Searches for LLPs with CMS

Eighth LHC LLP Community Workshop

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on behalf of the
CMS Collaboration

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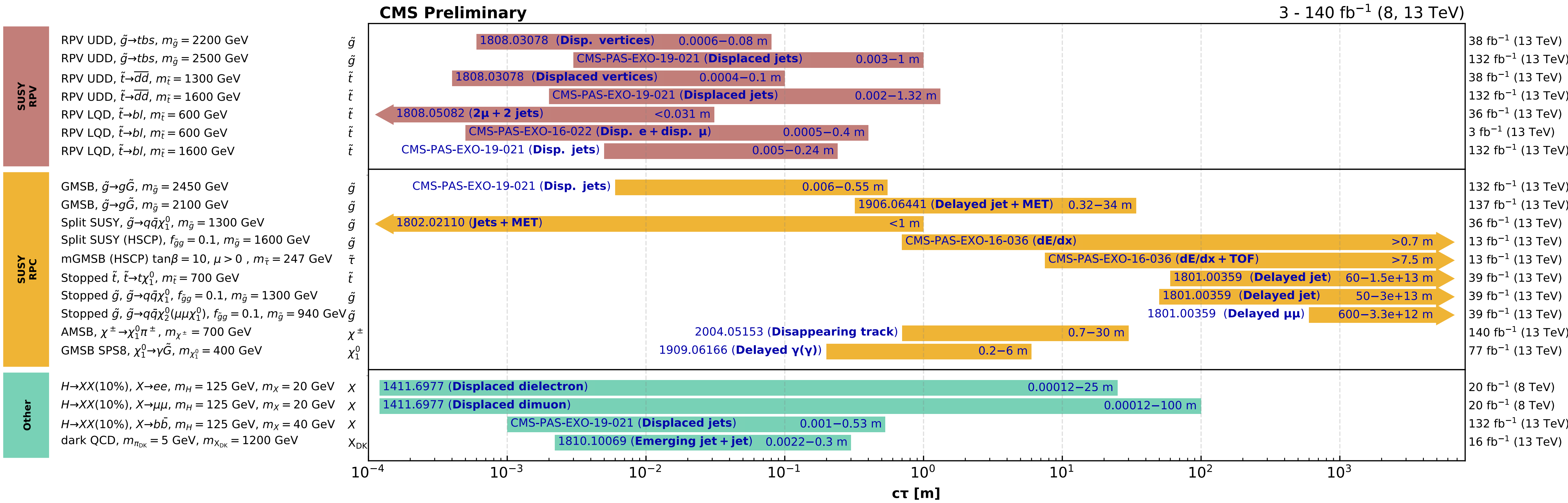
Existing CMS LLP Searches

Overview of CMS long-lived particle searches



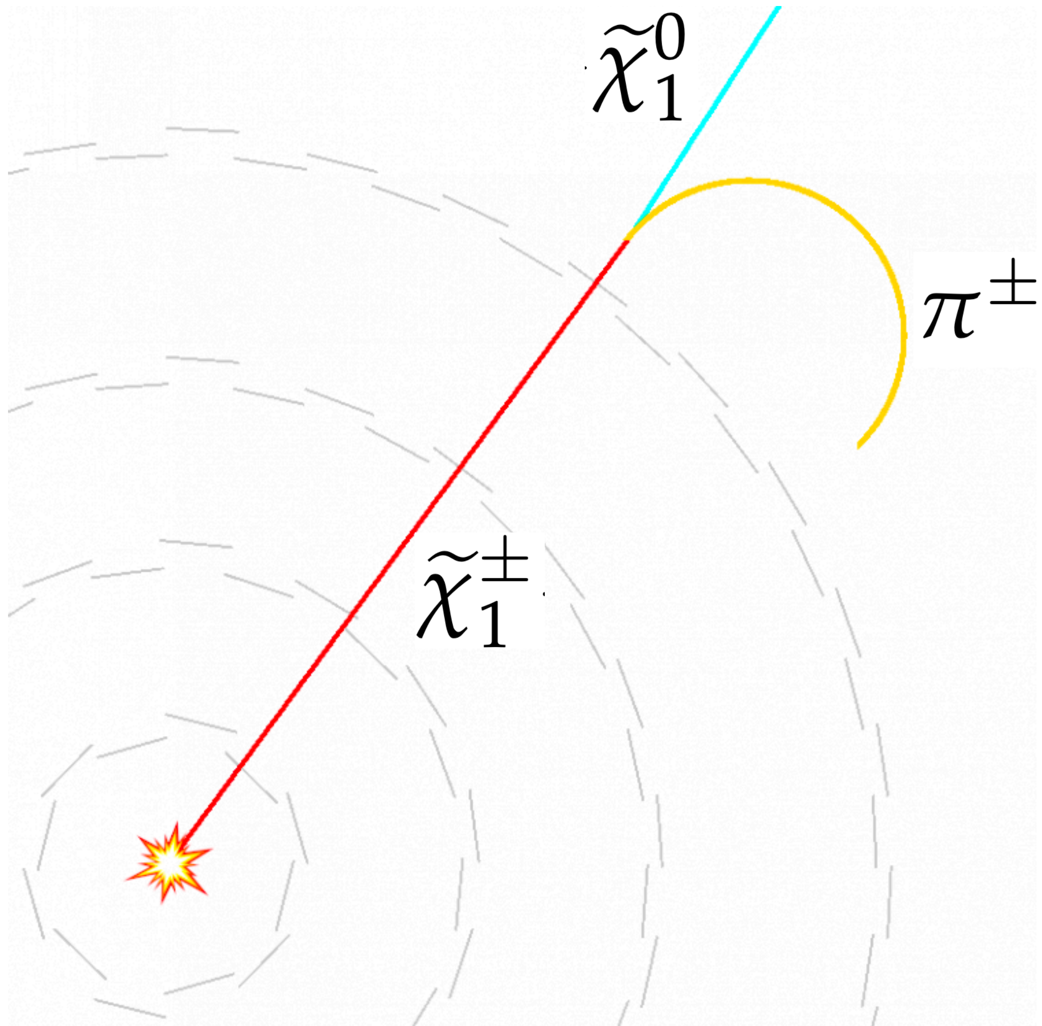
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

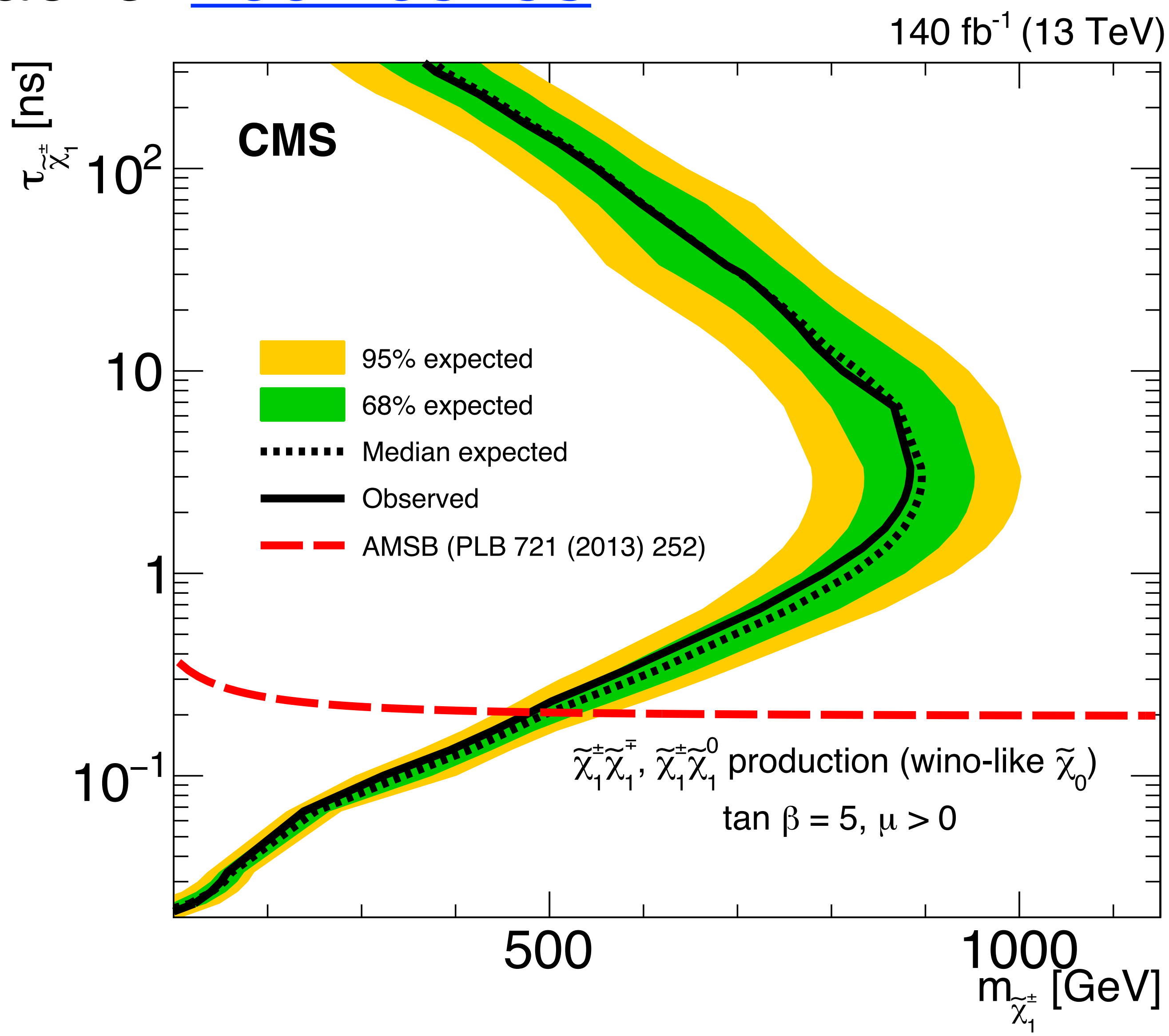
CMS has covered a wide range of models and LLP signatures across many orders of magnitude in cτ

[CMS Exotica Summary Plots]

CMS Highlights from LLP7 (May 2020)

Disappearing Tracks: 2004.05153





Distinct signature!

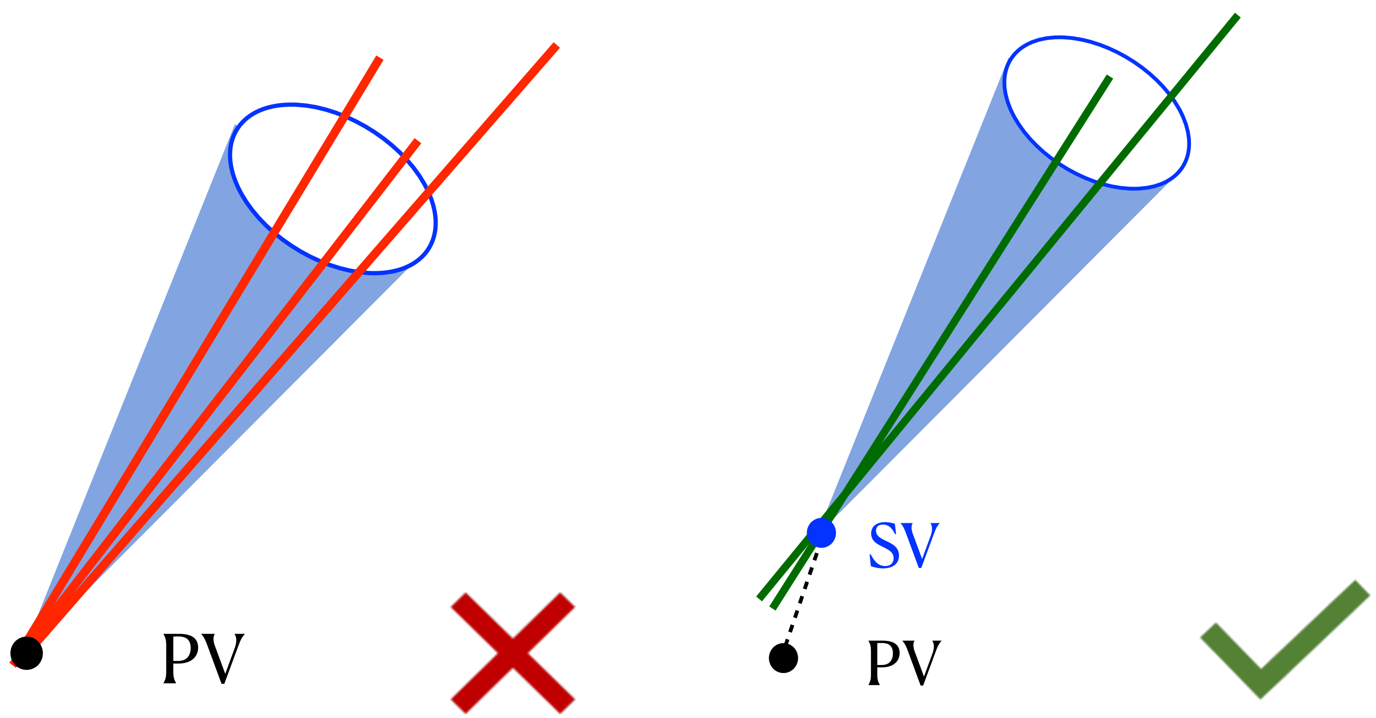
Arises naturally in AMSB and compressed SUSY scenarios with $\mathcal{O}$(100 MeV) splittings

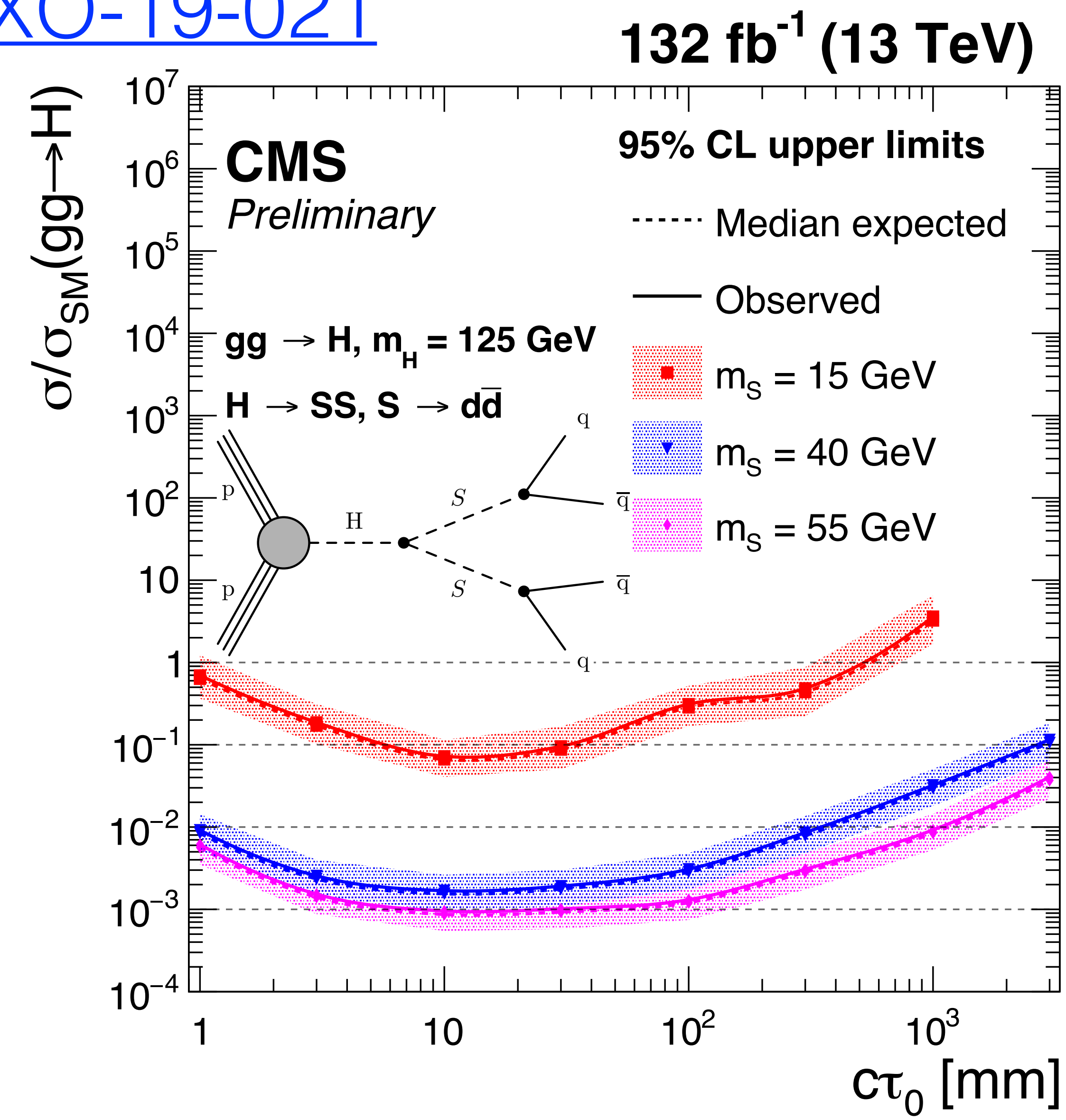
Charginos excluded for pure $\widetilde{W}$ LSP scenarios up to 474 GeV and 0.2 ns (175 GeV and 0.05 ns for $\widetilde{H}$ LSP)

LLP7 slides from B. Francis

CMS Highlights from LLP7 (May 2020)

Displaced Jets: EXO-19-021





Dedicated trigger selects events containing jets with ≤2 prompt tracks

Reconstruct SVs using pairs of jets; use a NI-veto map and a GBDT to suppress background.

Sensitive to many LL models with decays within the tracker (~1 mm to ~1 m)

LLP7 slides from J. Luo

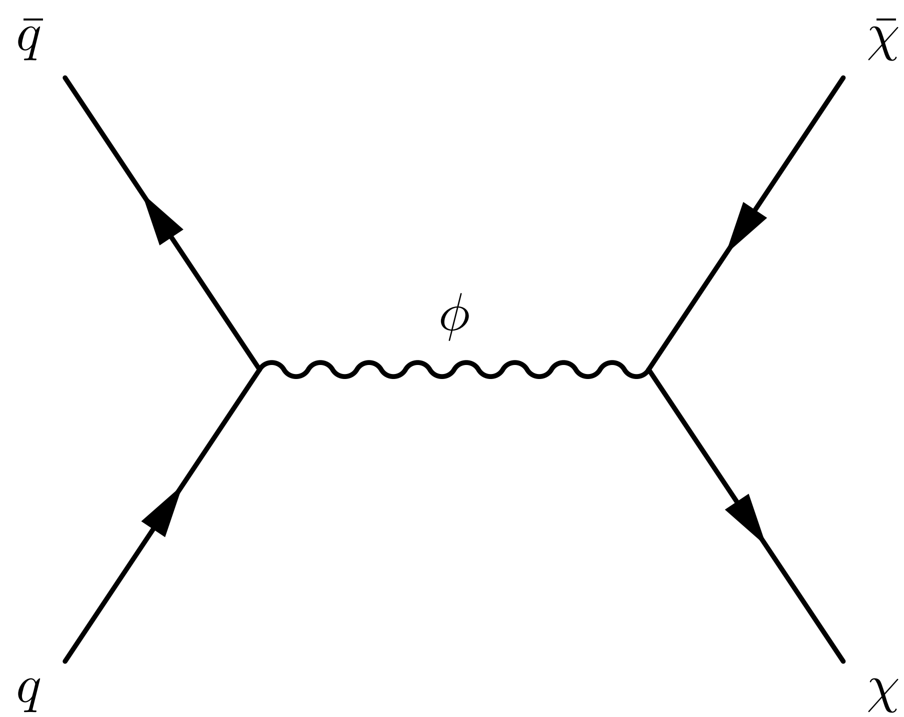
Search for strongly interacting massive particles with trackless jets

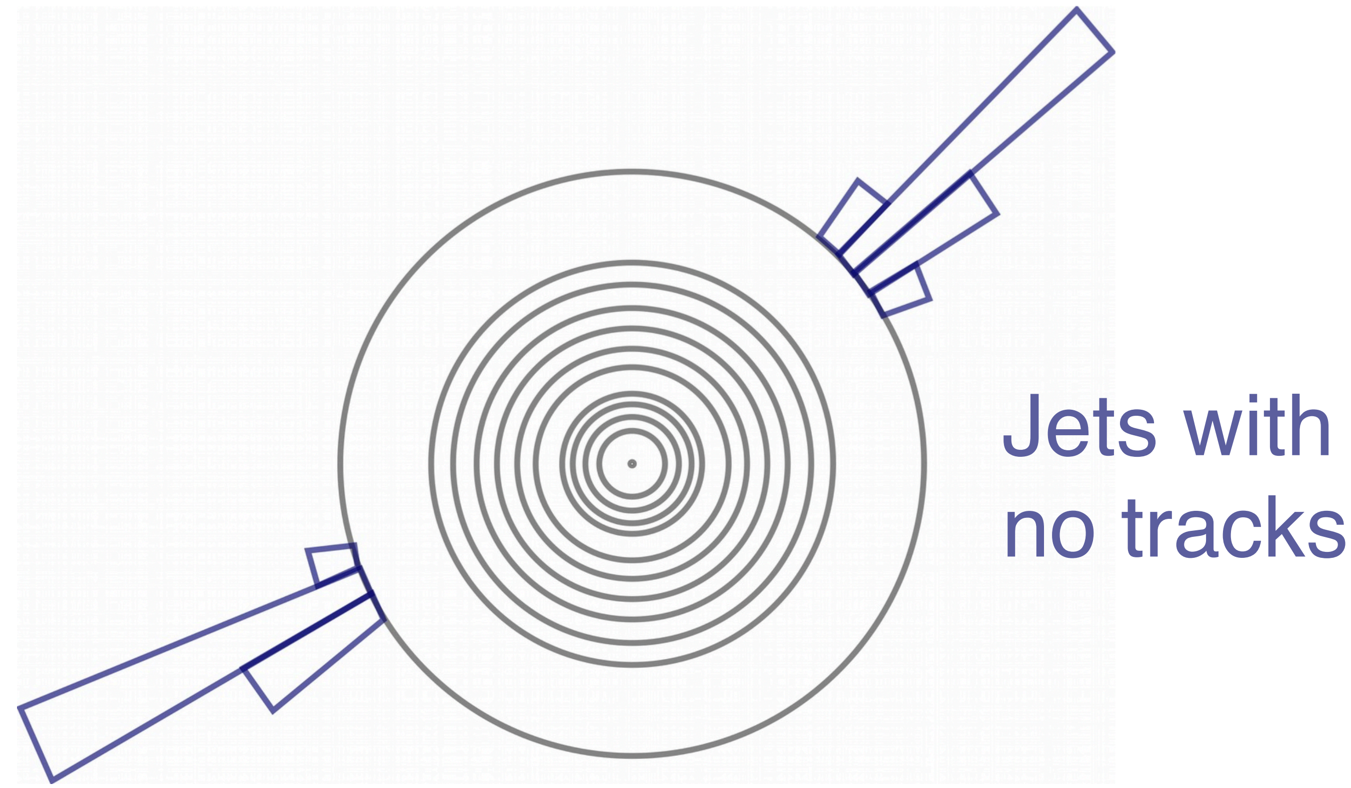
EXO-17-010

SIMP model

Most DM searches focus on WIMPs, but SIMPs can be DM too!

- Repulsive SIMP-nucleon couplings to avoid bound states

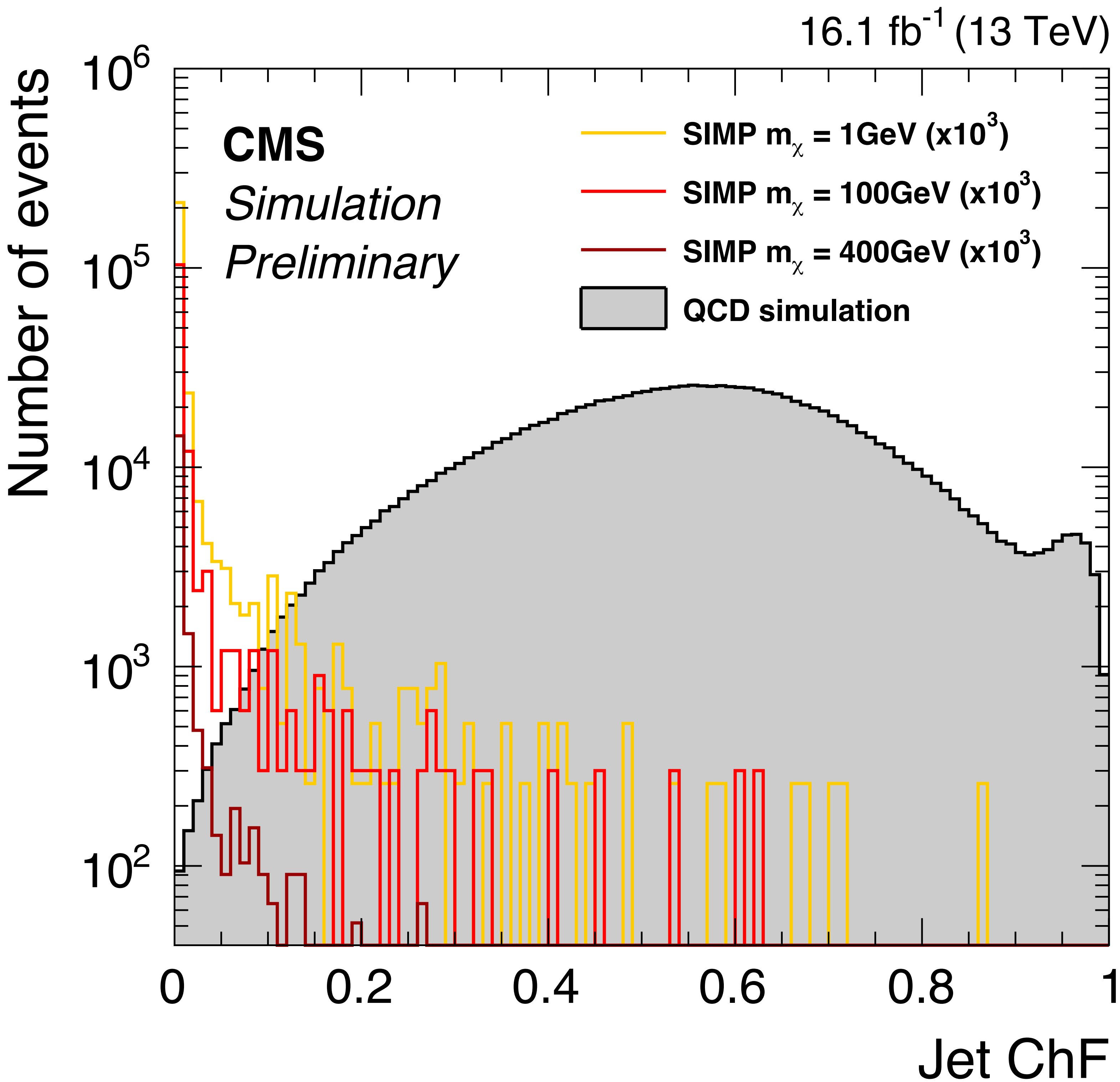




SIMPs (χ) produced via mediator (ϕ) and interact strongly with SM.

- Simplified model (1503.05505) has couplings which result in hadronic showers that start and are contained in the HCAL
- Model in **`GEANT4`** as a heavy neutron (w/ adjustable mass)

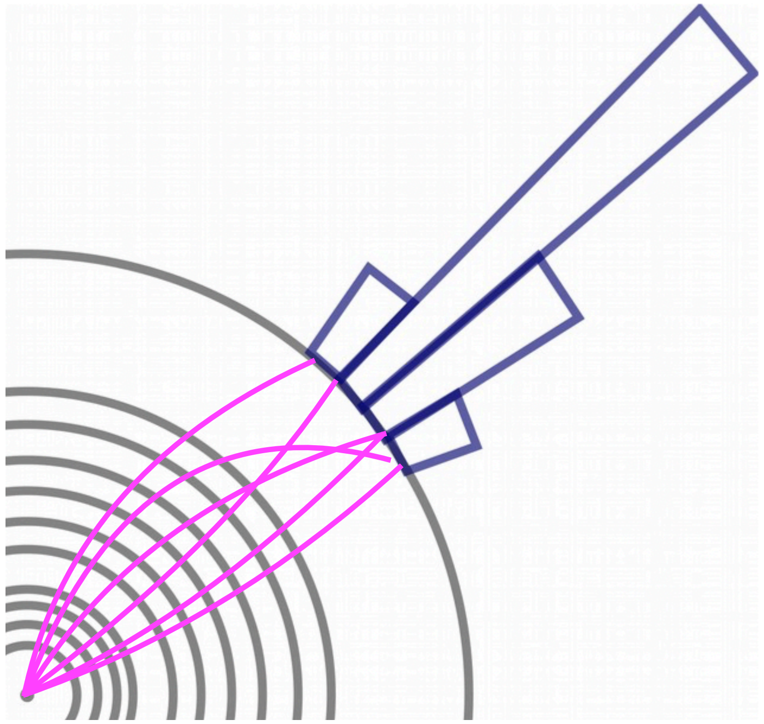
Search Strategy



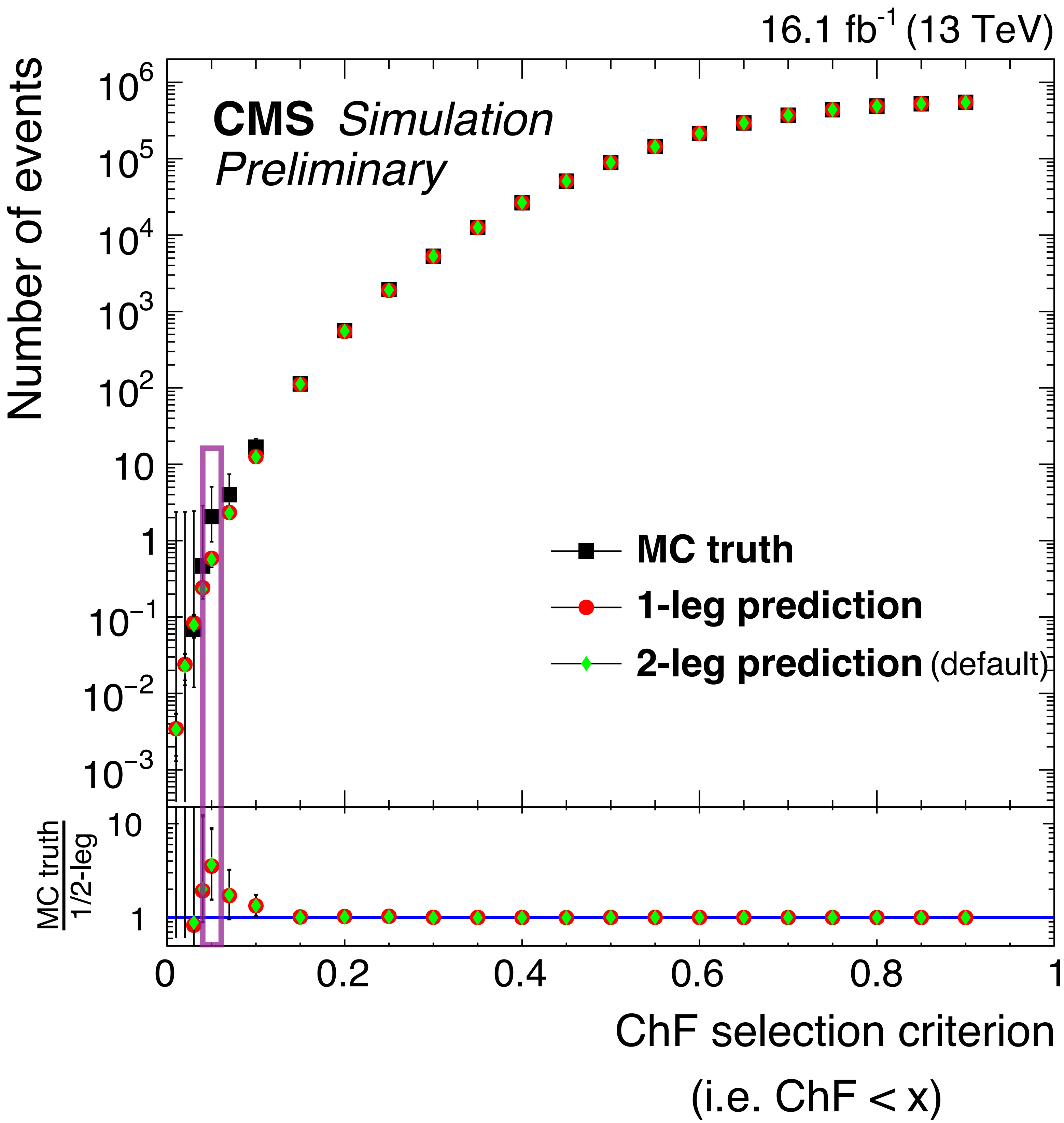
SIMPs have small fraction of their energy from charged particles.

Use ChF as the primary discriminator against background!

Event Selection

Baseline Selection	Search Region	Control Sample
Trigger: jet $p_T > 450$ GeV	**Both jets** with ChF < 0.05	At least one jet with ChF > 0.25
Exactly two jets with $p_T > 550$ GeV, $\|\eta\| < 2$, and $\Delta\phi > 2$	Repeat selection with alt. reco using different PV hypothesis	*Use a "tag-and-probe" method to measure ε(ChF < 0.05) with these events*
Veto potential photon and beam halo backgrounds	(avoid trackless jets in background due to pileup track suppression)	
Use 16.1 fb^{-1} of 2016 data (w/o silicon strip readout issues)		

Data-Driven Background Estimation

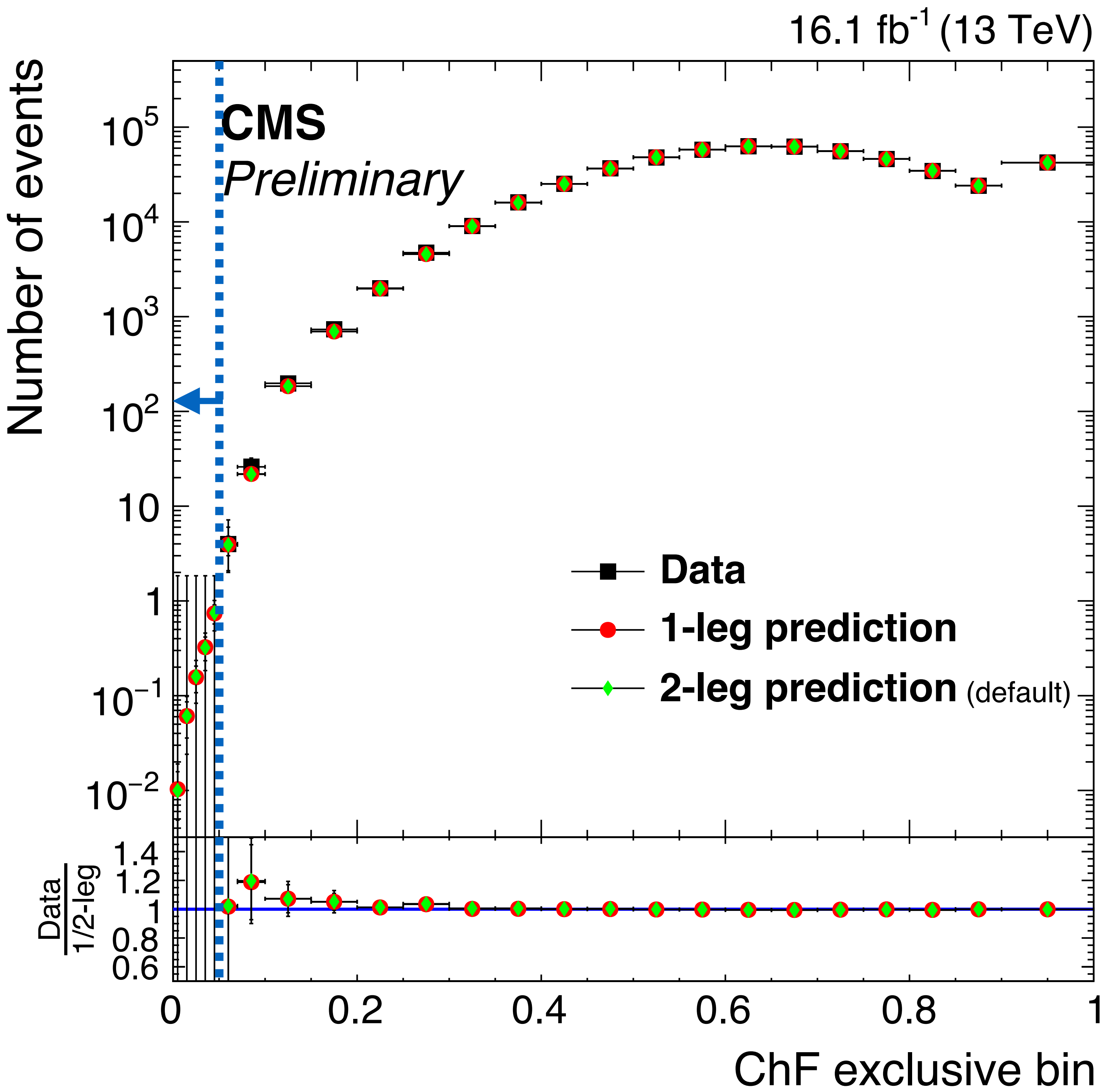


Estimate background by applying the efficiencies to both jets in baseline events.

MC closure test validates the procedure.

(differences used as syst uncertainty)

Search Region

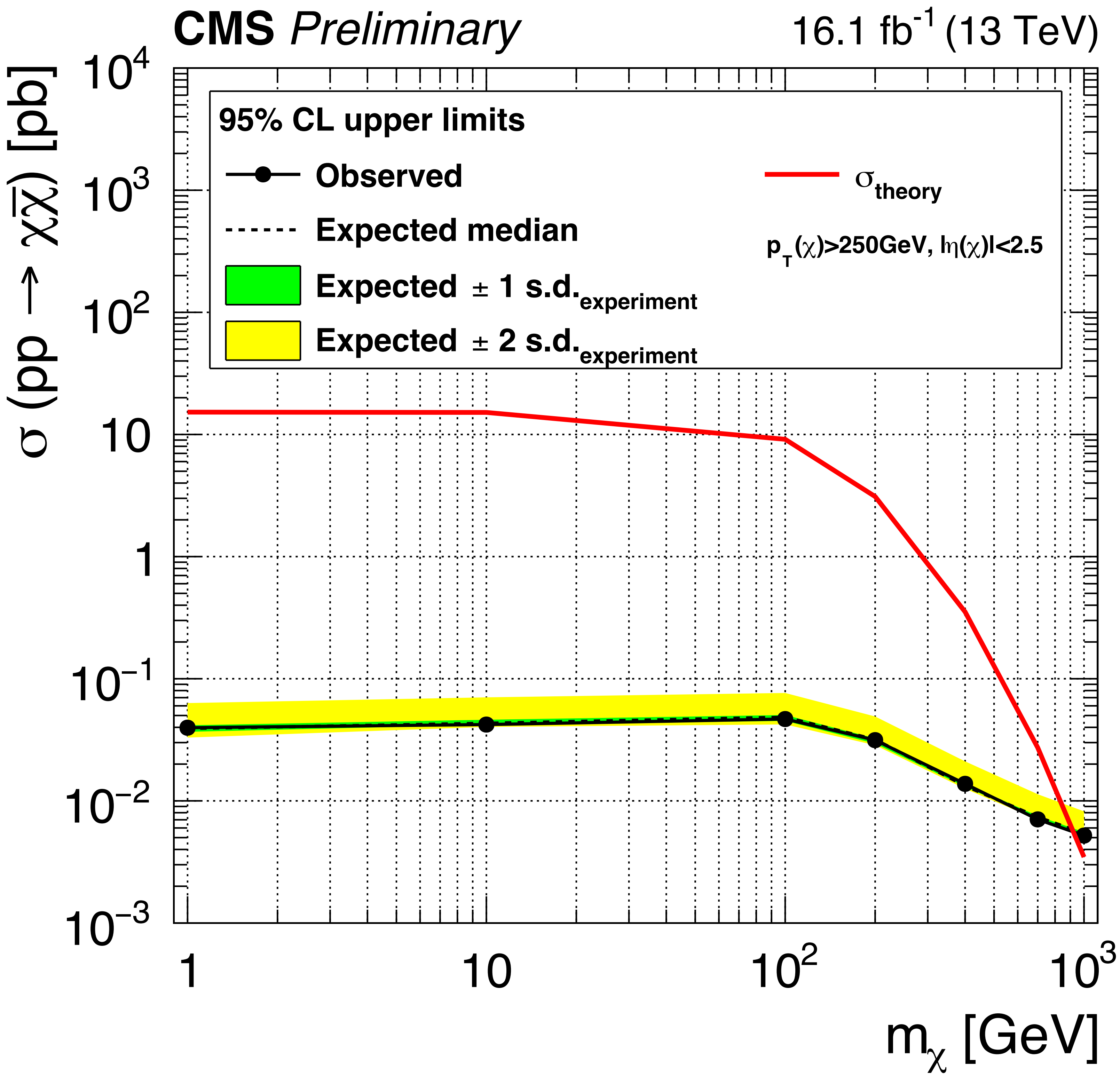


In the search region with ChF < 0.05, zero data events observed.

$\Longrightarrow$ Consistent with the background prediction!

ChF selection criterion	data prediction	observed	SIMP signal [m_χ]	
			1 GeV	1000 GeV
< 0.05	1.28 ± 0.22 (stat.) $^{+3.40}_{-1.28}$ (syst.)	0	1101 ± 53	1.90 ± 0.06

Results



SIMPs excluded for masses up to 900 GeV!

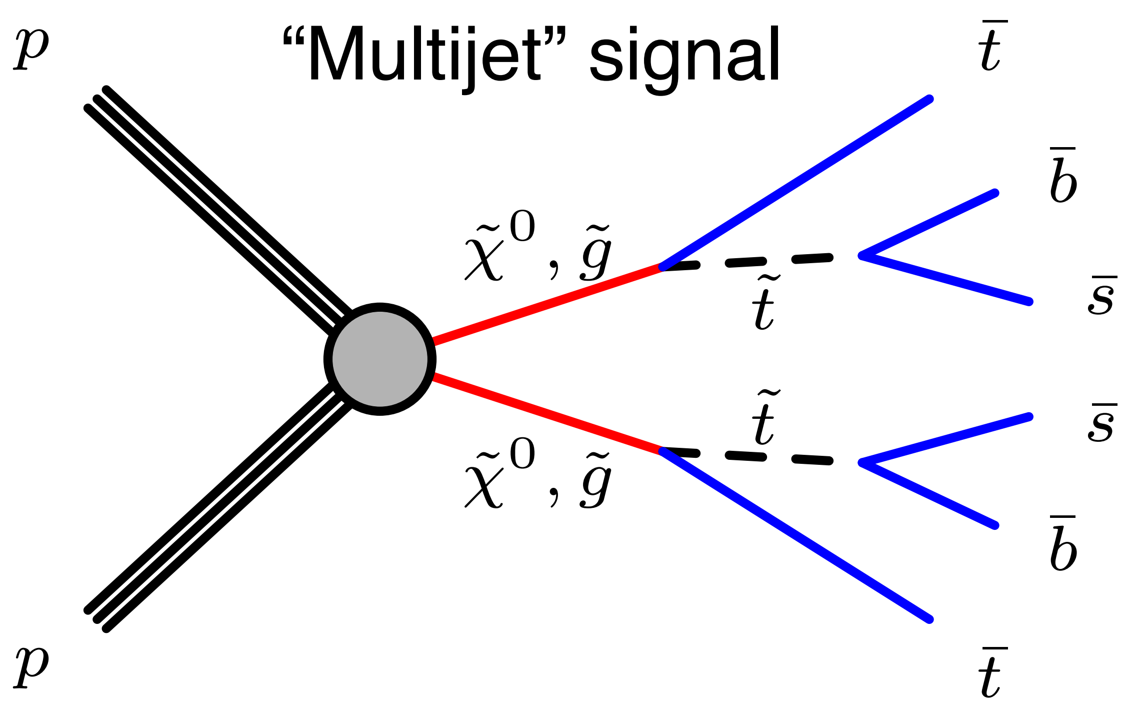
Search for long-lived particles decaying to jets with displaced vertices

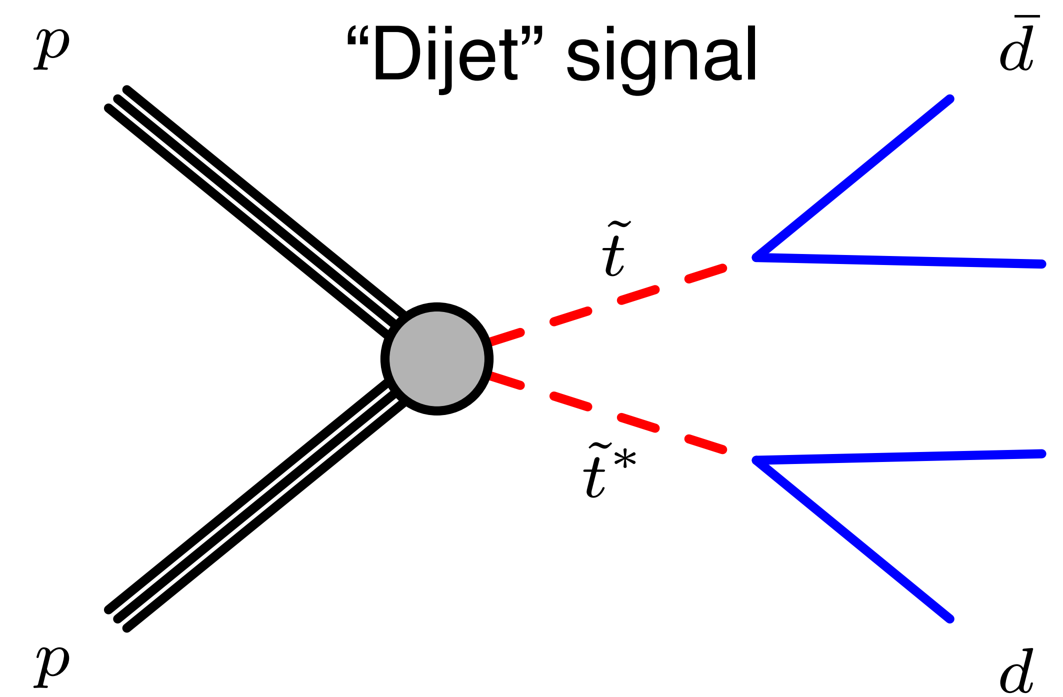
EXO-19-013

Extension of 1808.03078,
now with the full Run 2 dataset
(+ the upgraded CMS Pixel Tracker)

Signal Models

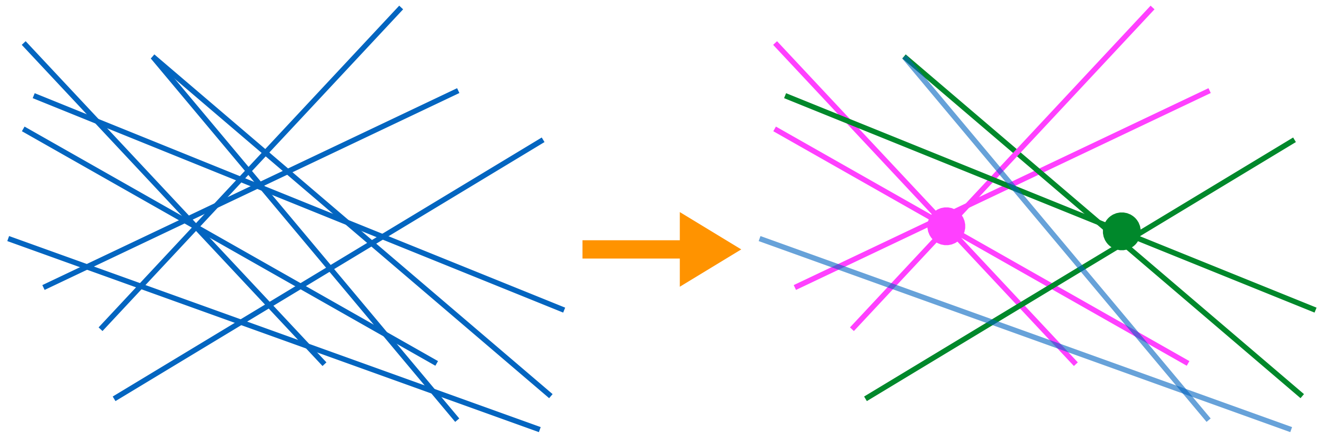
Many models predict final states w/ hadronically decaying pairs of LLPs





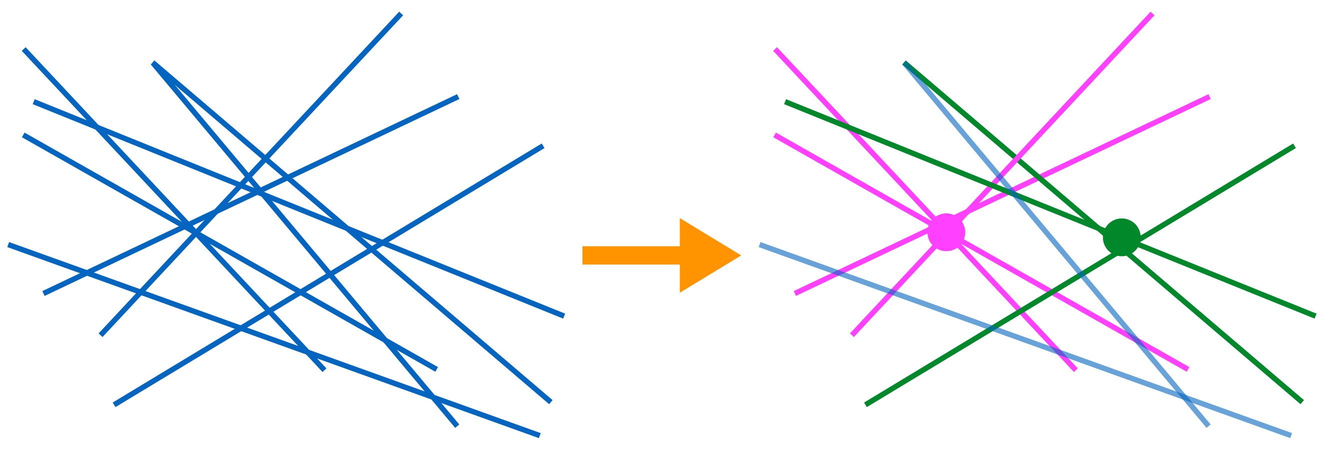
- RPV SUSY benchmark models, but the search is model-independent!
- Use high-quality displaced tracks to reconstruct the LLP decay points as two displaced vertices
- Select events using H_T trigger; require $H_T > 1200$ GeV and ≥4 jets

Vertex Reconstruction and Selection



Custom vertex reconstruction: iteratively merge tracks into vertices, fit w/ Kalman filter, and arbitrate w/ quality requirements.

Vertex Reconstruction and Selection



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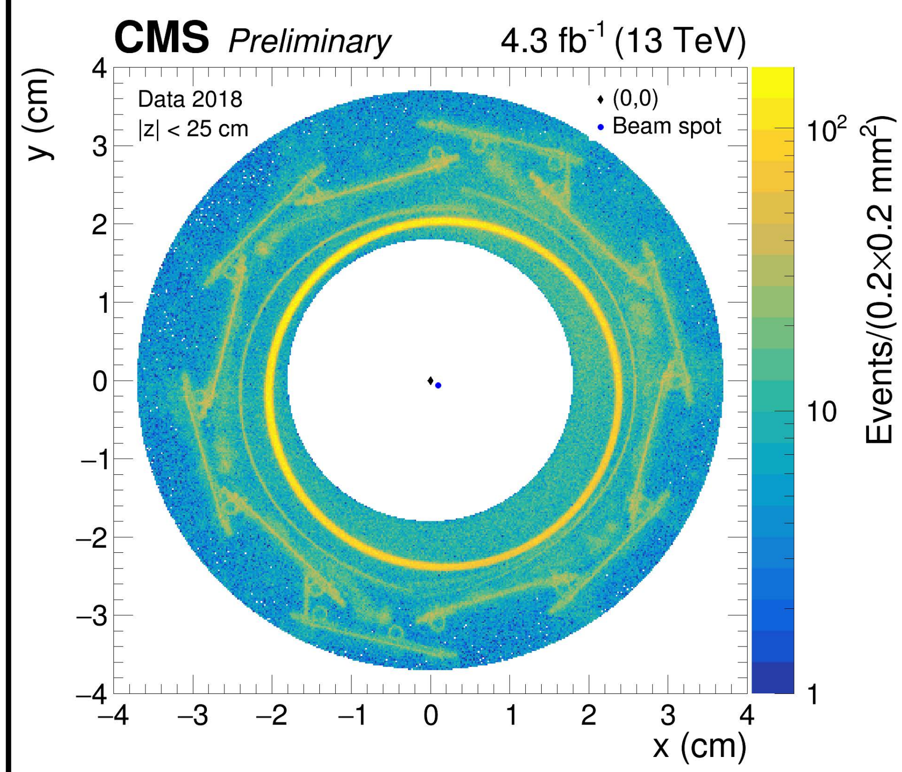
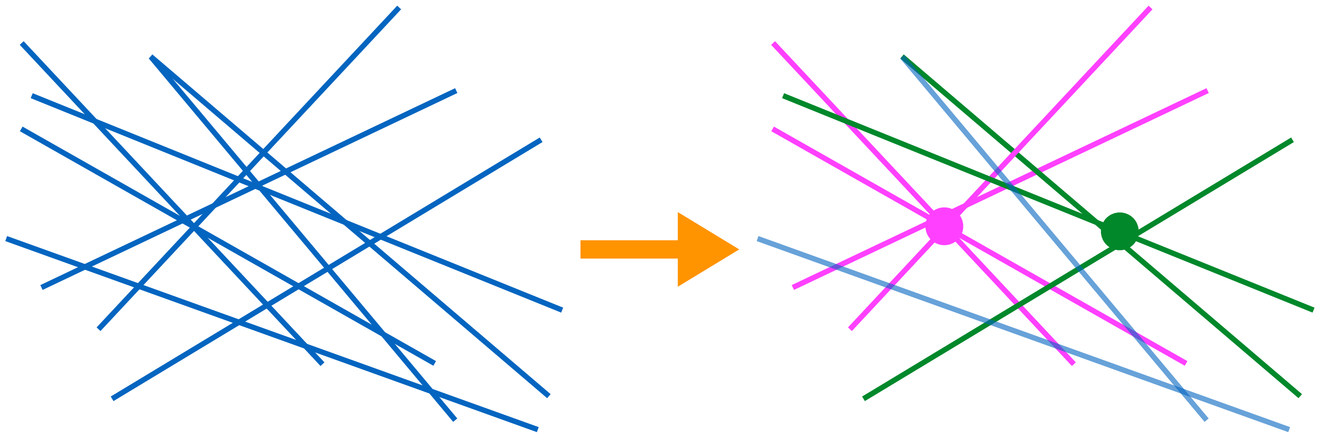


Only accept DVs within beam pipe

TrackerMaterialPosition2018

Vertex Reconstruction and Selection



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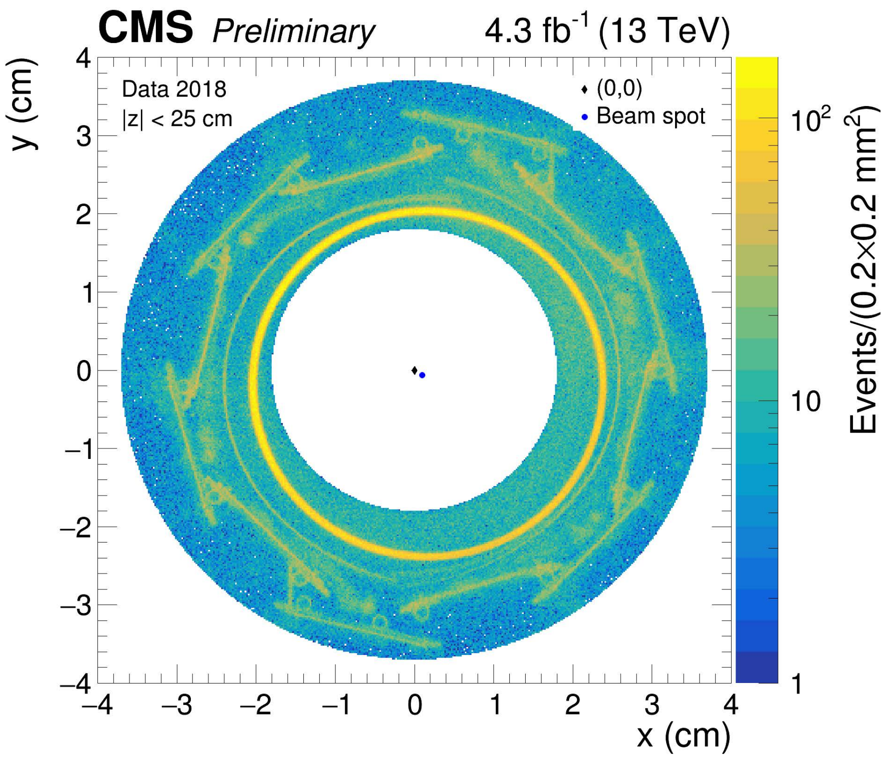

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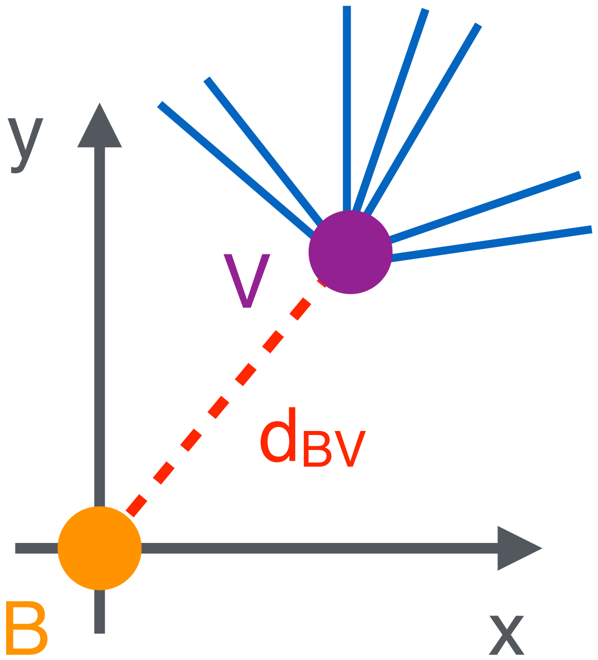
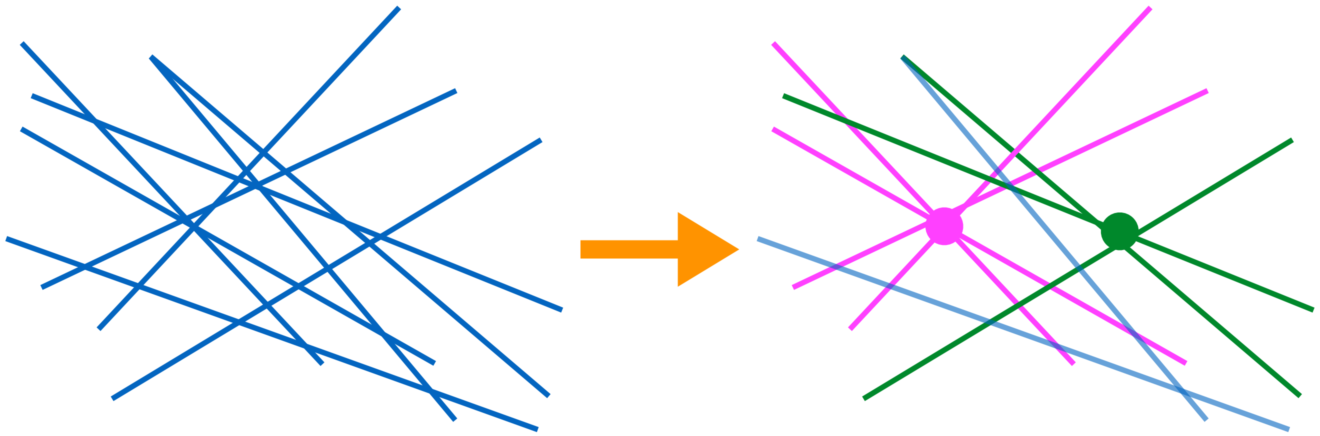


Require $d_{BV} > 100$ µm (avoid displaced PVs)

$\sigma(d_{BV}) < 25$ µm allows us to suppress b-jet vertices (collimated)

Vertex Reconstruction and Selection



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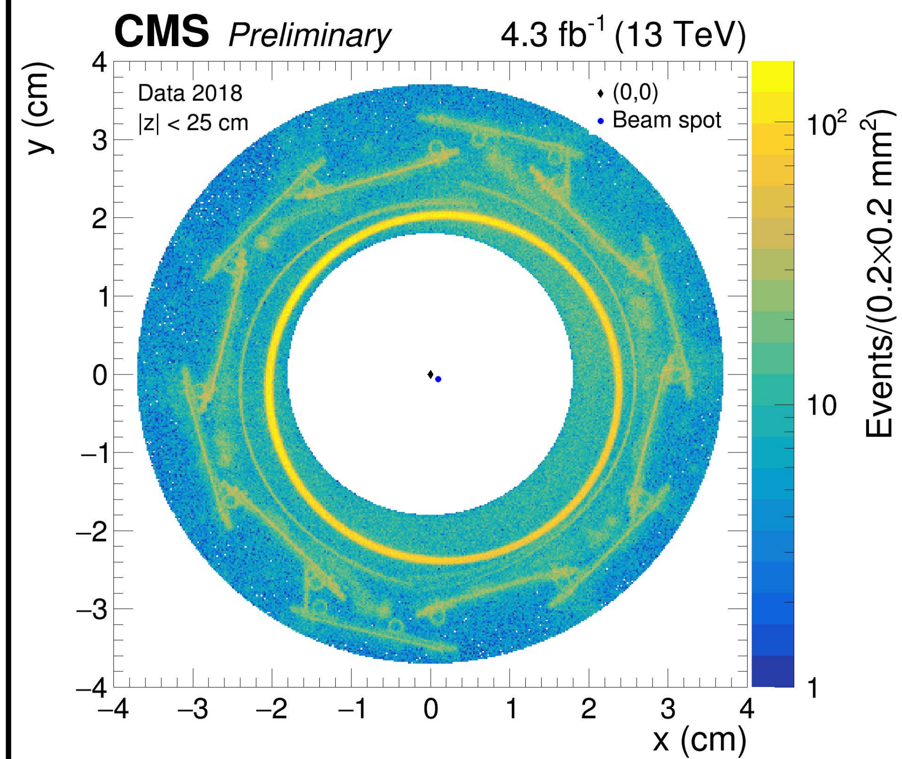

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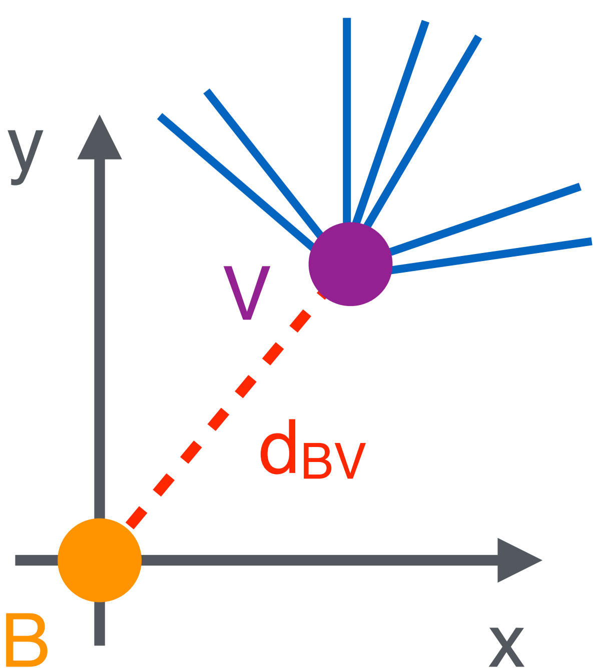
[TrackerMaterialPosition2018]



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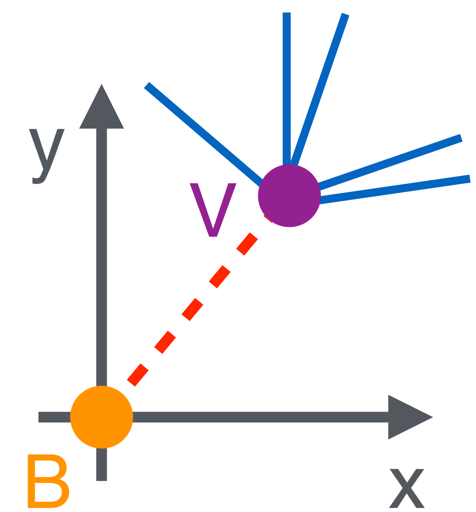
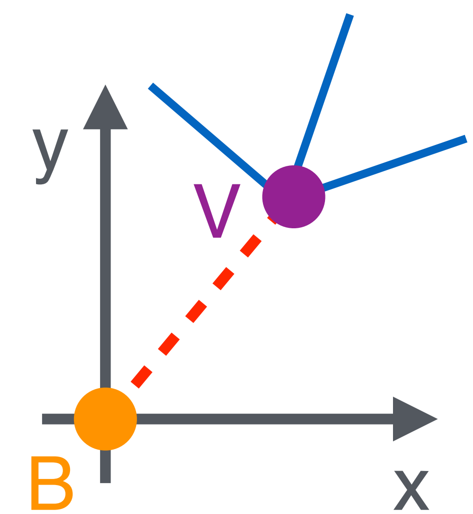
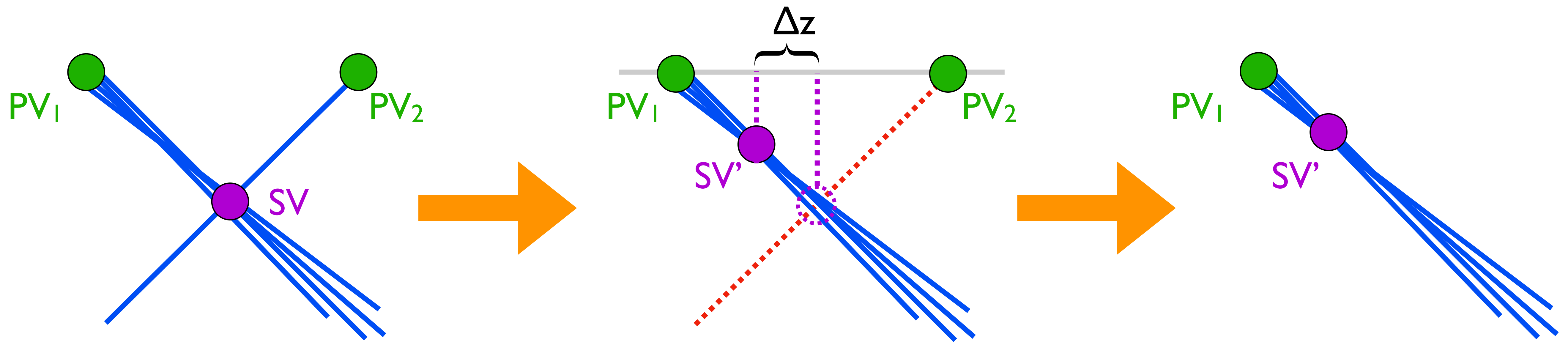


Signal vertices: $n_{track} \geq 5$



Control sample: $n_{track} = 3$ or 4

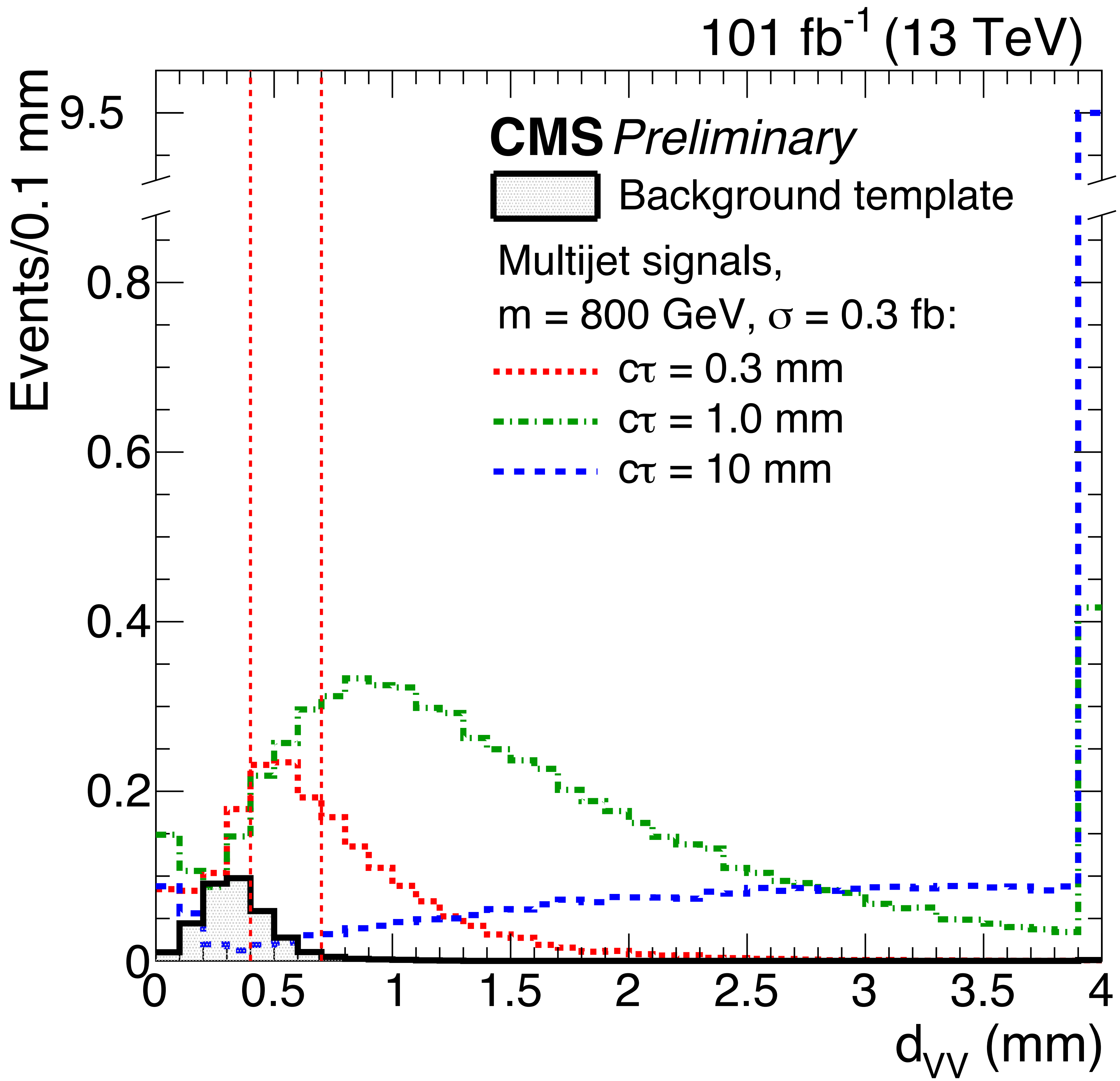
Suppression of pileup tracks

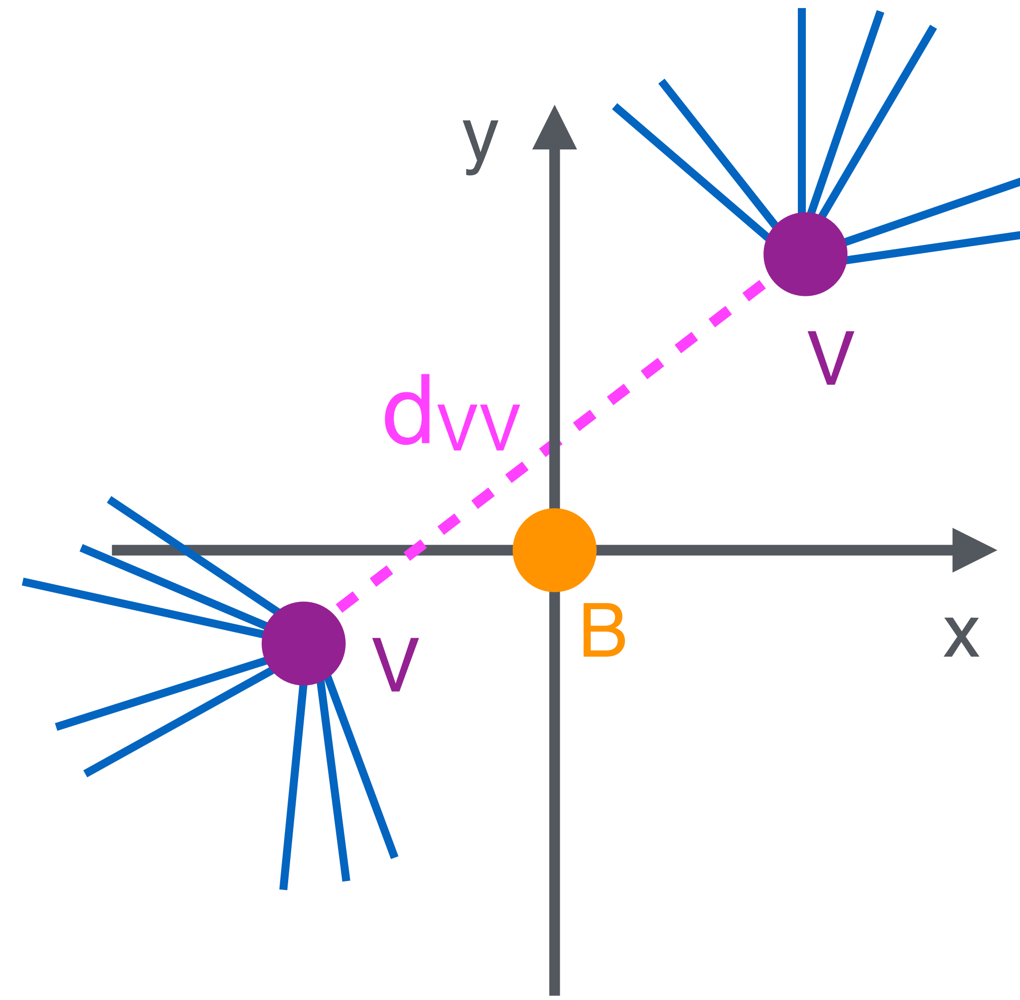


During vertex reconstruction, remove any tracks that significantly affect vertex z position by > 50 μm

Reduces background by 40% with small impact on signal efficiency!

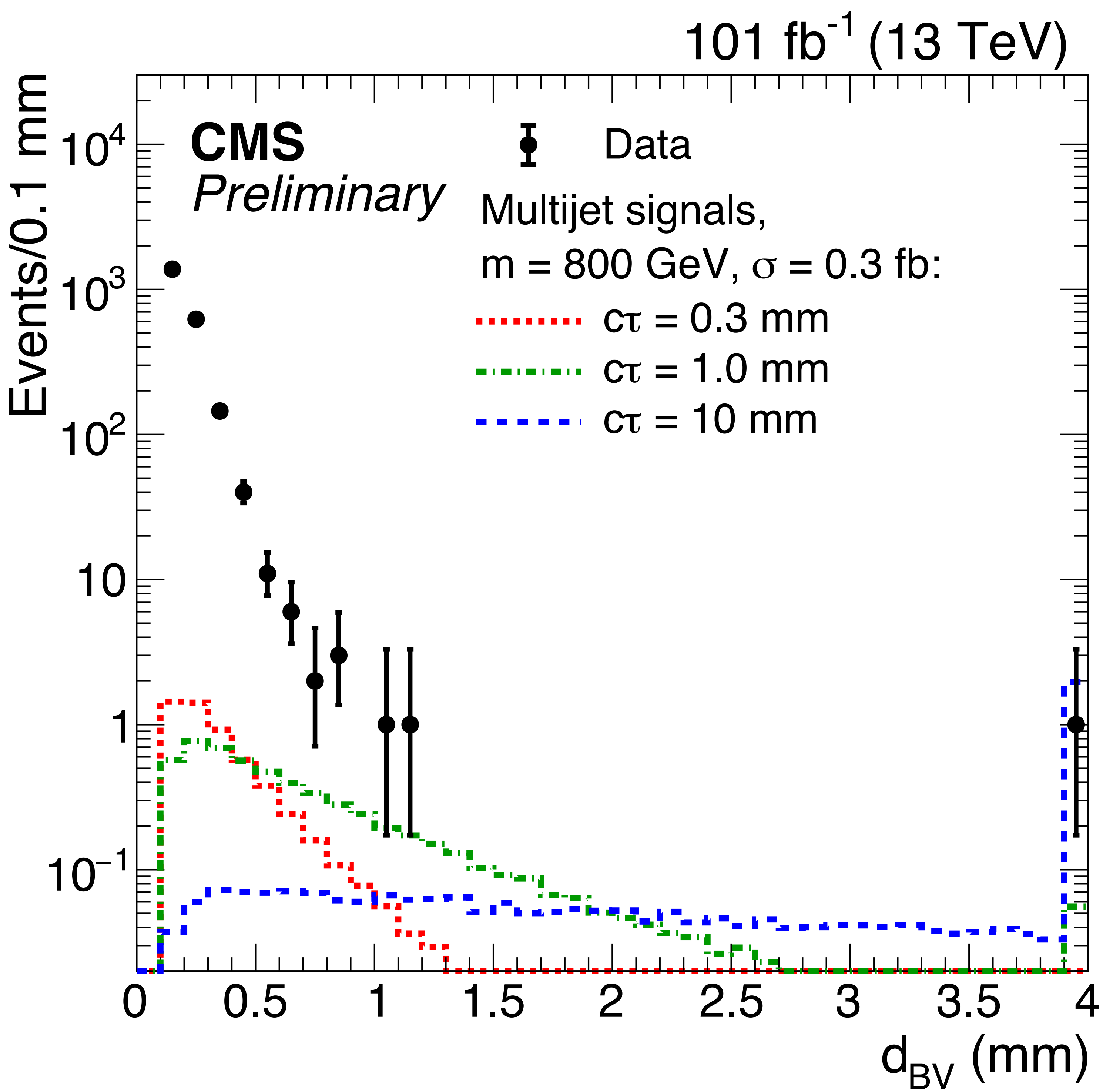
Search Strategy





d_{VV} is the primary discriminating variable, and three search bins are used.

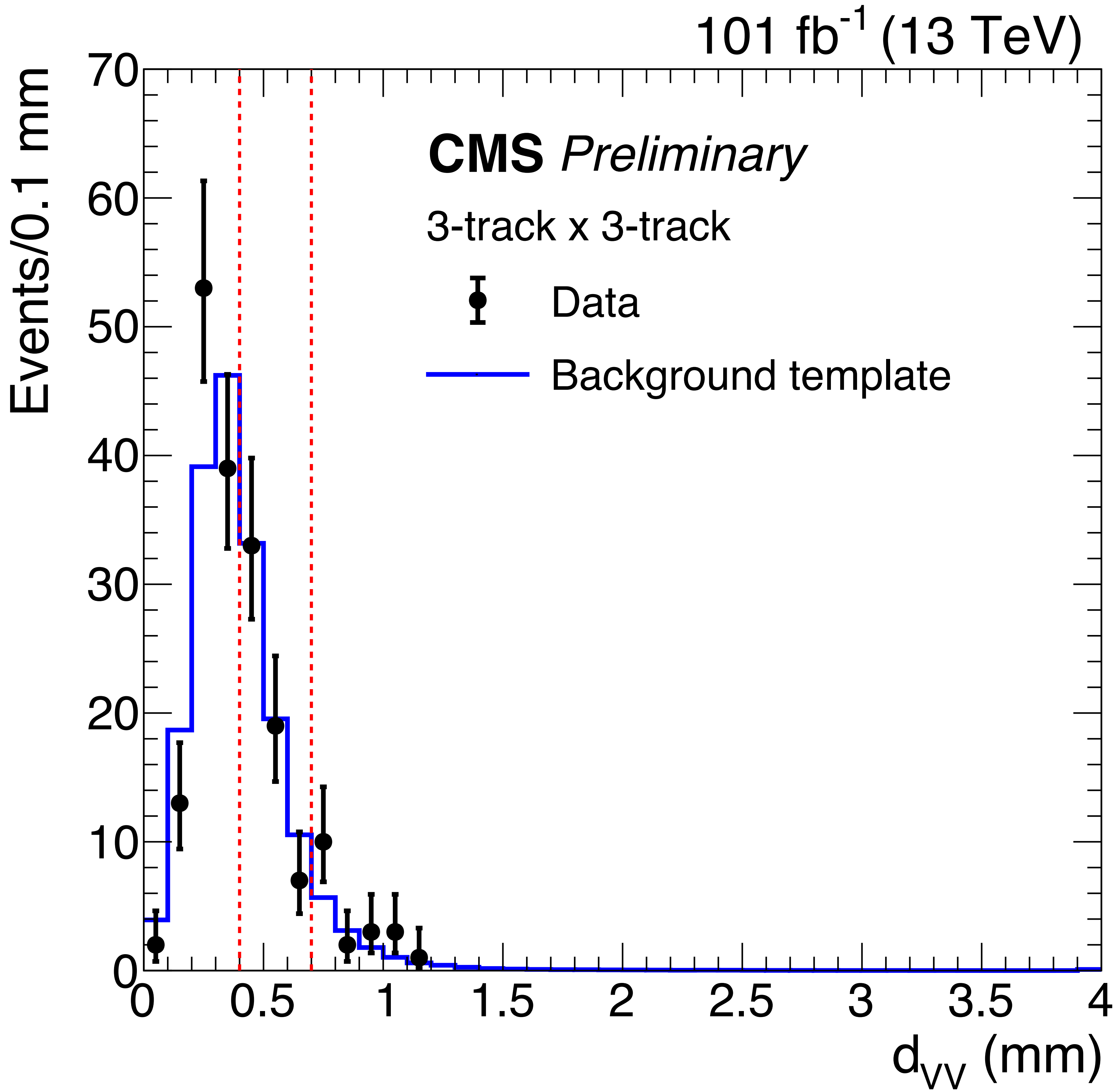
Data-Driven Background Estimation



Background-dominated single vertex events are used to construct a background d_{VV} template in data using:

- Two random d_{BV} values
- Randomly chosen $\Delta\phi_{VV}$, estimated via jet angles
- Corrections for b-quarks (larger displacements) and overlapping vertices

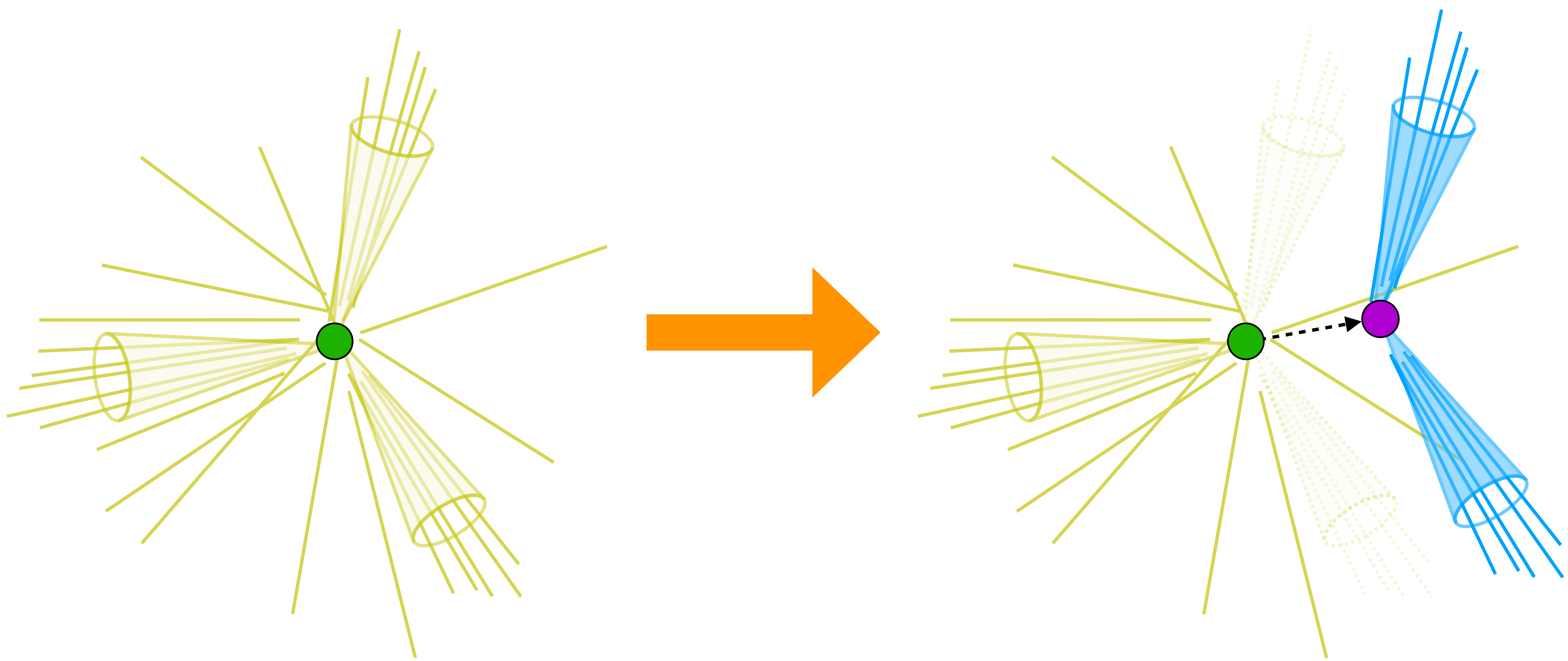
Background Validation



Events with pairs of vertices with <5-tracks validate the procedure.

(use any differences as syst uncertainty)

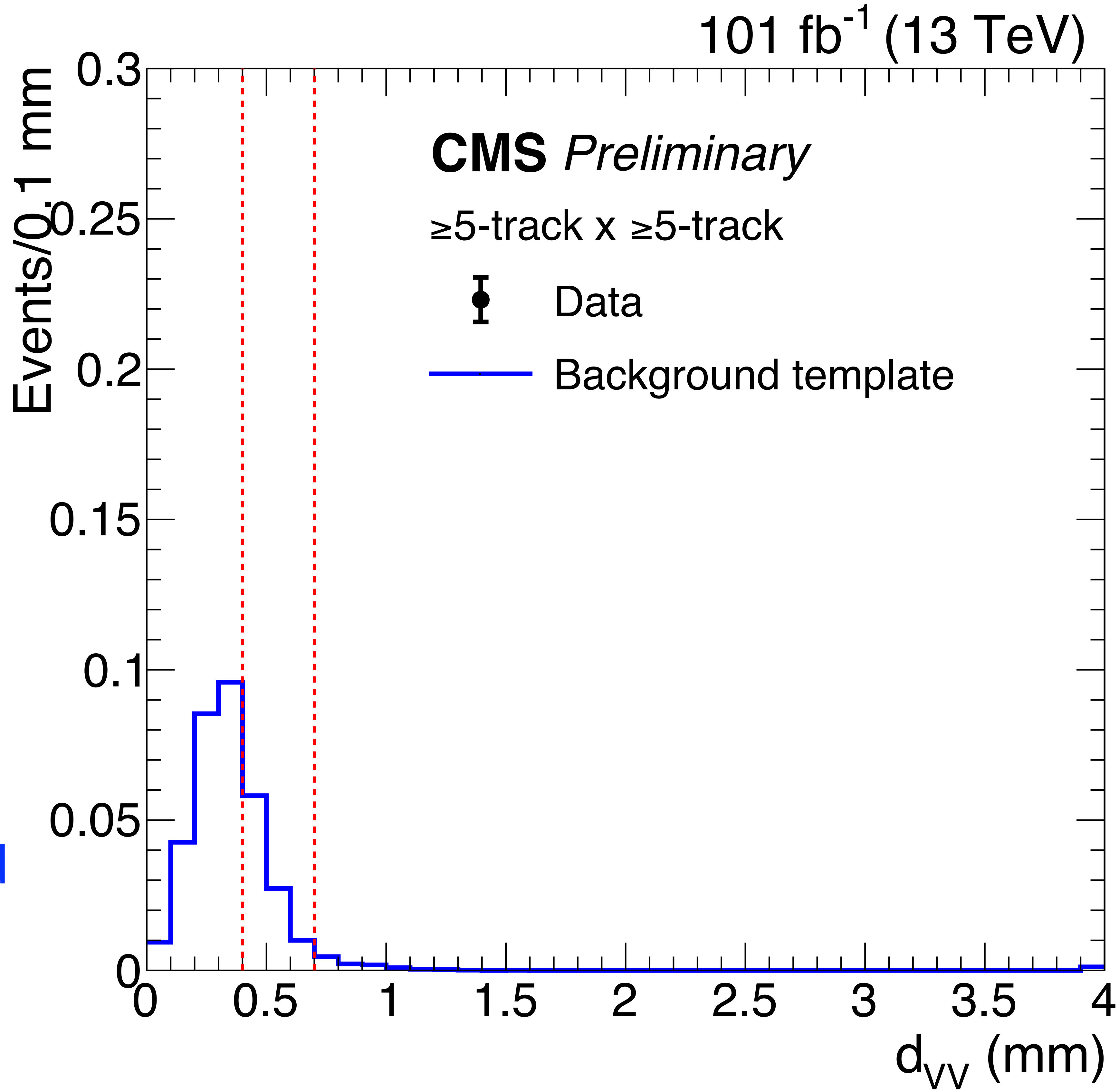
Signal Efficiency and Systematics



Manually displace tracks from SM jets in data and MC to create artificial displaced vertices.

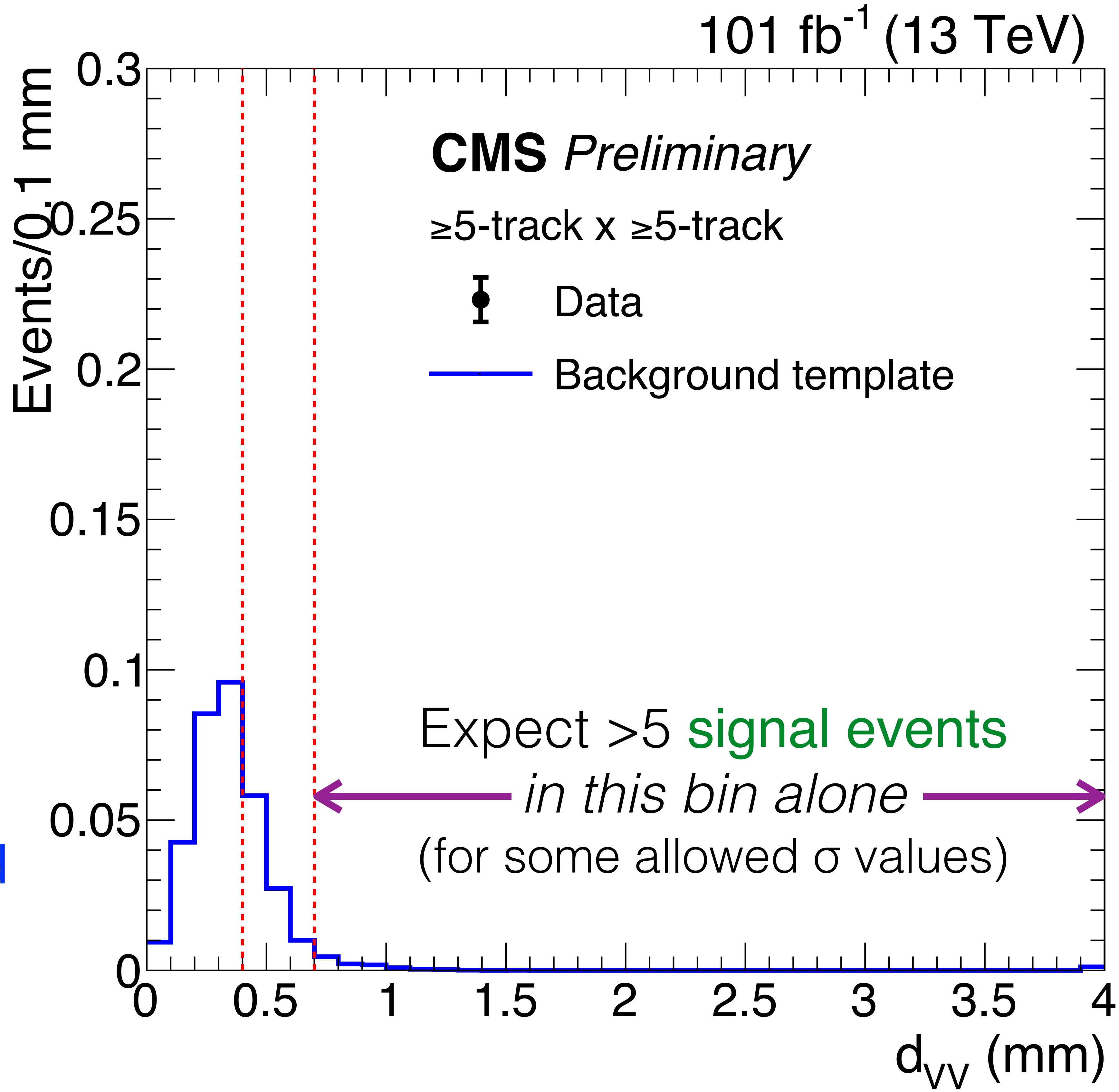
Measure vertexing ε to determine ε corrections and systematic uncertainties to apply to signal MC.

≥5-track 2-vertex Search Region



Predicted 0.342 total background events

≥5-track 2-vertex Search Region



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≥5-track 2-vertex Search Region

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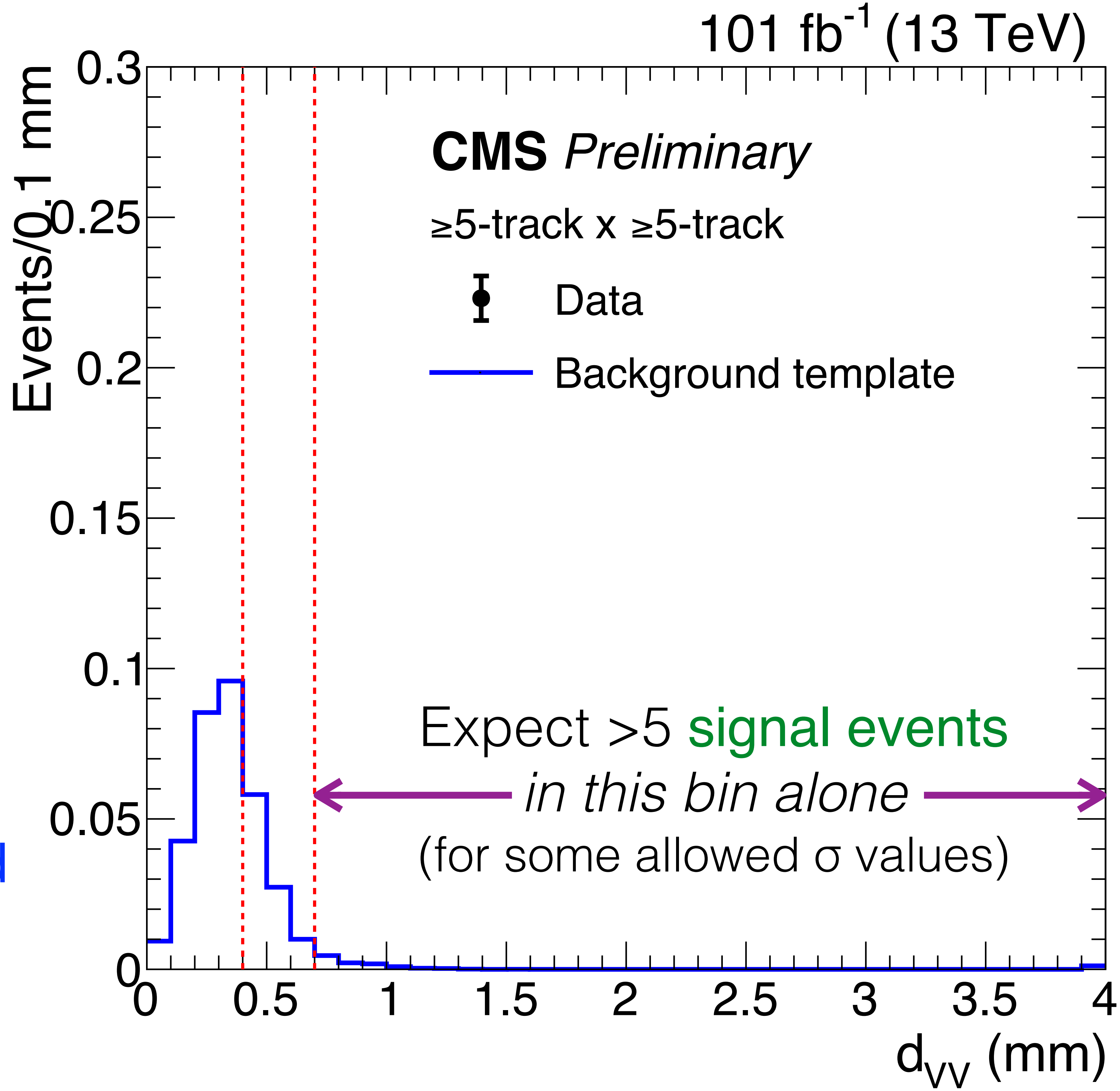
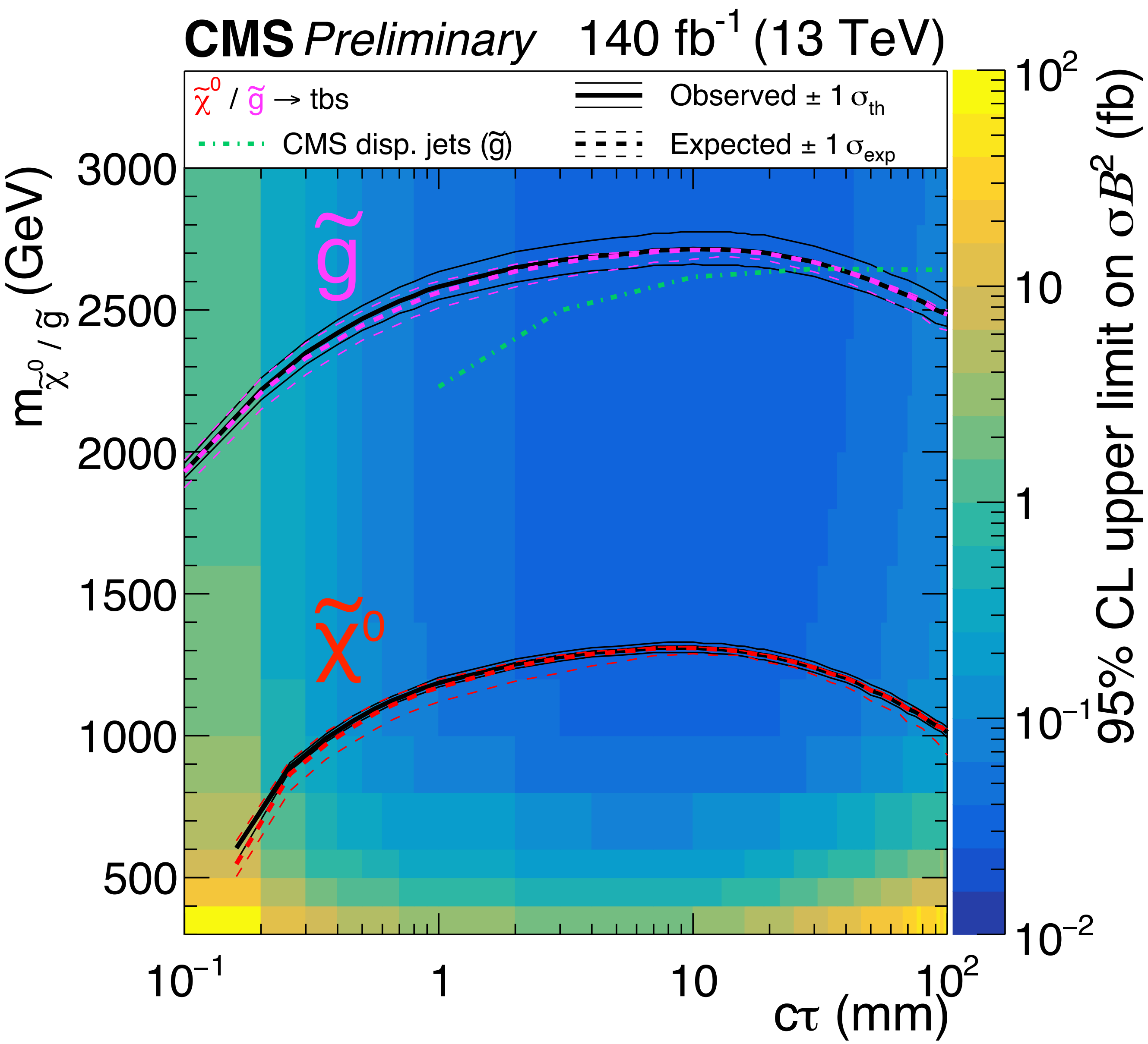
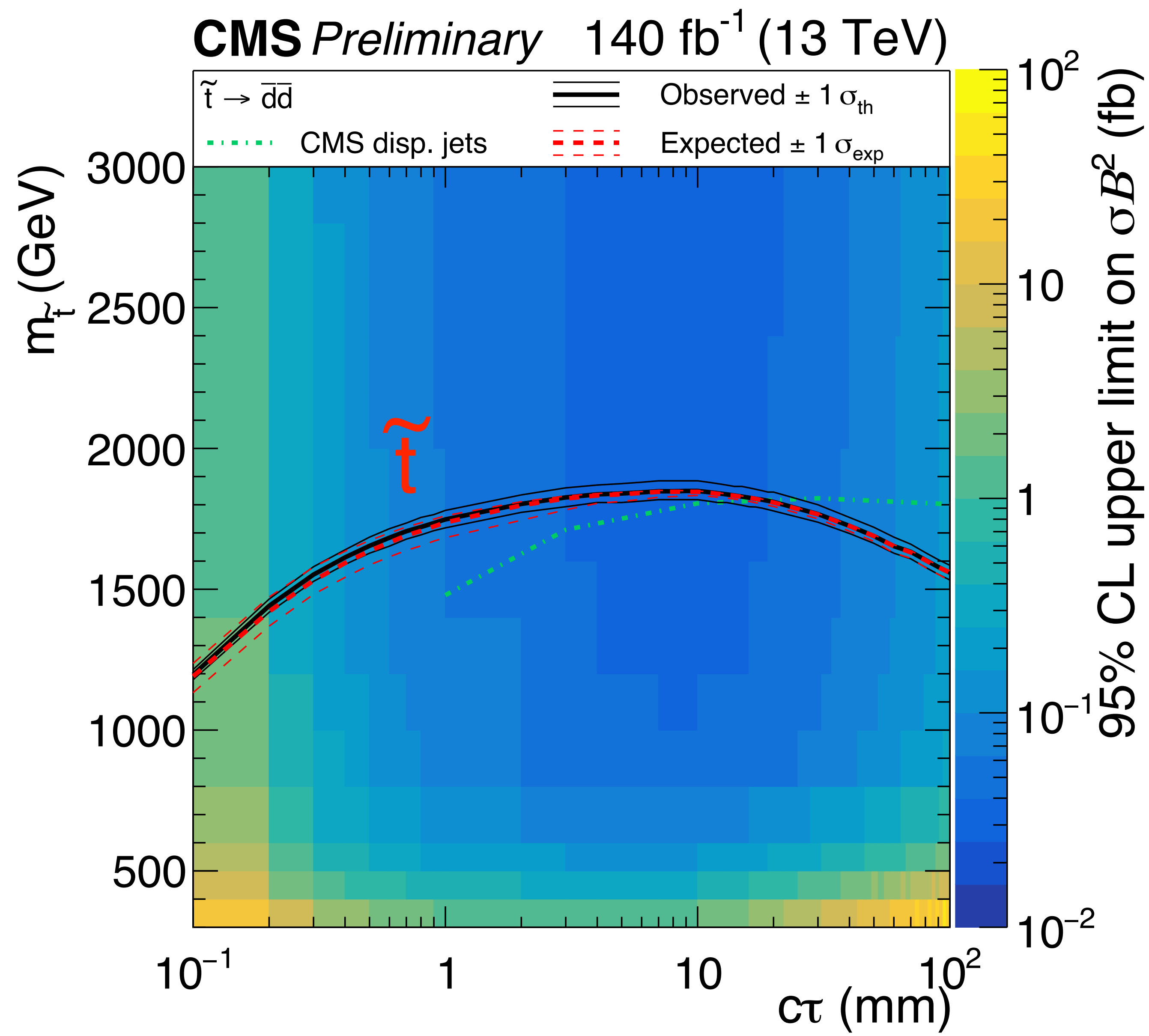


And observed zero!

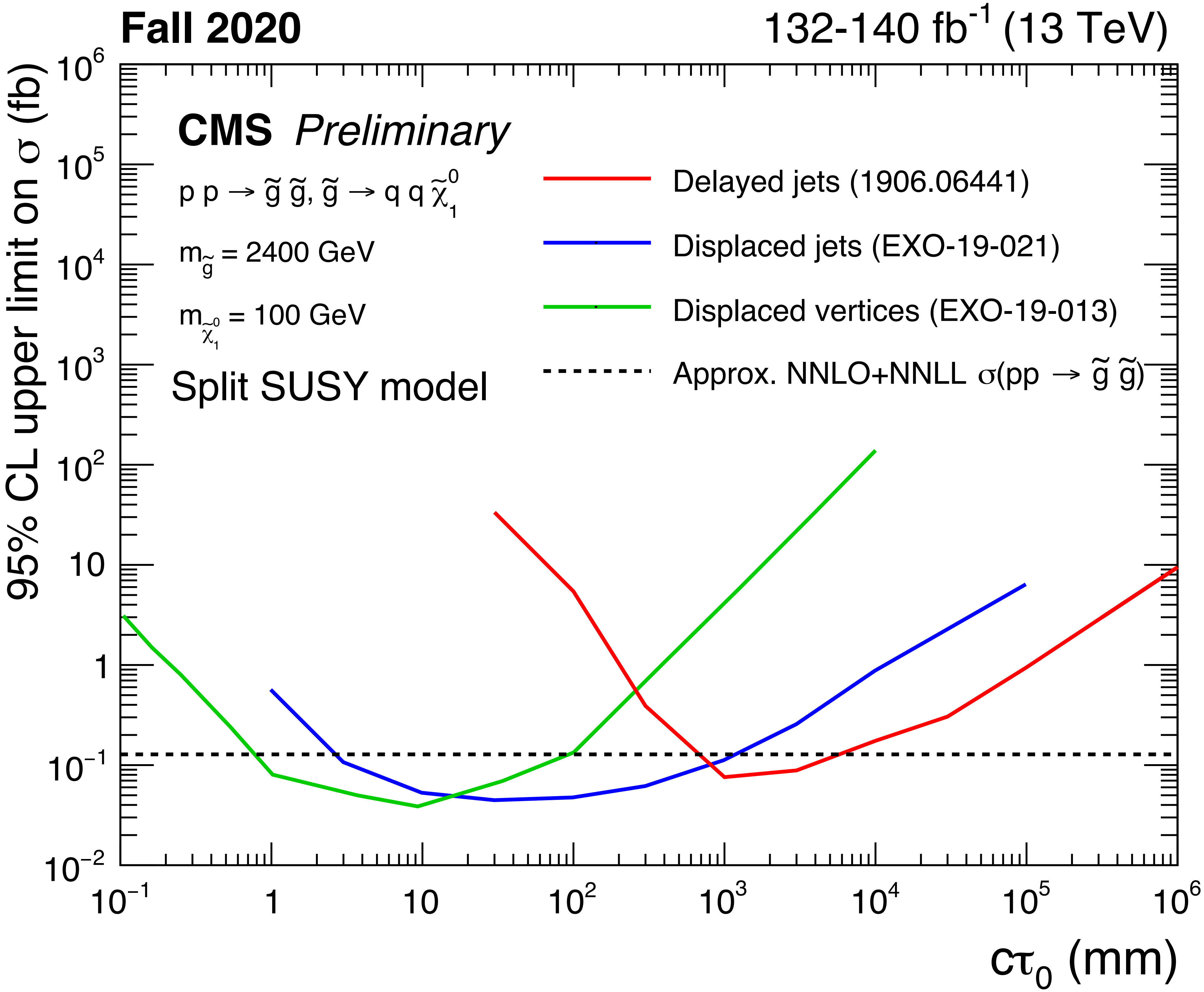
Results





Reinterpretation recipe available in EXO-19-013!

Hadronic LLP Summary



DV search nicely complements other CMS searches at longer lifetimes

CMS Exotica Summary Plots

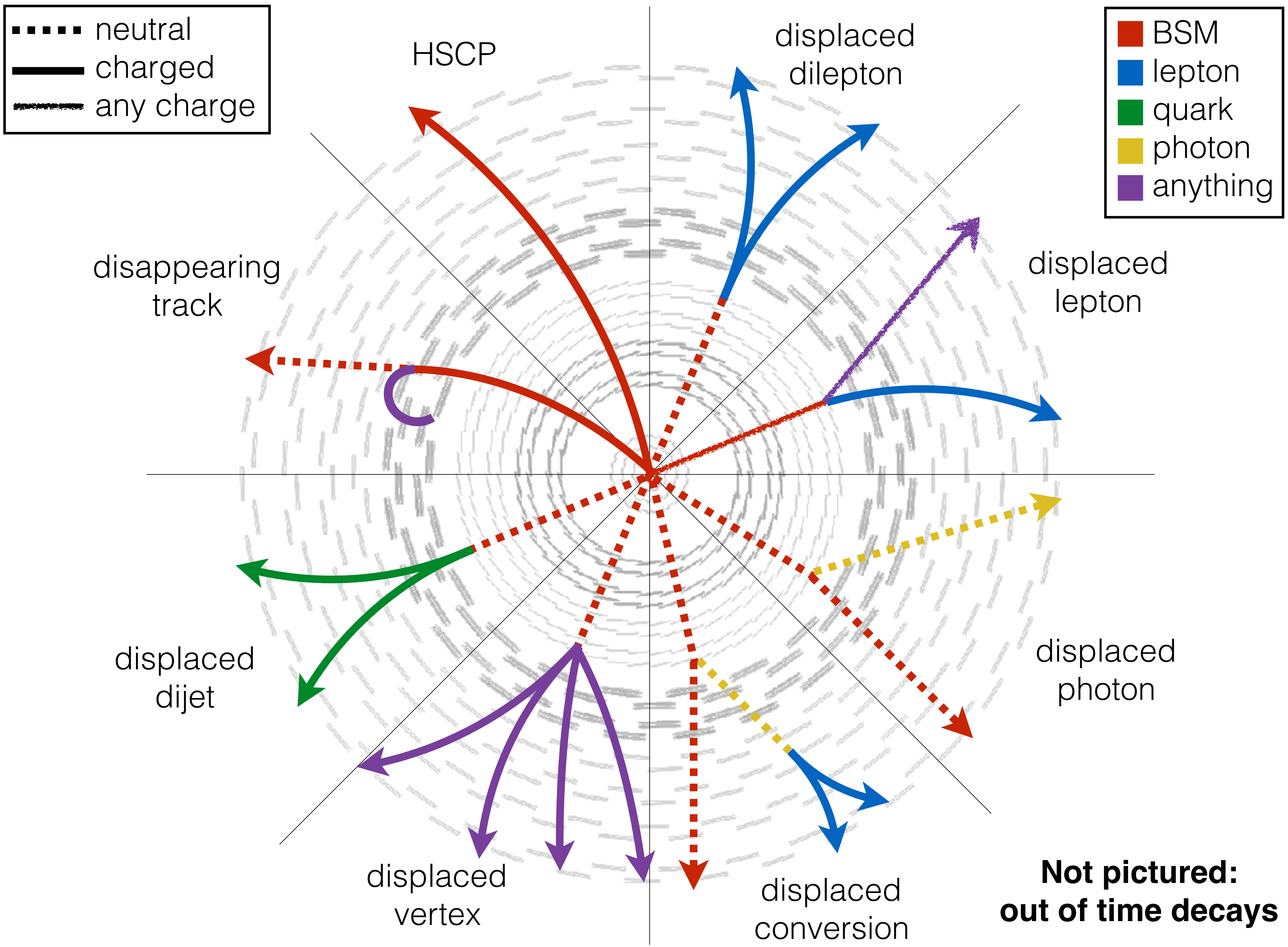
Summary

CMS has a well-established LLP search program

- No evidence for new LLPs yet
- However: we have a **huge** phase space to cover with many potential exotic signatures
- Plenty of new ideas can be explored
  - with the existing Run 2 data
  - as well as the future Run 3 and HL-LHC data!

Backup

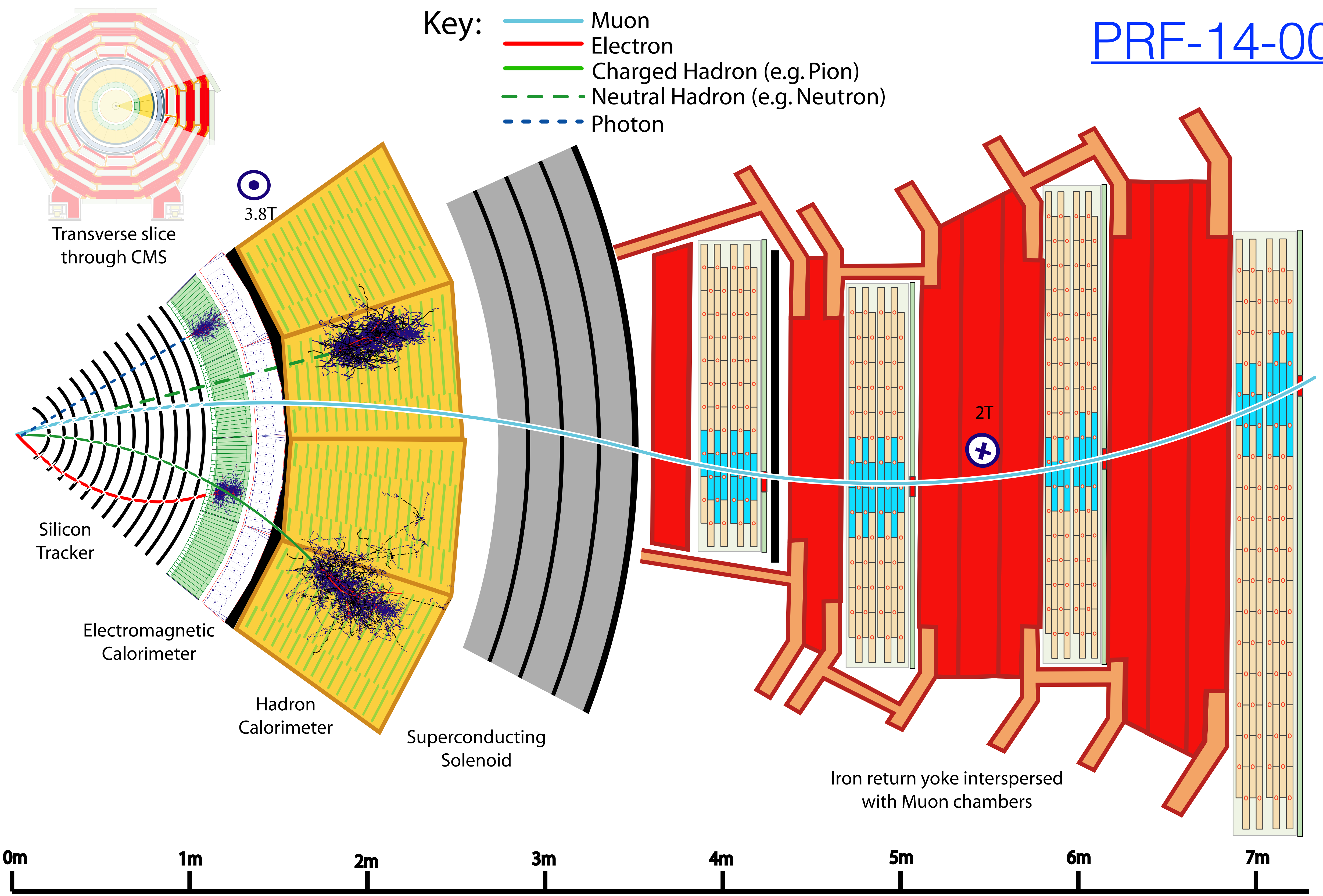
LLP Signatures



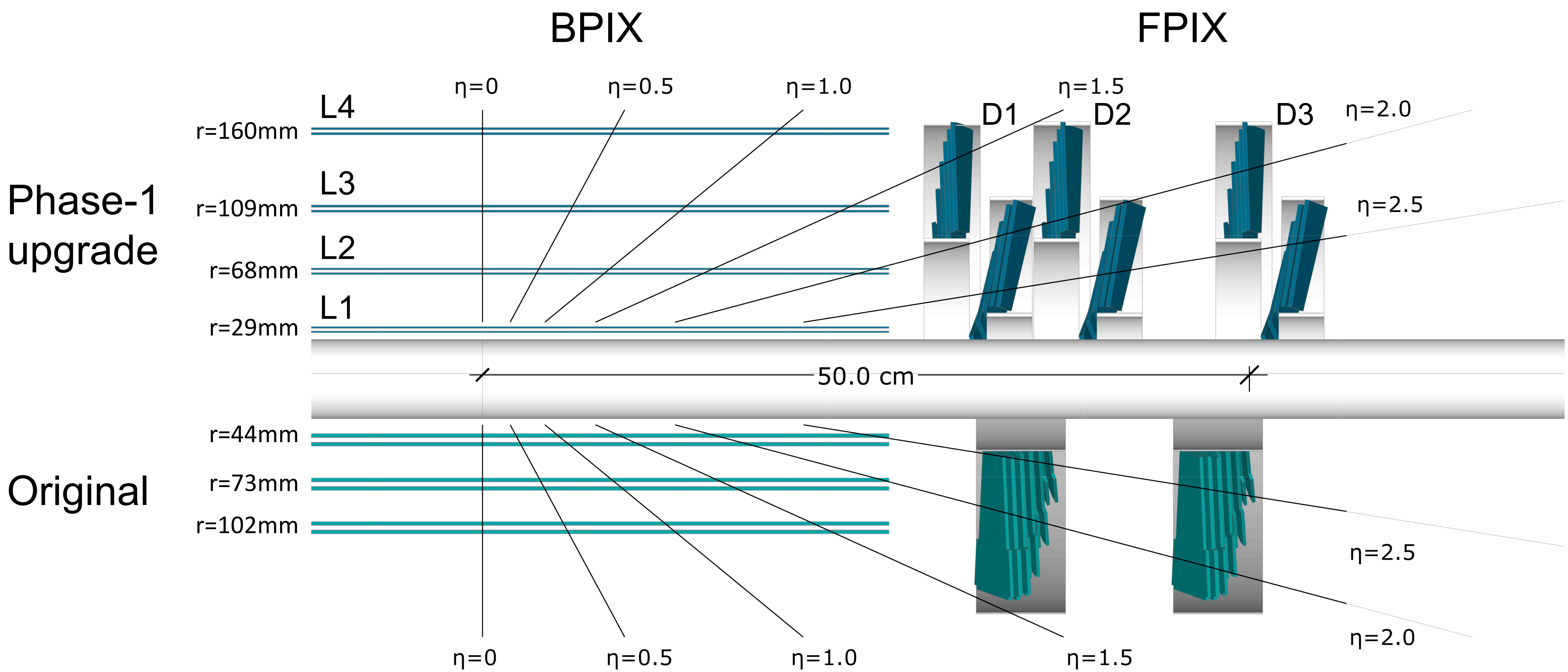
Not pictured:
out of time decays

CMS Detector and a Sense of Scale

PRF-14-001



Phase-1 Pixel Detector Upgrade



Displaced Vertices Event Yields

Observed in control samples + search region:

Event category	3-track	4-track × 3-track	4-track	≥5-track
one-vertex	61818	—	14730	2211
two-vertex	185	101	12	0

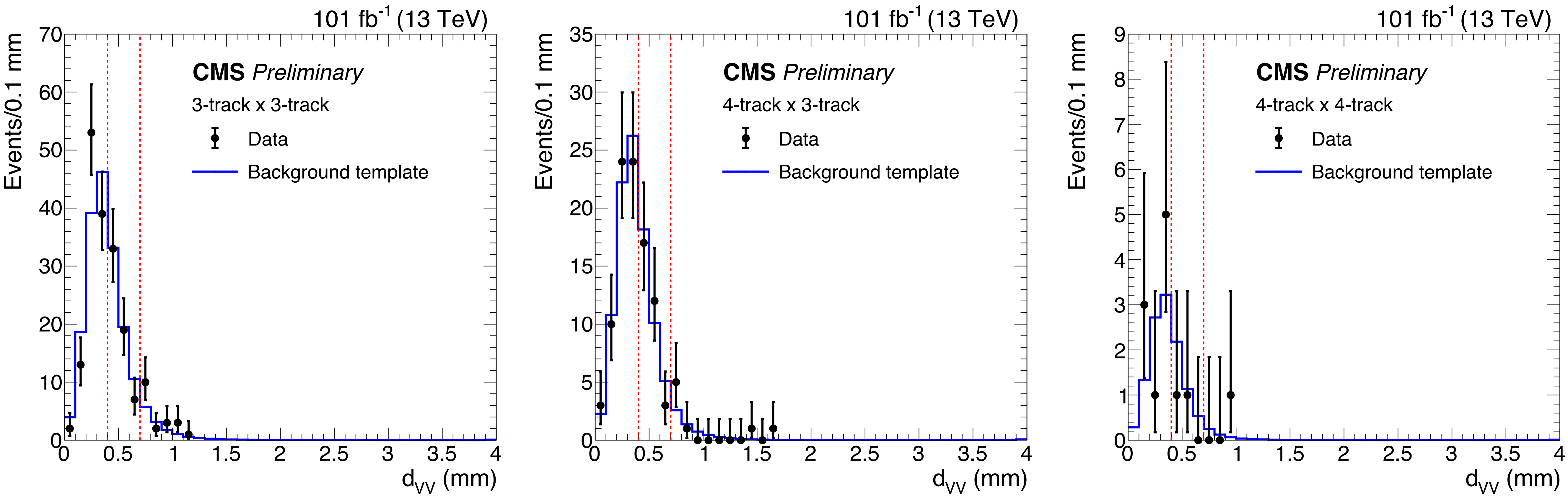
Observed and predicted in search region bins:

		Predicted multijet signal yields			
d_{VV} range	Predicted background yield	0.3 mm	1.0 mm	10 mm	Observed
0–0.4 mm	0.235 ± 0.003 (stat) ± 0.059 (syst)	0.7 ± 0.2	0.7 ± 0.1	0.20 ± 0.02	0
0.4–0.7 mm	0.096 ± 0.003 (stat) ± 0.031 (syst)	0.8 ± 0.2	1.1 ± 0.2	0.10 ± 0.01	0
0.7–40 mm	0.011 ± 0.001 (stat) ± 0.006 (syst)	0.8 ± 0.2	5.4 ± 0.9	12 ± 1	0

800 GeV, σ = 0.3 fb

Note: Overall normalization of the background template:
$N_{pred} \approx$ (bkg vertex ε)^2 w/ corrections à la template construction

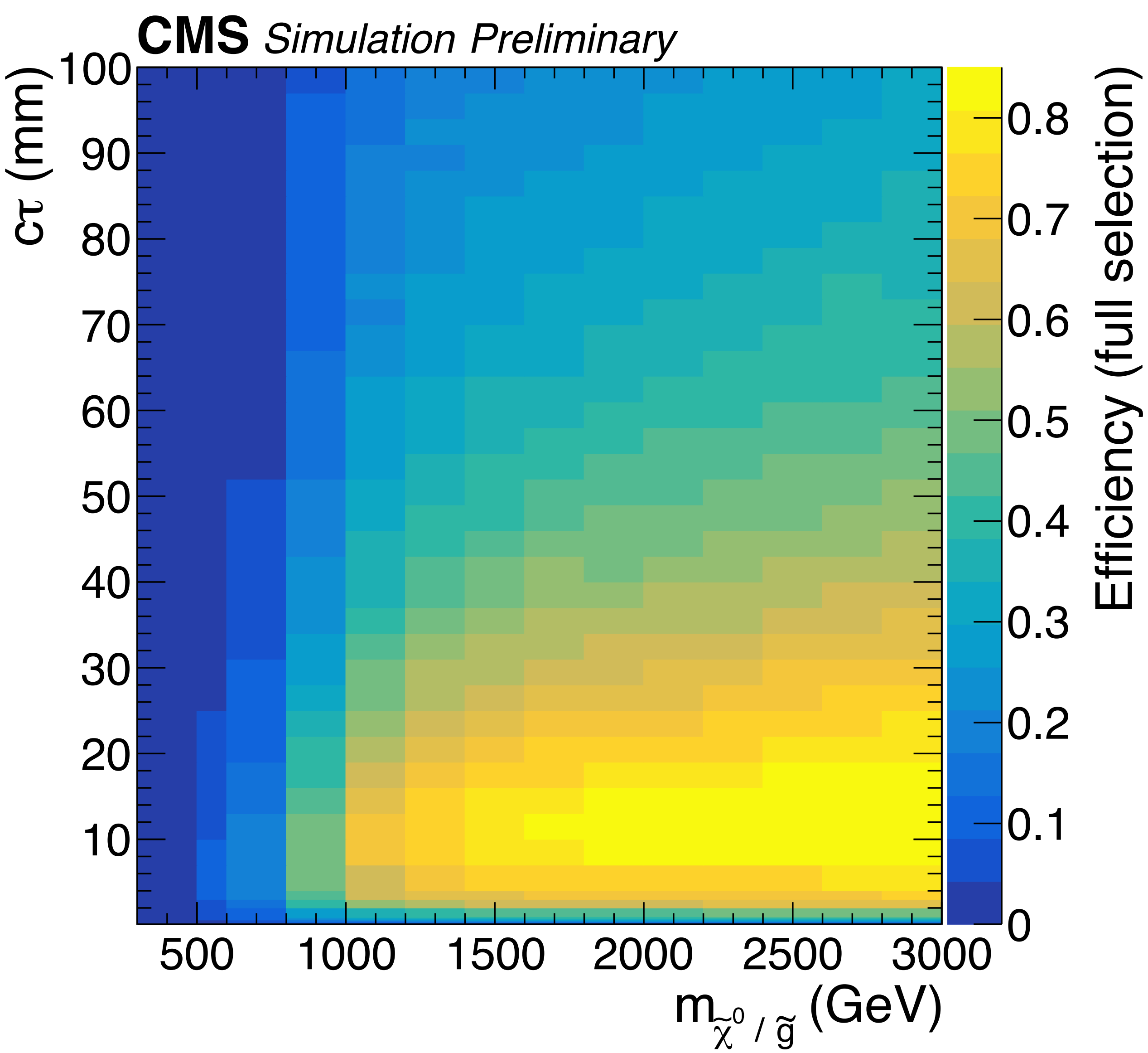
Displaced Vertices Background Validation

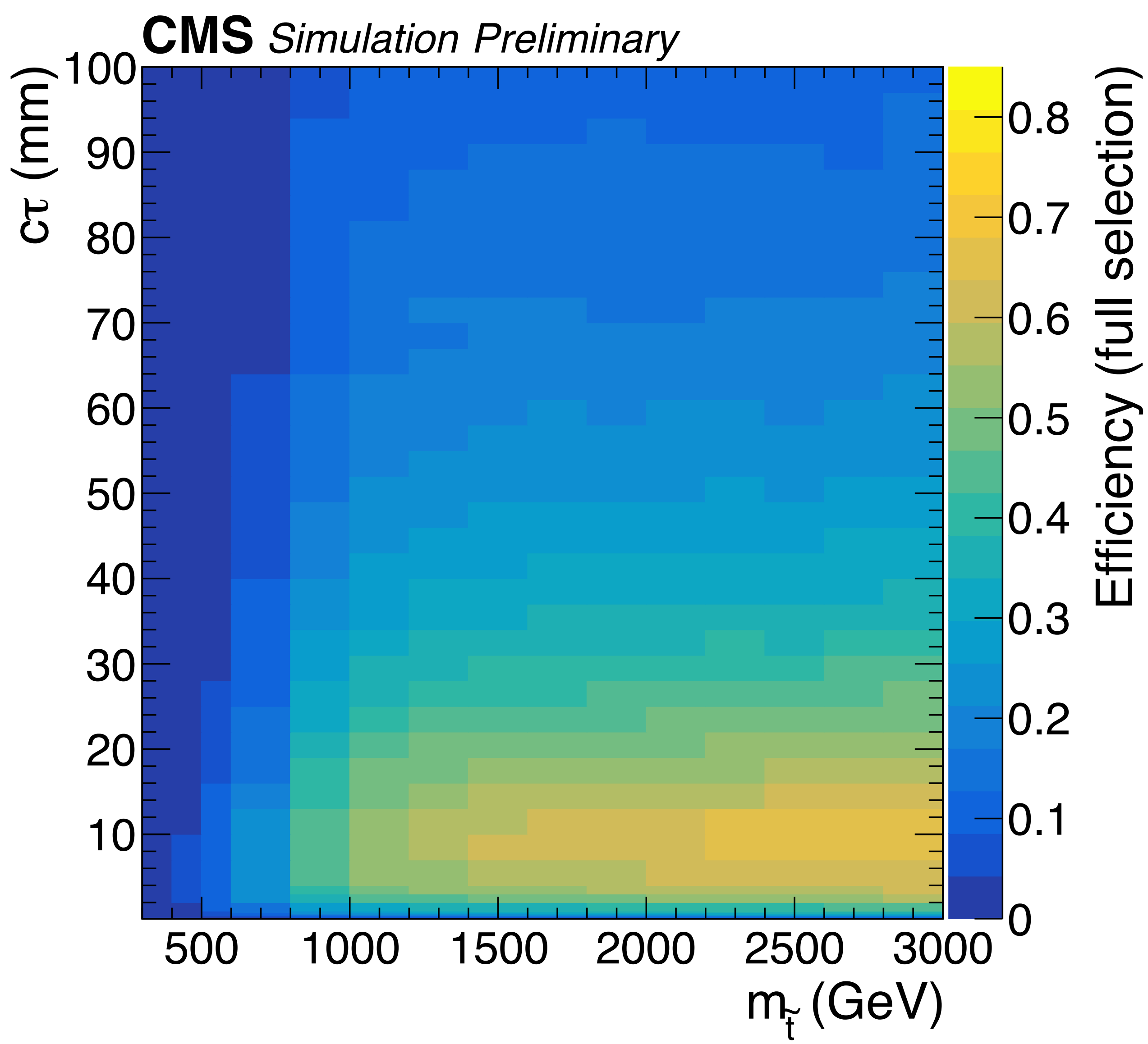


Events with pairs of vertices with <5-tracks used to validate the procedure—good agreement observed!

(and any differences used as syst uncertainty)

Displaced Vertices Signal Efficiencies





Systematics

SIMP signal systs

source	uncertainty
jet energy corrections	2.2 - 5.4%
integrated luminosity	2.5%
trigger inefficiency	2%

DV signal systs

Systematic effect	Dijet uncertainty (%)	Multijet uncertainty (%)
Vertex reconstruction	11–41	1–36
PDF 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
Overall	13-42	7-36

DV background systs

	Shift $\pm$ Statistical Uncertainty (%)		
Systematic effect	0–0.4 mm	0.4–0.7 mm	0.7–40 mm
Closure in 3-track control sample	1 ± 10	7 ± 12	38 ± 32
$\geq$5-track template normalization factor	23 ± 7	23 ± 7	23 ± 7
Difference from 3-track vertices to $\geq$5-track vertices:			
Modeling of vertex pair survival efficiency	$9 \pm < 0.5$	20 ± 1	25 ± 5
Modeling of $\Delta\phi_{\mathrm{VV}}$	$3 \pm < 0.5$	6 ± 1	5 ± 3
Variation of b-tag fraction	$1 \pm < 0.5$	3 ± 1	5 ± 3
Variation of b-tag correction factors	$0 \pm < 0.5$	$0 \pm < 0.5$	1 ± 1
Overall	25 ± 12	32 ± 14	51 ± 33