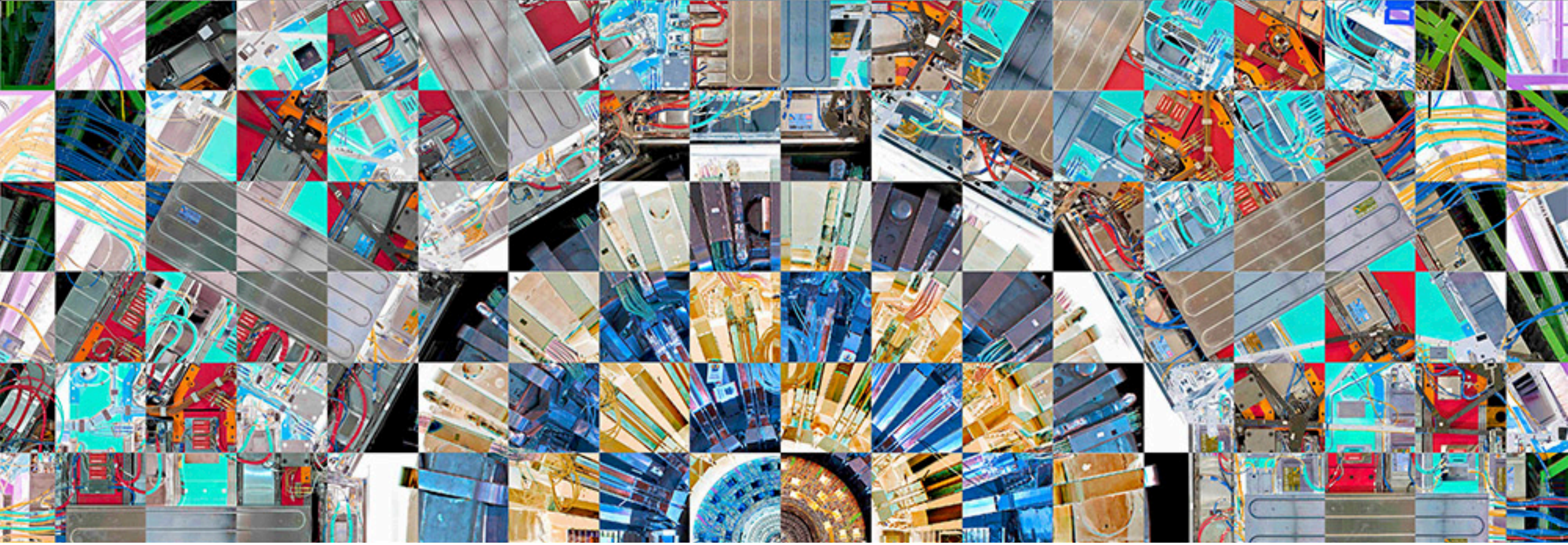


Searches with non-standard signatures with CMS

Livia Soffi
on behalf of CMS Collaboration

Cornell University

Going Wild at LHC

Non conventional final states ⟷ Non conventional Analysis Strategies

- **Unique detector signatures**
- Final states can include **non SM particles**
- **Unusual interactions** of new particles with the detectors

- **Trigger** unusual objects
- **Background usually data driven**
- **Creative analysis techniques** exploiting all aspects of detector

- **Extend the coverage & reach !**

Explore more final states

Increase luminosity & improve detector performance

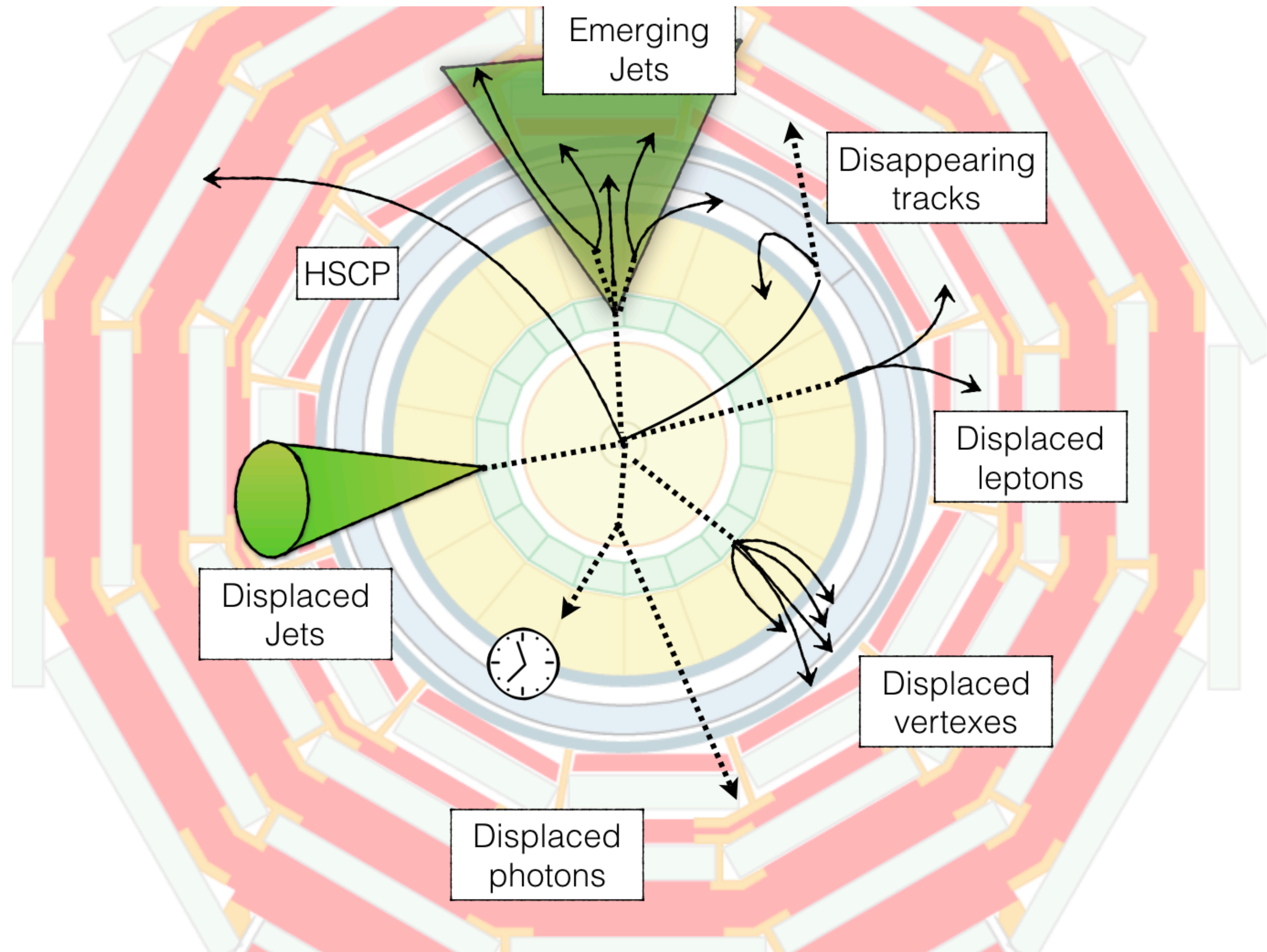
Rediscovered Interest in LLP

- *Strong* ***interest for Run2 and HL-Phase2***

  - **No hints** of new physics in **prompt searches**

  - Very **small backgrounds** from SM

  - **Dark Matter** related signatures



- *Why LL?*

amplitude suppressed

$$\Gamma = g^2 |A^2| \frac{\Phi}{M}$$

small coupling

phase space suppressed

- Be as much as model-independent as possible: **BSM scenarios**, such as SUSY or Hidden Valley as benchmark models to test the **significance of the searches**

Disappearing Tracks	EXO-16-044/ Submitted JHEP	2015+2016; 38.4 fb^{-1}
HSCP and Stopped Particles	EXO-16-036 and JHEP 05 (2018) 127	2016; 12.9 fb^{-1} and 2015+2016; 38.4 fb^{-1}
Displaced Jets	EXO-16-003/ PLB 780 (2018) 432-454	2015; 2.6 fb^{-1}
NEW **Displaced Vertices**	EXO-17-018	2015+2016; 38.5 fb^{-1}
Displaced Leptons	HIG-16-035 (low mass mumu)	2015; 2.8 fb^{-1}
Displaced Photons	Projection at HL LHC TDR-17-006	HL LHC proj.
NEW **Emerging Jets**	EXO-18-001	2016; 16.1 fb^{-1}

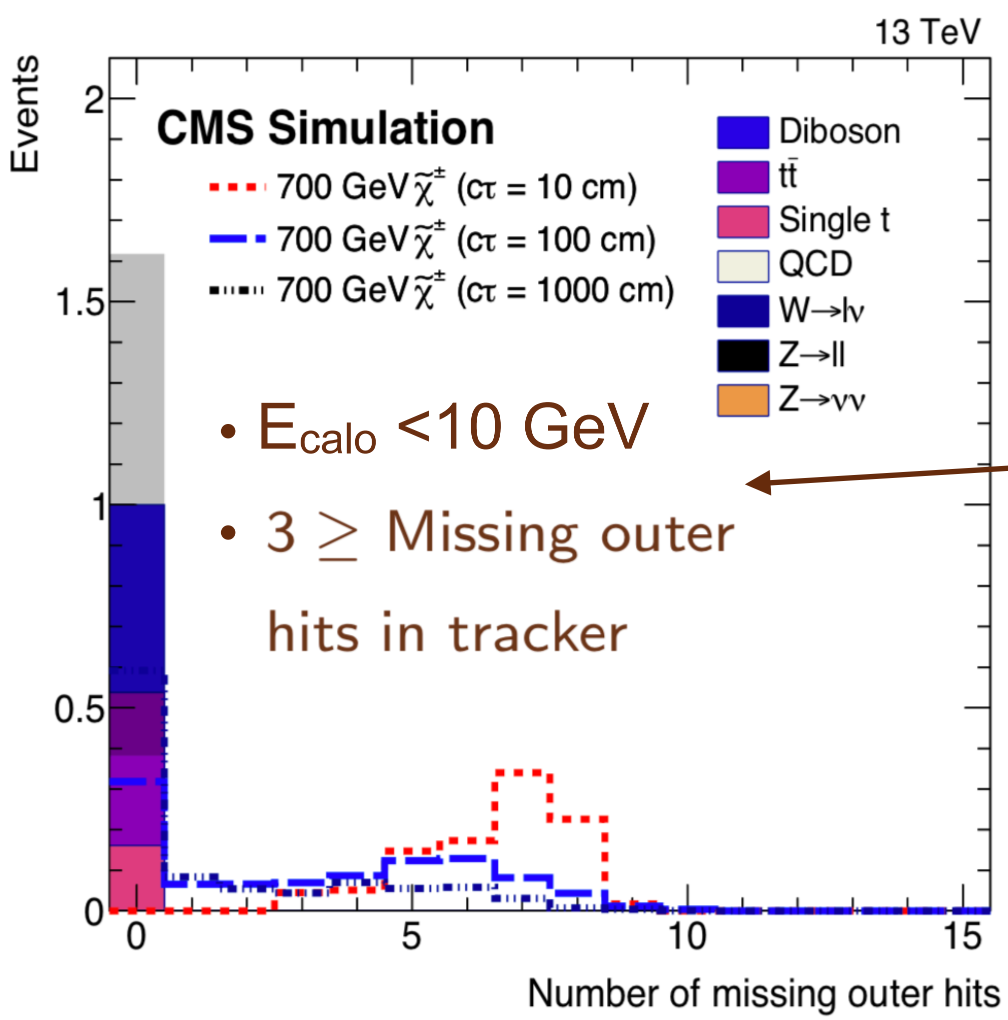
Disappearing Tracks I

- Isolated prompt track with **missing hits in the outer layers of the silicon tracker** without energy in the calorimeters or muon detectors.

Model: Anomaly Mediated SUSY Breaking (AMSB)

$$\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^0 \pi^{\pm}$$

- LL $\chi^{\pm}$ due to small mass splitting:
  $m_{\tilde{\chi}^{\pm}} - m_{\tilde{\chi}^0} \rightarrow \pi^{\pm}$ too soft to be reconstructed, O(MeV).



- E_{calo} <10 GeV
- $3 \geq$ Missing outer hits in tracker

New w.r.t. 2015

- Trigger: MET > 75 GeV && p_T^{iso}-trk > 50 GeV
- Estimated background from data

Tracks Selection:

- 3 hits in pixel + ≥ 6 hits in tracker
- |d0| < 0.02 cm and |z0| < 0.5 cm

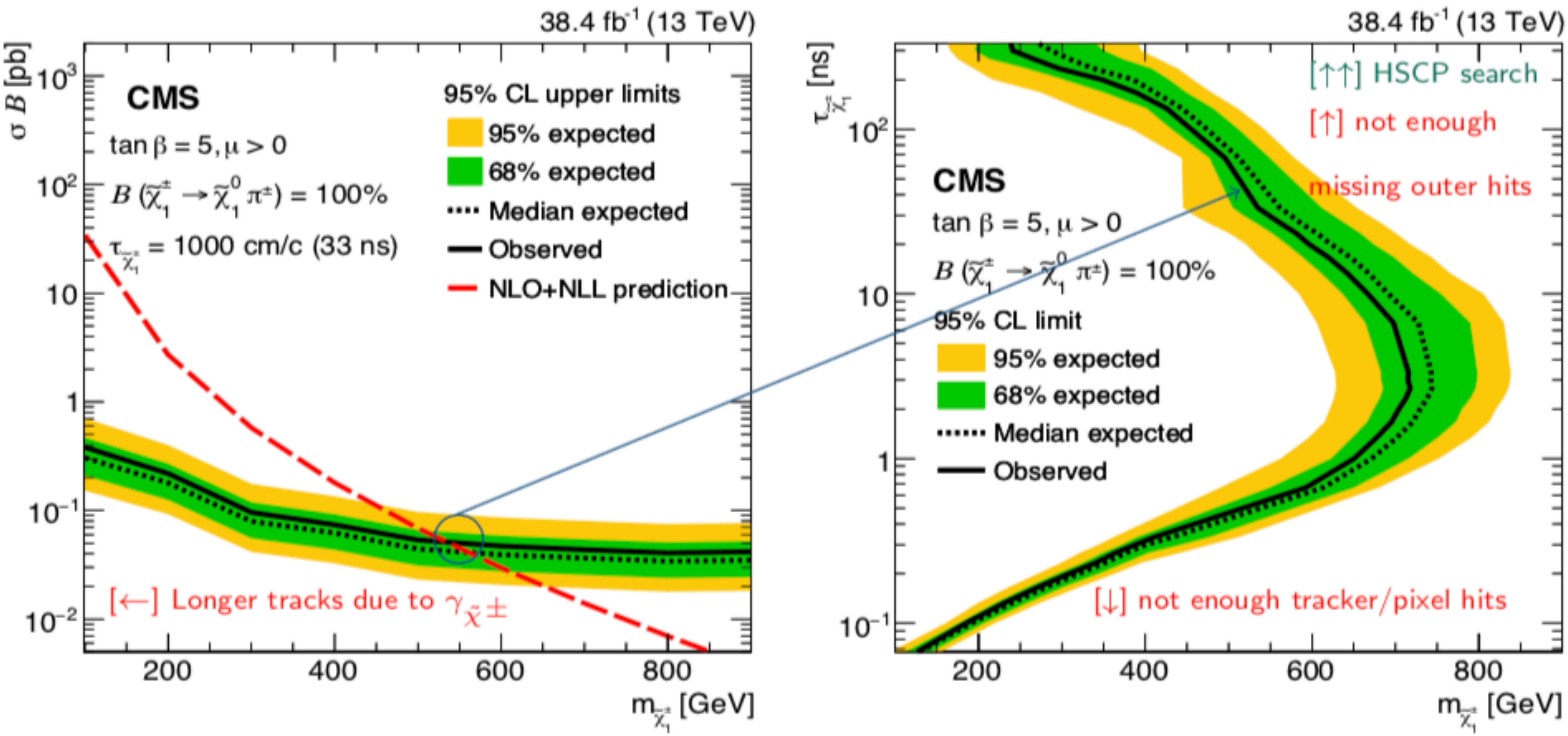
Reduce Spurious tracks

- ΔR(track, lepton) < 0.15 are vetoed
- Vetoing tracks within gaps in acceptance

Reduce Isolated leptons

Disappearing Tracks II

Run period	Estimated number of background events			Observed events
	Leptons	Spurious tracks	Total	
2015	0.1 ± 0.1	$0^{+0.1}_{-0}$	0.1 ± 0.1	1
2016A	$2.0 \pm 0.4 \pm 0.1$	$0.4 \pm 0.2 \pm 0.4$	$2.4 \pm 0.5 \pm 0.4$	2
2016B	$3.1 \pm 0.6 \pm 0.2$	$0.9 \pm 0.4 \pm 0.9$	$4.0 \pm 0.7 \pm 0.9$	4
→ Total	$5.2 \pm 0.8 \pm 0.3$	$1.3 \pm 0.4 \pm 1.0$	$6.5 \pm 0.9 \pm 1.0$	7 ←



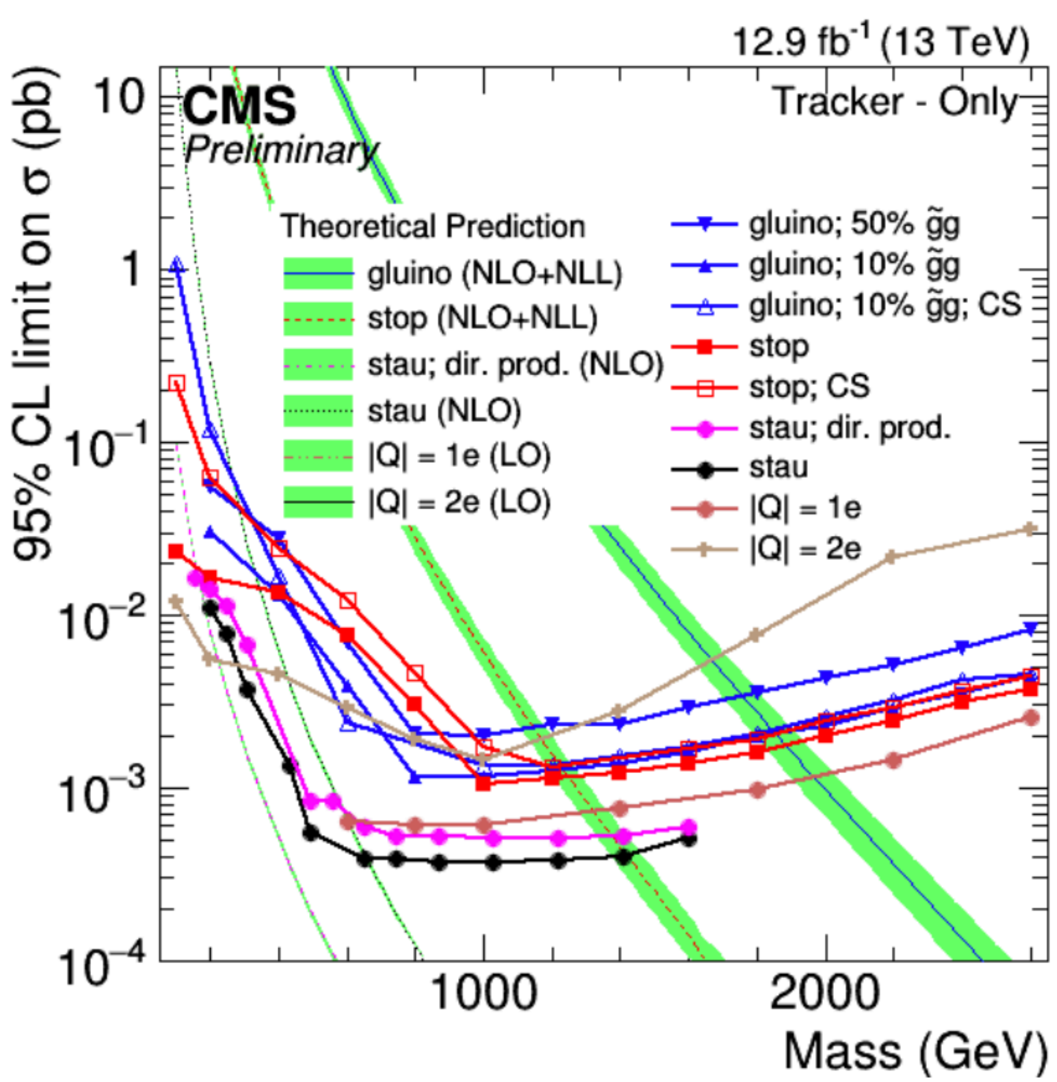
HSCP and Stable Particles

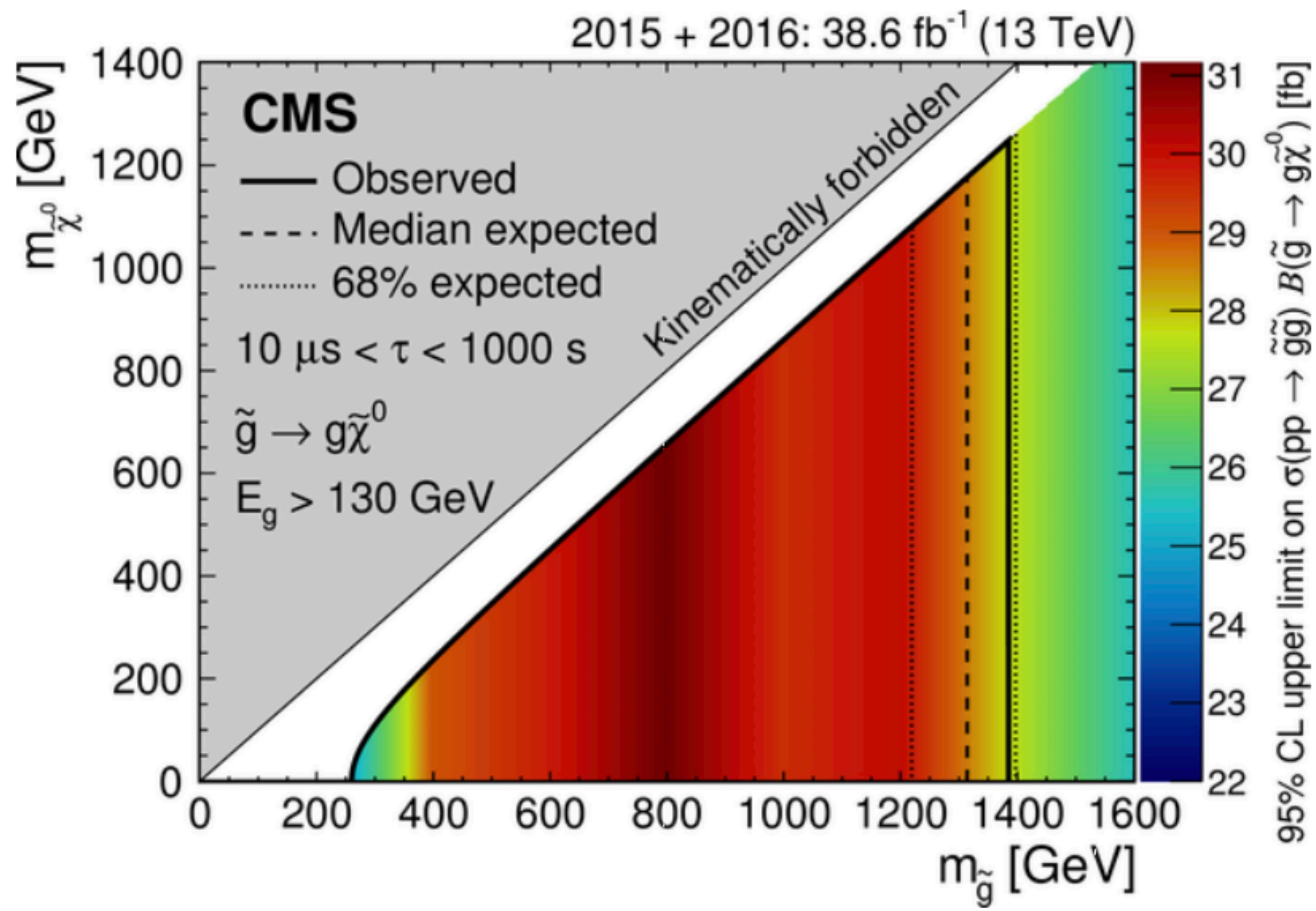
- HSCP: **Heavy Stable Charged Particles** leave **anomalous dE/dx + measuring time in muon chambers**
  - Tracker Only/Tracker +TOF

$\beta < 0.9$

- Stopped particles: **LLPs trapped in the calorimeters** decay when no collisions after long times ≈ (**100ns to 10 days**).
  - Hadronic (calorimeters) and leptonic (muon chambers) decays

$\beta < 0.5$

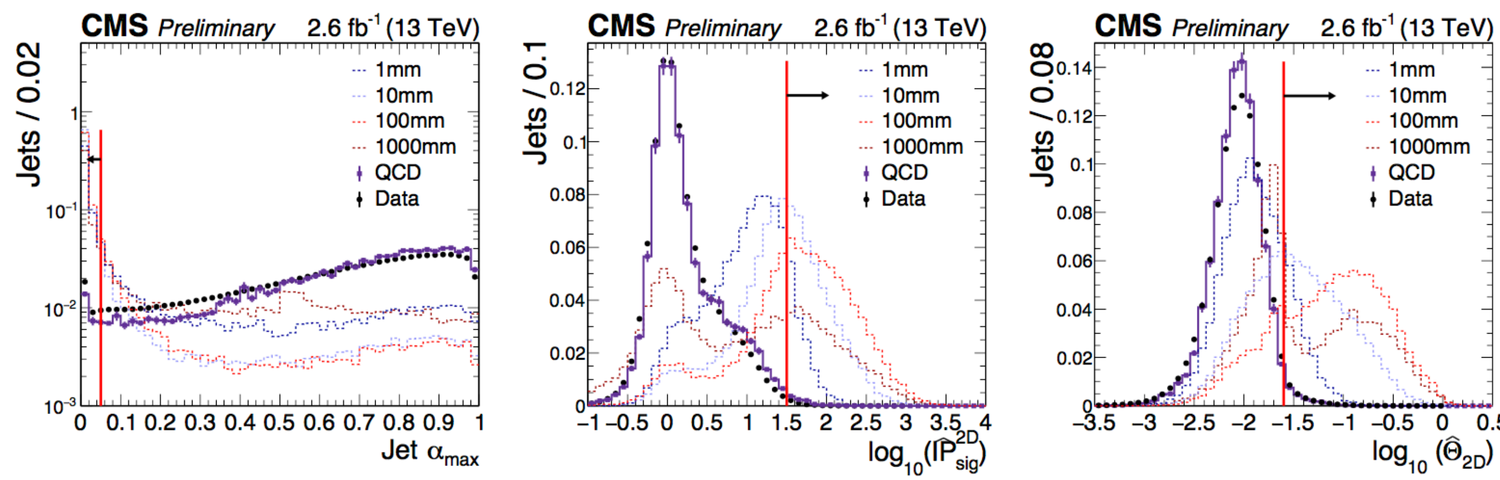




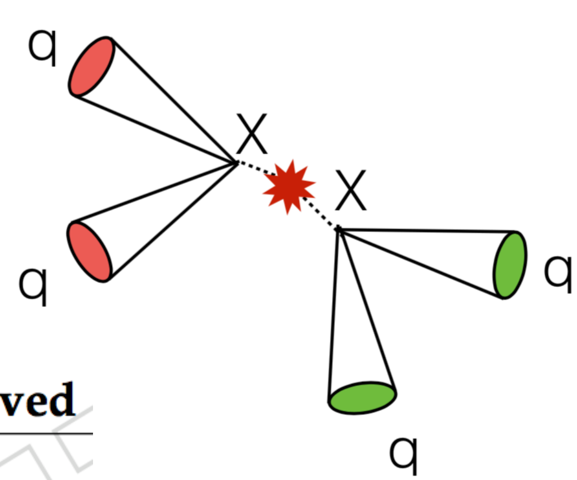
Inclusive Displaced Jets

- **Pair-produced long-lived** scalar neutral particles /top squarks (RPV) decaying to jets and leptons
- Information from **reconstructed tracks** used to discriminate the **displaced-jets signal** from multijet events.

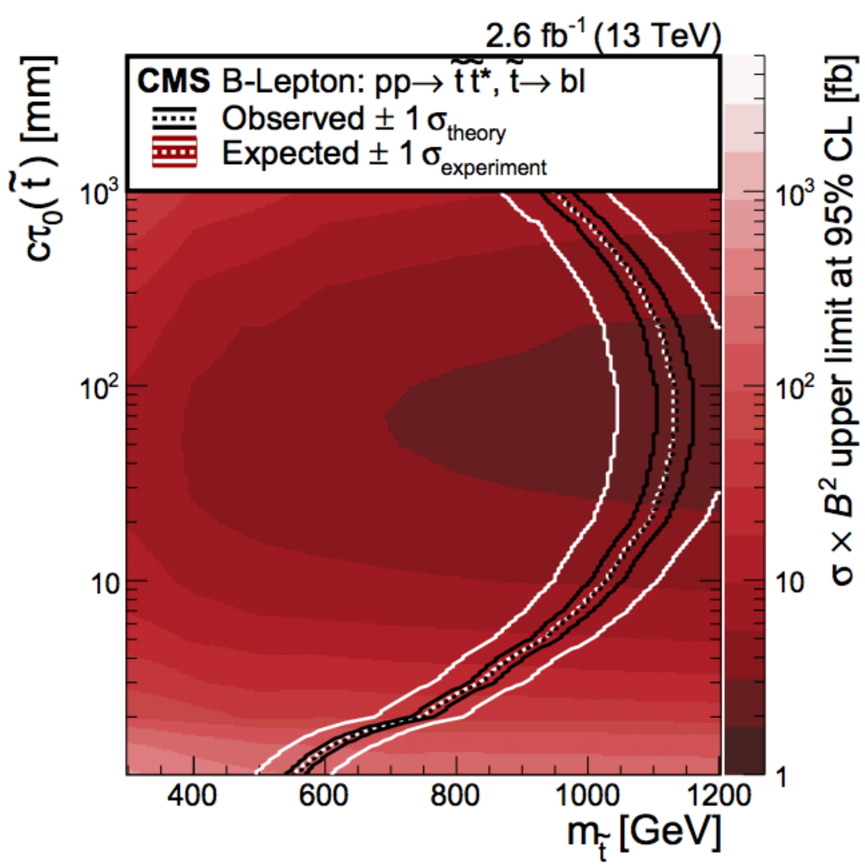
- Dedicated **tagging algorithm** to identify displaced jets.



- Study of **exclusive categories**: Jet-Jet/B-Lepton



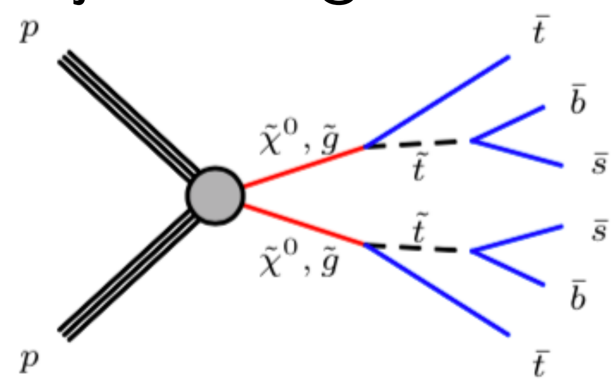
N_{tags}	Expected	Observed
2	1.09 ± 0.16	1
≥ 3	$(4.9 \pm 1.0) \times 10^{-4}$	0



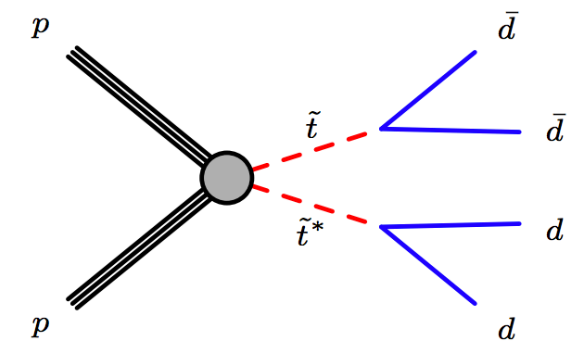
Displaced Vertices I

- **Pairs of multitrack displaced vertices** produced inside the beampipe (< 2 cm) with transverse distance dVV.

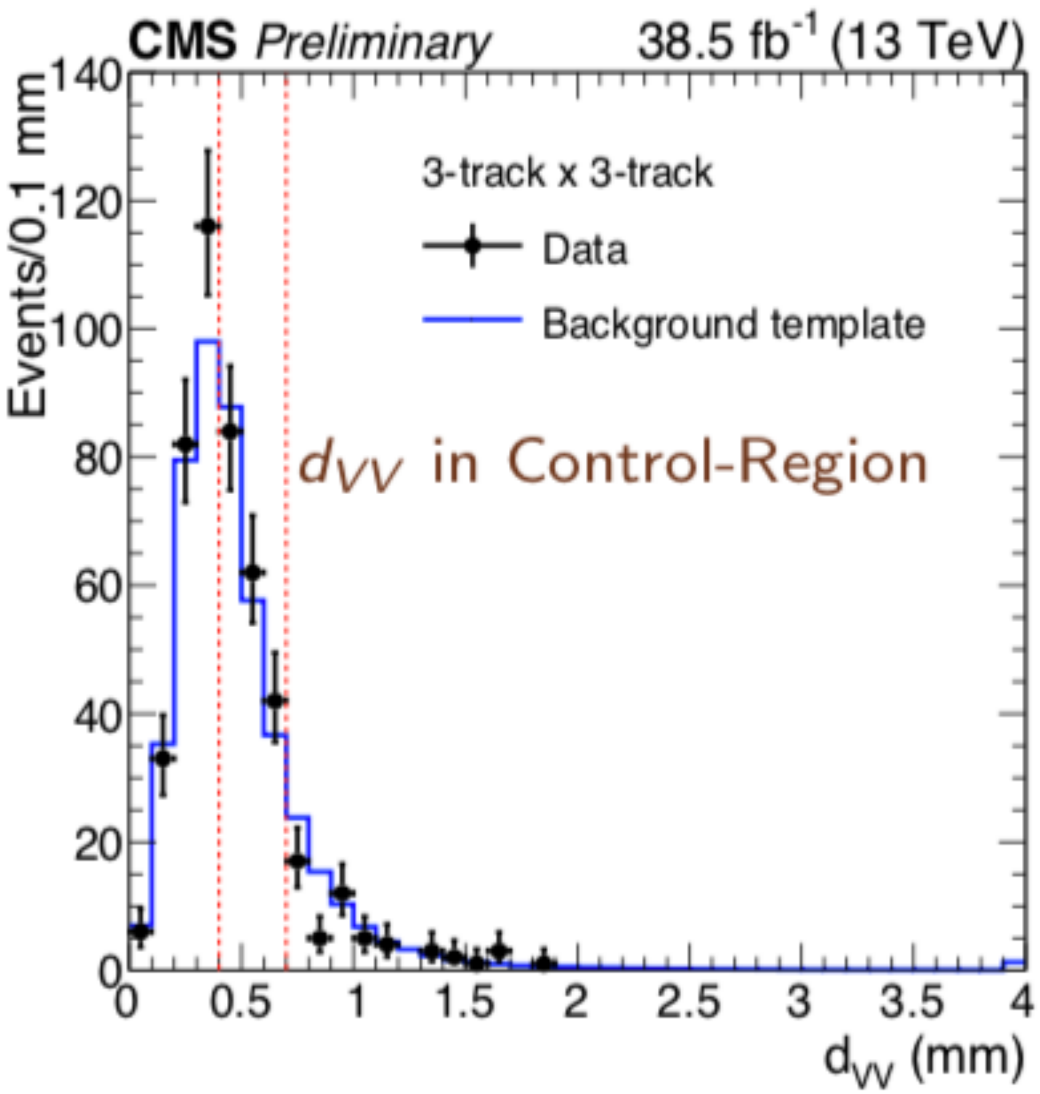
Multijet: Long lived $\tilde{\chi}^0/\tilde{g}$



Dijet: Long lived $\tilde{t}$



- ***Models: RPV-SUSY:***



- ***Dedicated displaced vertexing:***

- Vertex made of ≥ 5 tracks with dxy / σ(dxy) > 4

- Including hits in the innermost pixel layer.

- ***Data-driven backgrounds:***

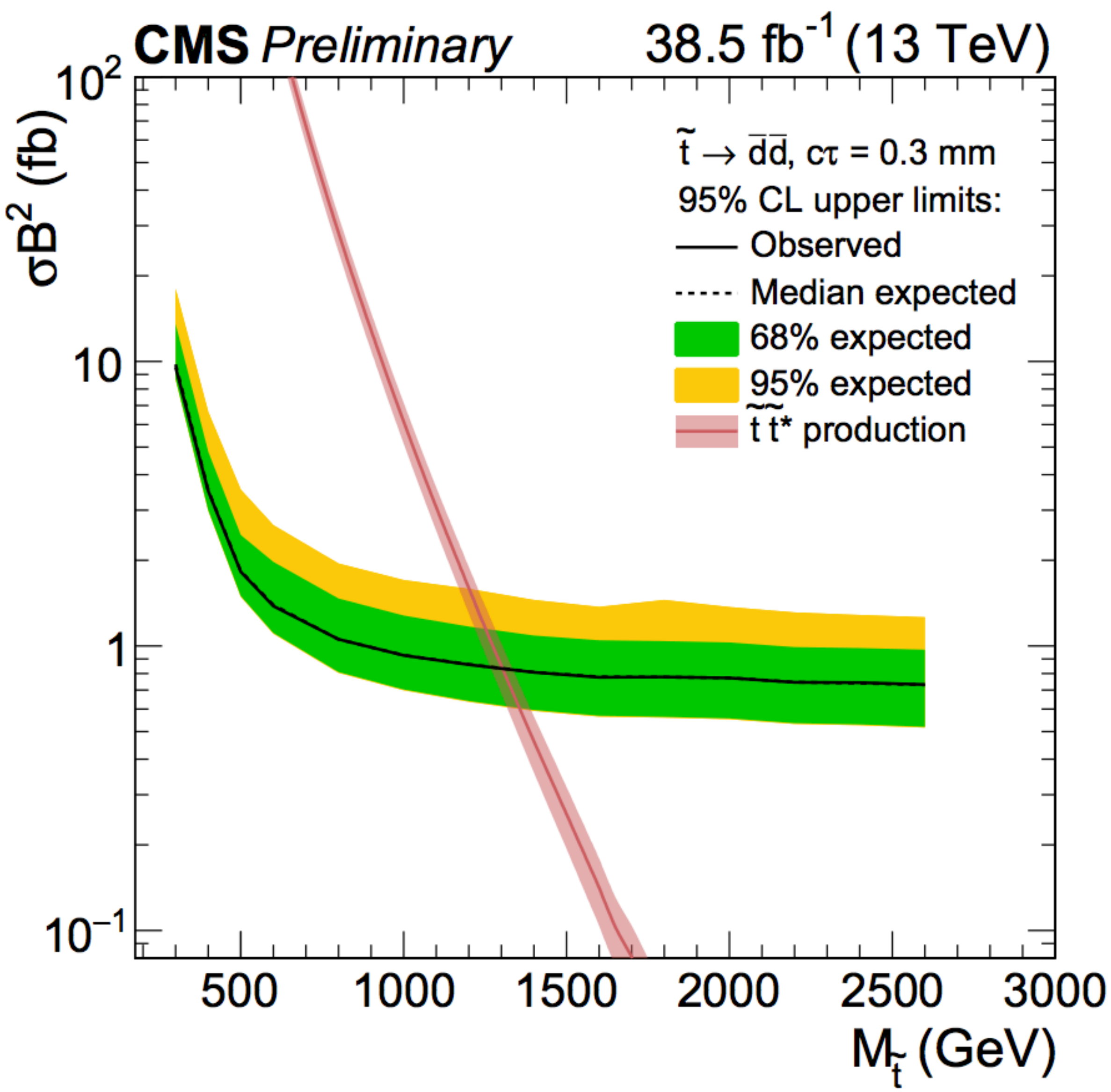
Evaluated in Control-Regions built using displaced vertices with ≤ 4 tracks.

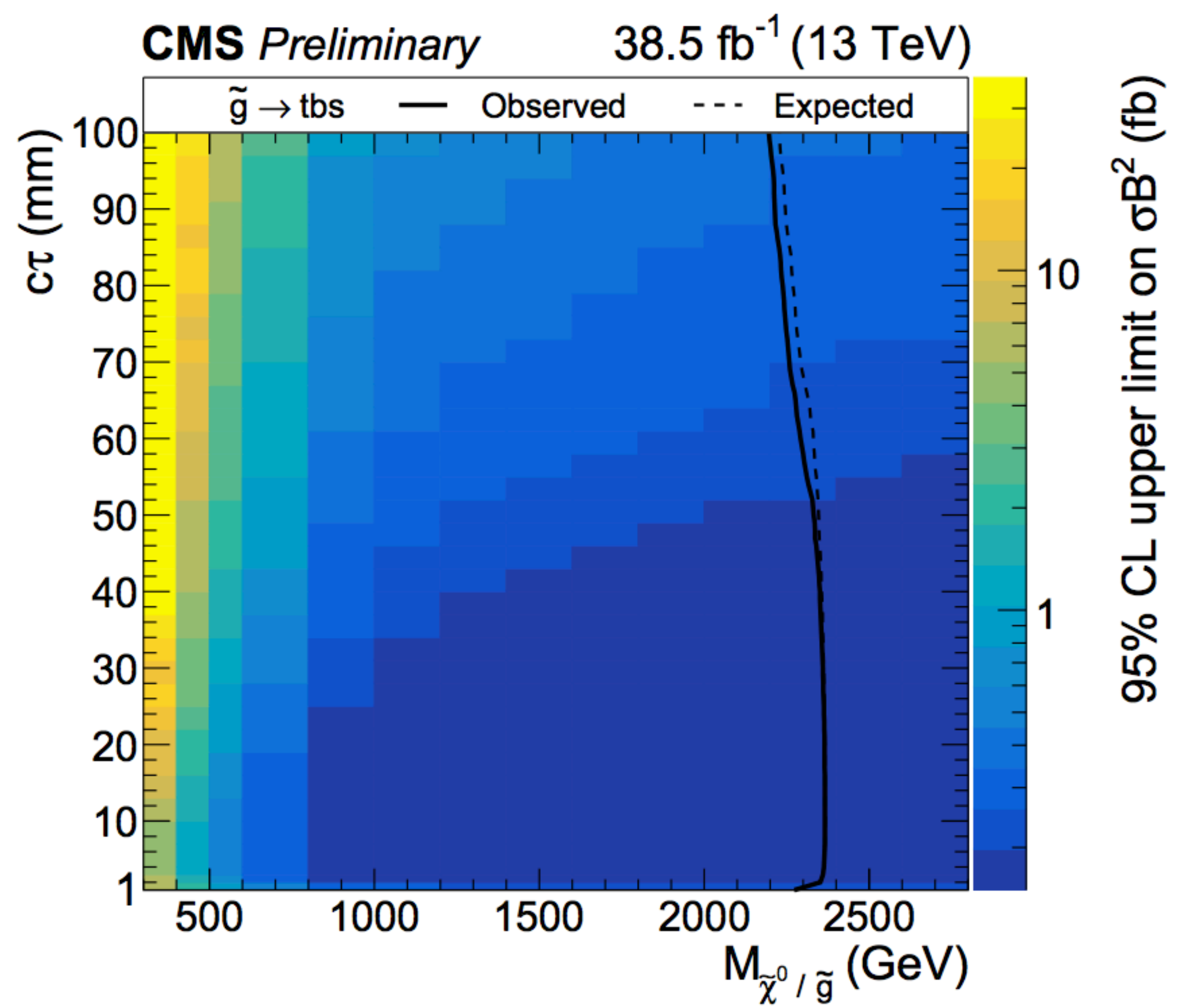
- Fit the distribution of $\mathbf{d_{VV}}$ to extract signal

Displaced Vertices II

n ≥5-track two-vertex events

d_{VV} range	Fitted background yield	Observed	Predicted signal yields 0.3 mm	1 mm	10 mm
0–0.4 mm	0.51 ± 0.01 (stat) ± 0.13 (syst)	1	2.8 ± 0.7	3.5 ± 0.8	1.0 ± 0.2
0.4–0.7 mm	0.37 ± 0.02 (stat) ± 0.09 (syst)	0	2.0 ± 0.5	3.7 ± 0.9	0.5 ± 0.1
0.7–40 mm	0.12 ± 0.02 (stat) ± 0.08 (syst)	0	1.1 ± 0.3	11 ± 3	31 ± 7



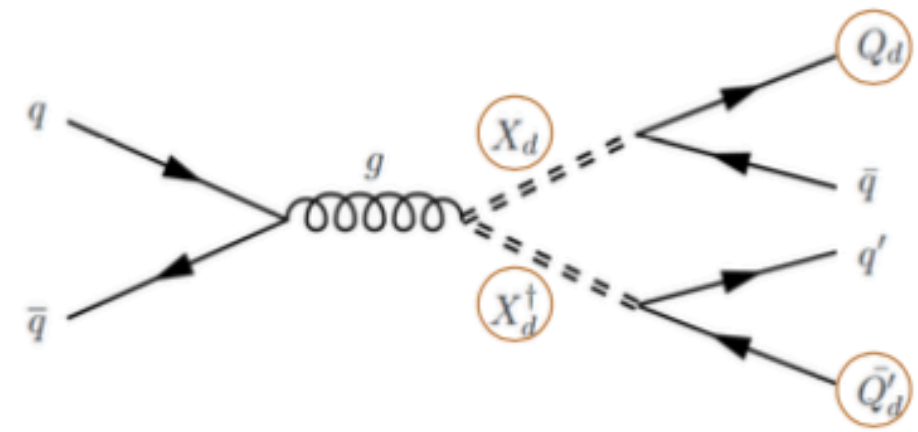


Emerging Jets

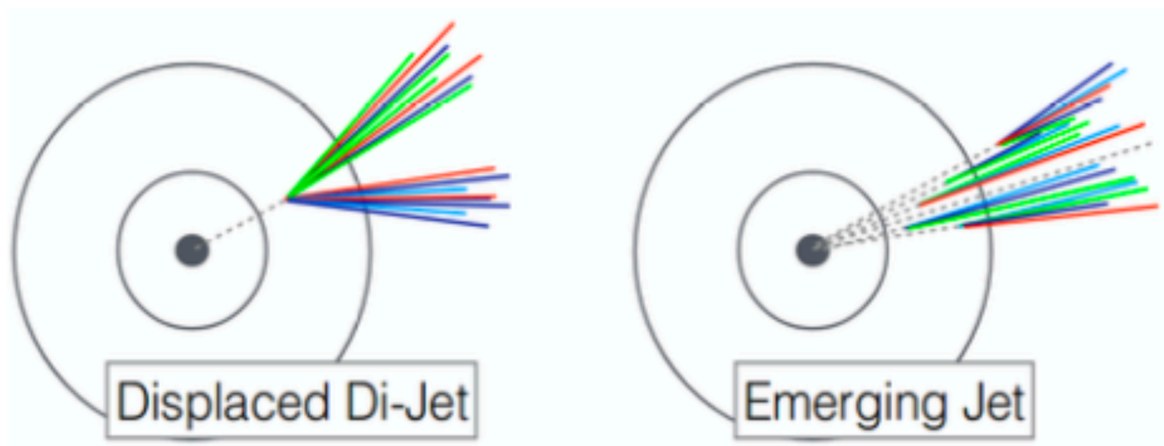
The **Dark QCD** model: arXiv:1502.05409.

- Mediator, X_d, charged under dark-QCD and QCD.
- Dark fermions, Q_d, that hadronize and form dark jets containg dark hadrons, ex: long-lived dark-pions, π_d.

  → π_d can decay back to SM particles.



Emerging jets are produced in the hadronization of dark-fermions, Q_d, and contain multiple displaced vertices from the decay of dark-pions:



Signal: 2 Prompt Jets
+2 Emerging Jets

Signal model parameters	List of values
Dark mediator mass M_{X_d} [GeV]	400, 600, 800, 1000, 1250, 1500, 2000
Dark pion mass m_{π_d} [GeV]	1, 2, 5, 10
Dark pion decay length τ_{π_d} [mm]	1, 2, 5, 25, 45, 60, 100, 150, 225, 300, 500, 1000

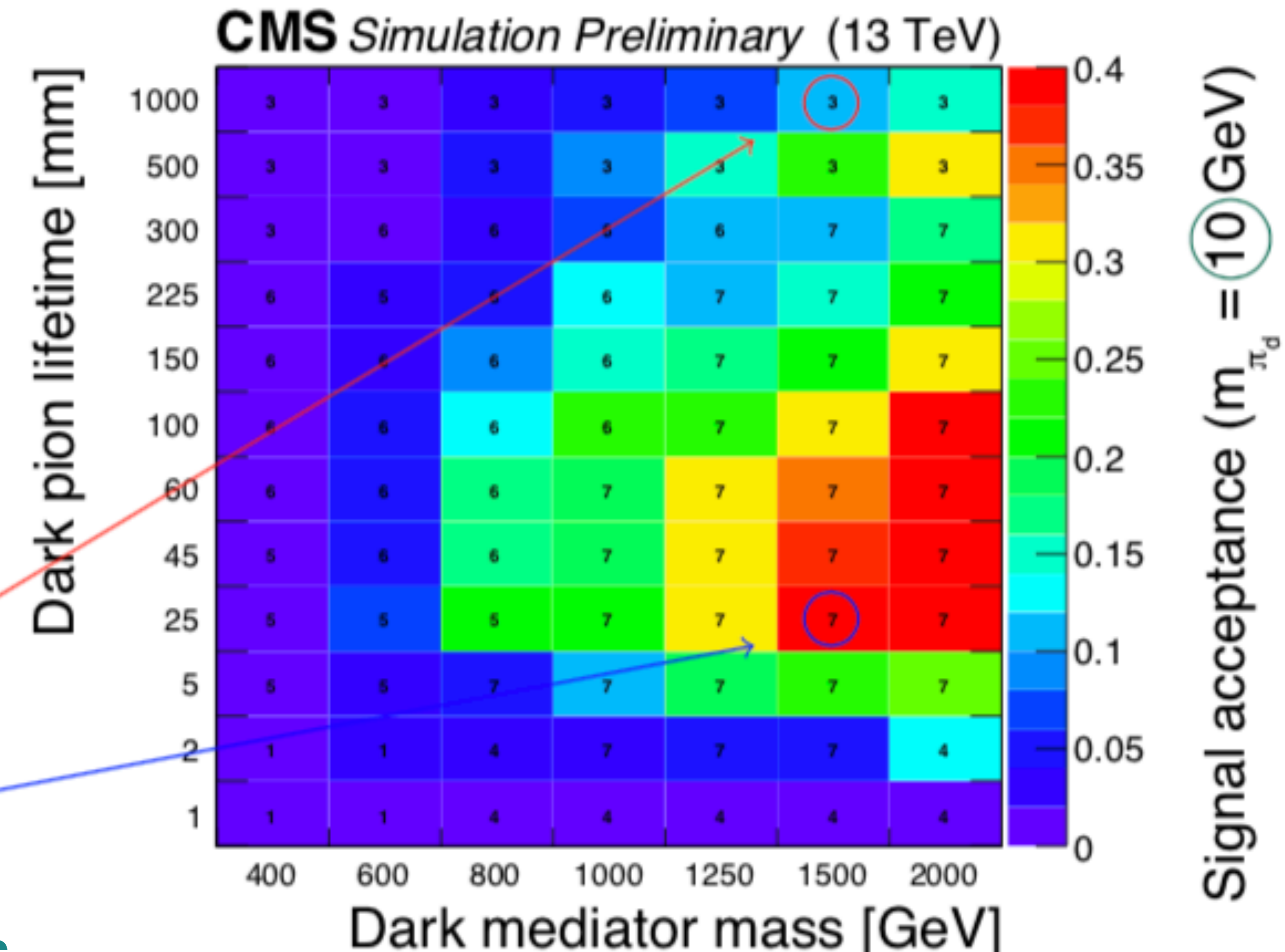
Analysis optimized for each of the 336 signal hyphotesis

Emerging Jets

Idea: Extension of the displaced jet search and tagger to emerging jets.

7 Different Signal Regions (SR) cover the 336 Dark QCD signal hyphotesis.

- Dedicated optimized kinematic selection.
- Dedicated emerging jet tag selection.



Example of 3 and 7 selections

Set number	H_T	$p_{T,1}$	$p_{T,2}$	$p_{T,3}$	$p_{T,4}$	p_T^{miss}	$n_{em}(\geq)$	PU_{dz} (<)	D_N (<)	$\langle IP_{2D}\rangle$ (>) [cm]	α_{3D} (<)
3	900	225	100	100	100	200	1	4.0	20	0.25	0.25
7	1200	300	250	200	150	0	2	2.5	10	0.05	0.25

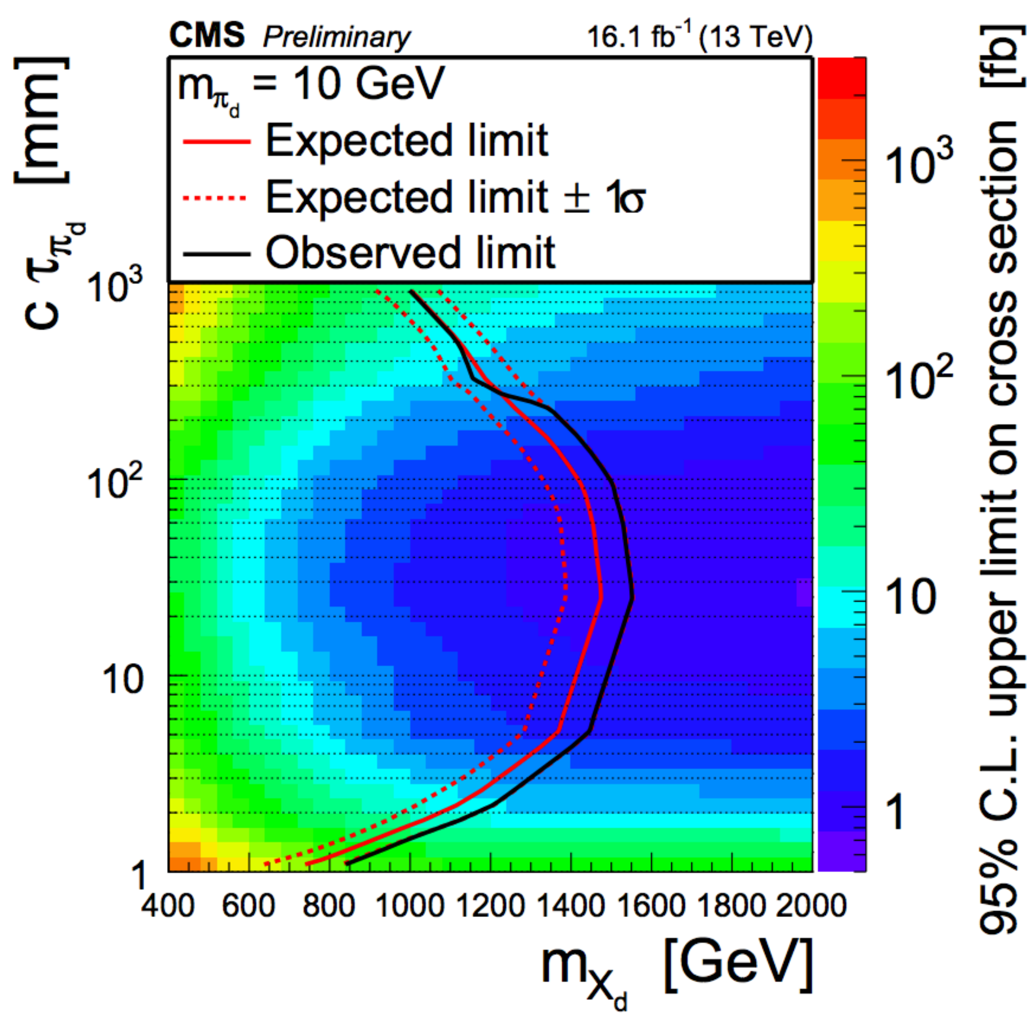
kinematic selection

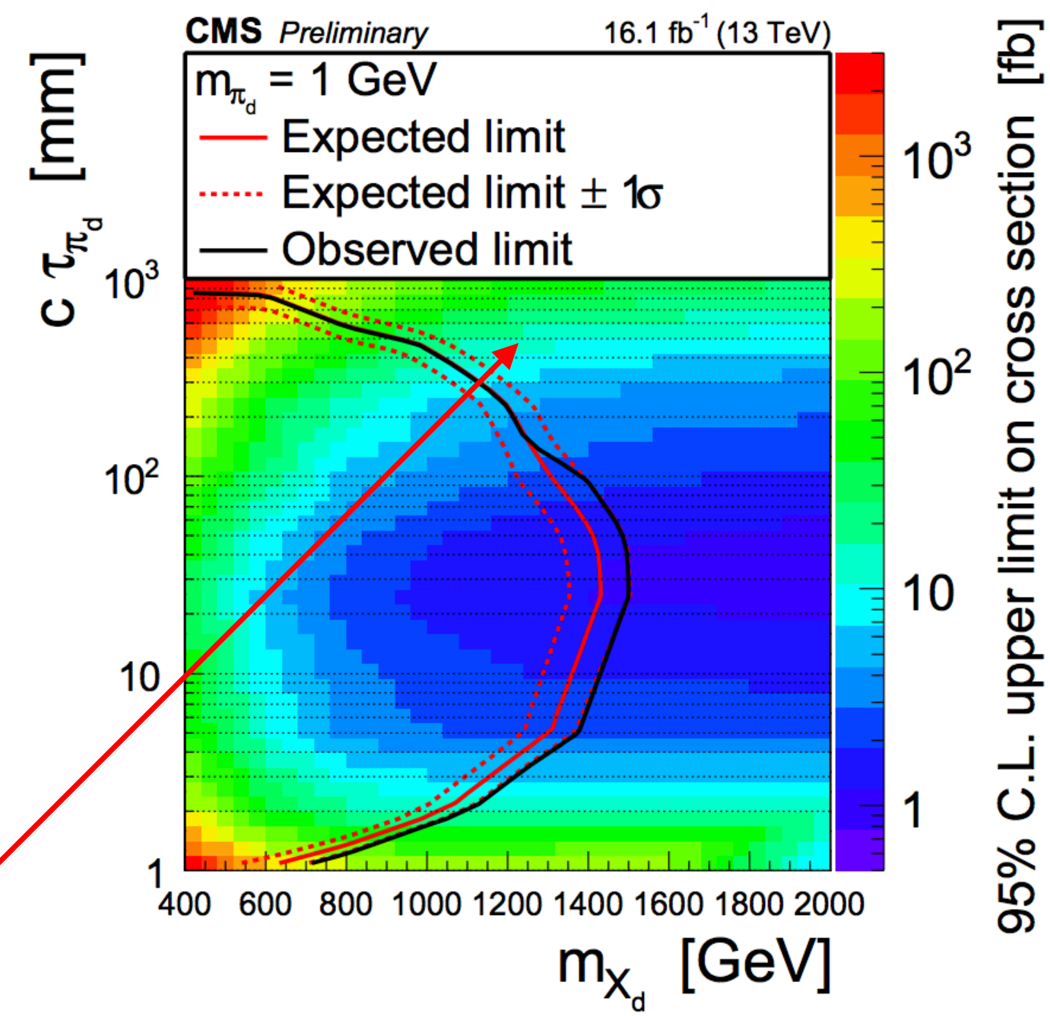
emerging jet selection

Emerging Jets

Set number	Expected	Observed
1	168 ± 15 (syst$_1$) ± 5 (syst$_2$)	131
2	31.8 ± 5.0 (syst$_1$) ± 1.4 (syst$_2$)	47
3	19.4 ± 7.0 (syst$_1$) ± 5.5 (syst$_2$)	20
4	22.5 ± 2.5 (syst$_1$) ± 1.5 (syst$_2$)	16
5	13.9 ± 1.9 (syst$_1$) ± 0.6 (syst$_2$)	14
6	9.4 ± 2.0 (syst$_1$) ± 0.3 (syst$_2$)	11
7	4.40 ± 0.84 (syst$_1$) ± 0.28 (syst$_2$)	2

Observed events in agreement with backround expectations in all 7 regions.
→ First Dark QCD limits from CMS.





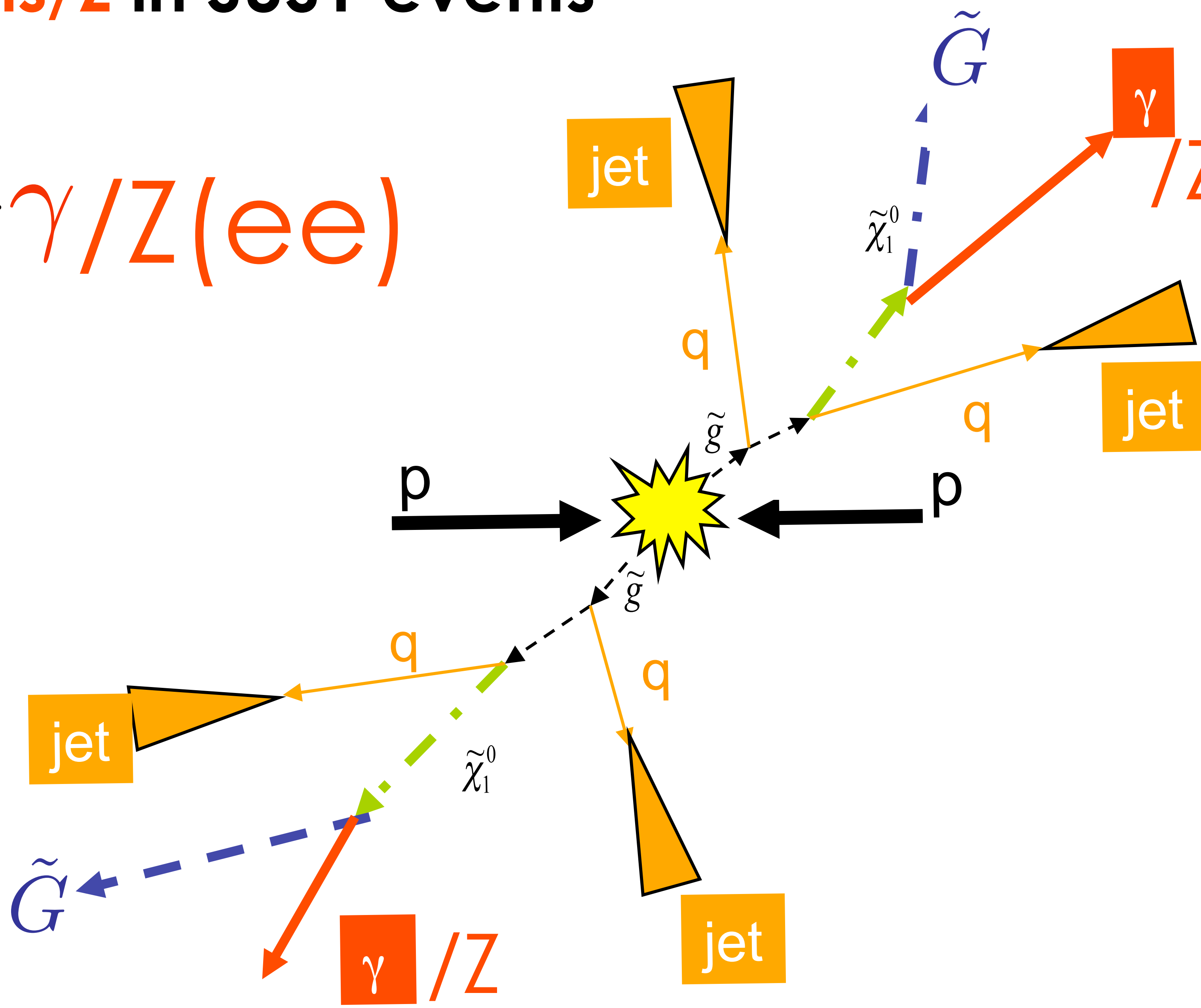
[*] Weaker constraints for $m_{\pi_d} = 1$ GeV and $c\tau_{\pi_d} \gtrsim 10$ cm due more decays beyond pixel tracker.

Exploring the unconventional for HL LHC..

Promising signatures with delayed photons/Z

Search for delayed photons/Z in SUSY events

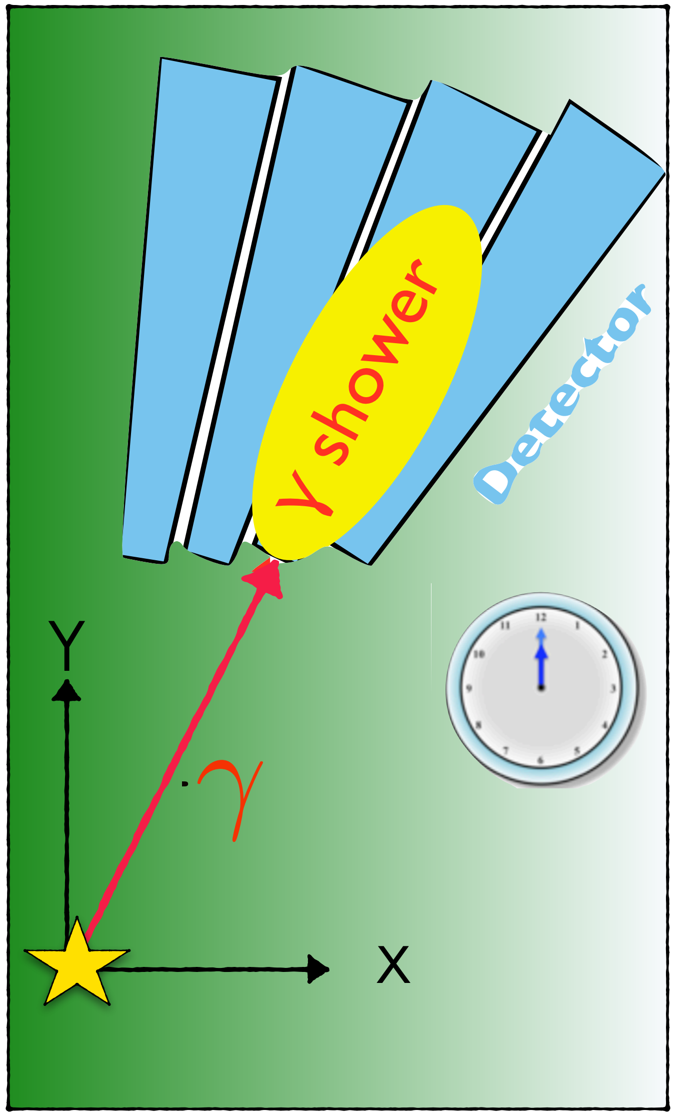
$$\tilde{\chi}_1^0 \rightarrow \tilde{G} + \gamma/Z(ee)$$



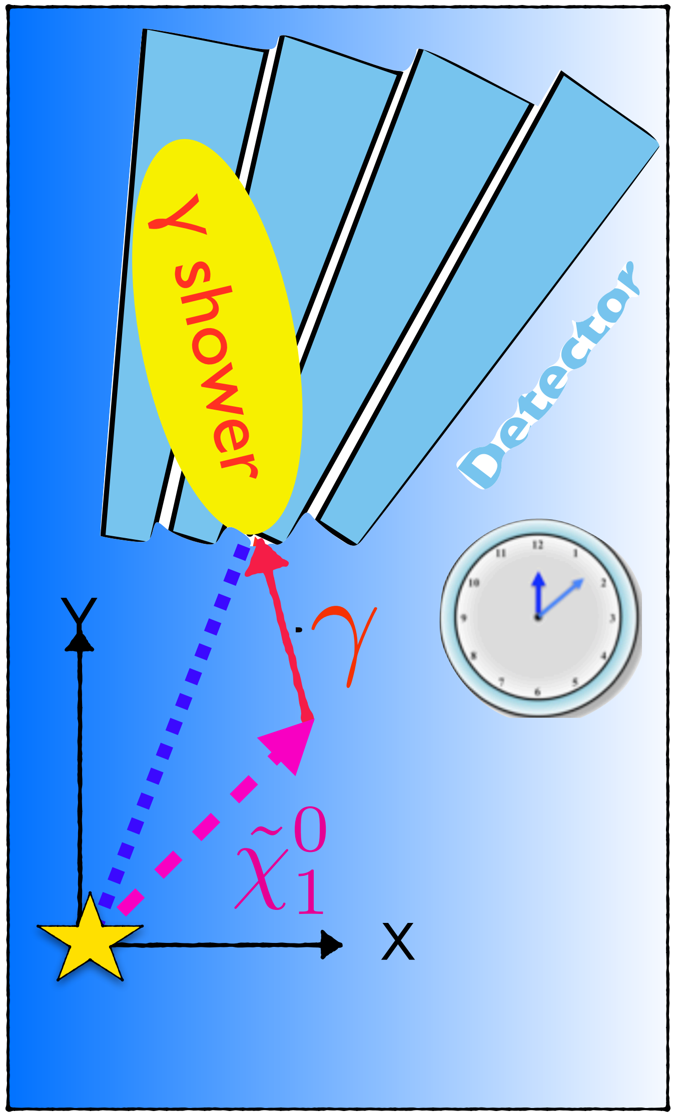
- If **neutralino** is **long-lived**:
  - **Photon/Z (ee)** arrives **on ECAL in delay** w.r.t. prompt particles
  - So far tagging events w/ **ECAL time** information (res 200-300 ps)

Challenges of the search:
- **Non-standard electromagnetic objects**, customize **trigger/ reconstruction/simulation**

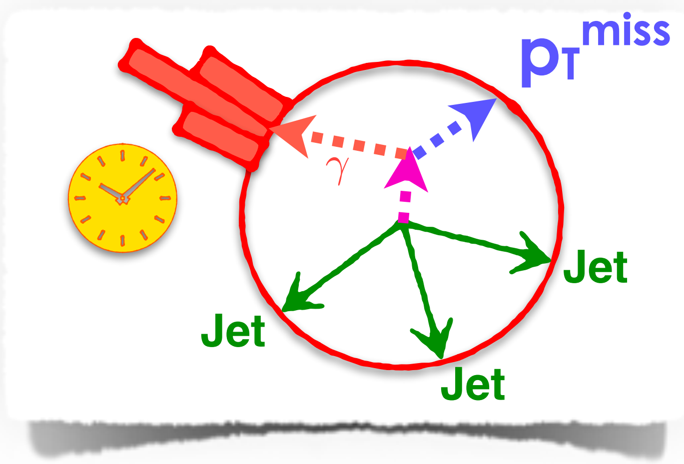
Out Of Time Photons Detection

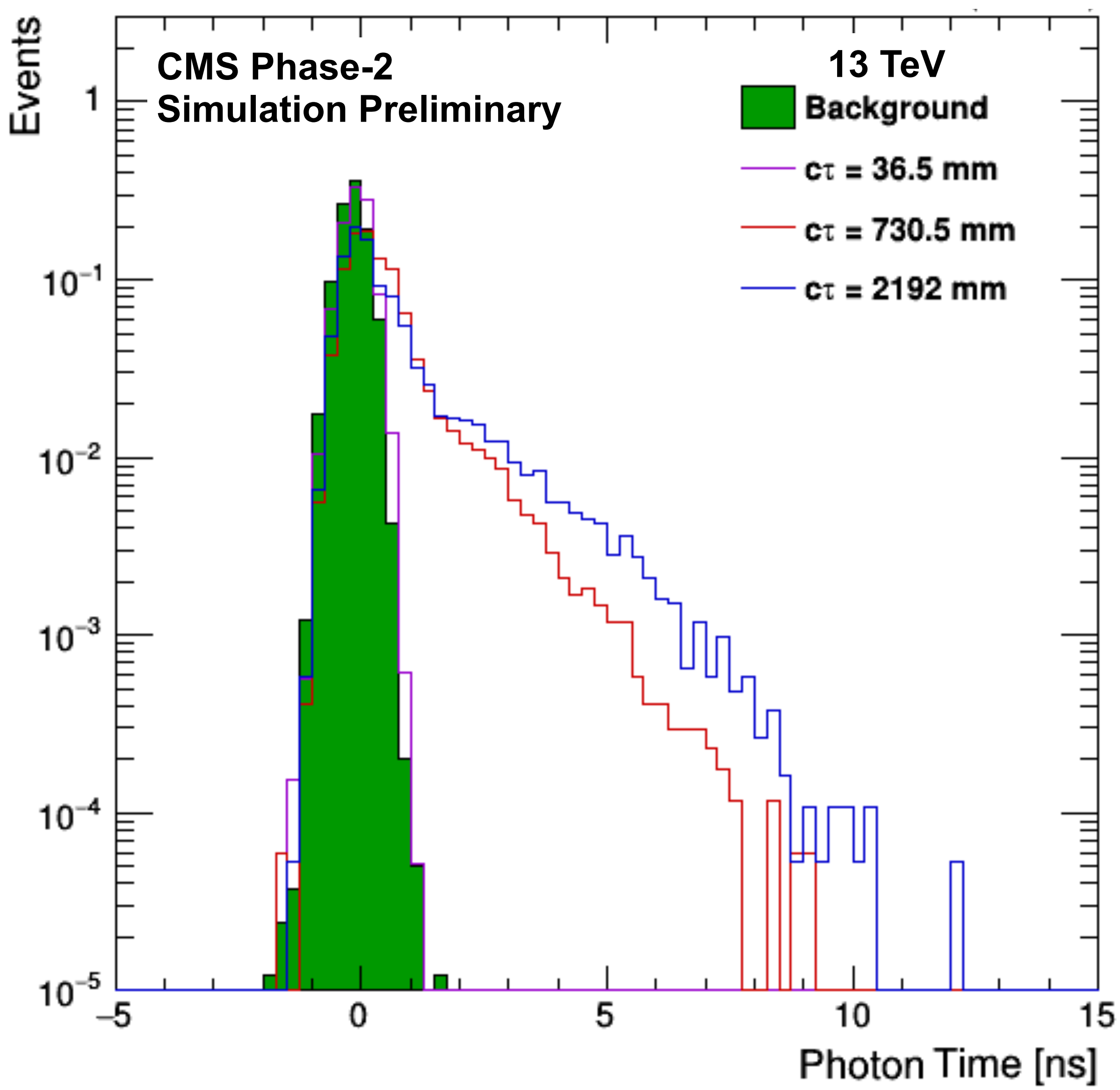


Time compatible with that of a **relativistic particle from the IP**



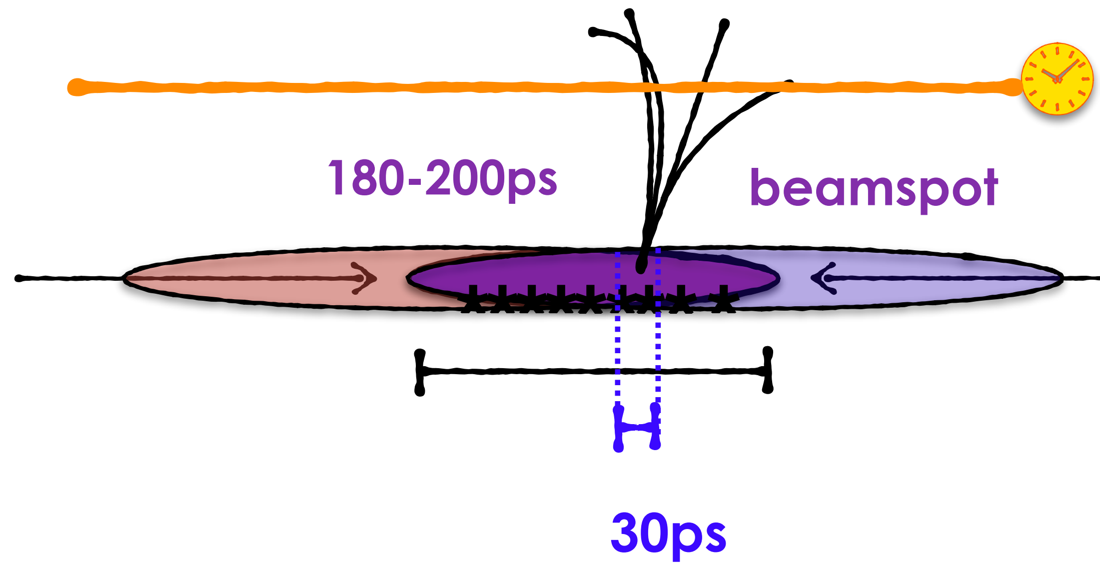
Time sensibly increase with **parent particle lifetime O(ns)**

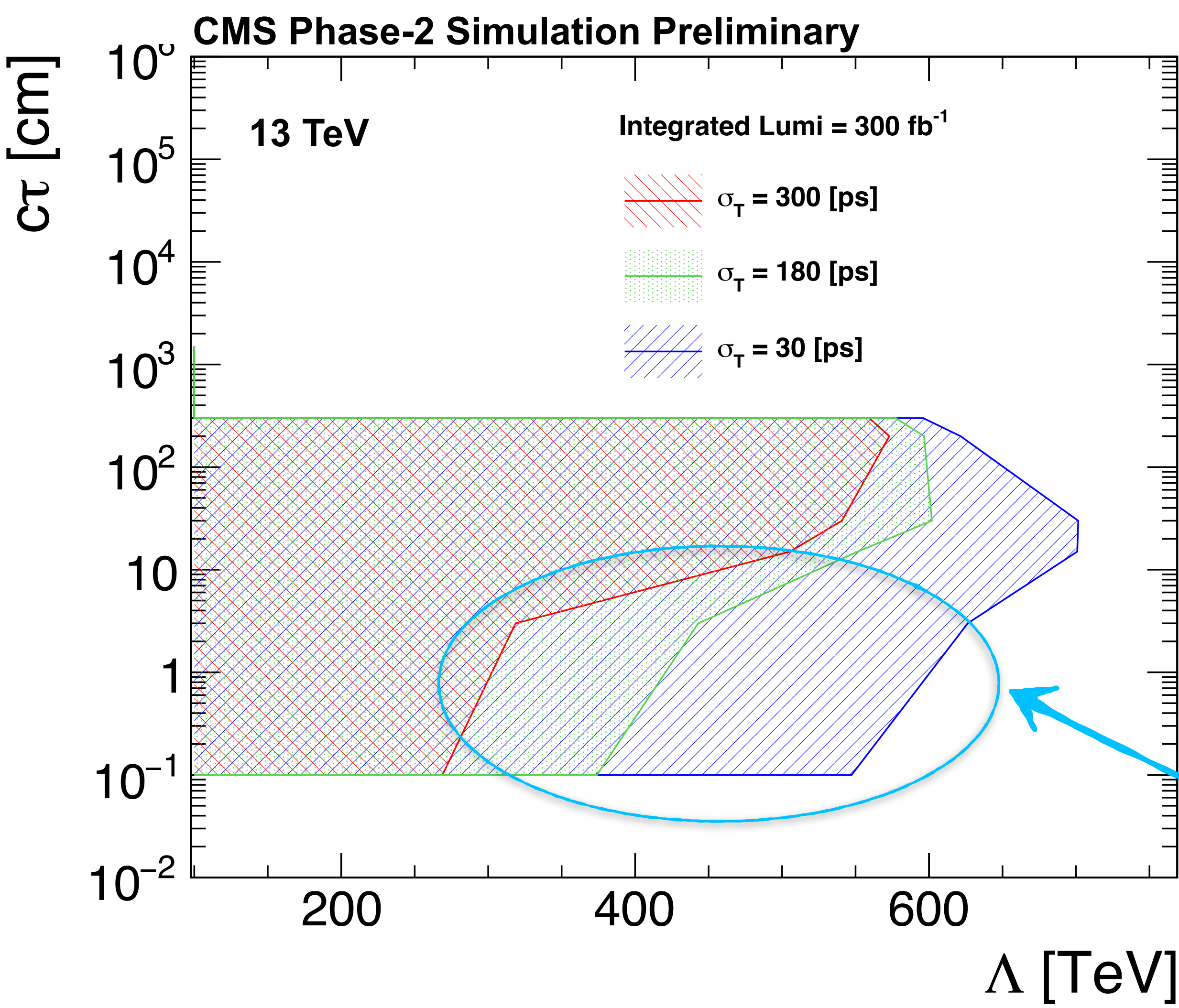




Displaced Photons w/ MTD at HL-LHC

- ***Upgrade to Precision timing at HL LHC to:***
  1. Reject spurious secondary vertices and **reduce beamspot uncertainty**
  2. Measure precisely **photon time of flight in ECAL**



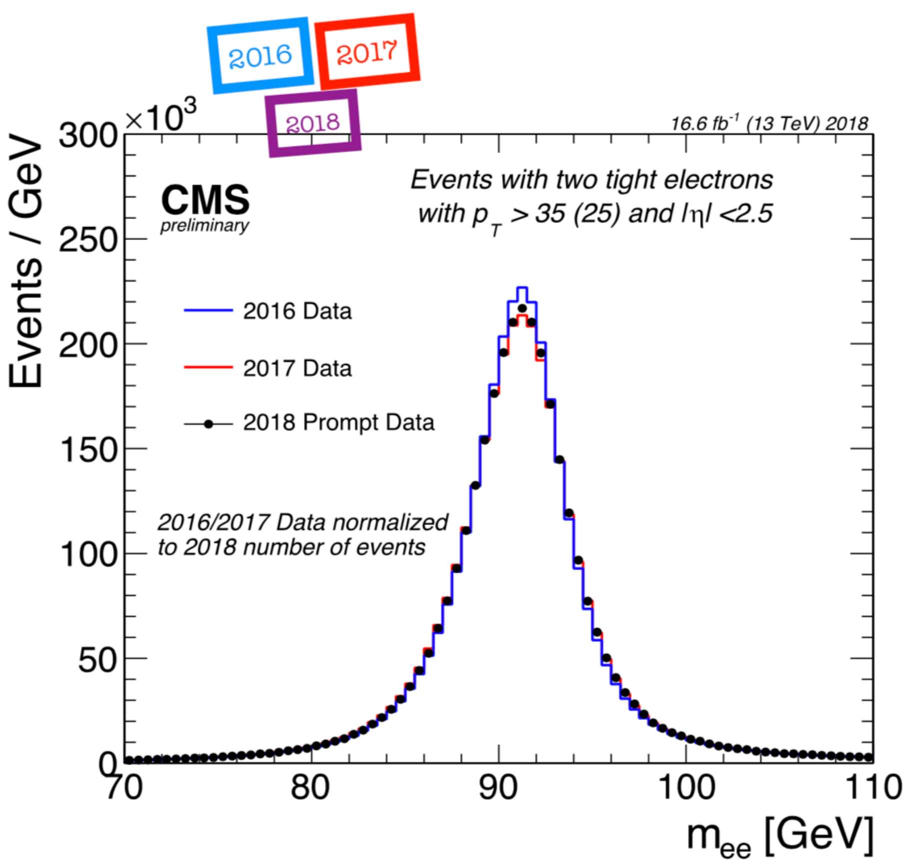


- ECAL Phase1
- ECAL Phase2(beamspot dominant)
- ECAL Phase2 + Timing Layer

- Increase sensitivity to short lifetimes

Conclusions

- Extensive **search program in CMS targeting different LLP**: charged/neutral, fast/slow, decays to quarks/leptons/photons..
- Target **signatures also for HL LHC** exploiting full potential of the detector: precision timing is a key ingredient!
- So far **all observations are compatible with the SM expectation**
- Many new results **exploiting full 2016 and 2017 data** under process of approval will be shown soon
- Looking forward for **new data coming in 2018!**



Backup

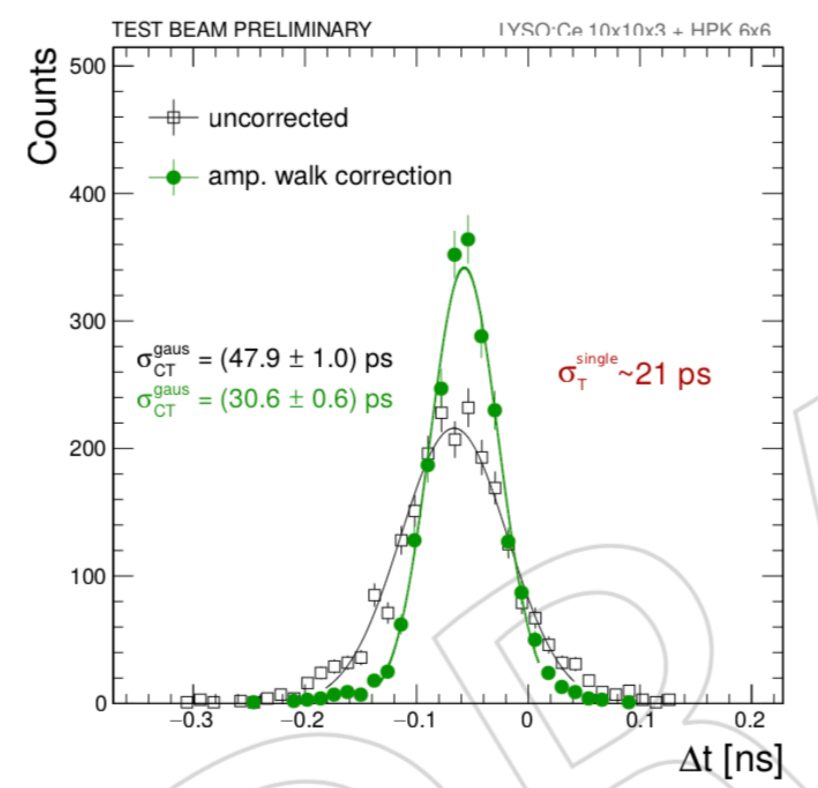
- **Phase-2 upgrade for HL-LHC 2026:** maintain excellent performance of the detector in efficiency, resolution, and background rejection

-> withstand **radiation damage** and **pileup**

CE nor the ECAL no precision timing information for MIP

⇩

dedicated MIP Timing Detector (MTD)



- **Objects Performances**

tracks from pileup vertices

jets and p^{miss}

identification ability of isolated leptons and photons

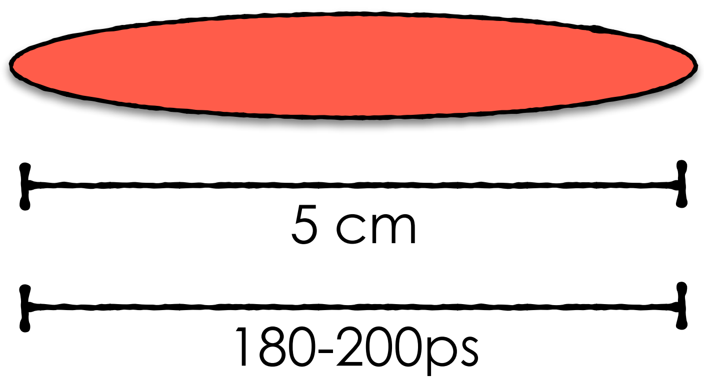
b jet identification

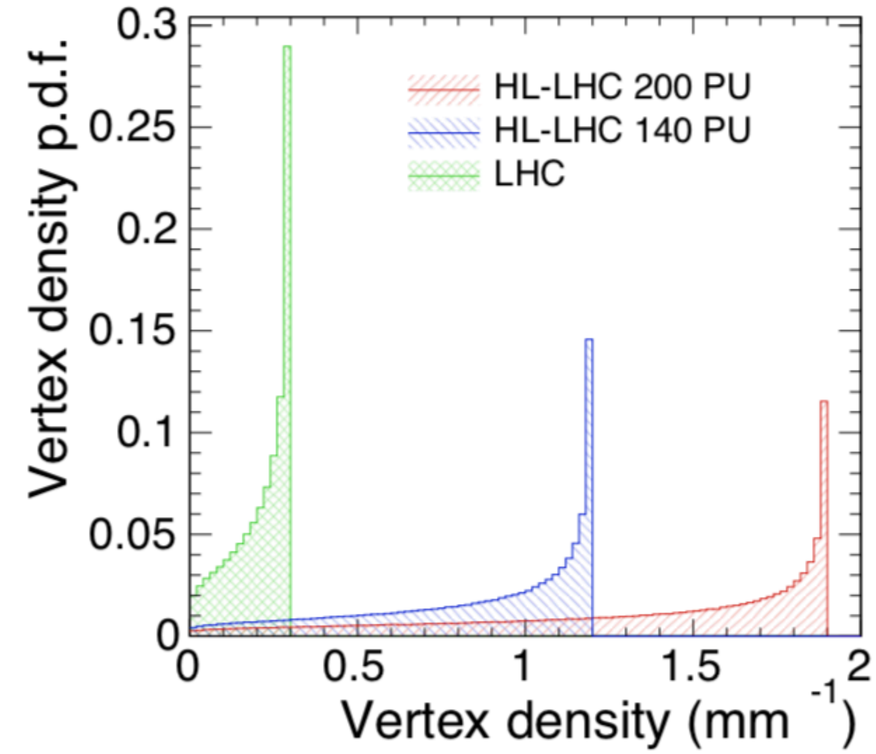
acceptance extension for isolated objects

diphoton vertex location

HL-LHC Pileup

Inst Lumi @ HL-LHC: 5.2 or 7.2×10^{34} $cm^{-2}s^{-1}$, yielding 140 or 200 pileup





- spatial overlap of tracks and energy deposits:

  degrade identification and reconstruction and confuse the **trigger**.

MTD:

- slicing the beam spot in consecutive **time exposures of 30 ps**:

  ⇨ **reduce the 'effective multiplicity'** of pileup recovering the Phase-1 track purity of vertices.

- consolidate the particle-flow performance @140 and extend it up to 200

Displaced Signatures

The previous CMS search excluded at 95% confidence level (CL) direct electroweak production of charginos with a mass less than 505 GeV for a mean proper lifetime of 7 ns, while the ATLAS search at 13 TeV extended the exclusion limits on chargino mass to 460 GeV for a lifetime of 0.2 ns. These searches are complementary to searches for heavy stable charged particles, which are able to exclude charginos with much longer lifetimes [15, 16]. Two significant improvements with respect to the 8 TeV search for disappearing tracks have been implemented for this search at 13 TeV: a new dedicated trigger developed specifically for this search, and an estimation of the background from standard model (SM) leptons entirely based on control samples in data.

The branching fraction for χe ± 1 → χe 0 1π ± is set to 100%, and tan β is fixed to 5 with μ > 0, where tan β is the ratio of the vacuum expectation values of the two Higgs doublets and μ is the higgsino mass parameter. In practice the χe ± 1 -χe 0 1 mass difference has little dependence on tan β and the sign of μ

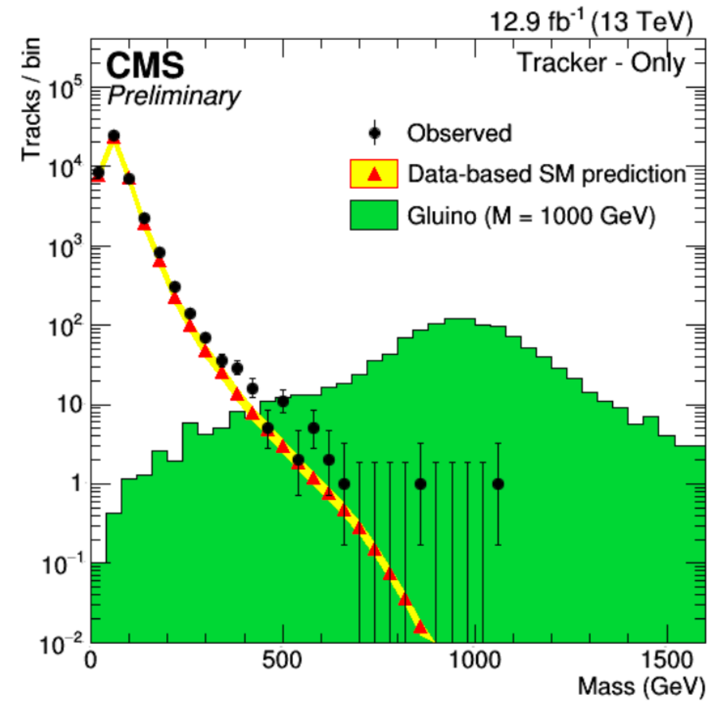
HSCP CMS

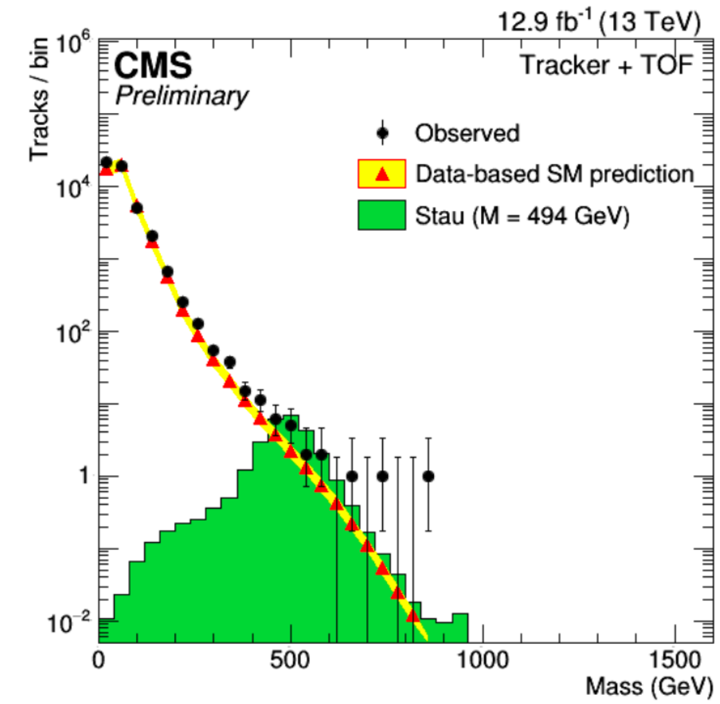
- Stable R-hadrons with lifetimes from 1ns to O(10) ns

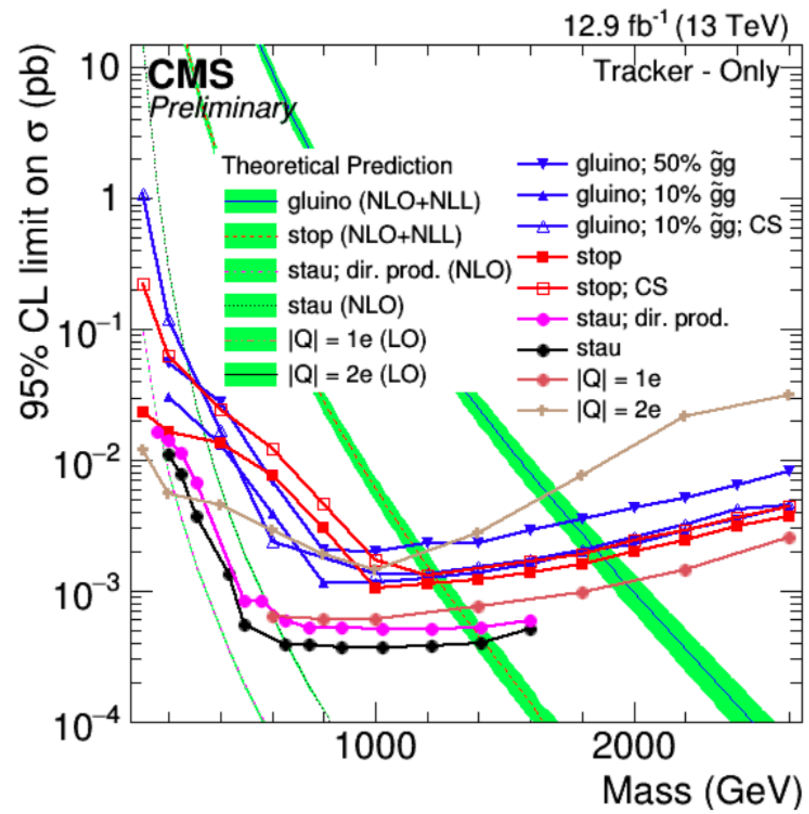
- Heavy, long-lived, charged particles that might have speed, *v*, significantly less than the speed of light, *c*, and/or charge, Q, not equal to ±1e.

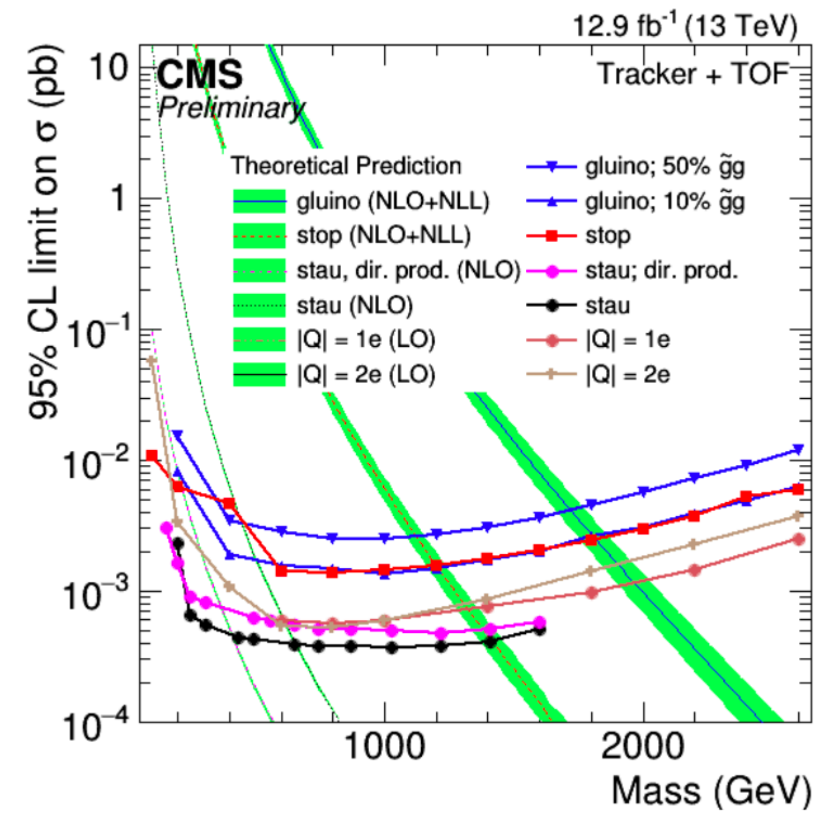
- Distinctive signatures of large *dE*/*dx* and long time-of-flight

- dE/dx measurement performed by the silicon tracker subdetectors









HSCP

- The **first** type of signal consists of HSCPs that interact via the strong force and hadronize with SM quarks to form R-hadrons. As in Refs. [31, 34], events involving pair production of g and e et1, with mass values in the range 300-2600 GeV, are generated under the **Split SUSY scenarios**.

- As in Refs. [31, 34], two scenarios of R-hadron strong interactions with matter are considered: the first follows the model in Refs. [36, 37] while the second is one of complete charge suppression, where **any nuclear interaction leaves the R-hadron as a neutral particle**

- The **second** type of signal consists of HSCPs that behave like leptons. The minimal gauge mediated supersymmetry breaking (mGMSB) model [38] is selected as a benchmark for lepton-like HSCPs. Production of supersymmetric quasi-stable leptons (τ˜1) at the LHC can proceed either directly or via production of heavier supersymmetric particles (mainly squarks and gluino pairs) that decay and lead to one or more τ˜1 particles at the end of the decay chain

- The **last** type of signal is based on modified Drell–Yan production of long-lived lepton-like fermions. In this scenario, new massive spin-1/2 particles have arbitrary electric charge but are neutral under SU(3)C and SU(2)L, and therefore couple only to the photon and the Z boson

	Selection cuts				Numbers of events 2016	
	p_T (GeV)	I_{as}	$1/\beta$	Mass (GeV)	Pred.	Obs.
Trk-only	> 65	> 0.3	-	> 0	92.4 ± 18.9	94
				> 100	43.2 ± 8.9	46
				> 200	4.3 ± 0.9	7
				> 300	0.86 ± 0.18	0
				> 400	0.25 ± 0.05	0
Trk+TOF	> 65	> 0.175	> 1.250	> 0	53.1 ± 10.6	50
				> 100	7.7 ± 1.5	8
				> 200	0.82 ± 0.17	2
				> 300	0.15 ± 0.03	1
				> 400	0.04 ± 0.01	1

Stopped Particles

- In an LHC orbit there are 3564 bunch slots (BXs), which are 25 ns long. Each BX could be filled with proton bunches, which usually occupy the first 2.5 ns of the BX, or could be empty. The trains may be spaced such that there could be multiple empty BXs between filled BXs. To search for LLP decays during these empty BXs, dedicated triggers select events at least two BX away from any proton bunches

- In the calorimeter search, we interpret the results in the context of two-body (ge → gχe 0) and three-body (ge → qqχe 0) decays of a gluino into the lightest supersymmetric (SUSY) particle (LSP), the neutralino (χe 0). Long-lived gluinos are predicted by “split SUSY” [37, 38], in which gauginos have relatively small masses with respect to sfermions, which could be massive, since SUSY is broken at a scale much higher than the weak scale. This large mass splitting causes the long lifetime of the gluinos, since gluinos can only decay via a virtual squark. We also consider the decay of a long-lived top squark (et → tχe 0) that can be the next-to-LSP particle (NLSP) in various dark matter scenarios [39–41]. Here the LSP should be loosely interpreted as any new, neutral, non-interacting fermion, and not necessarily as a SUSY neutralino.

- In the muon search, we consider a different model for a three-body decay of the gluino (ge → qqχe 0 2 , χe 0 2 → μ +μ −χe 0), which is complementary to the calorimeter search. In this model, the mass of the LSP neutralino (χe 0) is chosen to be 0.25 times the gluino mass, and the mass of the NLSP neutralino (χe 0 2) is chosen to be 2.5 times the LSP neutralino mass. A second simplified model used in the muon search predicts exotic particles called MCHAMPs, whose charges are multiples of the elementary charge e and which are predicted by several BSM theories [20]. We assume an MCHAMP with charge |Q| = 2e decays into two same-sign muons (MCHAMP → μ ±μ ±).

Stopped Particles

- The major background sources are cosmic rays, beam halo, and HCAL noise. Cosmic ray and beam halo muons can emit a shower of photons via bremsstrahlung, which could be reconstructed as a jet and mistaken for signal. HCAL noise [51] can give rise to spurious signals, which in the barrel could appear in one or several HPDs within a single RBX, and thus be incorrectly reconstructed as a jet.

- In the muon search, we look for LLPs where the decay products include two muons. We expect the signal to look like a pair of muons originating anywhere in the detector material, but displaced from the IP. The muons would be back-to-back in the two-body MCHAMP decay, but not for the three-body gluino decay. The primary background sources in the muon search include cosmic ray muons, beam halo, and muon detector noise. The latter two background sources are negligible after we apply the full selection.

Table 4: The background prediction for the calorimeter search. The total background median value is listed in parentheses; this value corresponds directly to the median expected limits shown below.

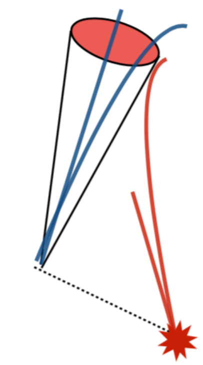
LHC period	Trigger livetime [hrs]	HCAL noise	Cosmic ray muons	Beam halo	Total background
2015	135	$0.4^{+2.9}_{-0.4}$	2.6 ± 0.9	1.1 ± 0.1	$4.1^{+3.0}_{-1.0}$ (6.2)
2016	586	$0.0^{+9.8}_{-0.0}$	8.8 ± 3.1	2.6 ± 0.2	$11.4^{+10.3}_{-3.1}$ (17.4)

- Given this extrapolation, we predict 0.04 background events in 2015 data, with a negligible statistical uncertainty, and 0.50 ± 0.02 background events in 2016 data, where the uncertainty given is statistical only.

Displaced Jets CMS

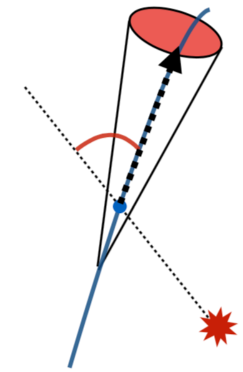
The first variable quantifies how likely it is that the jet originates from a given PV. For a given jet, $\alpha_{\text{jet}}(\text{PV})$ is defined for each PV as

$$\alpha_{\text{jet}}(\text{PV}) = \frac{\sum_{\text{tracks}\in\text{PV}} p_{\text{T}}^{\text{tracks}}}{\sum_{\text{tracks}} p_{\text{T}}^{\text{tracks}}}, \tag{1}$$



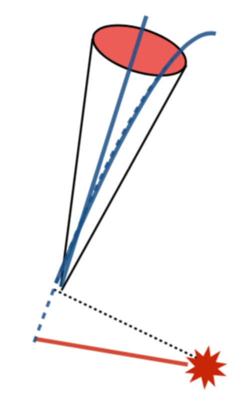
α_{Max}

The second variable quantifies the typical recoil angle of a given track in a jet from the flight direction of the long-lived candidate particle. For each track, Θ_{2D} is computed as the angle between the track $\vec{p}_{\text{T}} = (p_{\text{x}}, p_{\text{y}})$ at the track's innermost hit and the vector connecting the chosen PV to this hit in the transverse plane. The tagging variable $\widehat{\Theta}_{\text{2D}}$ is the median of the Θ_{2D} distribution for the tracks associated to the jet.



Θ_{2D}

The third variable quantifies the significance of the measured transverse displacement for the jet. For each track associated to the jet, the significance of the track's transverse impact parameter, $IP^{\text{2D}}_{\text{sig}}$, is computed as the ratio of the track's transverse impact parameter and its uncertainty. The tagging variable $\widehat{IP}^{\text{2D}}_{\text{sig}}$ is the median of the $IP^{\text{2D}}_{\text{sig}}$ distribution of all tracks in a jet.



$2DIP_{sig}$

Displaced Vertices

Displaced vertices are reconstructed from tracks in the silicon tracker. These tracks are required to have pT > 1 GeV; measurements in at least two layers of the pixel detector, including one in the innermost layer; measurements in at least six layers of the strip detector if $|\eta| < 2$, or in at least seven layers if $|\eta| \geq 2$; and significance of the impact parameter with respect to the beam axis measured in the x-y plane (the magnitude of the impact parameter divided by its uncertainty, referred to as $|dxy|/\sigma dxy$) of at least 4. The first three criteria are track quality requirements, imposed in order to select tracks with small impact parameter uncertainties. The requirement on $|dxy|/\sigma dxy$ favors vertices that are displaced from the beam axis. The vertex reconstruction algorithm forms seed vertices from all pairs of tracks satisfying the track selection criteria, and then merges them iteratively until no track is used more than once. A set of tracks is considered to be a vertex if a fit with the Kalman filter approach [30] has a χ 2 per degree of freedom (χ 2/dof) that is less than 5. For each pair of vertices that shares a track, the vertices are merged if the three-dimensional distance between the vertices is less than 4 times the uncertainty in that distance and the fit has χ 2/dof < 5.

Each vertex is required to have at least five tracks; distance from the detector origin measured in the x-y plane of less than 20 mm, to avoid vertices from interactions in the beam pipe or detector material; distance from the beam axis measured in the x-y plane, defined as dBV, of at least 0.1 mm, to suppress displaced primary vertices; and uncertainty in dBV of less than 25 μm, to select only well-reconstructed vertices. Since signal events contain a pair of long-lived particles, we require events to have two or more vertices satisfying the above requirements

Four variables are used to select the emerging jets:

1.the **median of the unsigned transverse impact parameters** of associated tracks (<IP2D>)

2. the **distance between the z position of the track at its distance of closest approach to the PV and the z of the PV** (PUdz), used to reject tracks from pileup vertices

3. a variable called DN, defined as:

$$D_{\rm N} = \sqrt{[\frac{z_{\rm PV} - z_{\rm trk}}{0.01\,{\rm cm}}]^2 + [IP_{\rm sig}]^2},$$

,where zPV is the z position of the primary vertex, ztrk is the z of the track at its closest approach to the PV, and IPsig is the transverse impact parameter significance of the track at its closest approach to the PV

4. α3D, which is the **scalar sum of the pT's of the associated tracks passing a selection on DN divided by the scalar sum of the pT's of all associated tracks**

Emerging Jets

Set number	PU_{dz} (<)	D_N (<)	$\langle IP_{2D} \rangle$ (>) [cm]	α_{3D} (<)
EMJ-1	2.5	4	0.05	0.25
EMJ-2	4.0	4	0.10	0.25
EMJ-3	4.0	20	0.25	0.25
EMJ-4	2.5	4	0.10	0.25
EMJ-5	2.5	20	0.05	0.25
EMJ-6	2.5	10	0.05	0.25
EMJ-7	2.5	4	0.05	0.40
EMJ-8	4.0	20	0.10	0.50

Set number	H_T	$p_{T,1}$	$p_{T,2}$	$p_{T,3}$	$p_{T,4}$	p_T^{miss}	$n_{em}(\geq)$	EMJ set	no. models
1	900	225	100	100	100	0	2	1	12
2	900	225	100	100	100	0	2	2	2
3	900	225	100	100	100	200	1	3	96
4	1100	275	250	150	150	0	2	1	49
5	1000	250	150	100	100	0	2	4	41
6	1000	250	150	100	100	0	2	5	33
7	1200	300	250	200	150	0	2	6	103
8	900	225	100	100	100	0	2	7	QCD-enhanced
9	900	225	100	100	100	200	1	8	