Searches for long-lived particles using displaced jets and displaced vertices at CMS

Jingyu Luo

Brown University

On behalf of the CMS Collaboration

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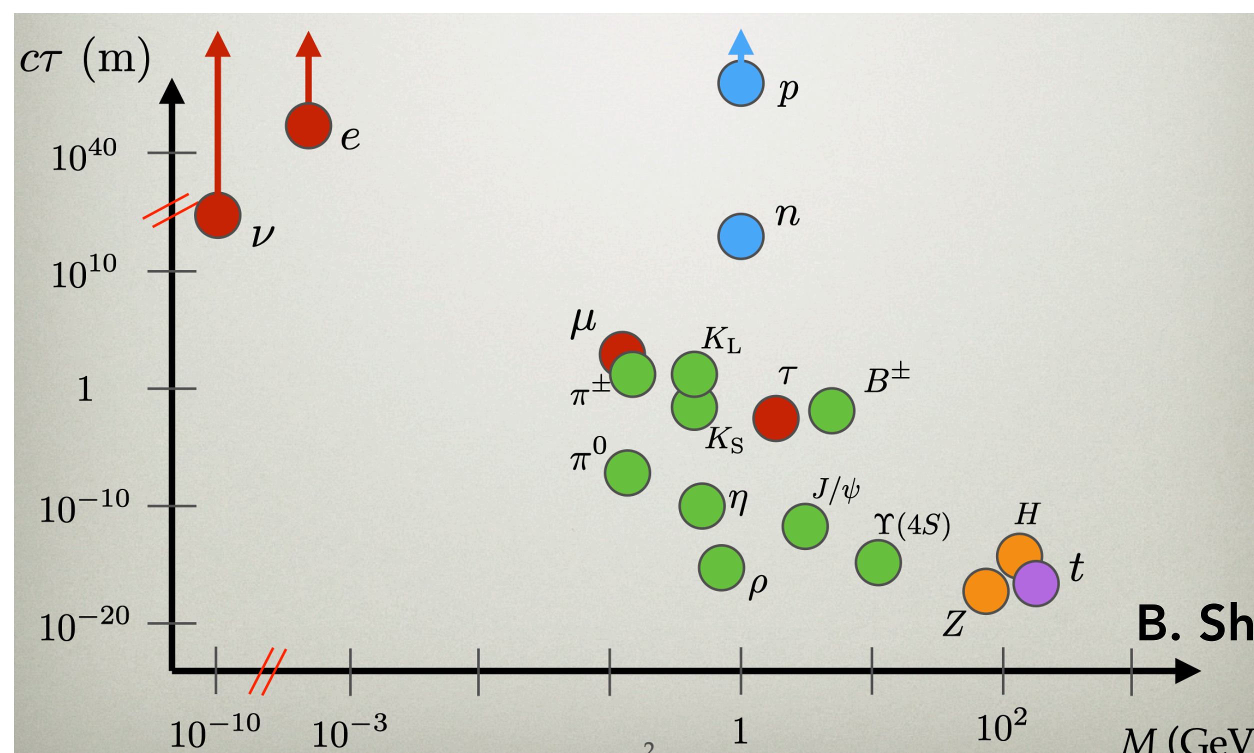
Why long-lived particles

- The existence of long-lived particles (LLPs) is a common occurrence in many beyond the standard model scenarios

$$\tau_0^{-1} = \Gamma \sim \frac{1}{m} \int d\Pi_f \left|\mathcal{M}_{\rm decay}\right|^2,$$

- A given particle is long-lived when:
  - The relevant coupling is small;
  - The decay is suppressed by some large scale;
  - The allowed final state phase space is small (i.e. with a nearly-degenerate mass spectrum)

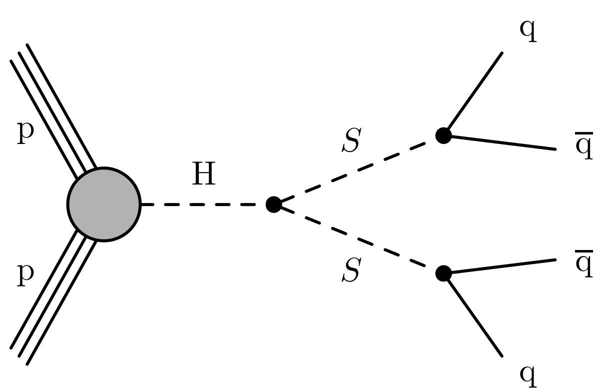
- Many particles in the standard model are long-lived. LLPs in BSM scenarios are also well-motivated.



B. Shuve

LLP examples: exotic Higgs decays

- SM-like Higgs decays to LLPs in the hidden sector, the LLPs then decays back to SM particles



[Strassler, Zurek, 2006]
[Craig, Knapen, Longhi, 2015],
[Craig, Katz, Strassler, Sundrum, 2015],
[Curtin, Vehaaren, 2015]
…

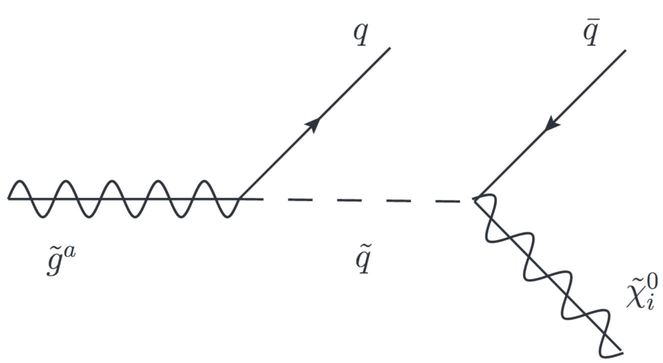
> *"The idea of looking for hidden sectors is so natural, and so well-motivated, and so interesting, that you should just start with that."*
>
> — **Nima Arkani-Hamed, IAS, Princeton**

LLP examples: split SUSY

- **Split-SUSY:** **the squarks are ultra-heavy, while gauginos can still be light through the protection of *R*-symmetry → a split mass spectrum**

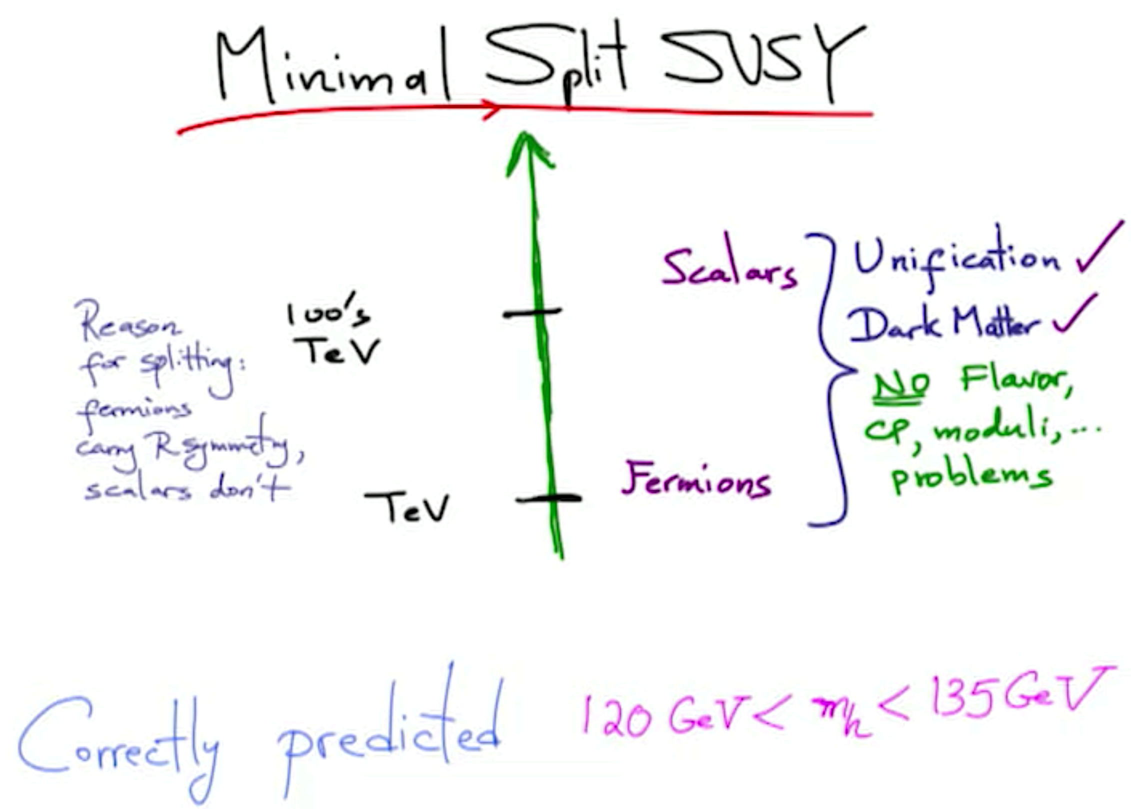
[Arkani-Hamed, Dimopoulos, 2004]
[Giudice, Romanino, 2004]
[Arvanitaki, Craig, Dimopoulos, Villadoro, 2012]
[Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski 2012],…

Important consequences of split-SUSY:
gluino decays are mediated by heavy squarks
→ gluinos are long-lived.



$$c\tau_0 \sim 10^{-5}\ \mathrm{m}\left(\frac{m_{\tilde{q}}}{\mathrm{PeV}}\right)^4\left(\frac{\mathrm{TeV}}{m_{\tilde{g}}}\right)^5$$

[Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski 2012],…



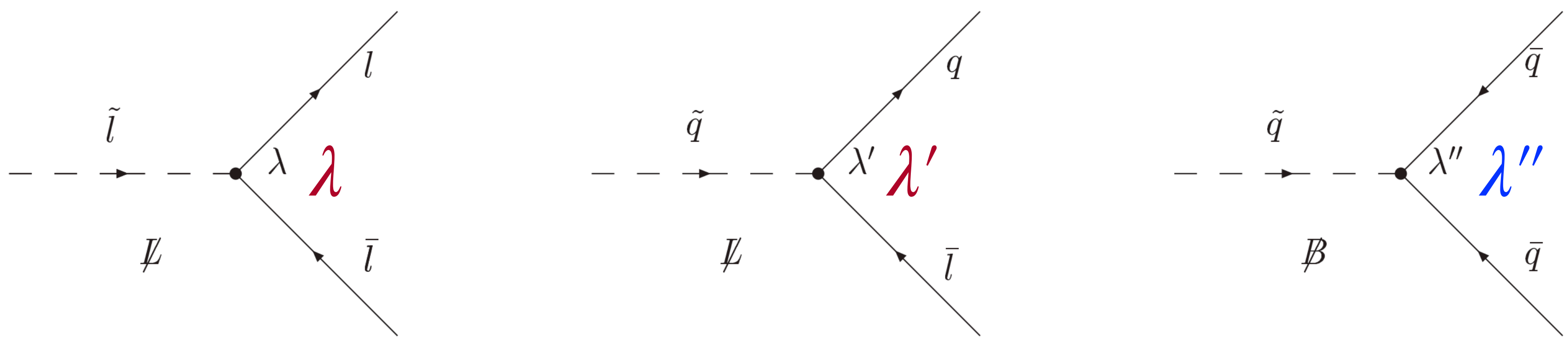
(Nima Arkani-Hamed, Strings 2019)

LLP examples: R-parity violation

- **Renormalizable $SU(3)_c \times SU(2)_L \times U(1)_Y$ -invariant R-parity violating superpotential:**

$$W_{\mathrm{RPV}} = \mu_i' L_i H_u + \frac{1}{2}\lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \frac{1}{2}\lambda''_{ijk} \overline{U}_i \overline{D}_j \overline{D}_k.$$

[S. Weinberg, 1982],
[L. Hall, M. Suzuki, 1984],
…



- RPV couplings usually need to be small→ the lightest SUSY particle (LSP) is usually long-lived→ **displaced jets, displaced leptons**

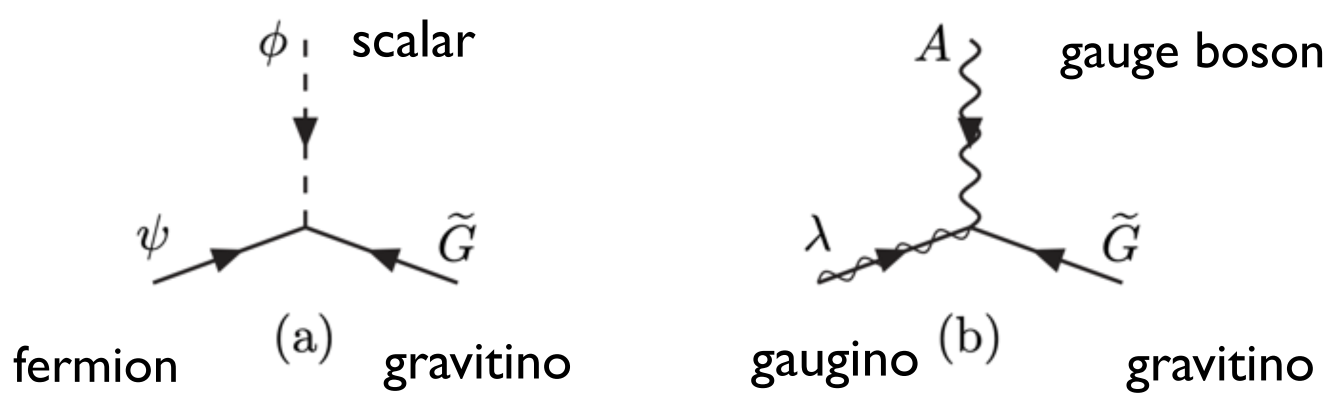
  - ➢ other possibilities : dynamical-RPV through non-renormalizable nonholomorphic interactions

[Csaki, Kuflik, Volansky 2014]

LLP examples: gauge mediation

- **The couplings of gravitino to other particles are suppressed by the SUSY-breaking scale.**

$$\propto \frac{1}{\langle F \rangle_0}$$



- Gauge-mediated supersymmetry breaking (GMSB): gravitino is the LSP, the NLSP decay is suppressed by the SUSY breaking scale → the NLSP is long-lived
- **Traditional GMSB**: the NLSP is usually bino-like neutralino or stau→ **displaced photon, displaced tau**
- **General Gauge Mediation:** the NLSP could be any superparticle [Meade, Seiberg, Shih, 2008],...

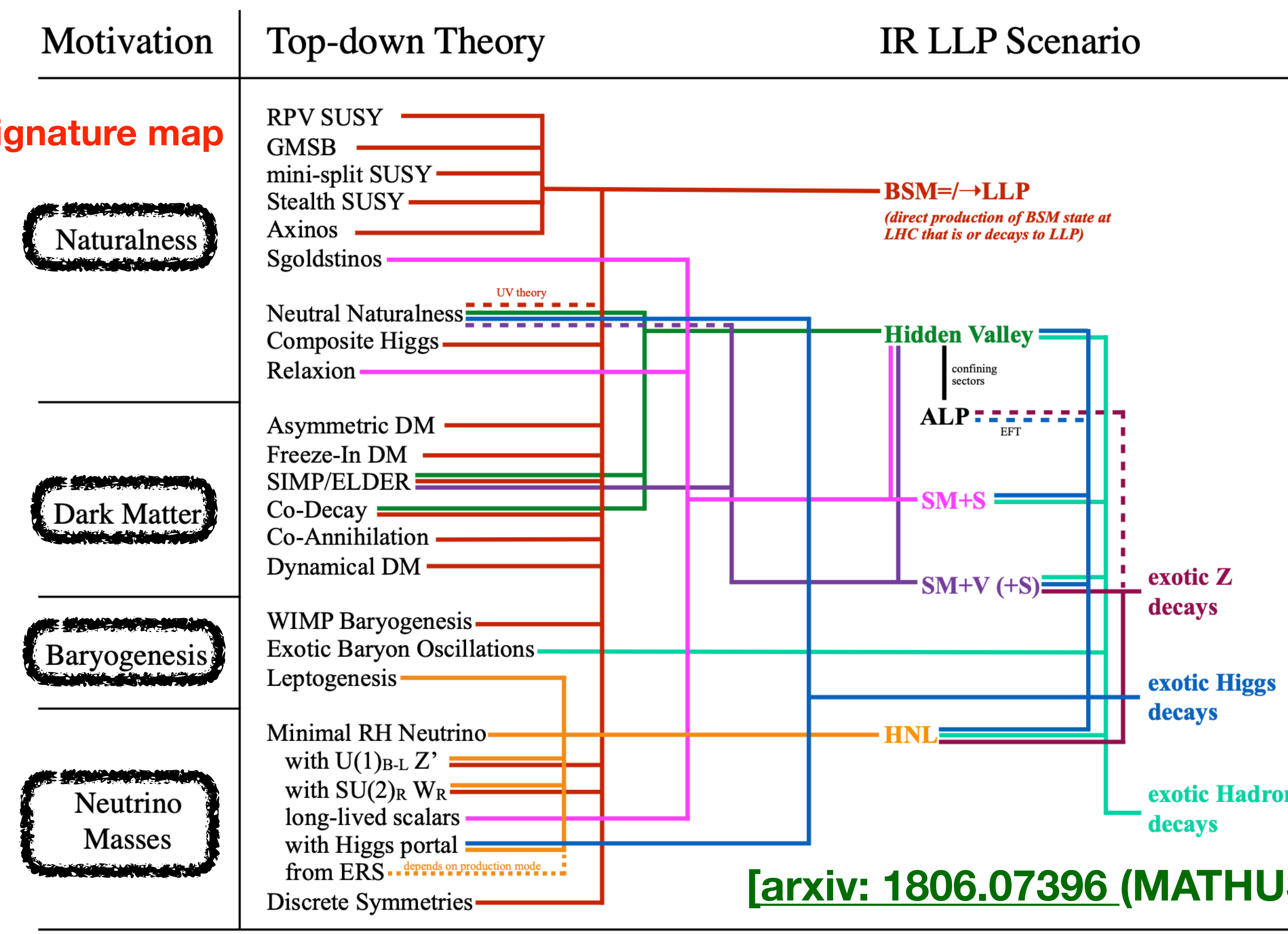
NLSP lifetime: $$c\tau_0 \sim 0.3 \text{ mm} \left(\frac{100 \text{ GeV}}{m_{\text{NLSP}}}\right)^5 \left(\frac{\sqrt{\langle F \rangle_0}}{100 \text{ TeV}}\right)^4$$

Motivations of displaced-jets/vertices searches

❖ Theoretical motivations are extremely rich:

- Other examples include stealth SUSY, “hidden-valley” models, heavy neutral leptons, axions, dark matter candidates, …

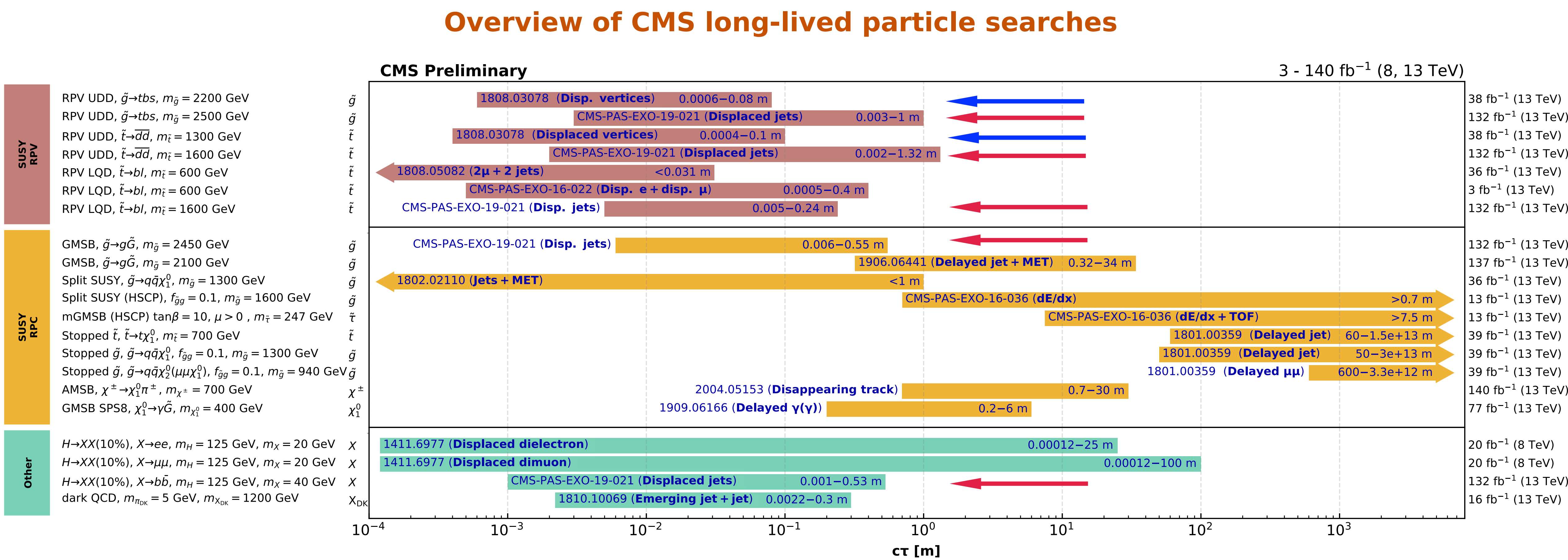
(neutral) LLP signature map



[arxiv: 1806.07396 (MATHUSLA physics case)]

Overview of CMS LLP program

❖ Overview of current CMS LLP results



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.

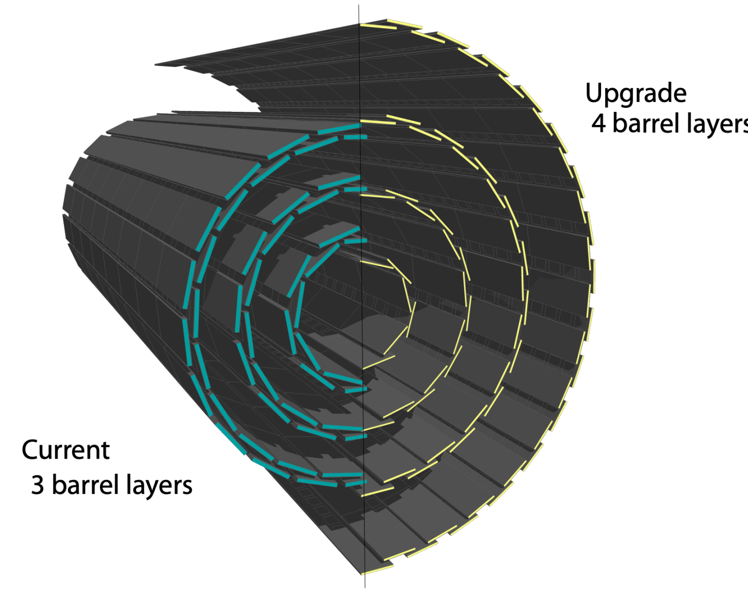
❖ CMS LLP program has a wide coverage on a variety of signatures/ lifetimes/models;

❖ Today I'll mainly talk about two recent results:

- Displaced-jets search (CMS-PAS-EXO-19-021)
- Displaced-vertices search (CMS-PAS-EXO-19-013)

Tracking at CMS

- **In 2017, the original CMS pixel detector was replaced with a new "phase-1" pixel detector**
  - Additional barrel layer;
  - Innermost pixel layer moved closer to the beam line;
  - Reduced material budget.

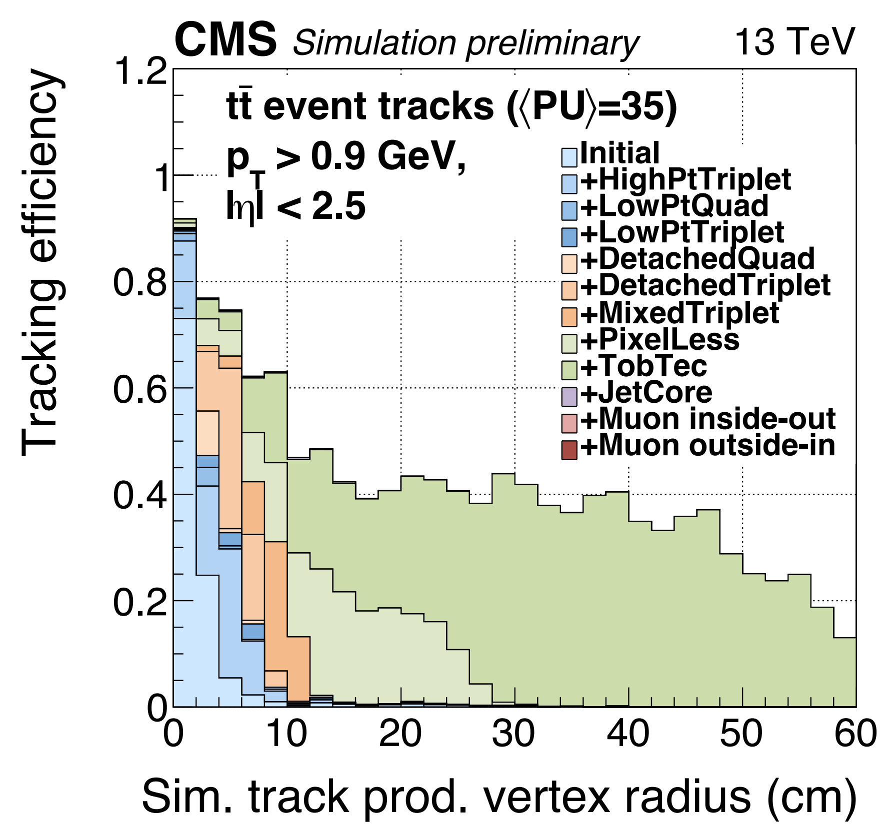


Improved tracking/vertexing performance

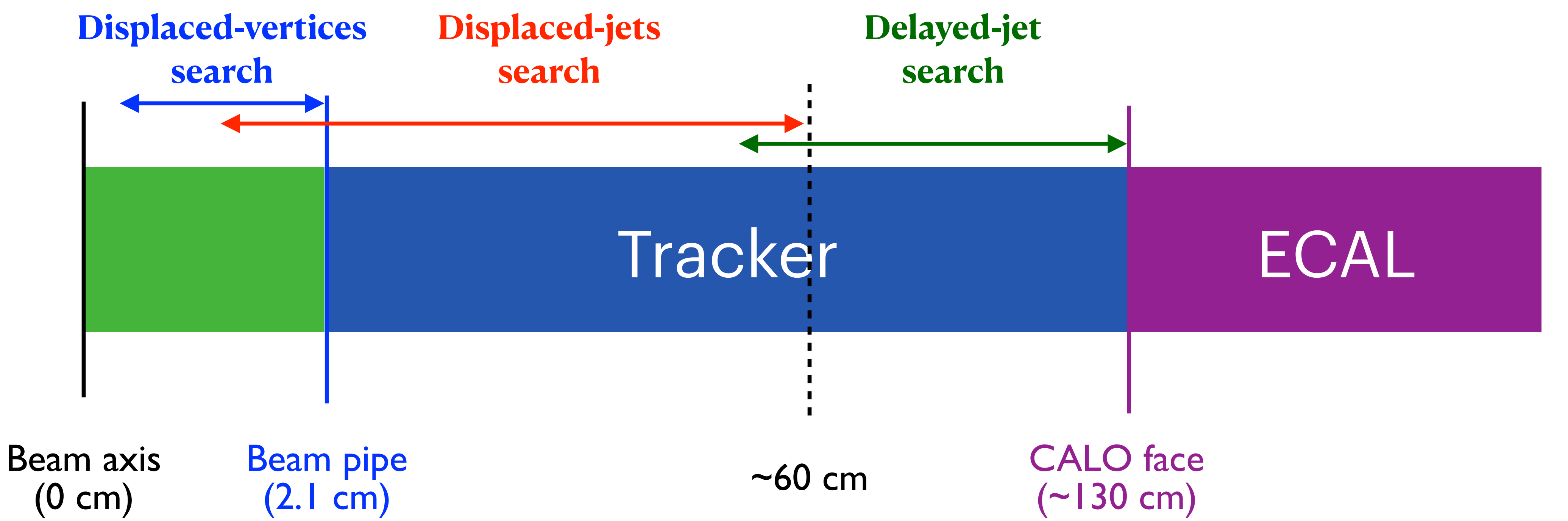
- **CMS adopts an iterative approach for track reconstruction**
  - Earlier iterations target prompt tracks;
  - Later iterations focus on more challenging displaced tracks.

Also available in the high-level trigger system of CMS

Crucial for searches for LLPs decaying inside the inner tracking system of CMS



Searches for LLPs with hadronic decays at CMS



- **Displaced-vertices search:** displacement between ~0.1 mm and 21 mm, $H_T > \sim 1000 \text{GeV}$;
- **Displaced-jets search:** displacement between ~1 mm and ~60 cm, $H_T > \sim 400 \text{GeV}$ (With specialized displaced-jet triggers);

(H_T: scalar sum of jet p_T for jets with $p_T > 40$ GeV and $|\eta| < 2.5$)

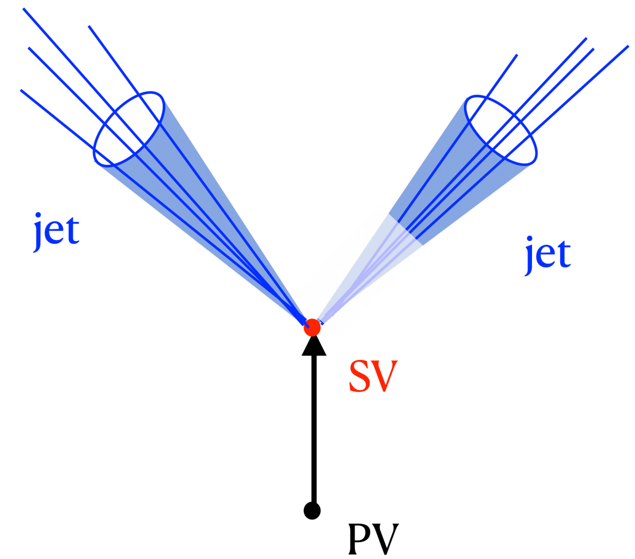
- **Delayed-jet search (utilizing ECAL timing):** displacement between ~50 cm and ~130 cm, $p_T^{miss} > 300 \text{GeV}$; (arXiv:1906.06441)

Overview of the displaced-jets search

Displaced-jets search

CMS-PAS-EXO-19-021 (132 fb^{-1})

[2016-only results (36fb-1): arXiv: 1811.07991]



- Special displaced-jet triggers to lower H_T threshold (from ~1000GeV to ~400GeV);
- Search for 1 displaced (secondary) vertex accompanied with 2 non-prompt jets;
- Displacement of the secondary vertex is between ~1 mm and ~60 cm (within the tracker acceptance);
- Multivariate discriminant based on customized variables to separate signal from background;
- Sensitive to a large number of LLP models;

Goals of the displaced-jets search

Given the large number of BSM scenarios where displaced-jets signatures can appear, it is important to conduct a model-independent search.

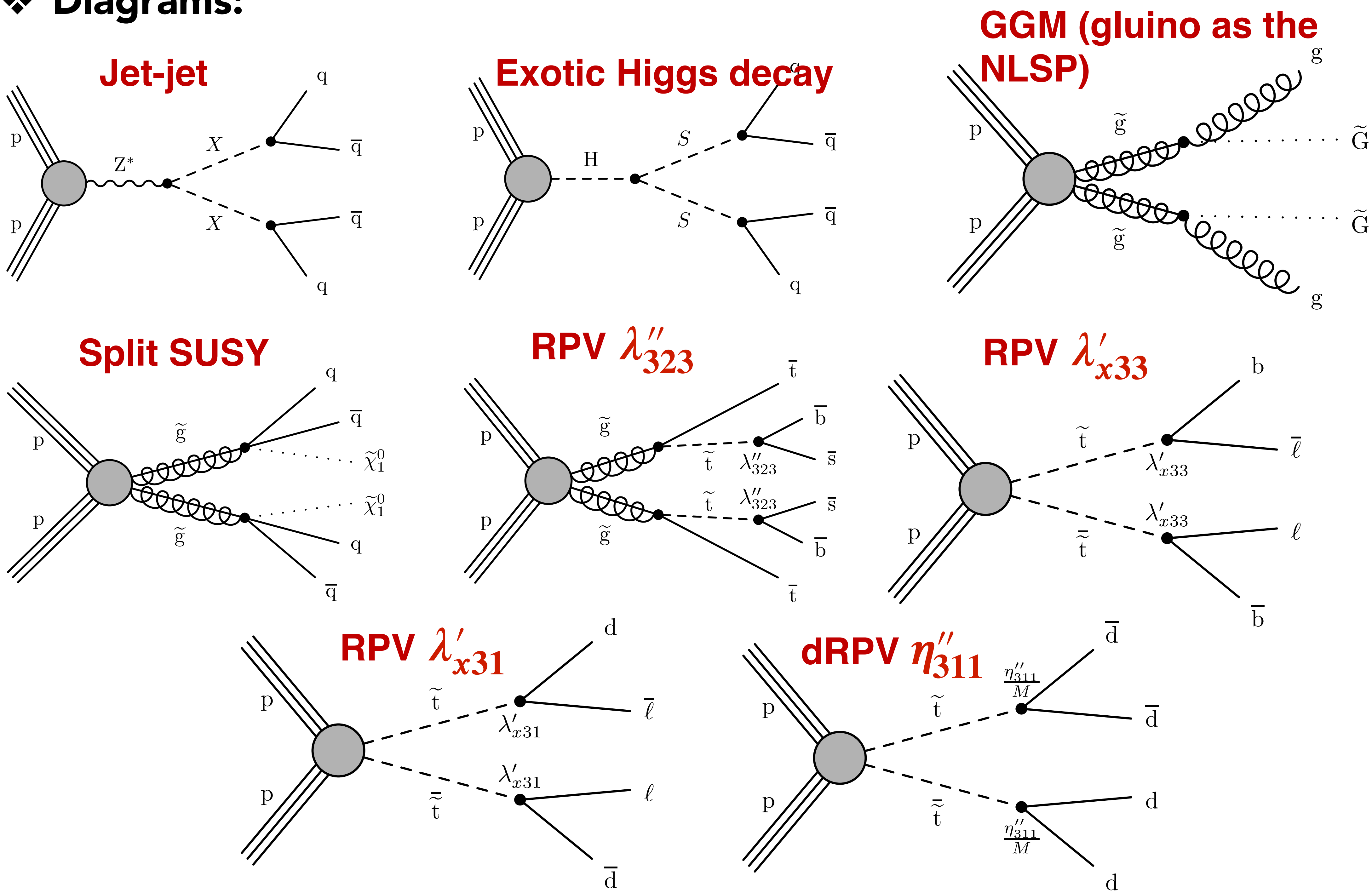
- **Our goal for the displaced-jets search:** to develop a search that is as model independent as possible, while still can have excellent sensitivities to each individual channel

$$\text{LLP} \rightarrow j + \ell/\text{MET},$$
$$\text{LLP} \rightarrow jj,$$
$$\text{LLP} \rightarrow jjj,$$
$$\ldots$$

In addition, we also wanted our search to cover a large range of LLP masses.

Signal models

❖ **Diagrams:**



Challenges of the displaced-jets search

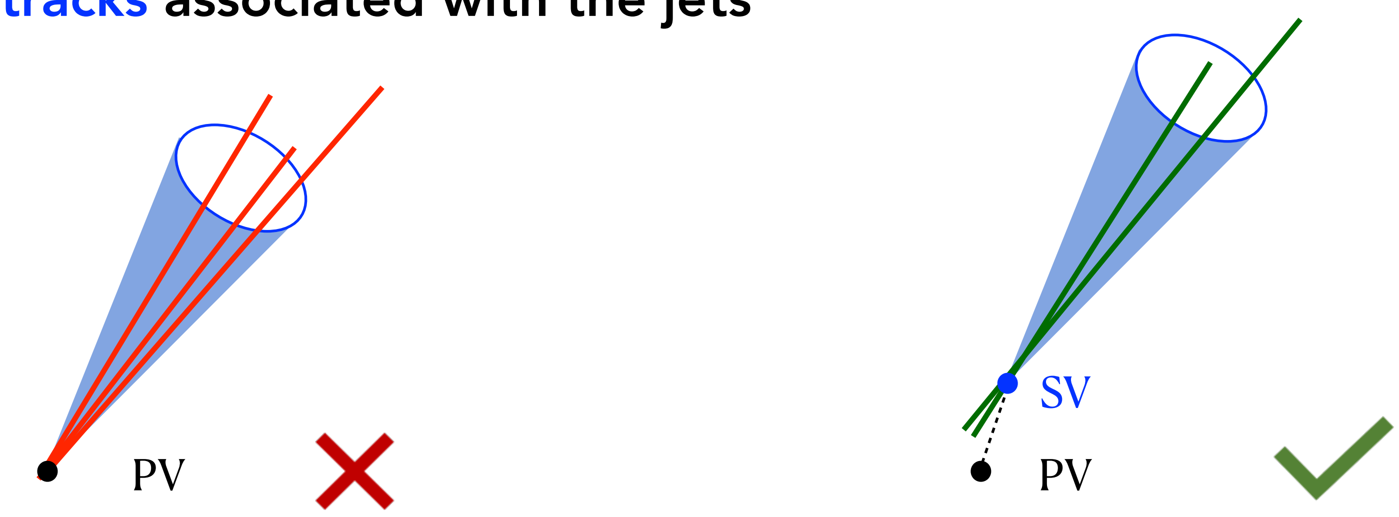
- **With the goal of conducting a model-independent displaced-jets search, there comes many challenges:**
  - Need specialized triggers to have minimum requirement on additional objects;
  - Standard reconstructions are tuned for prompt objects, need to develop special reconstruction techniques;
  - Background rejection is extremely challenging — need a background rejection power of ~10^{10} in total, ~10^{7} offline (due to the enormous QCD cross section)

    (Background sources: nuclear interactions, heavy flavor decays, randomly crossing tracks)
  - Offline discrimination techniques need to be carefully designed to be inclusive to different LLP models

Specialized displaced-jet triggers

- The high-level trigger (HLT) system of CMS has the ability of reconstructing prompt tracks and displaced tracks online.
  - Enables us to capture the displaced-jet signatures in a model-independent way;
  - Unique sensitivities to low-mass LLPs (e.g. Exotic decays of the SM-like Higgs)

- We can tag displaced-jets with the HLT system by counting the number of prompt/displaced tracks associated with the jets



- Veto jets with a large number of prompt tracks;
- Tag jets with displaced tracks;

Specialized displaced-jet triggers

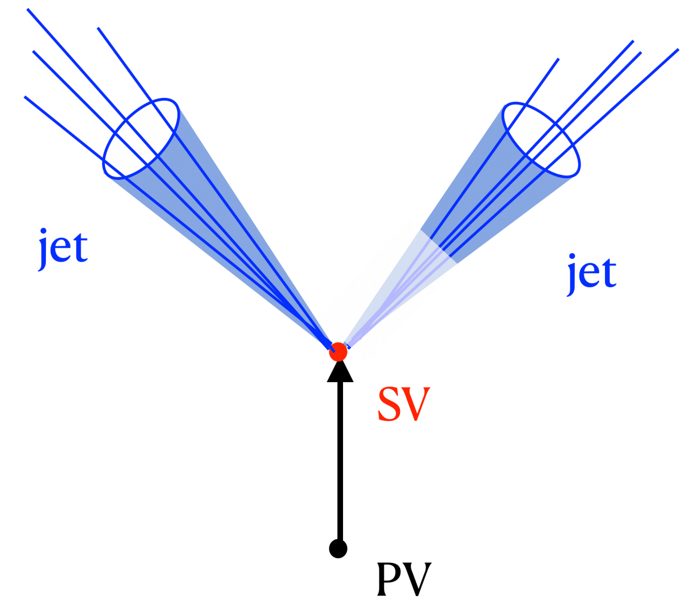
❖ **Implemented two dedicated displaced-jet triggers to lower H_T threshold**

"Displaced" trigger	**"Inclusive" trigger**
Online CALO $H_T >$ 430 GeV	Online CALO $H_T >$ 650 GeV
At least **two online jets,** each jet satisfying:	
$p_T >$ 40 GeV, $|\eta| < 2.0$;	$p_T >$ 60 GeV, $|\eta| < 2.0$;
At most two **prompt tacks** (IP_{2D}<1mm)	At most two **prompt tacks** (IP_{2D}<1mm)
At least one **displaced track** (IP_{2D}>0.5mm, Sig[IP_{2D}]>5)	No requirement

- **"Displaced" trigger:** better efficiency for low-mass LLPs ($m_{\text{LLP}} \lesssim 500$ GeV);
- **"Inclusive" trigger:** better efficiency for high-mass LLPs with small ($\lesssim 3$ mm) or large ($\gtrsim 300$ mm) lifetimes (new development in 2017/2018)

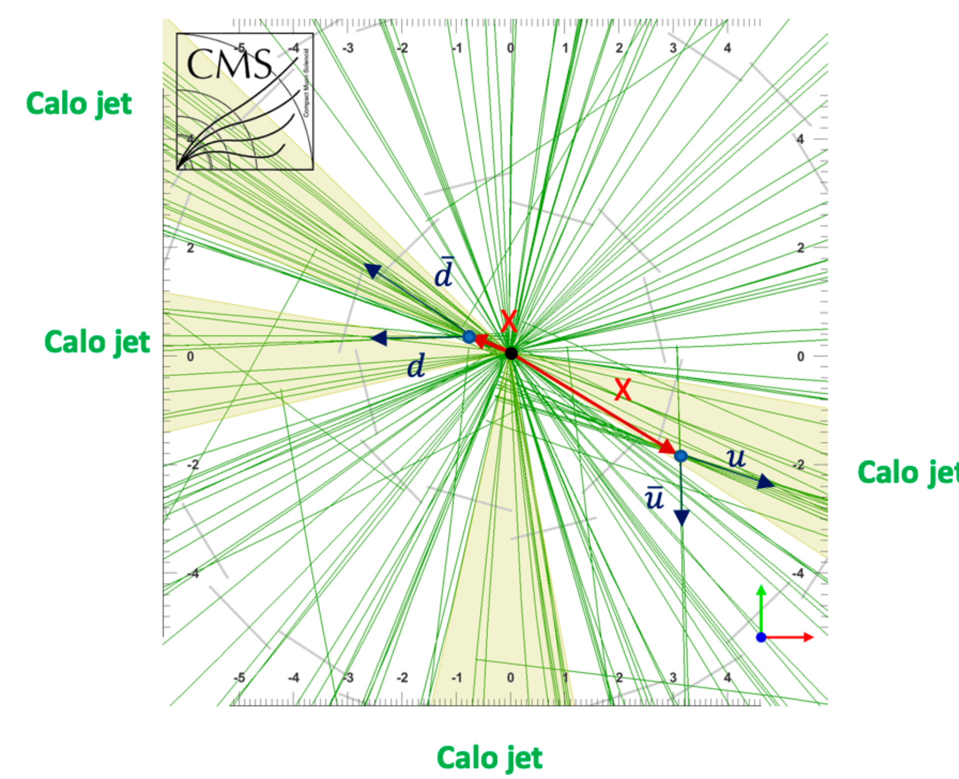
Secondary vertex reconstruction

Standard CMS SV reconstruction is tuned for b-tagging, and is not efficient in reconstructing decays of LLPs



- **Track selection:** $p_{\mathrm{T}} > 1$ GeV, "high purity" ;
- **Tracks are associated to jets by requiring** $\Delta R < 0.5$;
- **Examine all possible jet pairs (passing offline jet** p_{T} **selections); For each jet pair, we attempt to reconstruct an SV using displaced tracks associated with the two jets:**
  - Two-body decay is very common;
  - Even if one of the decay products is "invisible", we can still find two non-prompt jets if the LLPs are pair produced;
  - Can also be sensitive to three-body, four-body decays, etc.

Reconstructed tracks (and CALO jets) in a simulated LLP event



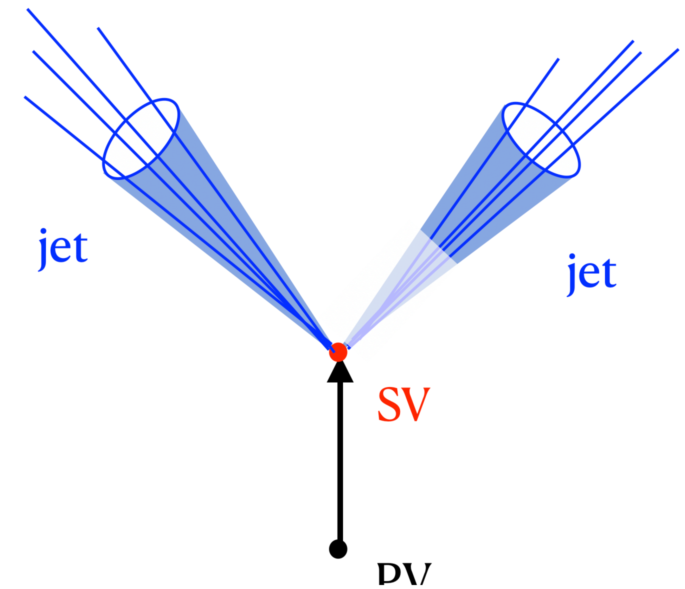
Secondary vertex reconstruction

- **Displaced tracks:** IP_{2D}>0.5mm, Sig[IP_{2D}]>5
- **Reconstruct a secondary vertex using the displaced tracks associated with the two jets;**
- **Vertex reconstruction is achieved using the adaptive vertex fitter** (a deterministic annealing algorithm);

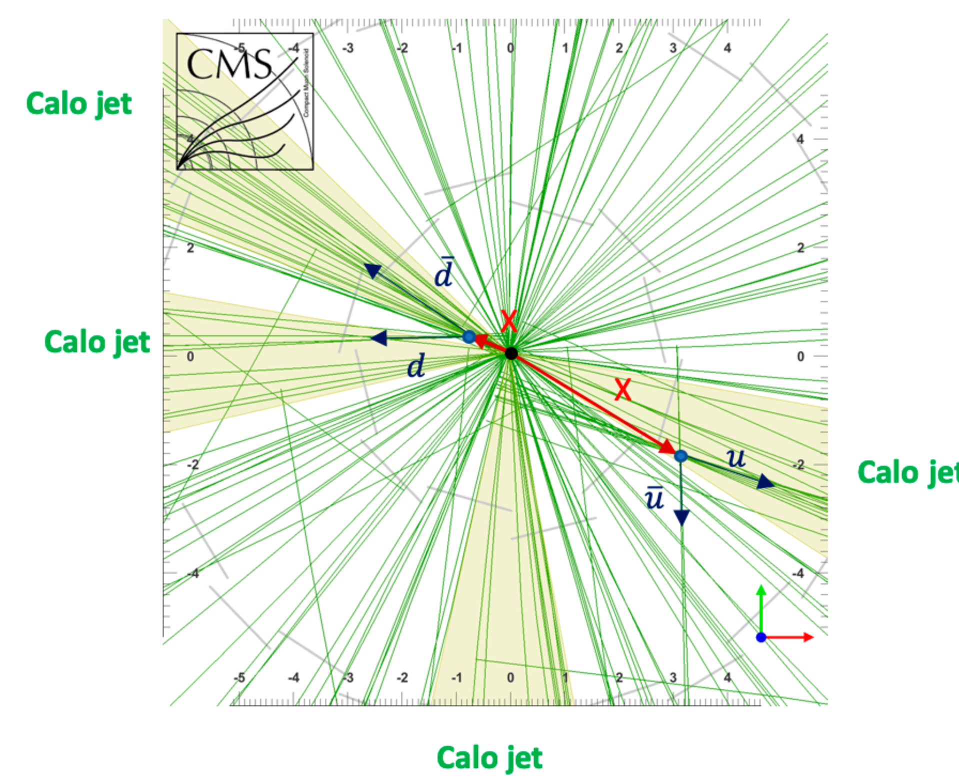
[Waltenberger, Frühwirth, & Vanlaer, J. Phys. G 34 (2007) N34

- **Vertex fitting quality:** $\chi^2/\mathrm{ndof} < 5$

The SV is not required to have tracks from both jets, such that the search can also be sensitive to LLP $\rightarrow j + \ell$/MET, and thus is more model independent

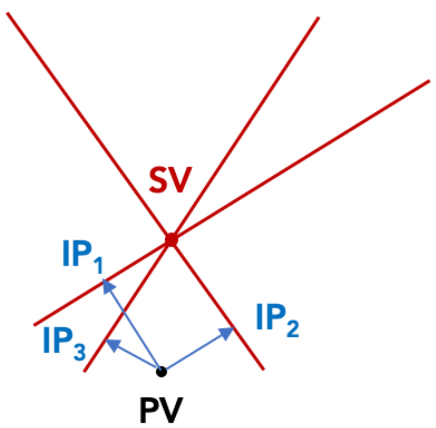


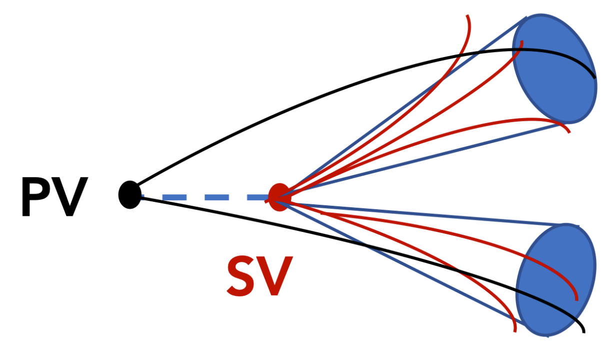
Reconstructed tracks (and CALO jets) in a simulated LLP event

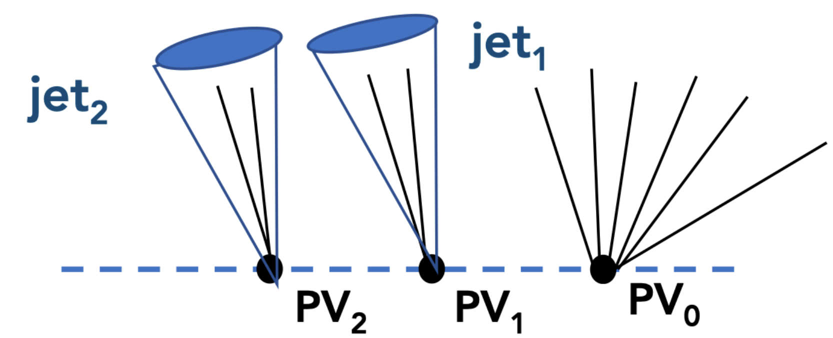


Preselections on SV/dijet candidates

- **Vertex invariant mass > 4GeV, p_T > 8GeV: thresholds are kept to be relatively small to be sensitive to low-mass LLPs.**
- **Developed a set of customized variables to further improve the signal-background discrimination while still remain inclusive:**







- Second largest IP_{2D} significance for tracks assigned to the SV.
- Require this quantity to be larger than 15

- Fraction of the charged energy coming from the SV:

$$\frac{\sum_{\mathrm{track}\in\mathrm{SV}} E_{\mathrm{track}}}{\sum_{\mathrm{track}\in\mathrm{dijet}} E_{\mathrm{track}}}$$

- Require this quantity to be larger than 15%

- Energy fraction coming from the most compatible PVs:

$$\zeta = \frac{\sum_{\mathrm{track}\in\mathrm{PV}_1} E^{\mathrm{Jet}_1}_{\mathrm{track}} + \sum_{\mathrm{track}\in\mathrm{PV}_2} E^{\mathrm{Jet}_2}_{\mathrm{track}}}{E_{\mathrm{Jet}_1} + E_{\mathrm{Jet}_2}}$$

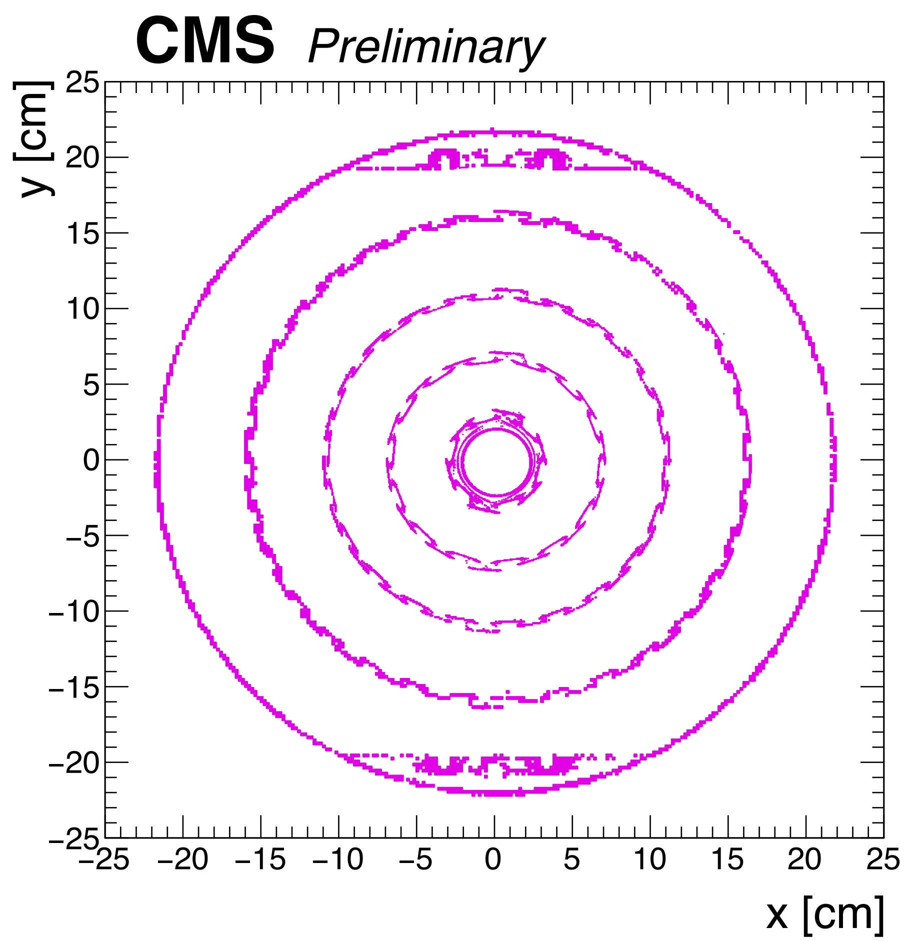
- Require this quantity to be smaller than 0.2

NI-veto map

- ❖ **(Auxiliary) NI-veto map to further improve the rejection against nuclear interactions (new development in 2017/2018)**
- ❖ **Map the pixel detector material in the transverse plane using data in 2017/2018**

◉ **Preselection:** vertex candidates overlapping with the NI-veto map are vetoed;

- The loss of fiducial volume for r<30cm is ~4%;
- The efficiencies for signal events to pass this requirement are generally well above 90%.



(~ × 3 gain in background rejection after all the other selections applied)

Summary of preselection criteria

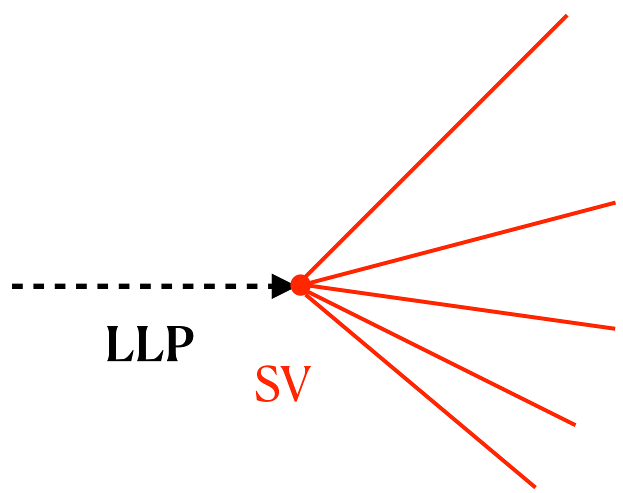
❖ **All the dijet/vertex candidates are required to satisfy following preselection criteria**

Secondary-vertex/dijet variable	Requirement
Vertex χ^2/n_{dof}	<5.0
Vertex invariant mass	>4 GeV
Vertex transverse momentum	>8 GeV
Second largest two-dimensional IP significance	>15
Vertex track energy fraction in the dijet	>0.15
ζ (charged energy fraction associated with compatible primary vertices)	<0.20
Vertex position in the x-y plane doesn't overlap with the tracker material map.	

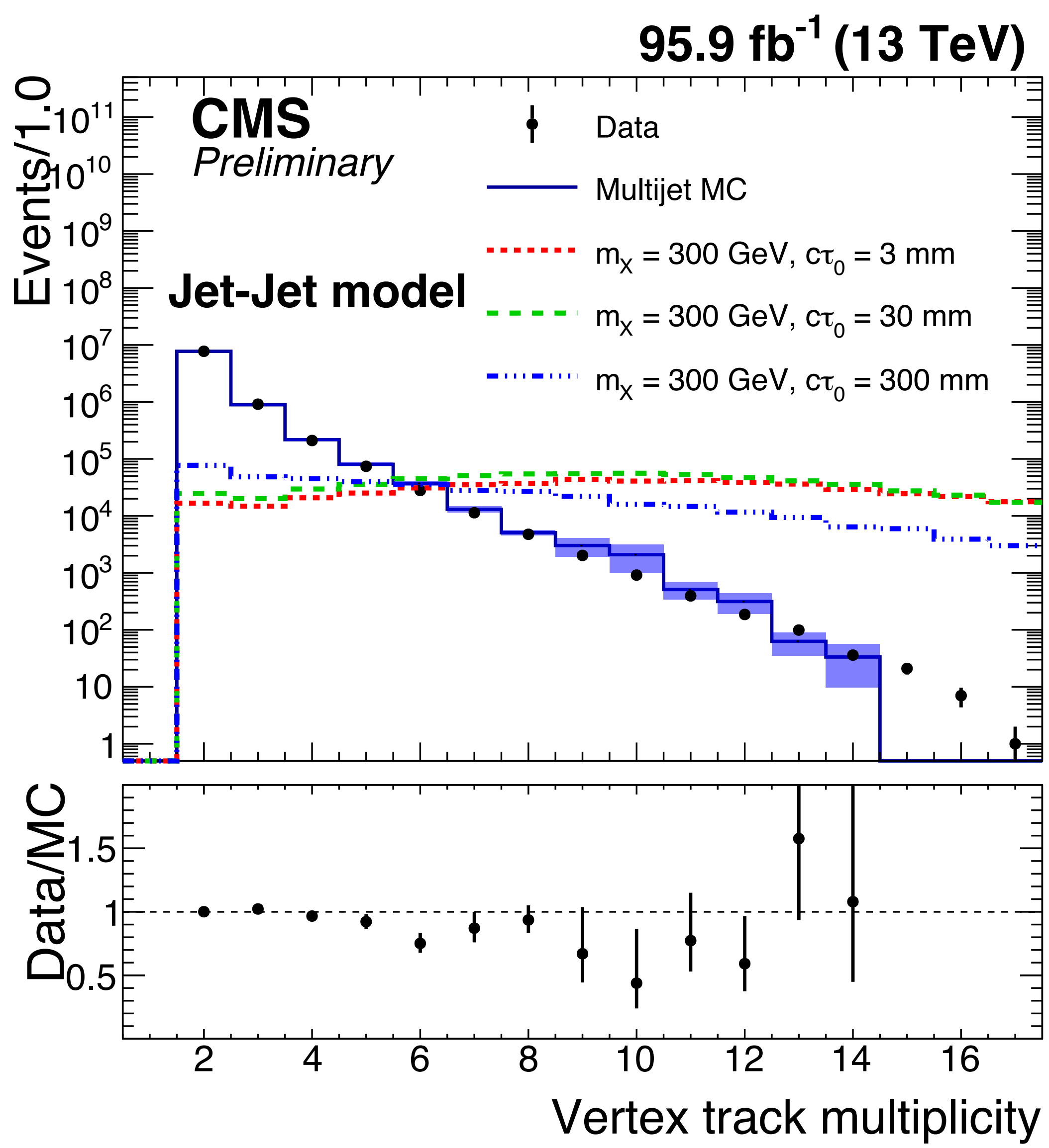
The preselection criteria are efficient for different LLP models with different final-state topologies.

Vertex track multiplicity

❖ **In addition to the preselection variables, we further build a MVA discriminant using some additional variables**

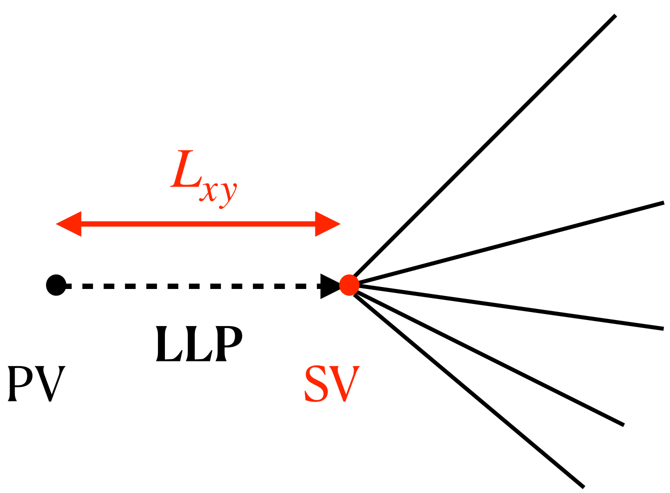


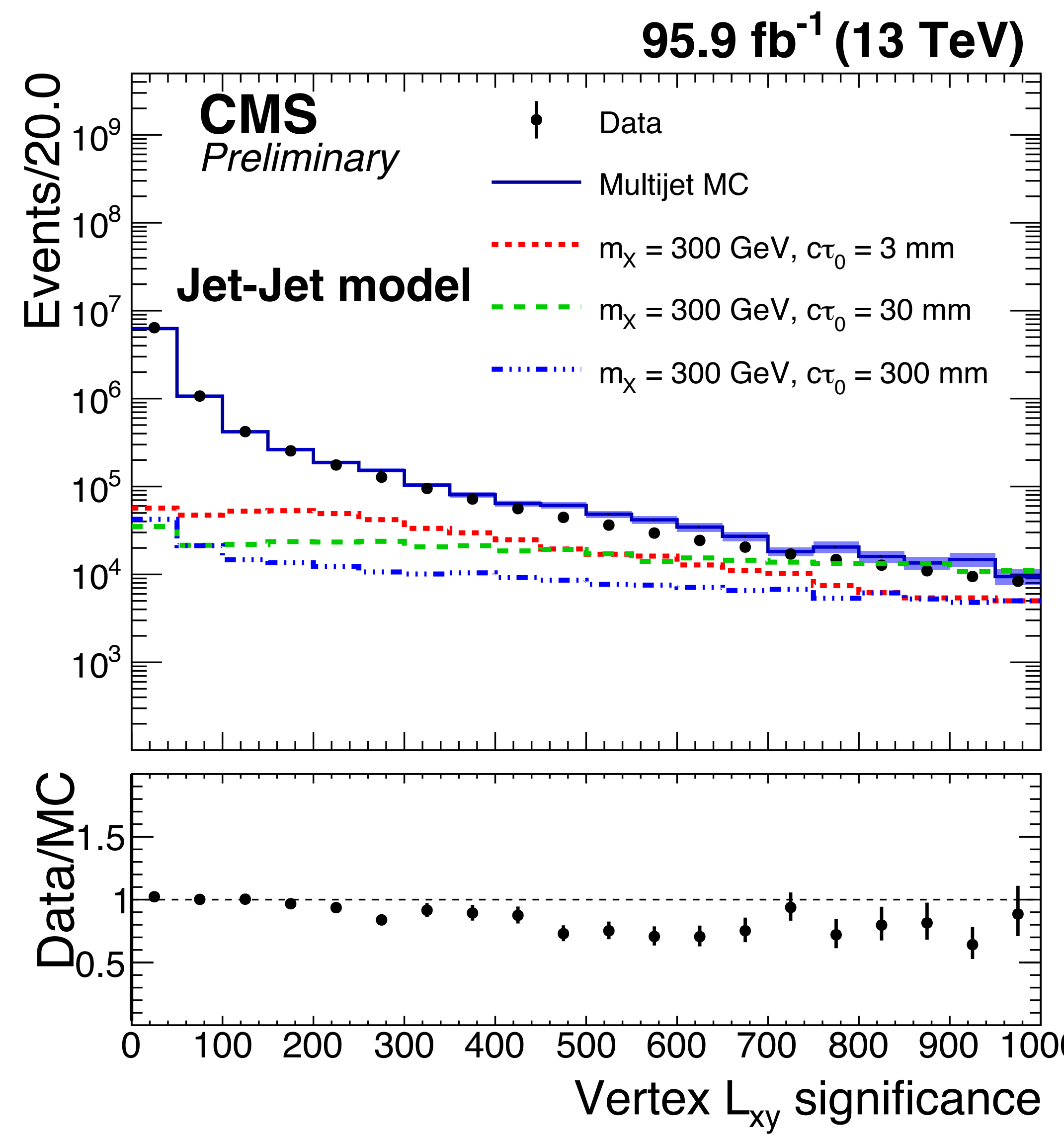
Number of tracks assigned to the secondary vertex



Transverse decay length significance

❖ **In addition to the preselection variables, we further build a MVA discriminant using some additional variables**



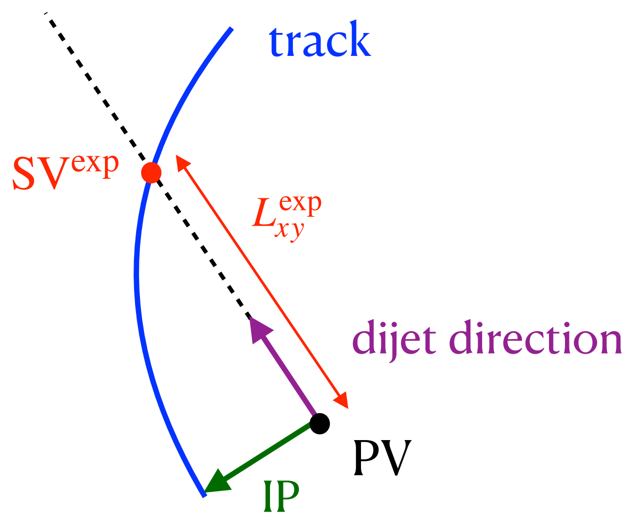


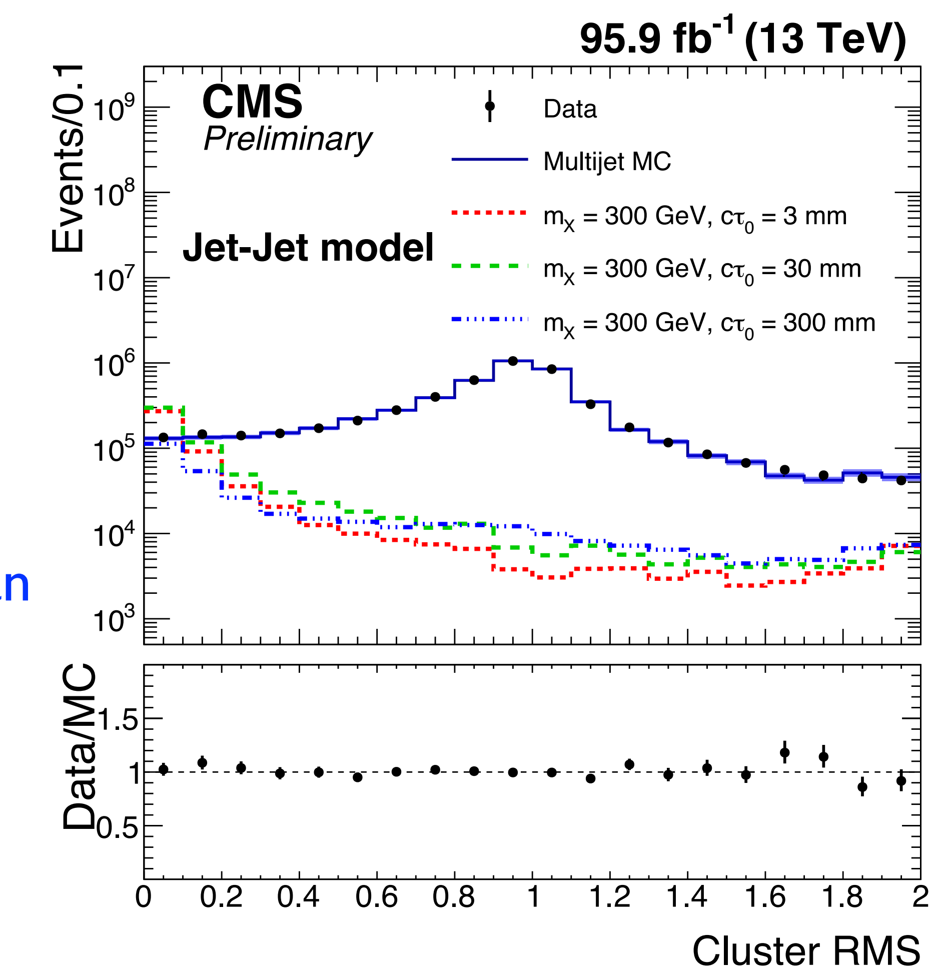
L_{xy} : **transverse decay length of the secondary vertex;**

L_{xy} **significance:** $L_{xy}/\sigma[L_{xy}]$

Cluster RMS

- ❖ Also developed other special variables for discrimination
- ❖ The idea is to check the consistency between the SV system and the dijet system



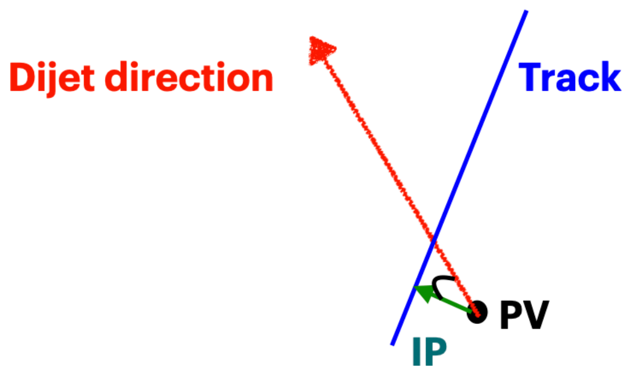


- if the dijet system is consistent with the SV system, we can estimate L_{xy} of the SV using impact parameter of each track and the dijet direction;
- We can then cluster the estimated L_{xy} (L_{xy}^{exp}) using hierarchical clustering algorithm.
- The cluster that is closest to the reconstructed vertex is chosen, an RMS is computed by comparing the cluster and the SV

$$\mathrm{RMS}_{\mathrm{cluster}} = \sqrt{\frac{1}{N_{\mathrm{tracks}}}\sum_{i=1}^{N_{\mathrm{tracks}}}\frac{(L_{xy}^{\mathrm{exp}}(i)-L_{xy})^2}{L_{xy}^2}}$$

Additional variable for discrimination

- Also developed other special variables for discrimination
- The idea is to check the consistency between the SV system and the dijet system

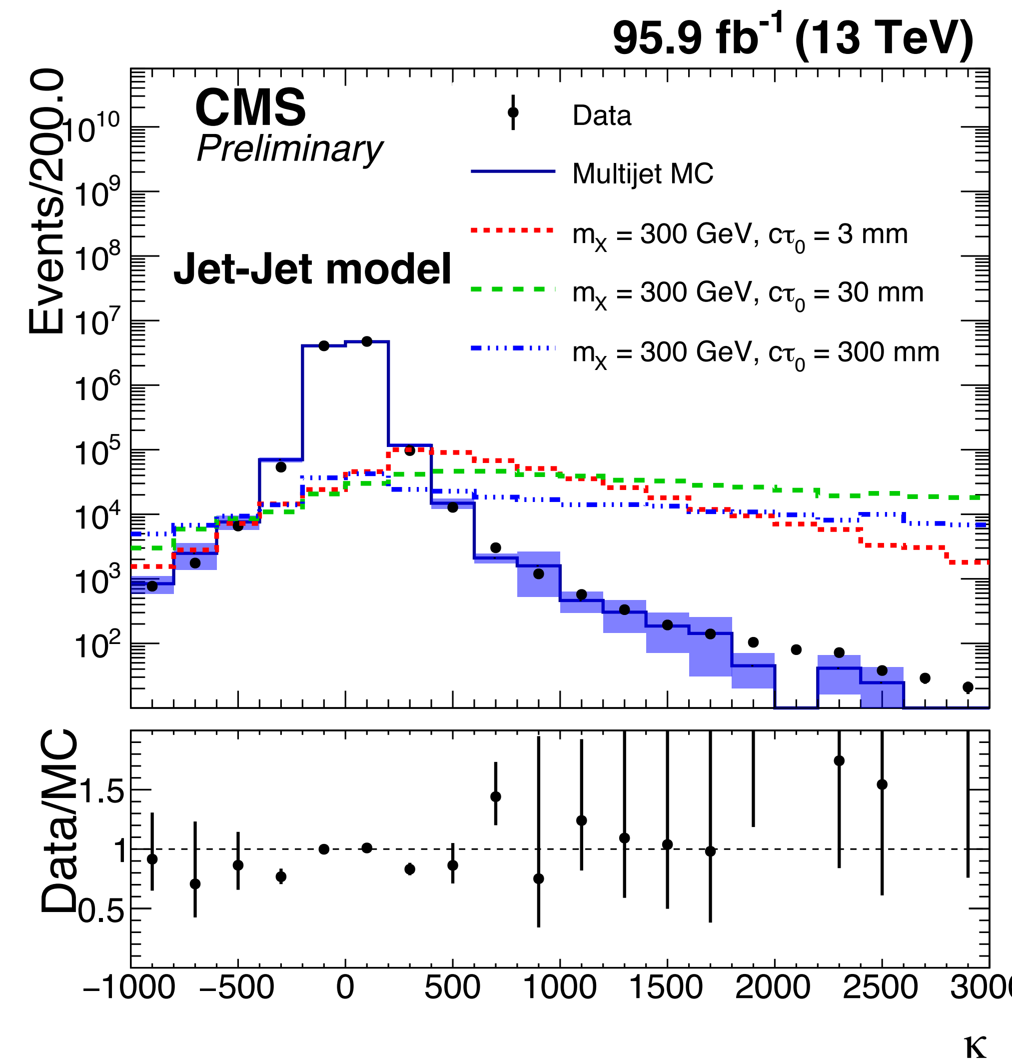


- For each track associated to the SV, assign a sign to the 2D impact parameter based on the angle between the IP and the dijet direction.

- We then take the sum of the signed 2D impact parameter significance of the first 6 tracks:

$$\kappa = \sum_1^6 \mathrm{Sig}[\mathrm{IP}_{2D}]$$

(new development in 2017/2018)



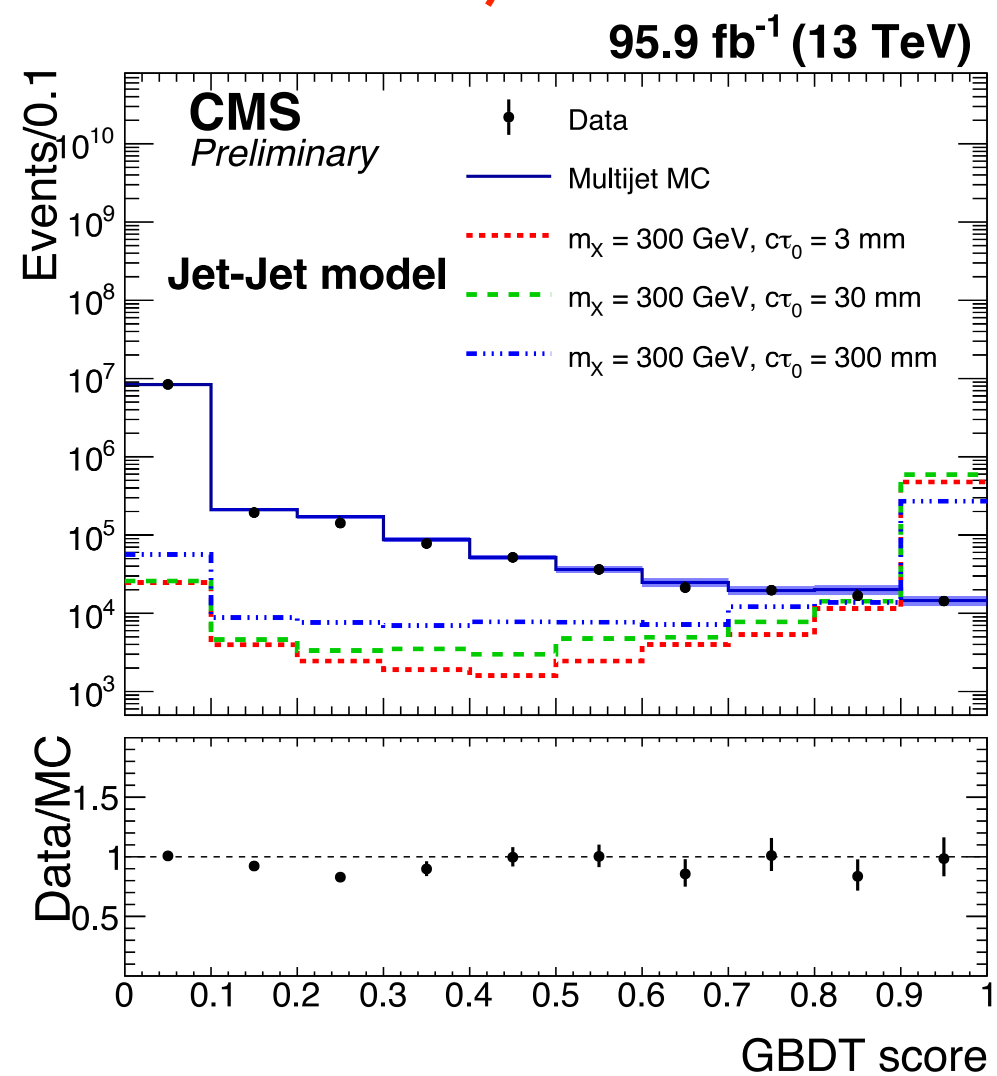
Multivariate discriminant based on gradient boosting

❖ Use gradient boosted decision tree (GBDT) as a multivariate discriminant **(new development in 2017/2018)**

[J. Friedman, Ann. Statist. 29 (2001) 1189]

◉ **Input variables:**
- Vertex track multiplicity;
- Significance of L_{xy}
- Cluster RMS;
- $|\kappa|$

◉ **Training samples:**
- **Signal sample:** LLP events with different masses and lifetimes
- **Background sample:** data in the control region (the statistics of simulated QCD events is limited)



The input variables were carefully designed and selected, such that the GBDT is efficient for different LLP models, masses, and lifetimes.

Final selections and background prediction

❖ In the vertex/dijet candidates passing preselections, choose the one with the largest GBDT score, and the smallest χ^2/ndof.

◉ **Three final selection criteria:**

Optimized selections:

Selection 1:
For the first jet: #3D prompt tracks ≤ 2;

Selection 2:
For the second jet: #3D prompt tracks ≤ 2;

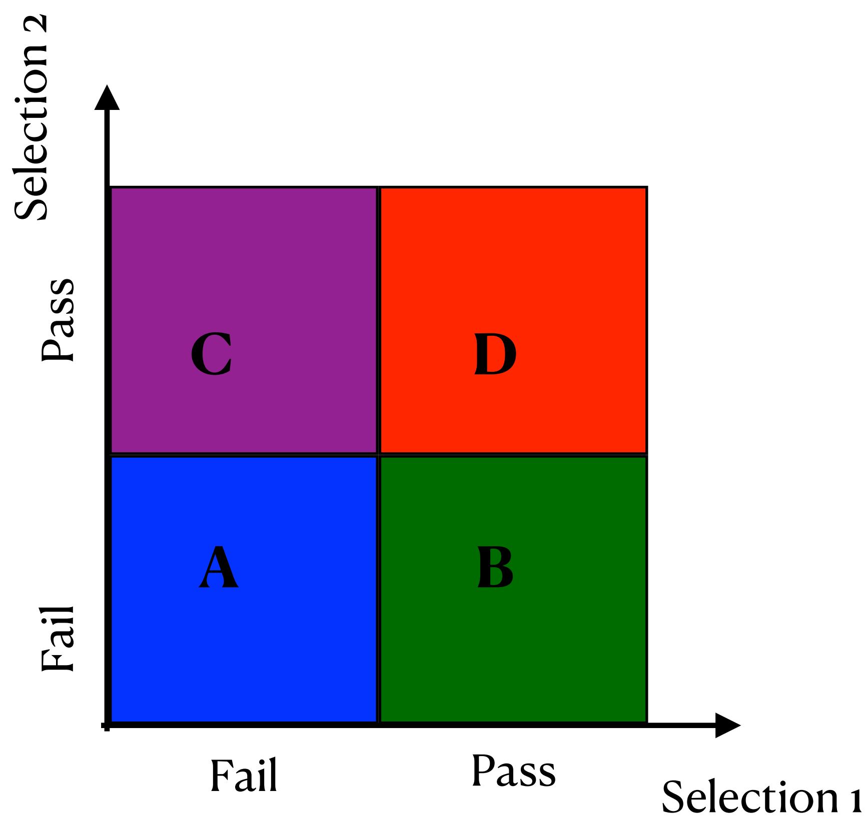
Selection 3: GBDT > 0.988

Region	Selection 1	Selection 2	Selection 3	Event count
A	Fail	Fail	Fail	N_{fff}
B	Pass	Fail	Fail	N_{pff}
C	Fail	Pass	Fail	N_{fpf}
D	Fail	Fail	Pass	N_{ffp}
E	Fail	Pass	Pass	N_{fpp}
F	Pass	Fail	Pass	N_{pfp}
G	Pass	Pass	Fail	N_{ppf}
H	Pass	Pass	Pass	N_{ppp}

◉ **Background prediction is purely data-driven (the statistics of simulated QCD events is far from enough), using ABCD(EFGH) method.**

Final selections and background prediction

- **ABCD(EFGH) method for background prediction:**
  - Selection 3 and selection 1/2 are independent for background processes;
  - Selection 3 and selection 1/2 have strong correlation for signal processes;



$D \sim BC/A$

Example in the two-dimensional case (i.e. with two selections)

Region	Selection 1	Selection 2	Selection 3	Event count
A	Fail	Fail	Fail	N_{fff}
B	Pass	Fail	Fail	N_{pff}
C	Fail	Pass	Fail	N_{fpf}
D	Fail	Fail	Pass	N_{ffp}
E	Fail	Pass	Pass	N_{fpp}
F	Pass	Fail	Pass	N_{pfp}
G	Pass	Pass	Fail	N_{ppf}
H	Pass	Pass	Pass	N_{ppp}

Extended to the three-dimensional case:

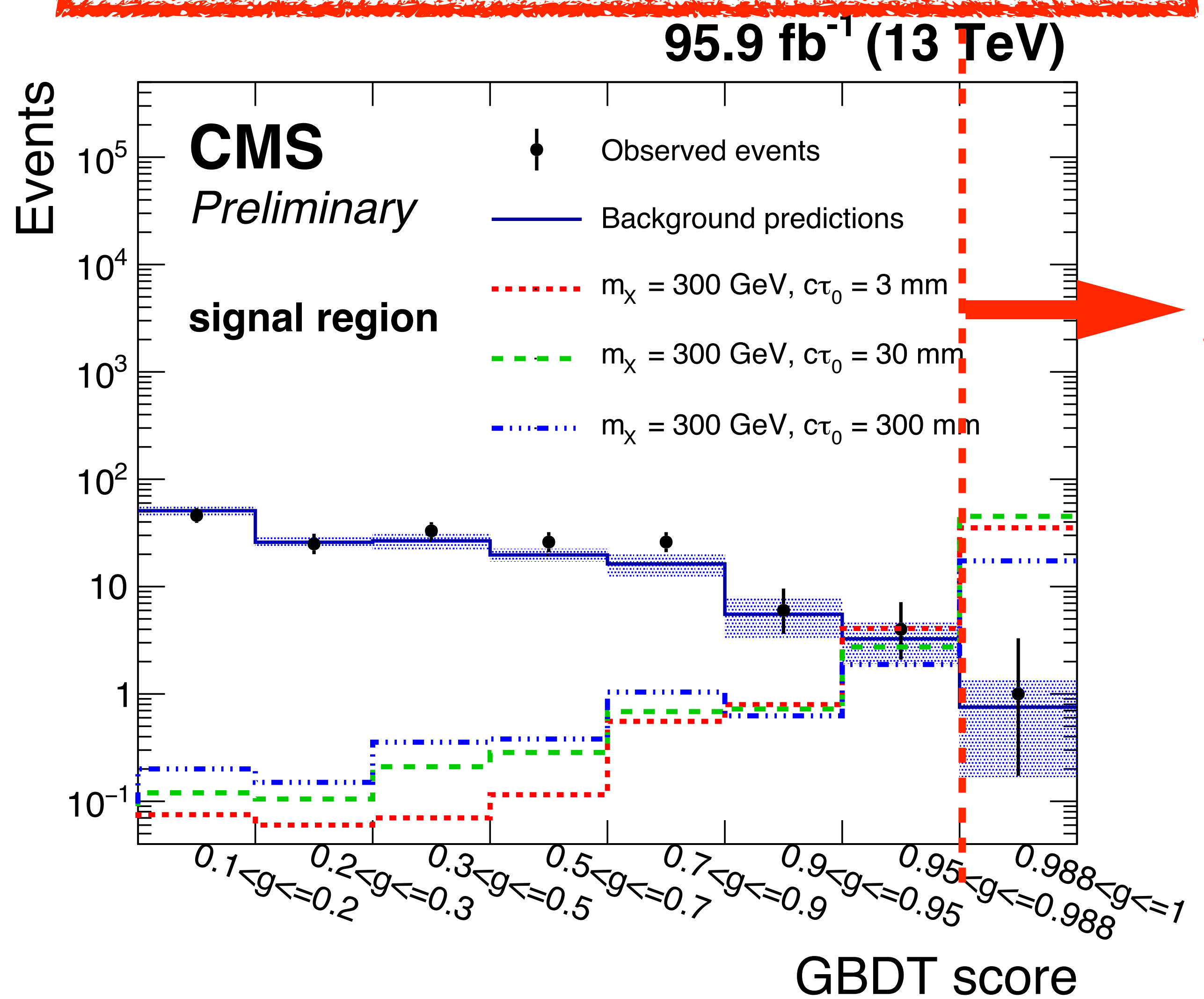
$$
\begin{aligned}
N_{ppp} &\sim N_{ppf}(N_{ffp} + N_{fpp} + N_{pfp})/(N_{fff} + N_{pff} + N_{fpf}) \\
&\sim N_{ppf}(N_{ffp} + N_{fpp})/(N_{fff} + N_{fpf}) \\
&\sim N_{ppf}(N_{ffp} + N_{pfp})/(N_{fff} + N_{pff}) \\
&\sim N_{ppf}(N_{fpp} + N_{pfp})/(N_{fpf} + N_{pff})
\end{aligned}
$$

Predictions and observations in the signal region

❖ The background prediction method was first tested with background MC sample, and was found to be robust both with and without signal contaminations;

❖ It's then tested with data in the control region, the observations and predictions are also consistent

Predictions and observations in the signal region



Final signal region

- **Expected background yield:** $0.75 \pm 0.44(stat) \pm 0.39(syst)$
- **Number of observed events: 1**

Systematic uncertainties

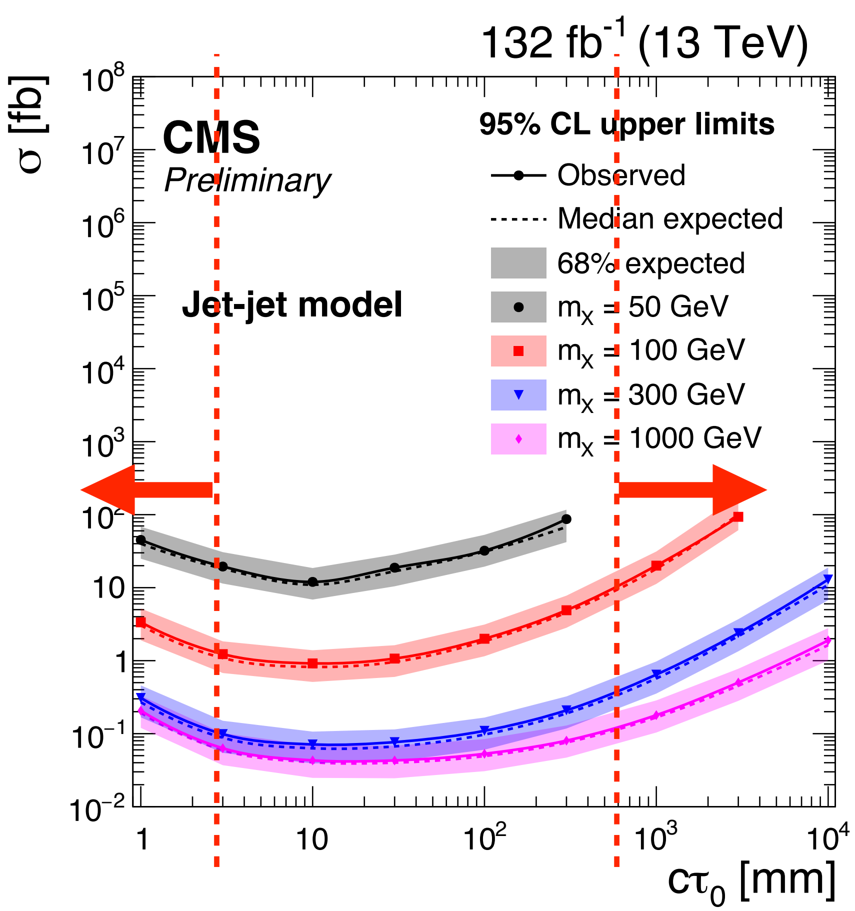
❖ **Summary of systematic uncertainties in the signal yields**

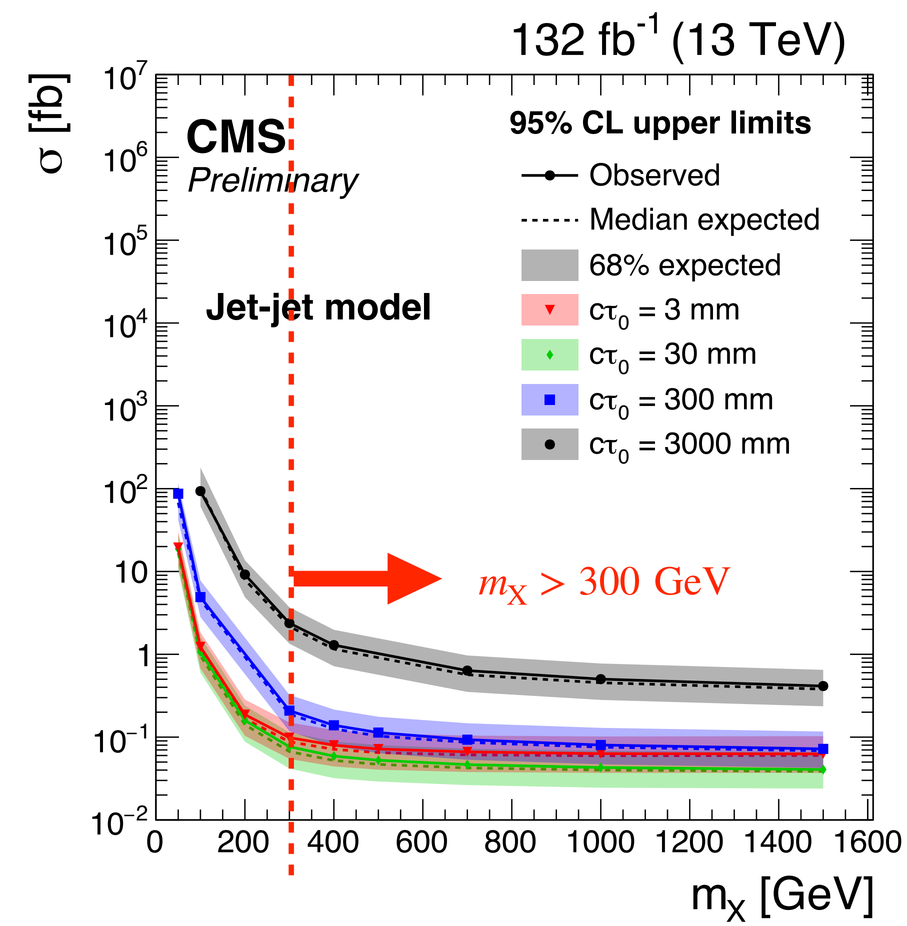
Source	Uncertainties (%)
Integrated luminosity	2.3 – 2.5
Online H_T requirement	0 – 2
Online jet p_T requirement	0 – 8
Offline vertexing	4 – 15
Track impact parameter modeling	8 – 18
Jet energy scale	0 – 3
PDF	4 – 6
Primary vertex selection	8 – 15
Total	17 – 25

- Main sources of systematic uncertainties: tracking and vertexing;
- Since the search is nearly background-free, the impact of systematic uncertainties on the final results is small.

Limits on jet-jet model

- **Jet-jet model:** a simplified model where LLPs are pair produced, and then each of them decays to a quark anti-quark pair.

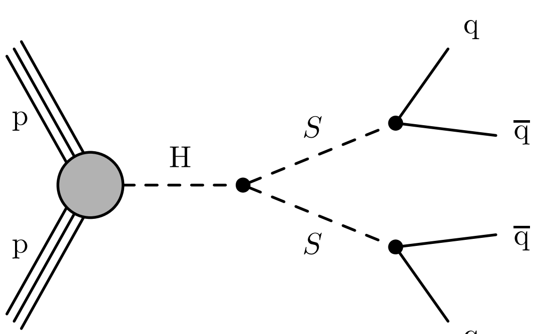


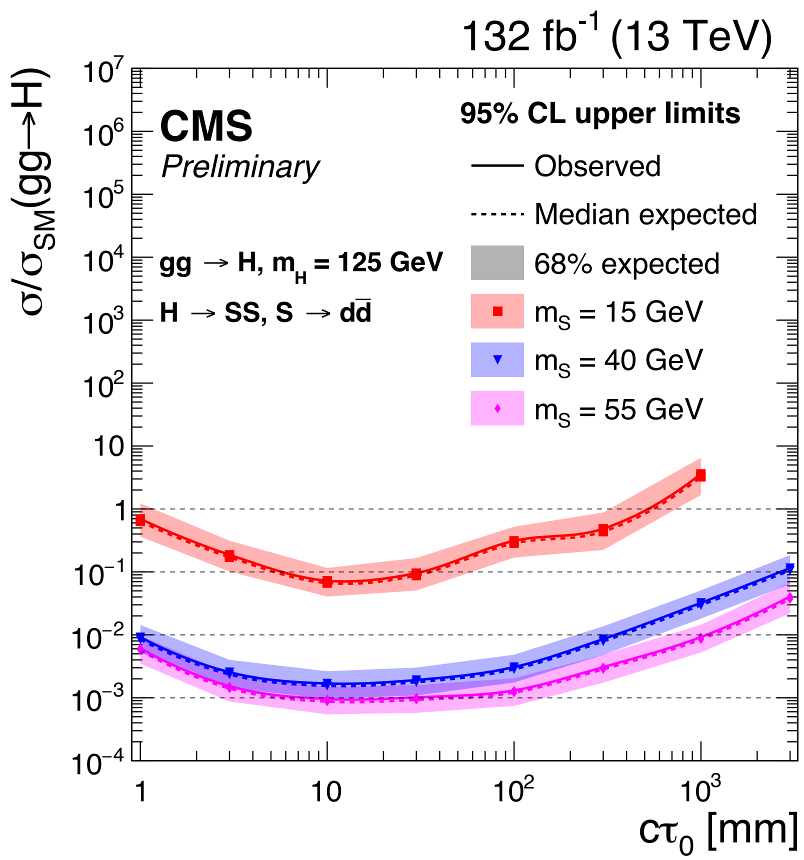


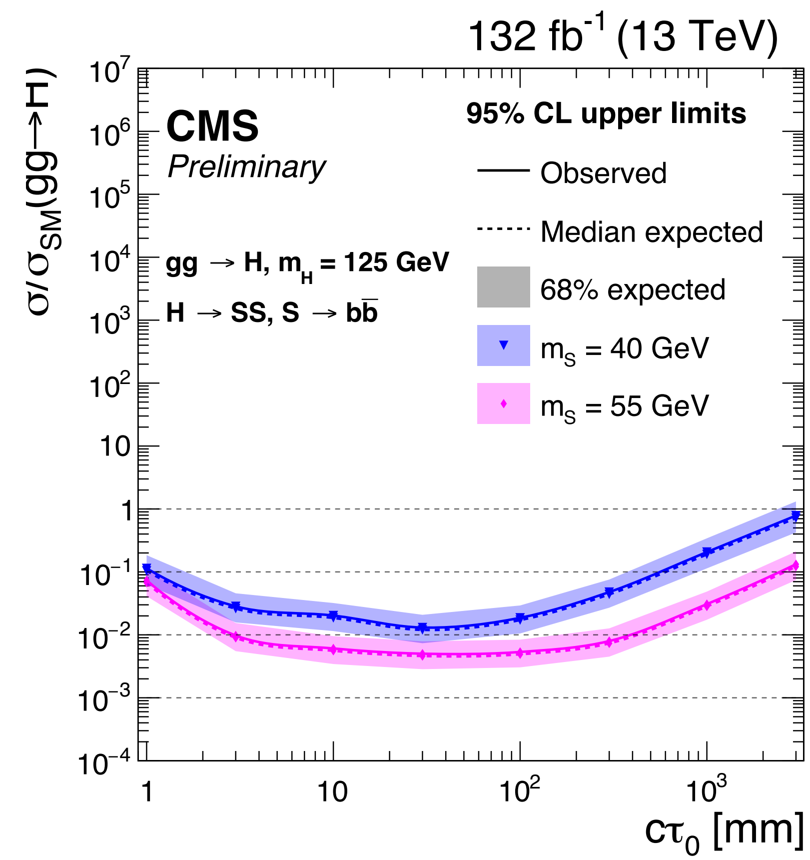
- Best limits reach ~0.04 fb @30mm, with ~70% signal efficiency in 2017/2018;
- Excellent sensitivities for LLP masses larger than 300 GeV;
- Although for $m_{\mathrm{LLP}} < 300$ GeV, the cross sections limits become worse, the search still provides unique sensitivities in this region compared to other existing searches.

Limits on exotic Higgs decay

- **Exotic decay of 125GeV Higgs :** SM-like Higgs decays to two long-lived scalars in the hidden sector, each of them then decays to a quark-antiquark pair **(Higgs as a portal to the hidden/dark sector)**



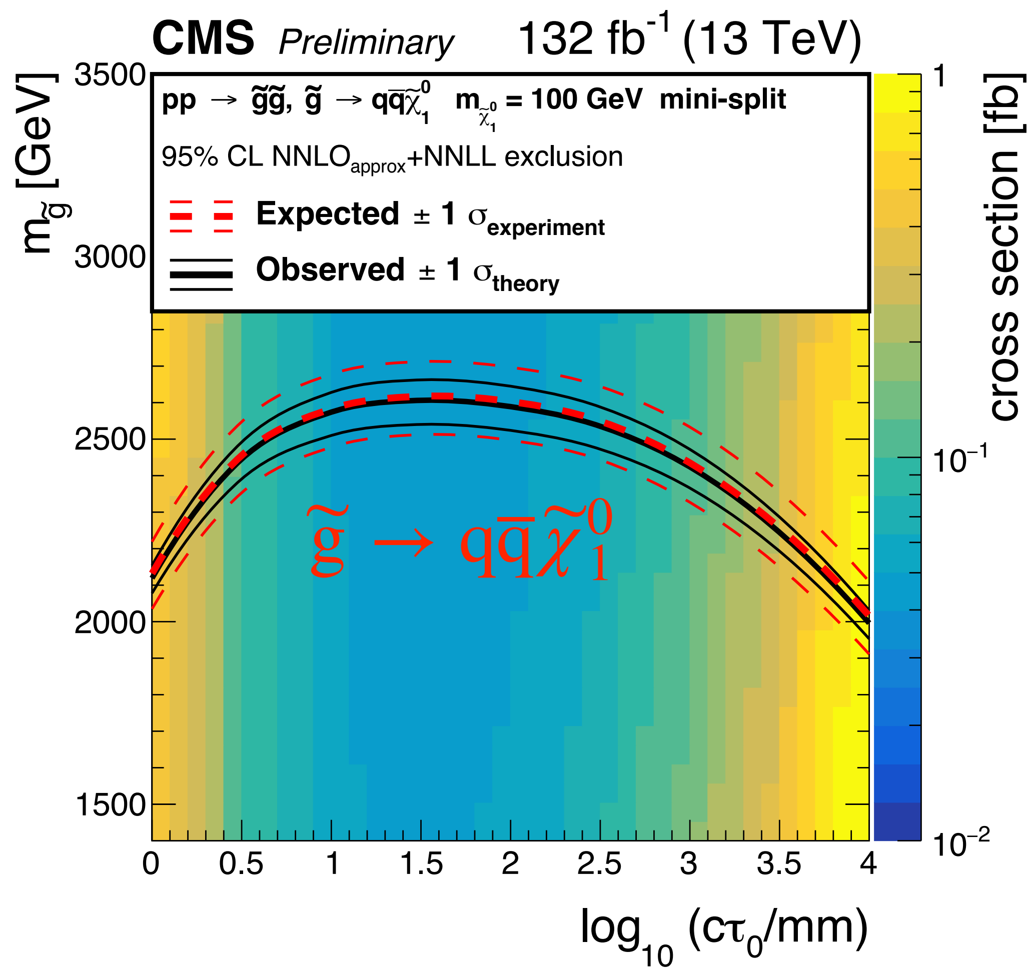


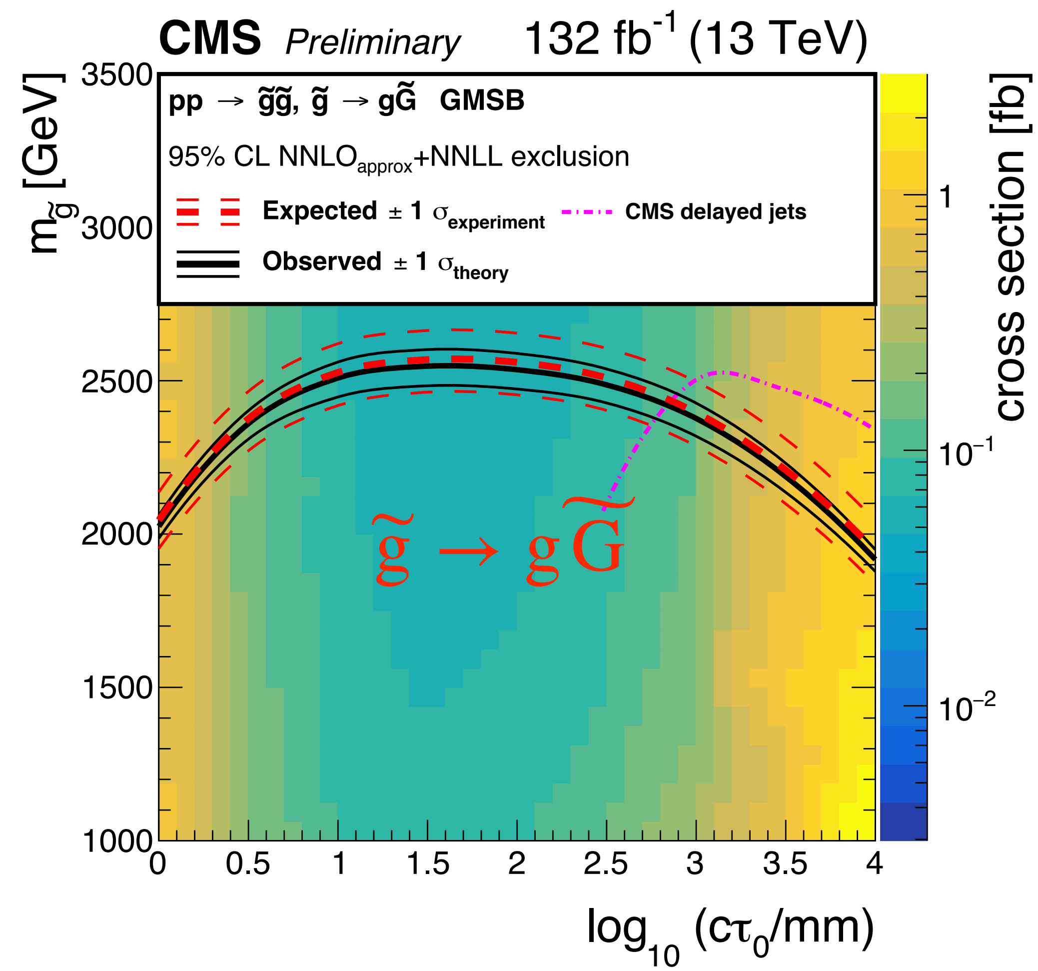


- Current best limits for $c\tau_0$ between 1mm and ~1m (orders of magnitudes of improvements compared to previous searches);
- Limits become worse for low-mass LLPs: tracks and jets are collimated due to the boosting;
- Limits become worse for heavy-flavor decay: need tertiary vertex reconstruction to recover the full decay chain

Limits on LLP → j/jj + MET

- **Mini-split SUSY:** pair-produced long-lived gluino decays to a quark-antiquark pair and an LSP
- **Gauge mediation:** pair-produced long-lived gluino decays to a gluon and a gravitino

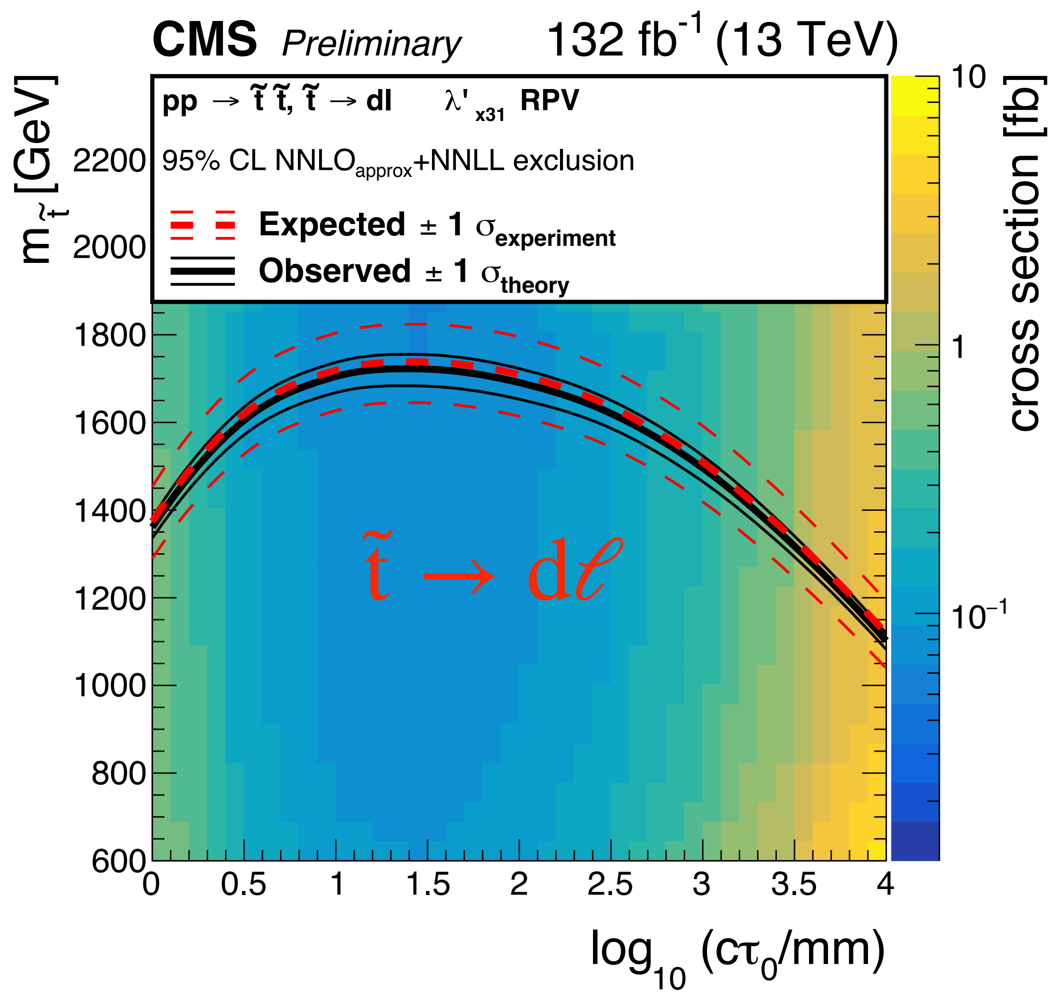


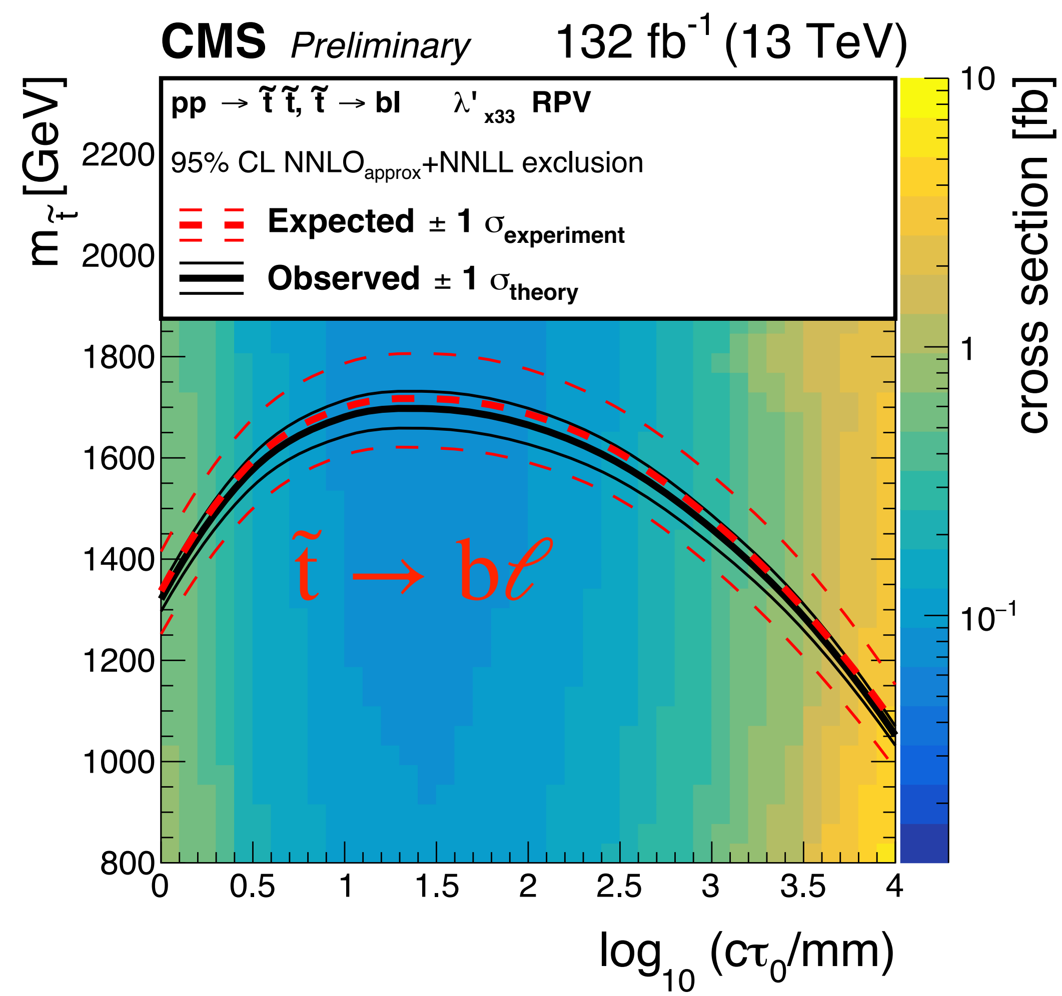


- Current best limits for $c\tau_0$ between 10(1) mm and ~1m (with up to ~70%/50% signal efficiency);
- Complementary to the CMS delayed-jet+MET search

Limits on semi-leptonic decays

- **RPV SUSY λ'_{x31} / λ'_{x33}: top squark is long-lived, and then decays to a down (bottom) quark and a charged lepton (with equal BR to e, μ, τ)**

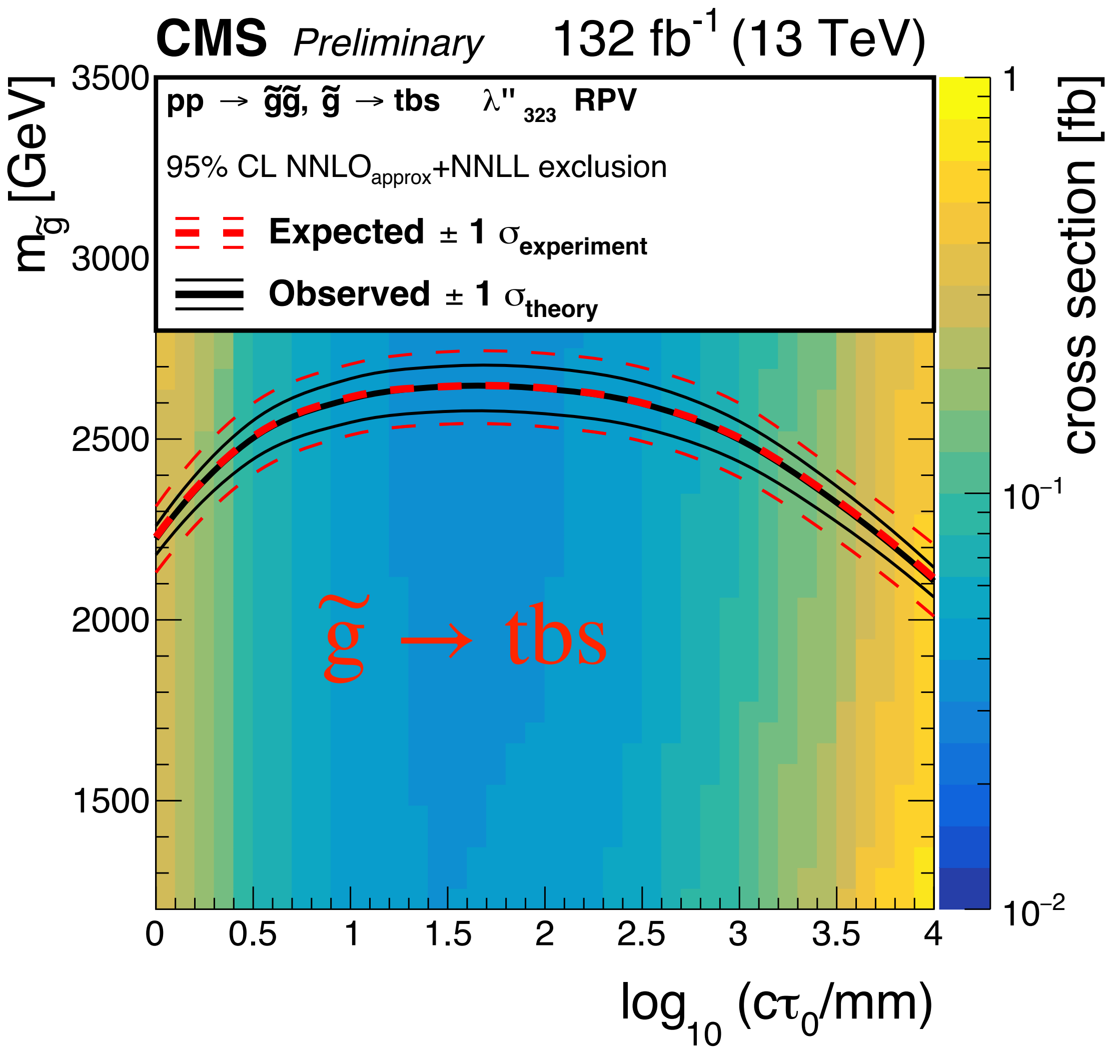


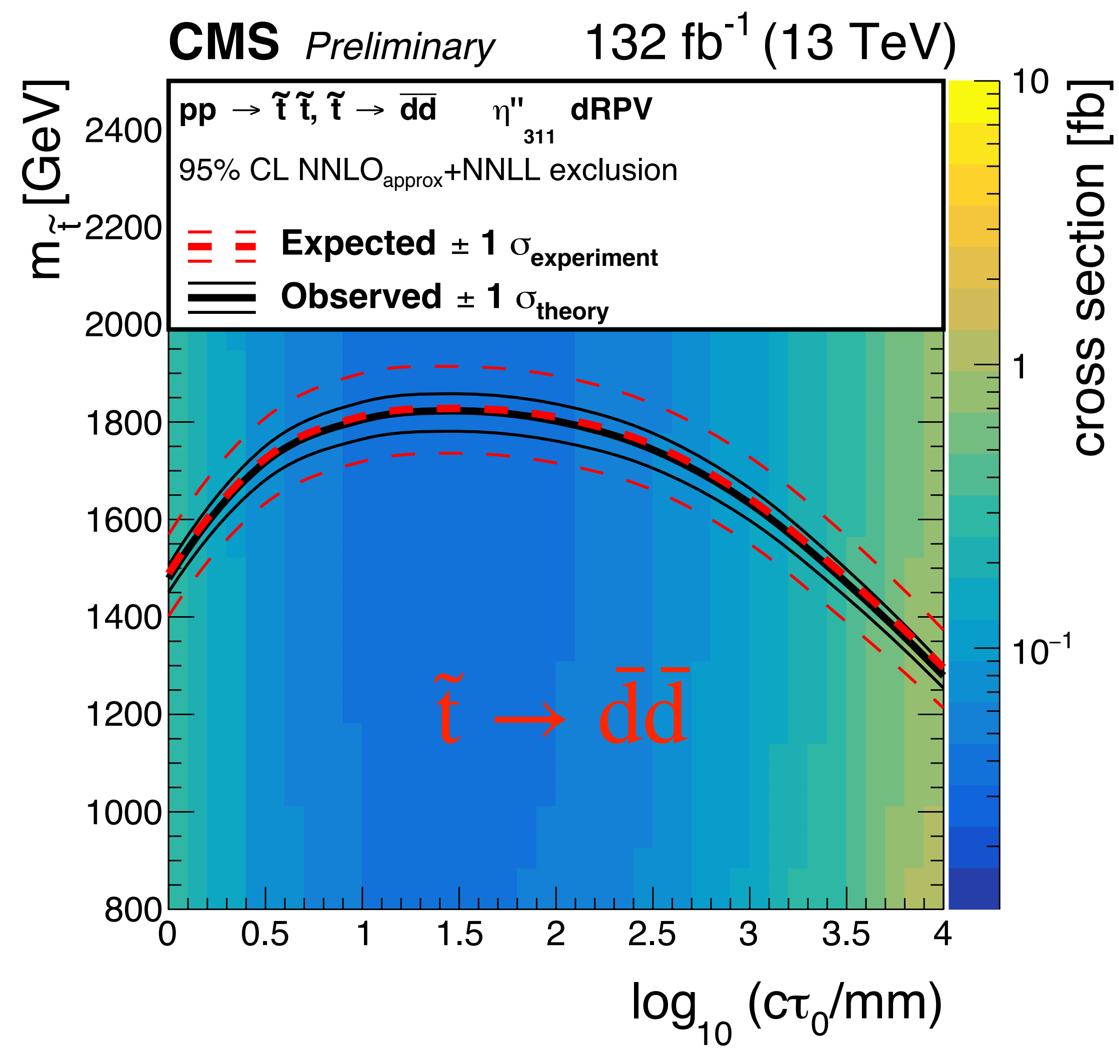


- **Top squark masses up to ~1700GeV can be excluded;**
- **Current best limits for $c\tau_0$ between 1mm and ~10m (with up to ~50%/40% signal efficiency);**

Limits on fully-hadronic decays

- **RPV SUSY** λ''_{323} / η''_{311}: $\tilde{g} \to tbs$ / $\tilde{t} \to \bar{d}\bar{d}$





- **Gluino masses up to ~2600GeV / top squark masses up to ~1800GeV can be excluded;**
- **Current best limits for $c\tau_0$ between ~10mm and ~10m (with up to ~80% signal efficiency) — complementary to the displaced-vertices search.**

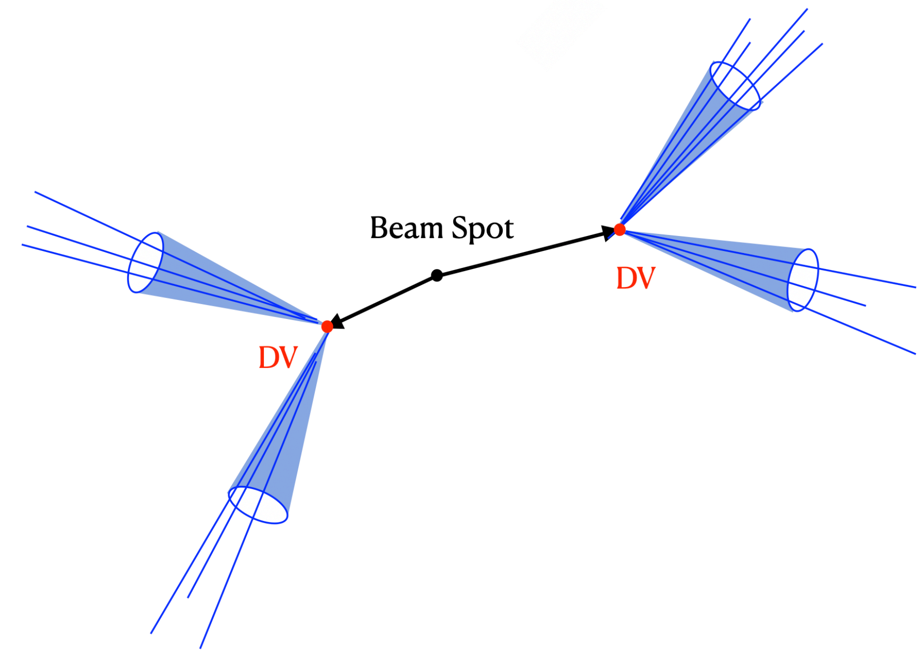
Overview of the displaced-vertices search

Displaced-vertices search

New!

CMS-PAS-EXO-19-013 (140 fb^{-1})

[2015+2016-only results (38.5fb-1): arXiv: 1808.03078]



- Triggering on a large jet activity: $H_T > 1050\mathrm{GeV}$;
- Search for 2 displaced (secondary) vertices accompanied with more than 4 jets: targeting pair-produced LLPs;
- Displacement of the displaced vertex is between ~0.1mm and ~21mm (within the the beam pipe):
  - targeting relatively small lifetime;
  - removing nuclear interaction background.
- Use the distance between the two DVs as the main search variable.

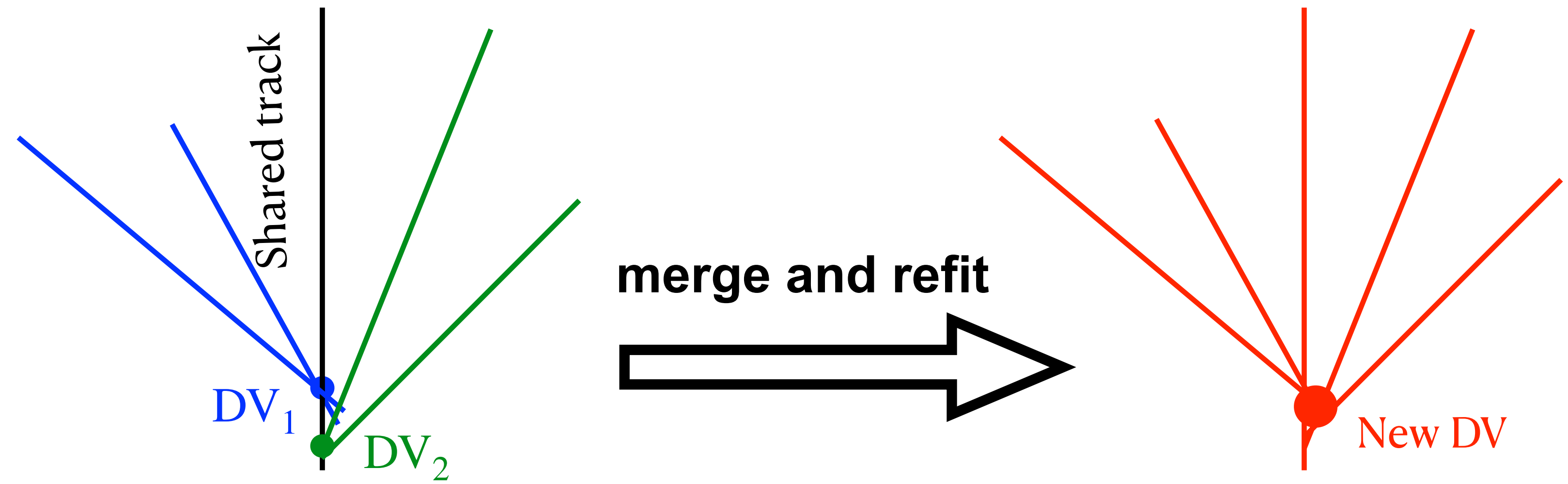
Event selections and track selections

- **Basic event selections:**
  - offline $H_T > 1200\text{GeV}$ (trigger on $H_T > 1050\text{GeV}$);
  - At least 4 jets with $p_T > 20$ GeV, $|\eta| < 2.5$;

- **Track selections (customized for LLPs decaying inside the beam pipe):**
  - Hit in the first pixel layer;
  - Pixel layer hits ≥ 2;
  - Strip layer hits ≥ 6;
  - $p_T > 1$ GeV.
  - 2D impact parameter (w.r.t. the beam spot) significance $d_{xy}/\sigma[d_{xy}] > 4$.

(Tracks are not required to be associated with the jets)

Displaced vertex reconstruction



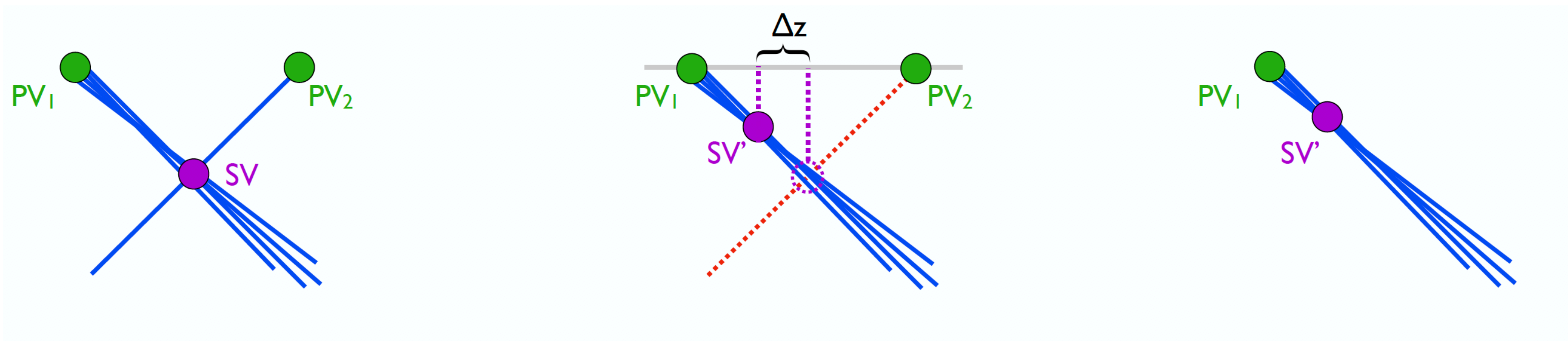
Again, the standard SV reconstruction is tuned for b-tagging, thus is not efficient in reconstructing the decays of LLPs

❖ **Displaced vertex (DV) reconstruction:**

- Iteratively merging vertex candidates, starting from all possible track pairs formed from the tracks satisfying the track selection criteria;
- **The merging criteria:** sharing a track, $d_{VV}/\sigma[d_{VV}] < 4$
- For the vertex merging, the new vertex is fitted with the Kalman filter;
- Vertex $\chi^2/\mathrm{ndof} < 5$

Suppression against vertex bias caused by pileup tracks

❖ **Accidentally crossing tracks from pileup vertices can result in secondary vertices with artificially large displacements.**



- During the vertex reconstruction, any track that affects a vertex's z position by $> 50\ \mu m$ is dropped from the vertex.

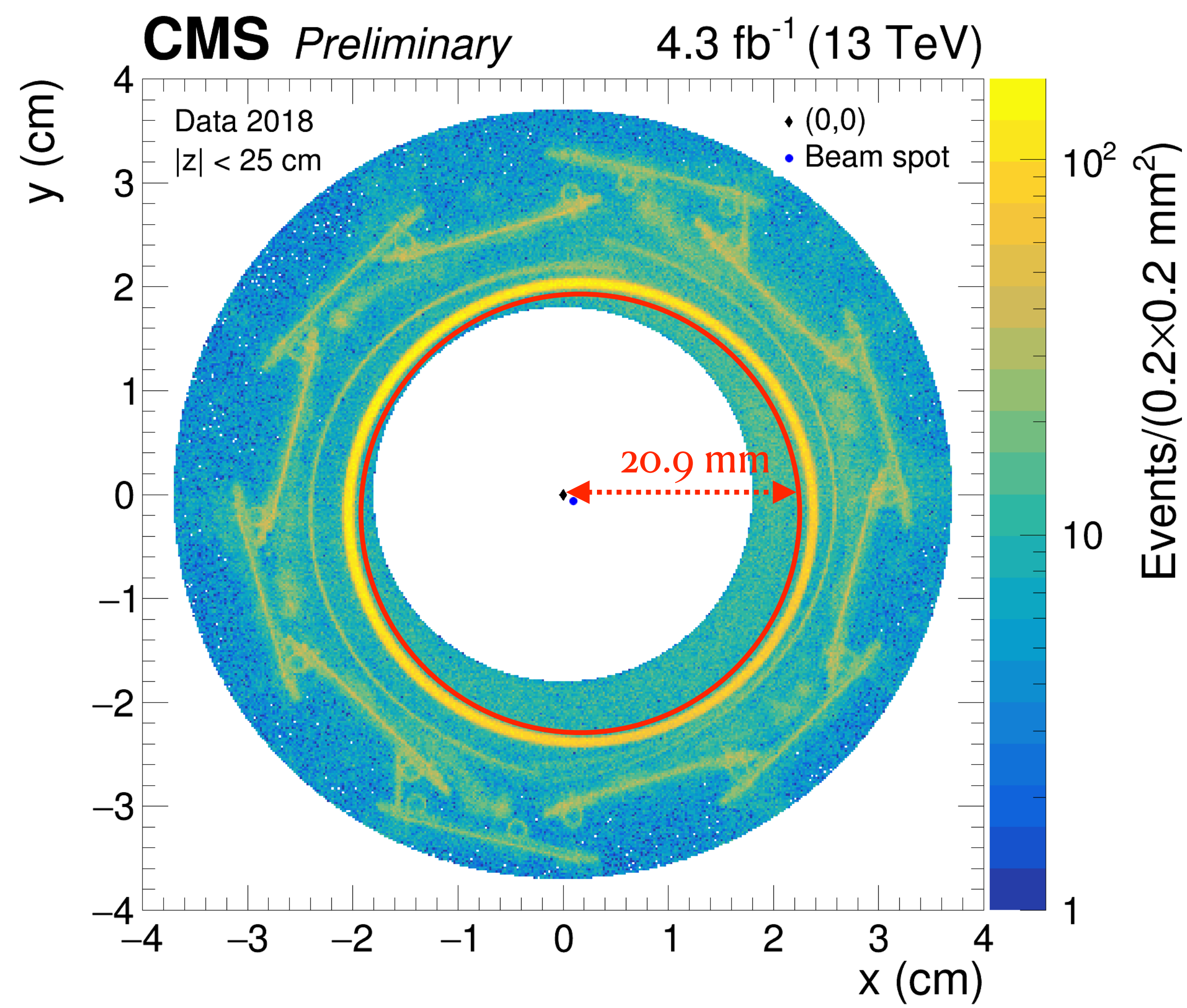
- Background vertices were removed by ~40% with minimal impact on the signal efficiency.

(new development in 2017/2018)

Vertex selections

❖ **Selections on the vertex position:**

- $\sqrt{x^2 + y^2} < 20.9$ mm **(within the beam pipe)**
- **Transverse distance w.r.t. the beam spot** $d_{\mathrm{BV}} > 0.1$ mm;
- $\sigma[d_{\mathrm{BV}}] < 0.025$ mm **(suppress background arising from boosted heavy-flavor decays)**

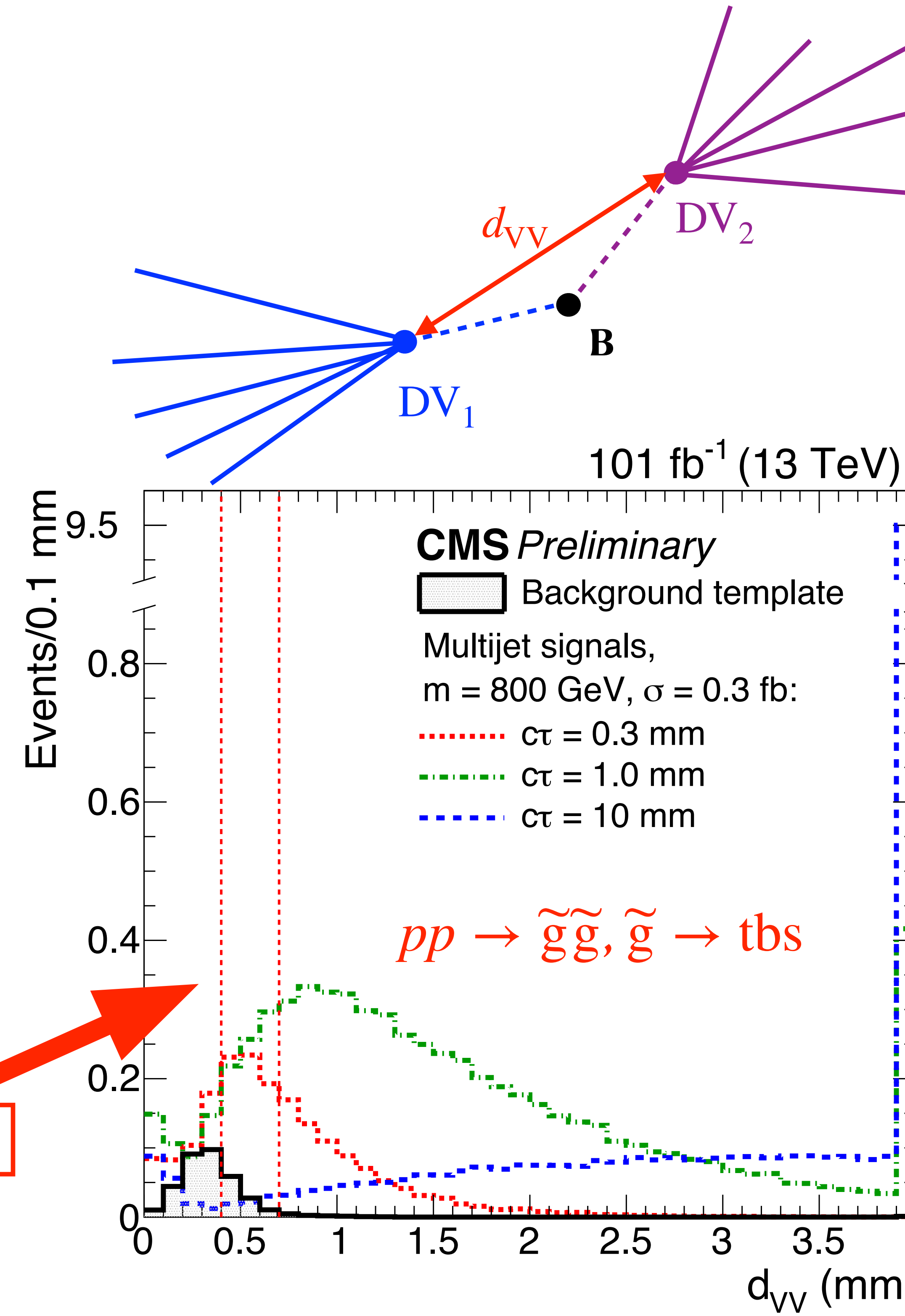


(Tracker material position study by CMS tracker DPG)

Search strategy

❖ **Focus on pair-produced LLPs → look for two DVs with large separation in the transverse plane**

- Look for two DVs with track multiplicity ≥ 5;
- Compute the transverse distance between the two DVs (d_{VV}), the d_{VV} distribution is used to search for LLP signatures.
- For interpretation, the d_{VV} distribution is divided into 3 bins: $0-0.4$ mm, $0.4-0.7$ mm, and $0.7-40$ mm



Event category	3-track	4-track×3-track	4-track	≥5-track
One-vertex	61818	—	14730	2211
Two-vertex	185	101	12	Signal region

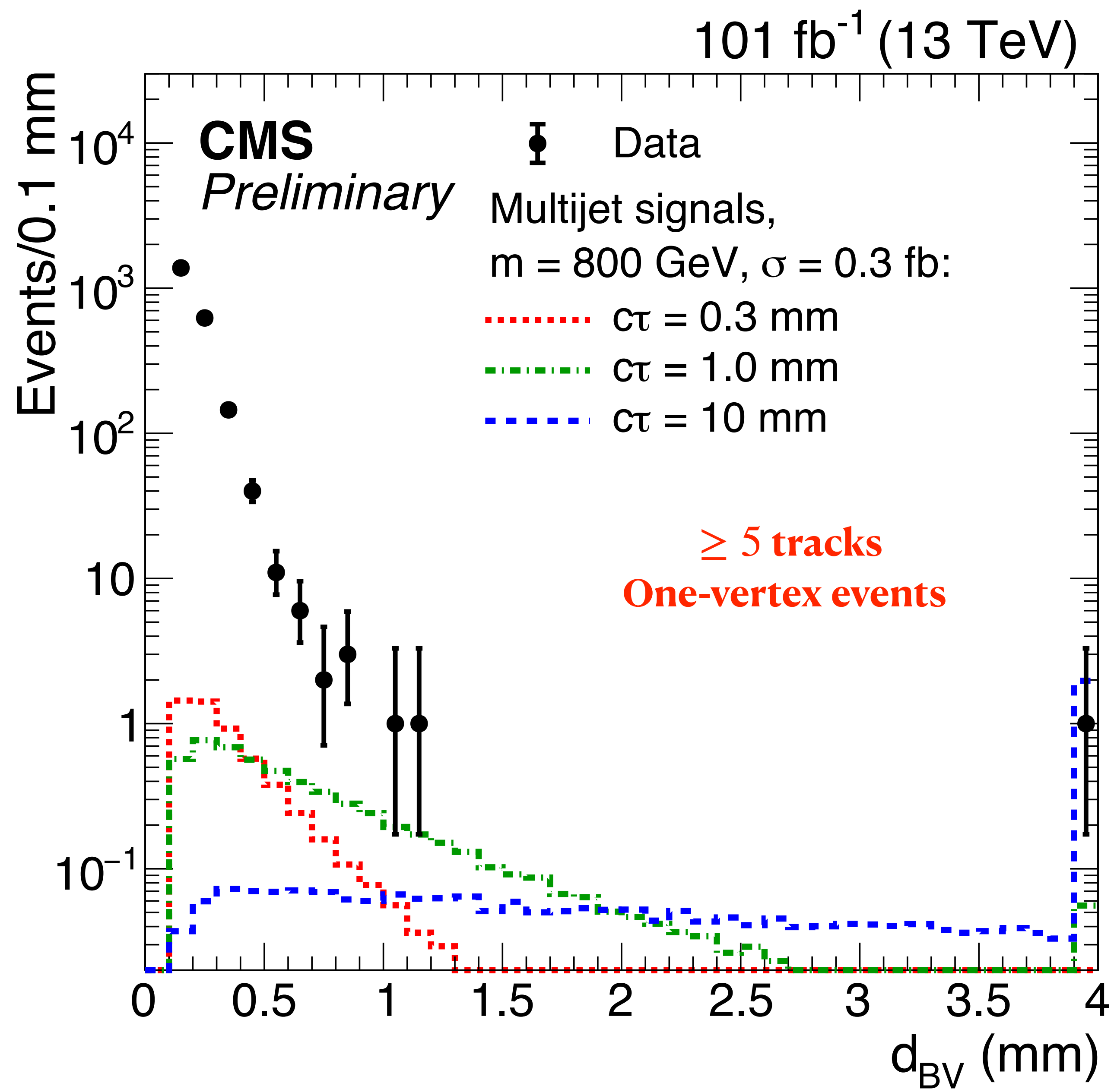
Background prediction

❖ **Background prediction is purely data-driven**

◉ **For background process the positions of the two DVs are mostly uncorrelated, while for signal process they are highly correlated since LLPs are pair produced.**

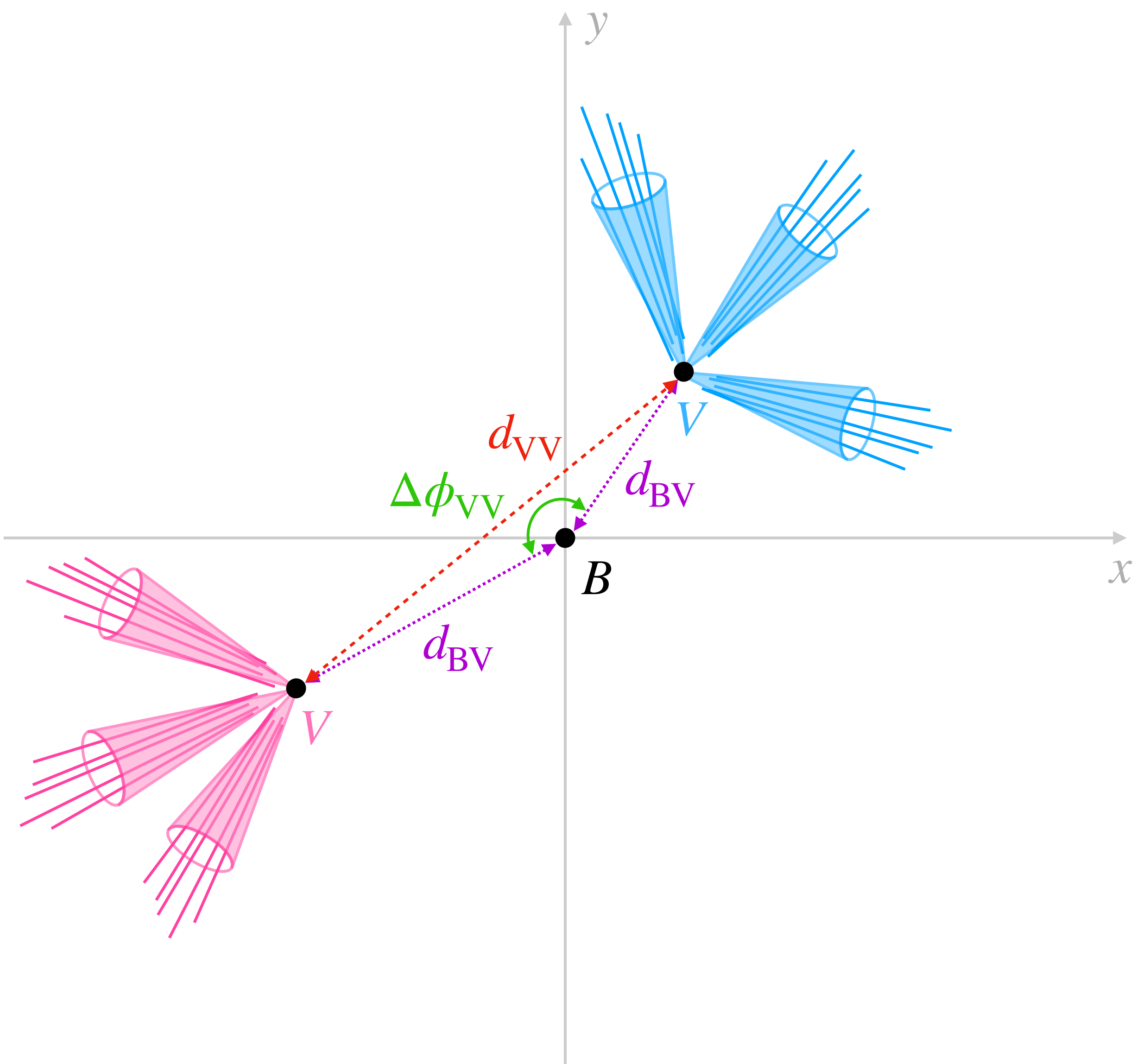
We can predict the d_{VV} distribution in two-vertex events using the d_{BV} distribution in one-vertex events

- Signal contamination is small;



Background prediction

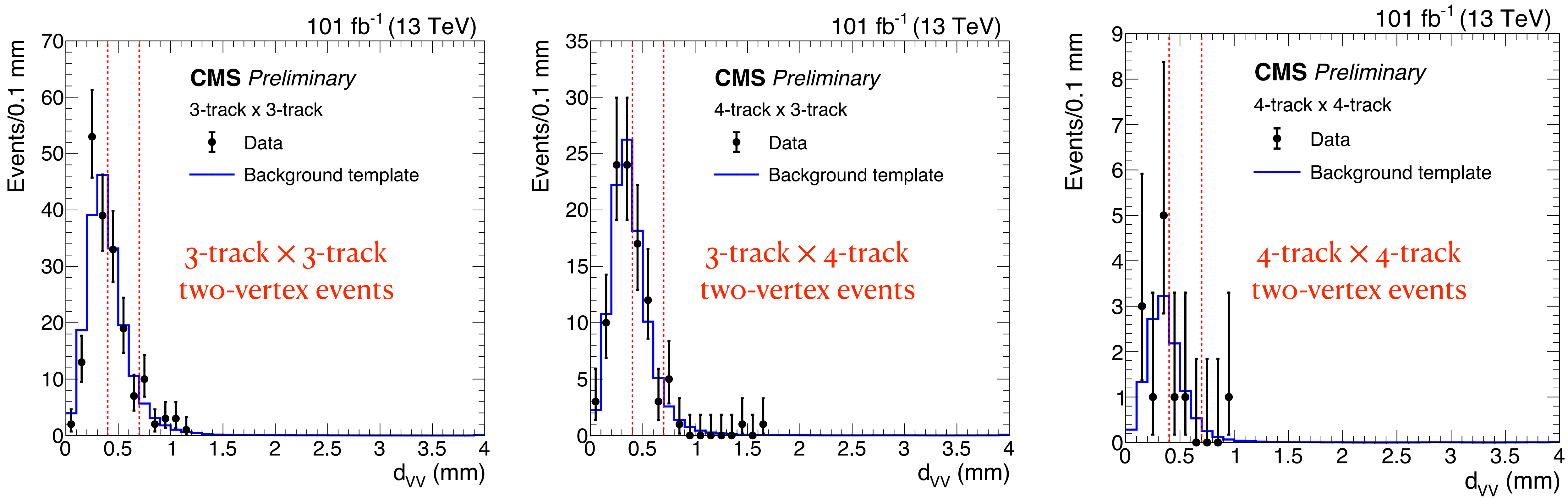
- **Construct the background template for d_{VV} distribution in two-vertex events:**
  - Draw two d_{BV} values from one-vertex events in data;
  - Draw $\Delta\phi_{\mathrm{VV}}$ values from jet-jet separation (the impact of the $\Delta\phi_{\mathrm{VV}}$ modeling is small)



- **Corrections**
  - Correction for the vertex-pair survival probability due to the merging of the two DVs when they are close to each other;
  - Small correction for events containing b-jets.

Validation of background prediction in control regions

- **Validation of background prediction method in the control regions with track multiplicity smaller than 5:**



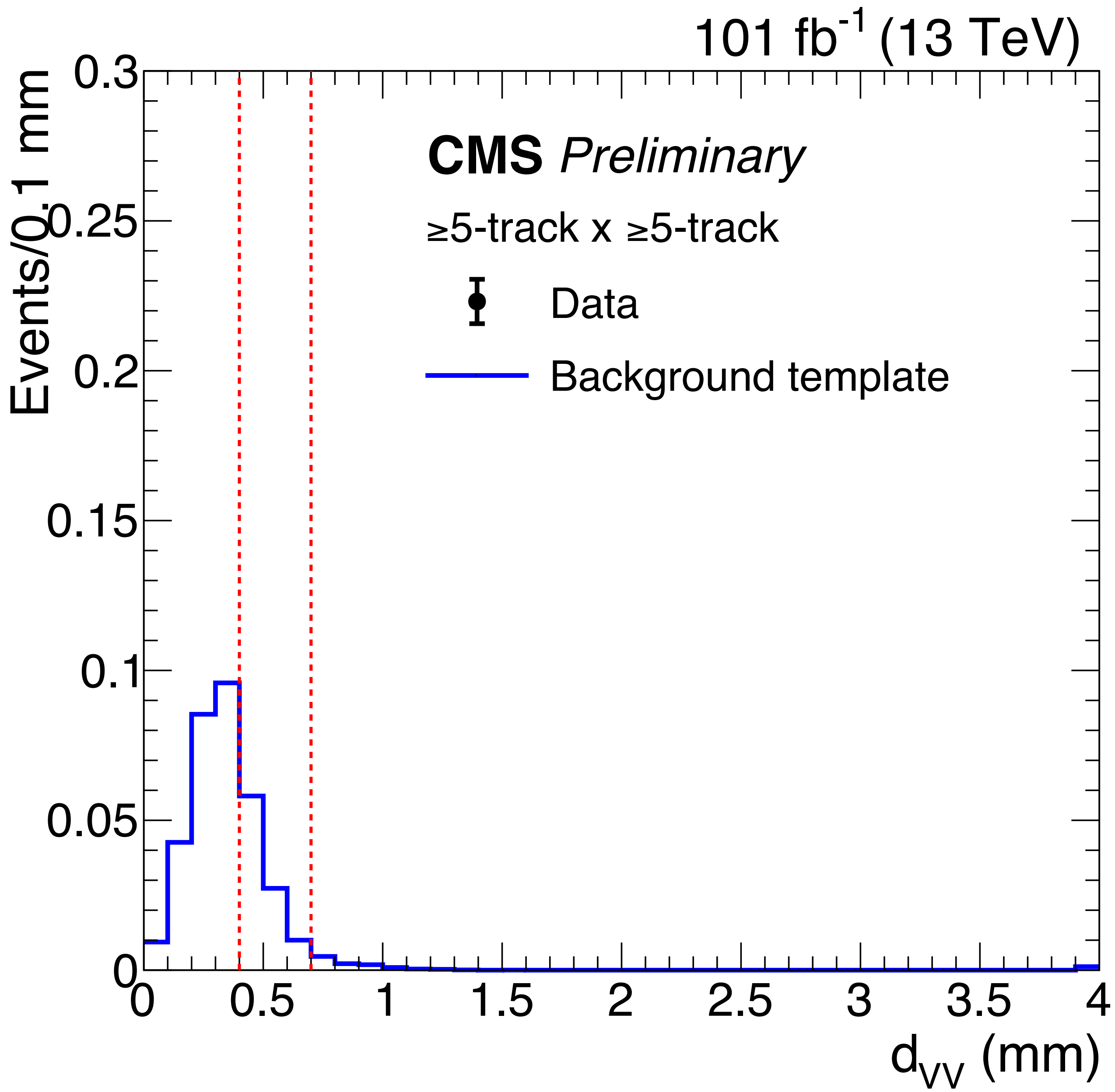
Observation/prediction in the different bins of d_{VV} (3-track × 3-track as an example)

d_{VV}	0-0.4 mm	0.4-0.7 mm	0.7-40 mm
Obs./Pred.	0.99±0.10	0.93±0.12	1.38±0.32

Background template and observation in the signal region

❖ d_{VV} **distribution for** $\geq$ 5-track$\times \geq$ 5-track **events in 2017 and 2018 data**

(Normalization for two-vertex event yields is derived from one-vertex events)

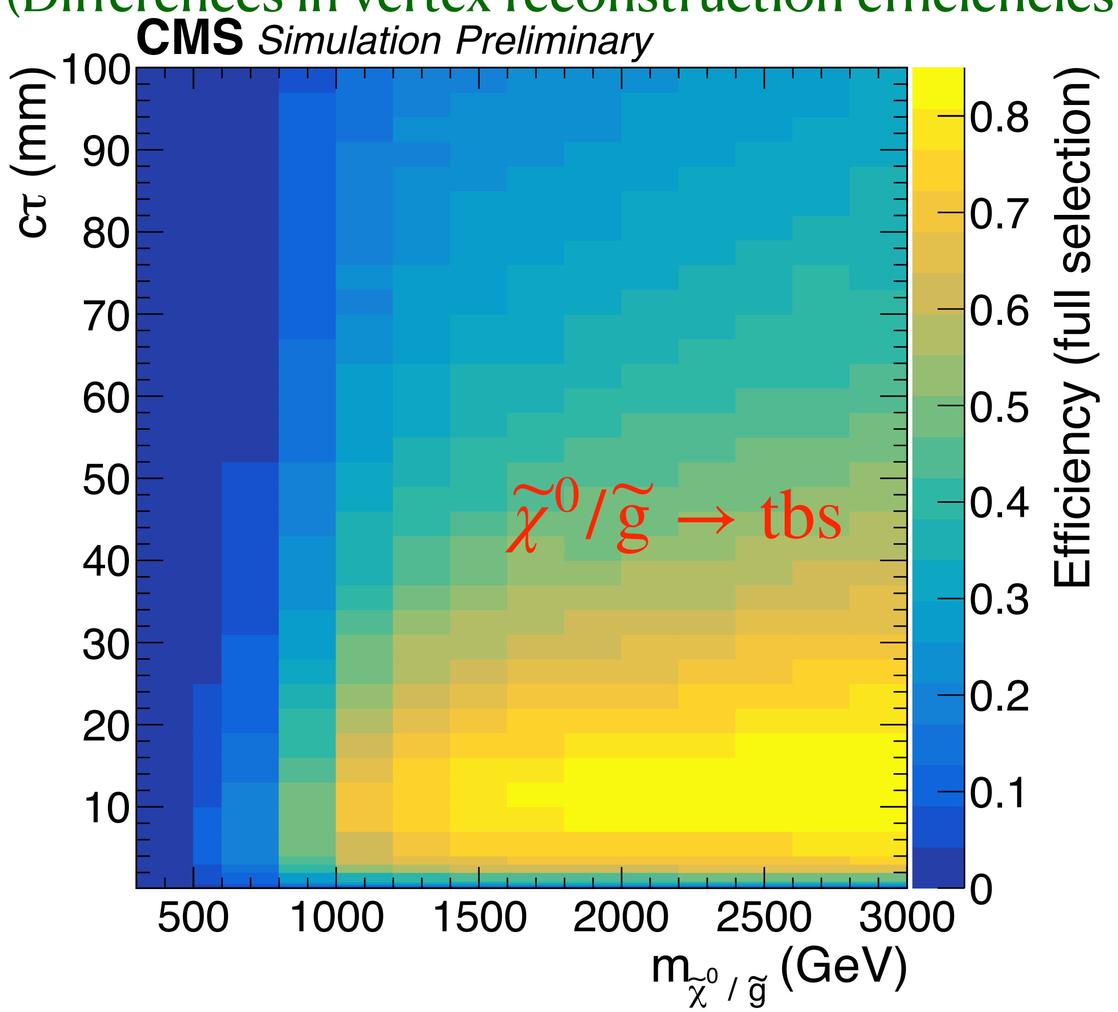


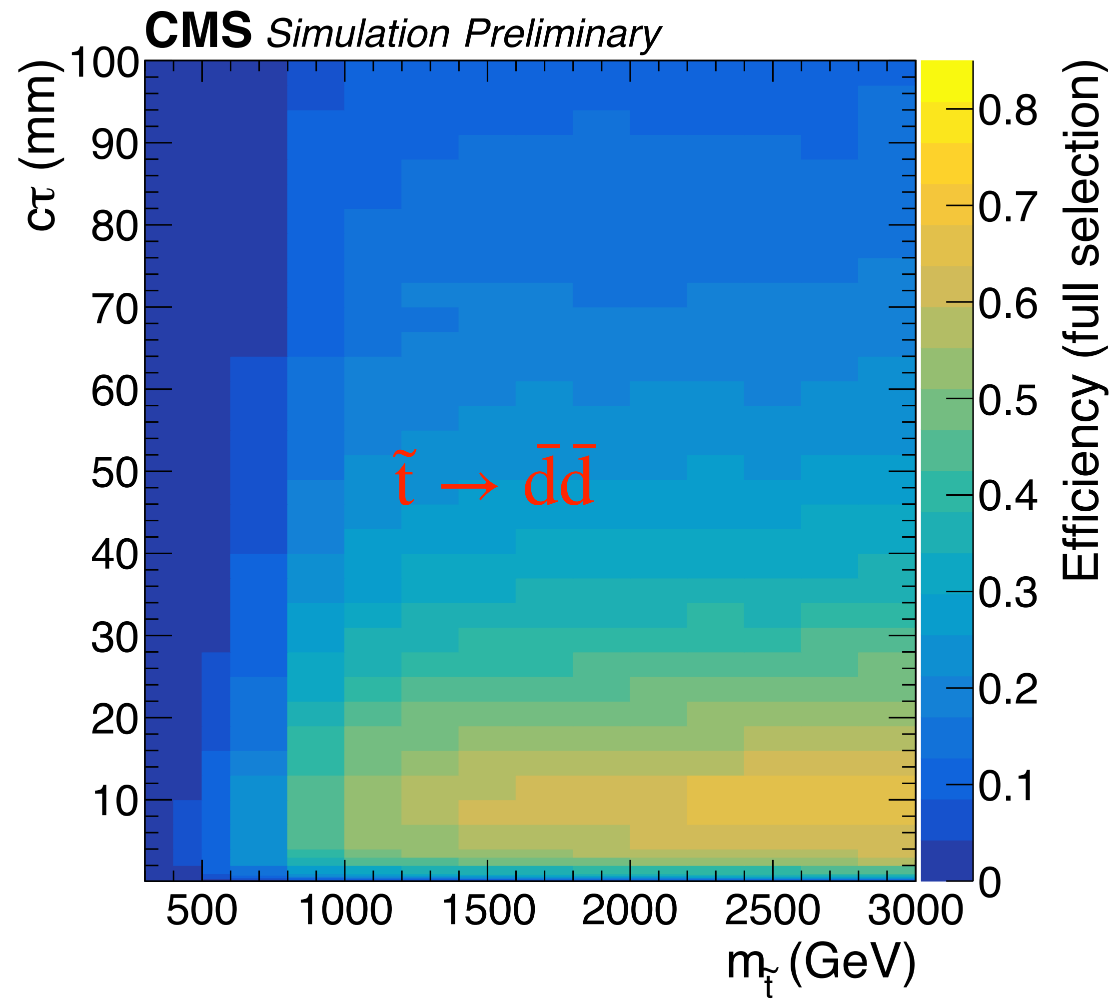
- **Observed 0 event in the signal region;**
- **Predicted background yields:**
  - 0-0.4 mm: 0.235±0.003(stat)±0.059(syst)
  - 0.4-0.7 mm: 0.096±0.003(stat)±0.031(syst)
  - 0.7-40 mm: 0.011±0.001(stat)±0.006(syst)

Signal Efficiencies

- Interpreted with $\widetilde{\chi}^0/\widetilde{g} \rightarrow \mathrm{tbs}$ and $\tilde{t} \rightarrow \bar{d}\bar{d}$ (pair produced, fully hadronic decays)

(Differences in vertex reconstruction efficiencies between data and MC are measured and corrected)





- Signal efficiencies reach ~70-80% for high-mass LLPs,
- Efficiencies are larger for $c\tau_0$ between ~2 mm and ~20 mm and mass larger than ~1000 GeV

Systematic uncertainties in the signal yields

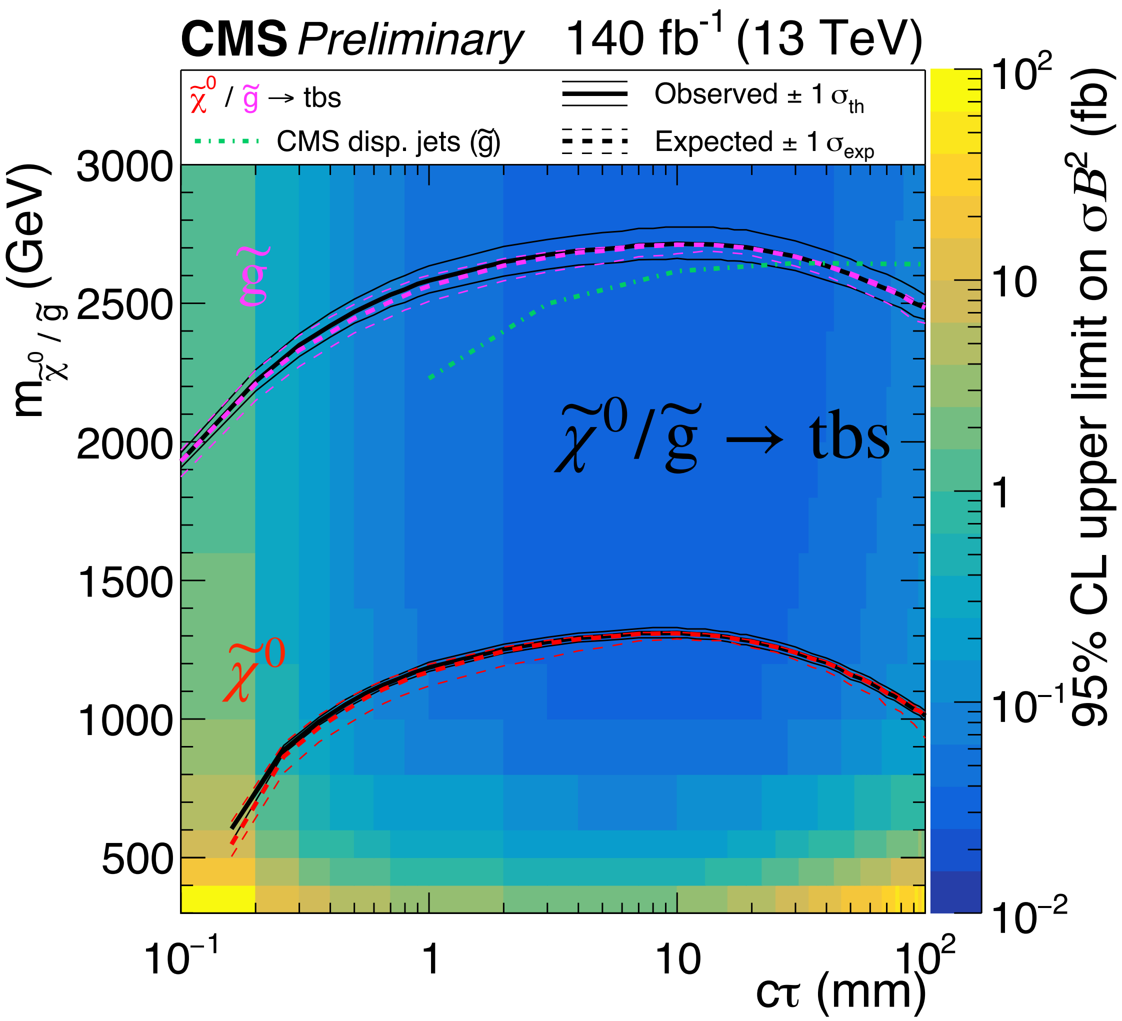
Systematic effect	Dijet uncertainty (%)	Multijet uncertainty (%)
Vertex reconstruction	11–41	1–36
PDF uncertainty	1–8	1–8
Integrated luminosity	2–3	2–3
Jet energy scale	5	5
Jet energy resolution	2	2
Pileup	2	2
Trigger efficiency	1	1
Changes in run conditions	1	1
Overall	13-42	7-36

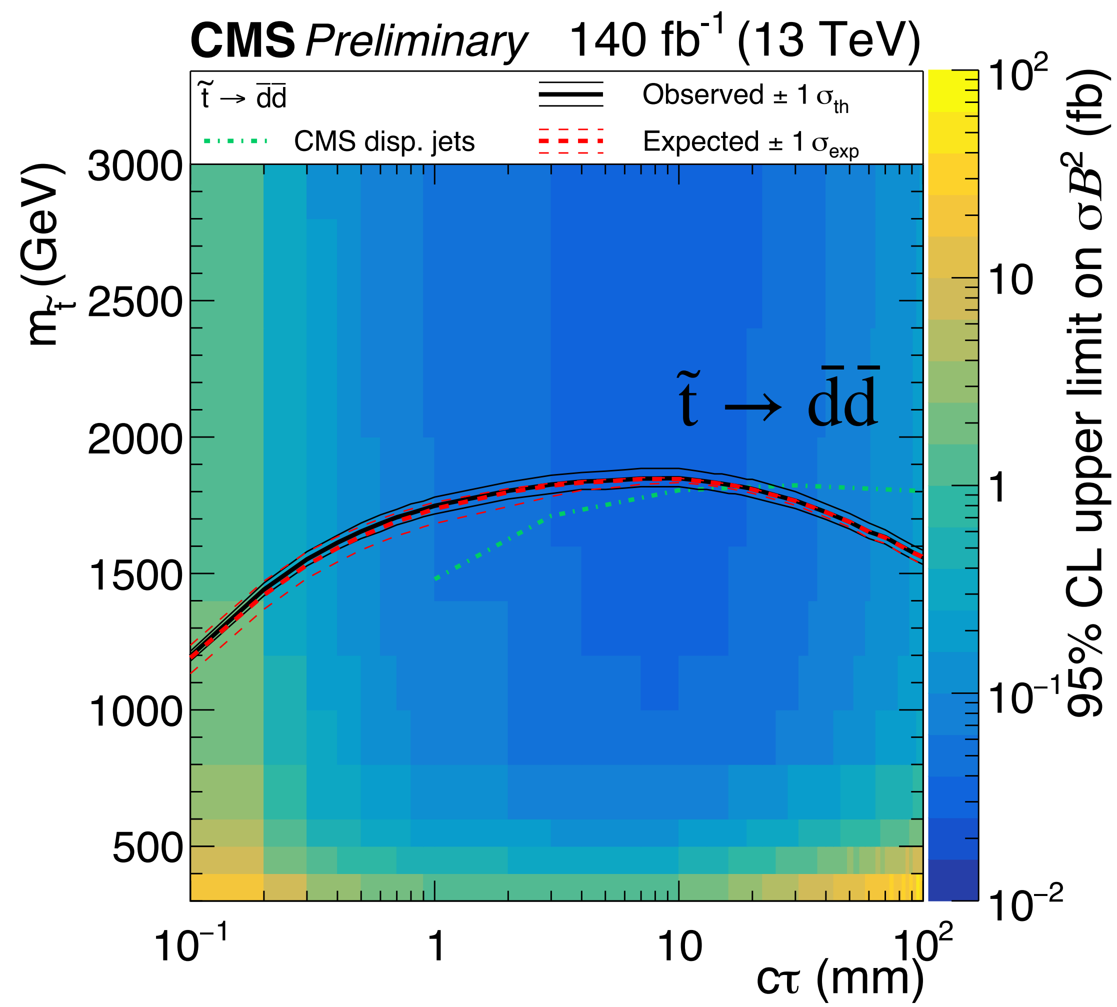
- Main sources of systematic uncertainties: vertex reconstruction.
- Since the search is nearly background-free, the impact of systematic uncertainties on the final results is small.

Excluded mass-lifetime

- **Interpreted with $\widetilde{\chi}^0/\widetilde{g} \to \mathrm{tbs}$ and $\tilde{t} \to \bar{d}\bar{d}$ (pair produced, fully hadronic decays)**

(Also provided reinterpretation recipe based on gen-level infos for other LLP models)





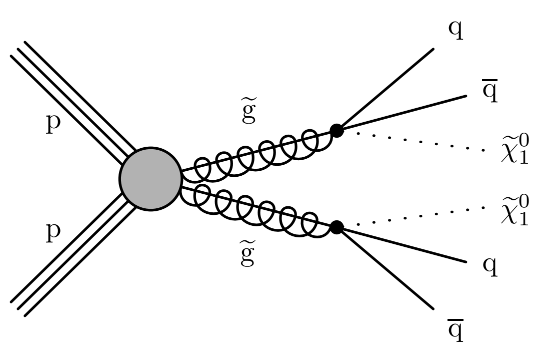
Green dashed line: observed limits from the displaced-jets search

- **Complementary to the displaced-jets search for $c\tau_0 <$ 10-30mm at large LLP masses.**

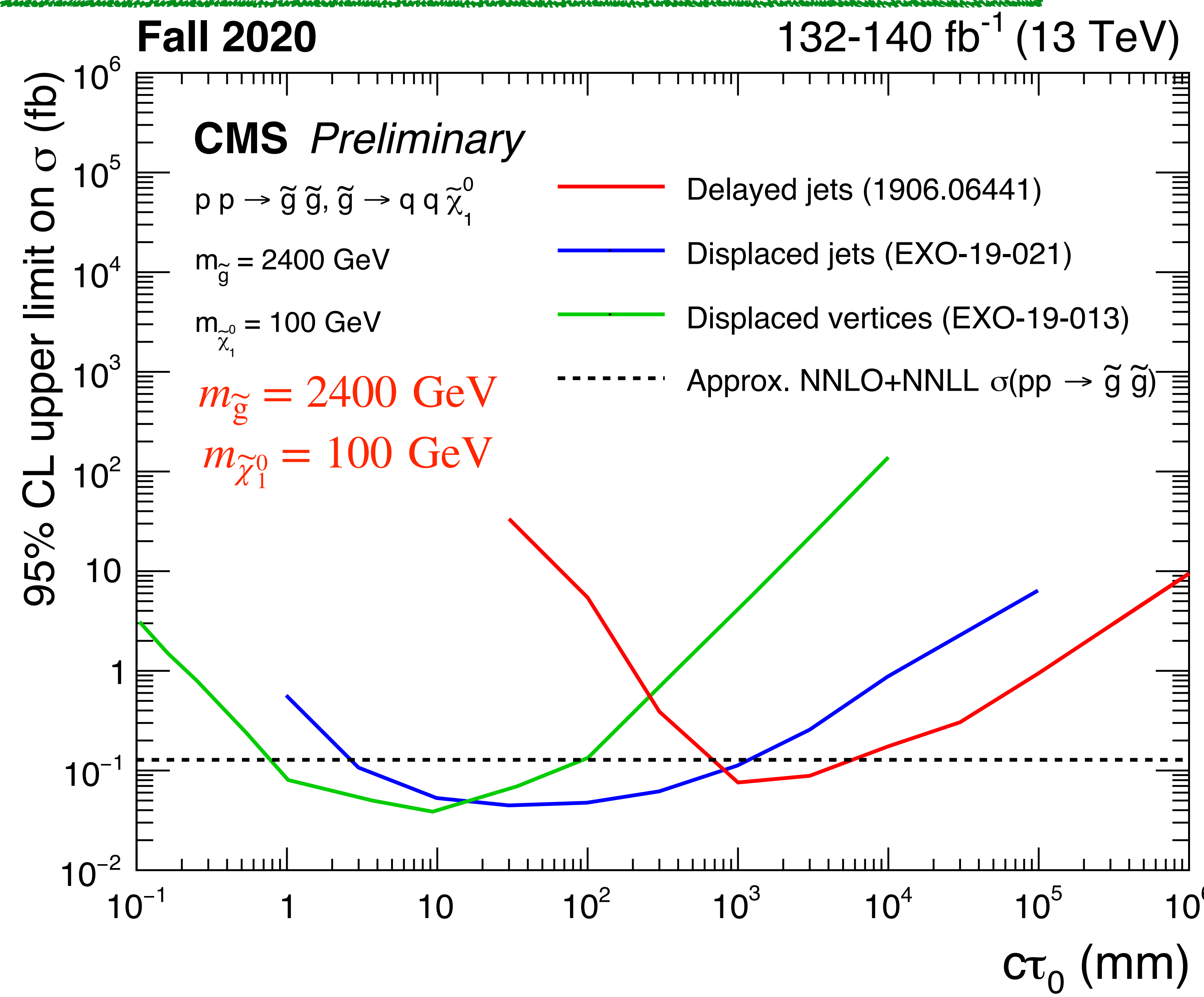
Complementarity of CMS LLP searches

- CMS displaced-jets, displaced-vertices, and **delayed-jets search** (arxiv: 1906.06441)

Interpret the three searches with the mini-Split SUSY model



- Gluino is long-lived;
- Large jet activities;
- Large MET.



For high-mass LLPs, the three CMS searches complement each other, and together provide excellent coverages over a large range of lifetime (~0.1mm-~1000m)

Summary

- **We present two searches looking for long-lived particles in events with jets at CMS using full Run-2 dataset, mainly focusing on decays inside the inner tracking system.**

- **Displaced-jets search:** inclusive search for long-lived particles decaying into jets, covering lifetime between ~1 mm to ~1 m, providing stringent limits on a large variety of LLP models;

- **Displaced-vertices search:** inclusive search for pair-produced LLPs decaying into jets, focusing on decays within the beam pipe, excellent sensitivities for lifetime between ~0.1mm and ~10 mm.

- **The two searches complement each other at different lifetime regions, together they provide excellent coverages over a large range of lifetime**

Outlook

Long-lived particle searches continue to be a creative field where many ingenious ideas/techniques are being proposed and developed

❖ **Many new opportunities/directions can be pursued:**

Near term / Run-3 of LHC

- *Novel L1/HLT algorithms to expand the coverage (especially for low-H_T region);*
- *Combine with the info in other sub-detectors to expand the coverage;*
- *More sophisticated reconstruction/discrimination techniques with advanced ML tools.*

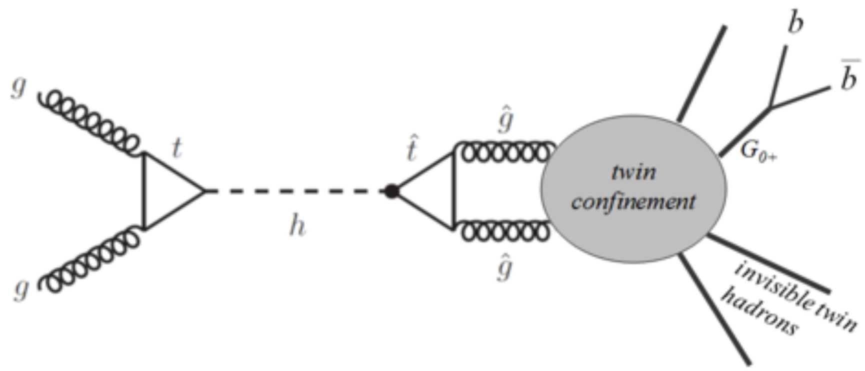
Long term / HL-LHC

- *MIP timing detector upgrade: providing precision timing information to help tag LLPs;*
- *L1 track trigger upgrade: providing unique sensitivities to low-mass LLPs.*

Backup

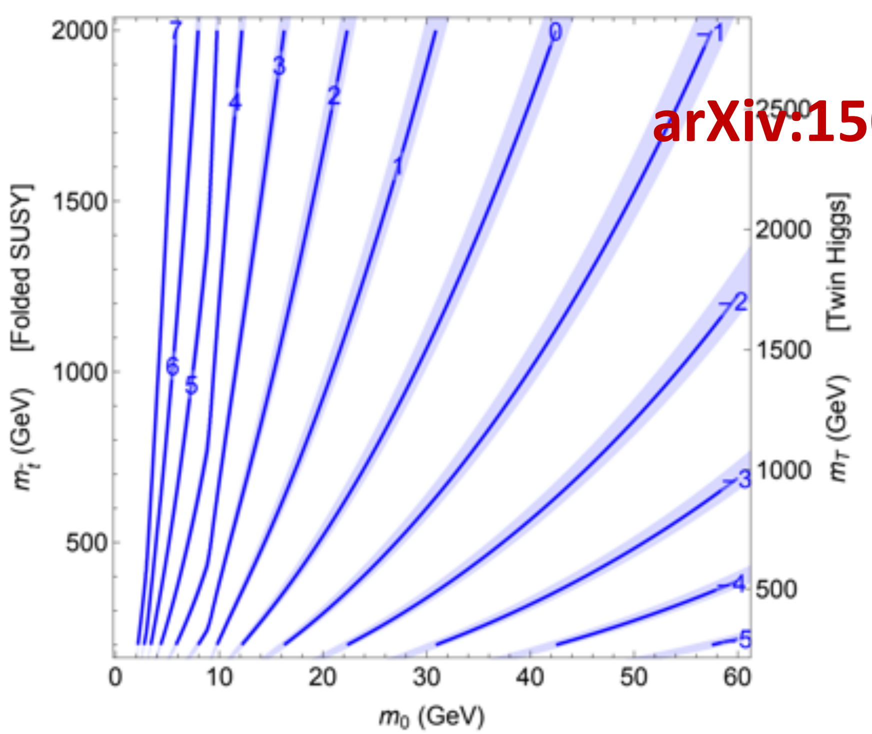
Exotic Higgs decays

❖**Neutral Naturalness:** Higgs mass stabilized by uncolored top partners in a hidden sector



Contours: mirror glueball lifetime (in $\log_{10}[c\tau/m]$)

top partner mass

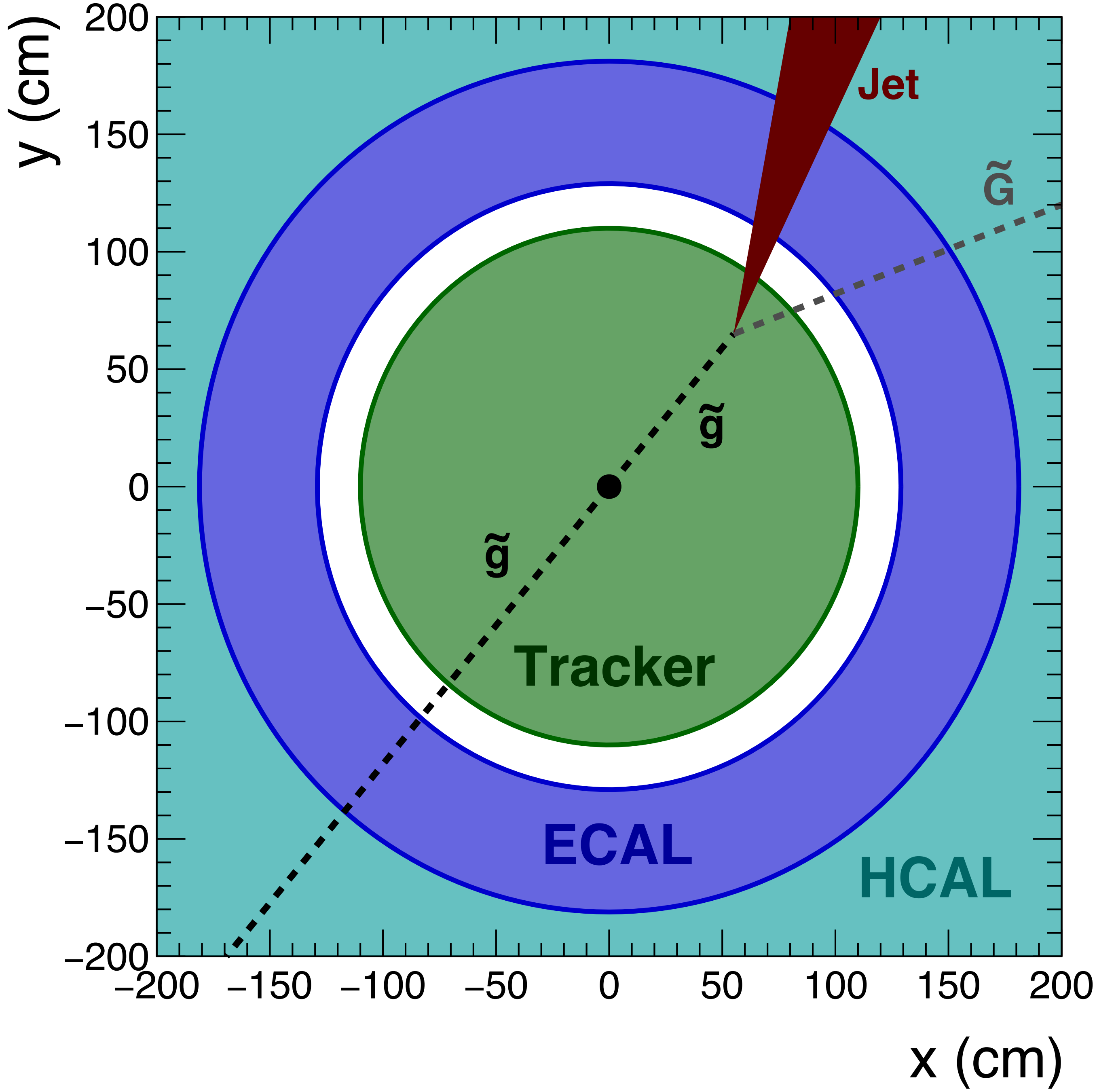


arXiv:1506.06141

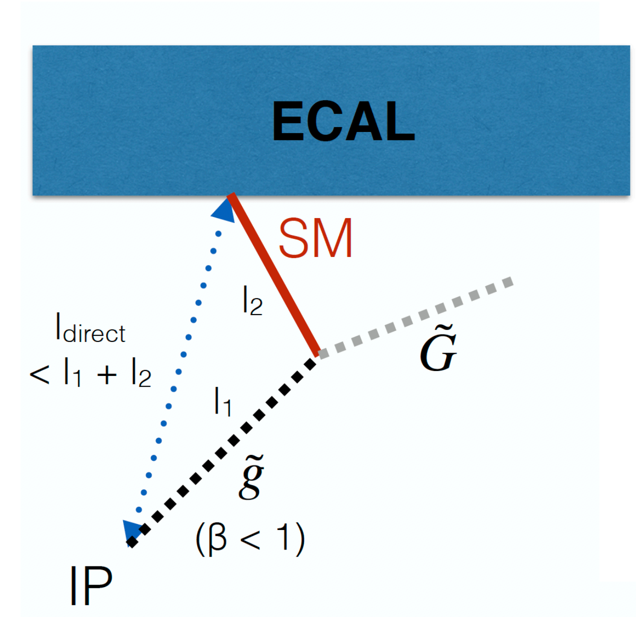
- The top partner doesn't have $SU(3)_C$ charge, but carries EW charge;
- SM Higgs decays to twin/mirror glueballs via top partner loop;
- Mirror glueballs then decay back to SM particles through higgs portal

Mirror glueballs are favored to have masses of ~10-60 GeV, and have a wide range of lifetimes

Delayed-jet search



Use timing from ECAL to search for LLPs



Jet time defined by the median time of all matched ECAL cells satisfying quality criteria — signal region: $t_{\text{jet}} > 3$ ns

Iterative tracking

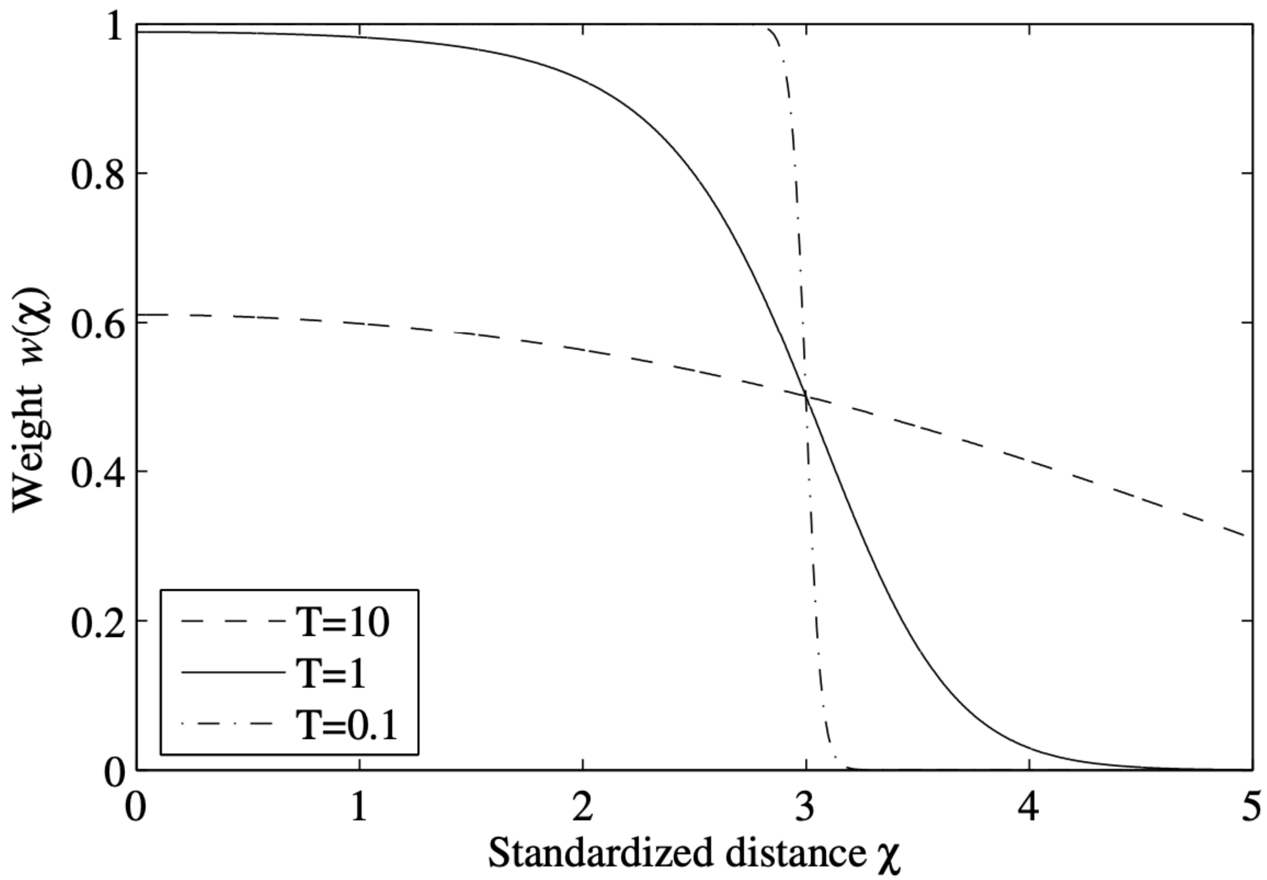
Iteration	Seeding	Target track
Initial	pixel quadruplets	prompt, high p_T
LowPtQuad	pixel quadruplets	prompt, low p_T
HighPtTriplet	pixel triplets	prompt, high p_T recovery
LowPtTriplet	pixel triplets	prompt, low p_T recovery
DetachedQuad	pixel quadruplets	displaced--
DetachedTriplet	pixel triplets	displaced-- recovery
MixedTriplet	pixel+strip triplets	displaced-
PixelLess	inner strip triplets	displaced+
TobTec	outer strip triplets	displaced++
JetCore	pixel pairs in jets	high-p_T jets
Muon inside-out	muon-tagged tracks	muon
Muon outside-in	standalone muon	muon

Adaptive vertex fitting

$$\frac{1}{2}\sum_{i=1}^{n}\chi_i^2(\boldsymbol{v}) = \frac{1}{2}\sum_{i=1}^{n} d_i^2(\boldsymbol{v})/\sigma_i^2.$$

$$w_i\left(\chi_i^2\right) = \frac{\exp(-\chi_i^2/2T)}{\exp(-\chi_i^2/2T)+\exp(-\chi_c^2/2T)}.$$

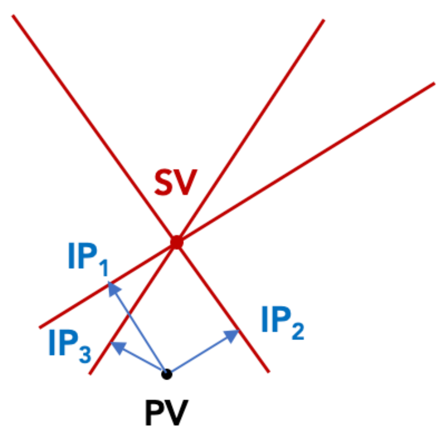
$$\sum_{i=1}^{n} w_i(\chi_i^2(\boldsymbol{v}))\chi_i(\boldsymbol{v})\frac{\partial\chi_i}{\partial\boldsymbol{v}} = 0.$$

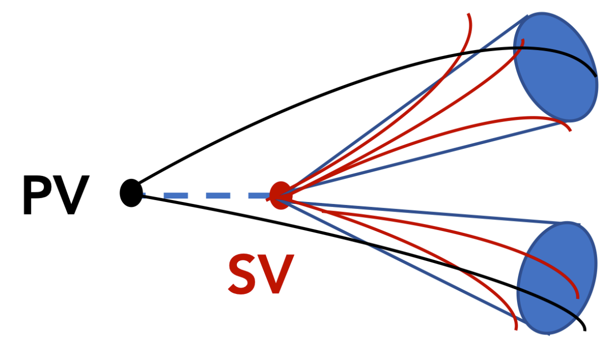


Preselections on SV/dijet candidates

❖ **Vertex invariant mass > 4GeV, p_T > 8GeV: thresholds are kept to be relatively small to be sensitive to low-mass LLPs.**

❖ **Developed a set of customized variables to further improve the signal-background discrimination while still remain inclusive:**





- For all the tracks assigned to the SV, find the one having the second largest $\mathrm{IP_{2D}}$ significance;
- Require this quantity to be larger than 15

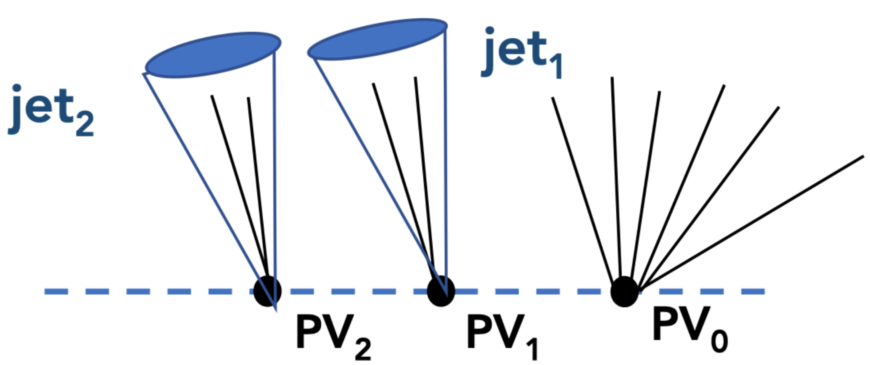
- Fraction of the charged energy coming from the SV:

$$\frac{\sum_{\mathrm{track}\in\mathrm{SV}} E_{\mathrm{track}}}{\sum_{\mathrm{track}\in\mathrm{dijet}} E_{\mathrm{track}}}$$

- Require this quantity to be larger than 15%

Preselections on SV/dijet candidates

❖ **Developed a set of customized variables to further improve the signal-background discrimination while still remain inclusive:**



- For each track, compute the IP_{3D} significances ($Sig[IP_{3D}]$) w.r.t. all primary vertices (including the leading PV and all PU vertices);
- For each track, we can identify the PV with the smallest $Sig[IP_{3D}]$, if this value is smaller than 5, assign the track to the PV;
- Compute the fraction of charged energy coming from the most compatible PVs for the dijet:

$$\zeta = \frac{\sum_{track \in PV_1} E_{track}^{Jet_1} + \sum_{track \in PV_2} E_{track}^{Jet_2}}{E_{Jet_1} + E_{Jet_2}}$$

- Require this quantity to be smaller than 0.2

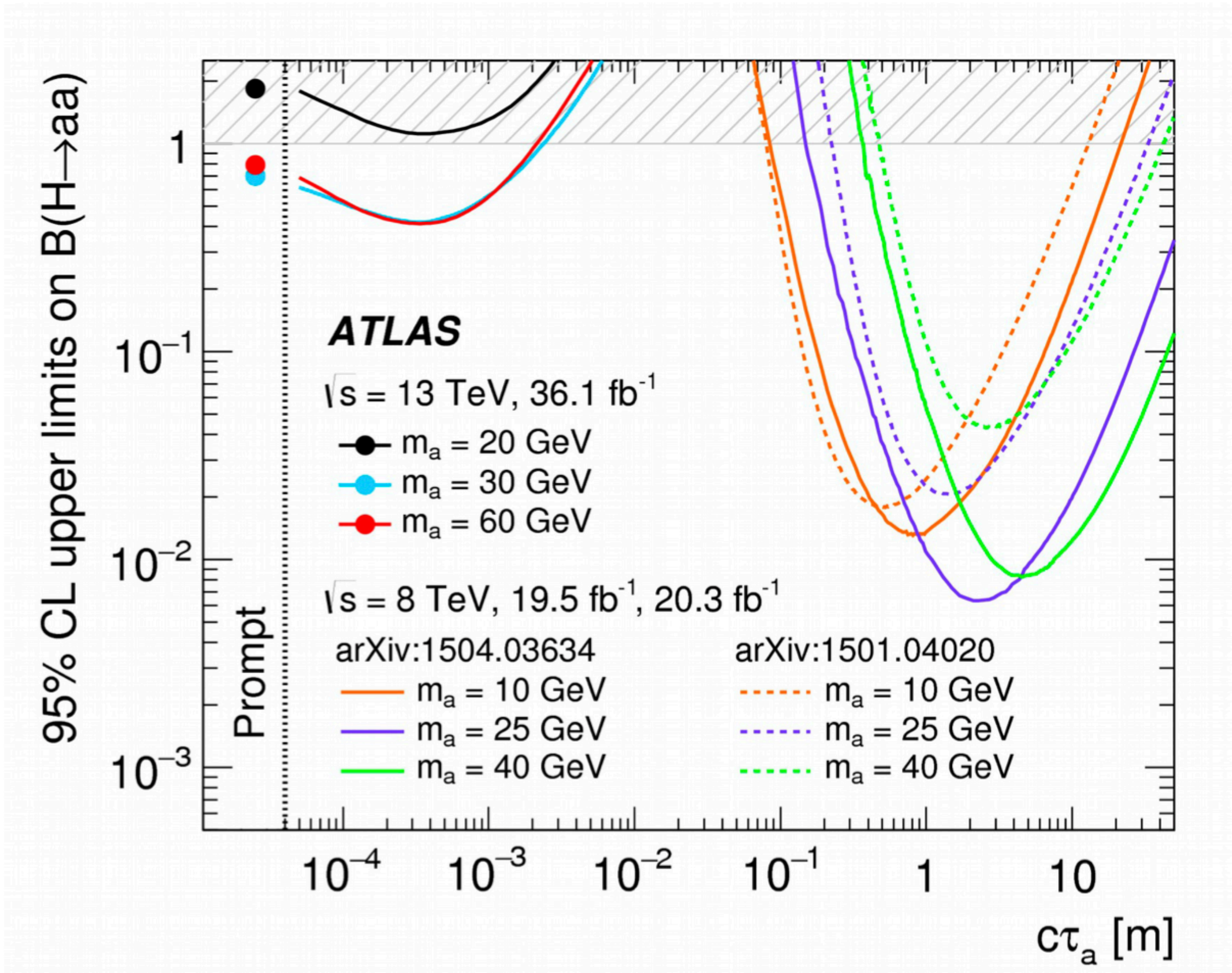
Displaced-jets cutflow

Selections	Observed events in data	Signal efficiency ($m_X = 1000\,\text{GeV}$) $c\tau_0$ 3 mm	30 mm	300 mm
Displaced-jet triggers, offline H_T selections	17758640	69.4%	91.2%	80.5%
Offline jet p_T and η selections, vertex $\chi^2/n_{dof} < 5.0$	8387775	68.9%	90.7%	73.5%
Vertex $p_T > 8\,\text{GeV}$	3794960	68.2%	90.3%	69.4%
Vertex invariant mass $> 4\,\text{GeV}$	1129531	66.5%	89.3%	61.6%
Second largest Sig[IP$_{2D}$] > 15	422449	66.0%	89.0%	60.9%
Secondary vertex track energy fraction > 0.15	93873	64.3%	87.6%	58.4%
$\zeta < 0.20$	15891	63.6%	86.9%	57.9%
Veto using the NI-veto map	13721	63.6%	84.9%	55.4%
Number of 3D prompt tracks < 3 for each jet	2753	54.6%	76.4%	48.4%
GBDT > 0.988	1	51.5%	73.5%	42.5%

Displaced-jets signal efficiencies

Efficiency (%)	m_X (GeV)	$c\tau_0$ 1 mm	10 mm	30 mm	100 mm	1000 mm
Trigger		29.47 ± 0.38	89.98 ± 0.67	91.16 ± 0.68	84.41 ± 0.65	71.72 ± 0.66
Preselection	1000	22.56 ± 0.34	85.22 ± 0.65	84.92 ± 0.65	73.83 ± 0.61	27.47 ± 0.41
Final selection		16.27 ± 0.29	73.63 ± 0.61	73.51 ± 0.61	61.51 ± 0.55	20.13 ± 0.35
Trigger		25.05 ± 0.35	70.50 ± 0.59	68.19 ± 0.58	58.97 ± 0.54	30.22 ± 0.39
Preselection	300	17.42 ± 0.30	59.89 ± 0.55	55.40 ± 0.53	42.38 ± 0.46	9.11 ± 0.21
Final selection		12.06 ± 0.25	48.41 ± 0.49	45.13 ± 0.48	32.42 ± 0.40	5.87 ± 0.17
Trigger		2.65 ± 0.12	6.97 ± 0.19	6.47 ± 0.18	4.87 ± 0.16	0.95 ± 0.07
Preselection	100	1.81 ± 0.10	4.94 ± 0.16	4.41 ± 0.15	2.59 ± 0.11	0.28 ± 0.04
Final selection		1.03 ± 0.07	3.47 ± 0.13	3.00 ± 0.12	1.64 ± 0.09	0.17 ± 0.03

Previous limits on exotic Higgs decays



Displaced-vertices background systematics

Systematic effect	Shift ± Statistical Uncertainty (%) 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