Search for long-lived particles using displaced vertices and missing transverse momentum

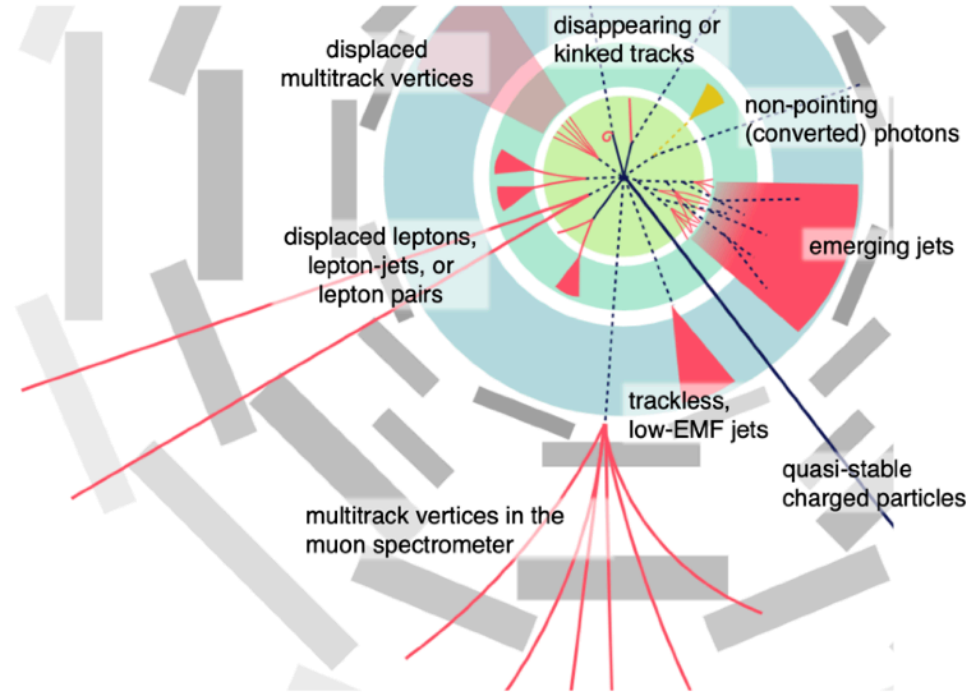
Ang Li
on behalf of the CMS collaboration

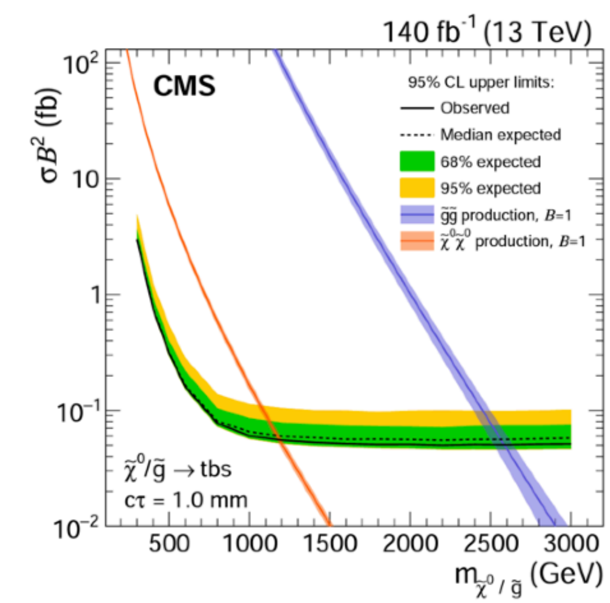
04 Jul 2024 **LLP2024**

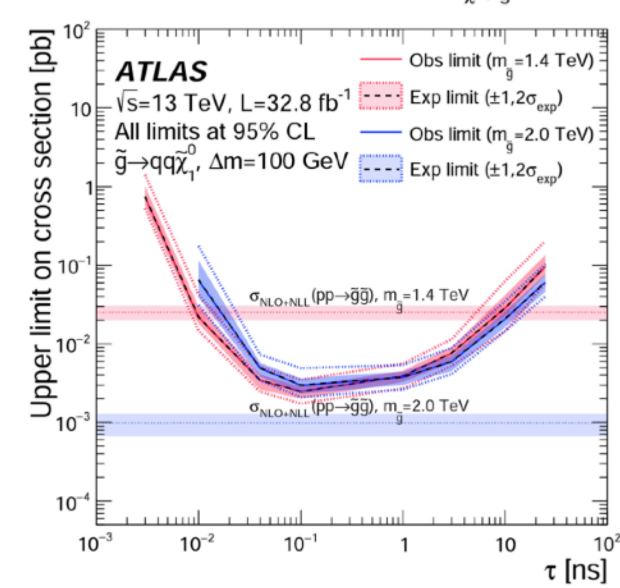
Published in PRD as DOI : 10.1103/PhysRevD.109.112005
arXiv: 2402.15804
CMS-EXO-22-020

Motivation

- Many physics models beyond standard model predict the existence of long-lived particles (LLPs)
- The long lifetimes of LLPs create **unique signatures**
  - Displaced vertex is one of them
- The ATLAS and CMS has conducted searches for displaced vertices before
  - The previous CMS search requires energetic final states
  - The previous ATLAS search requires large LLP lifetimes
- A gap is left by previous searches with relatively soft final states and small lifetimes

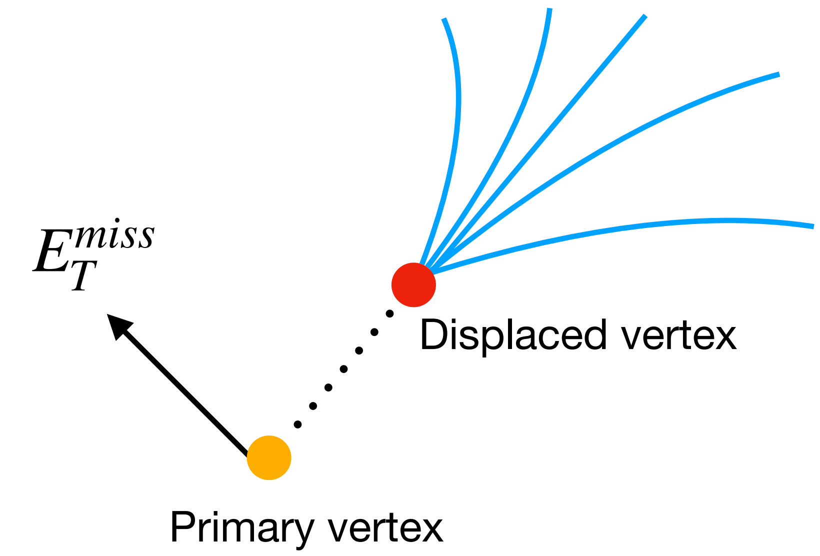


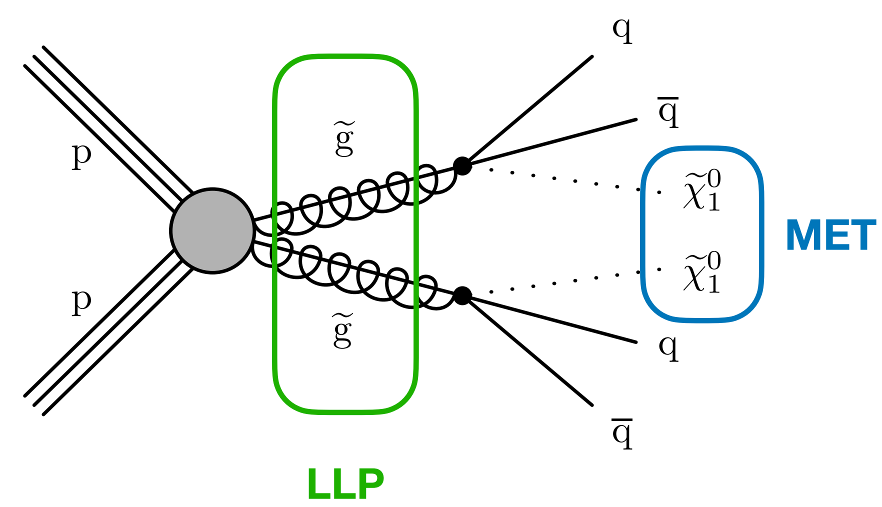


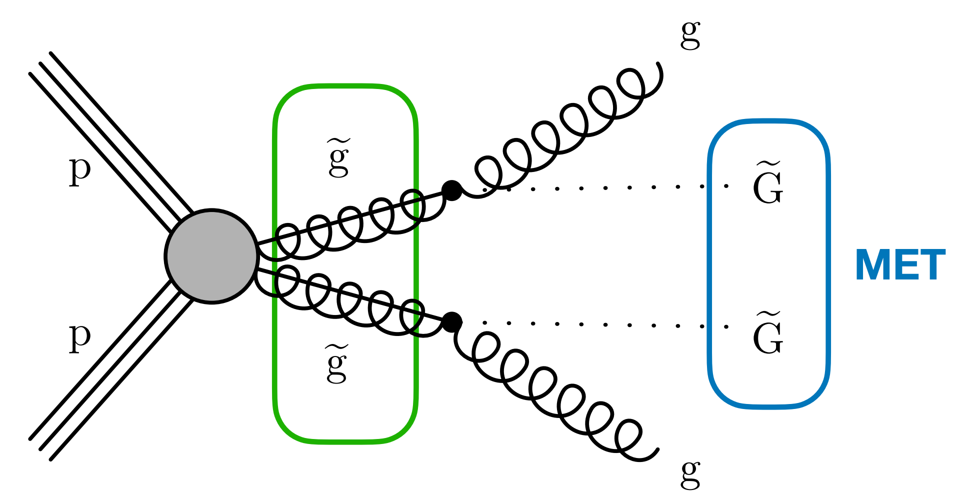


Motivation

- To fill the gap, this search targets at least 1 **displaced vertex** (within beampipe) + **MET**
    - Requiring only 1 displaced vertex enhances sensitivity to displaced vertices that are challenging to reconstruct
        - Single-produced LLP
        - Wider range of $c\tau$
    - MET helps exploring softer final states
- Search for signature and aim to be **model independent**
    - Different models can produce similar signatures in the detector
    - Used **split SUSY** and **gluing GMSB** samples as benchmark signal samples







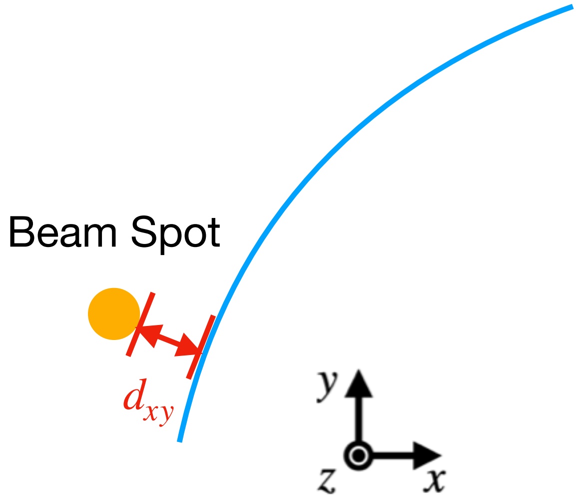
Analysis Strategy

- Select events with **MET** (MET trigger + offline selection at 200GeV)
- **Vertex reconstruction:**
  - Select well-measured and displaced tracks
  - Apply the dedicated vertex reconstruction algorithm on selected tracks
  - Select events with at least 1 vertex
- **Machine learning:**
  - Apply the interaction network to further discriminate signal from background
- **Background estimation:**
  - Define signal region by requiring vertex and ML output
  - Estimate background using events in control regions based on ABCD method
- Calculate **limits** based on the number of events in search regions

Vertex Reconstruction

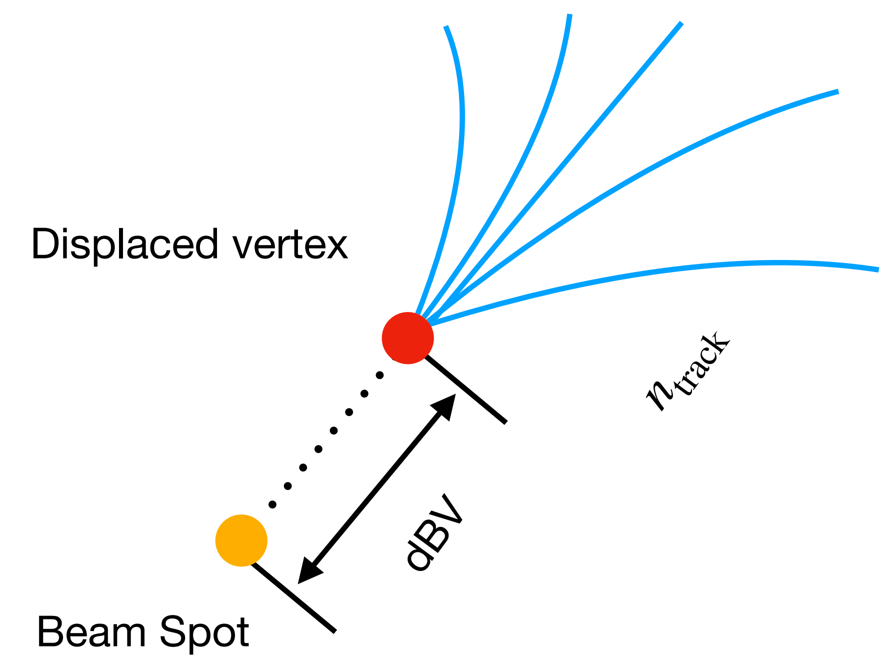
Track selection

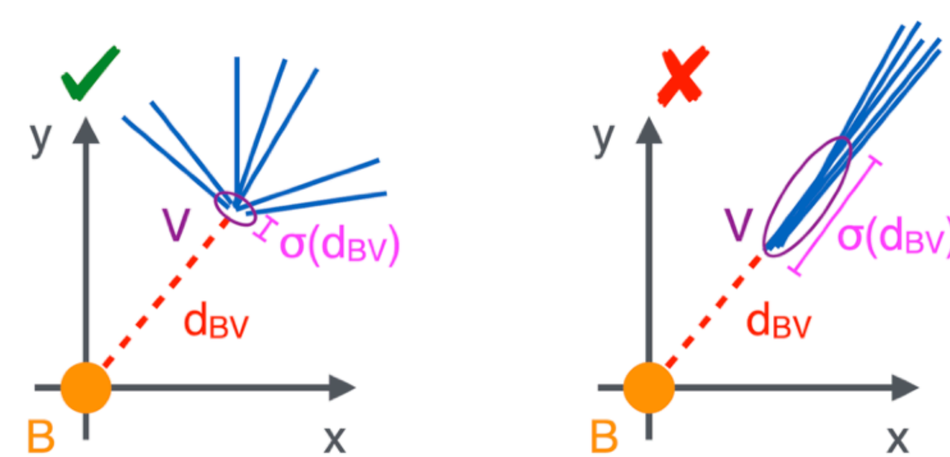
- This analysis uses the same vertex reconstruction algorithms as [arXiv:2104.13474]
- Tracks used to reconstruct displaced vertices are required to be well-measured and displaced:
  - Track $p_T > 1GeV$
  - Have a measured hit in the innermost barrel pixel layer
  - Have measured hits in at least two pixel layers
  - Have measured hits in at least six strip tracker layers
  - Have transverse impact parameter (d_{xy}) significance of at least 4



Vertex Reconstruction

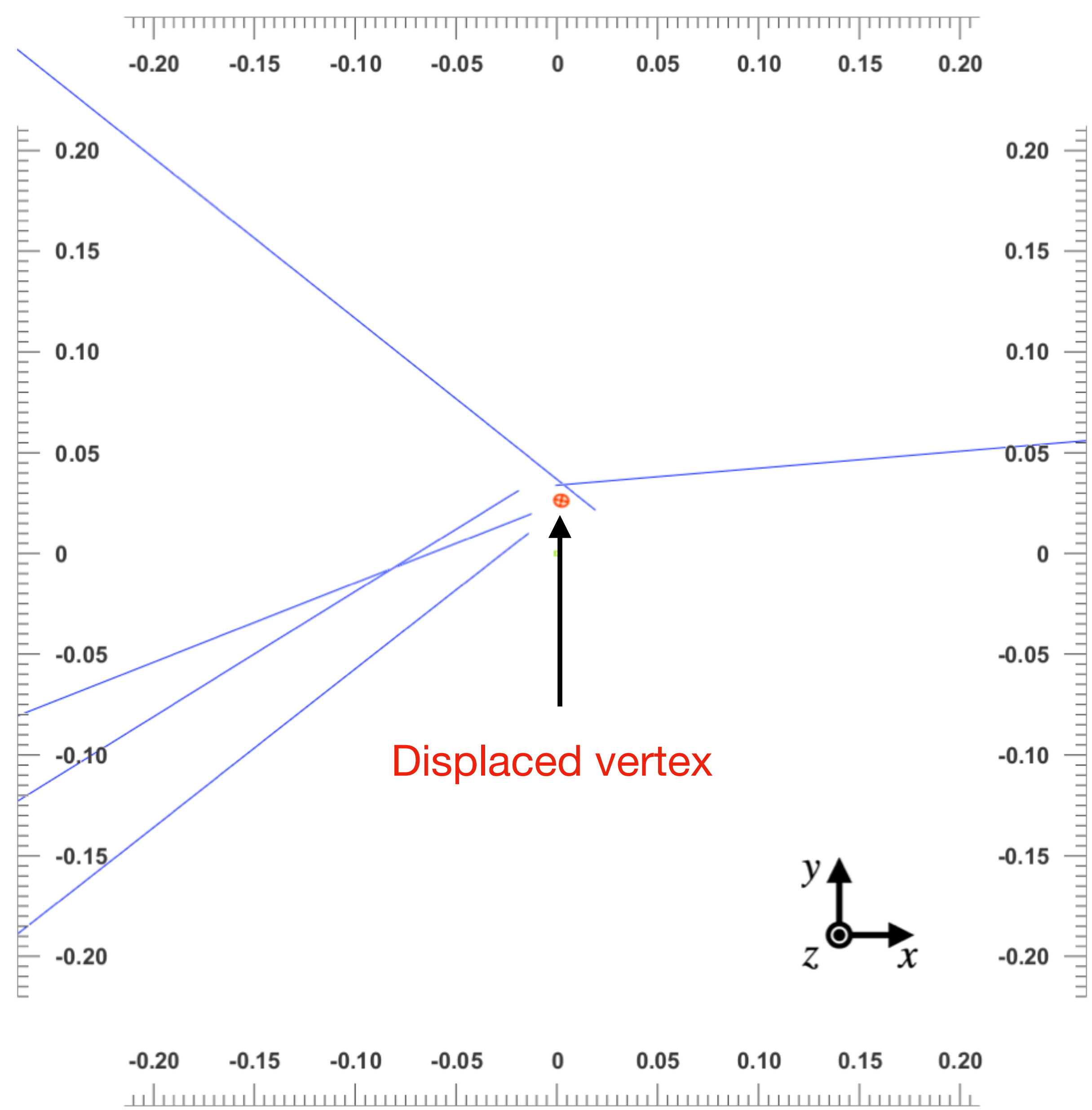
- Fit selected tracks into vertices with **Kalman filter**
- Iteratively **merge or reallocate track** for vertices that share tracks
- **Remove tracks** that significantly changes a vertex's z position to mitigate the effect of **pileup tracks**
- **Select vertices** with quality criteria:
  - Be composed of at least 3 tracks ($n_{\text{track}} \geq 3$)
    - $n_{\text{track}} \geq 5$ are signal-like, $n_{\text{track}} = 3$ or 4 are control regions
  - Be within the beam pipe radius to suppress background from material interactions
  - $\sigma_{dBV} < 25um$
    - To get rid of b hadron decays





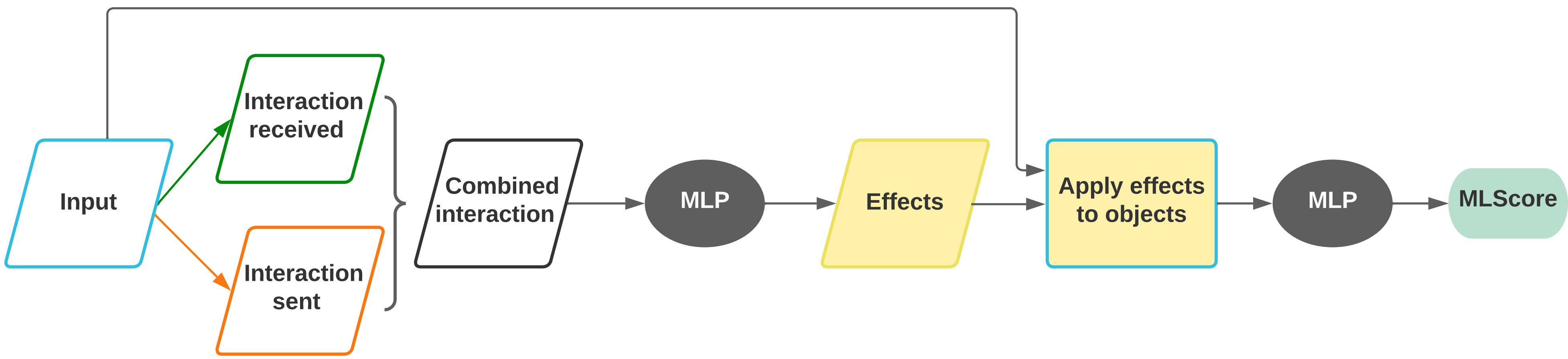
Background Source

- Vertex selections remove almost all SM LLP decays
- The remaining dominating background displaced vertices result from **unrelated tracks** randomly **crossing** each other



Machine Learning

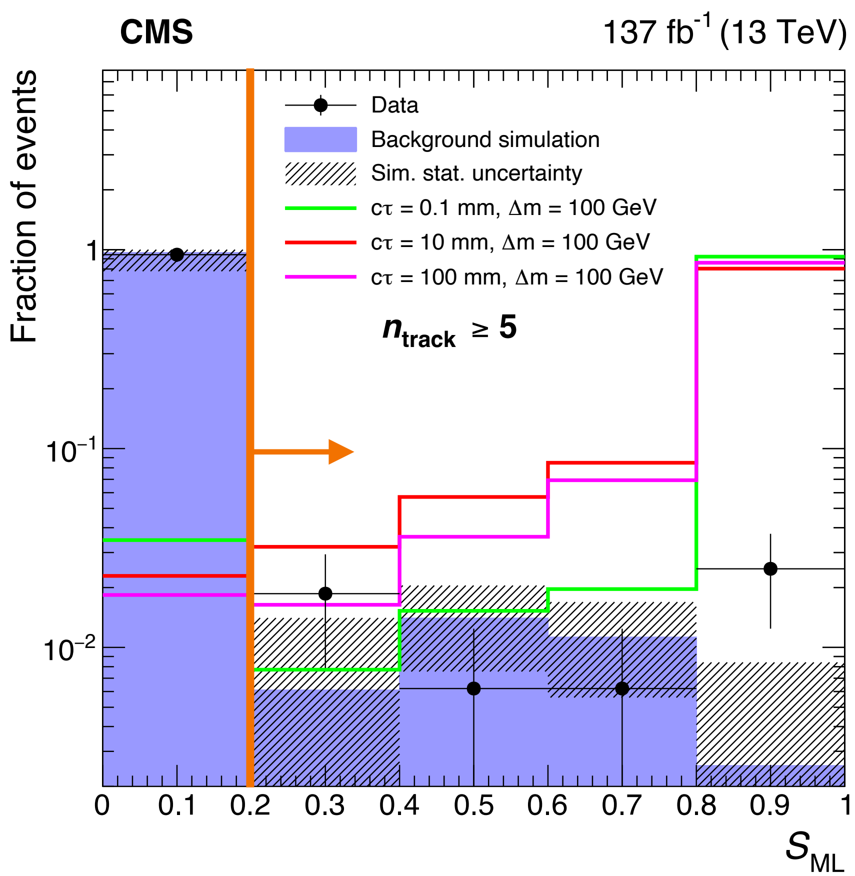
- Introduced **Interaction Network** as an **event discriminator** to
    - Increase the efficiency of selecting signal from background events
    - Perform background estimation
- Interaction Networks are a kind of **Graph Neural Network**
    - Designed to predict final states of multi-body interactions
    - Tracks are treated as single objects in the network and the "interactions" between each pair of tracks are calculated
    - Interaction Network can exploit more subtle relationships between tracks from LLPs than displaced vertex reconstruction alone
- Track information used in ML are: p_T , η , ϕ , dxy_{BS} , $sig(dxy_{BS})$, dz_{BS} , $sig(dz_{BS})$
- DisCo is applied to make ML output ($S_{\rm ML}$) **uncorrelated** with $n_{\rm track}$ for background estimation



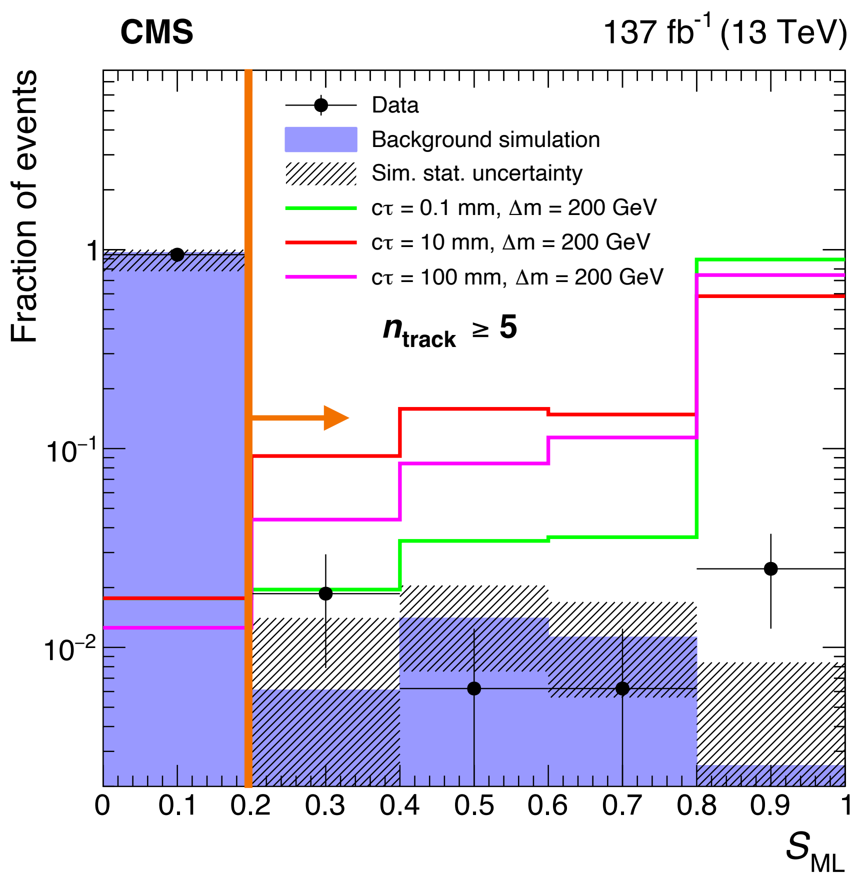
Machine Learning

- The trained Interaction Network is very powerful discriminating signal from background
  - Outstanding performance is observed for signal models with different mass splittings and $c\tau$ values
- Events with S_{ML}>0.2 are selected as signal-like

Mass splitting=100 GeV

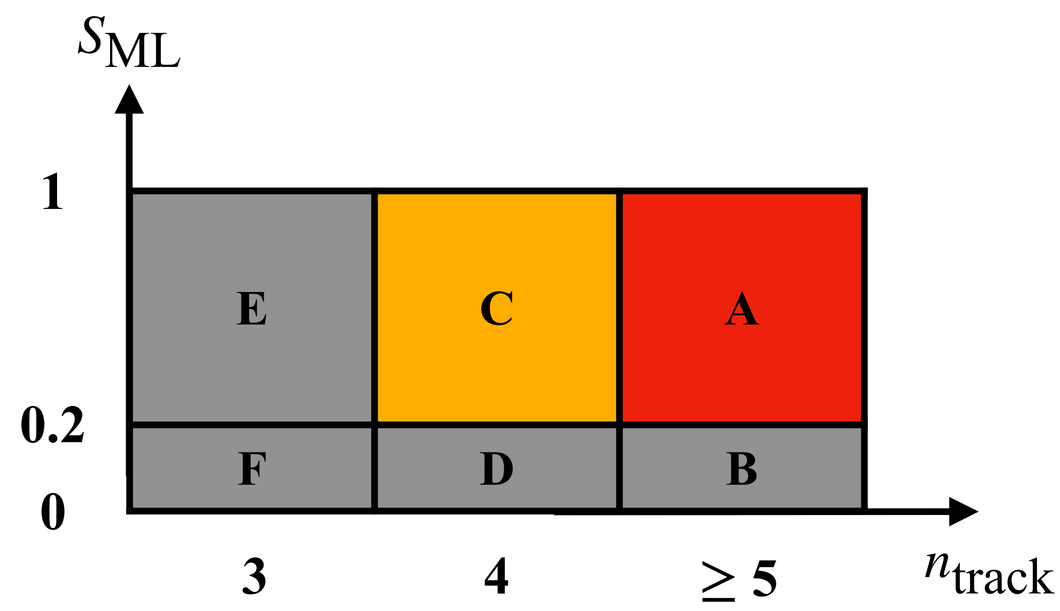


Mass splitting=200 GeV



Background Estimation

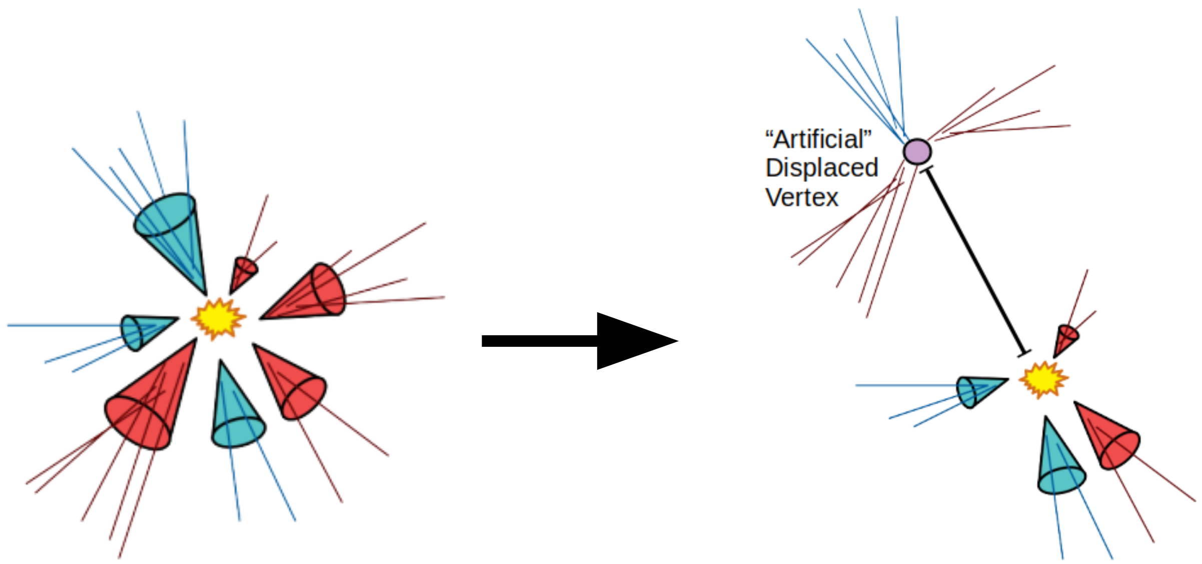
- Search Regions:
  - Signal region: n_{track} >= 5 **and** $S_{\mathrm{ML}} > 0.2$
  - Validation region: $n_{\mathrm{track}} = 4$ **and** $S_{\mathrm{ML}} > 0.2$
  - Control regions: $n_{\mathrm{track}} = 3$ **or** $S_{\mathrm{ML}} < 0.2$
- A **data-driven ABCD method** is used to estimate the background
  - n_{track} and S_{ML} are the two variables that define the search regions
  - The ABCD method requires n_{track} and S_{ML} to be decorrelated, which is achieved by applying DisCo technique when training the ML model



Systematic Uncertainties

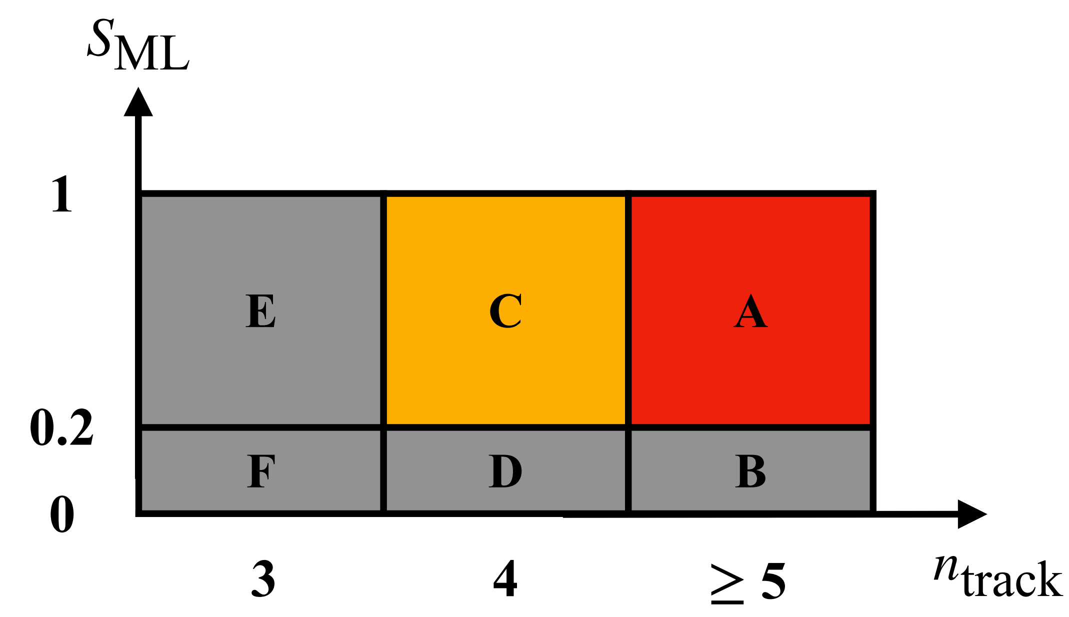
- Reconstruct **two-track displaced vertex** of $K_s^0 \to \pi^+\pi^-$ decay
- **Artificially displace tracks** in background events to mimic LLP decays
  - **Vertex reconstruction efficiency**
  - **ML tagging efficiency**

Systematic uncertainty	Magnitude (%)
Track reconstruction	6–21
Vertex reconstruction	3–20
ML tagging	$\leq$24
$\vec{p}_T^{miss}$ selection	$\leq$8
PDF uncertainty	1–85
Trigger efficiency	1–6
Pileup	2–15
Integrated luminosity	1–3
L1 trigger inefficiency	$\leq$1
Total	8–91



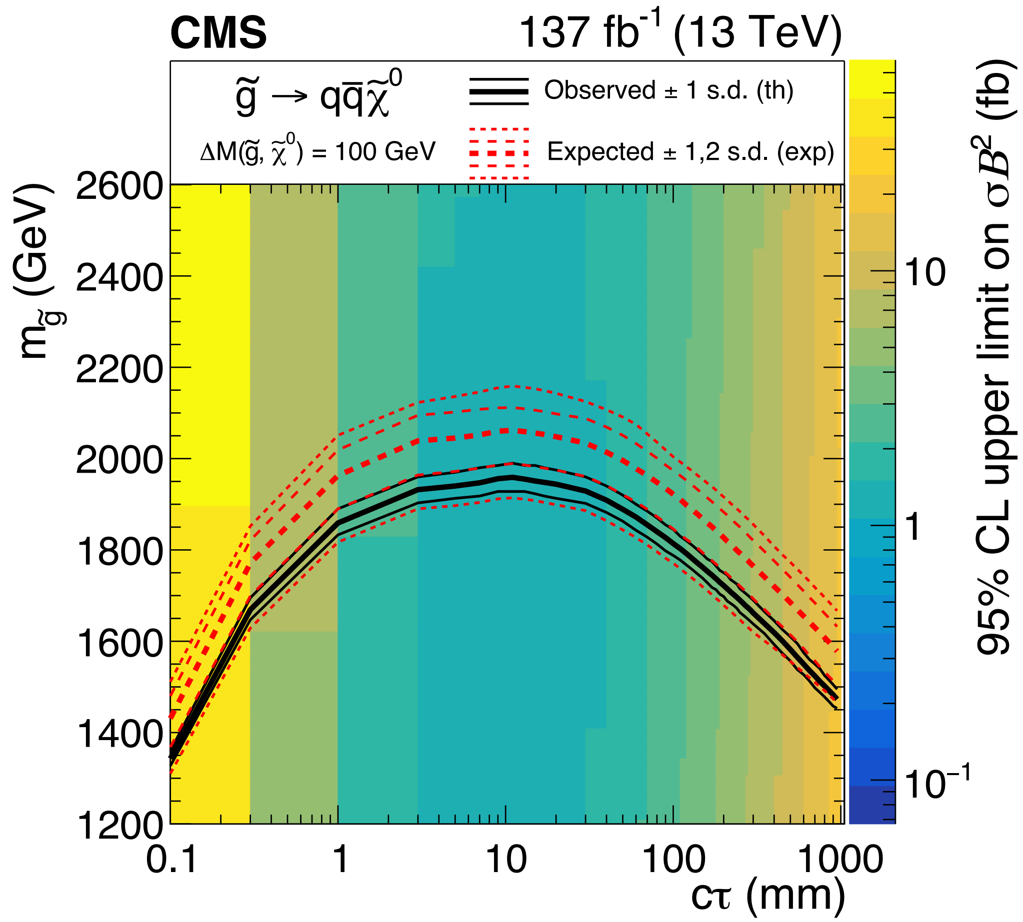
Results and Interpretation

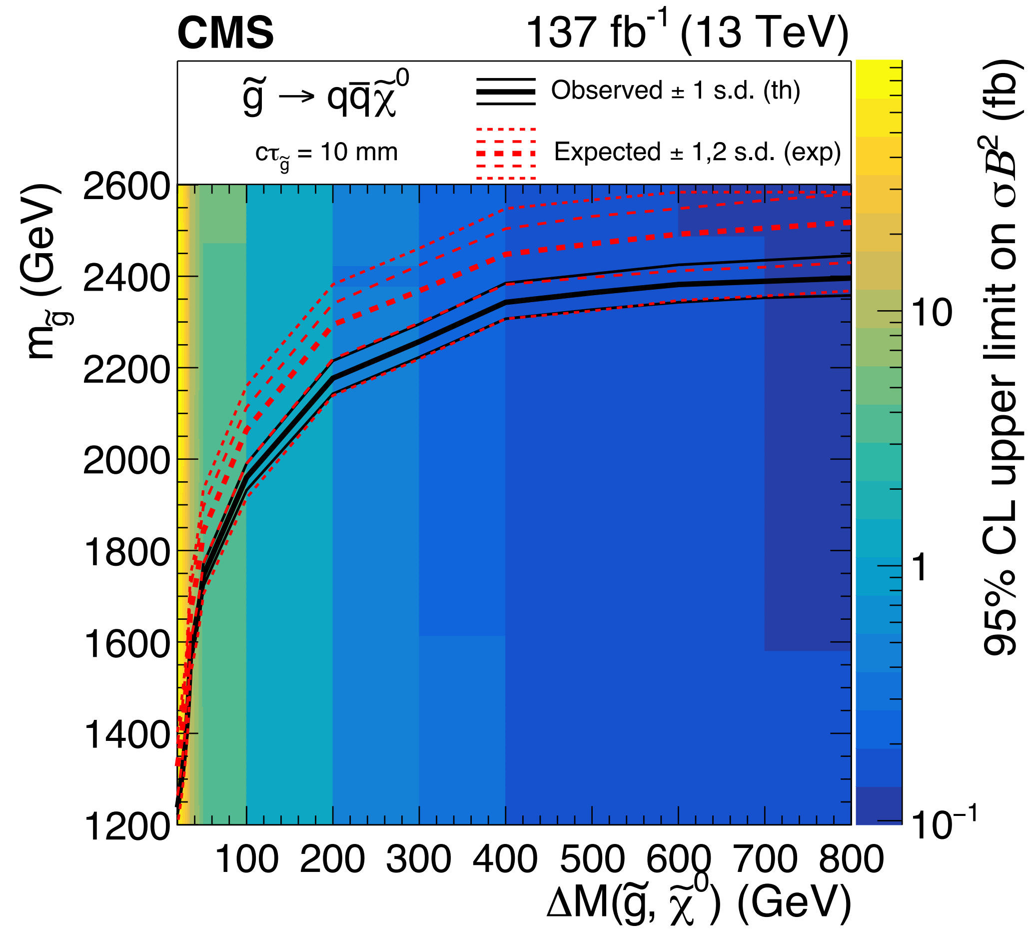
- Performed a maximum likelihood fit on all search regions under the background-only hypothesis
- No significant excess over the background-only prediction is observed



	$n_{track} = 3$	$n_{track} = 4$	$n_{track} \geq 5$
Predicted $S_{ML} > 0.2$	— (E)	38.0 ± 6.0 (C)	5.2 ± 0.5 (A)
Observed $S_{ML} > 0.2$	203 (E)	38 (C)	9 (A)
Observed $S_{ML} < 0.2$	6327 (F)	1276 (D)	152 (B)

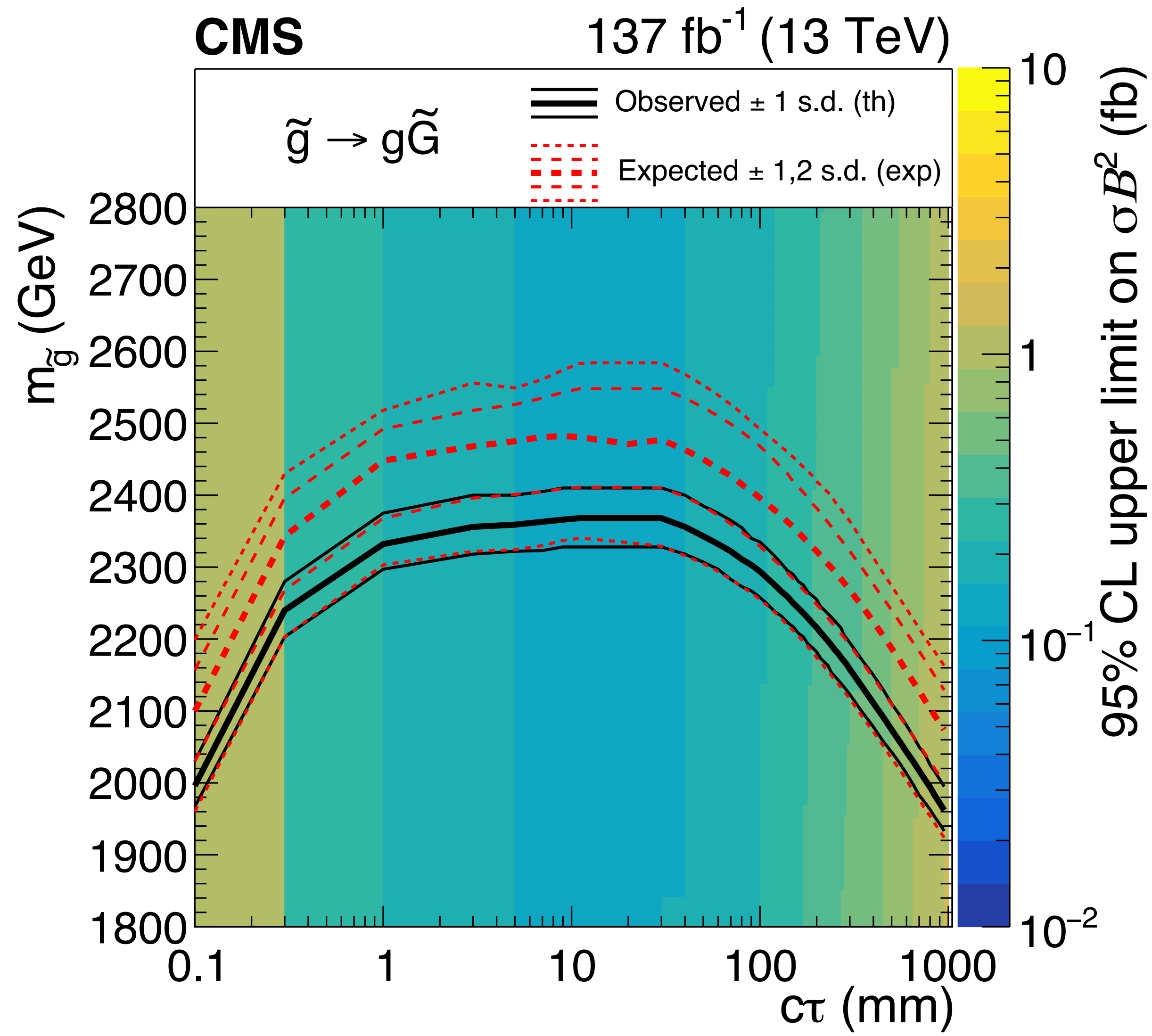
Results and Interpretation





- The sensitivity extends to $c\tau$ from 0.1 to 1000mm and Δm as low as 20GeV
  - Best limit achieved at $c\tau$ of 10mm
- For Δm of 100GeV, gluinos with mass below 1800GeV are excluded for $c\tau$ in 1-100mm
- For Δm above 50GeV, gluinos with mass below 1600GeV are excluded for $c\tau$ in 1-30mm
- Most stringent limit to date

Results and Interpretation



- Achieves the upper limit of O(1fb) for gluinos with $c\tau$ from 0.1 to 1000mm
- Excludes gluinos with $c\tau$ in the range 0.3–100mm and masses below 2240GeV
- Most stringent limit for gluinos with $c\tau$<6mm

Summary

- A search for long-lived particles using **displaced vertex** and **missing transverse energy** is presented
  - The first CMS search that targets one displaced vertex and missing traverse energy
  - Customized **vertex reconstruction** is used to reconstruct the displaced vertex
  - **Machine learning** algorithm is applied to discriminate signal from background
  - A **data-driven background estimation** based on vertex reconstruction and machine learning is developed
  - **World leading sensitivity** is achieved for the split SUSY and gluing GMSB benchmark models

Thanks!

Backup

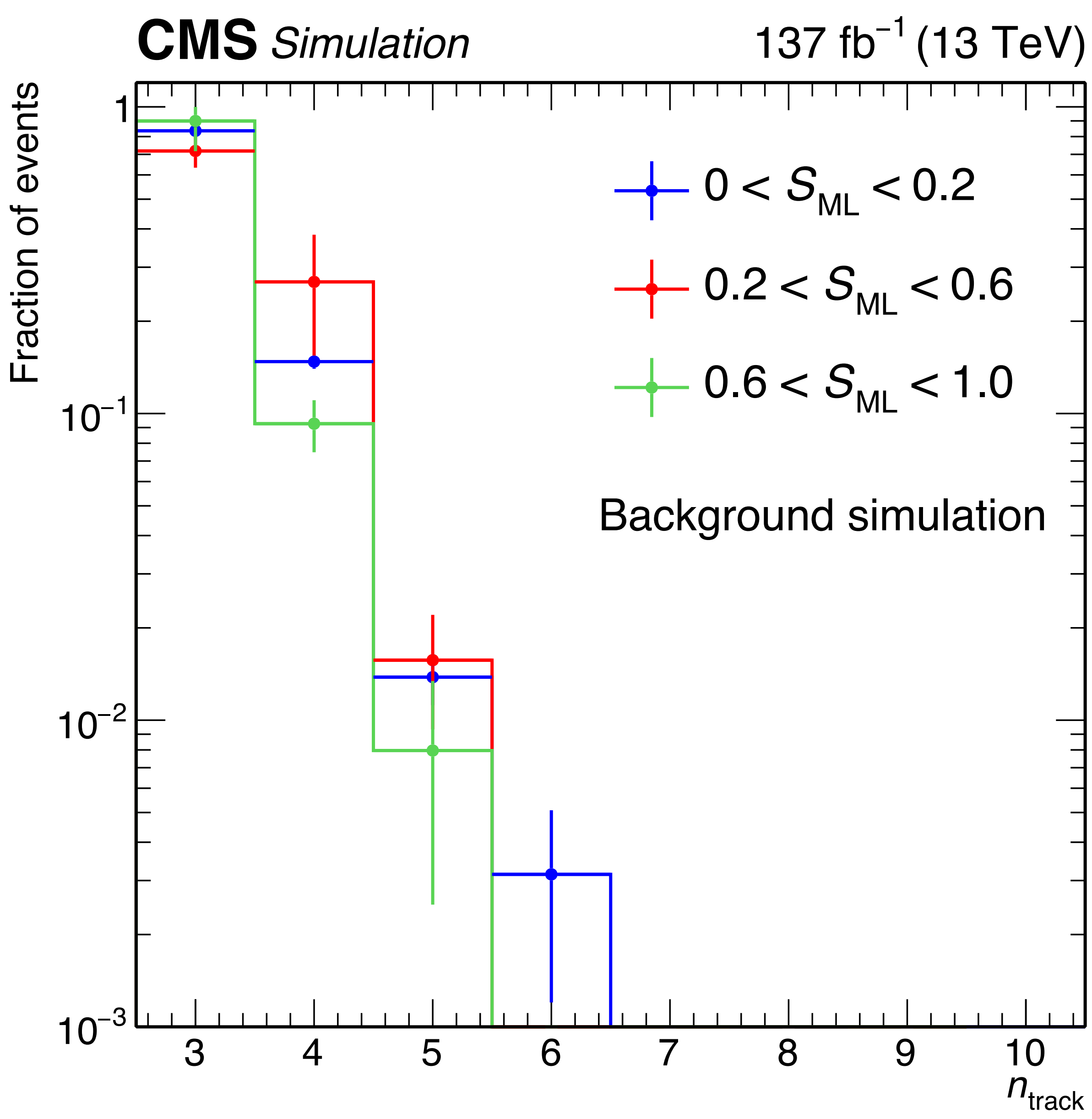
Machine Learning

- Interaction Network is very **computationally expensive** so only the leading 50 tracks in the event without displacement requirement are fed into ML
- Data and background simulation are mixed together as **background** for training
- Different mass points and lifetimes of signal samples are mixed as **signal** for training
- Training and testing events are selected to be **orthogonal** to avoid bias
    - Training and testing selections are shown in the table below
- DisCo is applied to make S_{ML} **uncorrelated** with n_{track} for background estimation

Training	Testing
- Pass event preselection with **modified** range $E_{T\ NoMu}^{miss}$ $[80{,}200)$ GeV - Have at least one reconstructed vertex	- Pass event preselection (including $E_{T\ NoMu}^{miss} > 200$ GeV) - Have at least one reconstructed vertex

Machine Learning

- The decorrelation effect for background is studied
- Categorize background MC events based on S_{ML}:
    - $0 < S_{\mathrm{ML}} < 0.2$
    - $0.2 < S_{\mathrm{ML}} < 0.6$
    - $0.6 < S_{\mathrm{ML}} < 1.0$
- n_{track} distributions are consistent for different categories
- n_{track} and S_{ML} are not correlated



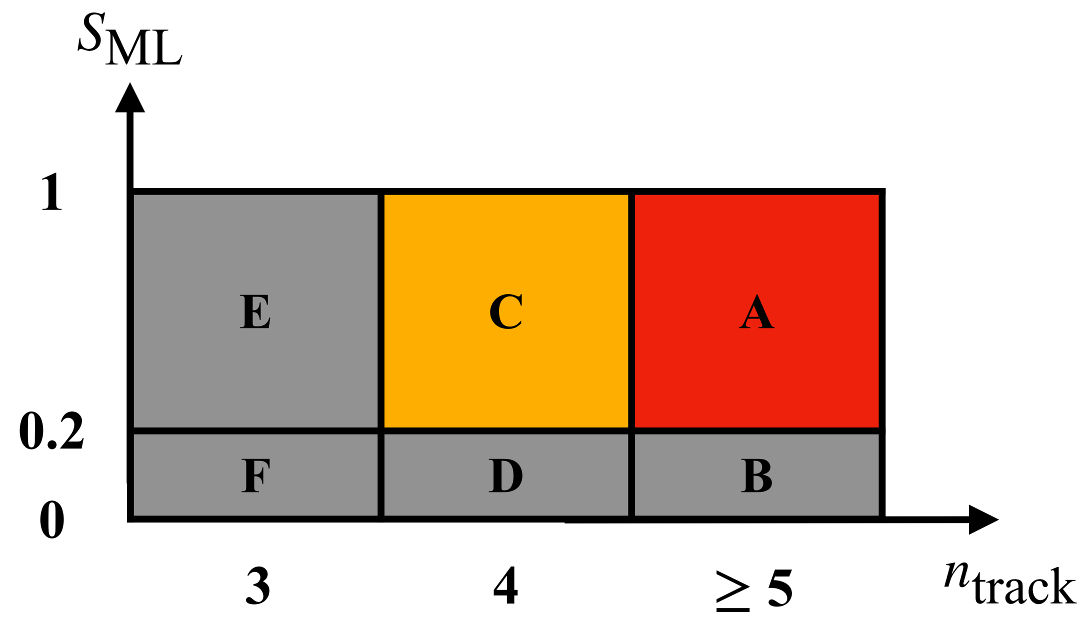
Analysis Selection

❖ Analysis Selection:

- MET trigger and filters
- $E_T^{miss} > 200\ GeV$
- Has at least 1 displaced vertex that satisfies:
  - Be composed of at least 3 tracks
  - $\sigma_{dBV} < 25um$
  - Within beam pipe

❖ Search Regions:

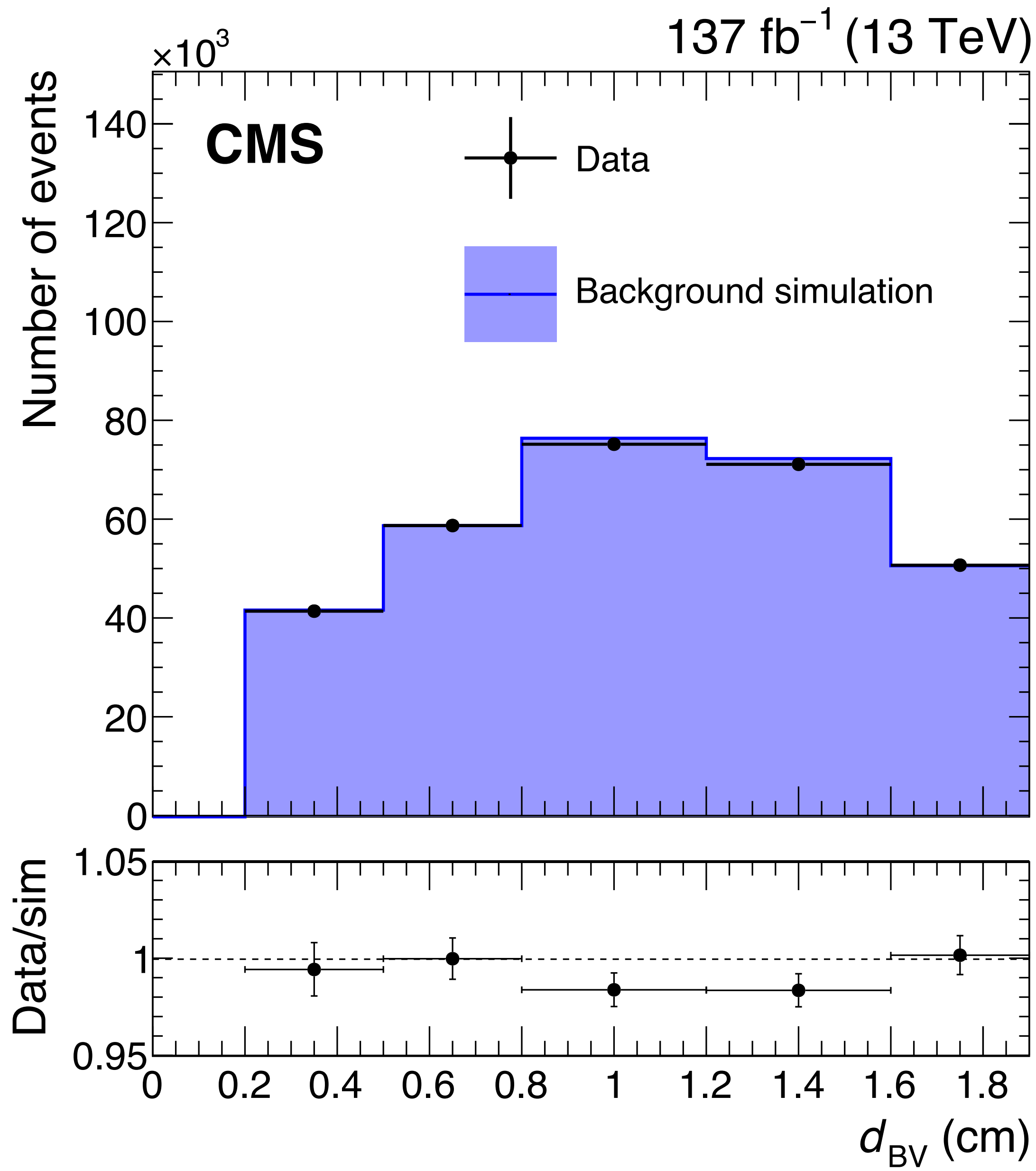
- Signal region: n_{track} >= 5 **and** S_{ML} > 0.2
- Validation region: n_{track} = 4 **and** S_{ML} > 0.2
- Control regions: n_{track} = 3 **or** S_{ML} < 0.2



Signal Efficiency

Track reconstruction efficiency

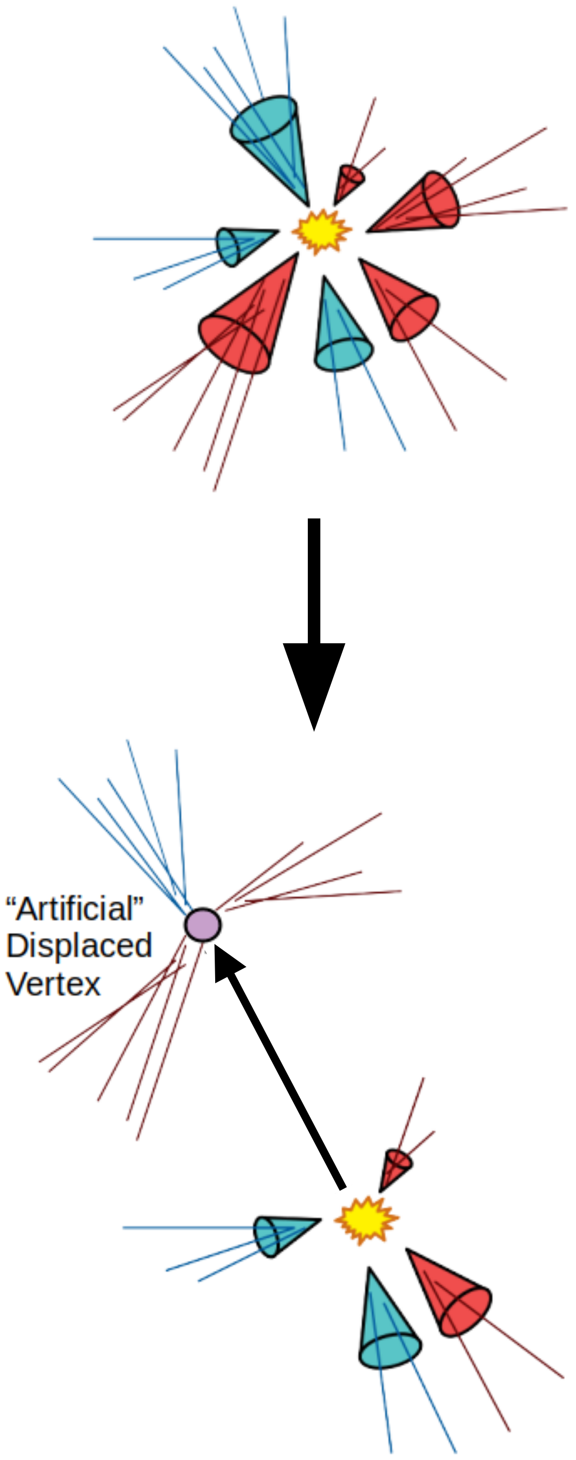
- Reconstruct **two-track displaced vertex** of $K_s^0 \to \pi^+\pi^-$ decay
- Compare the d_{BV} of K_s^0 vertices between data and simulation
- Each K_s^0 vertex include 2 tracks
  - Failing to reconstruct one track → failure of reconstructing the K_s^0 vertex
    - K_s^0 reconstruction efficiency → track reconstruction efficiency
- Data and simulation agree within 2% in all d_{BV} bins
- Track reconstruction efficiency → systematic uncertainty



Signal Efficiency

Artificially Displaced Vertices

- Make **artificially displaced vertices** to study:
    - Vertex reconstruction efficiency
    - ML tagging efficiency
- Artificially displace tracks in background events to mimic LLP decays
- **Procedure**:
    - Move jets away from their original positions
    - Move direction is determined by the vector sum of the momentum of moved jets with a smearing on the angle
    - Certain jet variables and transverse LLP travel distance are reweighted to better mimic the signal signature



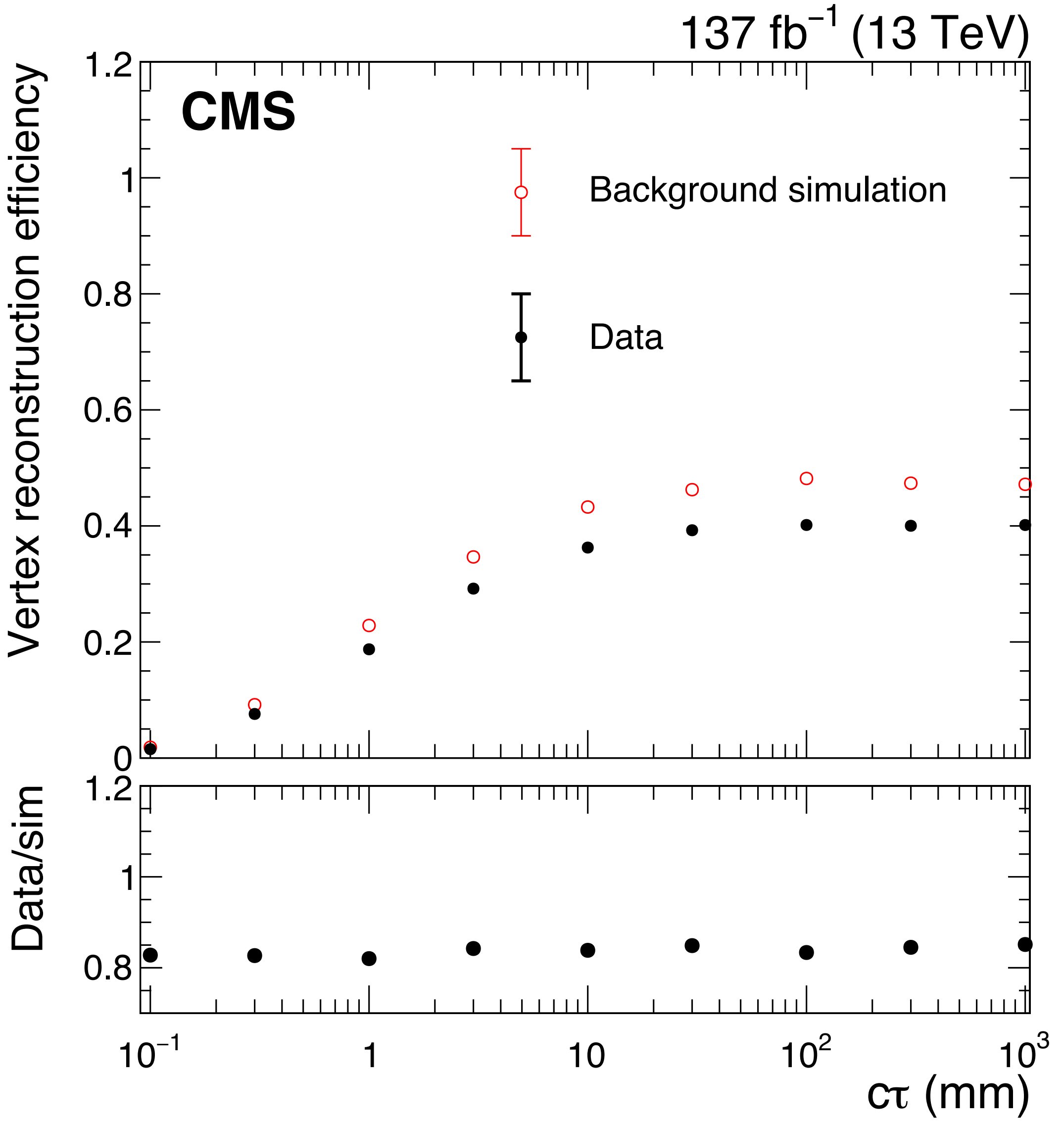
Signal Efficiency

- **Vertex reconstruction efficiency** is calculated as:

$$eff = \frac{N_{reconstructed\ vertices}}{N_{all\ artificial\ vertices}}$$

- The efficiency increases with $c\tau$ and reaches a plateau after 10mm
- Data/simulation ratio stays around 85% for different $c\tau$
- The data/simulation ratio is used to
  - Calibrate the vertex reconstruction efficiency
  - Calculate systematic uncertainty

$m_{\tilde{g}} = 2000GeV,\ m_{\tilde{\chi}^0} = 1800GeV$



Signal Efficiency

- **ML tagging efficiency** is calculated as

$$eff = \frac{N_{S_{\rm ML}>0.2}}{N_{all\ events}}$$

- ML recognizes most of the events as signal → **model independence**

- The data/simulation ratios are close to one for different $c\tau$

- The data/simulation ratio are used to calculate systematic uncertainty

$m_{\tilde{g}} = 2000GeV,\ m_{\tilde{\chi}^0} = 1800GeV$