Searches for long-lived particles in CMS

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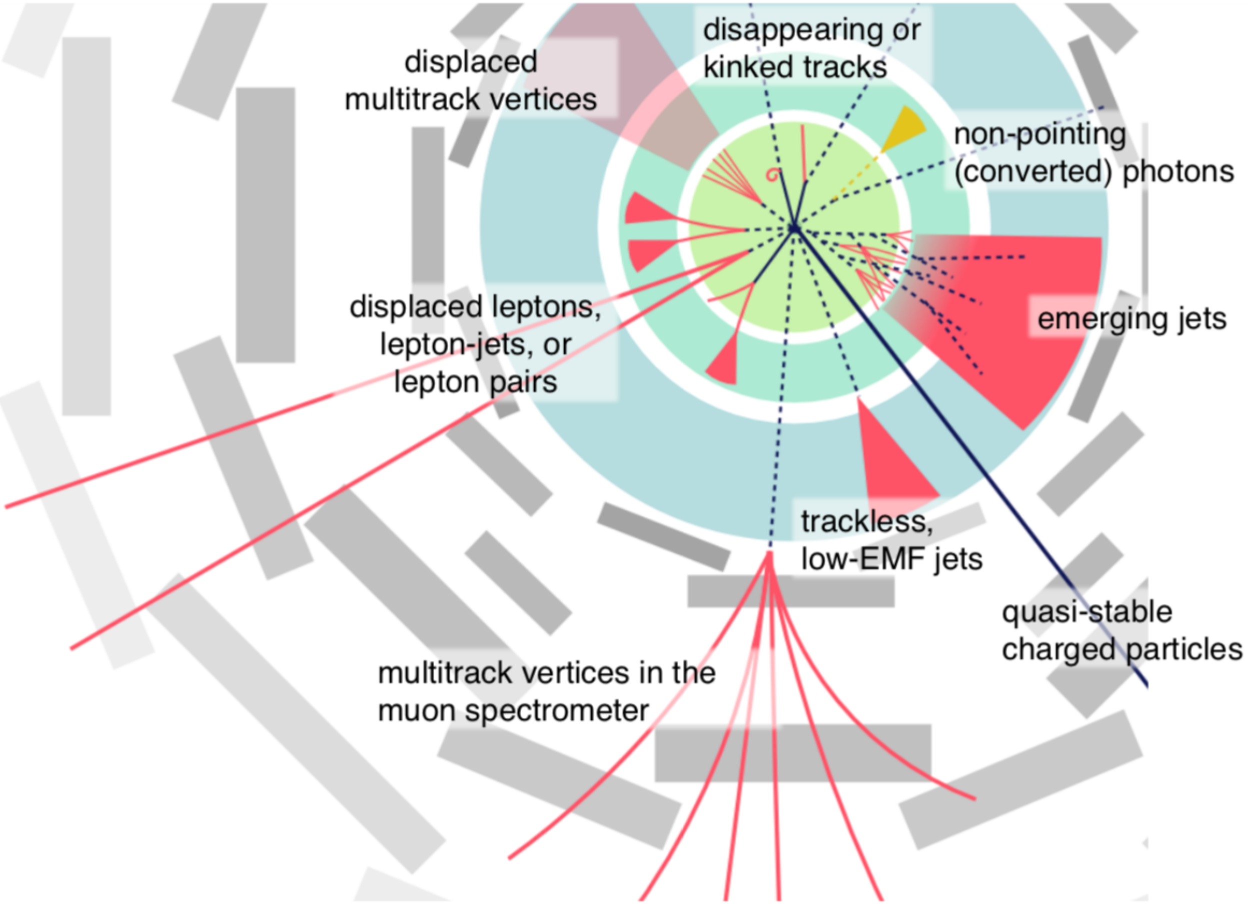
On behalf of the CMS Collaboration

May 28, 2020

Long-lived particle searches

- Long-lived particles (LLPs) appear in many well-motivated BSM models
  - Approximate symmetries, small mass splittings, small couplings
- Unique, challenging signatures
  - Not the way the CMS detector was designed to be used
  - Often require non-standard reconstruction techniques
  - Dominated by novel backgrounds such as nuclear interactions, tracking errors



Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider, arXiv:1903.04497

CMS LLP program

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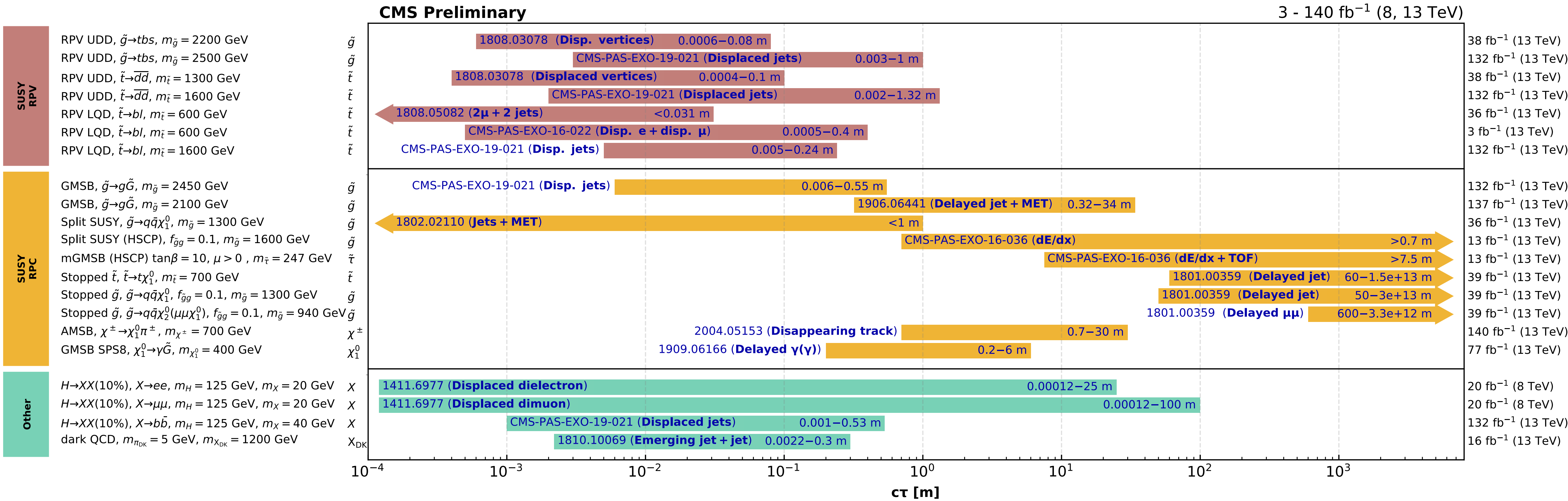
- CMS is pursuing a broad program of long-lived particle searches

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.

LHCP 2020

Full list, CMS Exotica results

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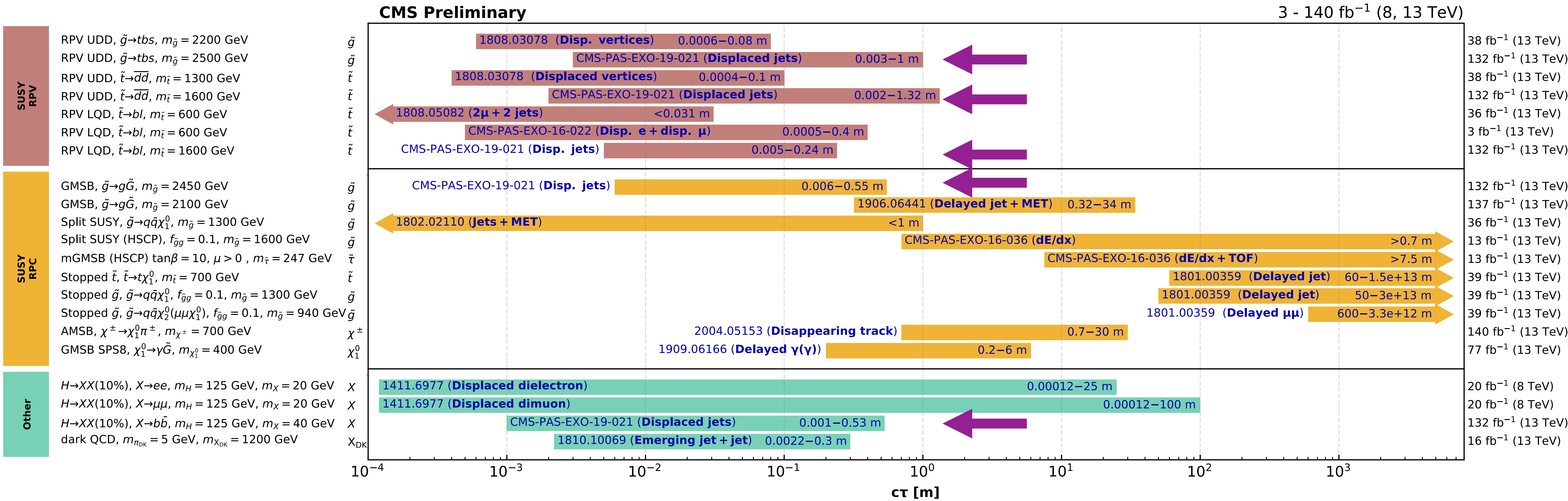
- Recent results: search for displaced jets

Overview of CMS long-lived particle searches



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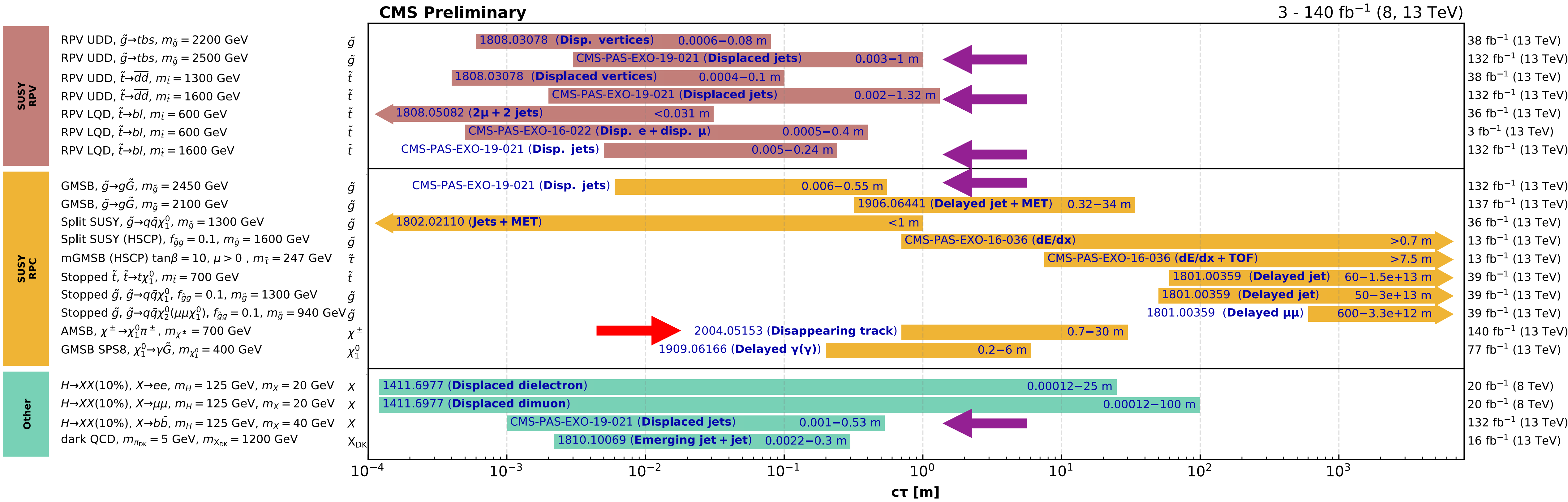

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Full list, CMS Exotica results

Displaced jets

CMS-PAS-EXO-19-021
http://cds.cern.ch/record/2717071

Search for displaced jets in CMS

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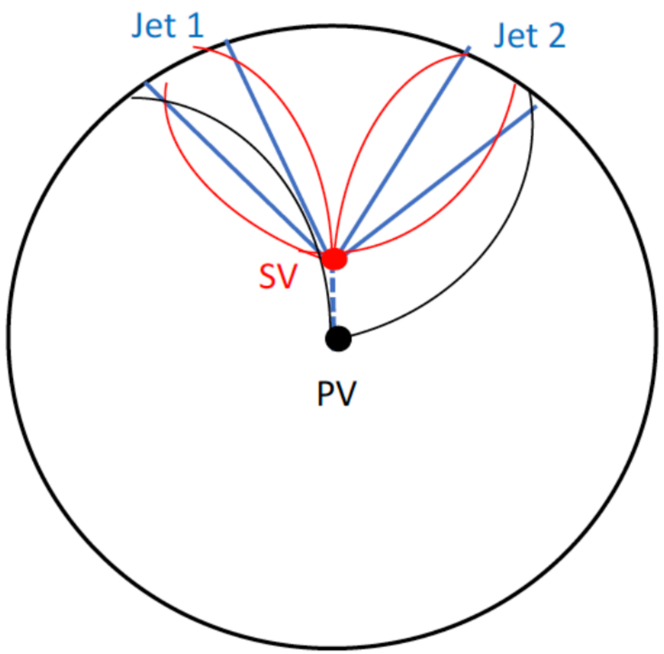
- Model-independent search for long-lived particles decaying into jets
- Look for a pair of displaced jets (dijet) and at least one secondary vertex (SV)
- Use 95 fb^{-1} collected in 2017/2018
  - Combine with 2016 datasets to set results using 132 fb^{-1}
- **Dedicated** displaced-jet triggers
  - Trigger on total energy in calorimeters (H_T) and jets passing cuts on number of prompt/displaced tracks
  - Allows **low-mass models** to be probed (eg $H \rightarrow SS$ decays in ggH production)



Signals models

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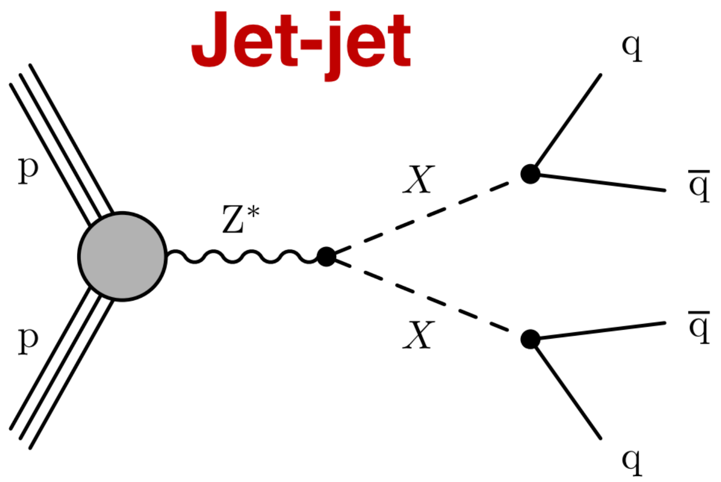
- **Simplified jet-jet model**: used as a benchmark
  - pp → XX, X → jj



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- **Simplified jet-jet model**: used as a benchmark
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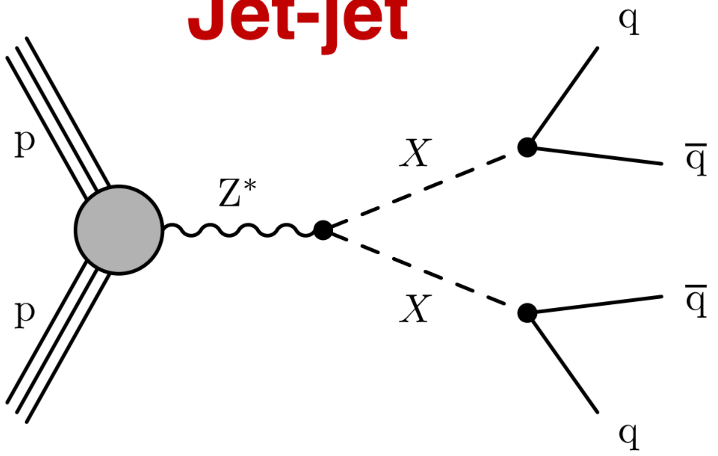
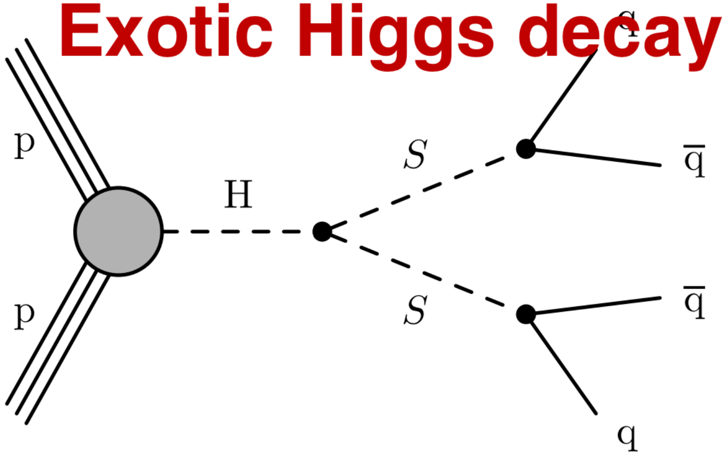
- **Exotic SM Higgs decay**: occurs in BSM scenarios such as Hidden Valley models
  - pp $\rightarrow$ H $\rightarrow$ SS, S $\rightarrow$ jj

Jet-jet



Exotic Higgs decay



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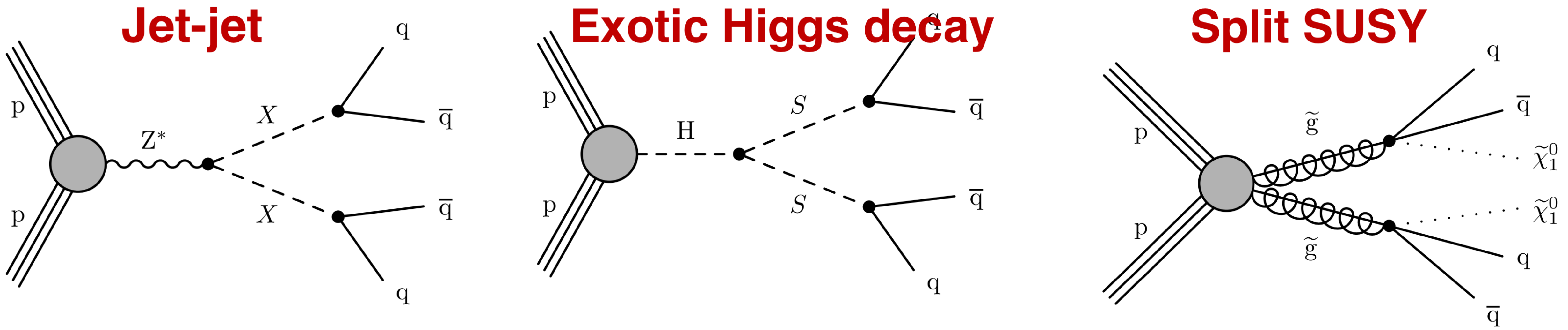
- **Split SUSY**: gluino decays suppressed by heavy squark
  - pp -> $\tilde{g}\tilde{g}$, $\tilde{g}$-> jj $\tilde{\chi}^0$



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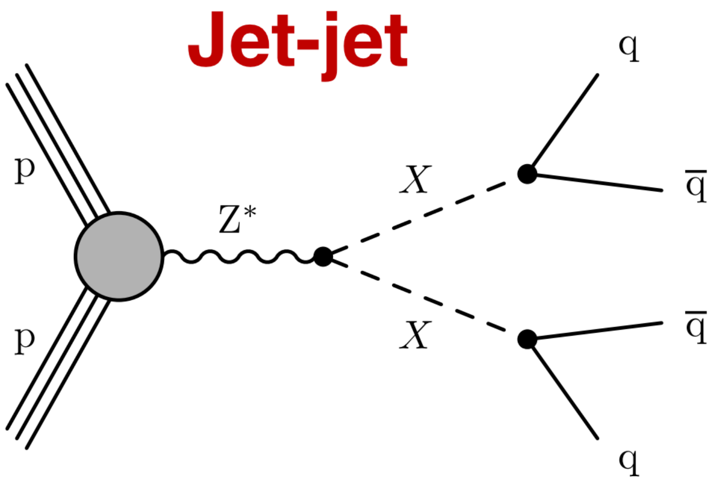
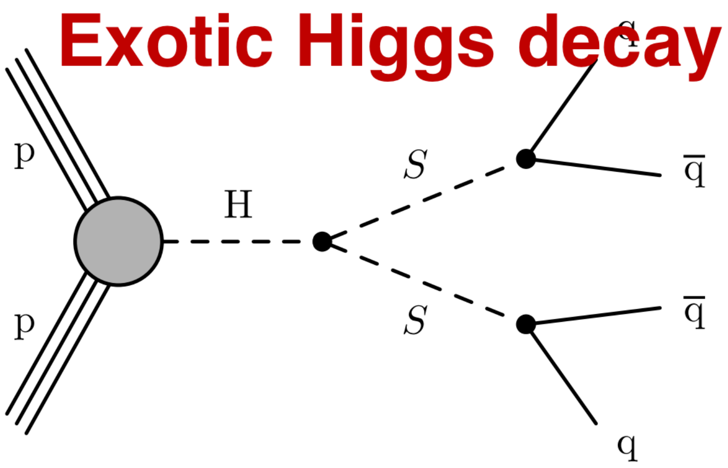
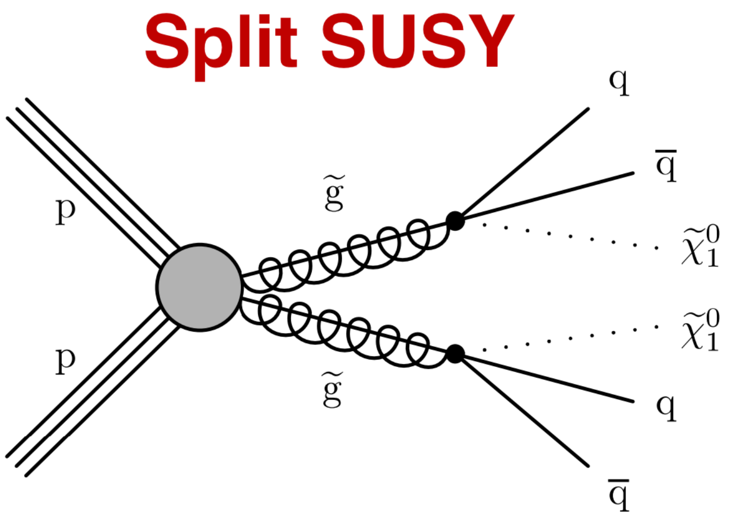
  - pp -> $\tilde{g}\tilde{g}$, $\tilde{g}$-> jj $\tilde{\chi}^0$
- Other models include GMSB SUSY, RPV SUSY models







Dijet and SV reconstruction

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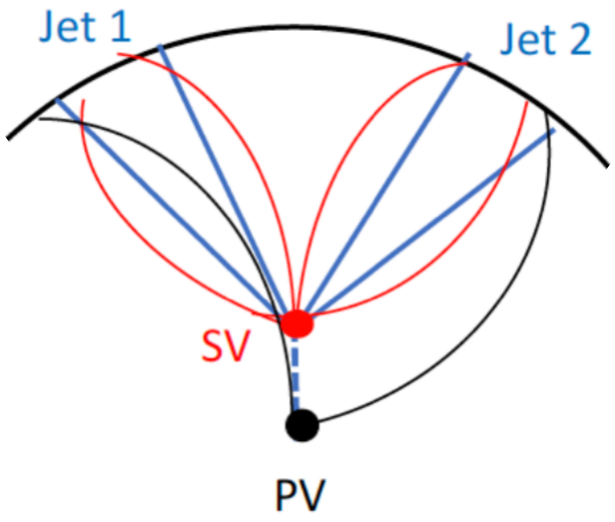
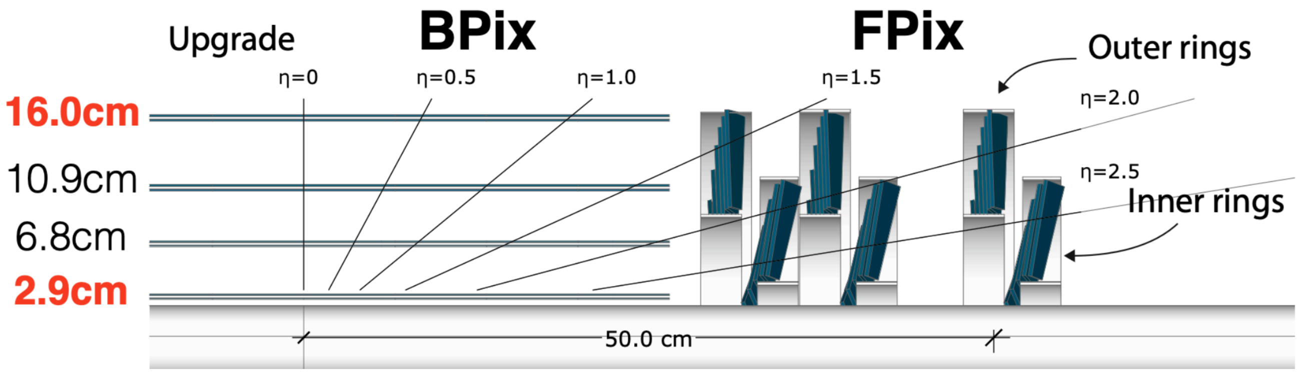
1. Construct dijet candidates
2. Match **tracks** to jets using ΔR
3. Construct secondary vertex
   - Inputs: displaced tracks ($IP_{2D} > 0.5$ mm) associated with dijet
   - Require vertex inv. mass > 4 GeV, $p_T > 8$ GeV
   - Additional cuts on χ^2, fraction of track energy from SV, compatibility with primary vertices, and second-highest IP_{2D}

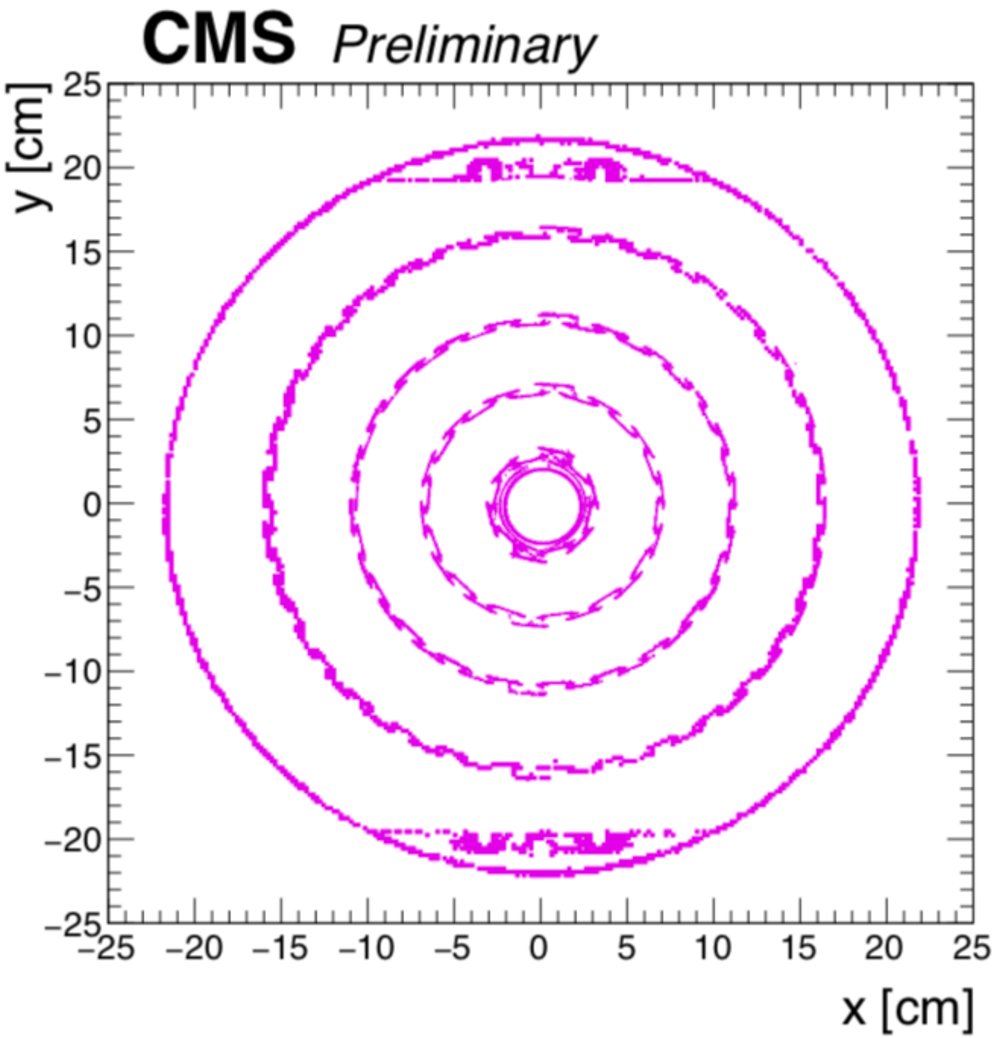


Require significant jet energy (> 500 GeV) for triggering

Nuclear interaction veto

- Nuclear interactions (NI) in material can produce displaced jet signature
- Map tracker material in transverse plane using data control region
- Vertex candidates that overlap with the NI map are vetoed

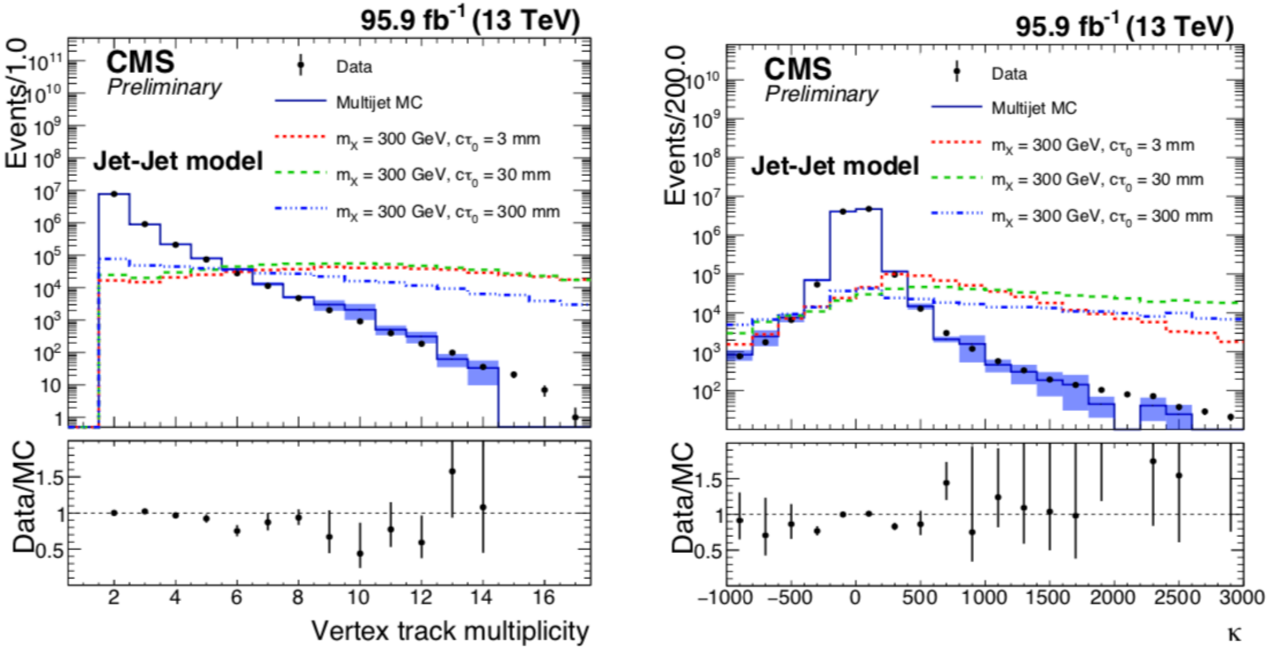




Gradient BDT

Fermilab

- After NI veto, primary background comes from QCD events
- Train using control region in data for background, jet-jet model for signal
- Input variables:
  - Vertex track multiplicity
  - Vertex L_{xy} significance
  - Cluster RMS (measure of consistency of vertex and tracks with dijet hypothesis)
  - Sum of signed IP_{2D}/σ_{IP} (κ)



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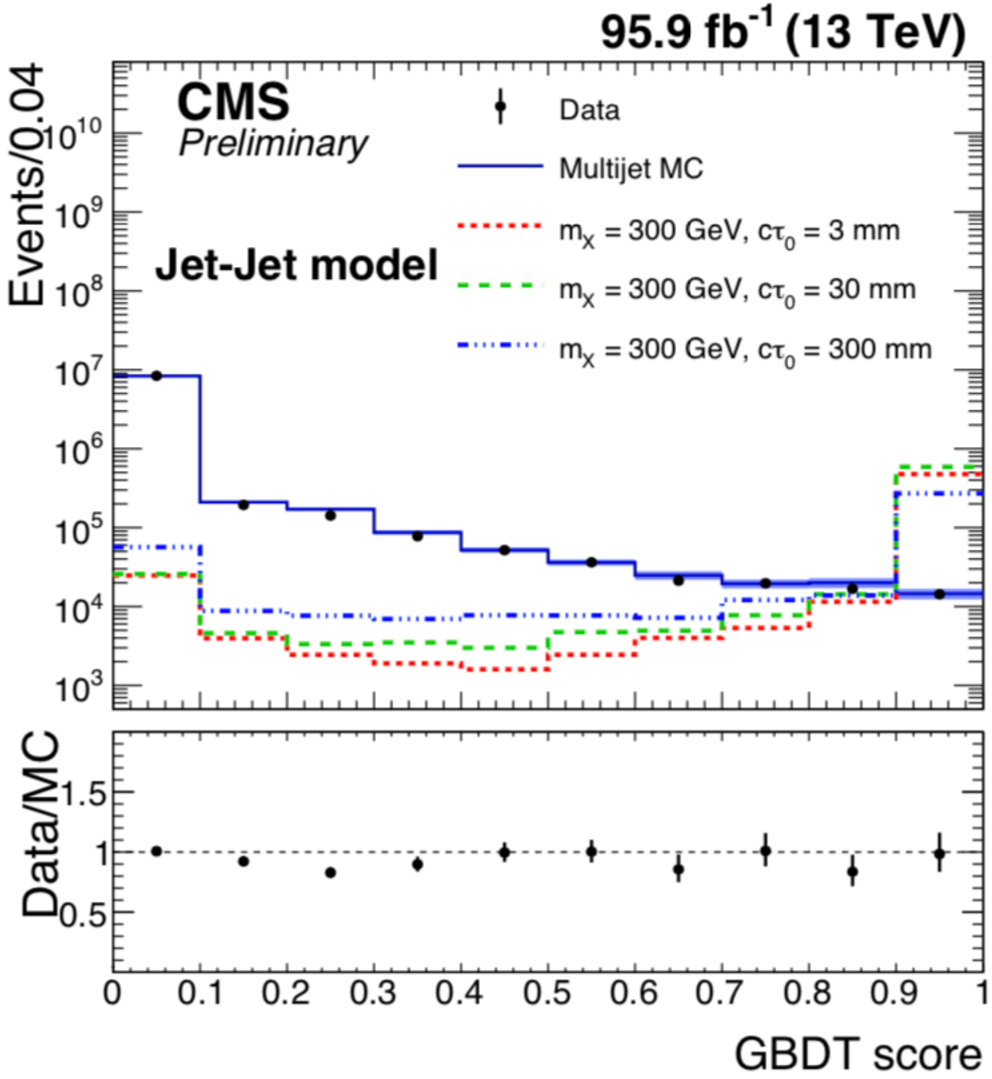
- Signal region: GBDT score > 0.988



Background prediction

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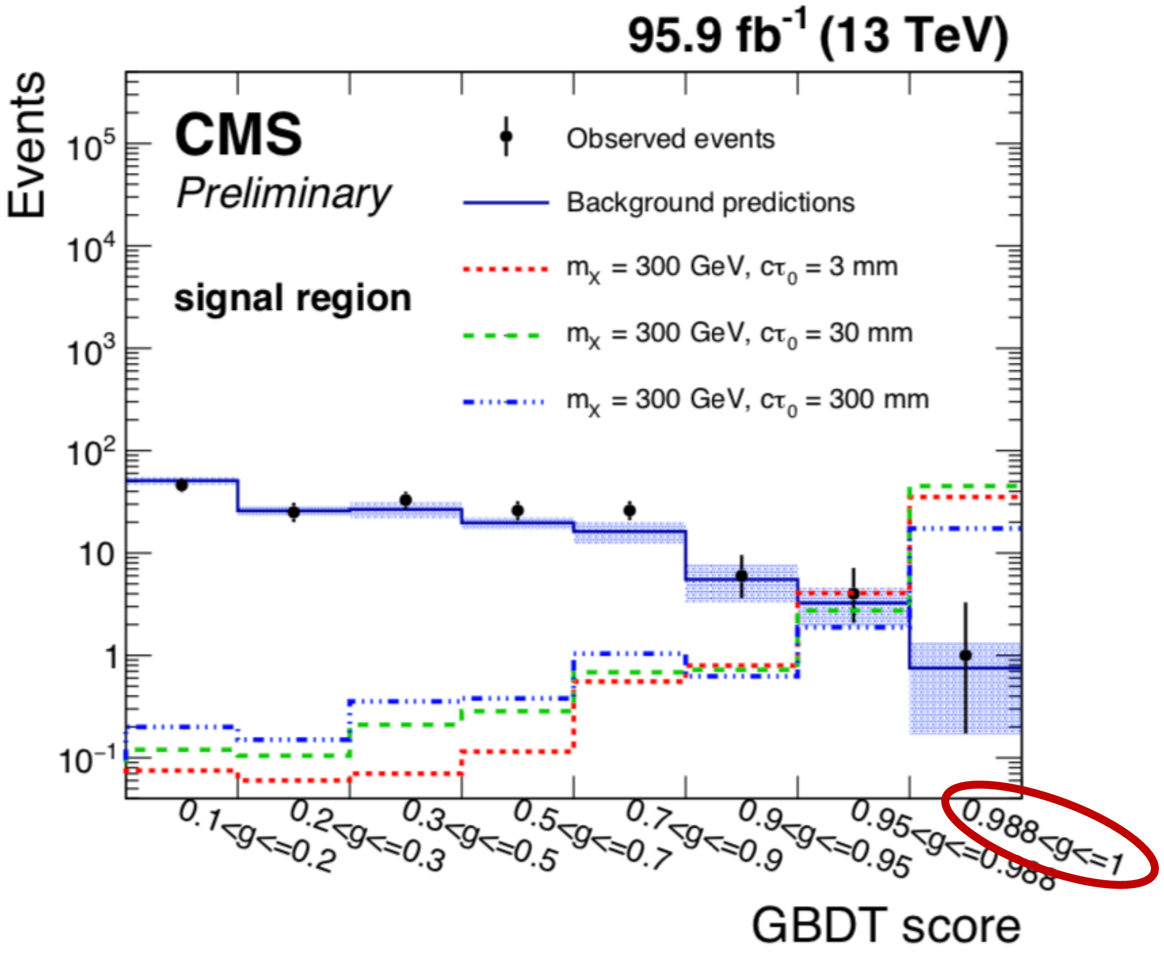
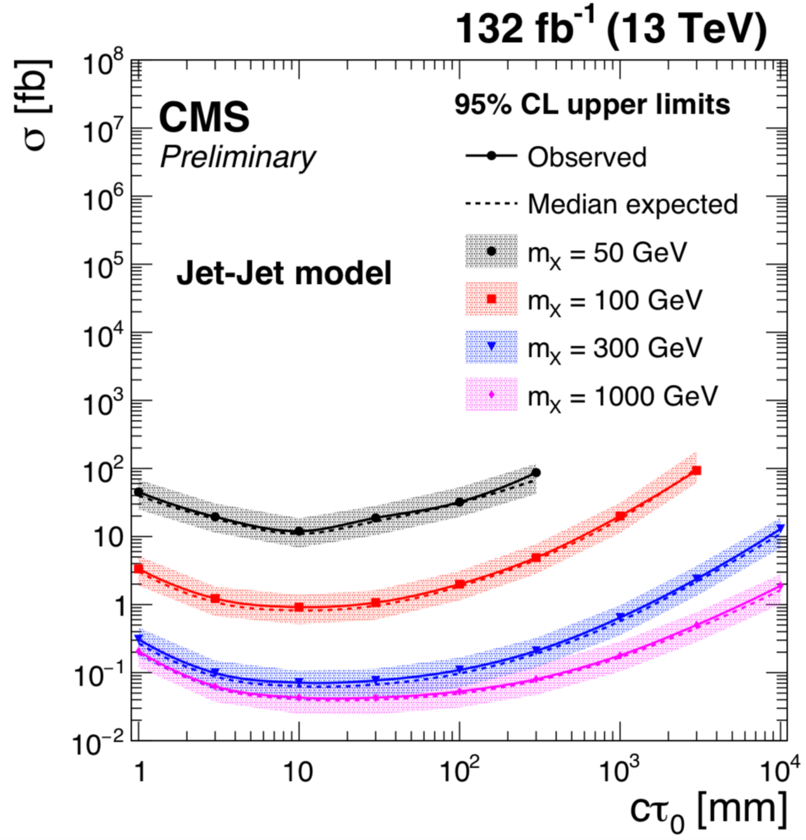
- Background prediction is purely data-driven
- Expanded ABCD method
  - Using number of 3D prompt tracks in each jet and overall event GBDT score
  - Signal region: both jets satisfy $N_{3D\ prompt} < 3$, and event GBDT score $> \mathbf{0.988}$
- Predicted background: **0.75 ± 0.44(stat) ± 0.39(syst) events**
- Observation: **1 event**



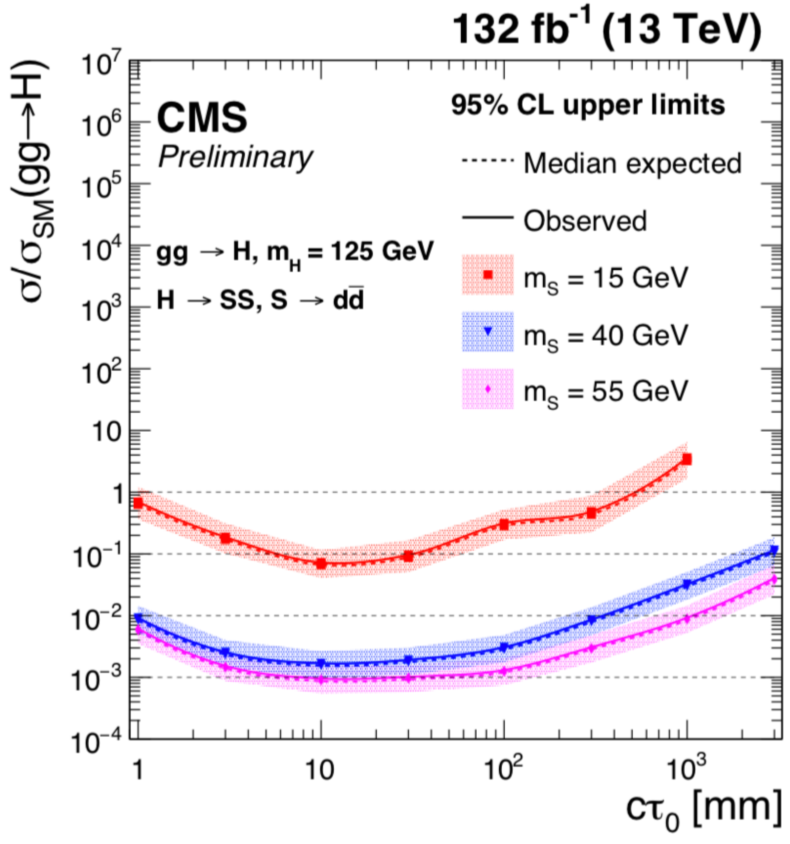
Results

- 95% confidence level limits set on signal models
- Exclude SM Higgs → SS → light quarks at **1% branching fraction**

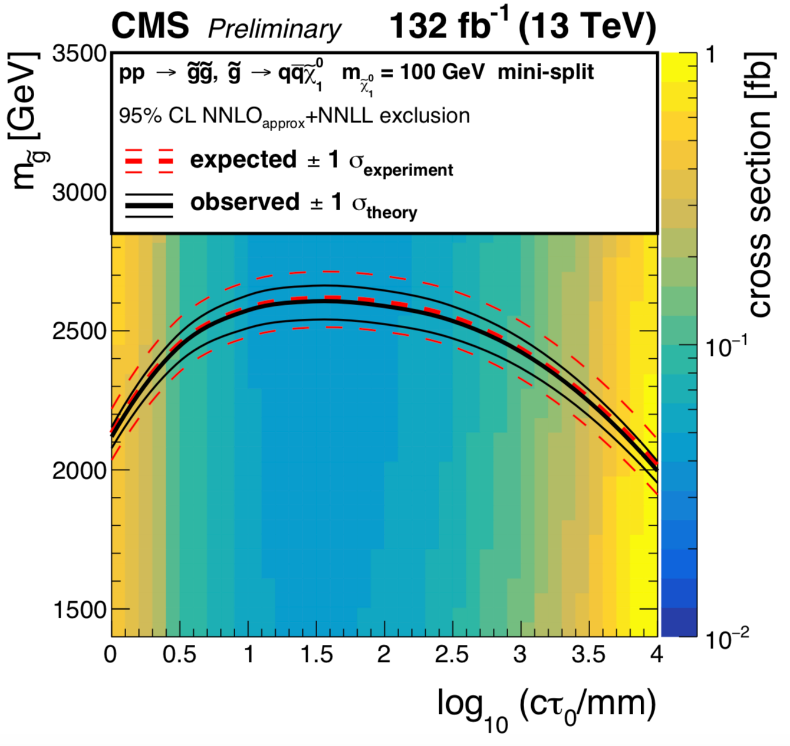
Jet-Jet model



Exotic SM Higgs decay



Split SUSY



Disappearing tracks

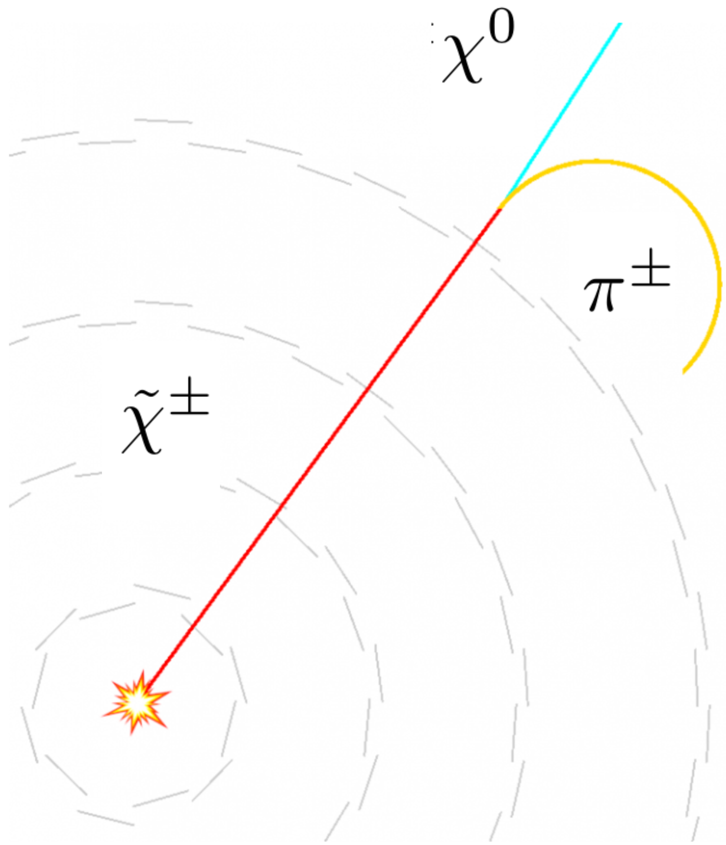
CMS-PAS-EXO-19-010
Accepted for publication in PLB
https://arxiv.org/abs/2004.05153

Search for disappearing tracks

- Signature driven search for **charged, long-lived particles** decaying within silicon tracker
- Use 13 TeV data from 2017/18, corresponding to 101 fb^{-1}
  - Combined with 2015/2016 data for 140 fb^{-1}
- Predicted by many models, including anomaly-mediated supersymmetry breaking (AMSB)

$$\tilde{\chi}^{\pm} \rightarrow \pi^{\pm}\chi^{0}$$

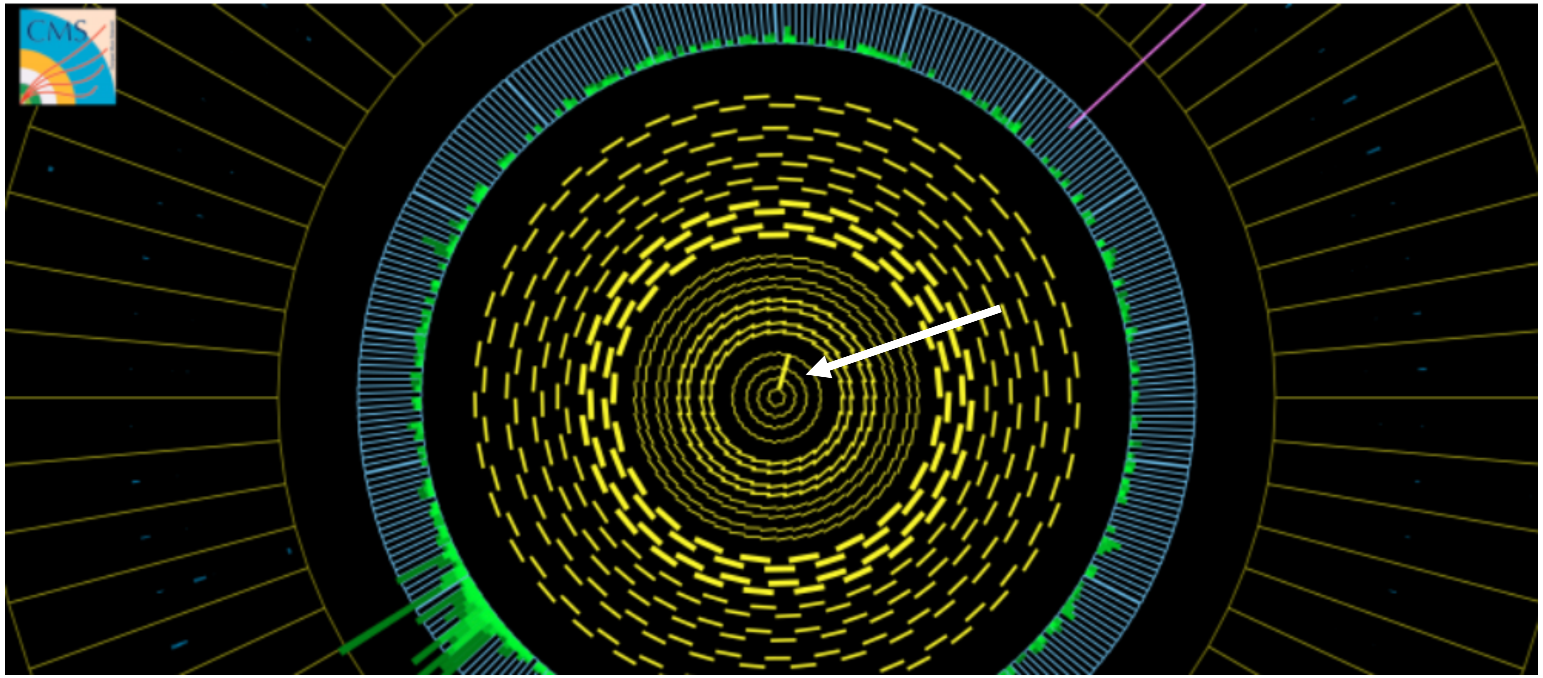
  - Chargino is long-lived due to small mass-splitting
  - Neutralino doesn't interact, pion is too soft to reconstruct



Analysis overview

- Look for isolated track with:
  - Missing outer hits
  - No energy in calorimeters or muon system
- Dedicated trigger using ISR jet at L1, isolated track at HLT

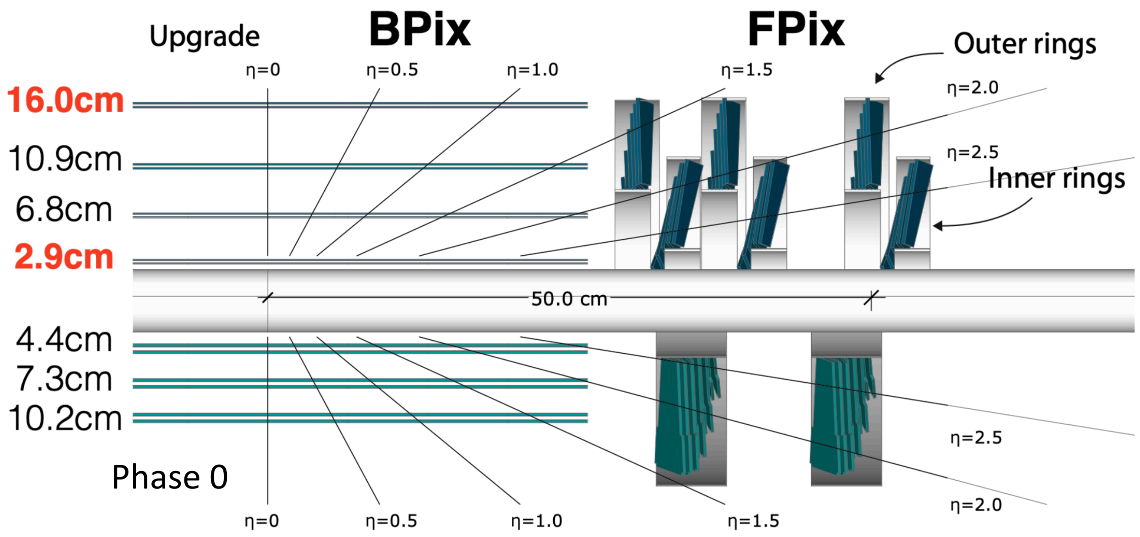
- Primary backgrounds:
  - Isolated, charged leptons that have energetic bremsstrahlung or are mis-reconstructed
  - Spurious tracks from pattern recognition errors



AMSB signal event in MC

Event selection

- ISR jet, MET > 120 GeV
- Track selection:
  - $p_T > 55$ GeV, $|\eta| < 2.1$
  - ≥ 4 pixel hits
  - Well-isolated from jets and leptons
  - Pass fiducial selections: veto coverage gaps, regions of low lepton reco efficiency
  - No missing inner/middle silicon hits (minimize spurious tracks)



- **Disappearing track:**
  - $E_{calo} < 10$ GeV within $\Delta R < 0.5$
  - ≥ 3 missing outer hits

3 signal categories based on number of layers: $N_{lay} = 4, 5, \geq 6$

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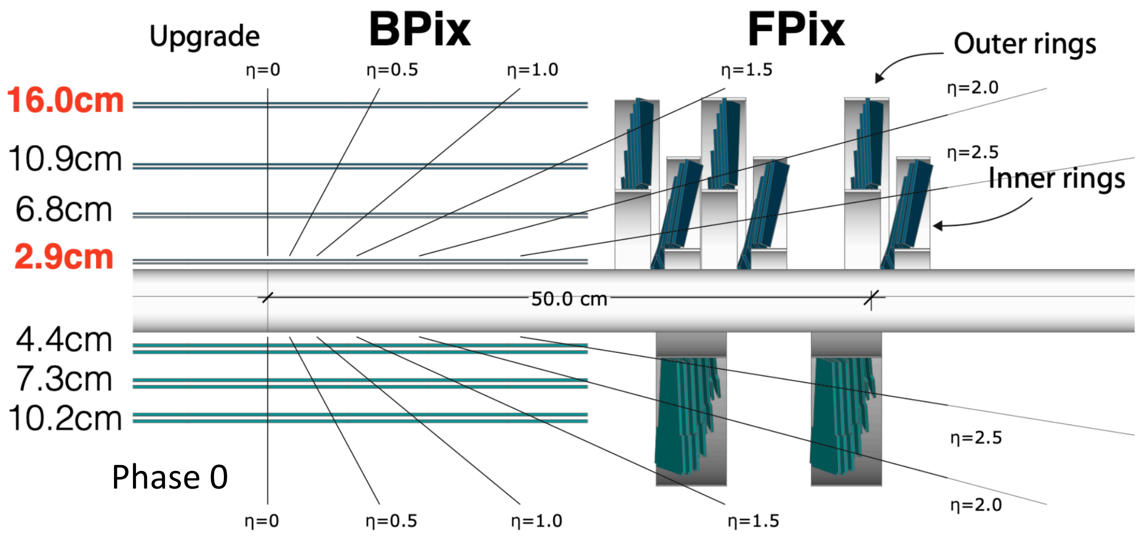
Benefit from CMS Phase I upgrades!



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Background estimate

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- Data-driven background methods
- For leptons, calculate probability for each flavor lepton to pass each step of selection
  - Apply probabilities to single lepton control region
- For spurious tracks, estimate in $Z \rightarrow \mu\mu$, $Z \rightarrow ee$ events using d_0 sideband
- Spurious tracks dominate at low n_{lay}, leptons dominate for long tracks
- Expected $47.8^{+2.7}_{-2.3}$(stat) $\pm$ 8.1 (syst) background events, observed 48 events

Data-taking period	n_{lay}	Expected backgrounds: Leptons	Expected backgrounds: Spurious Tracks	Expected backgrounds: Total	Observation
2017	4	$1.4 \pm 0.9 \pm 0.2$	$10.9 \pm 0.7 \pm 4.7$	$12.2 \pm 1.1 \pm 4.7$	17
	5	$1.1 \pm 0.4 \pm 0.1$	$1.0 \pm 0.2 \pm 0.6$	$2.1 \pm 0.4 \pm 0.6$	4
	≥ 6	$6.7 \pm 1.1 \pm 0.7$	$0.04 \pm 0.04^{+0.08}_{-0.04}$	$6.7 \pm 1.1 \pm 0.7$	6
2018 A	4	$1.1^{+1.0}_{-0.6} \pm 0.1$	$6.2 \pm 0.5 \pm 3.5$	$7.3^{+1.1}_{-0.8} \pm 3.5$	5
	5	$0.2^{+0.6}_{-0.2} \pm 0.0$	$0.5 \pm 0.1 \pm 0.3$	$0.6^{+0.6}_{-0.2} \pm 0.3$	0
	≥ 6	$1.8^{+0.6}_{-0.5} \pm 0.2$	$0.04 \pm 0.04^{+0.06}_{-0.04}$	$1.8^{+0.6}_{-0.5} \pm 0.2$	2
2018 B	4	$0.0^{+0.8}_{-0.0} \pm 0.0$	$10.3 \pm 0.6 \pm 5.4$	$10.3^{+1.0}_{-0.6} \pm 5.4$	11
	5	$0.4^{+0.7}_{-0.3} \pm 0.1$	$0.6 \pm 0.2 \pm 0.3$	$1.0^{+0.7}_{-0.3} \pm 0.3$	2
	≥ 6	$5.7^{+1.2}_{-1.1} \pm 0.6$	$0.00^{+0.04}_{-0.00} \pm 0.00$	$5.7^{+1.2}_{-1.1} \pm 0.6$	1

Results

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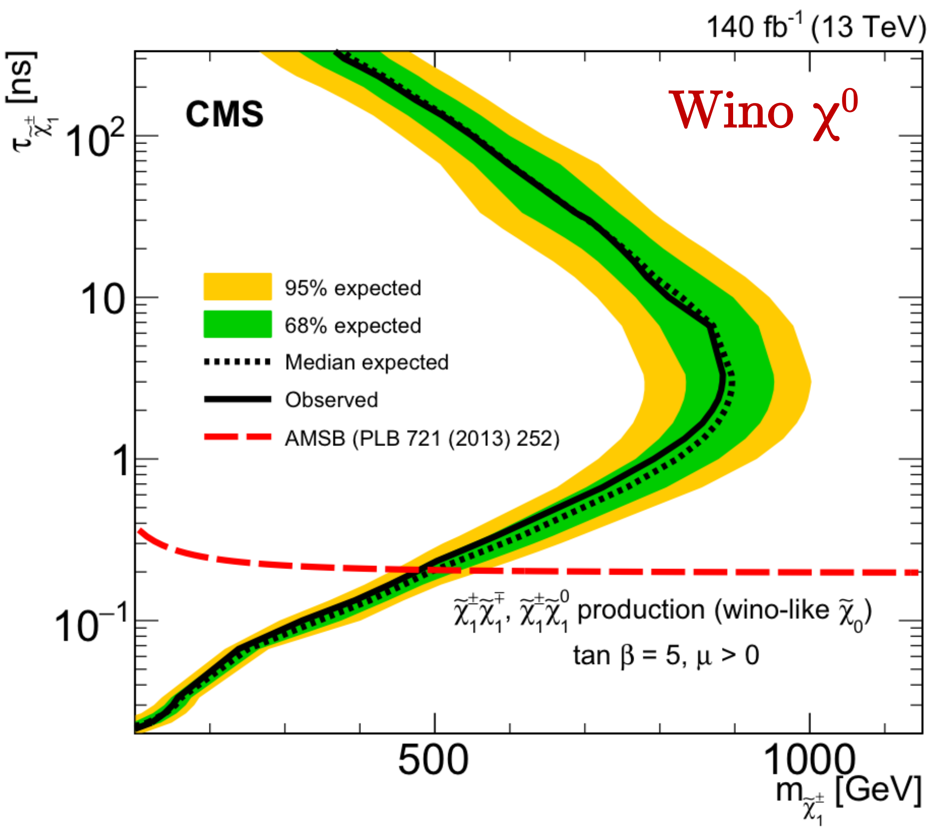
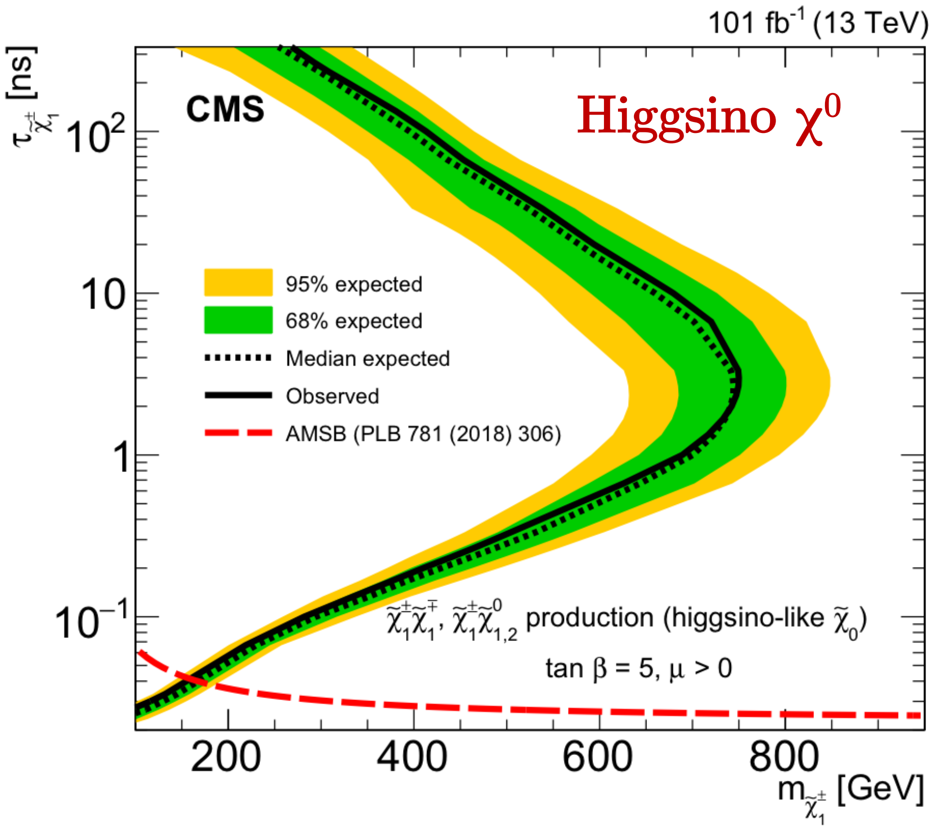
- Combined with 2015/2016 results for purely wino χ^0 → **best limits to date!**
  - Exclude up to 884 GeV at 3ns, 474 GeV at 0.2 ns
- **First limits** from disappearing track signature for higgsino χ^0
  - Exclude up to 750 GeV at 3ns, 175 GeV at 0.05 ns





Conclusions

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- CMS is pursuing a broad program of long-lived particle searches
- **Search for displaced jets:**
  - Reconstruct dijets and secondary vertex from displaced tracks
  - Exclude SM Higgs $\rightarrow$ SS, S $\rightarrow$ light quarks at **1% branching fraction**
  - Exclude gluino masses up to 2500 GeV in split SUSY model for 5 mm $< c\tau <$ 520 mm
- **Search for disappearing tracks:**
  - Improve limits on wino χ^0 by $>$ 150 GeV compared to previous CMS results, **strongest** limits to date on this model for this signature
  - **First limits** on higgsino χ^0 in AMSB using disappearing track signature
- More exciting results coming soon – stay tuned!

Full list, CMS Exotica results

Backup

Displaced jets – 2016 analysis

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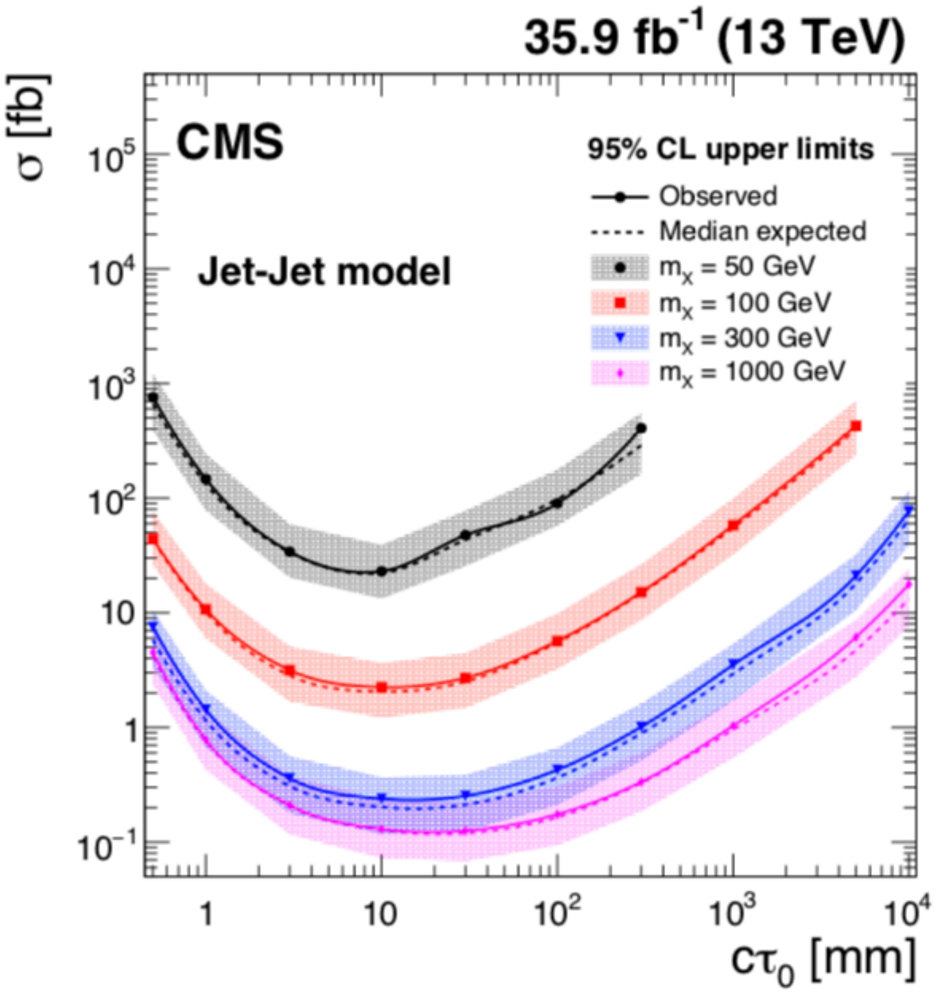
Phys. Rev. D **99** (2019) 032011, arXiv: 18011:07991

- Overall analysis strategy very similar to 2017+2018 result
- Likelihood discriminant instead of BDT
- No NI veto map
- Expected 1.03 ± 0.11 ± 0.19 events, observed 1 event
- For the jet-jet model, excluded cross sections as low as 0.15fb

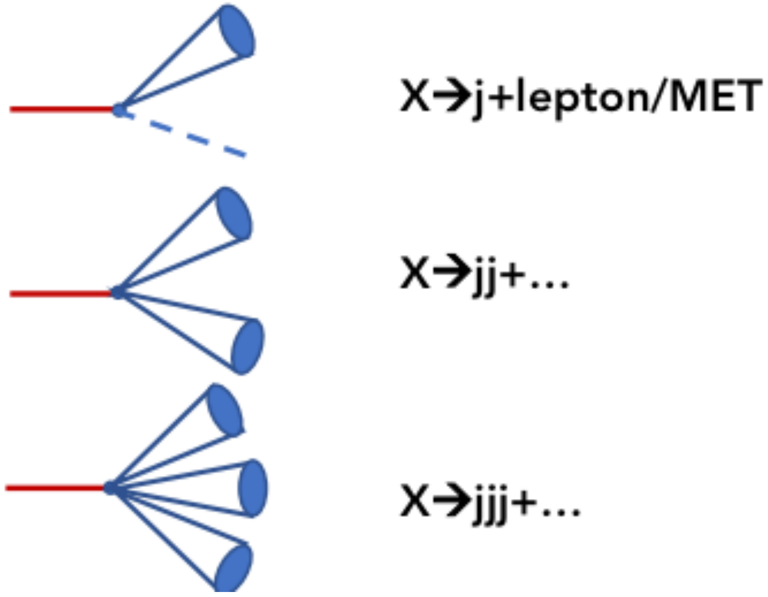


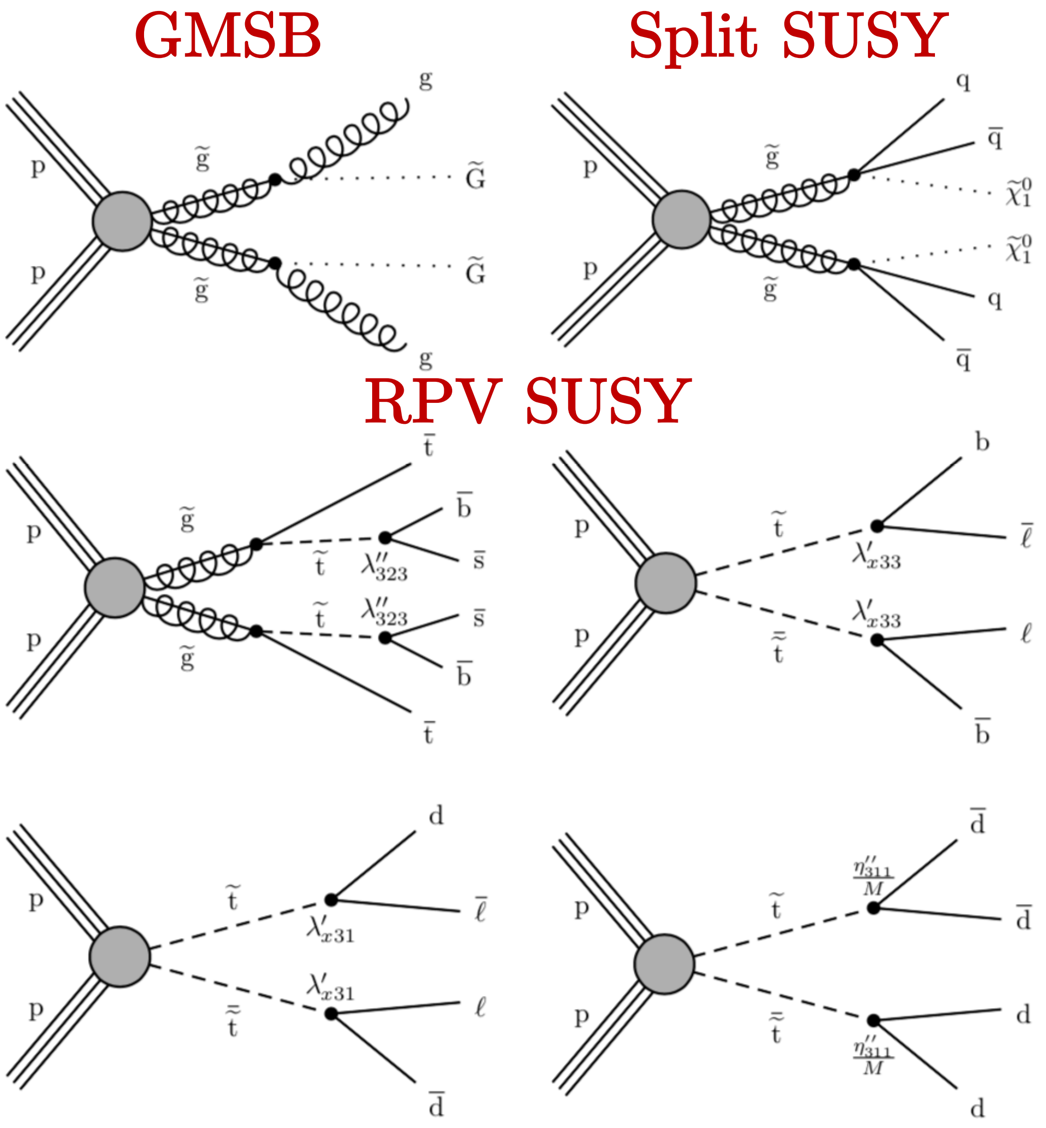
Displaced jets – triggers

- Displaced trigger:
  - Calo HT > 430 GeV
  - at least two jets, each satisfying
    - pT > 40, $\eta < 2.0$
    - At most two prompt tracks ($IP_{2D} < 1$ mm)
    - At least one displaced track ($IP_{2D} > 0.5$ mm, $IP_{2D} / \sigma_{IP} > 5.0$)
- Inclusive trigger:
  - Calo HT > 650 GeV
  - at least two jets, each satisfying
    - pT > 60, $\eta < 2.0$
    - At most two prompt tracks ($IP_{2D} < 1$ mm)
    - No requirement on number of displaced tracks

Displaced jets - interpretations

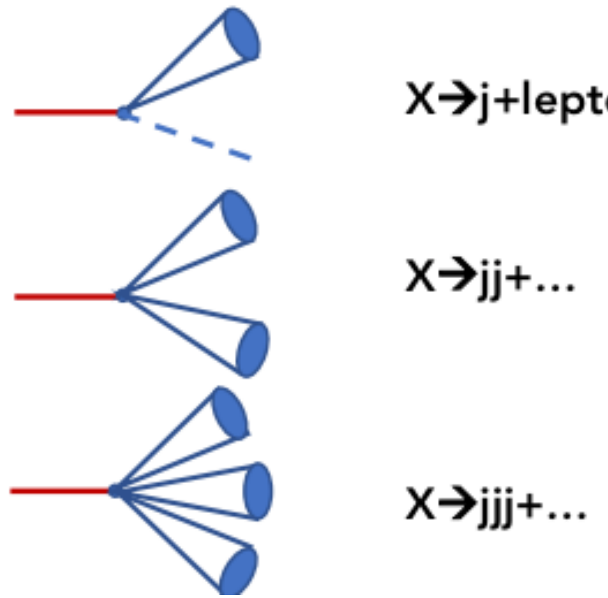
- Analysis is sensitive to different final state topologies
- SV not required to contain tracks from both jets – could arise from a single displaced jet

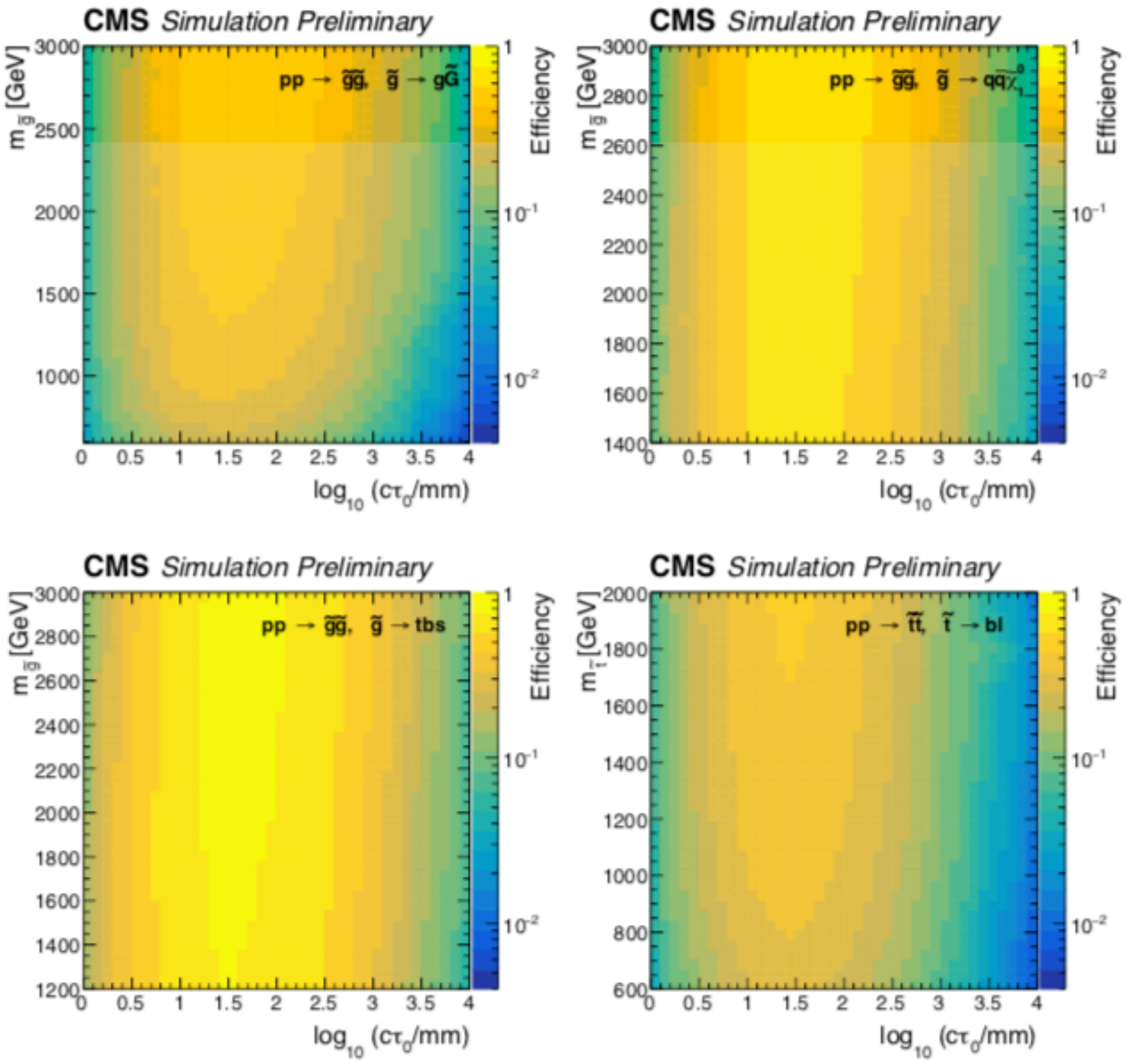




Displaced jets – signal efficiencies

- Analysis optimized for simplified jet-jet model but performant for a range of models
- Inclusive to different long-lived models with different final state topologies





Displaced jets – systematic uncertainties

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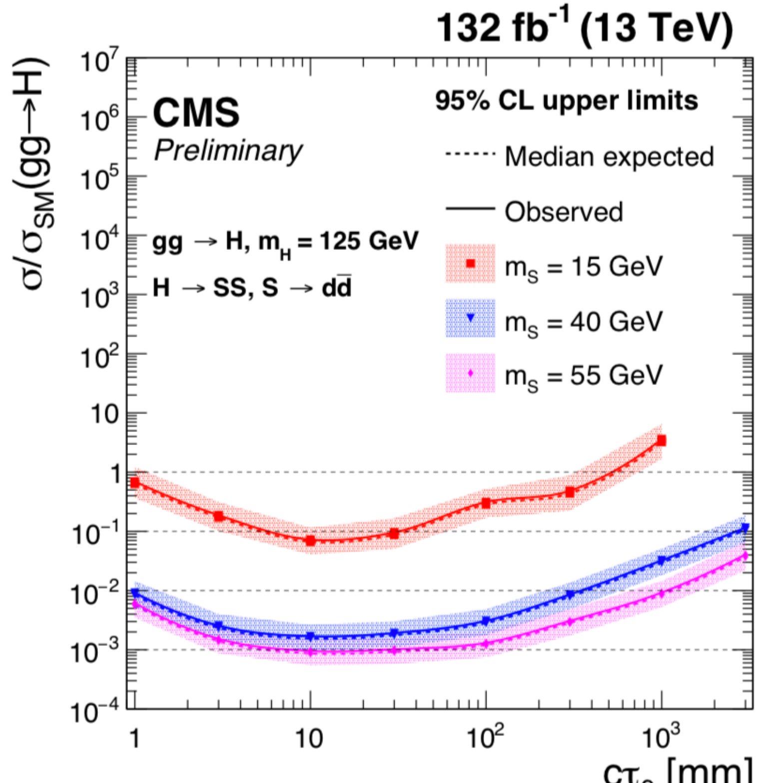
- Uncert. in background prediction taken as largest deviation found in cross-checks using additional ABCD regions: up to 52%
- Largest signal uncertainties come from the modeling of the vertexing and tracking

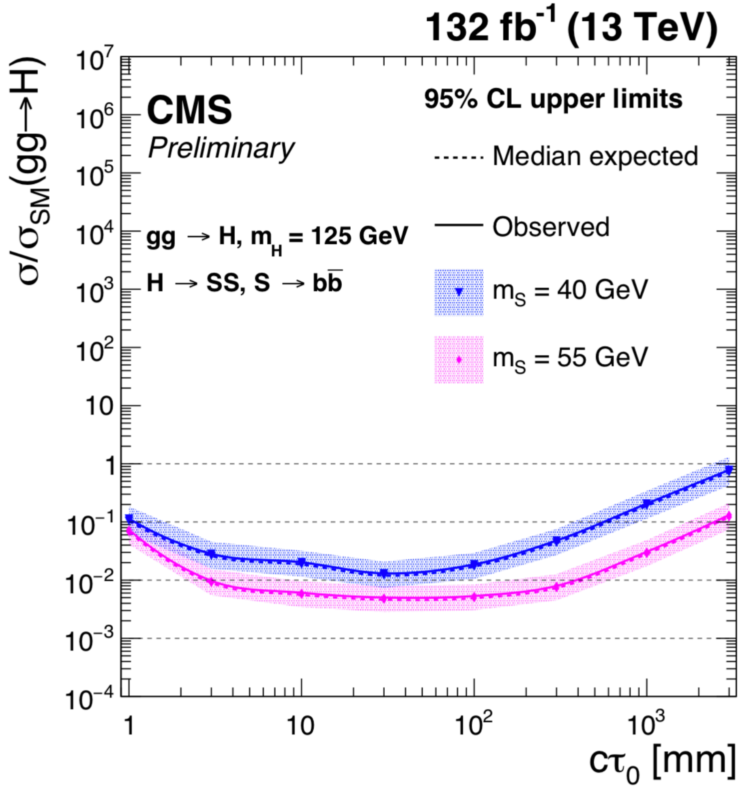
Table 3: Summary of the systematic uncertainties in signal yields.

Source	Uncertainties (%)
Integrated luminosity	2.3 – 2.5
Online H_T requirement	0 – 2
Online jet p_T requirement	0 – 8
Offline vertexing	4 – 15
Track impact parameter modeling	8 – 18
Jet energy scale	0 – 3
PDF	4 – 6
Primary vertex selection	8 – 15
Total	17 – 25

Displaced jets – SM Higgs limits

- Exclude SM Higgs → SS, S → bbar at **10% branching fraction**
  - Worse performance for decays to b quarks because tertiary vertices from b hadrons can be missed by SV reconstruction
- Exclude SM Higgs → SS, S → light quarks at **1% branching fraction**





Disappearing tracks – uncertainties

- Signal uncertainties dominated by the statistical uncertainty in the ISR corrections

Table 3: Summary of the systematic uncertainties in the signal efficiencies. Each value listed is the average across all data-taking periods, all chargino masses and lifetimes considered, and wino and higgsino cases. The values given as a dash are negligible.

Source	Uncertainty		
	$n_{\mathrm{lay}} = 4$	$n_{\mathrm{lay}} = 5$	$n_{\mathrm{lay}} \geq 6$
Pileup	3.0%	3.3%	2.8%
ISR	13%	13%	13%
Trigger efficiency	1.1%	0.8%	0.4%
Jet energy scale	0.6%	0.7%	1.6%
Jet energy resolution	0.5%	0.5%	1.3%
$p_{\mathrm{T}}^{\mathrm{miss}}$	0.3%	0.3%	0.4%
$E_{\mathrm{calo}}^{\Delta R<0.5}$	0.7%	0.7%	0.7%
Missing inner hits	2.3%	1.0%	0.3%
Missing middle hits	3.9%	5.1%	4.4%
Missing outer hits	—	—	0.2%
Reconstructed lepton veto efficiency	0.1%	0.1%	—
Track reconstruction efficiency	2.3%	2.3%	2.3%
Total	14%	15%	14%

Disappearing tracks – event yields

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- Each n_{lay} category in each period are treated as independent counting experiments

Table 4: Summary of the estimated backgrounds and the observation. The first and second uncertainties shown are the statistical and systematic contributions, respectively.

Data-taking period	n_{lay}	Expected backgrounds: Leptons	Expected backgrounds: Spurious tracks	Expected backgrounds: Total	Observation
2017	4	$1.4 \pm 0.9 \pm 0.2$	$10.9 \pm 0.7 \pm 4.7$	$12.2 \pm 1.1 \pm 4.7$	17
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	≥ 6	$6.7 \pm 1.1 \pm 0.7$	$0.04 \pm 0.04^{+0.08}_{-0.04}$	$6.7 \pm 1.1 \pm 0.7$	6
2018 A	4	$1.1^{+1.0}_{-0.6} \pm 0.1$	$6.2 \pm 0.5 \pm 3.5$	$7.3^{+1.1}_{-0.8} \pm 3.5$	5
	5	$0.2^{+0.6}_{-0.2} \pm 0.0$	$0.5 \pm 0.1 \pm 0.3$	$0.6^{+0.6}_{-0.2} \pm 0.3$	0
	≥ 6	$1.8^{+0.6}_{-0.5} \pm 0.2$	$0.04 \pm 0.04^{+0.06}_{-0.04}$	$1.8^{+0.6}_{-0.5} \pm 0.2$	2
2018 B	4	$0.0^{+0.8}_{-0.0} \pm 0.0$	$10.3 \pm 0.6 \pm 5.4$	$10.3^{+1.0}_{-0.6} \pm 5.4$	11
	5	$0.4^{+0.7}_{-0.3} \pm 0.1$	$0.6 \pm 0.2 \pm 0.3$	$1.0^{+0.7}_{-0.3} \pm 0.3$	2
	≥ 6	$5.7^{+1.2}_{-1.1} \pm 0.6$	$0.00^{+0.04}_{-0.00} \pm 0.00$	$5.7^{+1.2}_{-1.1} \pm 0.6$	1