Search for Displaced Vertices at CMS

FNAL LPC Physics Forum

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on behalf of the
CMS Collaboration

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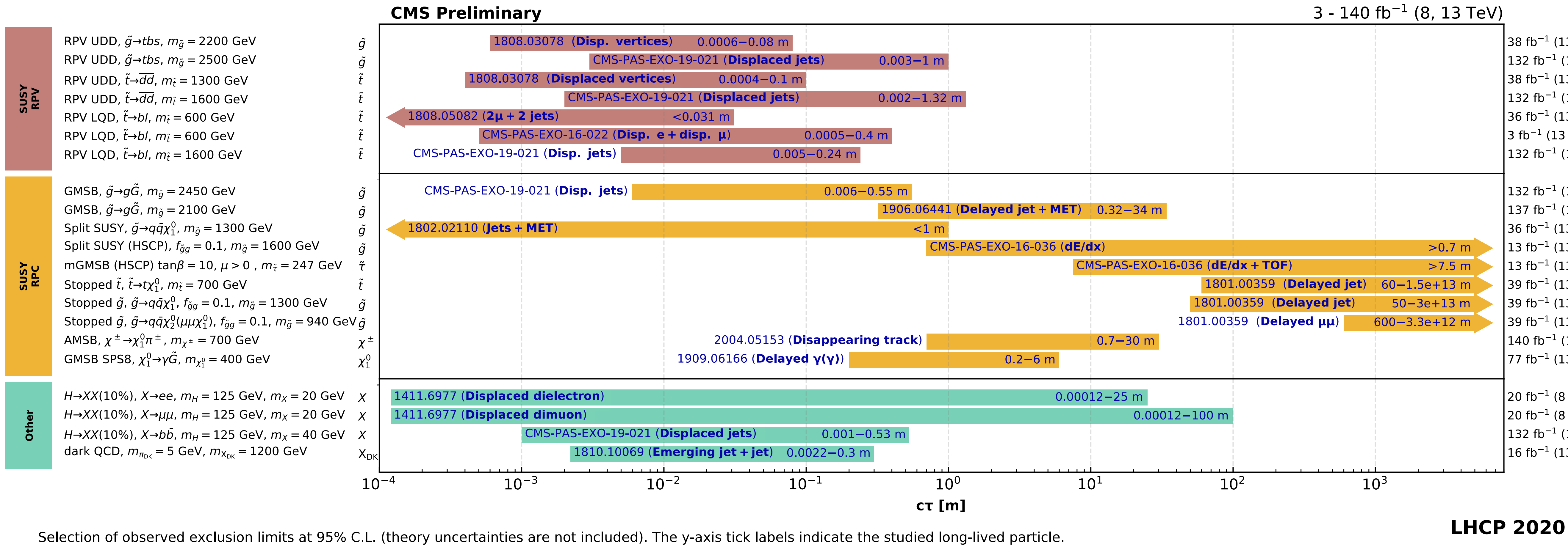
Snapshot of CMS LLP Searches

Overview of CMS long-lived particle searches



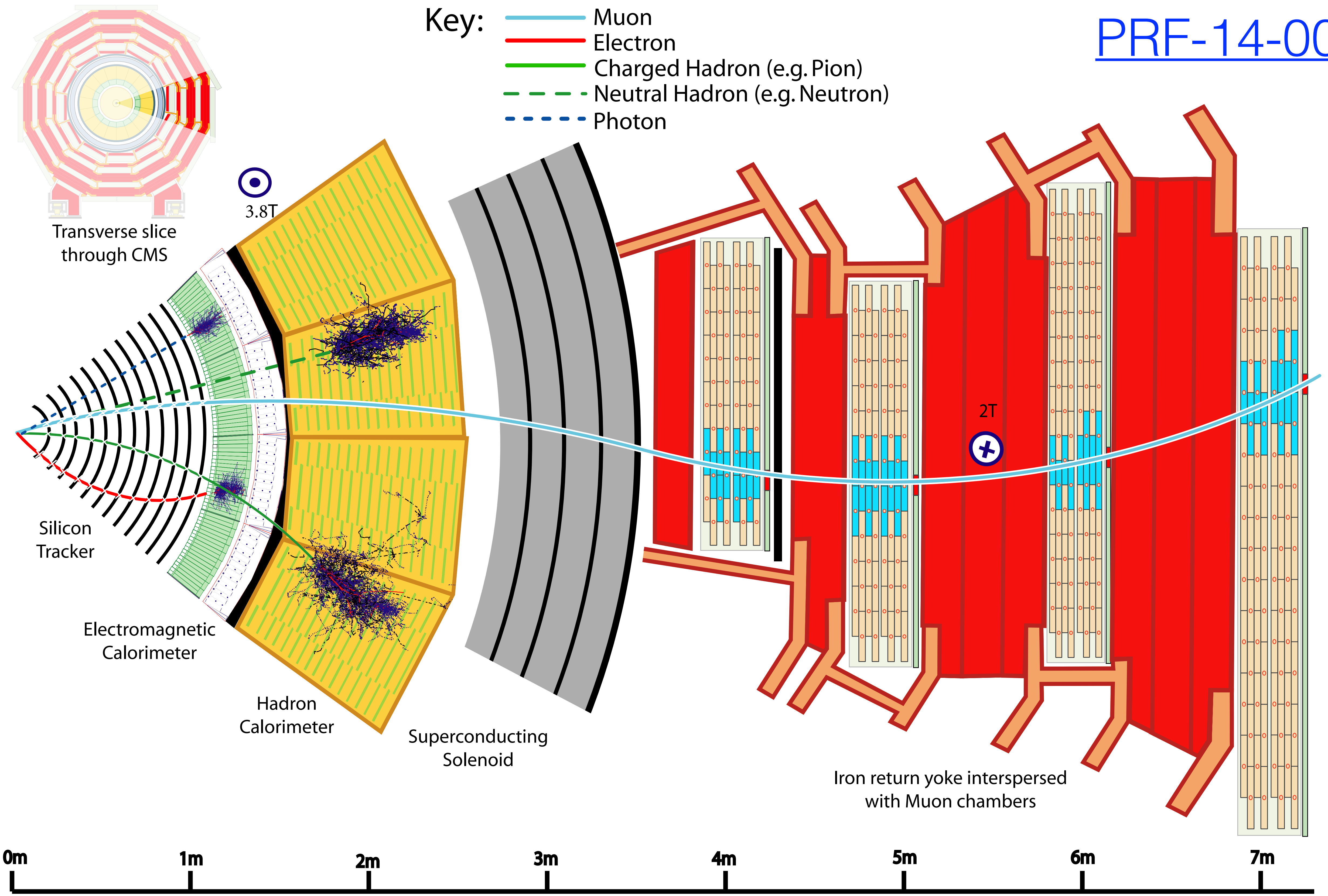
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

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

Note: 8th LHC LLP WS is this week! CMS Exotica Summary Plots

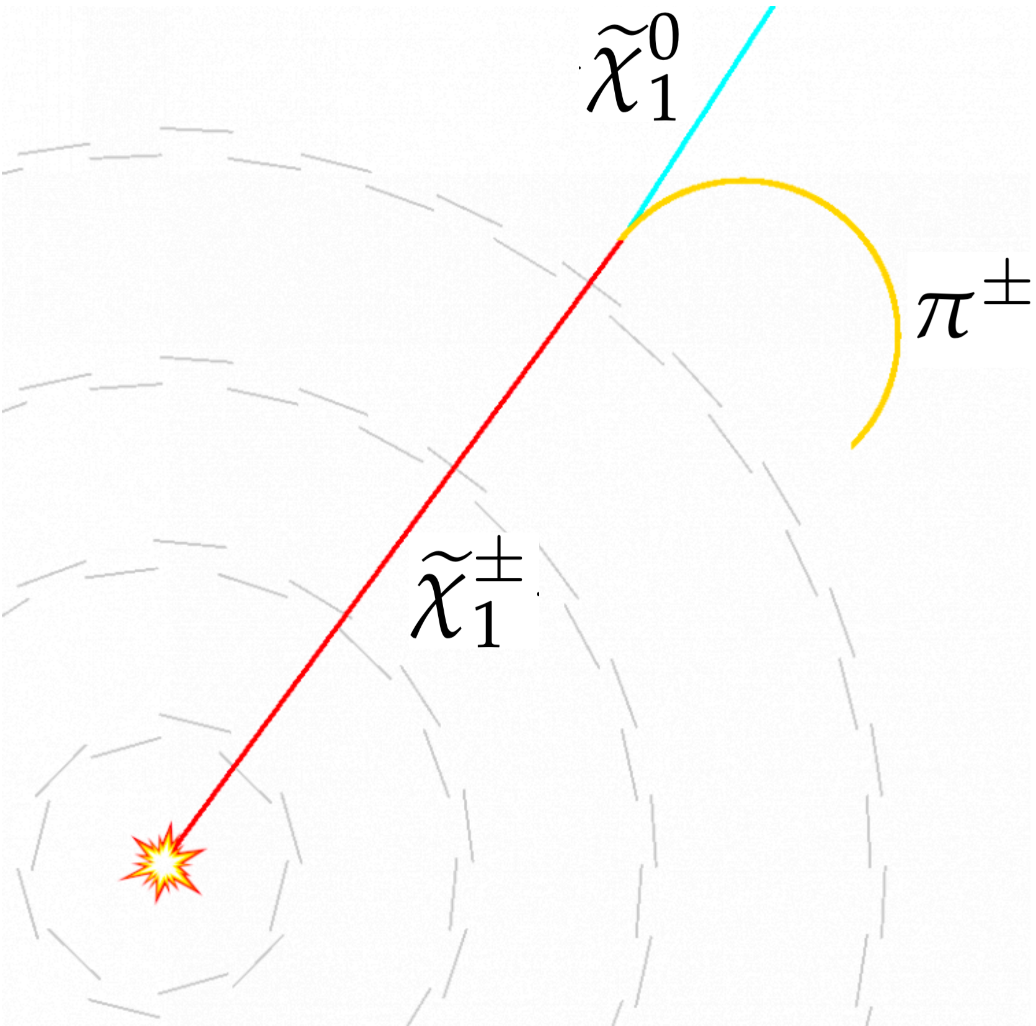
CMS Detector and a Sense of Scale

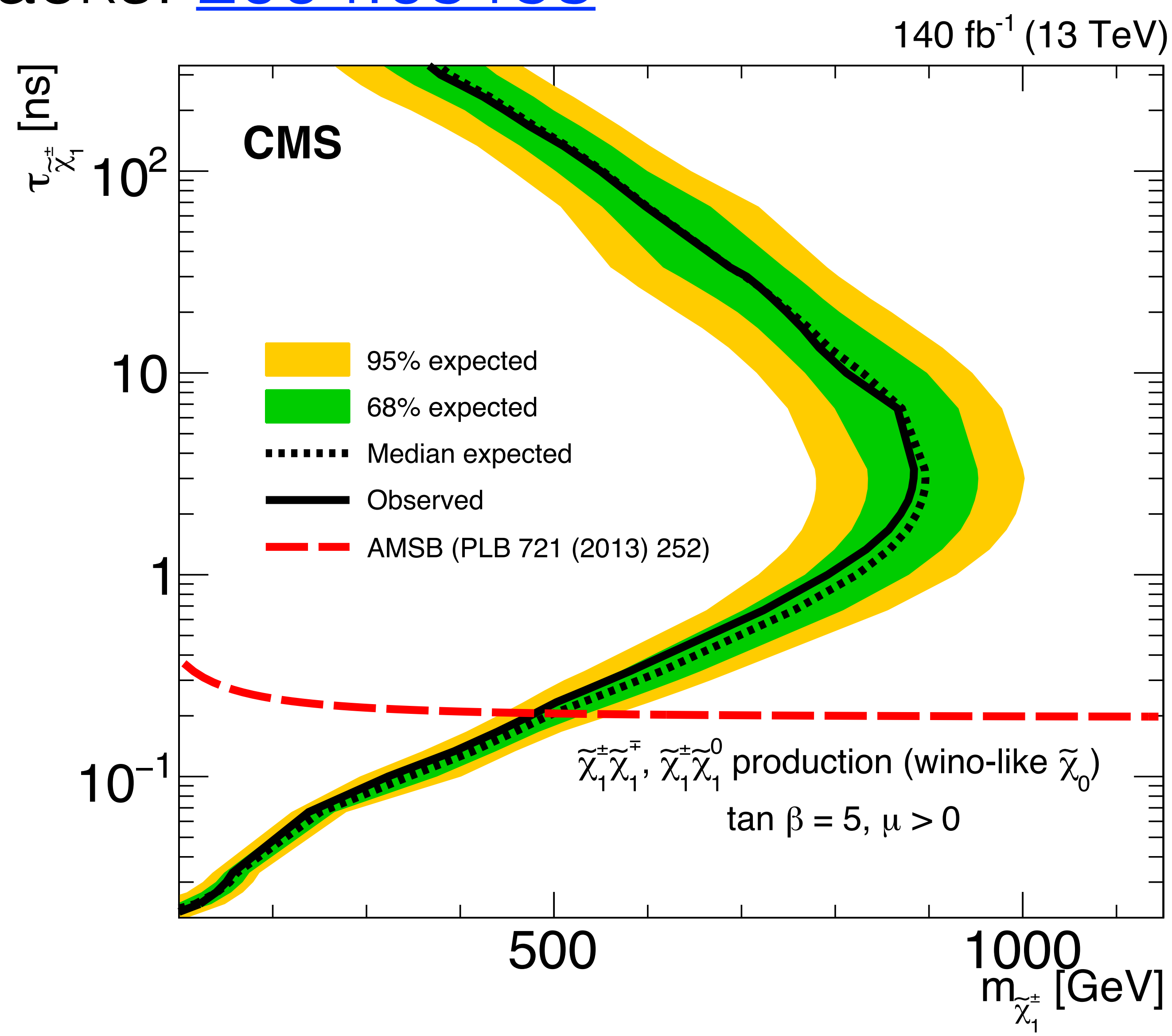
[PRF-14-001]



Recent LLP Results

Disappearing Tracks: [2004.05153]





Distinct signature!

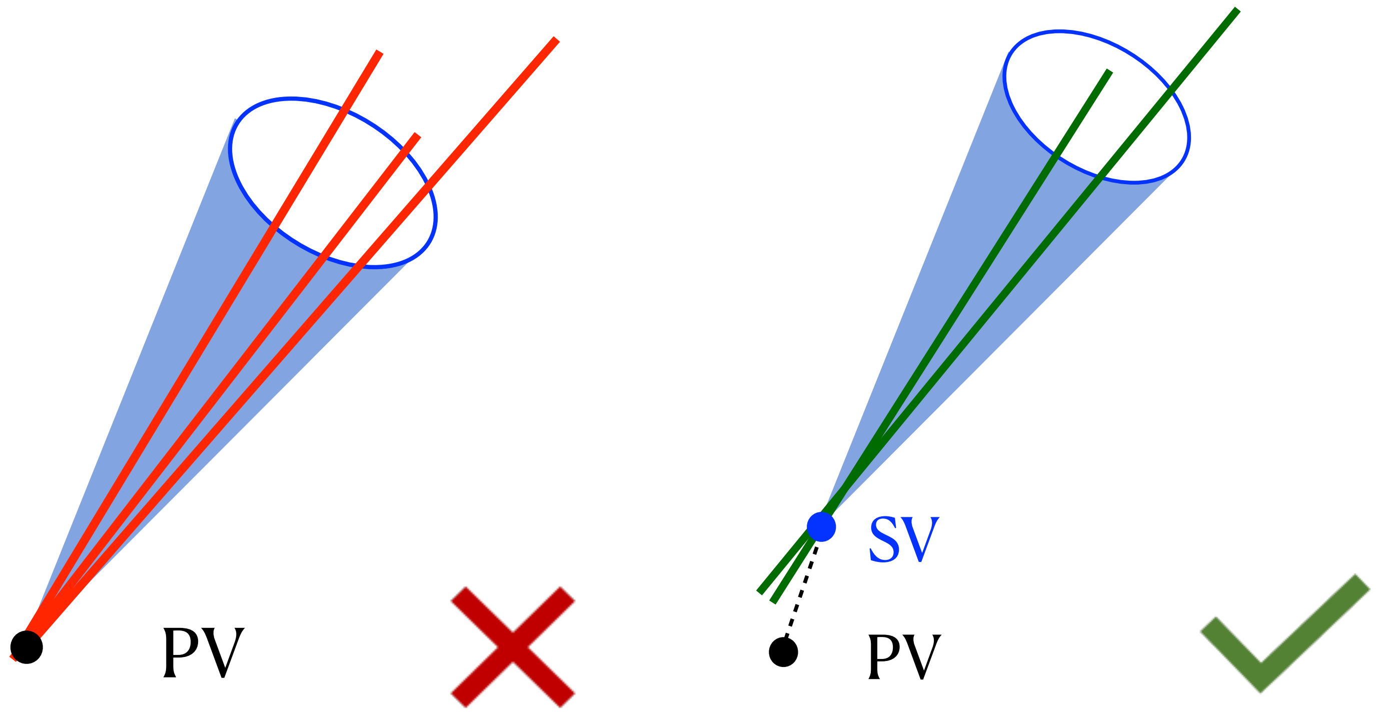
Arises naturally in AMSB and compressed SUSY scenarios with $\mathcal{O}$(100 MeV) splittings

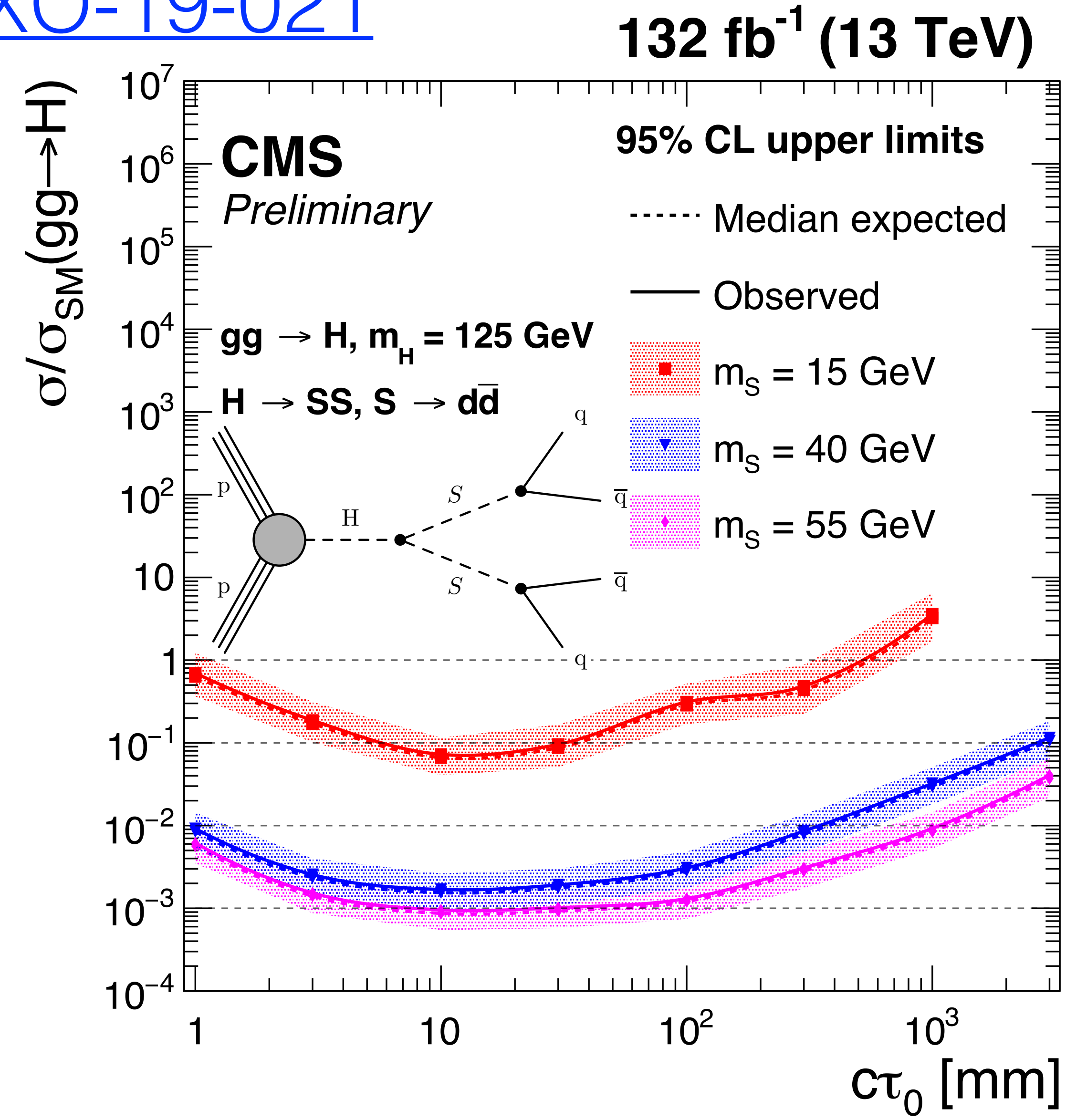
Charginos excluded for pure $\widetilde{W}$ LSP scenarios up to 474 GeV and 0.2 ns (175 GeV and 0.05 ns for $\widetilde{H}$ LSP)

LLP7 [slides] from B. Francis

Recent LLP Results

Displaced Jets: EXO-19-021





Dedicated trigger selects events containing jets with ≤2 prompt tracks

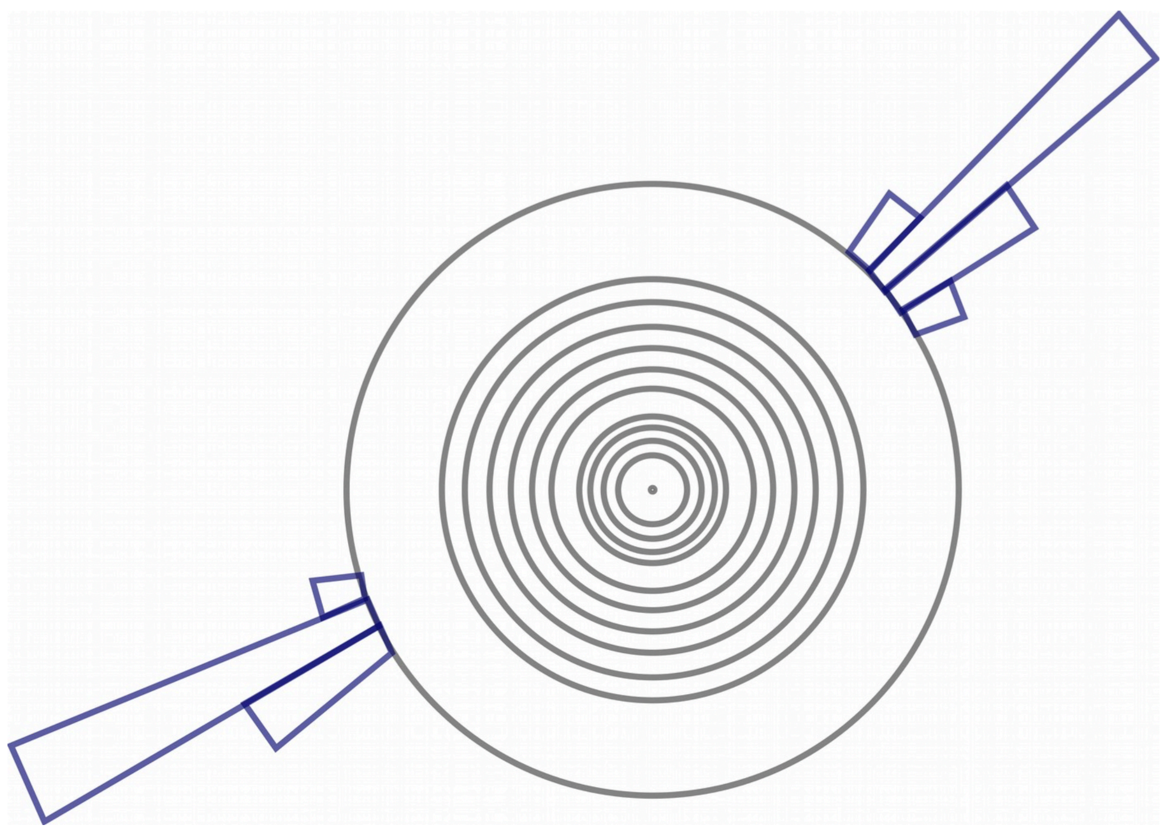
Reconstruct SVs using pairs of jets; use a NI-veto map and a GBDT to suppress background.

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

LLP7 slides from J. Luo

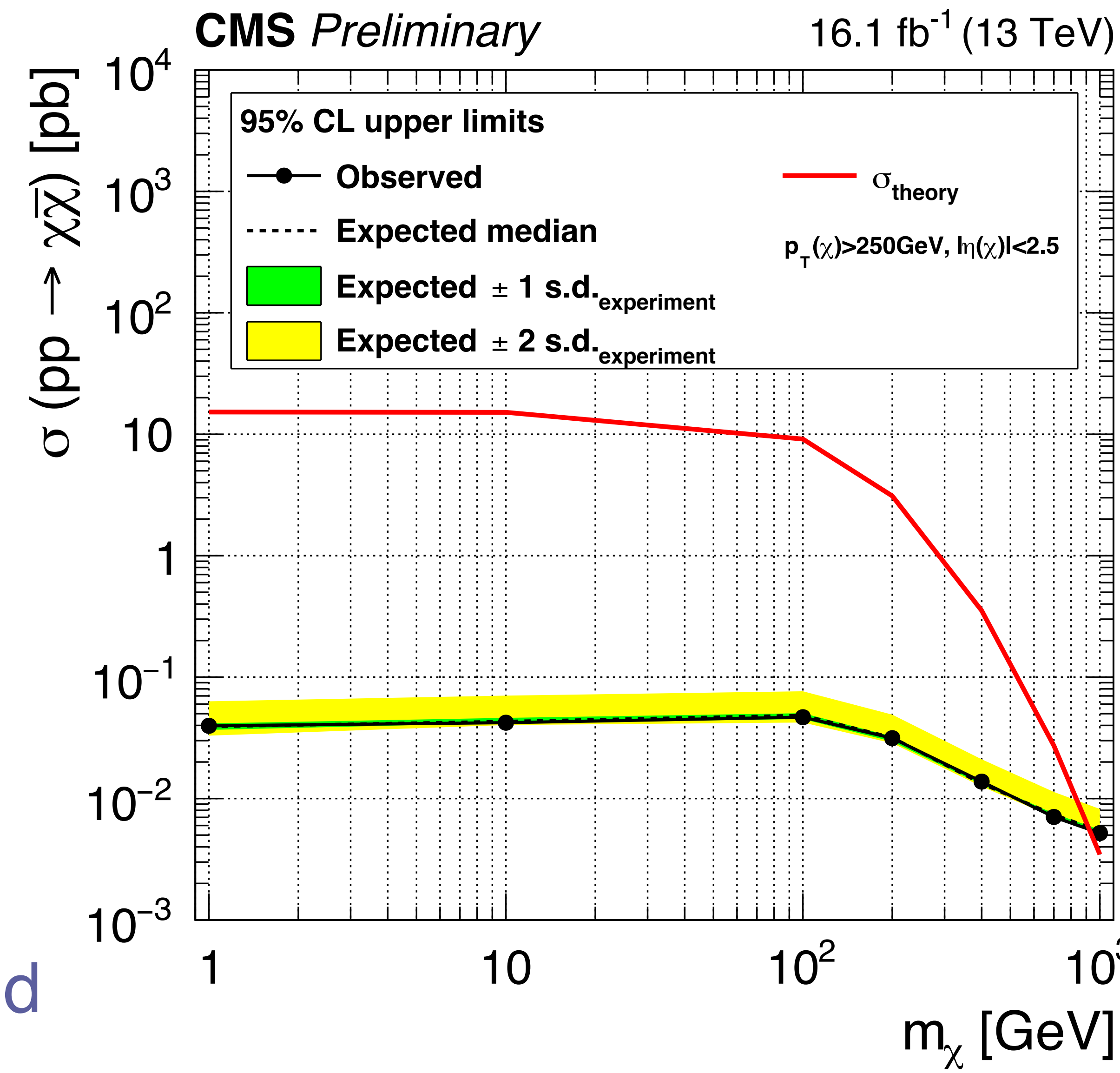
Recent LLP Results

SIMPs with Trackless Jets: EXO-17-010



Simplified model has SIMP couplings resulting in hadronic showers that start and are contained in the HCAL

Look for jet pairs w/ small ChF; estimate background with data-driven technique



SIMPs (w/ these couplings) excluded for masses up to 900 GeV!

My LLP8 slides

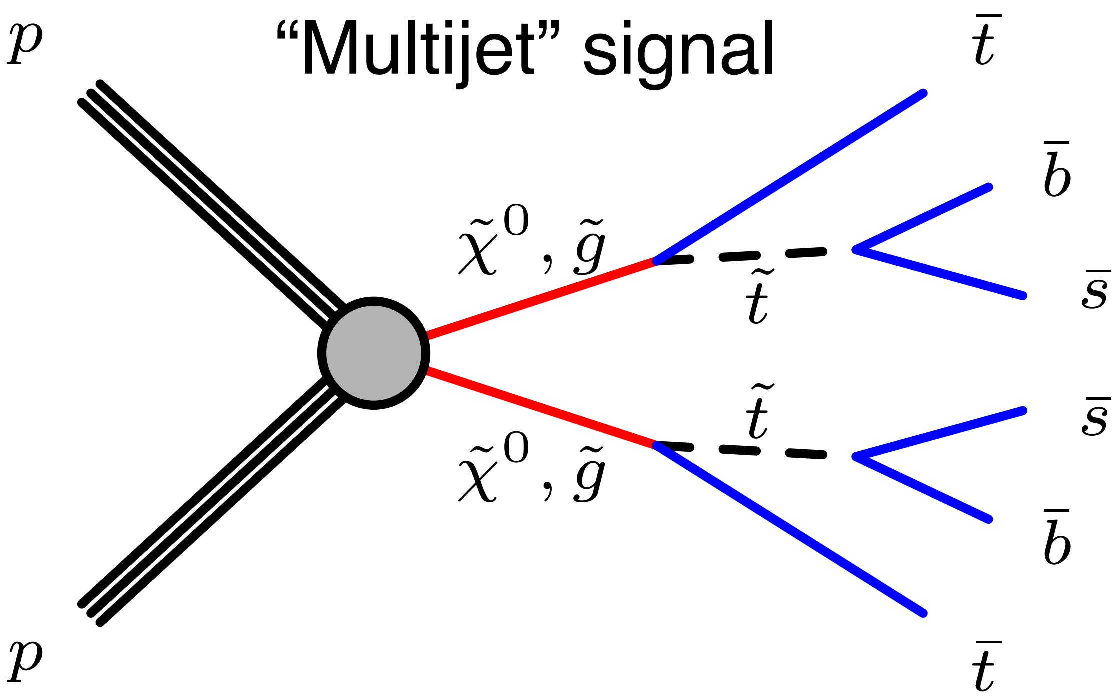
Search for long-lived particles decaying to jets with displaced vertices

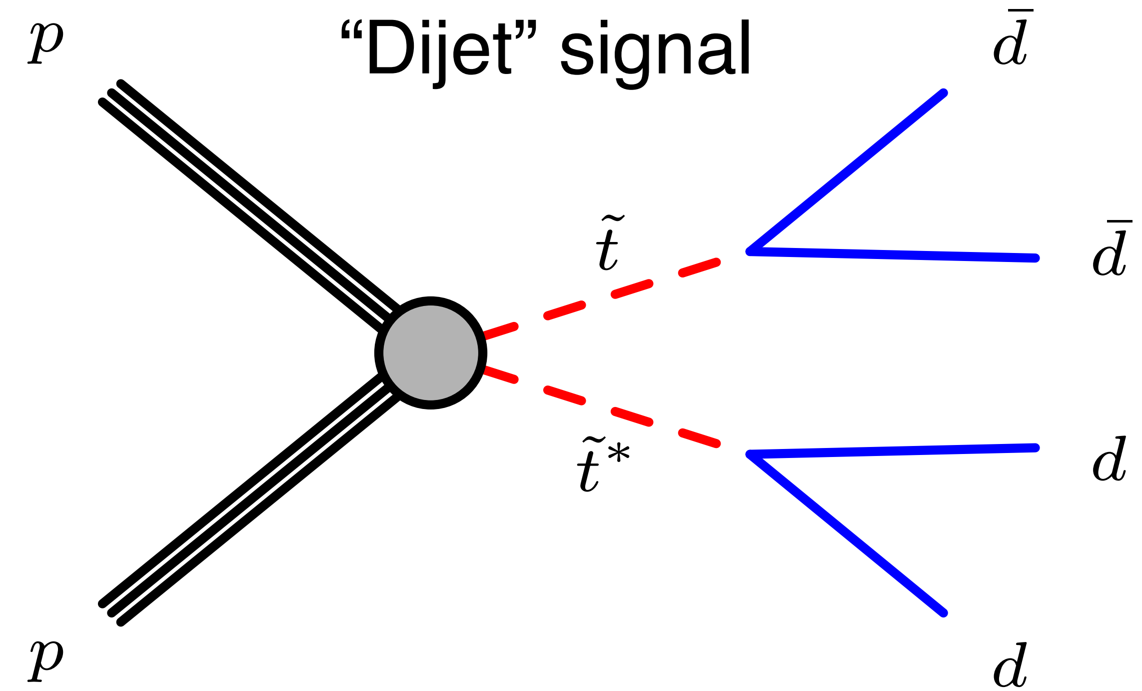
EXO-19-013

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 models w/ small couplings prevent e.g. proton decay, while allowing the LSP to be long-lived before decaying.

We use these as our benchmark models, but the search is fairly model-independent!

General Analysis Strategy

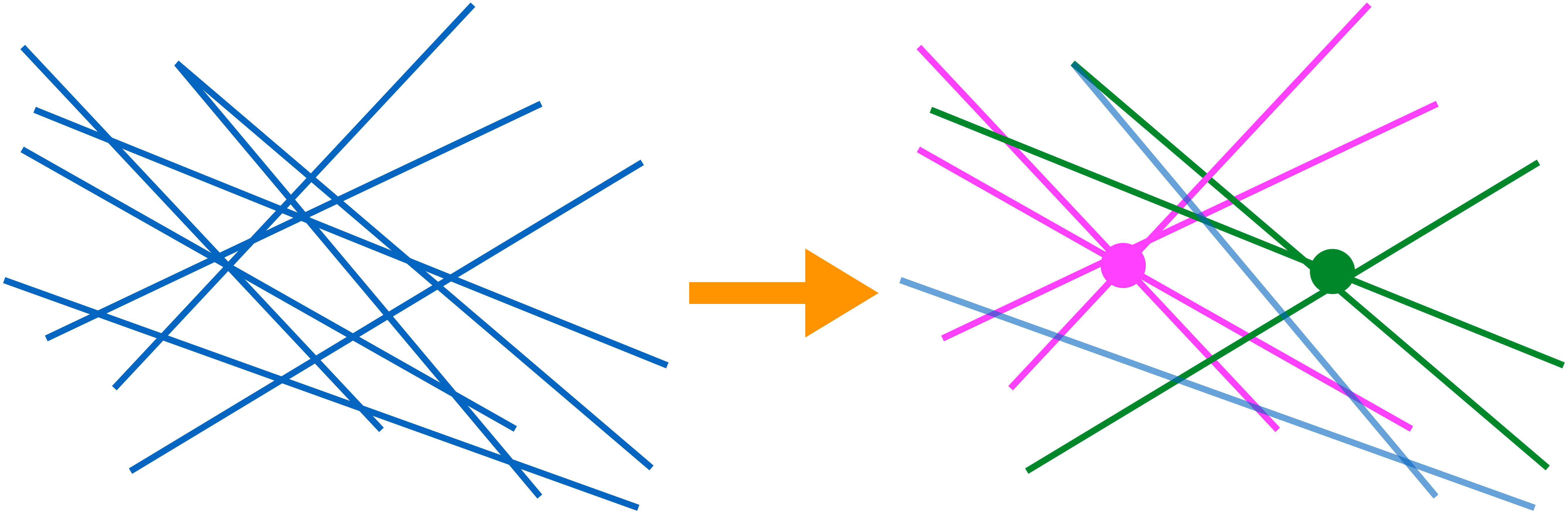
Select events using H_T trigger

- Require H_T > 1200 GeV and ≥4 jets

Use tracks to reconstruct the two LLP decay points as two displaced vertices. Select high-quality tracks with:

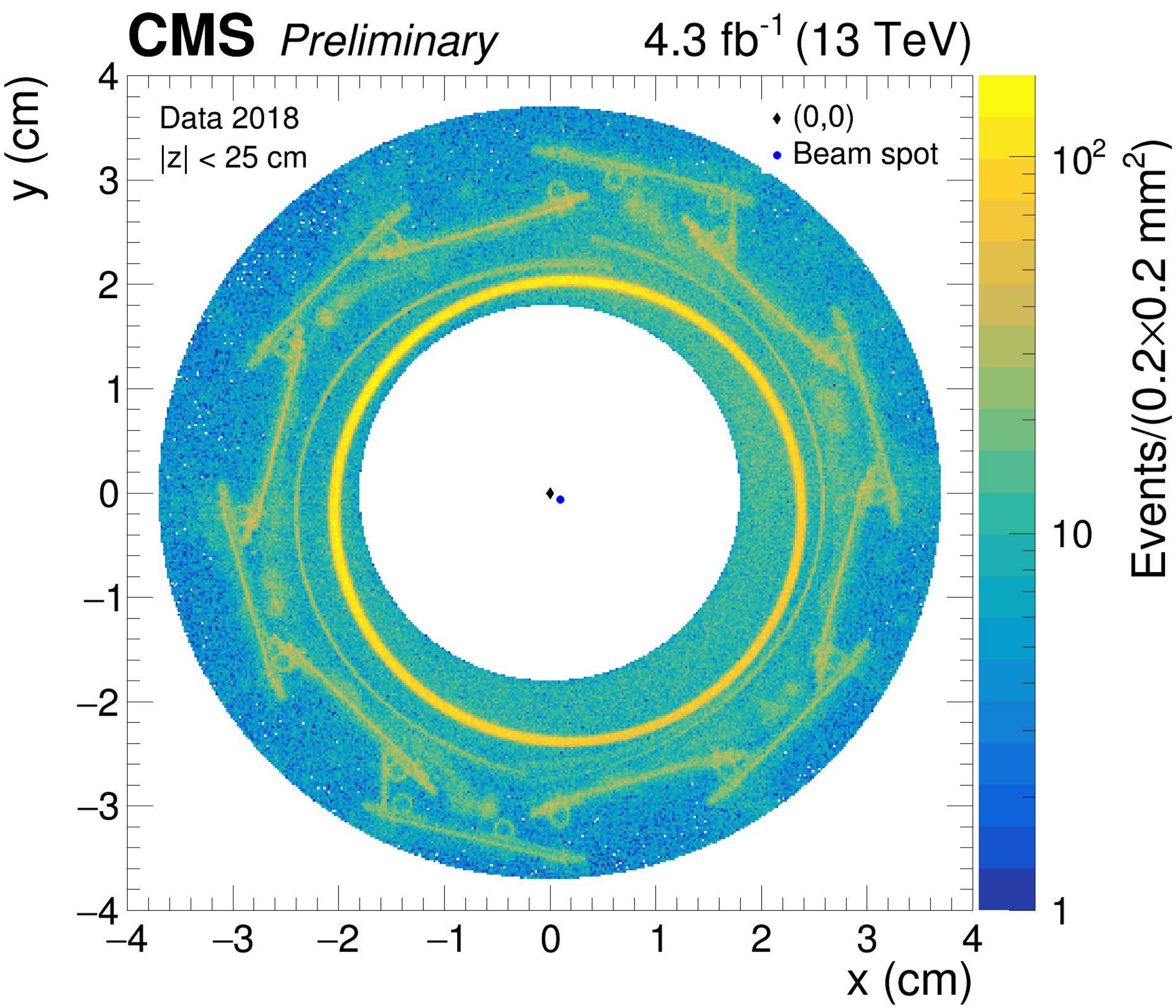
- p_T > 1 GeV
- $N_{pixel\ hits} \geq 2$, $N_{strip\ hits} \geq 6$
- Hit in the innermost pixel layer (results in $\langle\sigma(d_{xy})\rangle \approx 72$ μm)
- $d_{xy}/\sigma(d_{xy}) > 4$ to select displaced tracks

Vertex Reconstruction and Selection



Custom vertex reconstruction: iteratively merge tracks into vertices, fit w/ Kalman filter, and arbitrate w/ quality requirements (χ^2, vtx-vtx distance, trk-vtx IP, etc.).

Vertex Reconstruction and Selection



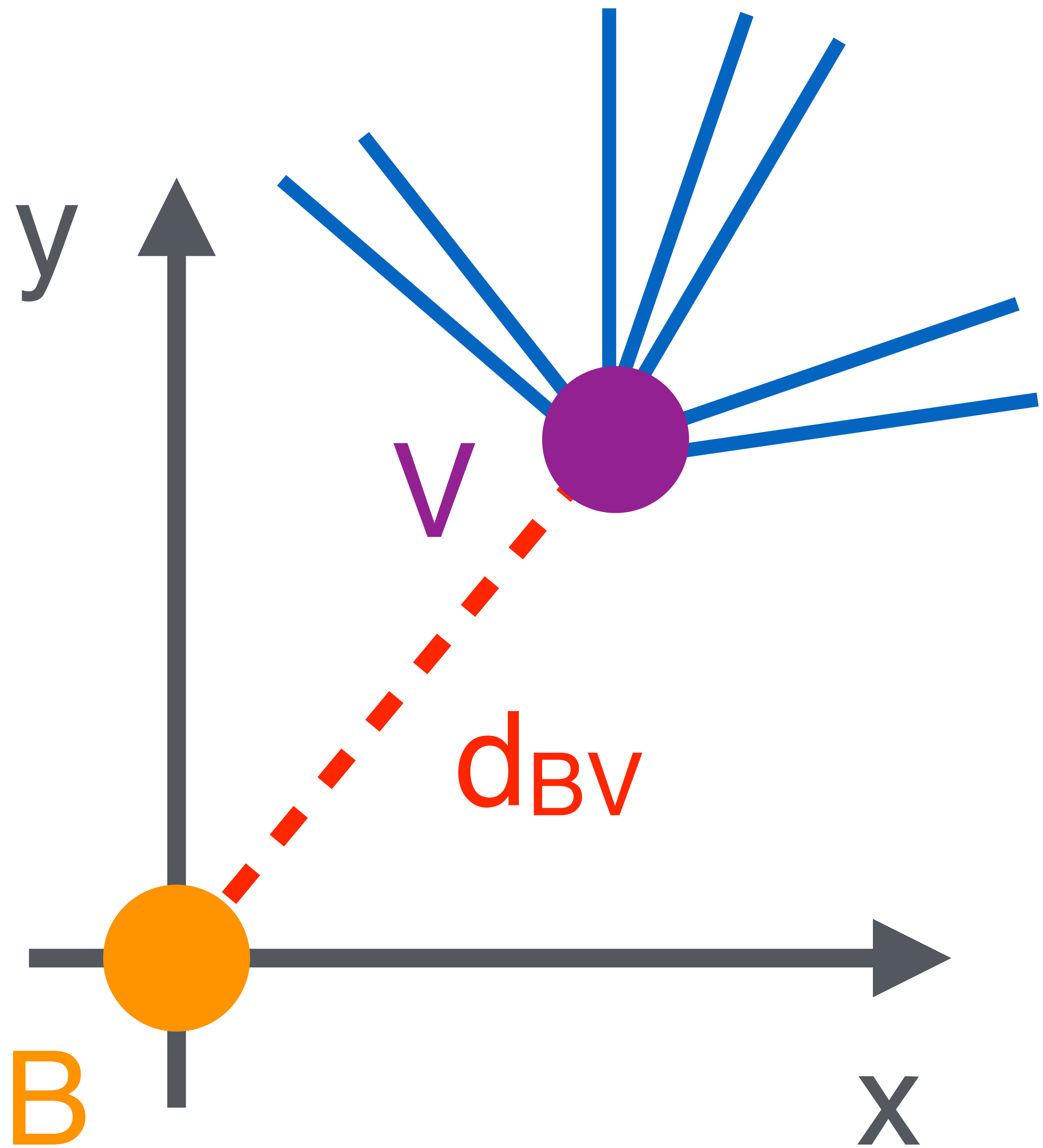
Note: r < 1.8 cm and r > 3.7 cm not shown for visibility

Only accept DVs within beam pipe

(avoid bkgs from material interactions)

[TrackerMaterialPosition2018]

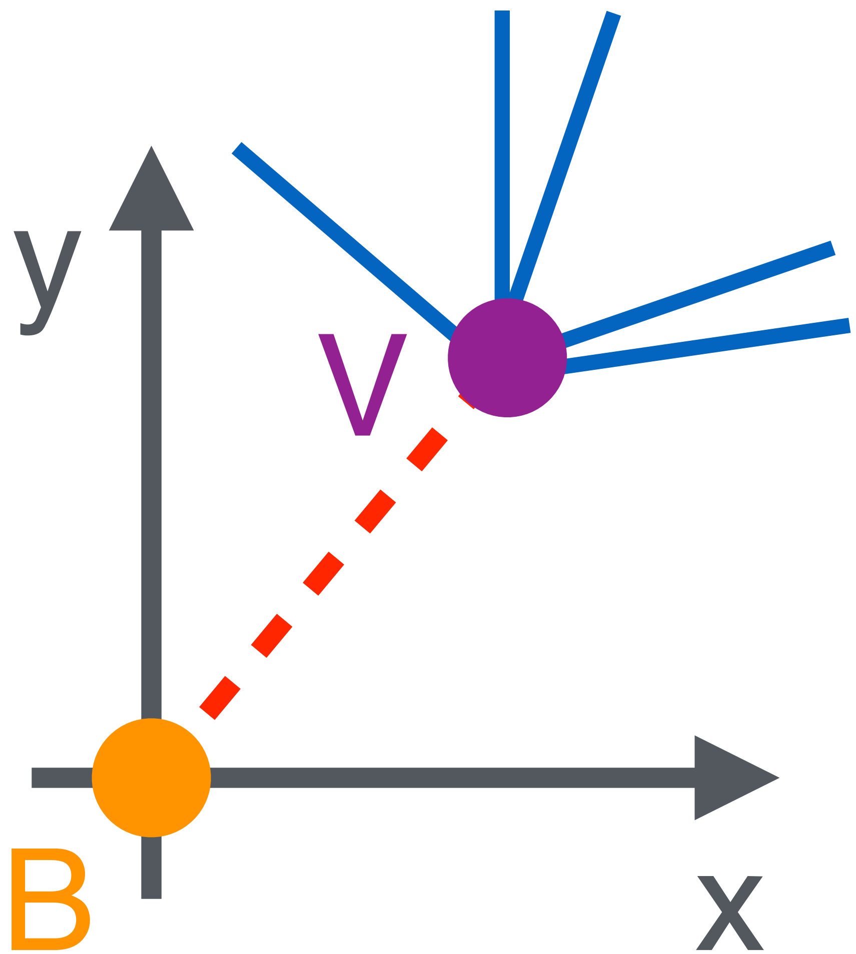
Vertex Reconstruction and Selection

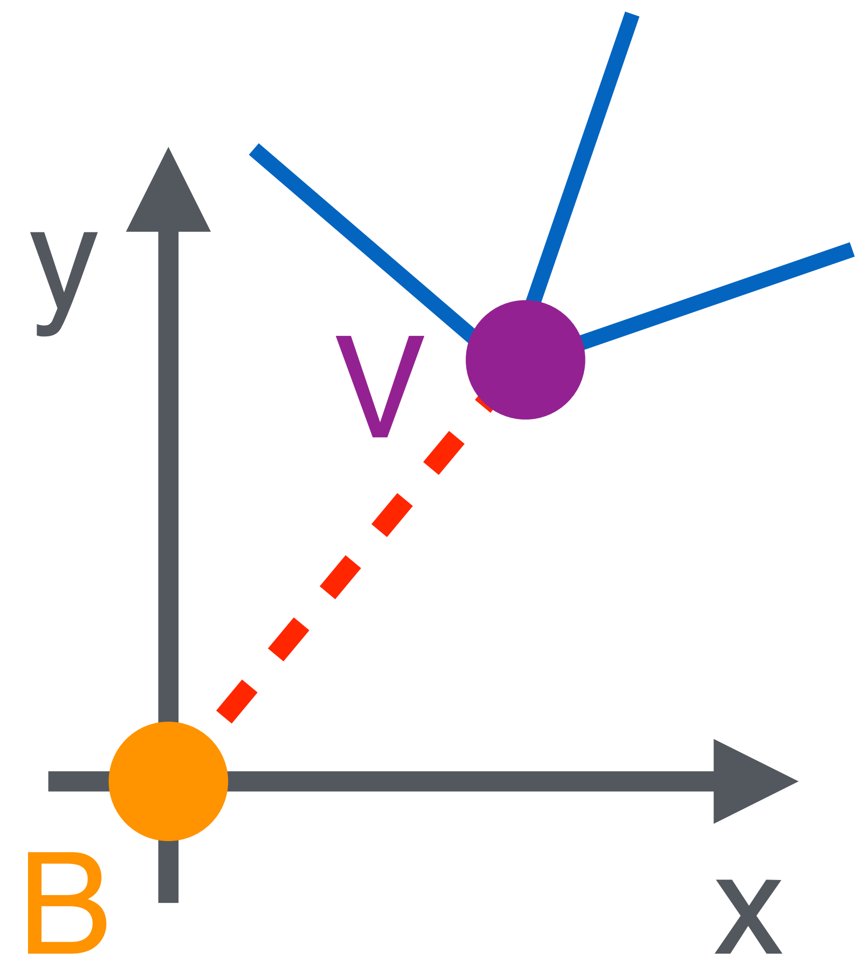


Require $d_{BV} > 100$ µm
(avoid displaced PVs)

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

Vertex Reconstruction and Selection

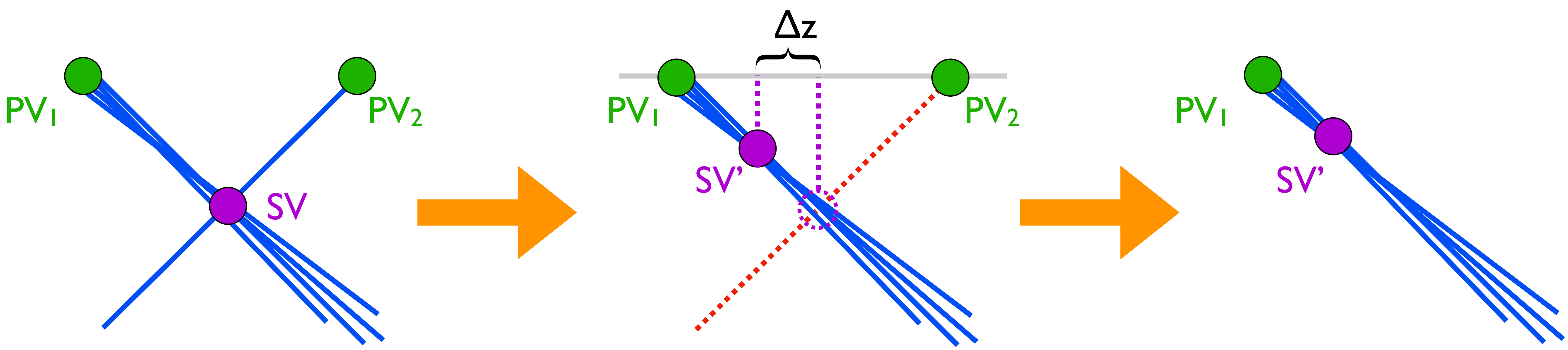




Signal vertices:
$n_{track} \geq 5$

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

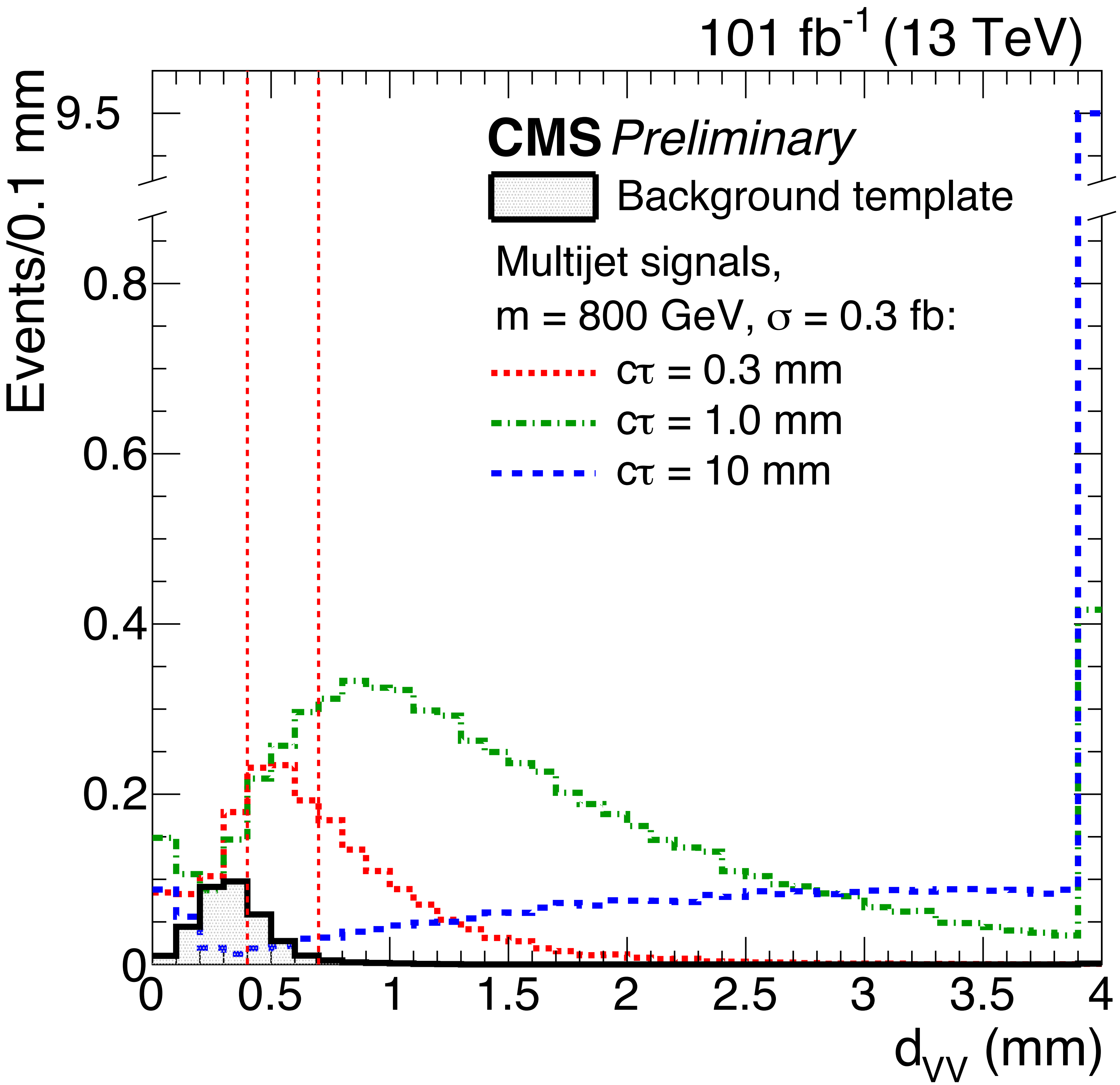
Suppression of pileup tracks

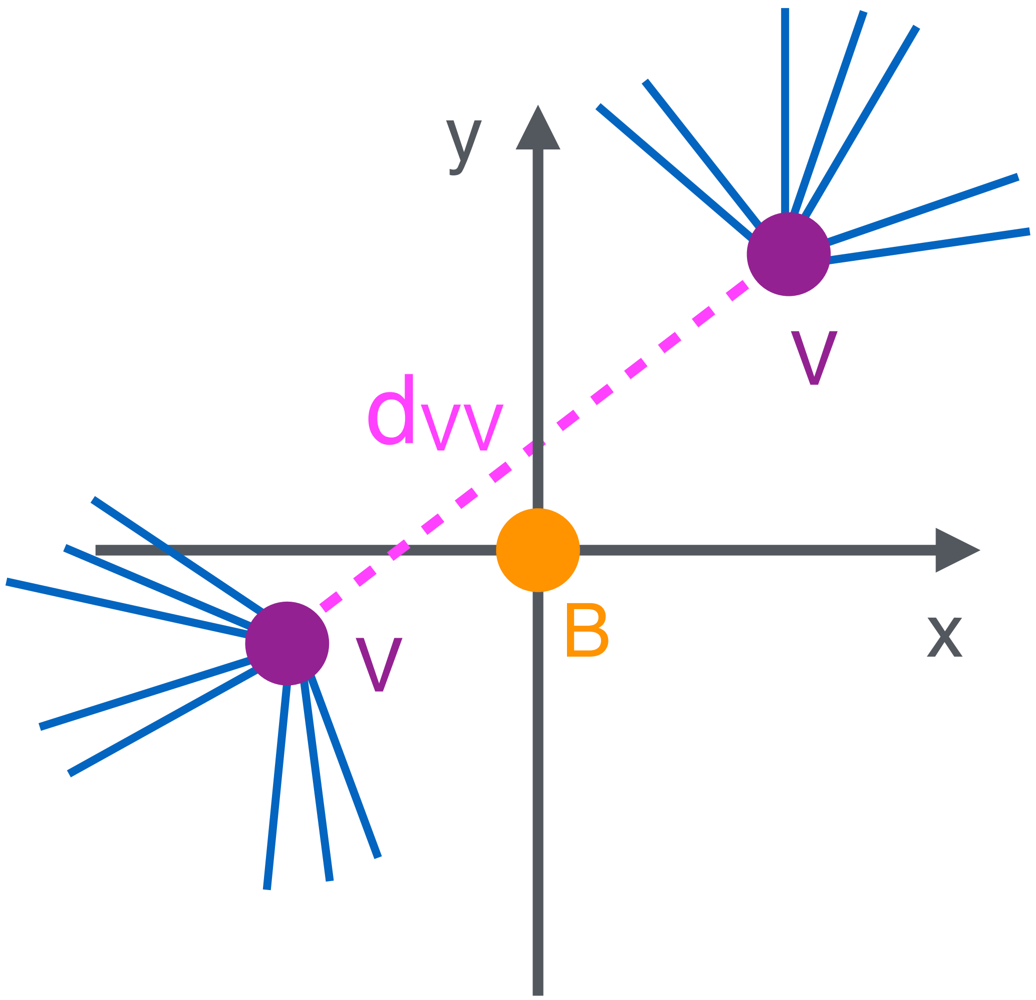


During vertex reconstruction, remove any tracks that significantly affect vertex z position by > 50 μm

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 vertices arise from misreconstructed tracks—no guarantee that simulation can faithfully reproduce such effects!

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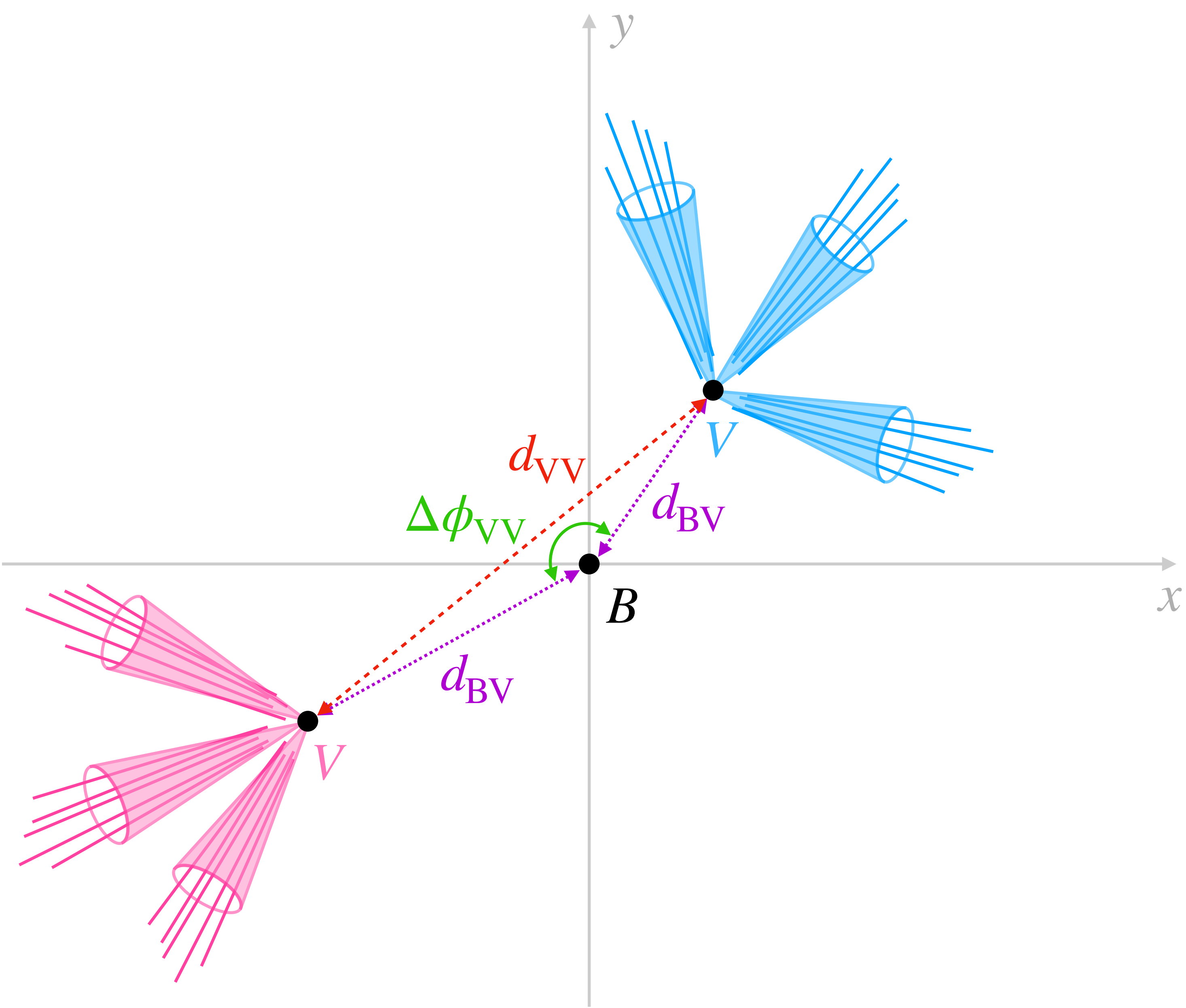
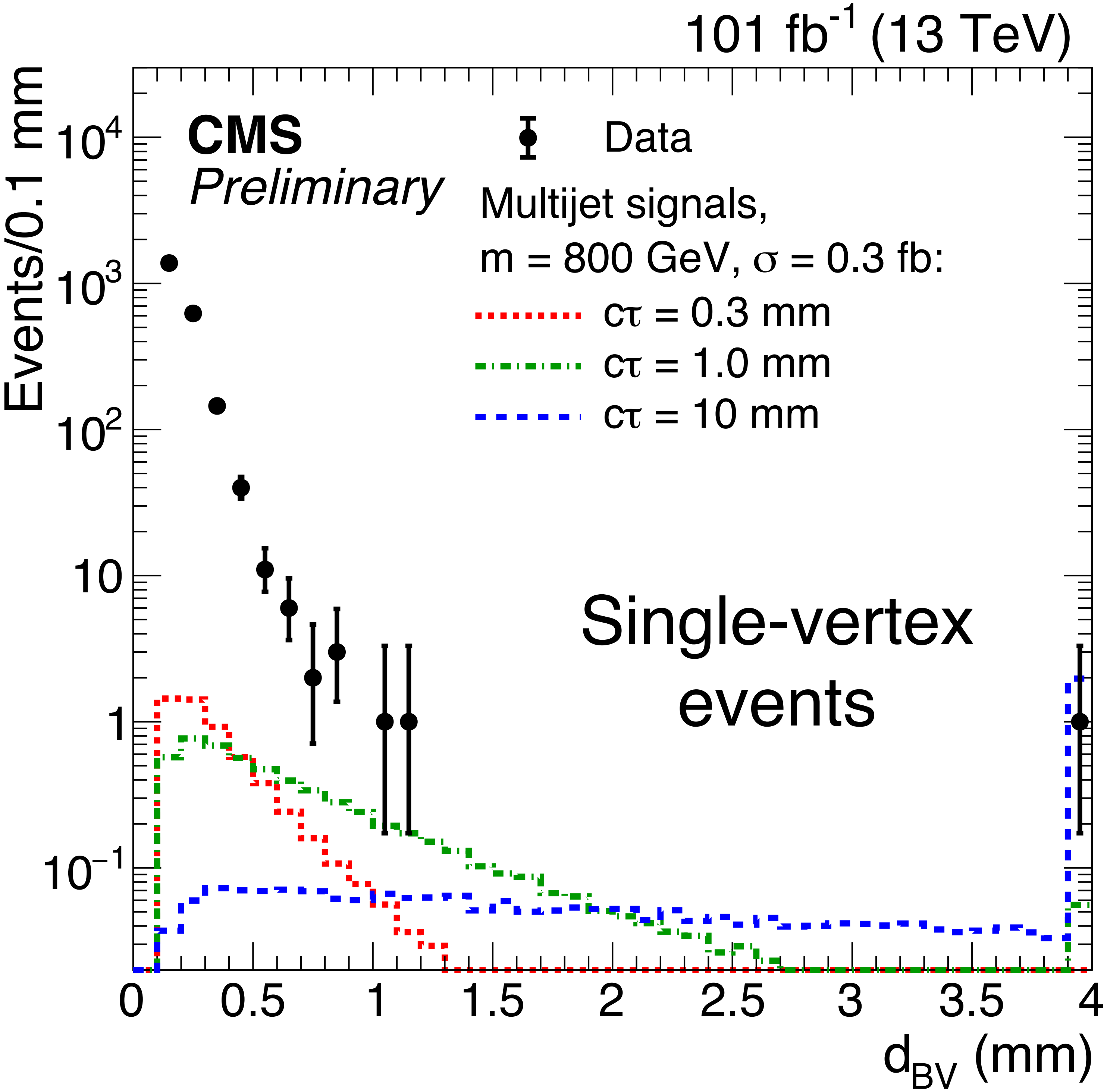


Instead:

- Look at characteristics of a two-vertex event
- *Emulate* d_{VV} in data using (bkg-dominated) single-vertex events

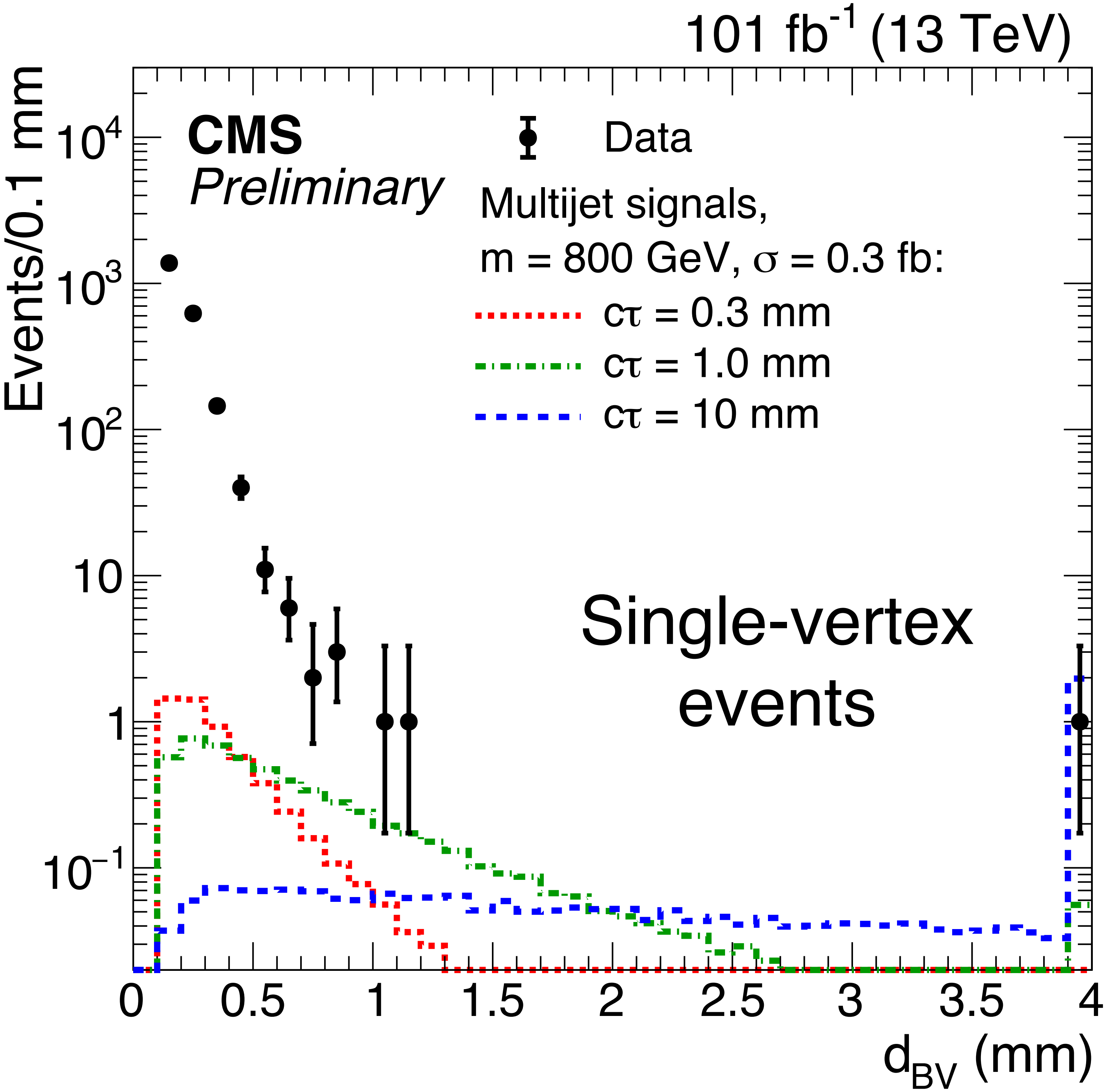
Data-Driven Background Estimation



Construct a **background d_{VV} template** from single-vertex data using:

- Two random d_{BV} values
- Randomly chosen $\Delta\phi_{VV}$, estimated via jet angles

Data-Driven Background Estimation



Construct a background d_{VV} template from single-vertex data using:

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- Randomly chosen $\Delta\phi_{VV}$, estimated via jet angles
- Corrections for b-quarks (larger displacements)

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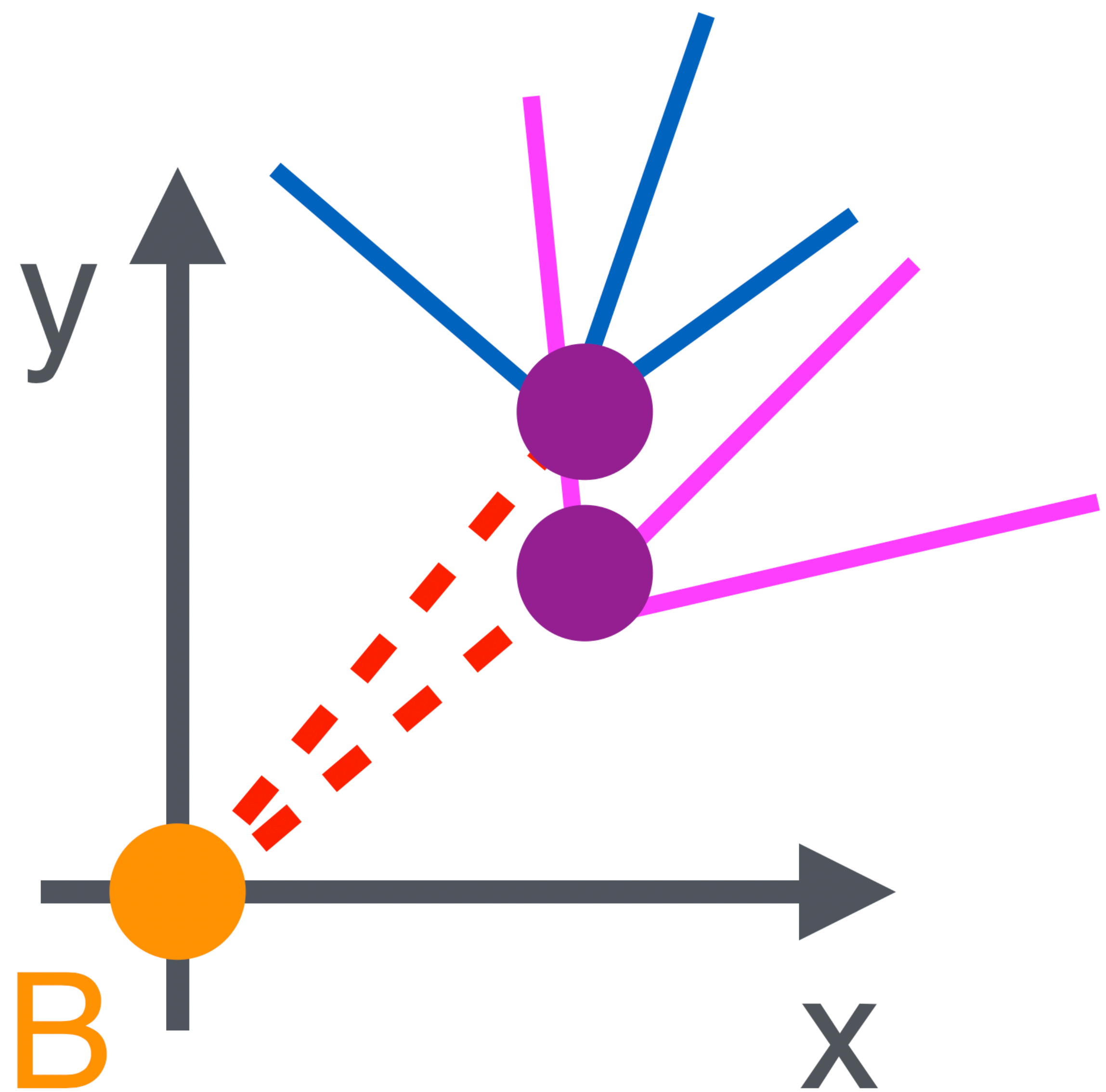

Construct a background d_{VV} template from single-vertex data using:

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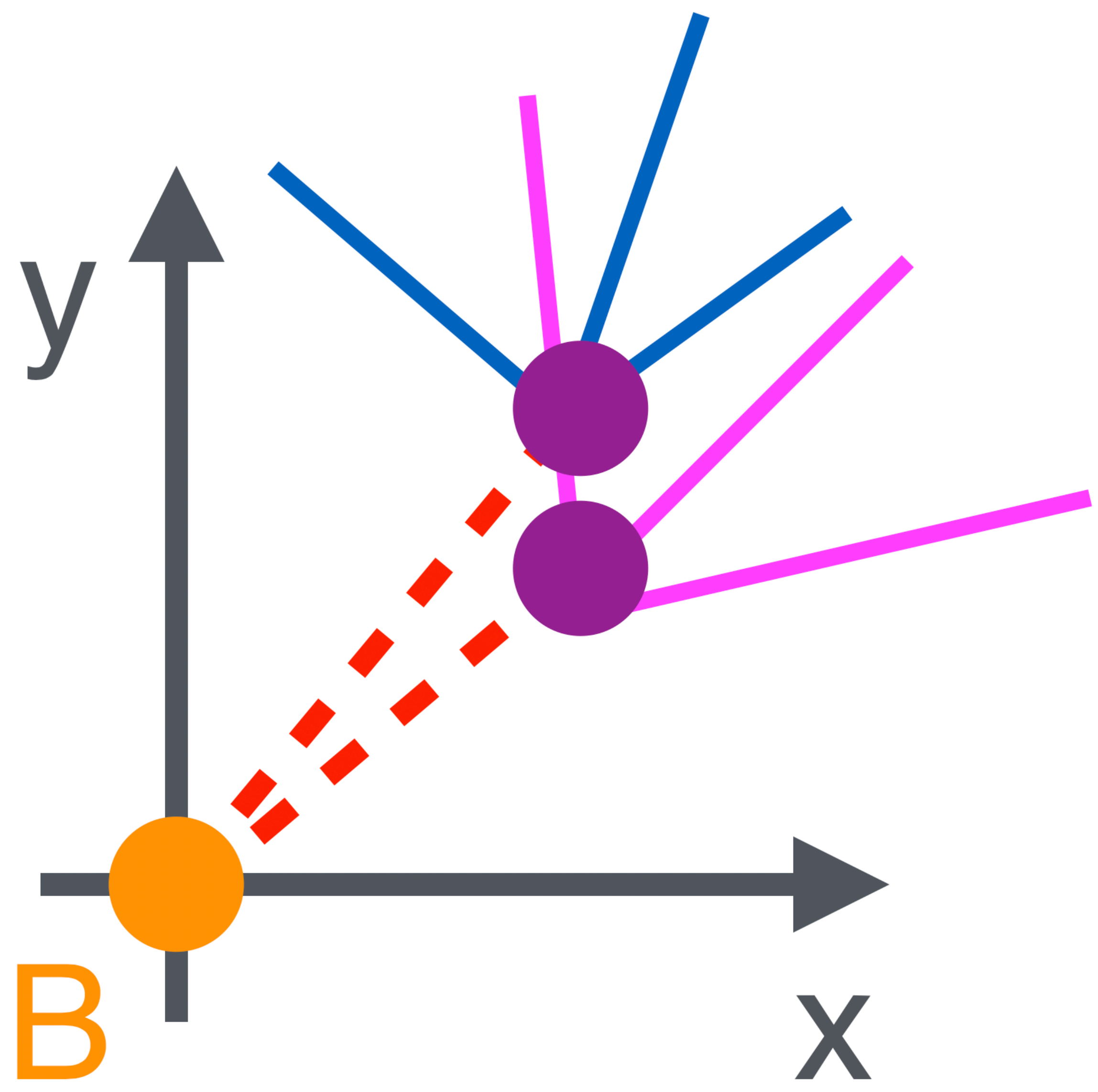

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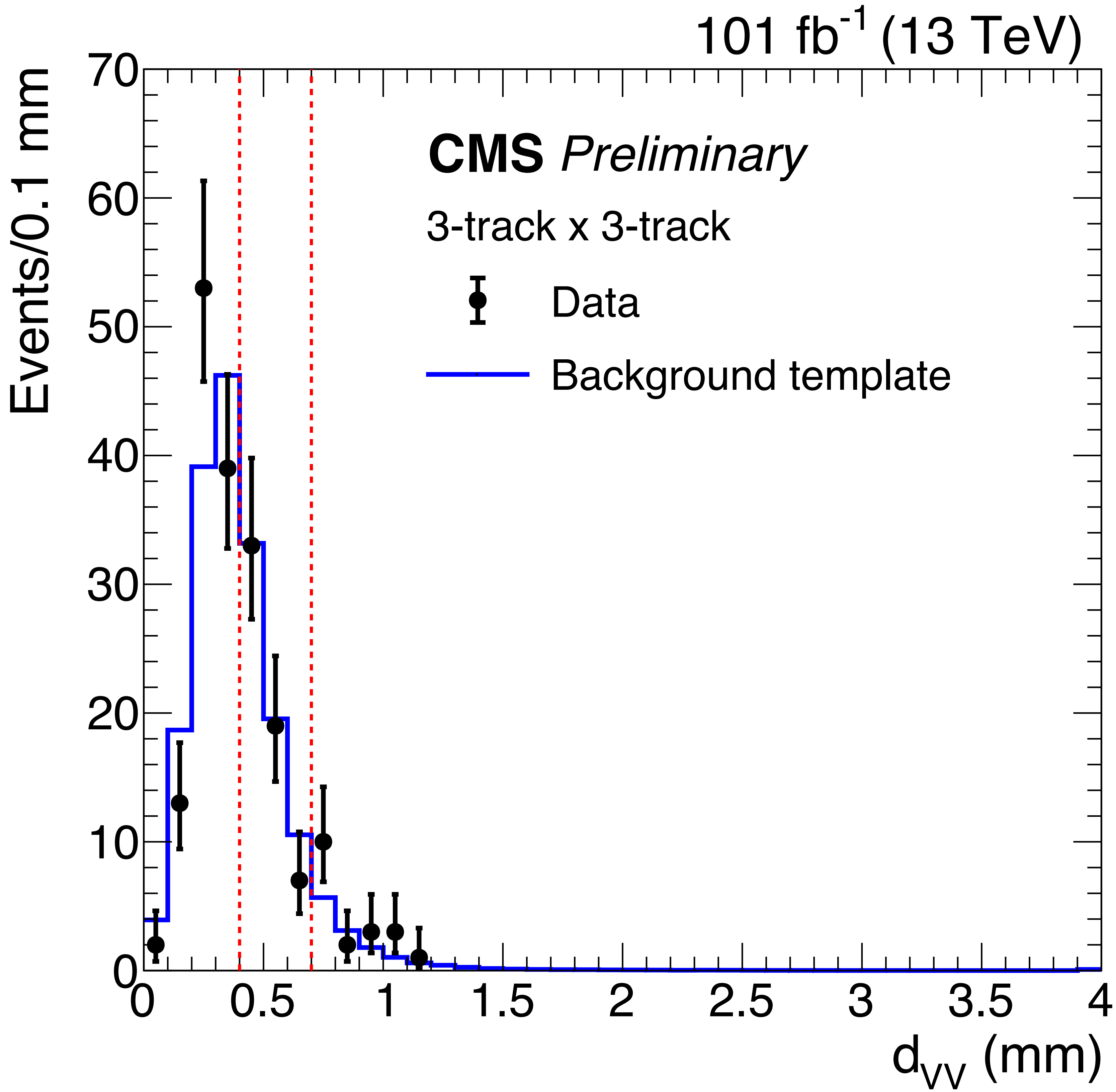
Overall normalization of the d_{VV} shape ≈ N_{presel} * (1-vtx bkg ε)^2, with these corrections accounted for

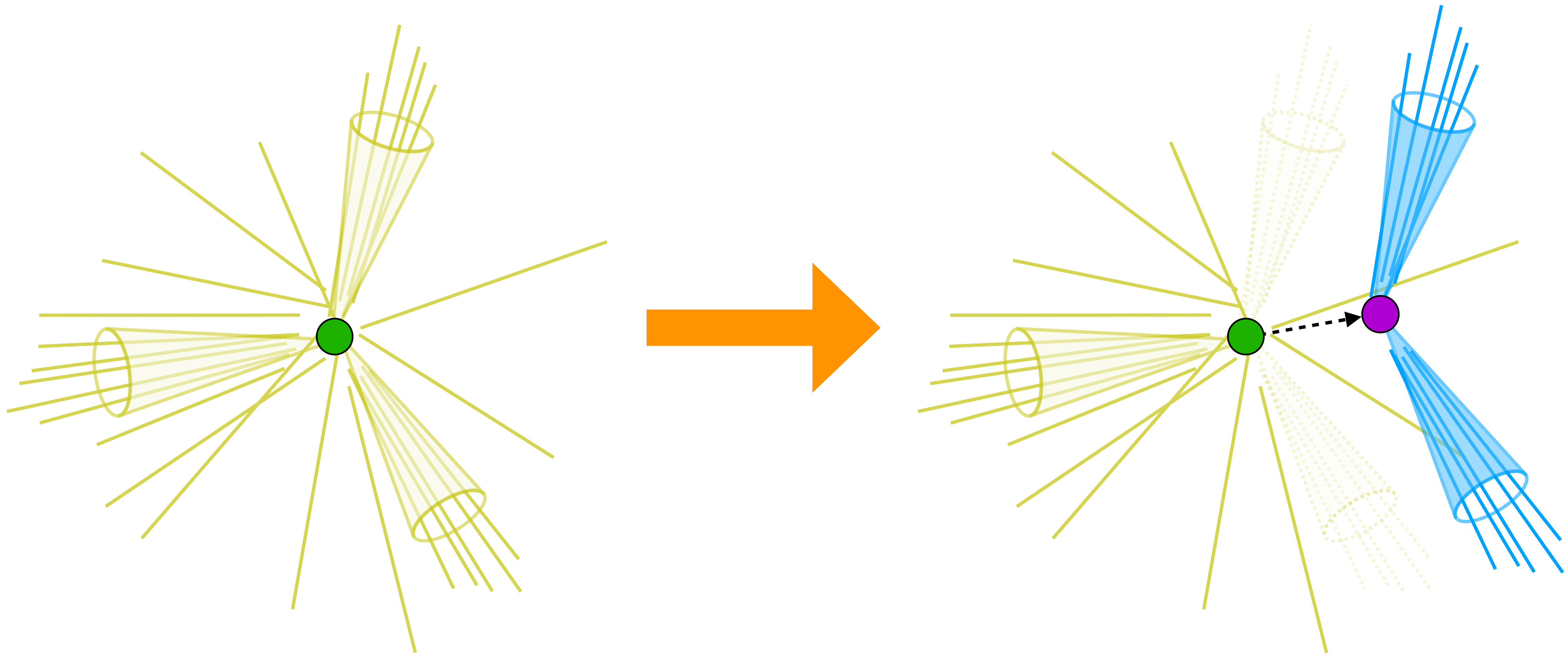
Background Validation



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

(use any differences as syst uncertainty)

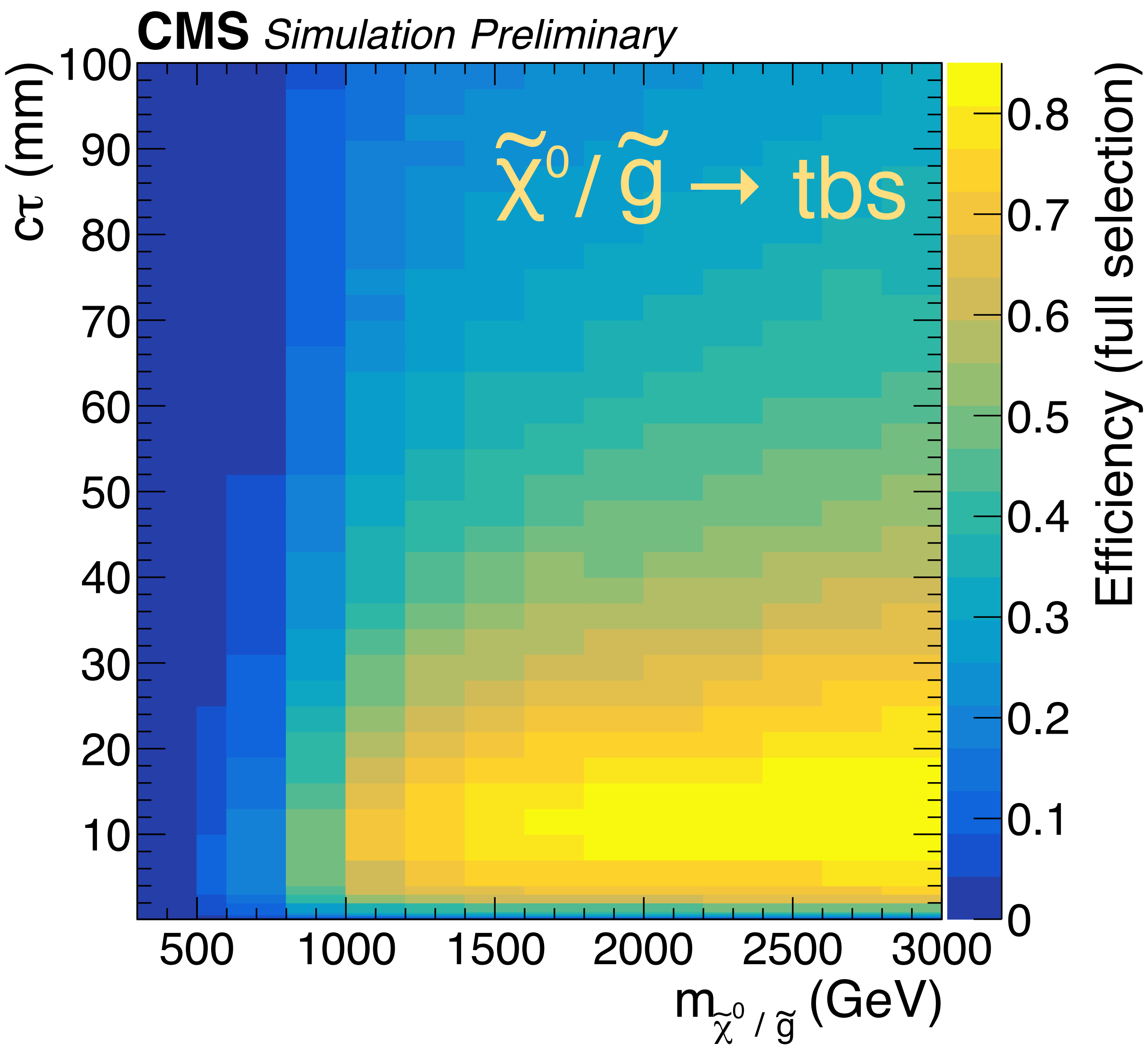
Signal Efficiency and Systematics

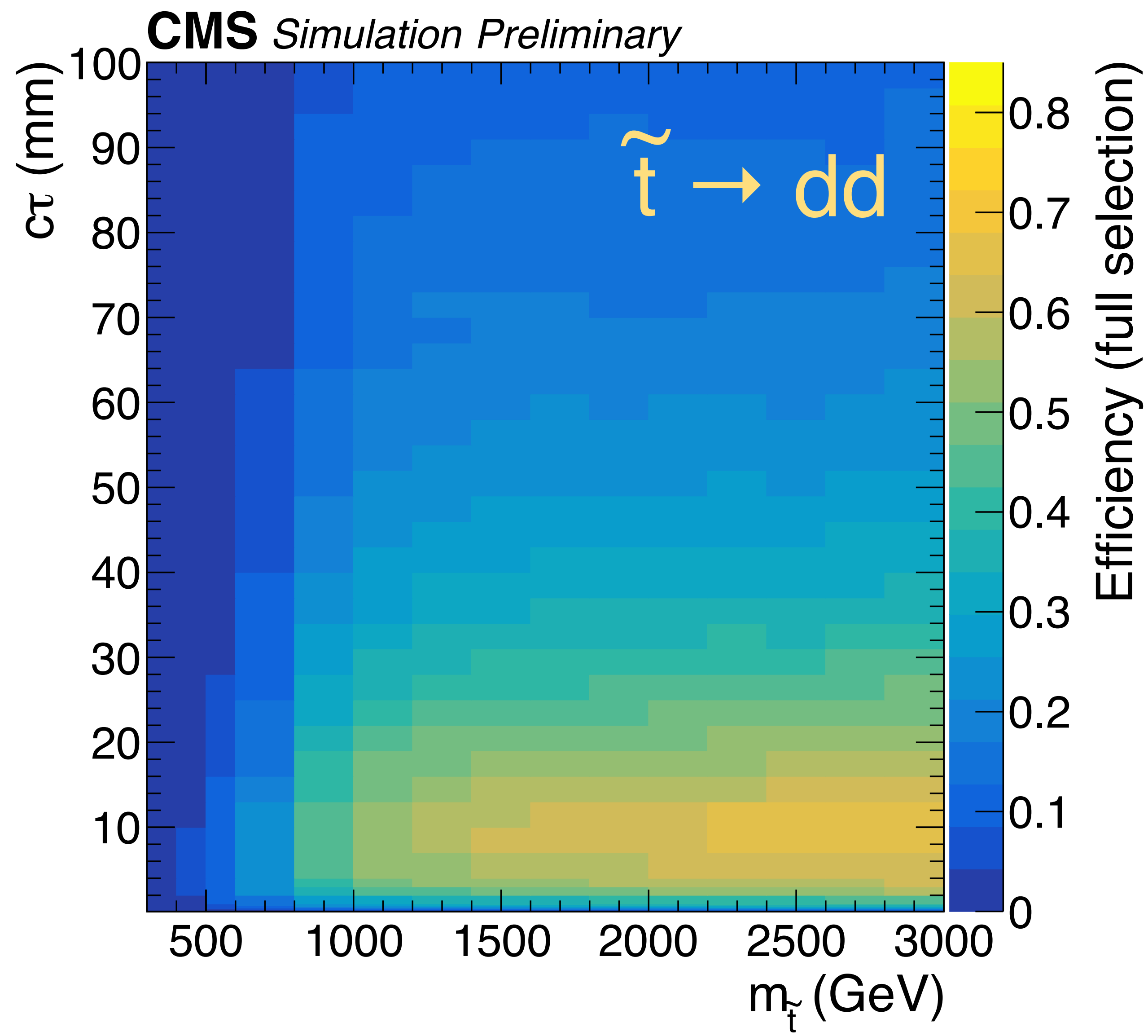


Manually displace tracks from SM jets in data and MC to create artificial displaced vertices.

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

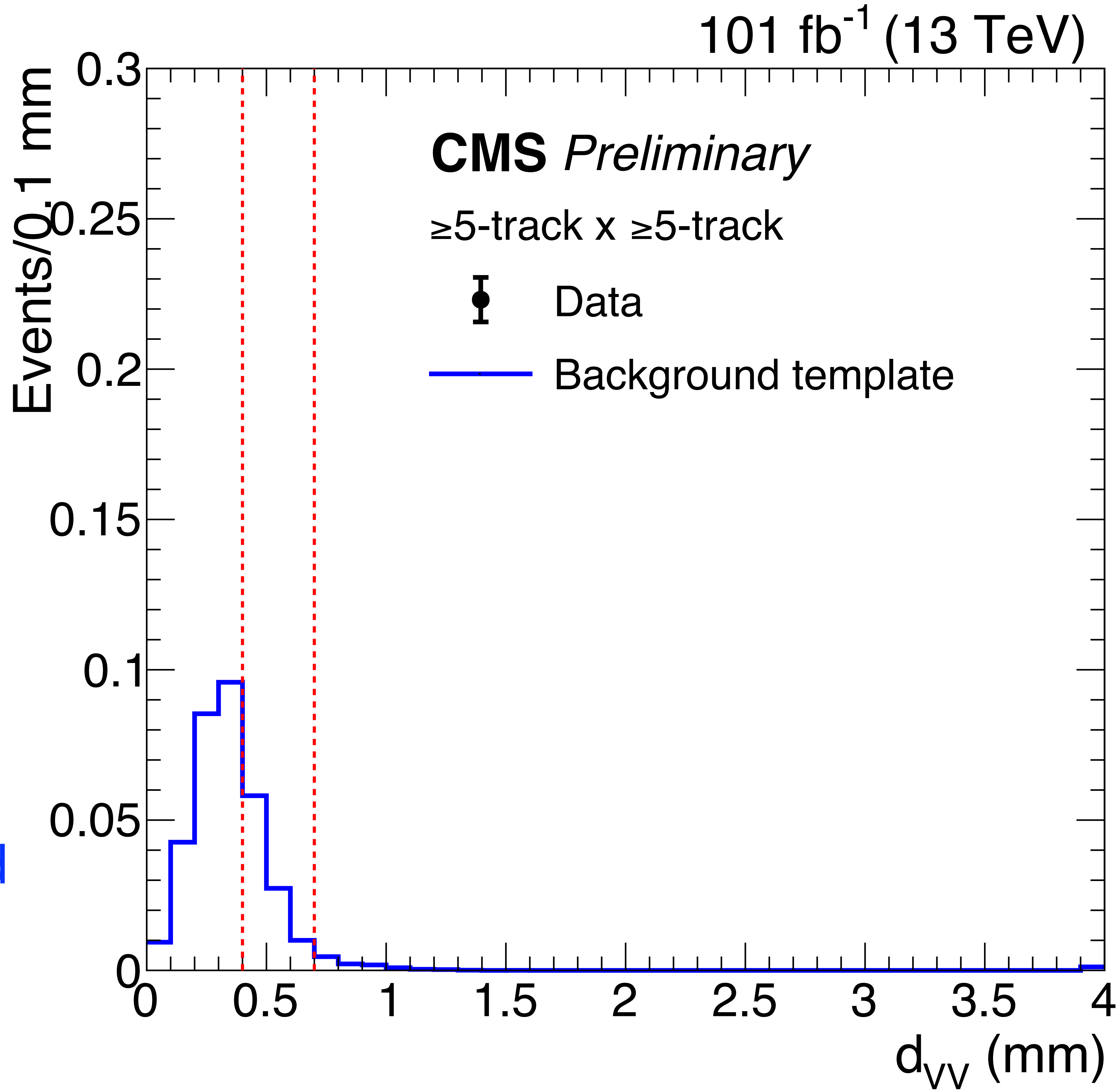
Signal Efficiencies





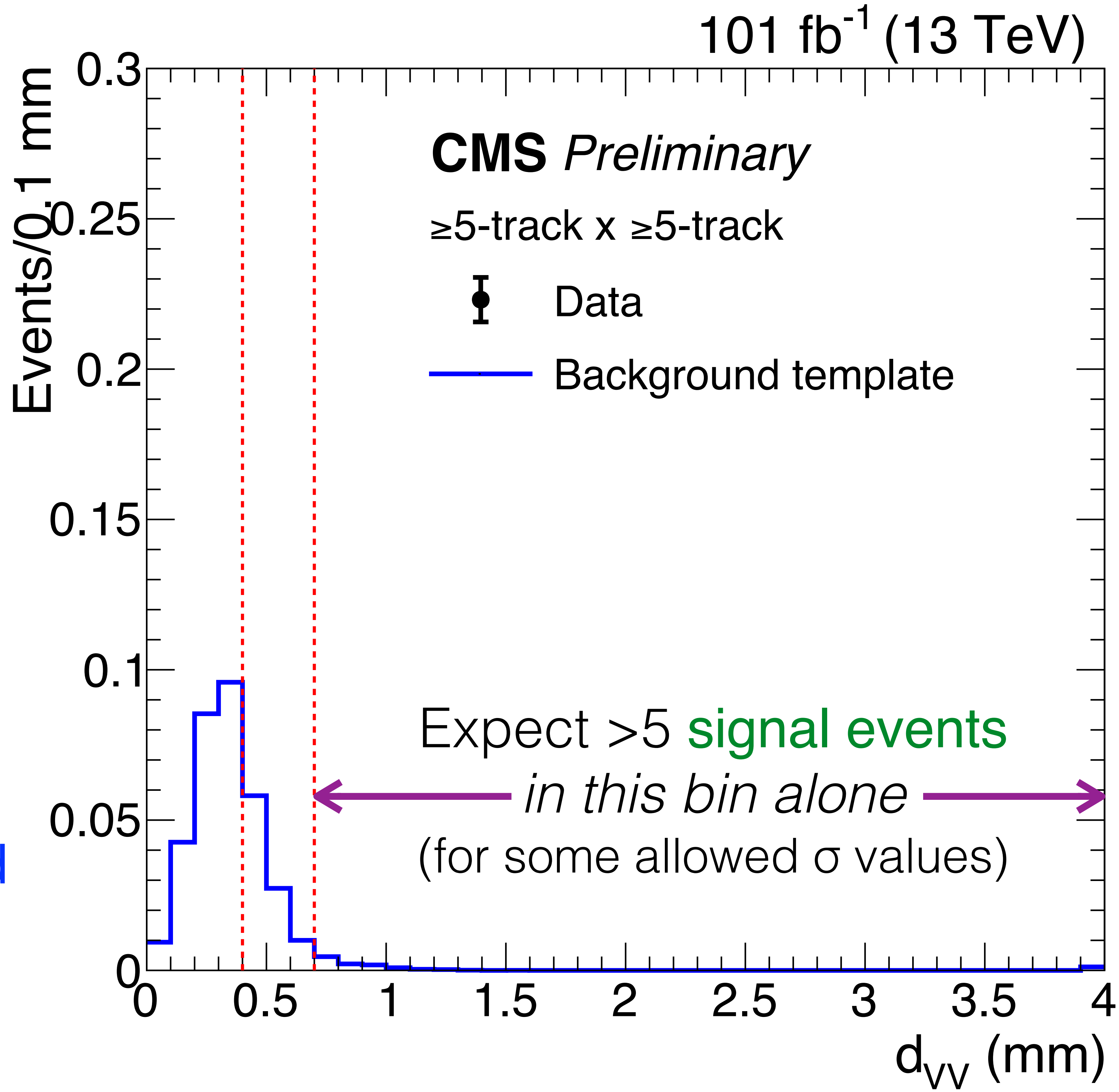
Efficiencies largest at high masses (due to HT requirement) and lifetimes compatible with beampipe constraint (≲ 20 mm).

≥5-track 2-vertex Search Region



Predicted 0.342 total background events

≥5-track 2-vertex Search Region



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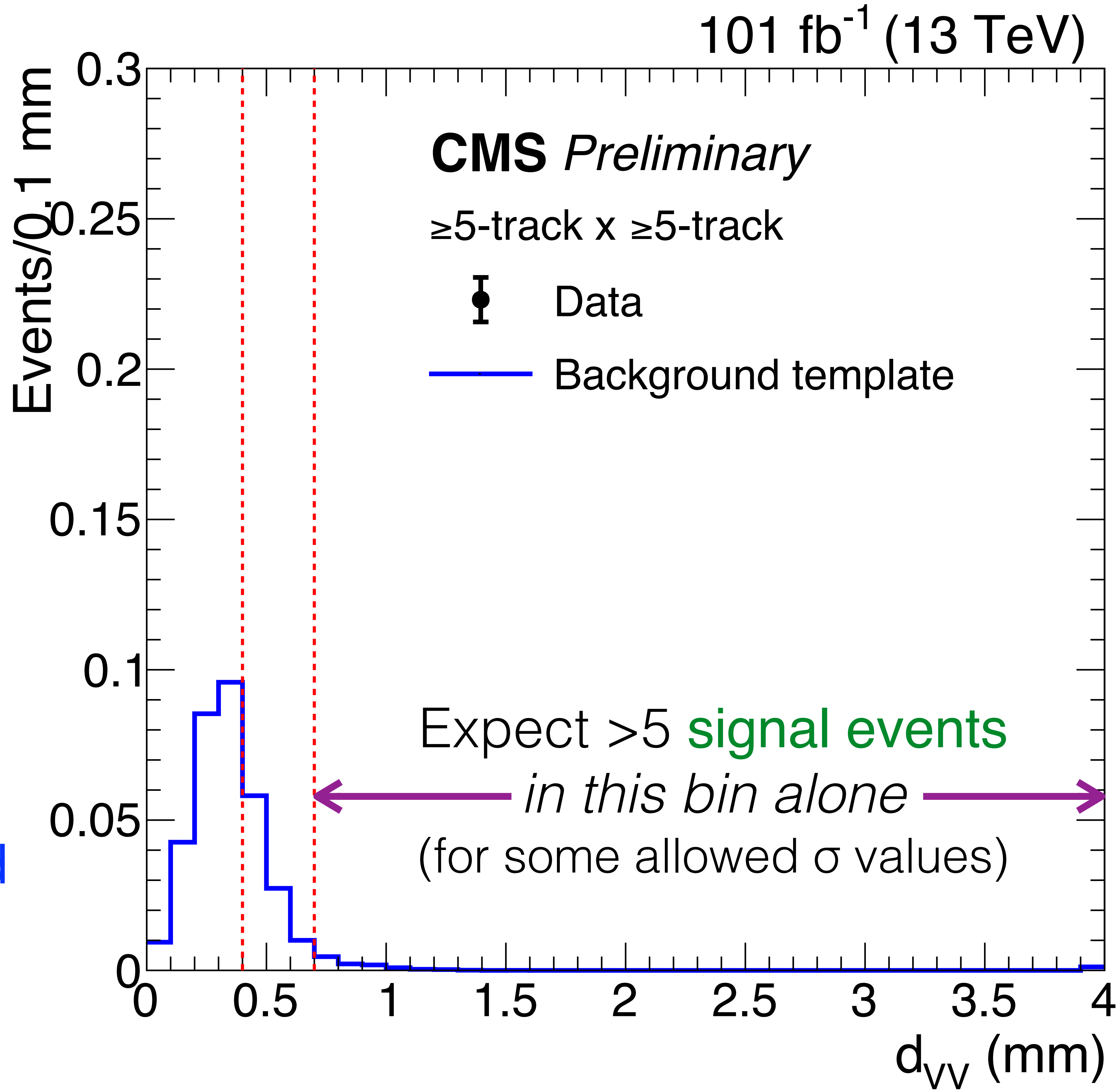
≥5-track 2-vertex Search Region

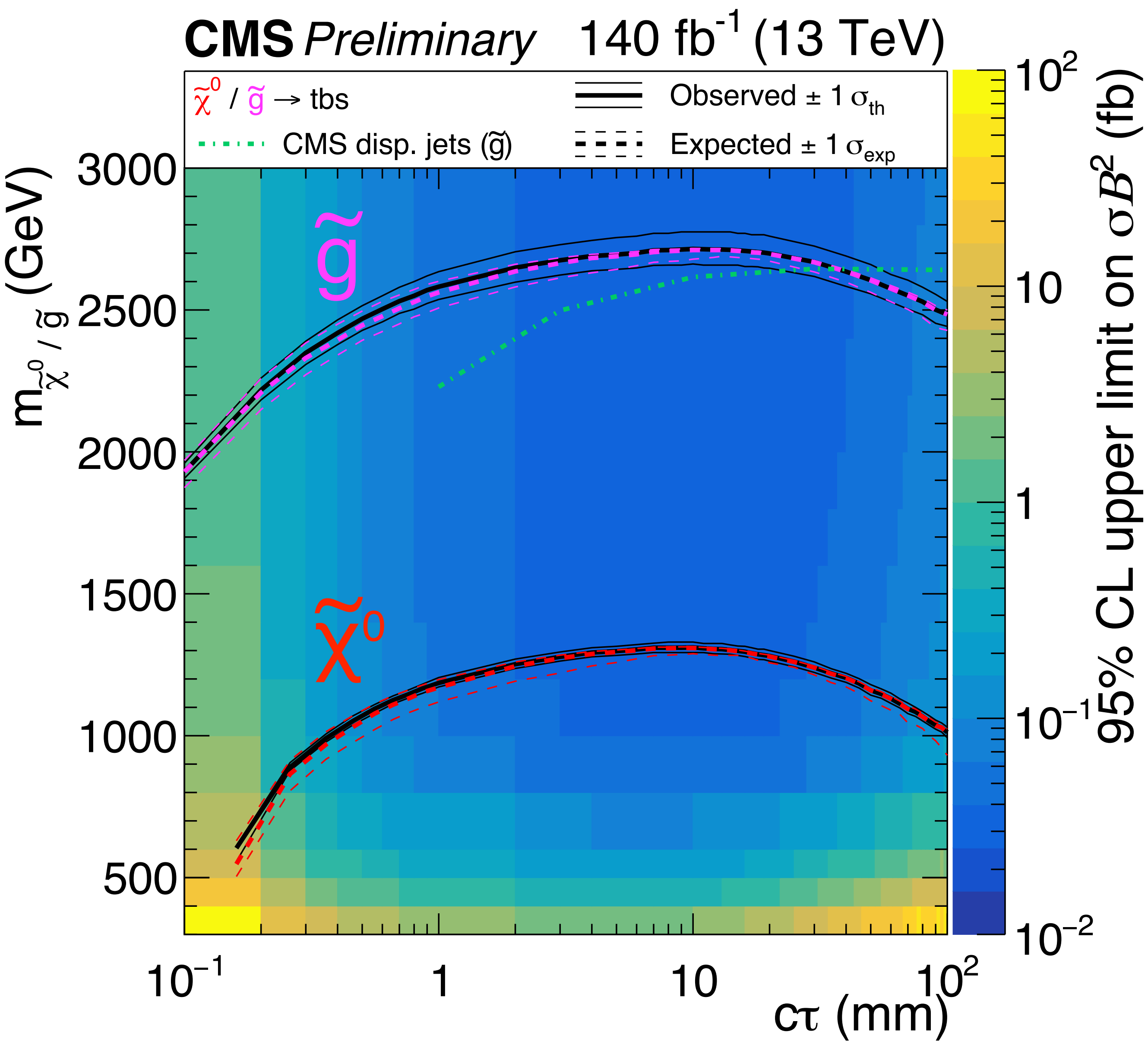


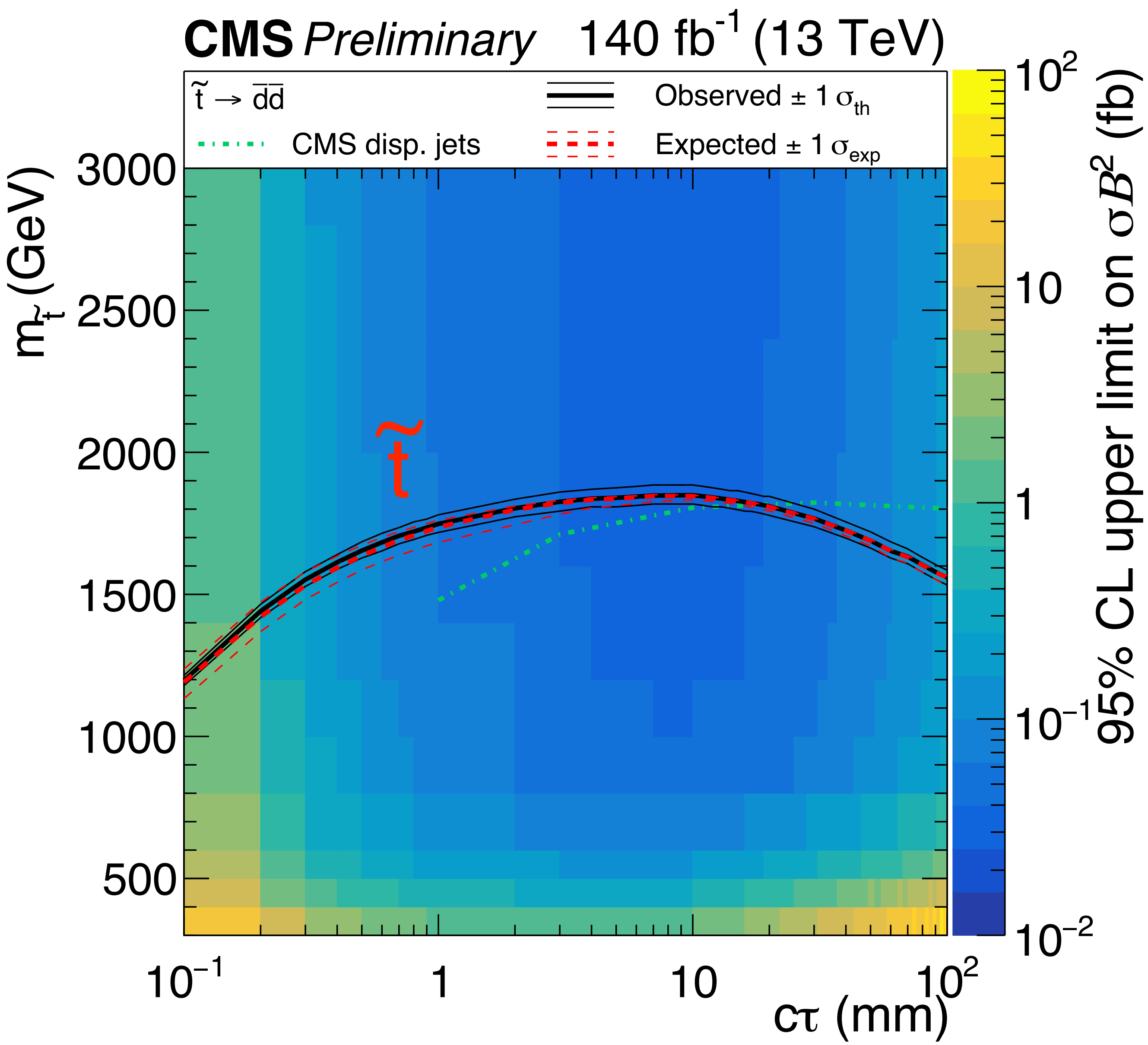
Predicted 0.342 total background events

Expect >5 signal events *in this bin alone* (for some allowed σ values)

And observed zero!

Results

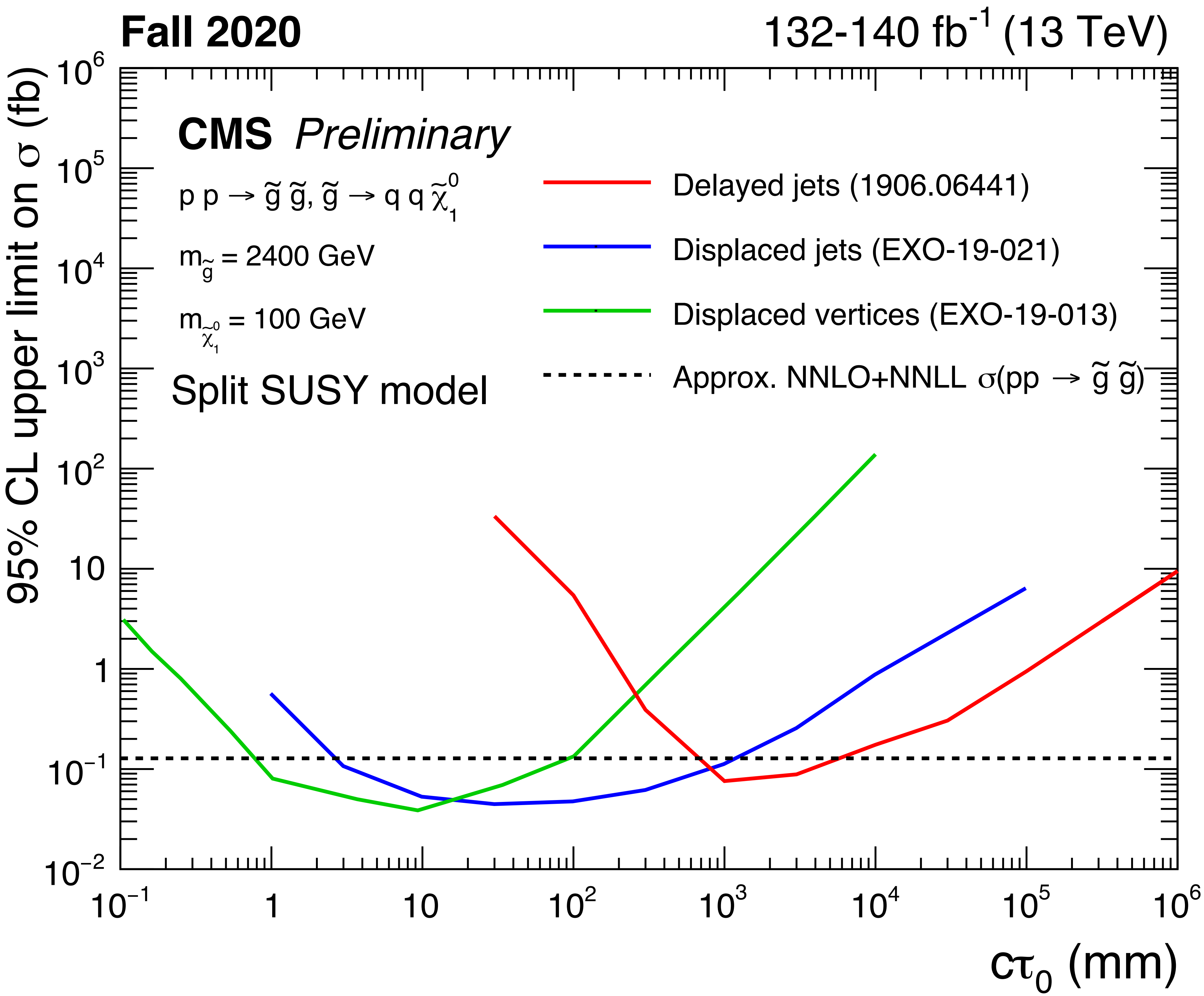




Reinterpretation recipe available in EXO-19-013!

Note: prompt RPV searches (36 fb^{-1}) currently have mass limits up to 1500 GeV for gluinos and 520 GeV for stops

Hadronic LLP Summary



DV search nicely complements other CMS searches at longer lifetimes

[CMS Exotica Summary Plots]

Summary

Displaced vertices provide a nice handle to search for LLPs

- No evidence for new LLPs yet
- CMS search is largely model-independent, and can be reinterpreted for other models
- Working on new ideas to extend the search, even with Run 2 data:
  - better sensitivity at low masses (alternative triggers)
  - new signal models to focus on
  - further understand/eliminate backgrounds, ultimately to relax other aspects of selection and improve signal ε

Summary

Displaced vertices provide a nice handle to search for LLPs

- No evidence for new LLPs yet
- CMS searc … an be reinterprete…
- Working or … with Run 2 data…
  - better sensitivity at low masses (alternative triggers)
  - new signal models to focus on
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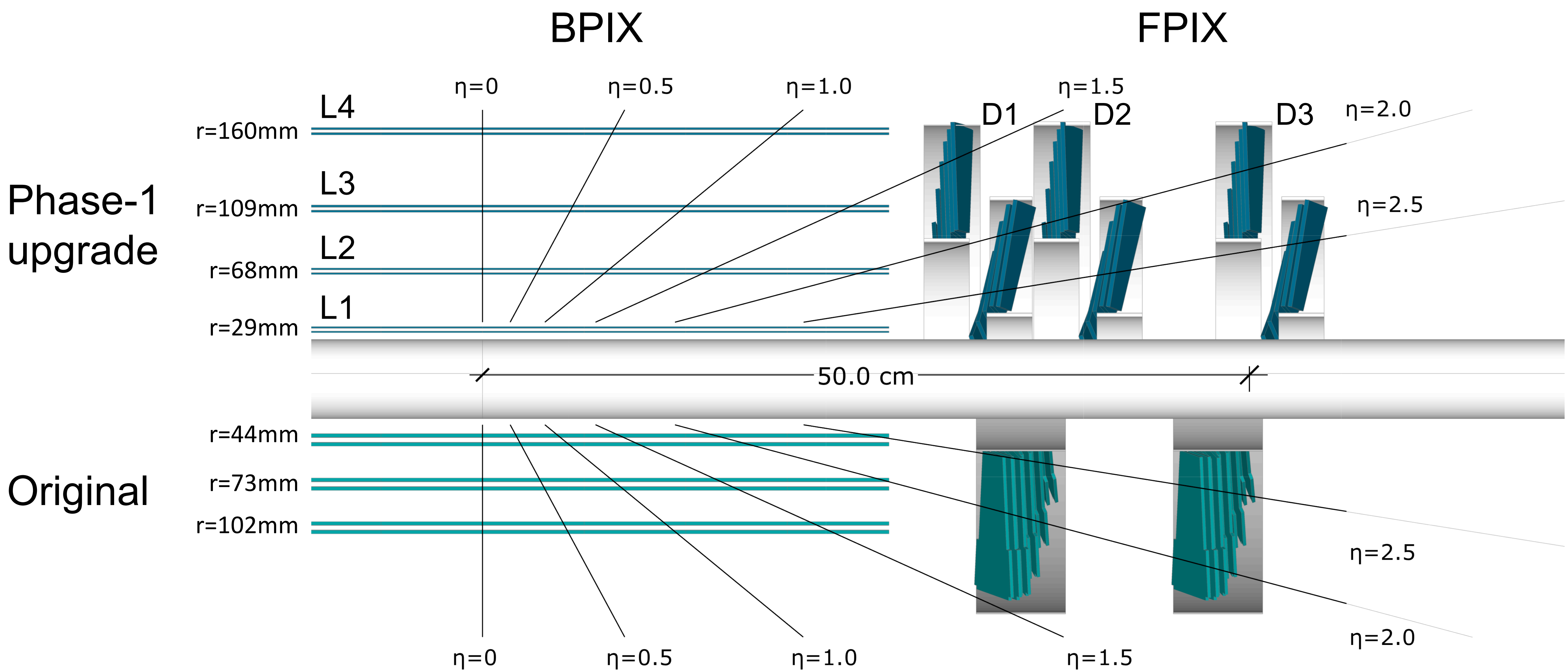
Thanks!

Backup

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

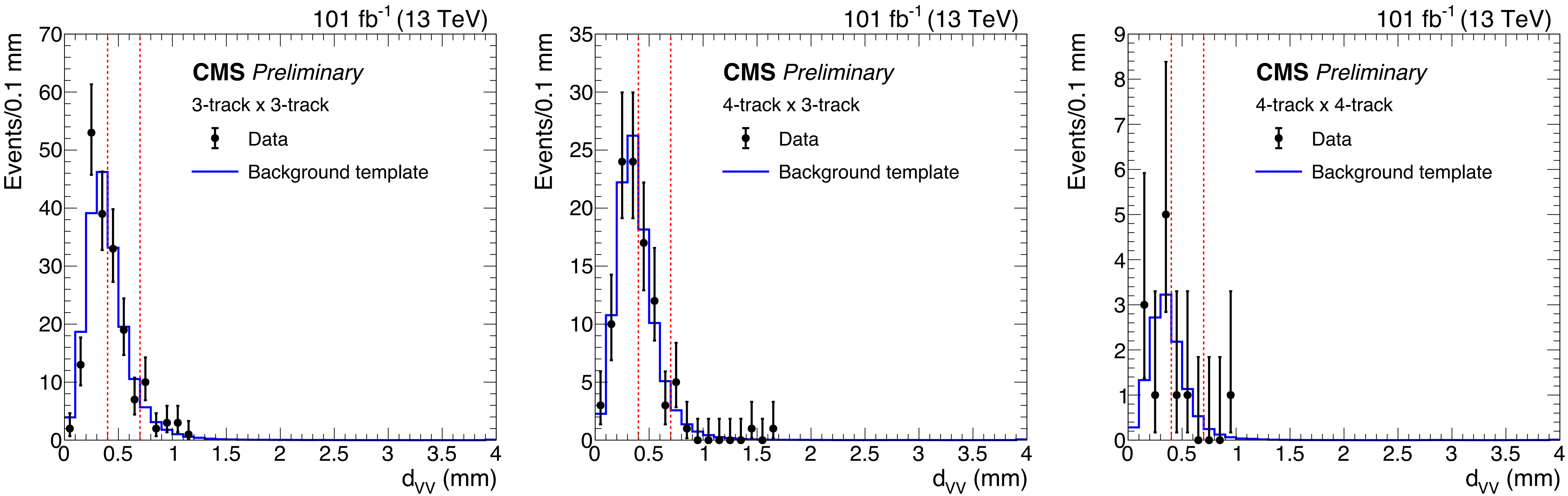
Observed and predicted in search region bins:

		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, $\sigma = 0.3$ fb

Note: Overall normalization of the background template:
$N_{pred} \approx (\text{bkg vertex } \varepsilon)^2$ 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)

Systematics

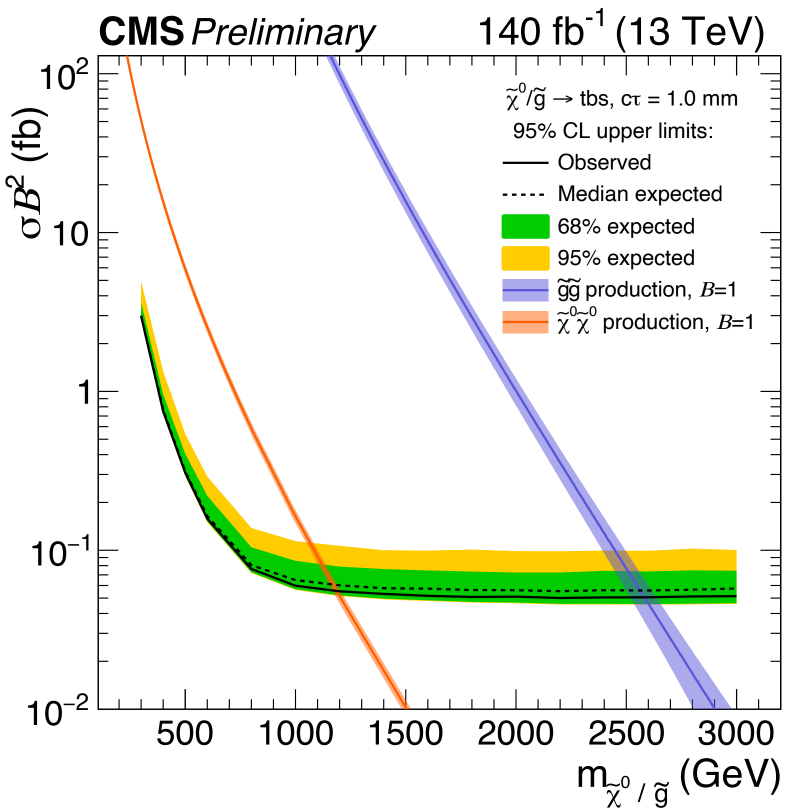
DV signal systs

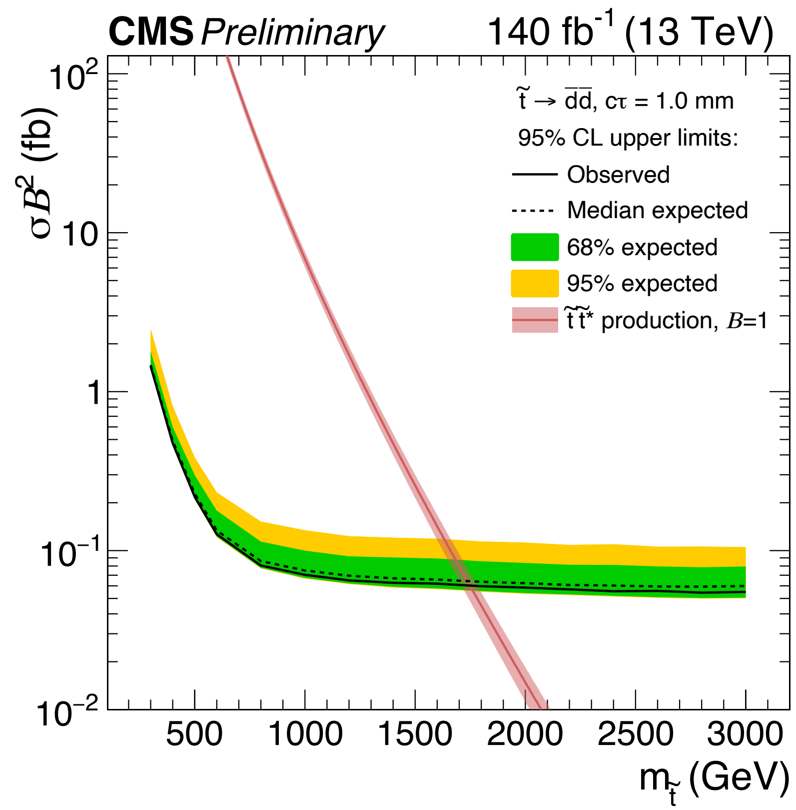
Systematic effect	Dijet uncertainty (%)	Multijet uncertainty (%)
Vertex reconstruction	11–41	1–36
PDF uncertainty	1–8	1–8
Integrated luminosity	2–3	2–3
Jet energy scale	5	5
Jet energy resolution	2	2
Pileup	2	2
Trigger efficiency	1	1
Changes in run conditions	1	1
Overall	13-42	7-36

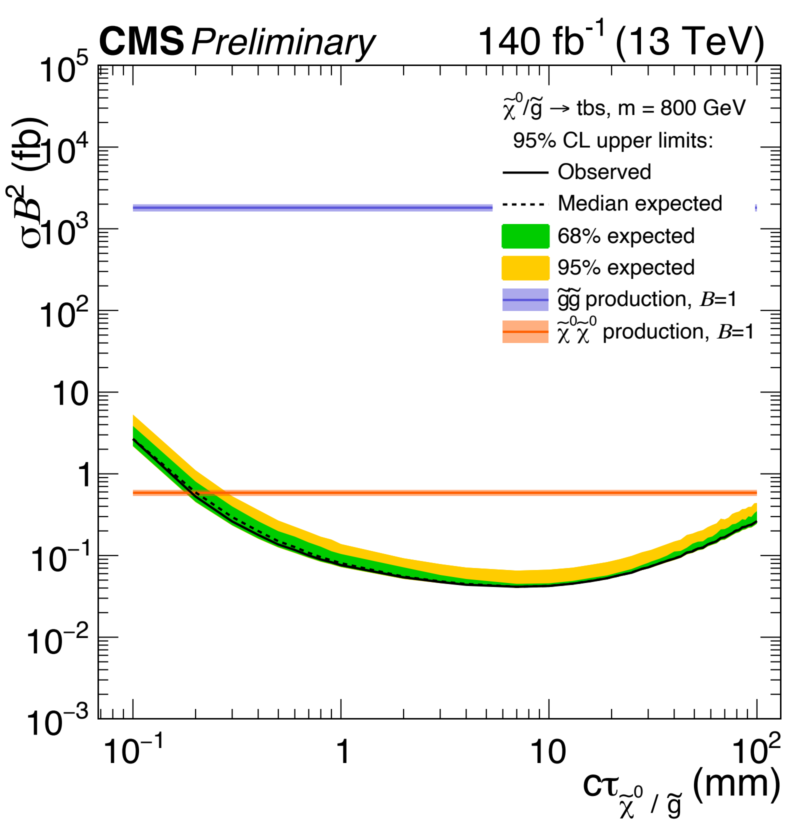
DV background systs

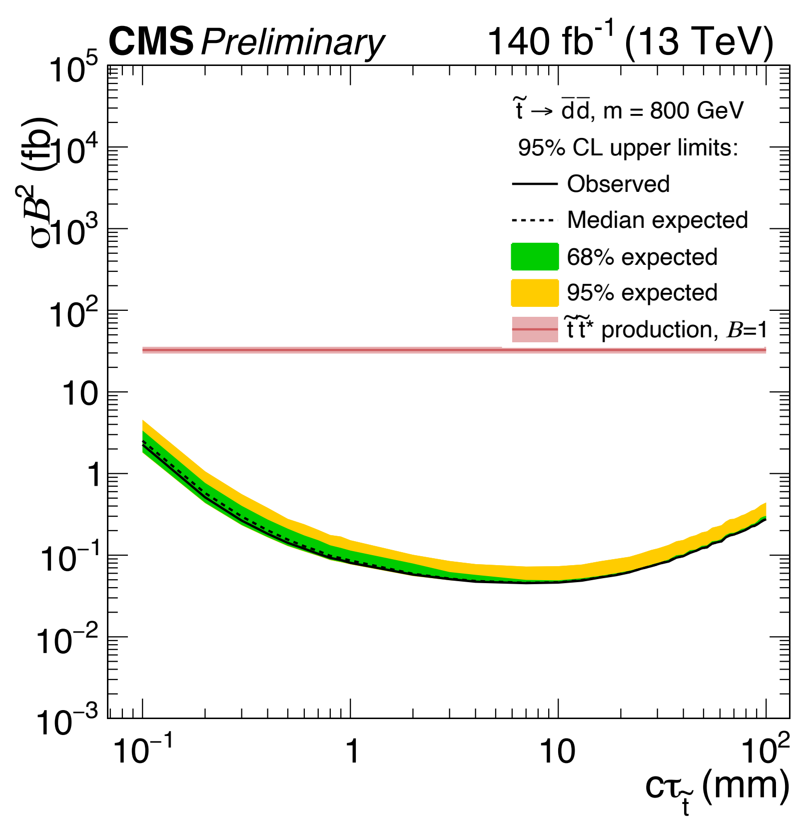
	Shift ± Statistical Uncertainty (%)		
Systematic effect	0–0.4 mm	0.4–0.7 mm	0.7–40 mm
Closure in 3-track control sample	1 ± 10	7 ± 12	38 ± 32
$\geq$5-track template normalization factor	23 ± 7	23 ± 7	23 ± 7
Difference from 3-track vertices to $\geq$5-track vertices:			
Modeling of vertex pair survival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

1D Limits









For a gluino with m = 800 GeV and cτ = 1 mm, we excluded:

σ = 0.3 fb
(2015+2016 only)

vs.

σ = 0.08 fb
(full Run 2)