Search for dark showers in the 2018 CMS B-parking dataset

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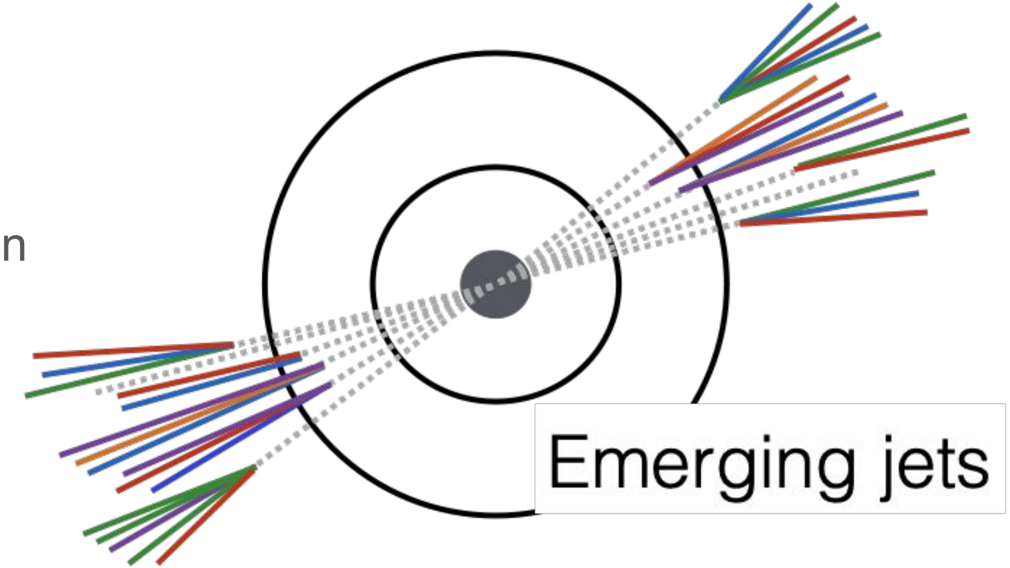
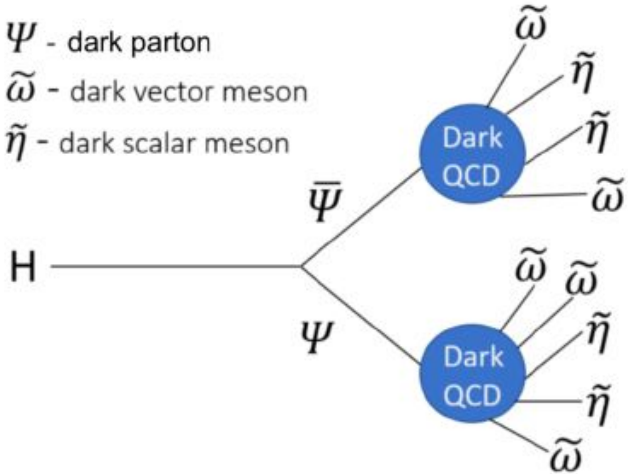
Talk outline

- Hidden Valley signal models
- Event selections and categorisation
- Fits and limits
- Summary and next steps



Overview

- Search for production of dark showers from the SM Higgs
- High branching fraction of dark shower decaying into muons
- Apply BDT selection to separate signal and background
- Signal extraction via fits to dimuon invariant mass

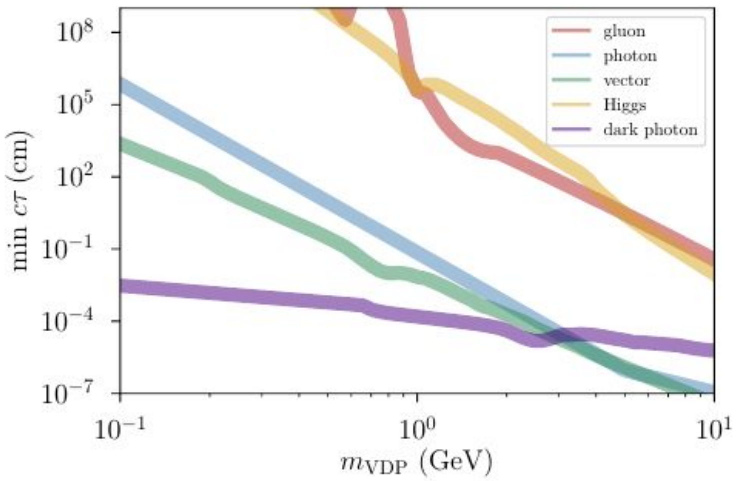


Benchmark models

S. Knapen, J. Shelton, D. Xu

https://arxiv.org/pdf/2103.01238.pdf

- Simplified scenario: only one of the dark mesons ($\tilde{\eta}$ or $\tilde{\omega}$) has a detector-relevant lifetime
- The unstable particle is called the visibly-decaying particle (VDP)
- The other meson either decays promptly to the VDP or escape the detector as missing energy

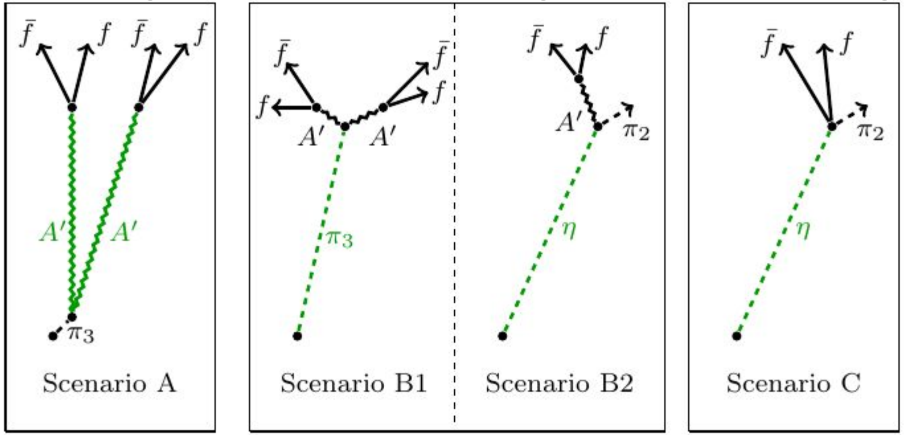


Decay portal	decay operator	VDP	other dark hadron	features
Gluon portal	$\tilde{\eta} G^{\mu\nu}\tilde{G}_{\mu\nu}$	$\tilde{\eta}$	$\tilde{\omega}$ stable or $\tilde{\omega} \to \tilde{\eta}\tilde{\eta}$	hadron-rich shower
Photon portal	$\tilde{\eta} F^{\mu\nu}\tilde{F}_{\mu\nu}$	$\tilde{\eta}$	$\tilde{\omega}$ stable or $\tilde{\omega} \to \tilde{\eta}\tilde{\eta}$	photon shower
Vector portal	$\tilde{\omega}^{\mu\nu} F_{\mu\nu}$	$\tilde{\omega}$	$\tilde{\eta}$ stable	semi-visible jet
Higgs portal	$\tilde{\eta} H^{\dagger} H$	$\tilde{\eta}$	$\tilde{\omega}$ stable or $\tilde{\omega} \to \tilde{\eta}\tilde{\eta}$	heavy flavour-rich shower
Dark photon portal	$\tilde{\eta} F'^{\mu\nu}\tilde{F}'_{\mu\nu} + \epsilon F'^{\mu\nu} F_{\mu\nu}$	A'	$\tilde{\omega}$ stable or $\tilde{\omega} \to \tilde{\eta}\tilde{\eta}$	lepton-rich shower

New Hidden Valley benchmark model

- New benchmark model featuring a light dark photon with dark flavour-violating couplings
- Contains two dark flavours instead of one ⇨ wider spectrum of dark hadrons
- Decay topologies can give non-pointing signals

Resonant, pointing | Resonant, non-pointing | Non-resonant, non-pointing



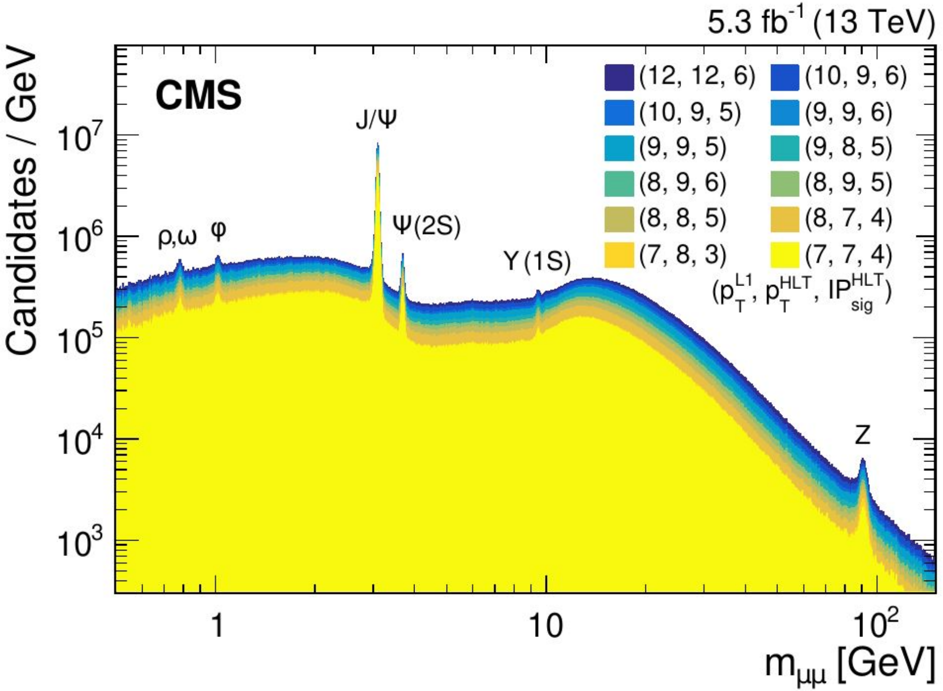
S. Born, R. Karur, S. Knapen, J. Shelton

https://arxiv.org/pdf/2303.04167.pdf

B-parking dataset

- Contains triggers that select displaced, low p_T muons
- More relaxed and inclusive trigger requirements ⇨ higher trigger rate than standard data streams
- Delayed offline reconstruction - allowed the reconstruction of 10^{10} unbiased B decays

Invariant mass distribution of oppositely charged muon pairs originating from a common vertex, obtained from a subset of the B parking data



https://arxiv.org/pdf/2403.16134.pdf

Selections

Baseline selections:

- Use a displaced muon trigger (33.6 fb^{-1}) from the 2018 B parking dataset
- Events contain muons; loose kinematic selections
- At least one muon being trigger matched and satisfying offline cuts

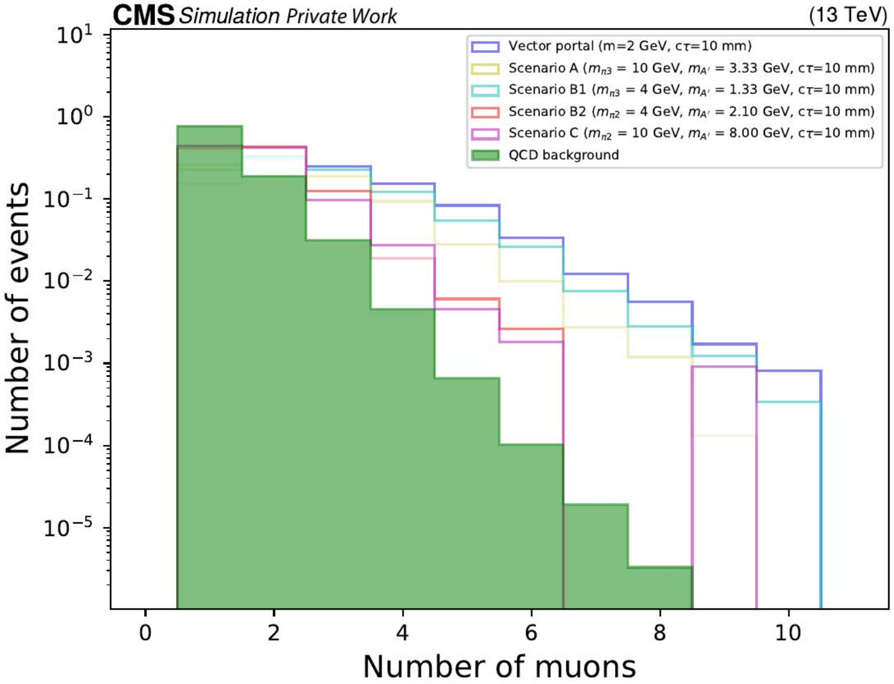
Further selections:

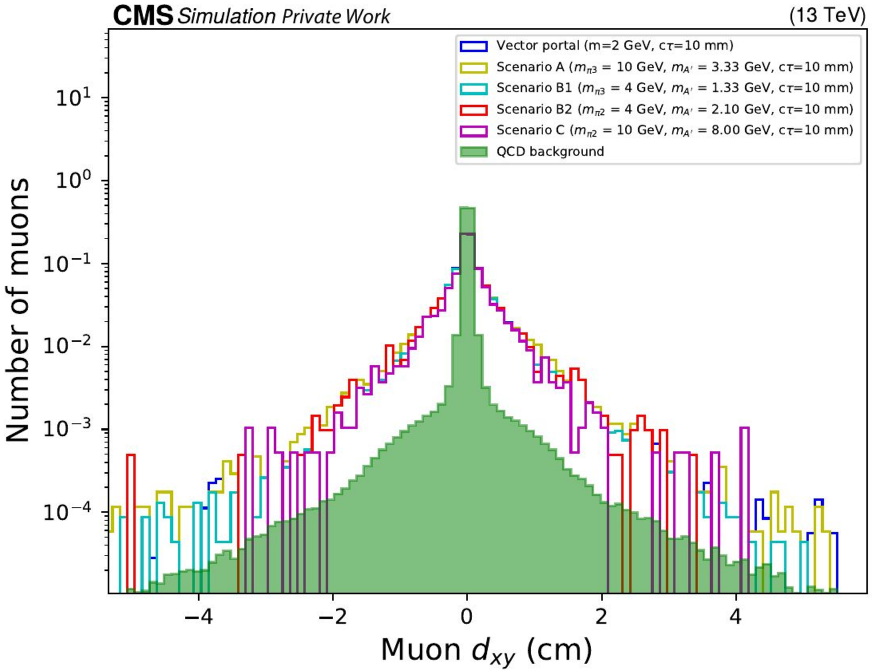
- BDT selection (10^4 background rejection as a working point)
  BDT trained with signal and background features

- At least one muon SV satisfying quality cuts
  Custom inclusive dimuon vertexing algorithm with high reconstruction efficiency

Signal and background features

- A higher number of muons in signal events compared to background events
- Muon variables provide excellent discrimination between signal and background



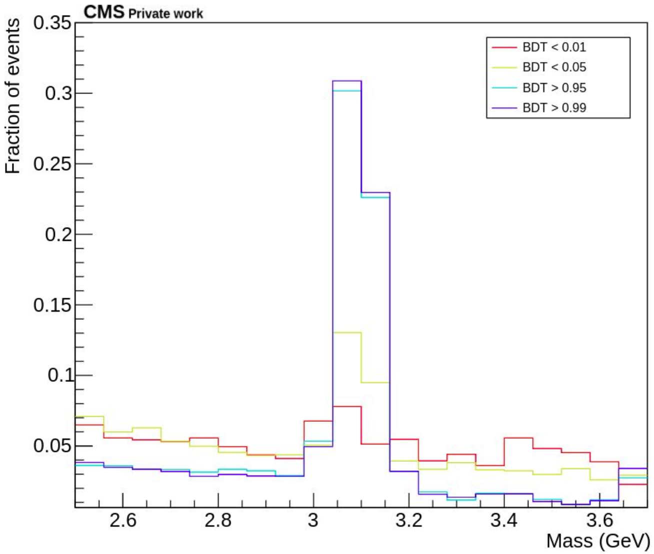


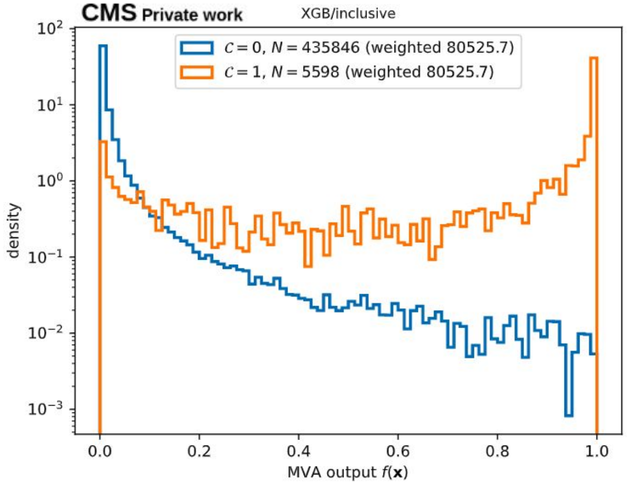
Event-level BDT to suppress background

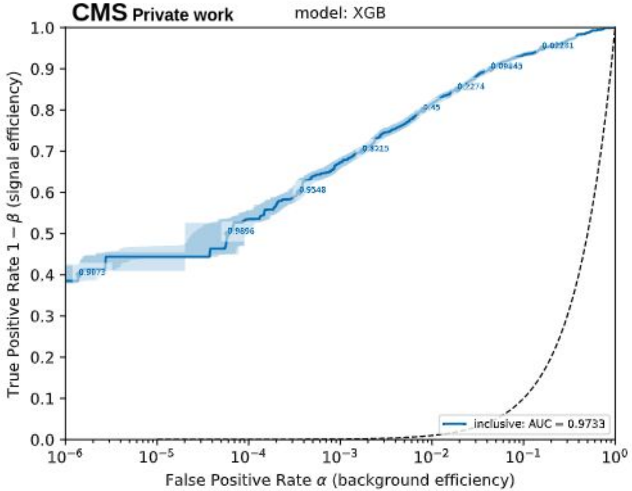
- BDT trained with event features as input
- Working point: 10^4 background rejection with > 40% signal efficiency
- Use B→J/ψX decay to demonstrate BDT performance in identifying displaced dimuons!

Using model trained with the Vector portal

Background muon SV mass distribution



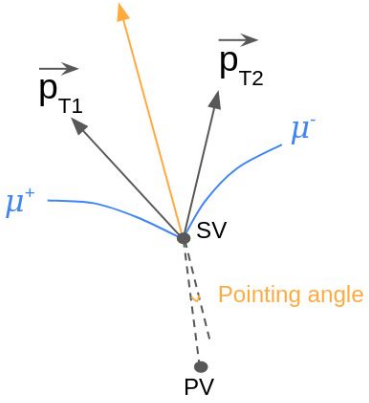


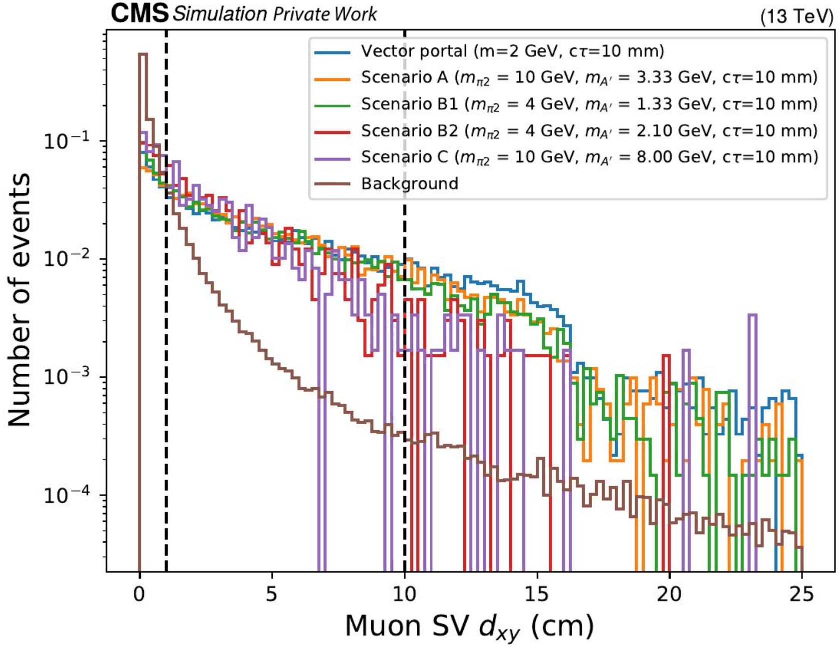


Scenario A training

Event categorisation

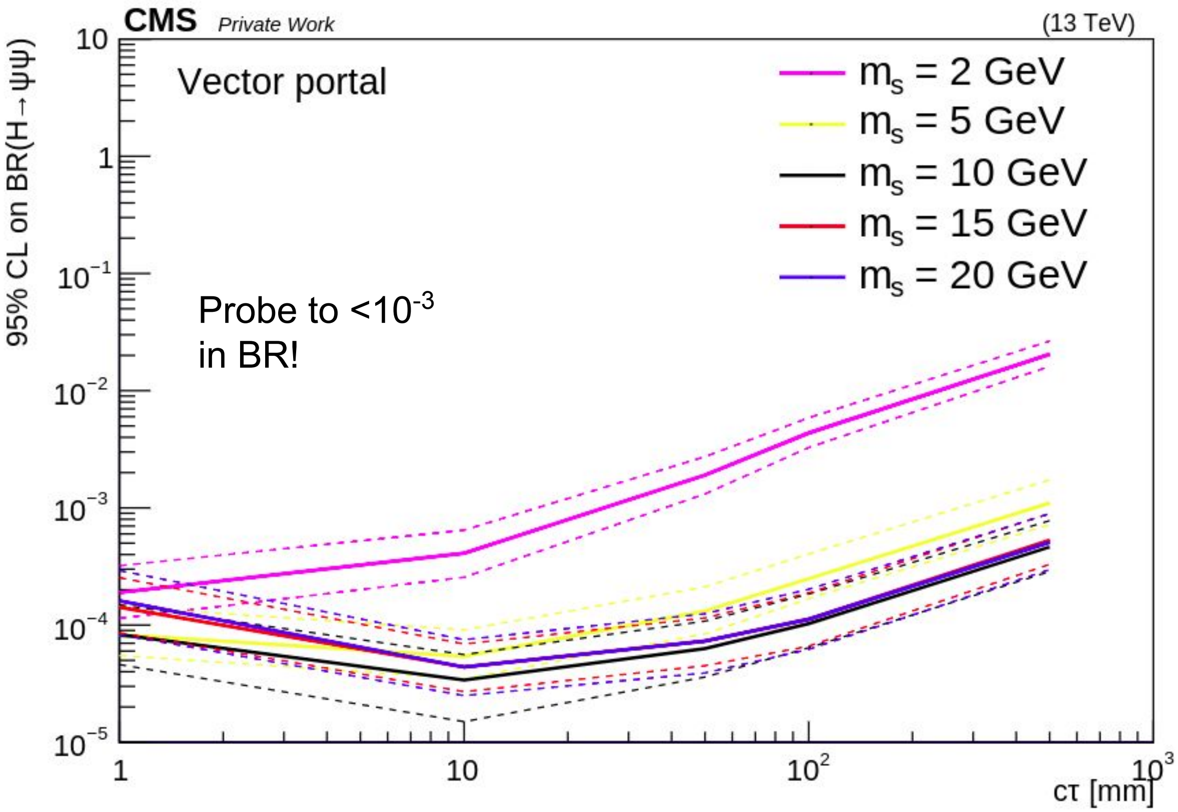
- Check all pairs of muon SV:
  - if there are at least two SVs with mass within 3% of each other ⟹ **multi vertex** category
  - Otherwise ⟹ **single vertex** category
- Categorise in **transverse displacement**:
  - d_{xy} < 1 cm (beam pipe),
  - 1 cm < d_{xy} < 10 cm (pixel tracker),
  - d_{xy} > 10 cm (anything beyond)
- Categorise in **pointing angle**:
  - pointing angle < 0.2,
  - pointing angle > 0.2





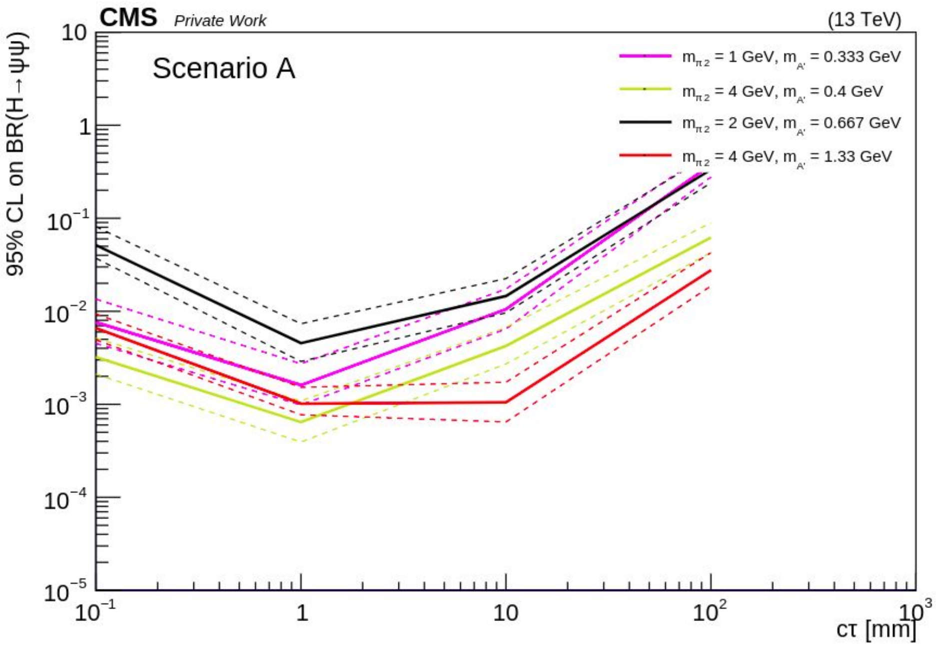
Limits - Vector portal

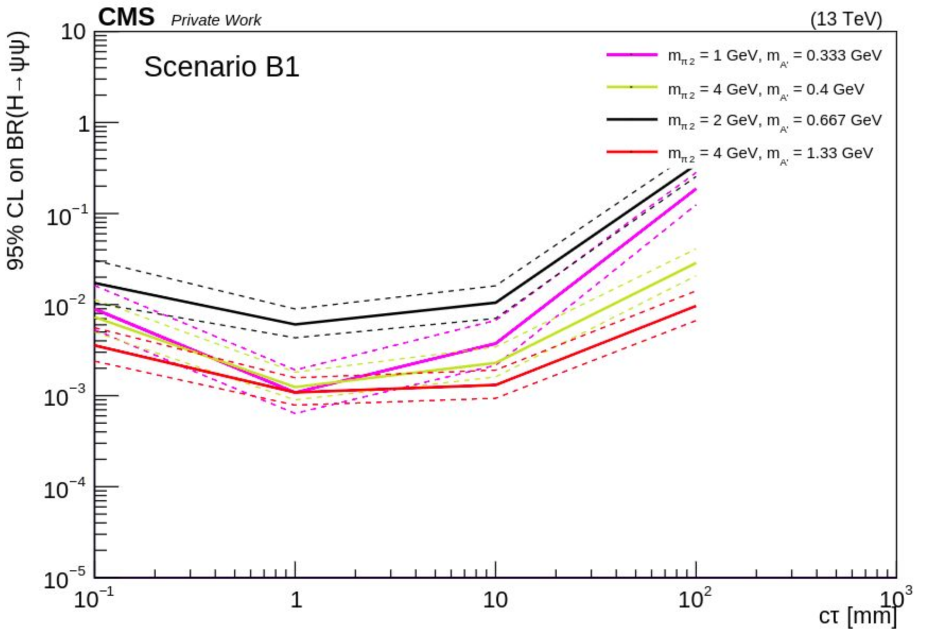
- Expected limits are obtained from fitting signal and background MC (sliding mass window)
  - Use a combination of parametric fits and counting experiments
- Systematics from the trigger, displaced muons, PU and luminosity, Higgs production cross-section and discrete profiling are implemented
- Placeholder systematic of 5% for the BDT selection



Limits - Scenario A, Scenario B1

- Achieve great sensitivities, particularly for Scenario B1 which is non-pointing
- Low mass models!

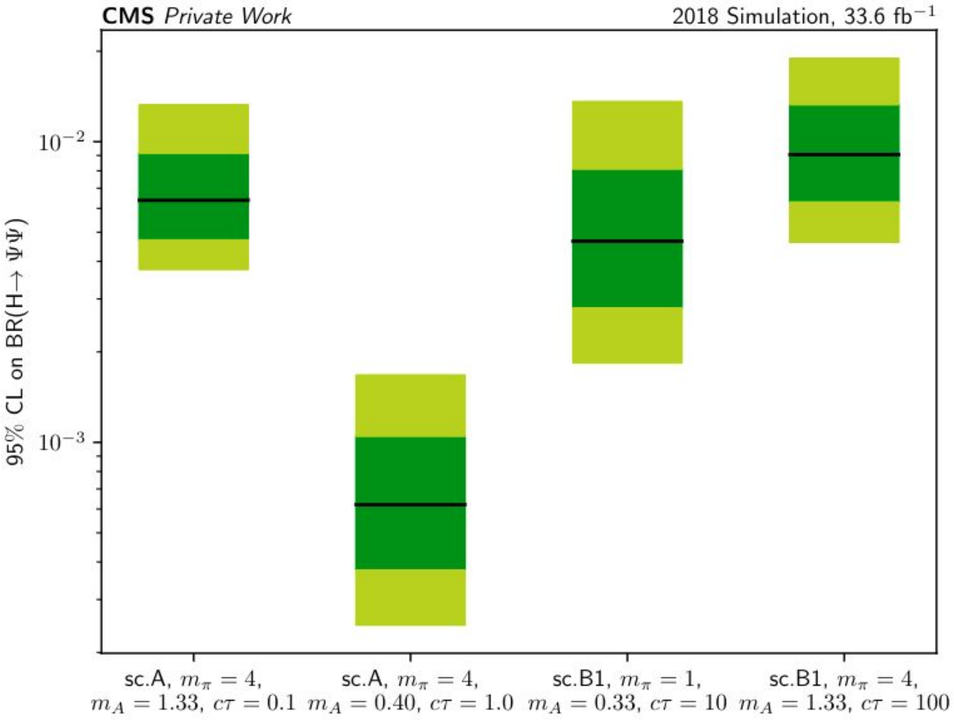




Probe to ~10^{-3} in BR!

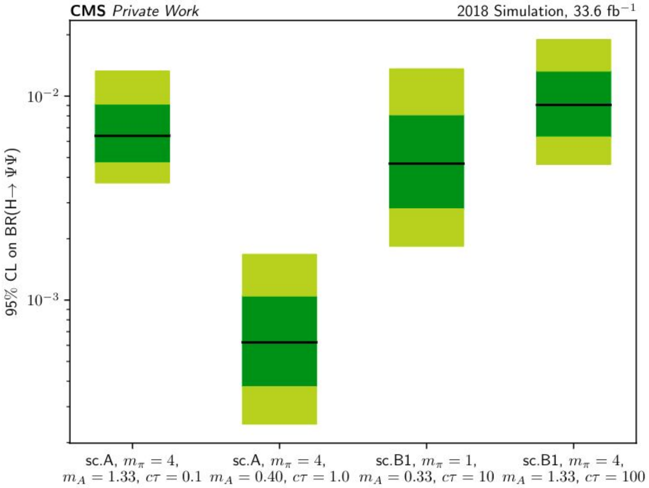
Limits - scenarios A, B1

- The expected limits at 95% CL on BR(H→ψψ) is considerably tighter than the corresponding limits on the invisible branching fraction of the Higgs, BR(H→inv) < 0.1



Summary and next steps

- Performed the Run 2 analysis for new dark shower models
  - Achieved great sensitivity, in particular for non-pointing models!
- Studied BDT selections applied on data - no sculpting on the mass distribution is observed
- Several systematics studies in place (including trigger scale factors and displaced muon scale factors)



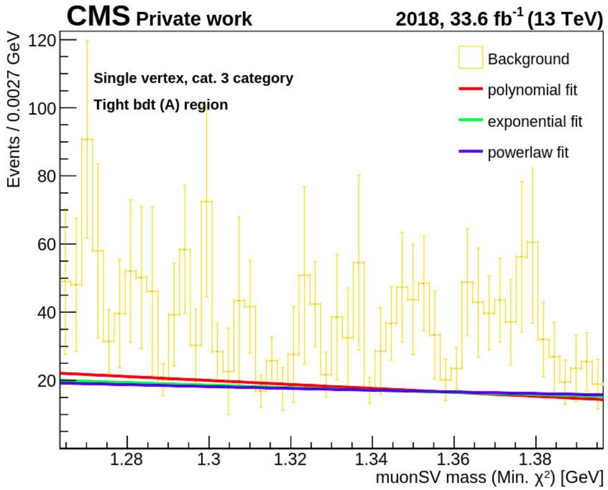
Next steps:

- Finalise unblinding strategy
- Finish systematics

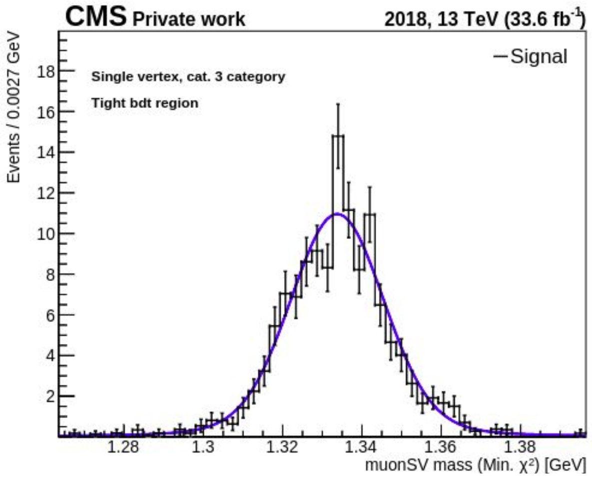
Backup slides

Signal and background fits

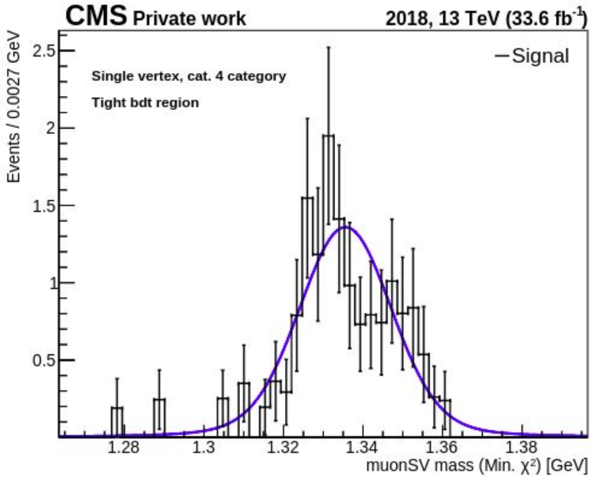
- Use the Voigtian function to model signal, and an envelope of functions for the background
  - Discrete profiling for systematic
- Fit with a sliding window of 5*HWHM of the signal
- Checks in data (see backup) shown no evidence for mass sculpting from BDT



Single vertex category 3
sigma = 0.011
gamma = 0.0044
HWHM = 0.015
chi2/ndf = 1.05

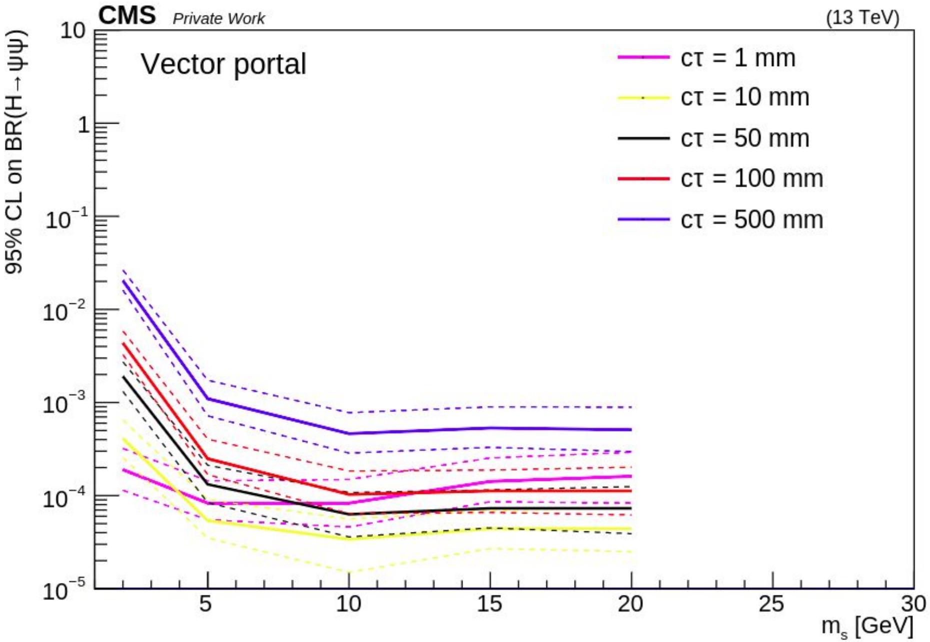


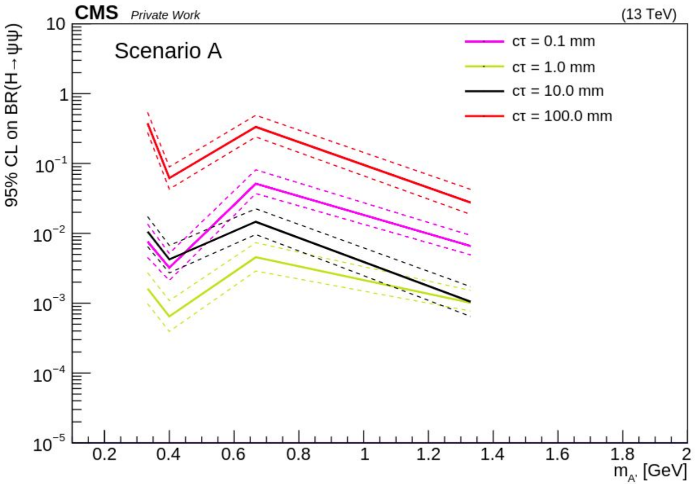
Single vertex category 4
sigma = 0.011
gamma = 0.0047
HWHM = 0.015
chi2/ndf = 0.90

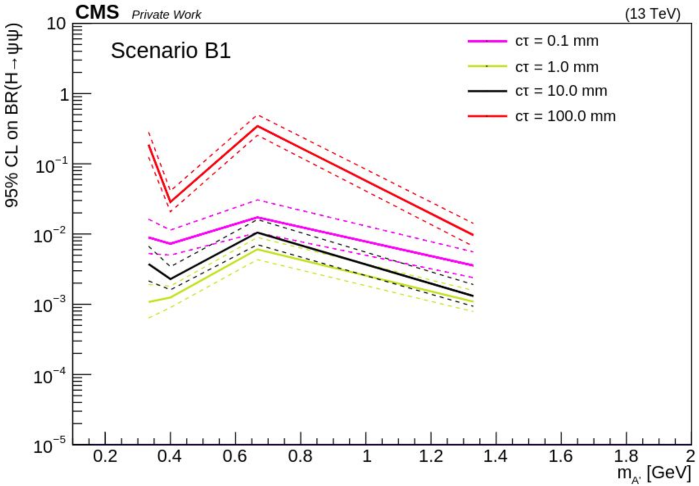


scenario A ($m_{\pi 3}$ = 4 GeV, $m_{A'}$ = 1.33 GeV, cτ = 10 mm)

Limits as a function of mass

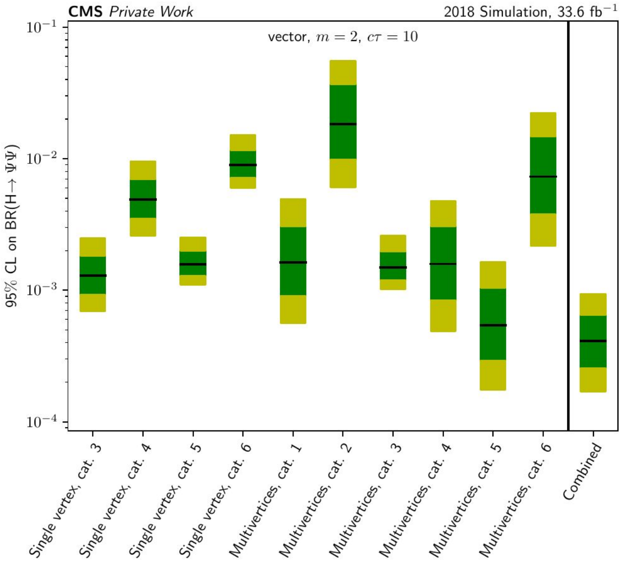


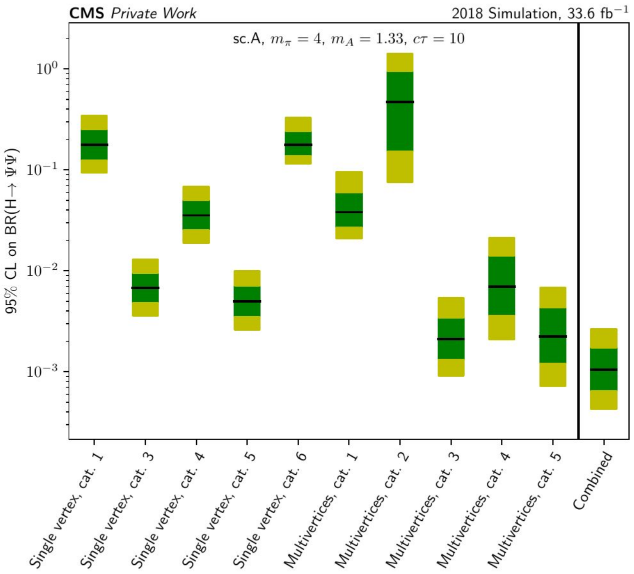


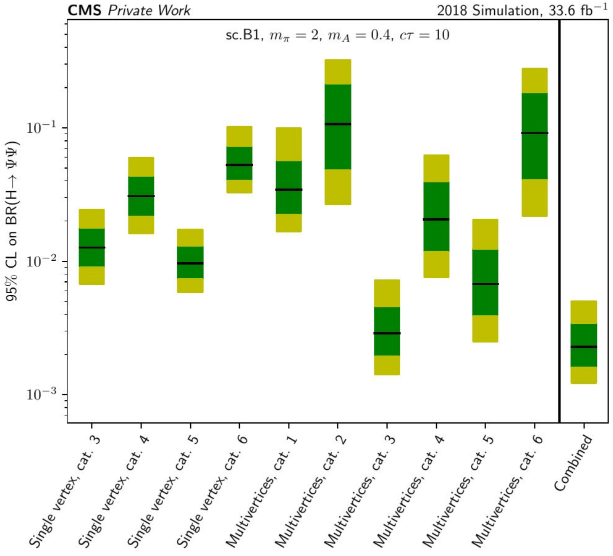


Limits per event category

- Limits per category for some example signal benchmark models
- As expected, multi-vertex categories with high displacements are the most sensitive categories



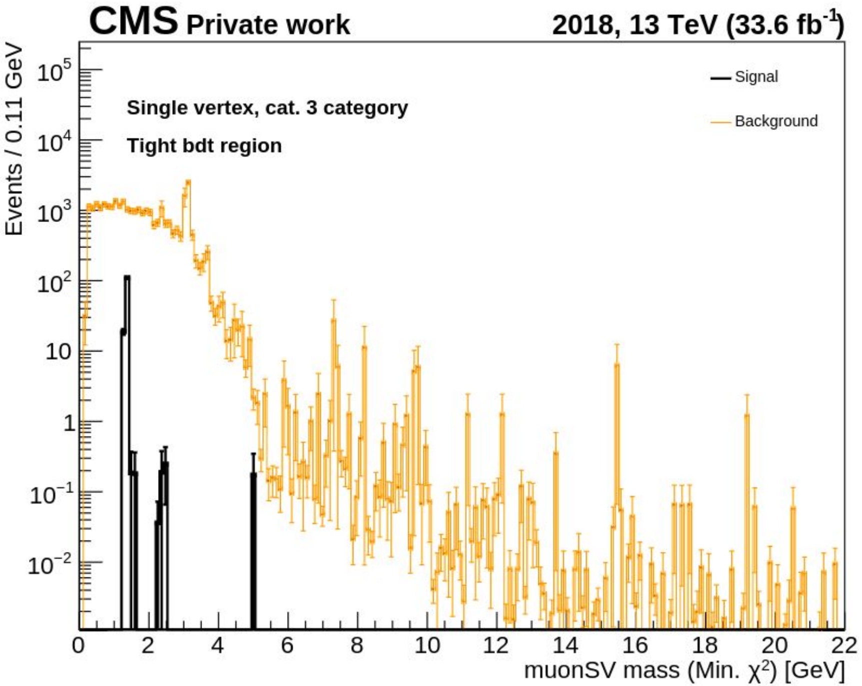




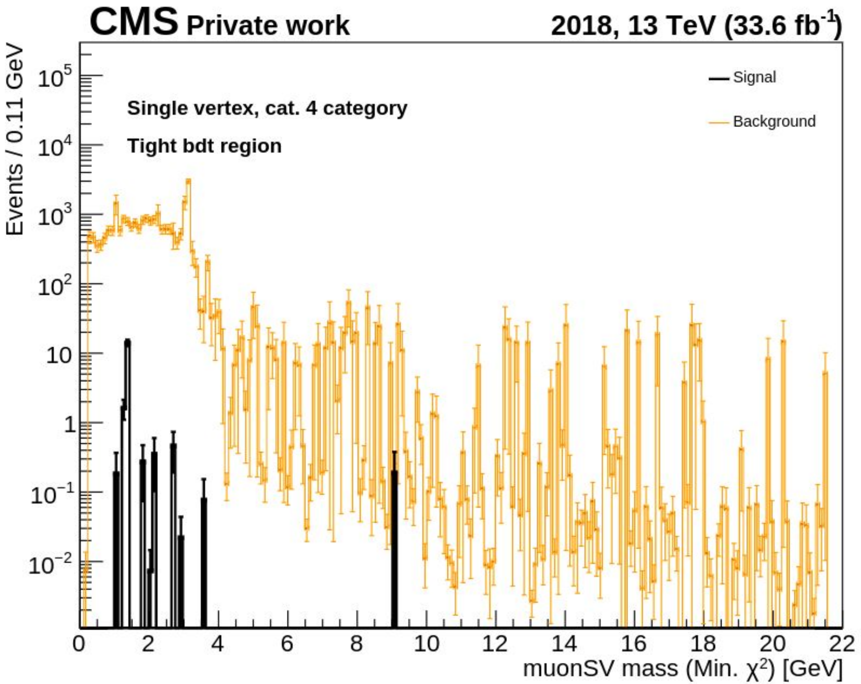
Single vertex - categories 3, 4

- Signal: scenario A ($m_{\pi 2}$ = 4 GeV, $m_{A'}$ = 1.33 GeV, cτ = 10 mm)
- 1 cm < d_{xy} < 10 cm

pAngle < 0.2



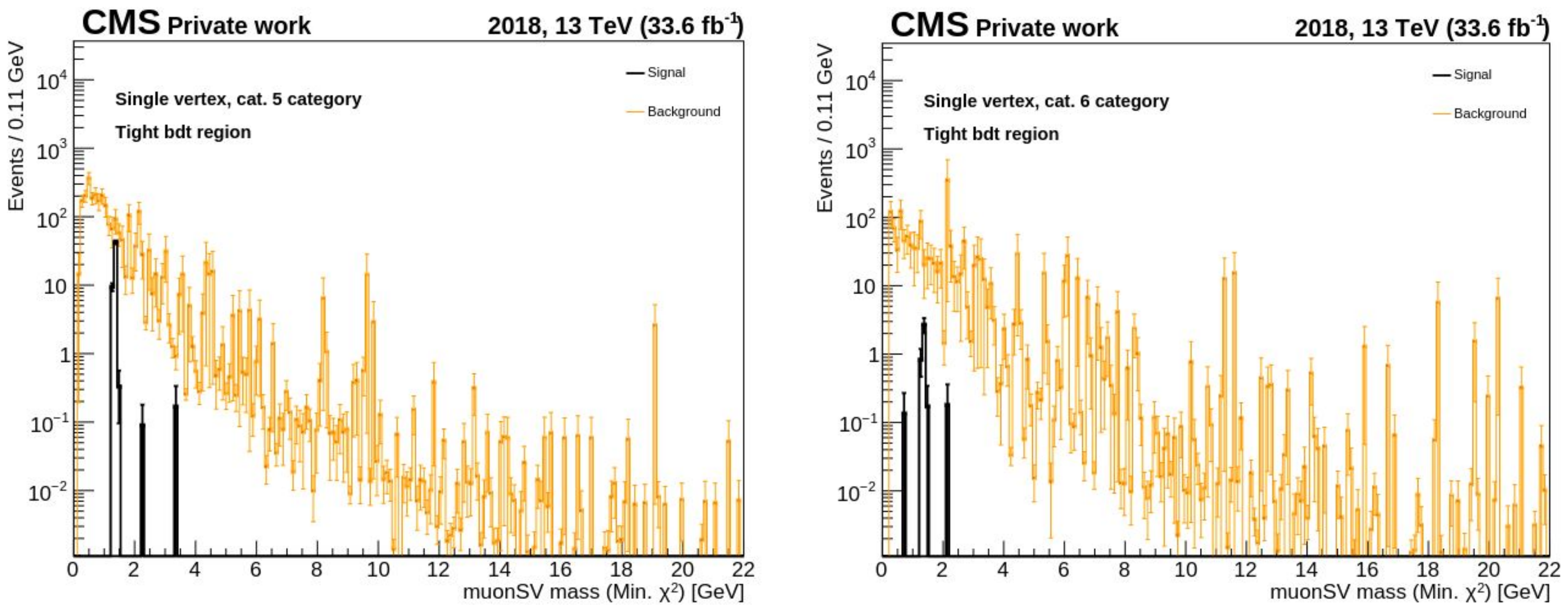
pAngle > 0.2



Single vertex - categories 5, 6

- Signal: scenario A ($m_{\pi 2}$ = 4 GeV, $m_{A'}$ = 1.33 GeV, cτ = 10 mm)
- High displacement categories - d_{xy} > 10 cm

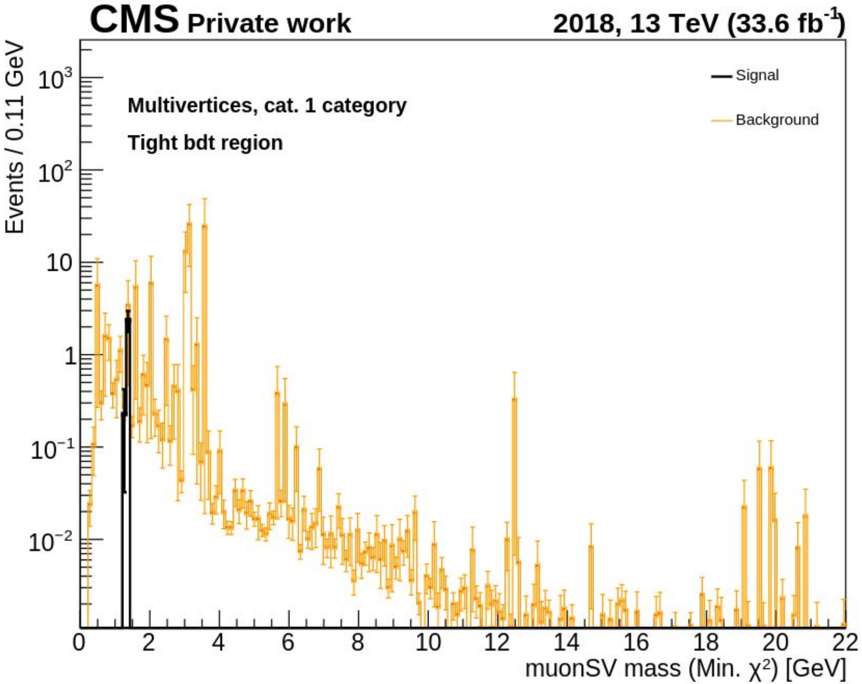
pAngle < 0.2 | pAngle > 0.2



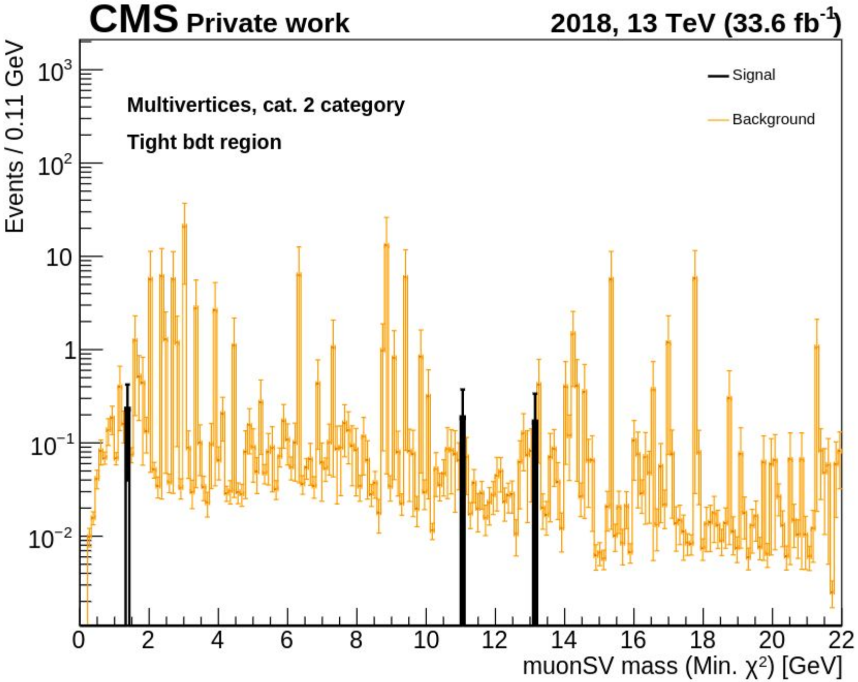
Multi vertex - categories 1, 2

- Signal: scenario A ($m_{\pi 2}$ = 4 GeV, $m_{A'}$ = 1.33 GeV, cτ = 10 mm)
- d_{xy} < 1 cm

pAngle < 0.2



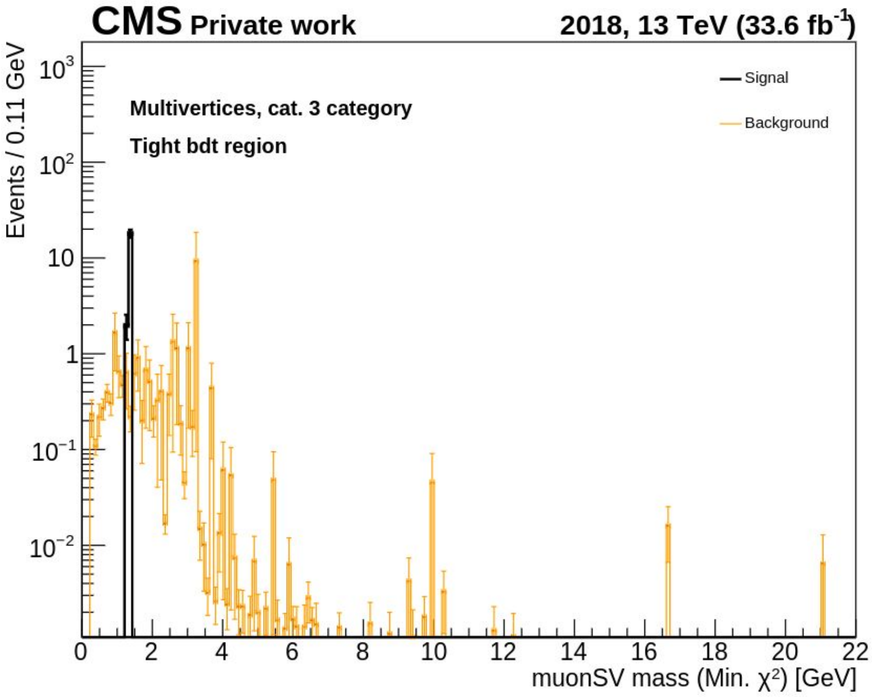
pAngle > 0.2



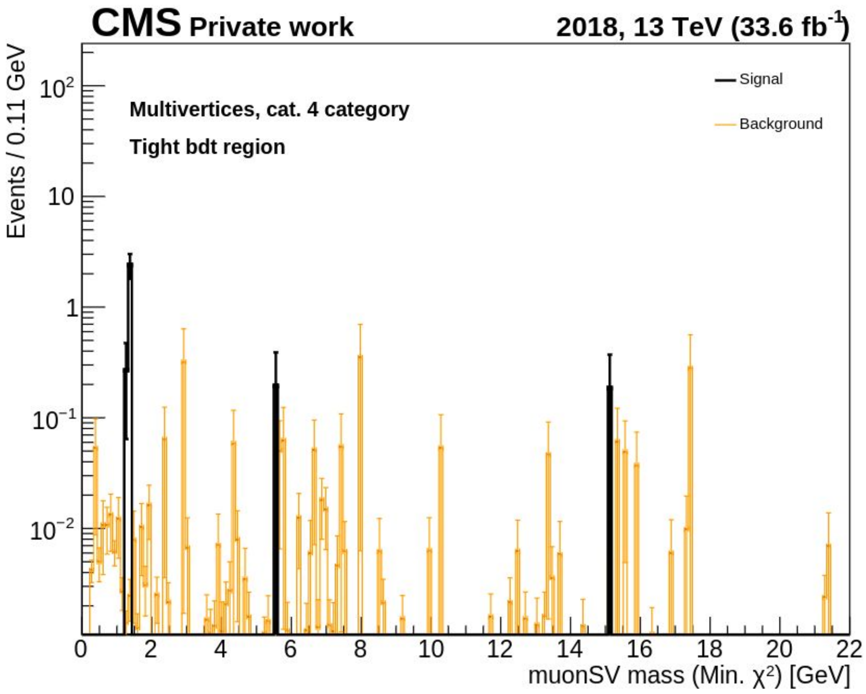
Multi vertex - categories 3, 4

- Signal: scenario A ($m_{\pi 2}$ = 4 GeV, $m_{A'}$ = 1.33 GeV, cτ = 10 mm)
- 1 cm < d_{xy} < 10 cm

pAngle < 0.2



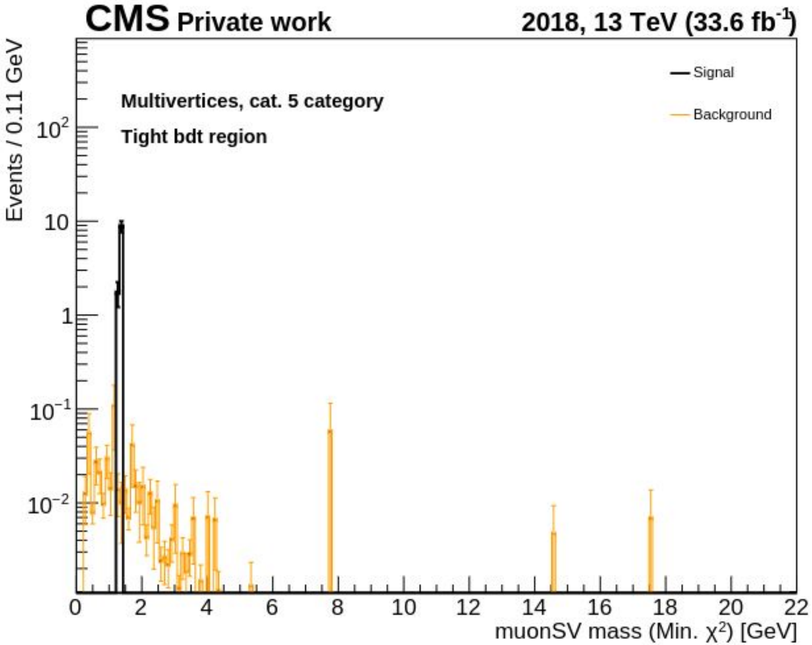
pAngle > 0.2



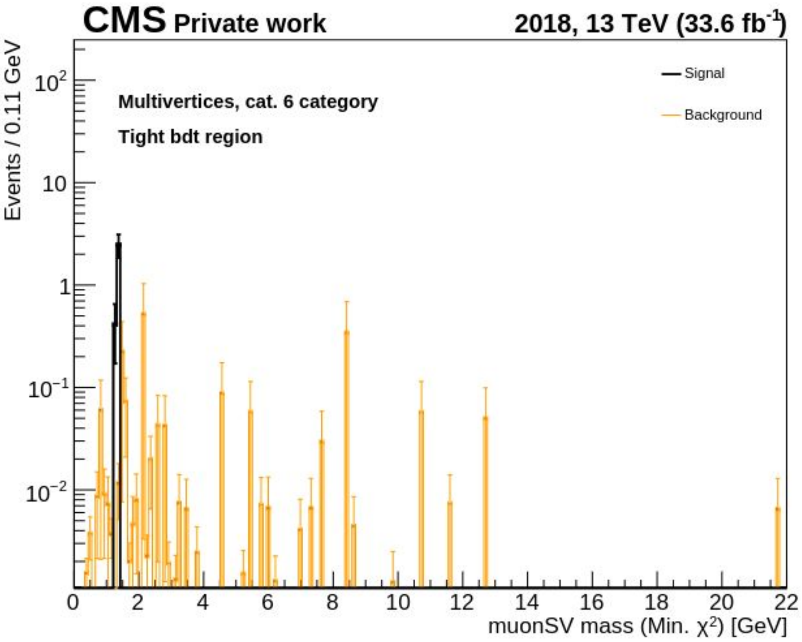
Multi vertex - categories 5, 6

- Signal: scenario A ($m_{\pi 2}$ = 4 GeV, $m_{A'}$ = 1.33 GeV, cτ = 10 mm)
- High displacement categories - d_{xy} > 10 cm
- Great sensitivity

pAngle < 0.2



pAngle > 0.2



Event level BDT

Multivariate input

- Muons: 16 variables
- SV: 14 variables
- Jets: 20 variables
- Muon SV: 15 variables
- Global variables (nMuons, nSV, nJets, ...)
- Parametric (conditional) model input (m0, ctau0, [xiO, xiL])
- Maximum of [6,6,6,6] leading (p_T) ordered muon, SV, jet, muon SV considered (max can be increased)

⇨ currently approx 390 dimensional input

Planning to reduce to ~50 inputs

Model

Additive scalar superposition of decision trees leaf outputs

- 200 trees, max depth 10 + XGBoost train regularization parameters

Systematics - displaced muon scale factors

- The “tag-and-probe” technique is used
- Tight quality selections are applied on the “tag” muon, which is then paired with a muon of opposite charge (the “probe” muon)
- The muon pair is required to have mass between 2.9 and 3.3 GeV (mass range of the J/ψ resonance)

Variables	Cuts
$p_T(\text{tag } \mu)$	> 8 GeV
$p_T(\text{probe } \mu)$	> 3 GeV
$\lvert\eta(\text{tag } \mu)\rvert$	< 2.4
$\lvert\eta(\text{probe } \mu)\rvert$	< 2.4
$\Delta R(\text{tag } \mu, \text{L1 tag } \mu)$	< 0.3
Trigger	HLT_Mu8_v == 1

Systematics - displaced muon scale factors

- The “tag-and-probe” technique is used, choosing muon pairs in the J/Psi mass region
- Consider different efficiencies for displaced muons
  - Muon track finding efficiency
  - Muon track reconstruction efficiency
  - Muon ID efficiency

$$\epsilon_{\text{track finding}} = \frac{N_{\text{probe}}(\text{tracks})}{N_{\text{probe}}(\text{standalone muons})} \quad (1)$$

$$\epsilon_{\text{track reconstruction}} = \frac{N_{\text{probe}}(\text{tracker muons})}{N_{\text{probe}}(\text{tracks})} \quad (2)$$

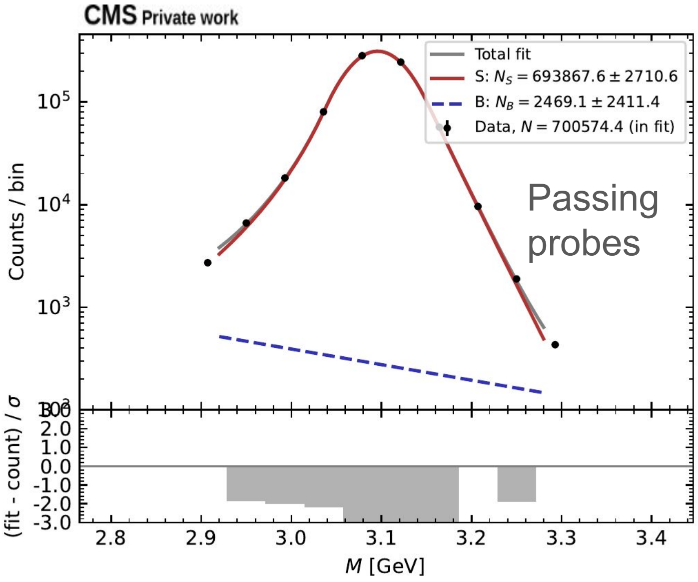
$$\epsilon_{\text{muon identification}} = \frac{N_{\text{probe}}(\text{loose muons})}{N_{\text{probe}}(\text{tracker muons})} \quad (3)$$

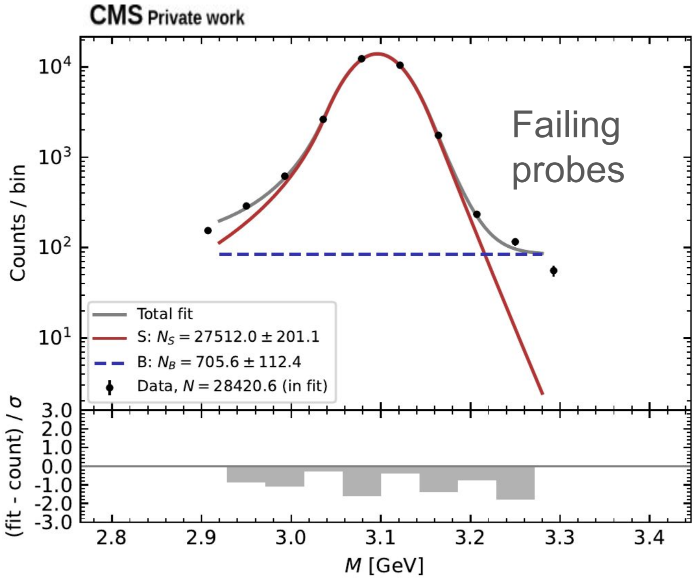
- Measure the combined efficiency:

$$\begin{aligned} \epsilon_{\text{combined}} &= \epsilon_{\text{track finding}} \times \epsilon_{\text{track reconstruction}} \times \epsilon_{\text{muon identification}} \\ &= \frac{N_{\text{probe}}(\text{loose muons})}{N_{\text{probe}}(\text{standalone muons})} \end{aligned} \quad (4)$$

Systematics - displaced muon scale factors

- The efficiencies in data and MC are derived by fitting the mass distributions of passing and failing dimuon pairs in bins of p_T and $|d_{xy}|$
- Signal fit: Double-sided Crystal Ball function
- Background fit: Exponential function

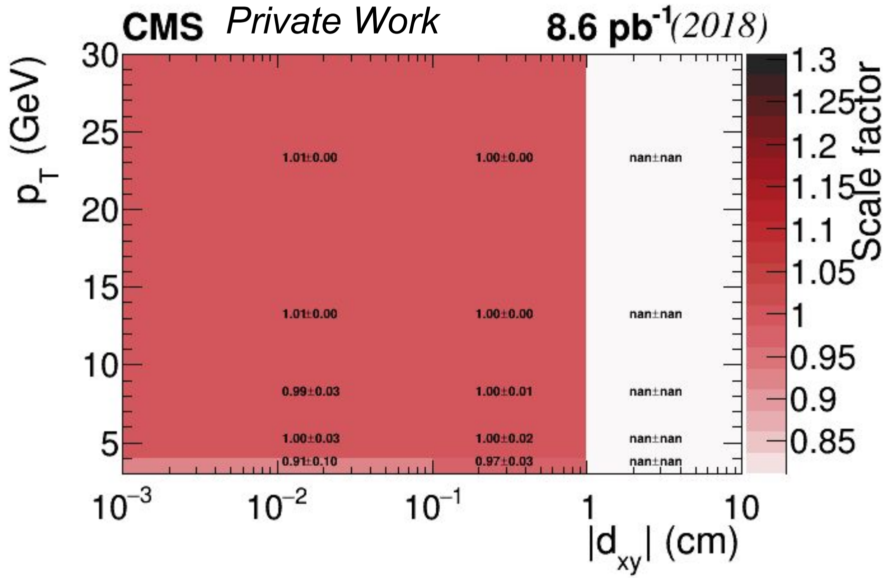


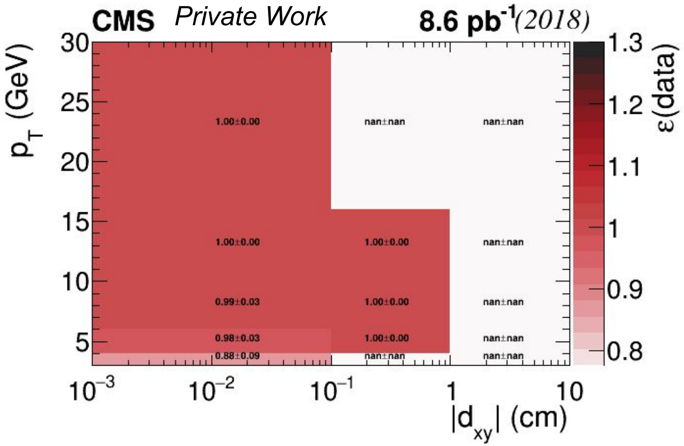


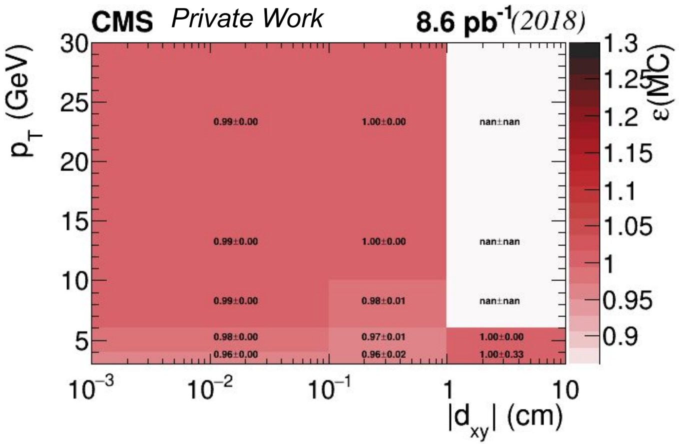
3 GeV < p_T < 4 GeV, 0.001 cm < $|d_{xy}|$ < 0.1 cm

Systematics - displaced muon scale factors

- Measure the combined muon track finding, track reconstruction and muon ID efficiency
- Fitting the J/Psi resonance
- Low statistics in 1 cm < $|d_{xy}|$ < 10 cm







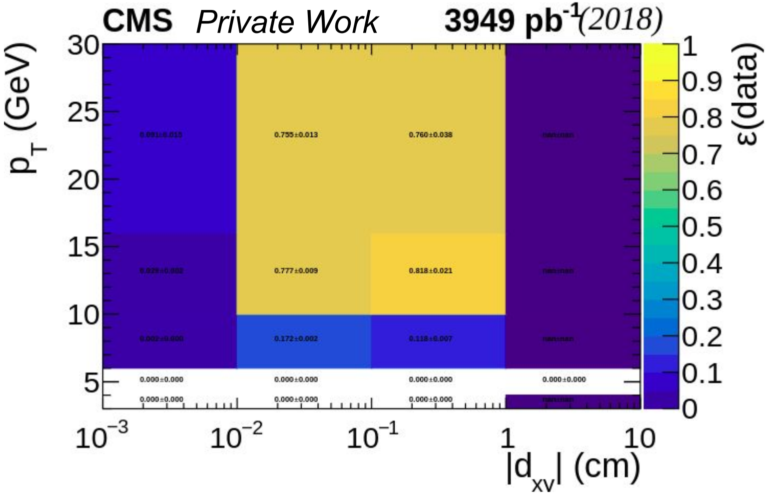
Systematics - trigger scale factors

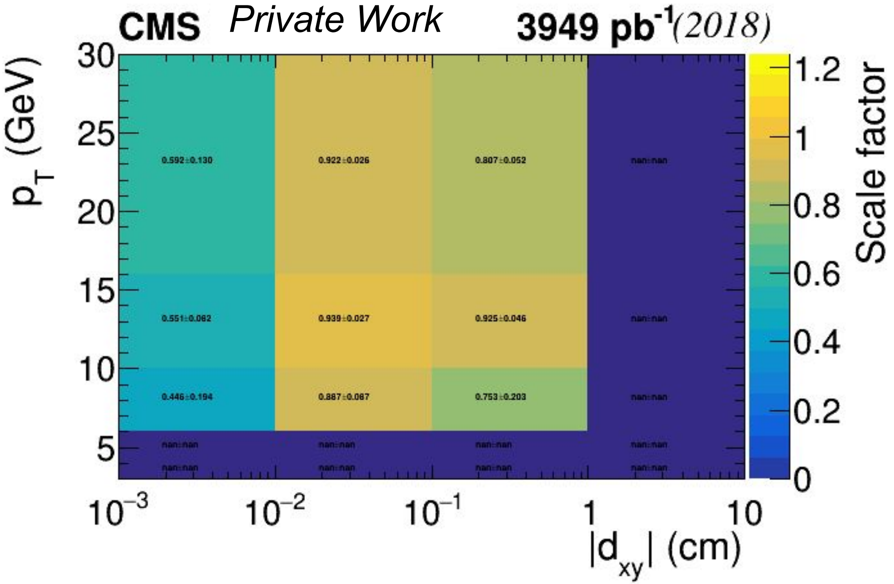
- Measure the trigger scale factors for HLT_Mu9_IP6 using the tag-and-probe technique
- Follow the study done in the R(K) analysis BPH-22-005
- Tight quality selections are applied on the tag muon
- The probe muon is classified as passing or failing based on whether it can be matched to the trigger muon
- $\epsilon_{\text{trigger}} = N_{\text{passing probes}} / N_{\text{all probes}}$

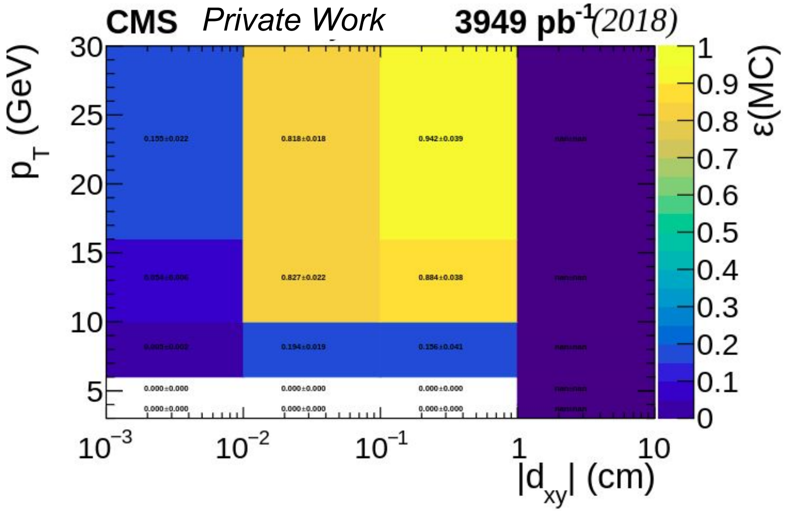
Variables	Cuts
Prob(μ, μ vtx)	> 0.01
Δ z	< 0.5 cm
d_{xy}/σ(tag μ)	> 8
p_T(tag μ)	> 10 GeV
p_T(L1 tag μ)	> 10 GeV
Δ R(tag μ, L1 tag μ)	< 0.5
Match tag μ with HLT μ	-
ΔR(tag μ, probe μ)	> 0.15
Muon ID (tag muon)	tight ID
Muon ID (probe muon)	medium ID

Systematics - trigger scale factors

- Follow the study done in the R(K) analysis BPH-22-005 - performed validation and see reasonable agreement
- Then perform the study binned in p_T and d_{xy}
- Low statistics in 1 cm < $|d_{xy}|$ < 10 cm



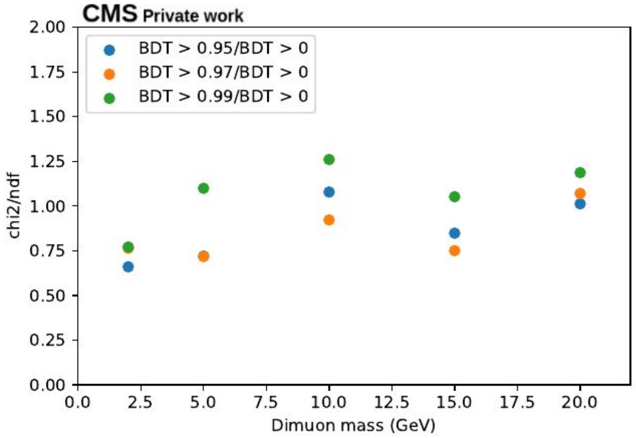


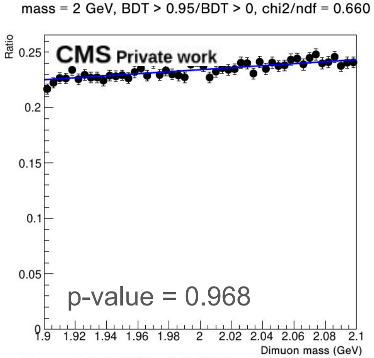


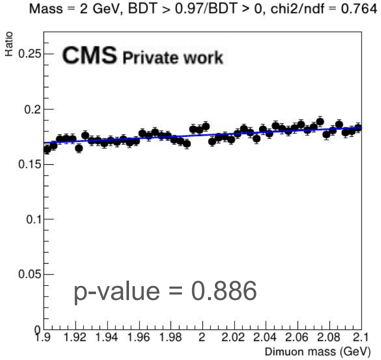
Checks in data for mass sculpting from BDT

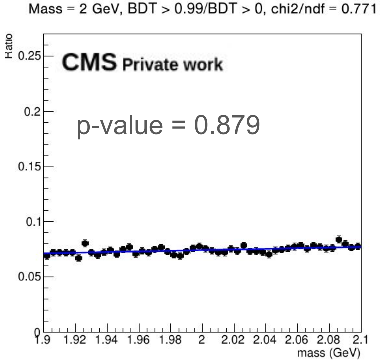
- Study the effect of BDT selections on the dimuon mass distribution using sliding mass windows of +/- 5σ of the signal mass at m = 2, 5, 10, 15 and 20 GeV
- Take the ratios of mass distributions with tightening BDT selections (BDT > 0.95, 0.97, 0.99) to the mass distribution without BDT selection
- Perform fits to the ratios by using linear/constant function

⇨ no sculpting is observed!









Data studies - BDT selections