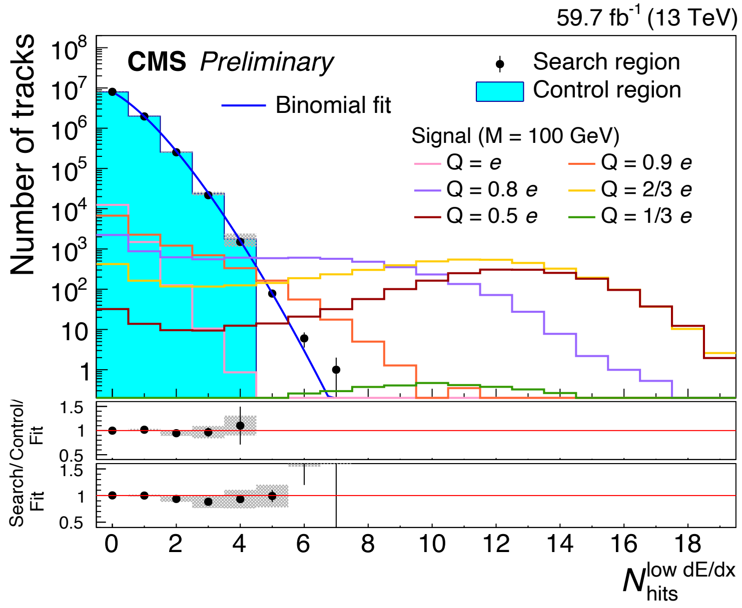
Search for fractionally charged particles

CMS-PAS-EXO-19-006

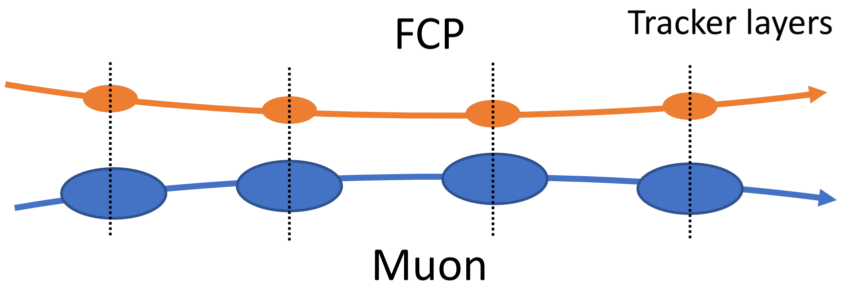
- Same dark photon model couples particles in the dark sector to the electromagnetic field
- Dirac fermion ψ charged under $U(1)_D$ but not under SM $SU(2)$, would have small charge ϵe from kinetic mixing







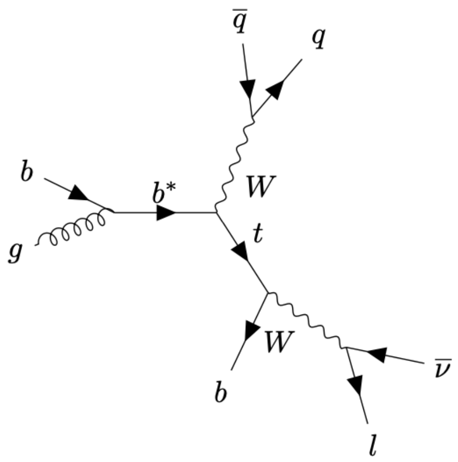
- Can look for fractionally charged particles in CMS using their **lower ionization power** (dE/dx) as discriminator variable

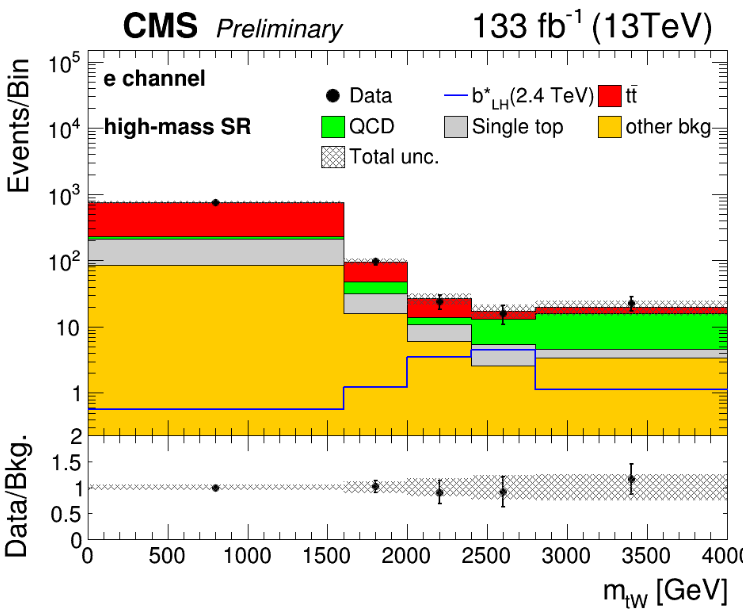


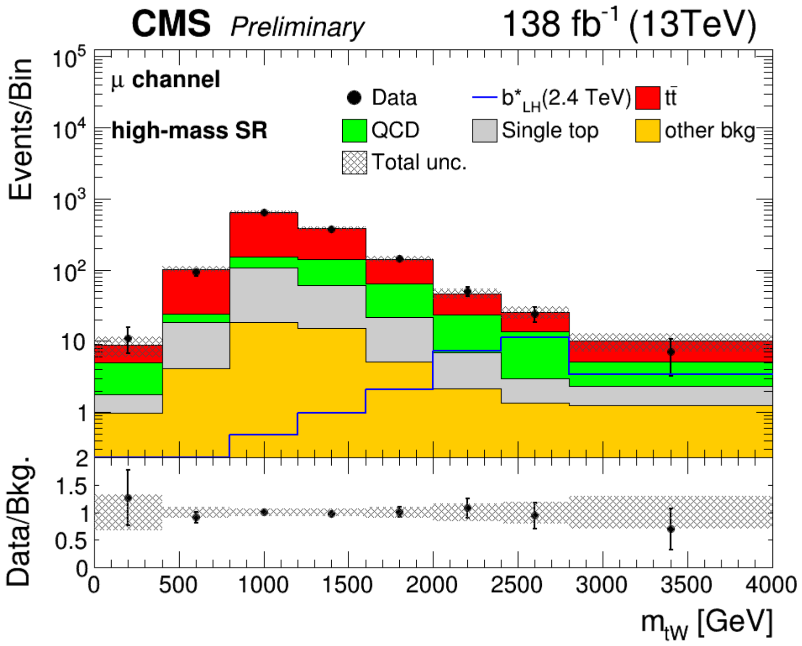
Search for excited bottom quarks

[CMS-PAS-B2G-21-005](CMS-PAS-B2G-21-005)

- Search for heavy excited bottom quarks b^* predicted in **compositeness models**
- Decay topology: $b^* \rightarrow tW \rightarrow (bl\nu)(\overline{qq})$
- $\mathrm{m}_{b^*} \gg \mathrm{m}_{\mathrm{W}}, \mathrm{m}_{\mathrm{t}}$ so both t and W are boosted, leading to **merged jets and non-isolated leptons**





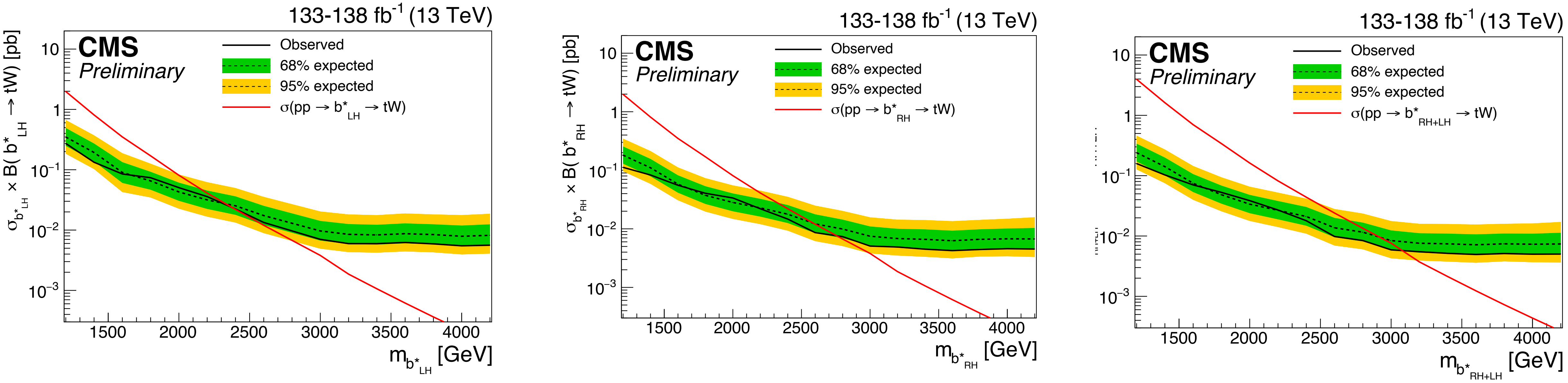


- Dominant backgrounds are QCD (estimated from CRs via ABCD) and $t\bar{t}$, estimated from simulation
- Simultaneous binned maximum-likelihood fit across all years and ABCD bins and SR's

Search for excited bottom quarks

CMS-PAS-B2G-21-005

- No excess over expected background
- Upper limits on $\sigma \times BR$ set for three hypotheses:
  - Left-handed coupling (left)
  - Right-handed coupling (center)
  - Vector-like coupling (right)
- Lower limits on m_{b^*} set using theory cross-section predictions: $>$ **2.4, 2.8, 3.1 TeV**



Conclusions

- The CMS program to search for BSM physics is broad and extensive
  - Probing several models of interest
  - Diverse event topologies and final-state signatures
  - Novel uses of the detector and creative reconstruction techniques to improve sensitivity to new physics
- Unfortunately, no convincing signs of new or unexplained processes have shown up in the data yet
- We will continue to devise new and improved searches, and Run 3 will provide a crucial boost in available statistics to search for rare processes
- Stay tuned for more CMS BSM results coming out this year!

Backup slides

Search for heavy scalar resonances

- Main backgrounds:
  - QCD multijet: data-driven using pass/fail ratio method
  - $t\bar{t}$: simulation with dedicated control region for corrections in data
- Hadronic selection:
  - Jet triggers (HT-based)
  - Two AK8 jets with $p_T > 350$ GeV, $|\eta| < 2.4$ (2016), $p_T > 450$ GeV, $|\eta| < 2.5$ (2017+2018)
  - No muons or electrons
  - $|\Delta\eta| < 1.3$
  - $M_{JJ} > 700$ GeV
  - H-candidate: $110 < M_{SD} < 140$ GeV
  - Y-candidate: $M_{SD} > 60$ GeV
  - ParticleNet tagging scores

Definitions of various areas

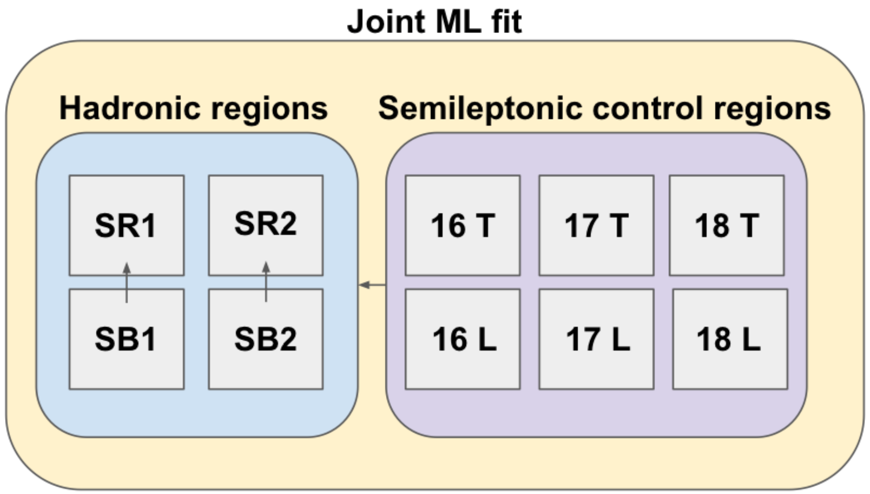
Region name and label in Fig. 1	ParticleNet discriminator		Purpose
	H Jet	Y jet	
Signal region 1 (SR1)	>0.98	>0.98	Signal
Signal region 2 (SR2) (excludes SR1)	>0.94	>0.94	Signal
Sideband 1 (SB1)	>0.98	<0.94	Sideband
Sideband 2 (SB2)	>0.94	<0.94	Sideband
Validation signal-like 1 (VS1)	0.8–0.94	>0.98	Validation
Validation signal-like 2 (VS2)	0.8–0.94	>0.94	Validation
Validation sideband 1 (VB1)	0.8–0.94	<0.94	Validation
Validation signal-like 3 (VS3)	0.6–0.8	>0.98	Validation
Validation signal-like 4 (VS4)	0.6–0.8	>0.94	Validation
Validation sideband 2 (VB2)	0.6–0.8	<0.94	Validation

Search for heavy scalar resonances

- Leptonic selection for ttbar background estimation:
  - Semileptonic $t\bar{t}$+jets MC samples ($t \to Wb \to l\nu b$)
  - Lepton triggers
  - Lepton $p_T > 40$ GeV, $|\eta| < 2.4$
  - Tight ID lepton w/ b-tagged AK4 jet close by ($\Delta R < 1.5$)
  - $H_T > 500$ GeV, $p_T^{miss} > 60$ GeV
  - AK8 “probe” jet opposite the lepton
    - Same p_T, η as hadronic plus $M_{SD} > 60$ GeV
    - ΔR(probe jet, lepton) > 2.0
  - Probe jets classified into tight and loose based on ParticleNet score (SR1 vs. SR2)

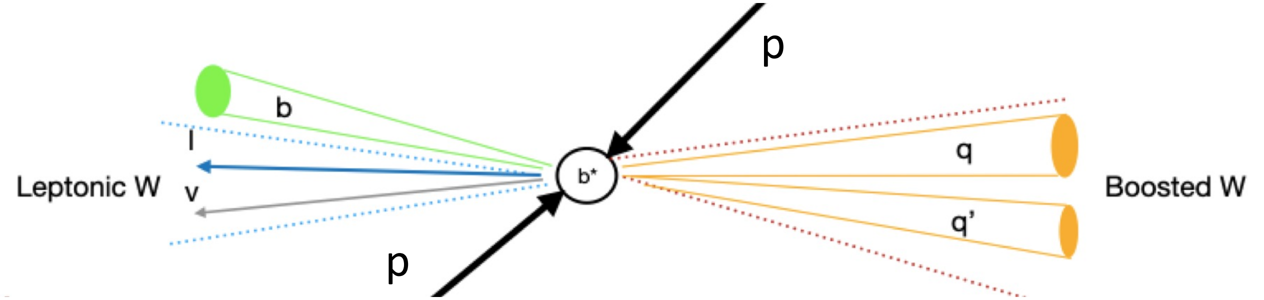
- Jet triggers:
  - Single AK8 jet with $p_T > 450/500$ GeV (2016/17+18)
  - Scalar H_T sum of AK4 jets $> 800{,}900$ GeV (2016) and 1050 GeV (2017+2018)

Simultaneous joint maximum likelihood fit

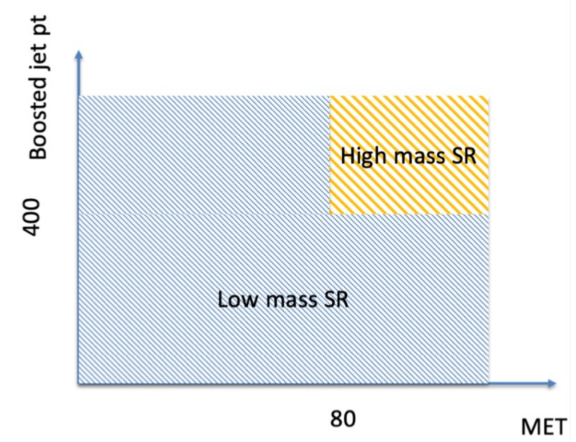


Search for excited bottom quarks

- Event preselection:
  - Exactly one lepton:
    - 2D isolation cut: ΔR(AK4 jet, lepton) > 0.4 or $p_T^{rel} >$ 15 GeV
    - Offline $p_T > 53$ GeV, $|\eta| < 2.4$
    - Muon channel:
      - Trigger with $p_T > 50$ GeV
      - Tight Muon ID
    - Electron channel:
      - Trigger with $p_T >$ 27-35 GeV
      - Tight ID except for isolation requirements
  - At least one b-tagged AK4 jet:
    - $p_T > 30$ GeV, $|\eta| < 2.4$
    - Medium working point of DeepJet b tag
    - ΔR(closest b-jet, lepton) < 2
  - Exactly one W-tagged AK8 jet:
    - $p_T > 200$ GeV, $|\eta| < 2.4$
    - W tag: $65 < m_{SD} < 105$ GeV, $\tau_{21} < 0.4$ (2016), 0.45(2017,2018)
    - ΔR(AK4 jet, AK8 jet) > 0.8



- Signal regions:
  - High-mass SR: $p_T^{miss} > 80$ GeV and AK8 jet $p_T >$ 400 GeV
  - Low-mass SR: the remaining plane



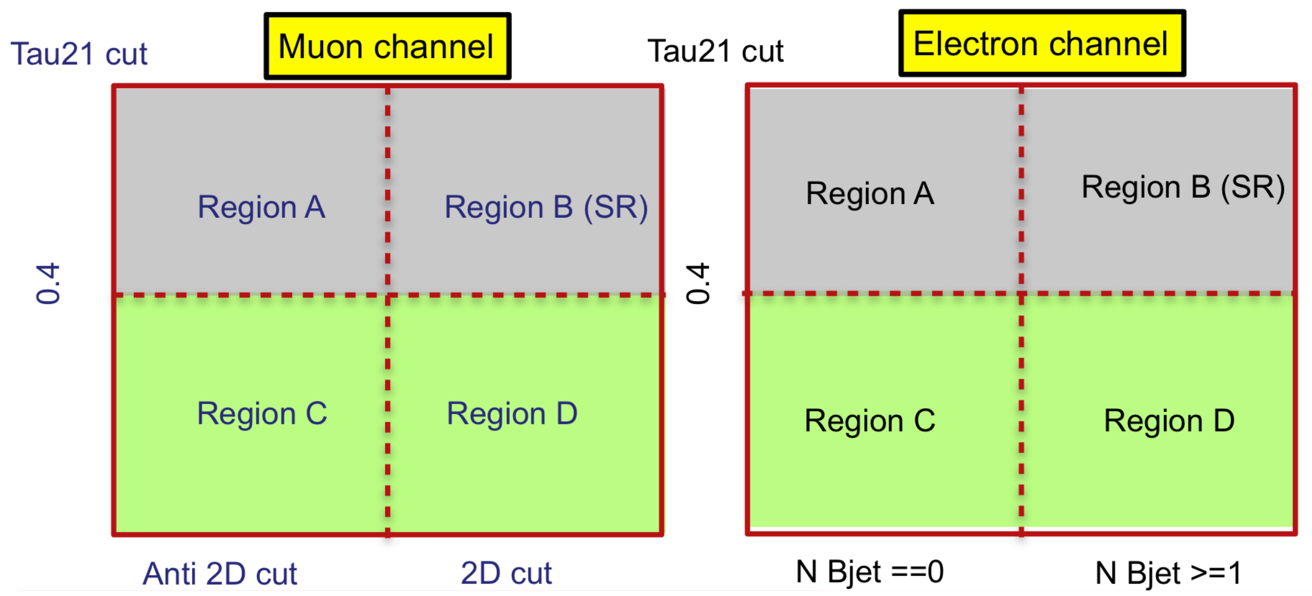
Search for excited bottom quarks

- Estimate ttbar background from MC, constraining with data in dedicated CR:
  - Top tag algorithm
  - AK8 jets with $p_T > 400$ GeV, $|\eta| < 2.4$
  - $105 < m_{SD} < 220$ GeV
  - $\tau_{32} < 0.65$

- Estimate QCD background from data with modified likelihood-based ABCD method

$$\mathcal{L} = \prod_{i}^{N_{\text{bins}}^{\ell,\text{year}}} \prod_{r}^{\text{ABCDE}} \text{P}\left(n_{r,i} \middle| \text{QCD}_{r,i} + \sum_k \text{Bkg}_{r,i}^k + \mu \text{Sig}_{r,i}\right)$$

- One ABCD system per bin of m_{tw}
- No 2D isolation in electron ABCD because of trigger isolation
- Bin “E” is the $t\bar{t}$ CR (and QCD yields are taken from MC there)
- k is summed over $t\bar{t}$, diboson, W+jets, and single top MC yields

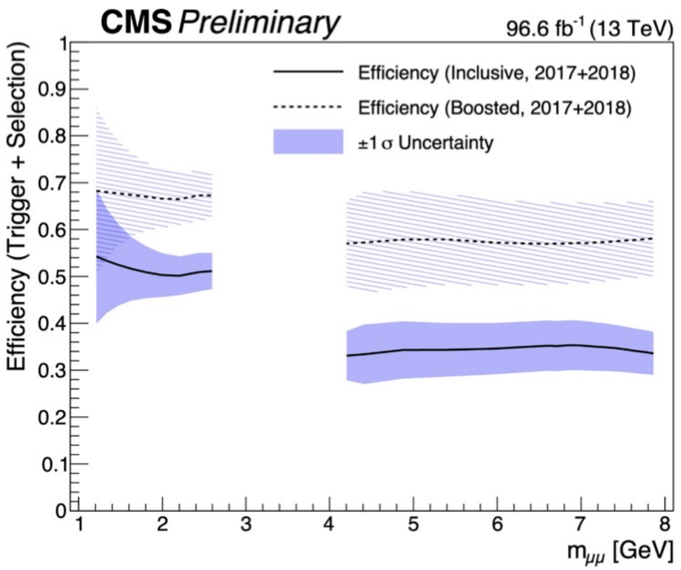


Search for light resonances with scouting

Event selection

Preselection	$L < 0.2\,\text{cm}$, $\lvert\eta^\mu\rvert < 1.9$, OS			
Category	Inclusive		Boosted	
Mass Range	$m_{\mu\mu} < 2.6\,\text{GeV}$	$m_{\mu\mu} > 4.2\,\text{GeV}$	$m_{\mu\mu} < 2.6\,\text{GeV}$	$m_{\mu\mu} > 4.2\,\text{GeV}$
p_T^μ	$> 4\,\text{GeV}$		$> 5\,\text{GeV}$	
BDT ID	J/ψ ID > -0.1	Υ ID > 0.0	J/ψ ID > -0.1	
Vertex	$\sigma_L < 3.5L$	$L < 0.015\,\text{cm}$	$\sigma_L < 3.5L$	
$p_T^{\mu\mu}$	–	–	$> 35\,\text{GeV}$	$> 20\,\text{GeV}$

Efficiencies



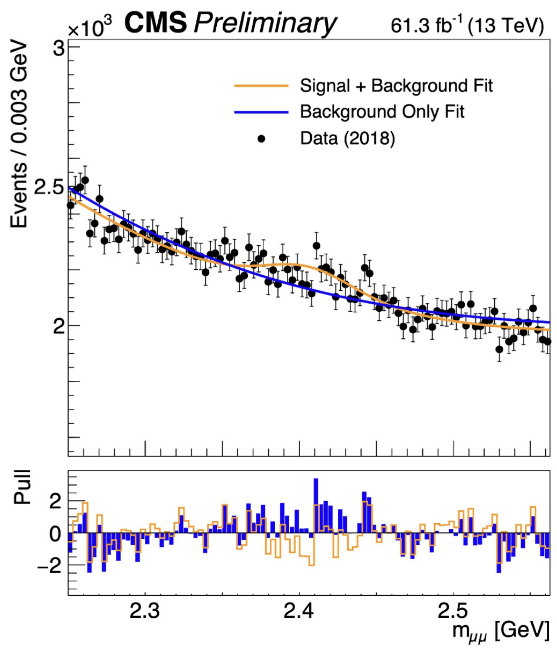
Information available for scouting muons

Kinematic quantities	ID variables	Track / Vertex
$p_T^\mu, \eta^\mu, \phi^\mu$	Ecal, Hcal, Track Iso.	$q/p, \lambda, \phi, d_{sz}$
$p_T^{\text{track}}, \eta^{\text{track}}, \phi^{\text{track}}$	#pixel, #strip, #muon hits	$\sigma_{q/p}, \sigma_\lambda, \sigma_\phi, \sigma_{d_{sz}}$
d_{xy}, d_z	#stations, #tracker layers	$\mu\mu$ vertex x, y, z
$\sigma_{d_{xy}}, \sigma_{d_z}$	χ^2, #d.o.f., i_{vertex}	$\mu\mu$ vertex $\sigma_x, \sigma_y, \sigma_z$

BDT ID training variables

	Per muon variables	Per event variables
J/ψ	nPixelHits, nTrkLayers, muTrkChi2, RelTrackIso	Vertexchi2
Upsilon	nPixelHits, nTrkLayers, muTrkChi2, RelTrackIso	Vertexchi2, L

Search for light resonances with scouting



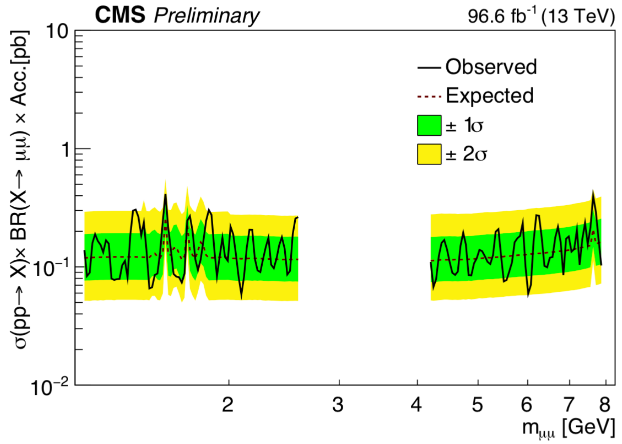
Largest excess at 2.4 GeV:
3.2σ local, 1.3σ global

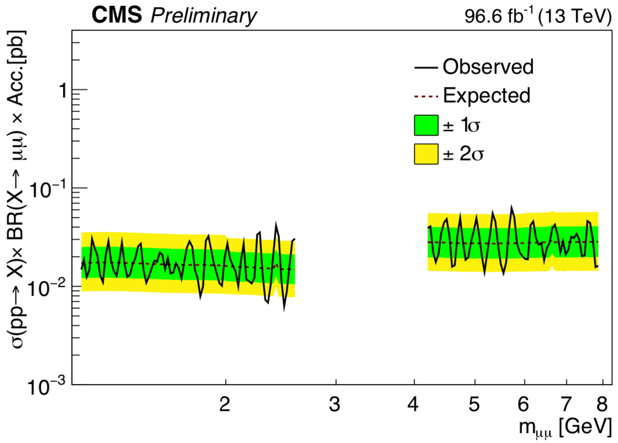
Conversion from independent to dependent limits:

$$\sigma_{\mathrm{pp}\to a} \cdot \sin^2(\theta_{\mathrm{H}}) \cdot \mathcal{B} \cdot A = \sigma_{\mathrm{limit}},$$

$$\sigma_{\mathrm{pp}\to \mathrm{Z_D}} \cdot \epsilon^2 \cdot \mathcal{B} \cdot A = \sigma_{\mathrm{limit}},$$

Model-independent limits





Search for inelastic dark matter

Event selection

- **Jet & MET selection:**
  - Trigger on MET triggers
  - Offline MET > 200 GeV
  - 1 or 2 jets only
  - Leading jet p_T > 80 GeV, |η| < 2.4
  - Sub-leading jet p_T > 30 GeV
  - |Δϕ|(MET, leading jet) > 1.5
  - |Δϕ|(MET, sub-leading jet) > 0.75
  - No b-tagged jets

- **Dimuon selection:**
  - 2 ID'd dSA muons
  - q_1 != q_2
  - Vertex χ^2/dof < 4 (pick lowest)
  - dR(muons) < 0.9
  - 3D angle $\alpha > 2.8$ rad
  - |Δϕ|(MET, muons) < 0.5

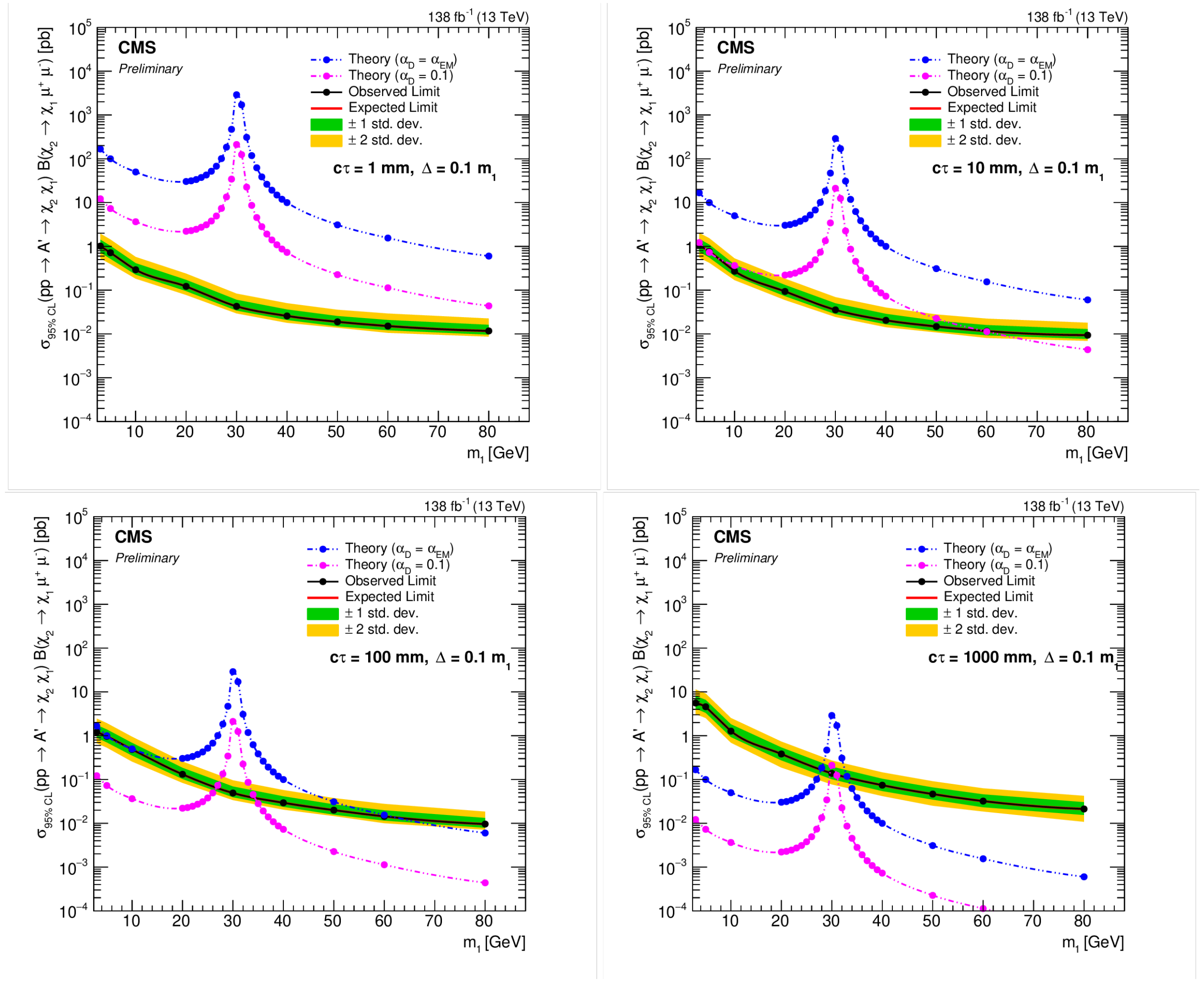
- **dSA ID:**
  - Number of muon chambers > 1
  - Number of muon hits > 12
  - And > 18 if no CSC hits
  - Track χ^2/dof < 2.5
  - $\sigma(p_T)$ / p_T < 1.0
  - & p_T > 5 GeV, $|\eta|$ < 2.4

- **"PF" Loose ID:**
  - Muon is a PF muon
  - And muon is a Global Muon
  - & p_T > 5 GeV, $|\eta|$ < 2.4

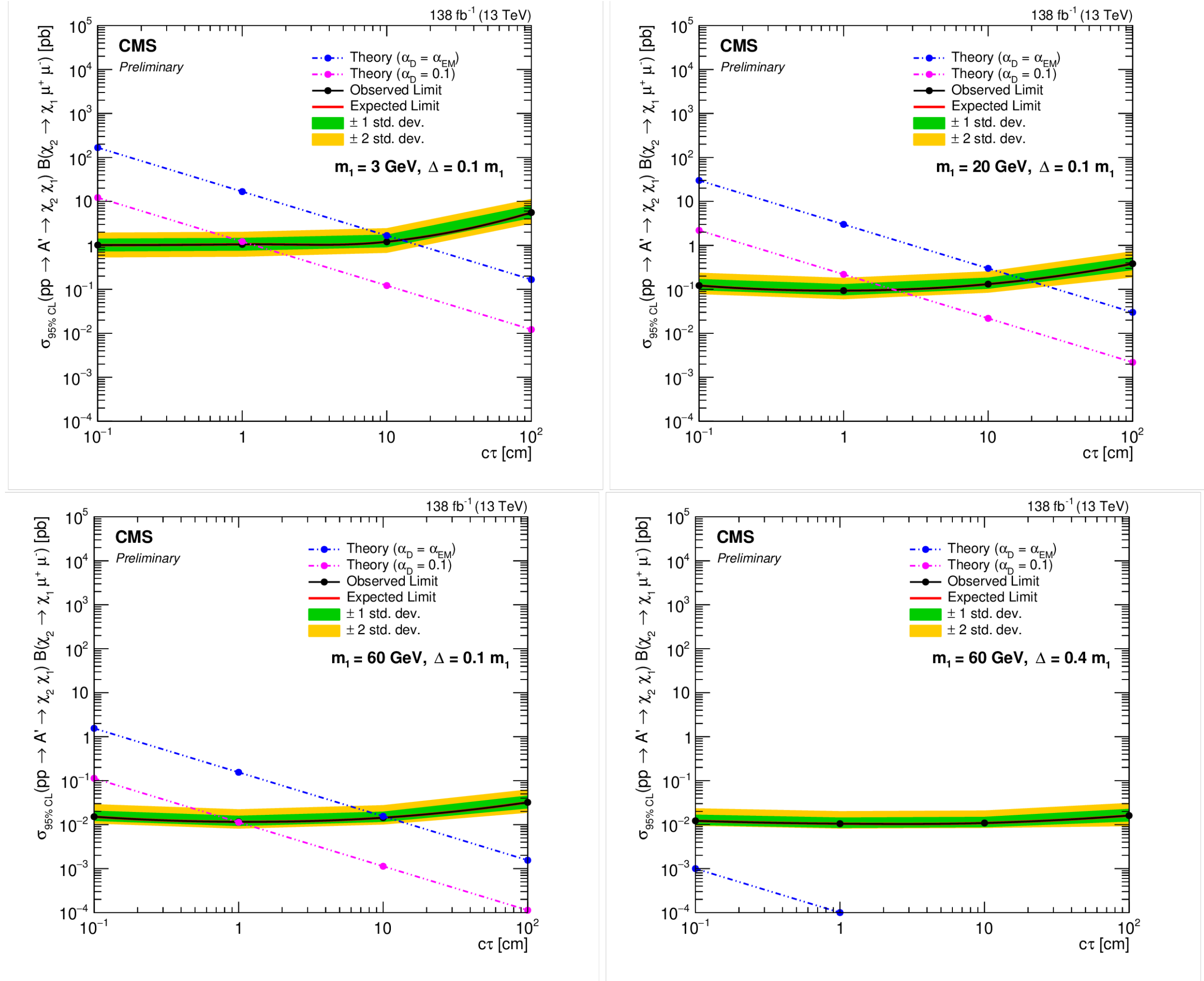
- **SR categorization:**
  - 0, 1, or 2 dSA matches with ID'd PF muons

Search for inelastic dark matter

Some 1D limits vs. m_1 for fixed lifetime



Some 1D limits vs. lifetime for fixed m_1



Search for fractionally charged particles

- Event selection:
  - Single muon trigger with $p_T > 50$ GeV
  - Offline muon $p_T > 55$ GeV
  - One central ($|\eta| < 1.5$) track w/ $p_T > 55$ GeV
    - At least 5 hits in the tracker
    - At least one hit in the pixel
  - Time-of-flight to muon chambers > 0 ns (slower than ultra-relativistic particles)
  - 3D angle between track and other high-p_T ($>$ 35 GeV) tracks or muons < 2.8 rads (cosmic veto)
  - One or two such tracks per event only

- Define signal and control regions:
  - Signal region: events with only one track or events with two tracks with invariant mass smaller than 80 or larger than 100 GeV
  - Control region: events with two tracks with invariant mass between 80 and 100 GeV

- Background prediction is done by extrapolating region with few low-energy deposition hits to region with many low-energy deposition hits
- Prediction is based on binomial fit
  - Track hits are a priori uncorrelated binary measurements by identical detector modules

Search for fractionally charged particles

Distributions for all years