Searches for long-lived particles with CMS detector

New Physics with Exotic and Long-Lived Particles: A Joint ICISE-CBPF Workshop
1 – 6 July 2019

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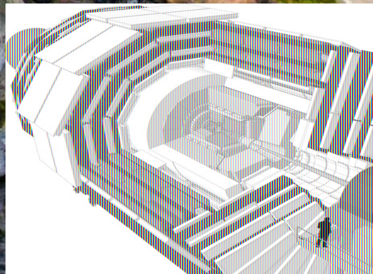
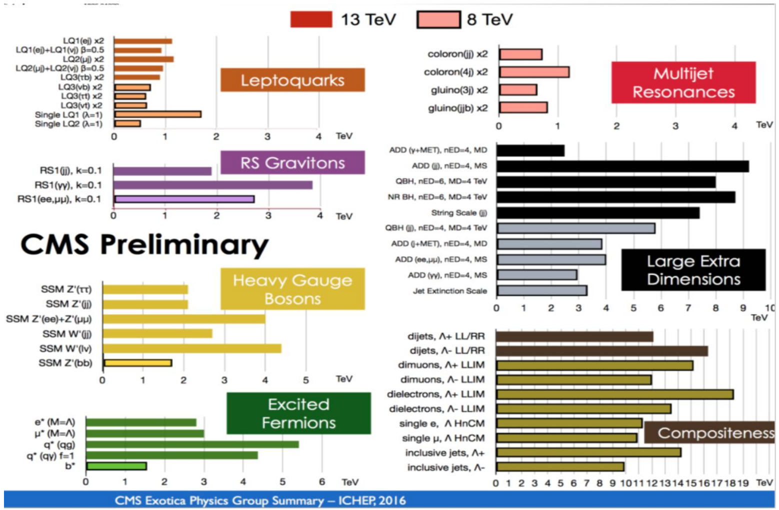


Outline

- *Introduction :*
  - *LLP searches in CMS : Why ?*
  - *Long-Lived searches in CMS overview.*
- *CMS Detector architecture*
- *Different LLP searches in CMS :*
  - *Disappearing tracks*
  - *Displaced vertices in multijet events*
  - *Emerging jets*
  - *Displaced jets*
  - *Stopped particles*
  - *Displaced Lepton Pairs*
- *Conclusion and summary*

LLP searches with CMS detector (why?)



- *BSM searches at LHC have not found anything yet*
  - ❑ *Classical searches : Exotica , Susy, Flavour Universality*
    - *Are we looking at the right place?*

This has motivated theorists to take a broader approach !

⇒ *Exploring different topologies: particles with Long-Life time.*

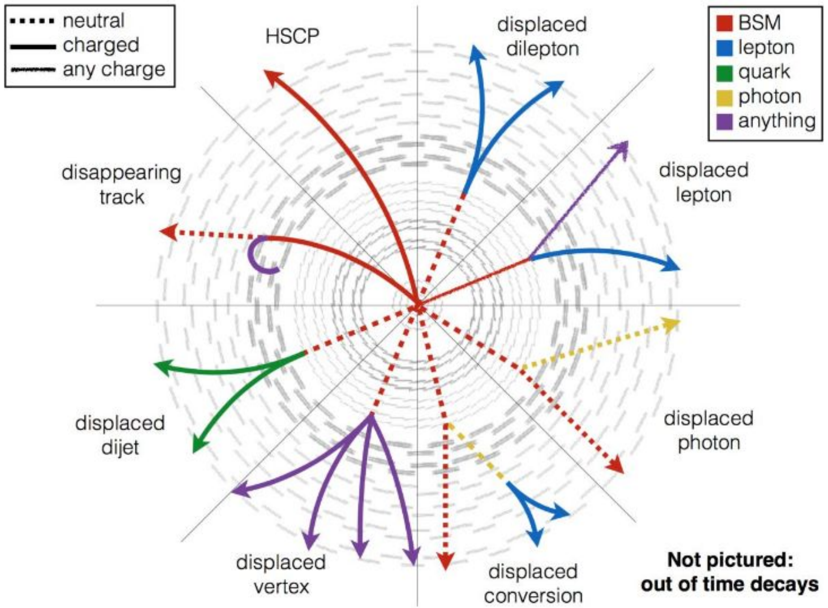
- *LL particles can arise from:*
  - ❑ *Small coupling*
  - ❑ *Hierarchy of scales*

Long Lived searches overview

❖ *Different signatures*

- *Displaced jets, dijets, vertices*
- *Disappearing tracks*
- *Displaced leptons & lepton jets*
- *Displaced photons*
- *Dark photon decays*
- *Heavy Stable Charged Particles*
- *Stopped particles*
- *Emerging jets.*

Jamie Antonelli

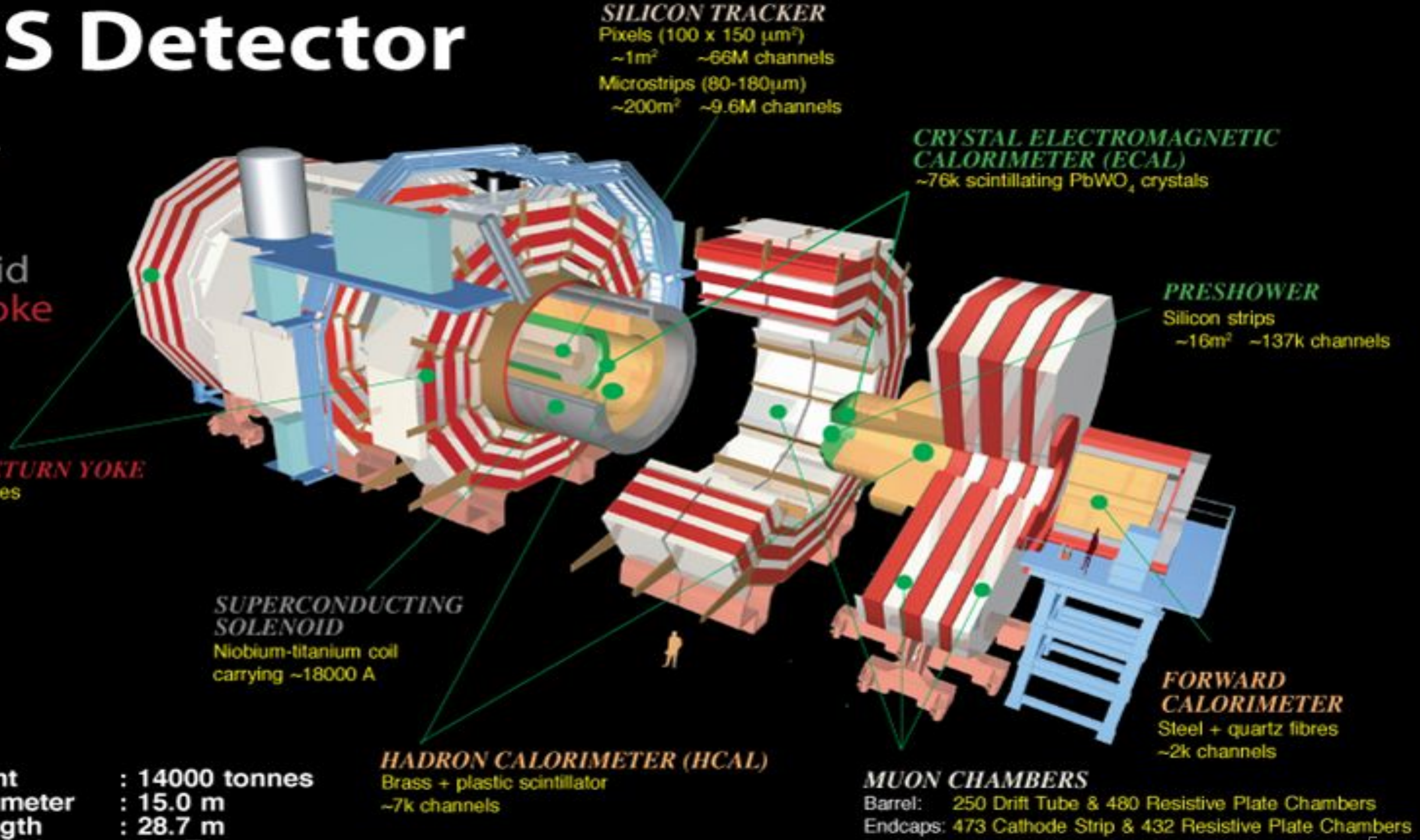


❖ *Challenges :* ⇒ *See Juliette's Talk.*

- *Difficulty to trigger on some of them, in some cases we need new trigger techniques.*
- *Some LL searches require special reconstruction eg displaced secondary vertices.*
- *Some LL searches have different type of Background than SM.*

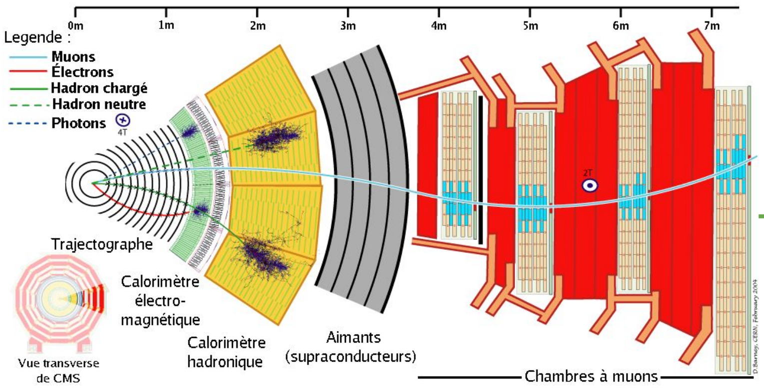
CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons

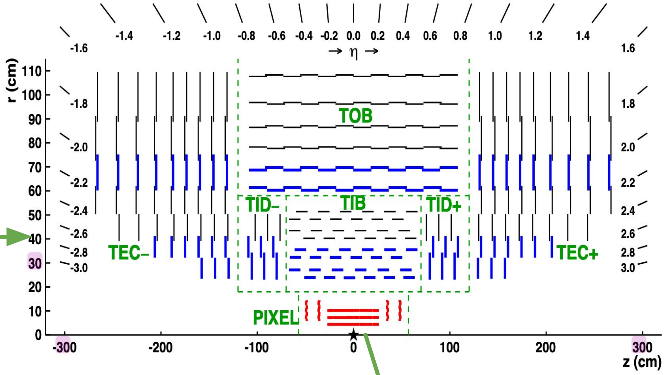


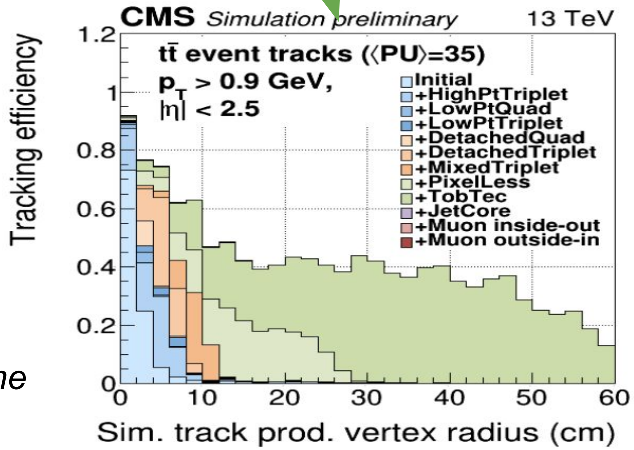
Total weight	: 14000 tonnes
Overall diameter	: 15.0 m
Overall length	: 28.7 m
Magnetic field	: 3.8 T

CMS Detector : architecture and tracking.



Zoom on the tracker





- *Very powerful silicon tracker. Use it !*
- *Standard tracking efficiency can be probed up to 60 cm in tracker barrel, enough to probe LL neutral particles decays and LL charged particles, through reconstructed tracks information (eg. impact parameter, number of tracker layers with or without hits...) or/and through vertexing.*

⇒ track information can be used with or without special reconstruction. (secondary vertices.)

- *Neutral particles with decay length larger than 60 cm can not be probed in the tracker region. Different topology and strategy is used.*
  ⇒ eg. Delayed jets analysis , Juliette's Talk.

Tracking POG performance 2017

Disappearing Tracks

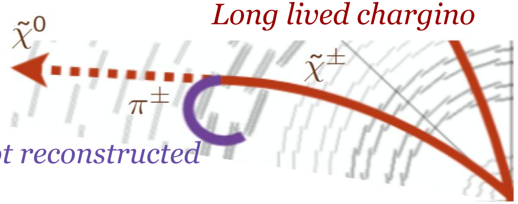
CMS-SUS-19-005

- Benchmark model Compressed SUSY model : 2 strategies

❑ MT2 classical search : Exploit the pT imbalance in MET + Jets events.

$$M_{\mathrm{T2}} = \min_{\vec{p}_{\mathrm{T}}^{\mathrm{miss}X(1)} + \vec{p}_{\mathrm{T}}^{\mathrm{miss}X(2)} = \vec{p}_{\mathrm{T}}^{\mathrm{miss}}} \left[\max \left(M_{\mathrm{T}}^{(1)}, M_{\mathrm{T}}^{(2)} \right) \right],$$

❑ Exo signature : 1 well isolated track with at least 2 missing hits in the outer layers in events with at least 2 jets. No calo energy deposit and no hits in the muon chamber.



$$\Delta(\tilde{\chi}^\pm, \tilde{\chi}^0) \approx 100MeV$$

❖ Trigger :

- Like for M_{T2} searches : based on, p_T, H_T, H_T^{miss}, p_T^{miss}

❖ Event selection :

- 1 disappearing track : the track should be well isolated + it should have at least 2 missing outer hits.
- Nb of jets >= 2.
- M_{T2} >= 200 GeV

Use tracks with a length down to pixel-only tracks

Disappearing Tracks

CMS-SUS-19-005

❖ *Search Strategy :*

- *Different search regions divided by :*
  - ❑ *HT and number of jets in the events.* ⇒ *Different topologies.*
  - ❑ *pT of the track.* ⇒ *Distinguish tracks with different precision.*
  - ❑ *Number of Layers*
    - ➢ *Short tracks "P" : 3 Pixel Layers.*
    - ➢ *Medium tracks "M" < 7 layers.*
    - ➢ *Long Tracks "L" > 7 layers.*

⇒ *Increasing sensitivity to a wider range of lifetimes of Long-Lived charged particles.*

❖ *Background :*

- ➢ *Fake tracks*
- ➢ *Charged pions + leptons poorly reconstructed or having significant interaction in the tracker.*

⇒ *Background is extracted from Data in the control region*

Control region : 60 GeV < M_{T2} < 100 GeV, *Validation Region:* 100 GeV < M_{T2} < 200 GeV, *Signal region* : M_{T2} > 200 GeV

Disappearing Tracks

CMS-SUS-19-005

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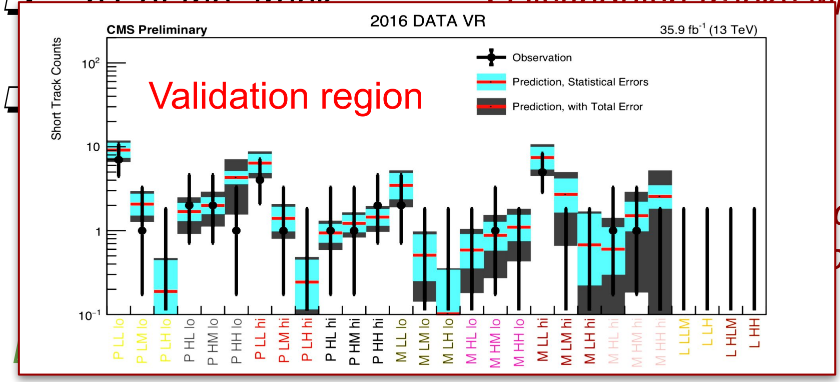

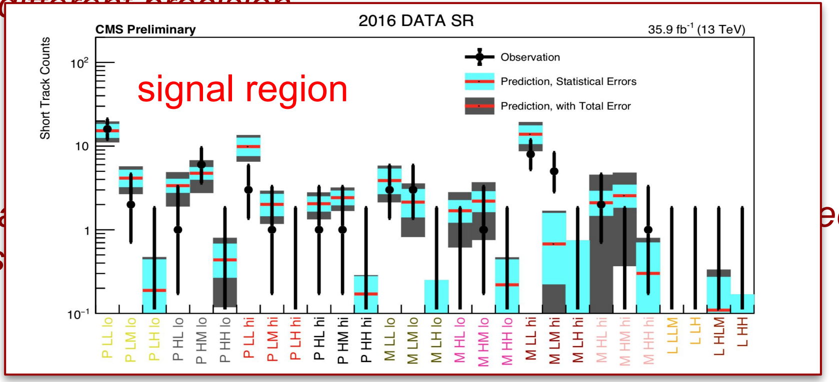

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cles

- ➢ *Fake tracks*
- ➢ *Charged pions + leptons poorly reconstructed or having significant interaction in the tracker.*

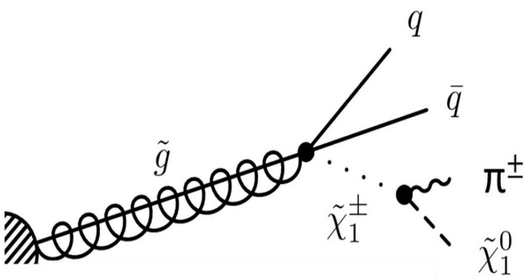
⇒ *Background is extracted from Data using Data Driven Technique in the control region*

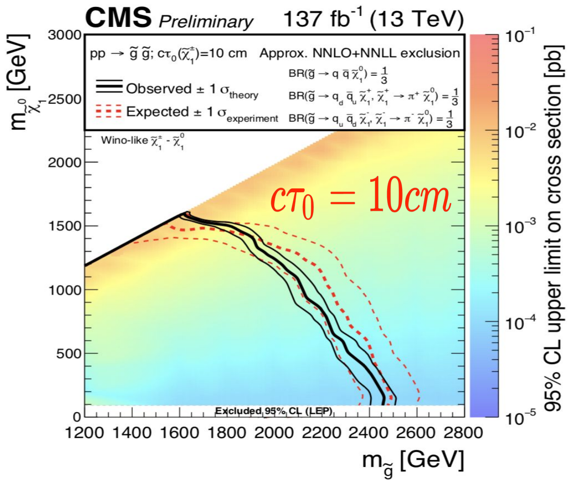
Control region : 60 GeV < MT2 < 100 GeV, *Validation Region:* 100 GeV <MT2 < 200 GeV, *Signal region* : MT2 > 200 GeV

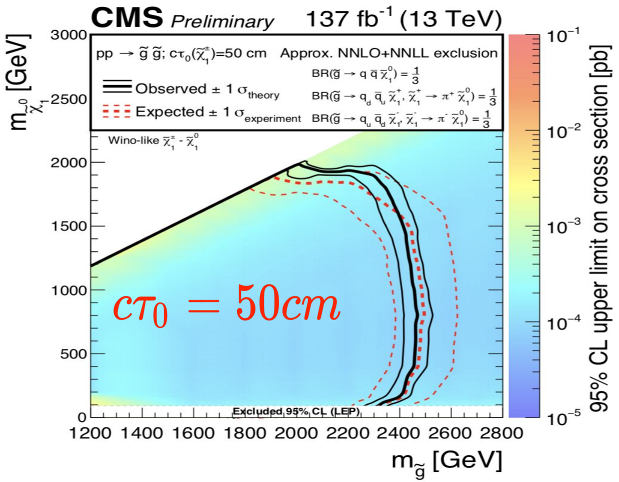
Disappearing Tracks

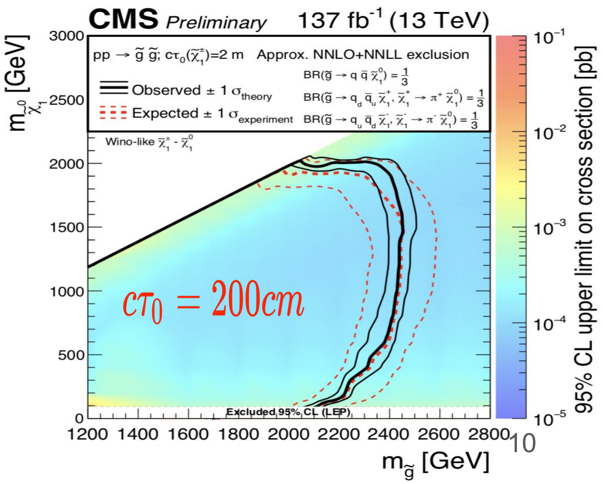
❖ Results :

- Exclusion on gluino mass up to 2.4 TeV.
- Exclusion on neutralino mass up to 2 TeV



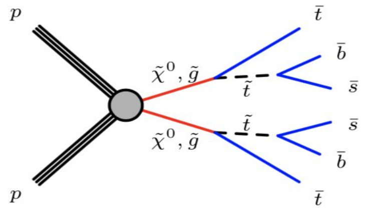


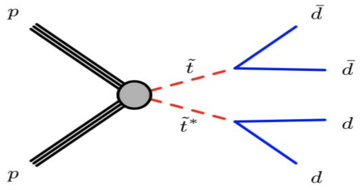




Displaced vertices in multijet event *CMS-EXO-17-018, arXiv 1808.03078*

- *Benchmark model : RPV SUSY*

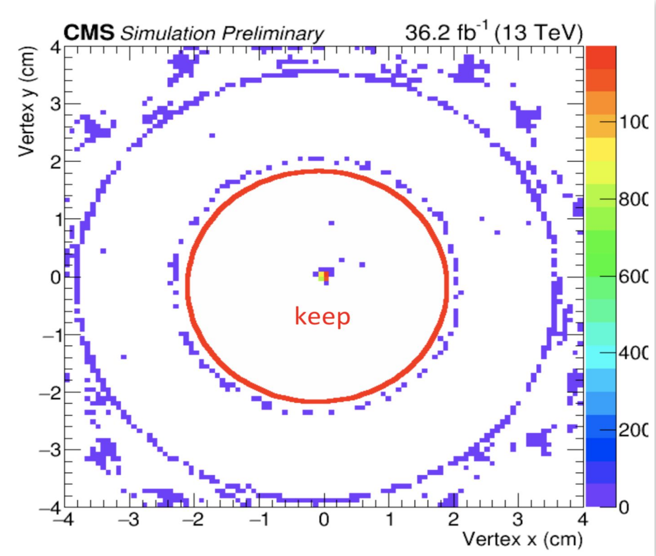




- *Pair produced long lived particles decaying to jets in the beam pipe.*

❖ *Event selection and vertexing :*

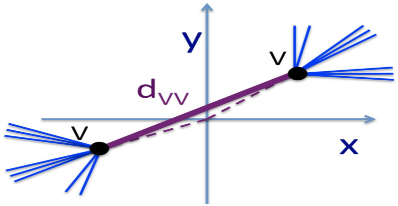
- *Trigger : HT > 1000 GeV and at least 4 jets .*
- *Vertex reconstruction based on specific tracks.*
- *Tracks :*
  - ❑ *pT > 1 GeV*
  - ❑ *Hit in the innermost pixel layer and at least 2 pixel hits and hits in the strip detector >= 6.*
  - ❑ *Impact parameter significance > 4 ⇒ insure displacement.*
- *vertex selections were used :*
  - ❑ *At least 5 tracks.*
  - ❑ *0.1 <Dbv(xy)< 20mm : avoiding different types of Background*
  - ❑ *Uncertainty on Dbv(xy) < 25 um.*



⇒ 2 good quality vertices or more are required for event selection

Displaced vertices in multijet event CMS-EXO-17-018, arXiv 1808.03078

❖ Search strategy



- *Key variable for the analysis : distance in x-y between 2 vertices dvv.*
- *Three signal regions were defined*
  1. *0 < dvv < 0.4 mm*
  2. *0.4 mm < dvv < 0.7 mm* ⇒ *2 and 3 low background vs 1*
  3. *0.7 mm<dvv<40 mm*

❖ Background

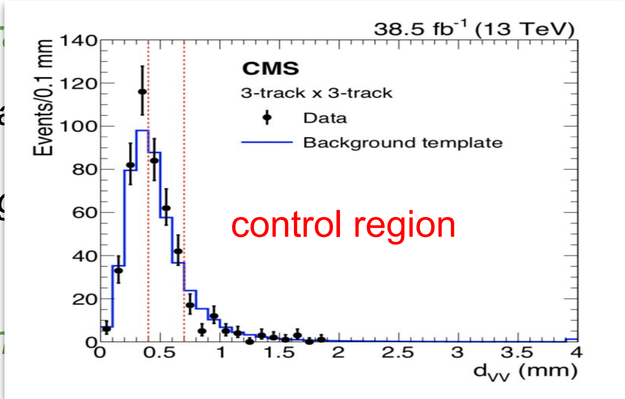
- *Background is constructed from exactly 1 vertex events from data (negligible contamination from Signal)*

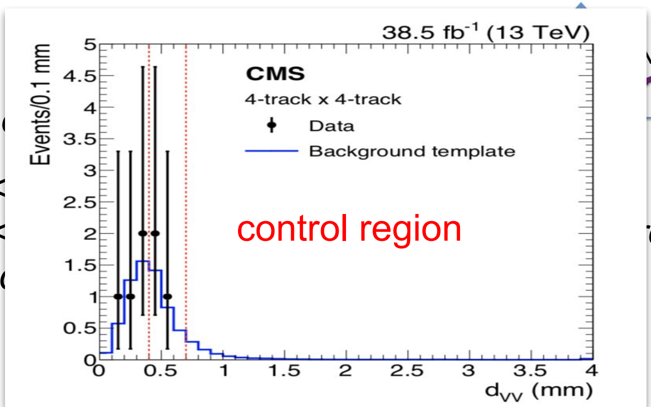
Event category	3-track	4-track × 3-track	4-track	≥5-track
one-vertex	109090	—	11923	1183
two-vertex	478	99	7	1

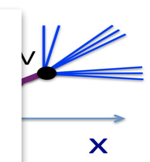
Background template : 1 vertex and > 5 tracks per vertex **VS** *Signal region : 2 vertex and > 5 tracks per vertex*

Displaced vertices in multijet event *CMS-EXO-17-018, arXiv 1808.03078*

❖ Search str







- Key varia ... etwe
- Three sig ... dvv < ... mm < ... mm<(... ound vs 1

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Displaced vertices in multijet event

CMS-EXO-17-018, arXiv 1808.03078

- Search str
  - Key varia ... etwe
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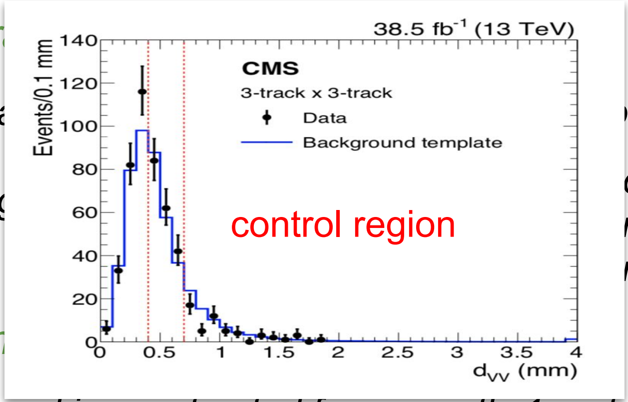
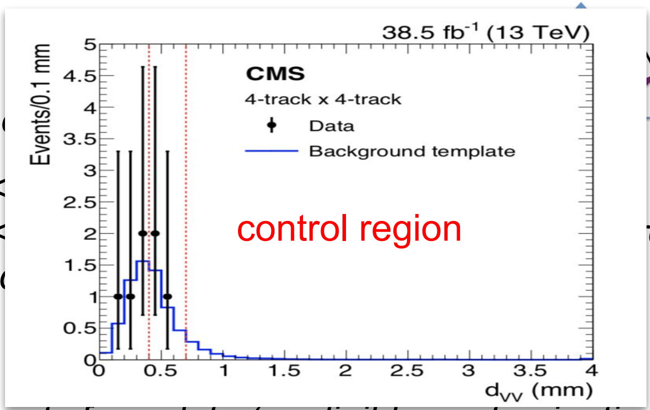
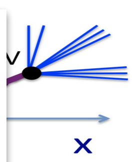
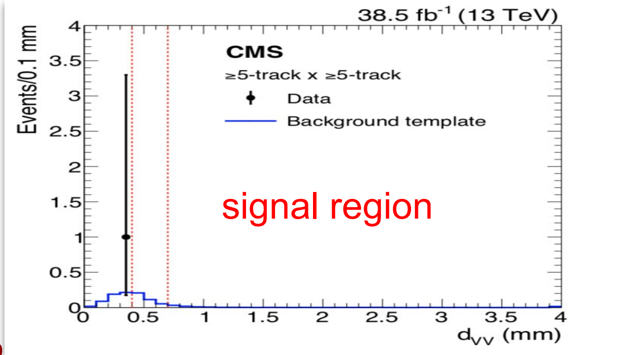






- Backgroun
  - Background is constructed from exactly 1 vertex events from data (negligible contamination from Signal)



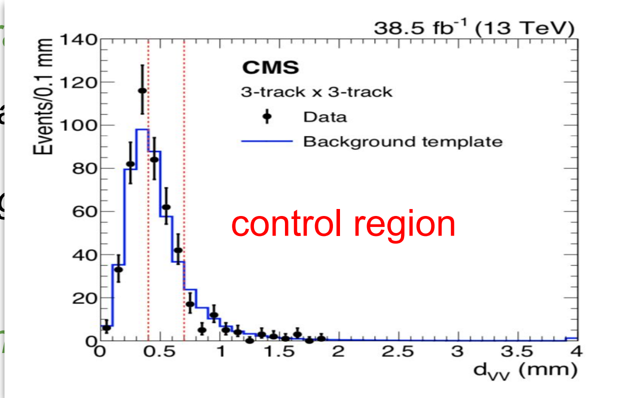
rack × 3-track	4-track	≥5-track
—	11923	1183
99	7	1

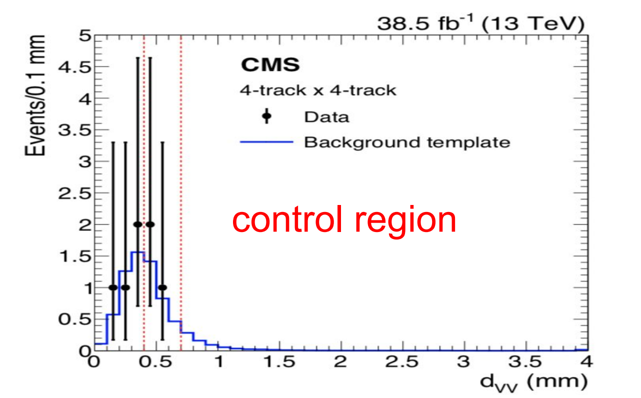
Background template ... vertex **VS** Signal region : 2 vertex and > 5 tracks per vertex

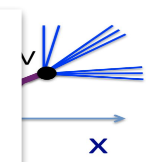
Displaced vertices in multijet event *CMS-EXO-17-018, arXiv 1808.03078*

❖ Search str

- *Key vari* ... *etwe*
- *Three si* ... *dvv <* ... *mm <* ... *mm<* ... *round vs 1*

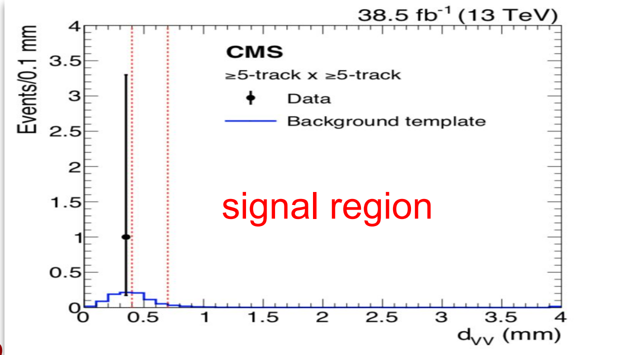






❖ Backgroun

- *Background is constructed from exactly 1 vertex events from data (negligible contamination from Signal)*

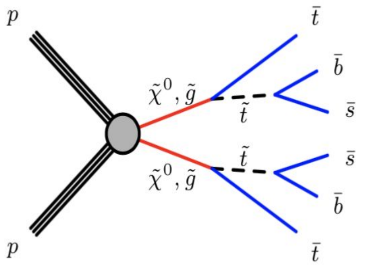


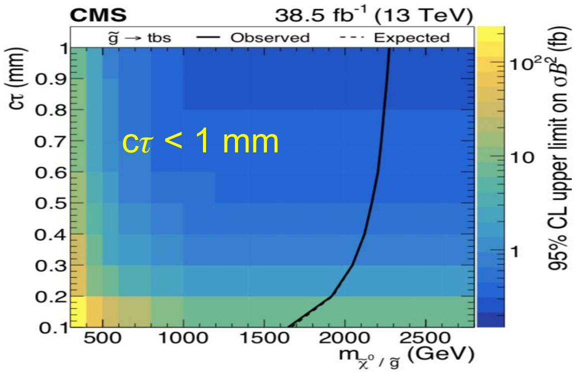
- ***1 event observed in agreement with background prediction.***

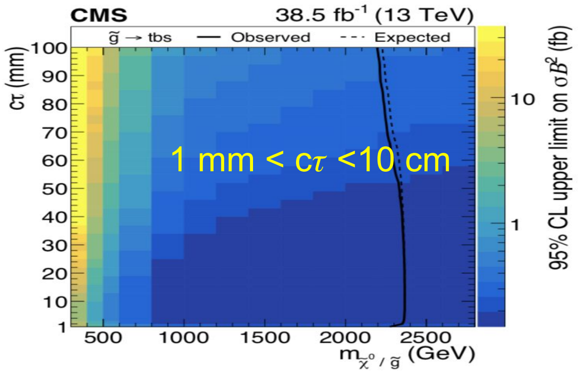
Background templ... : 1 vertex and > 5 tracks per vertex **VS** Signal region : 2 vertex and > 5 tracks per vertex

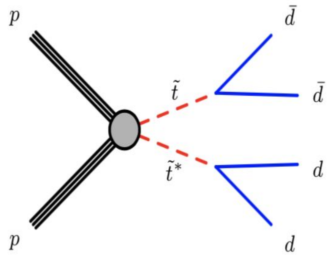
Displaced vertices in multijet event *CMS-EXO-17-018, arXiv 1808.03078*

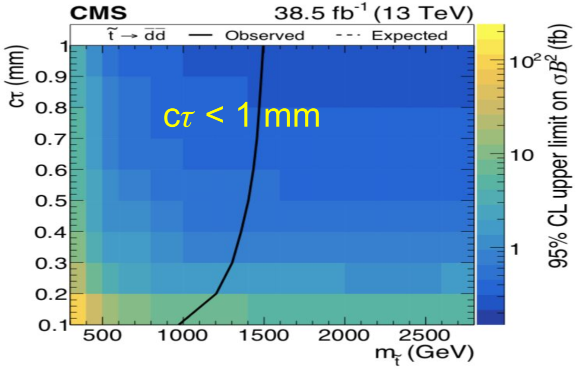
- *Results :*

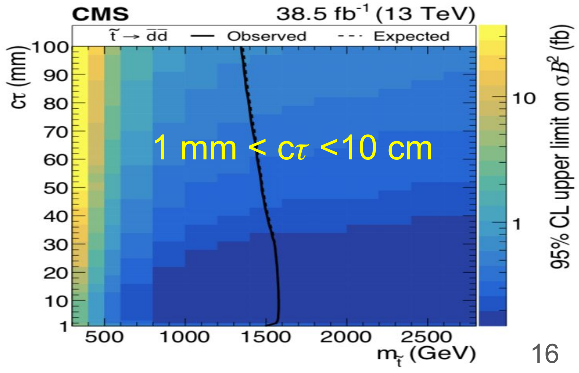








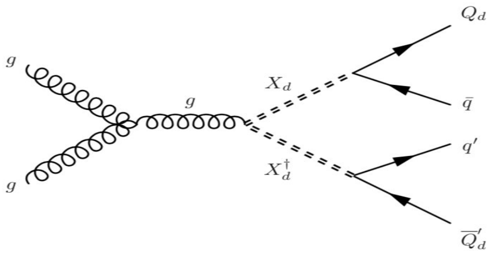




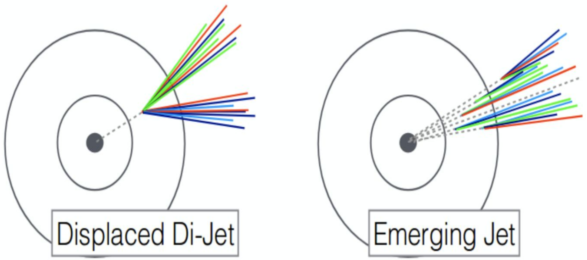
Emerging jets

CMS EXO-18-001, arXiv 1810.10069, HepData

- *Benchmark model : Dark QCD :*



  - Dark quarks hadronize in the hidden sector (dark pions) , then decay to visible sector leading to multiple secondary vertices with different displacement within the same jet object. 1 mm < $c\tau$ < 1 m.
  - Signature :
    - 2 prompt jets + 2 emerging jets.
    - 2 prompt jets + 1 emerging jet + large pT miss

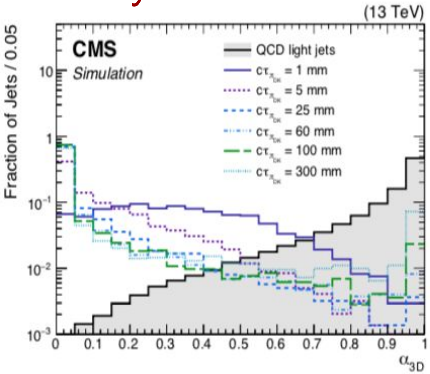


❖ Event selection and variables definition :

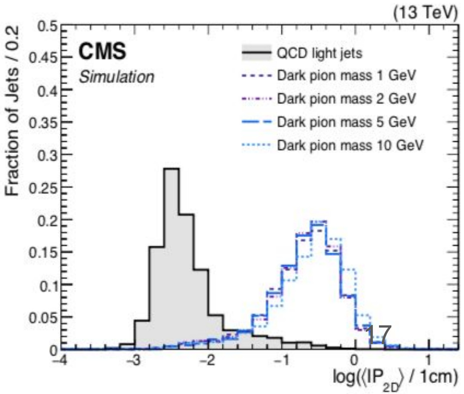
- At least 4 jets with HT > 900 GeV

★ Variables key for the analysis :

$$\alpha_{jet}(PV) = \frac{\sum_{i \in PV, tracks} p_t^i}{\sum_{j \in generalTracks} p_t^j}$$



The median of the 2DIP of the tracks within a jet

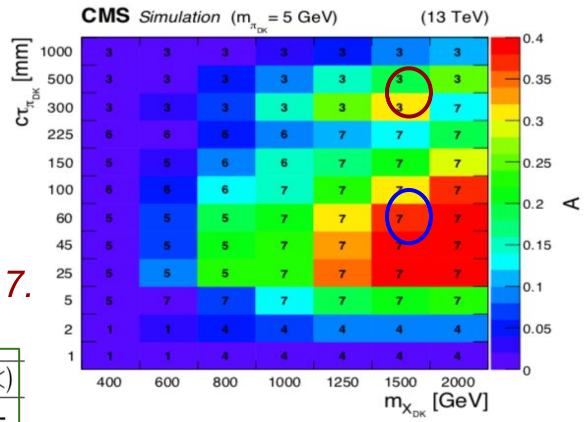


Emerging jets

CMS EXO-18-001, arXiv 1810.10069, HepData

❖ Search Strategy :

- *Different HT and pT selections of the jets.*
- *Different α_{3D} and <IP2D> selections of the jets.*
  ⇒ 7 search regions.
- *Highest acceptance is in the region of high mass with jet selection 3 and 7.*



Set number	H_T	$p_{T,1}$	$p_{T,2}$	$p_{T,3}$	$p_{T,4}$	p_T^{miss}	$n_{EMJ}(\geq)$	EMJ group
3	900	225	100	100	100	200	1	3
7	1200	300	250	200	150	0	2	6

Kinematic selection

Criteria group	PU_{dz} (<) [cm]	D_N (<)	$\langle IP_{2D}\rangle$ (>) [cm]	α_{3D} (<)
EMJ-3	4.0	20	0.25	0.25
EMJ-6	2.5	10	0.05	0.25

Emerging jet selection

➢ *Selection made to optimise S/B ratio.*

❖ Background :

- *QCD as main background (light jets and b-jets).*
- *Background extracted from data in the control region and well modeled in the the validation region.*

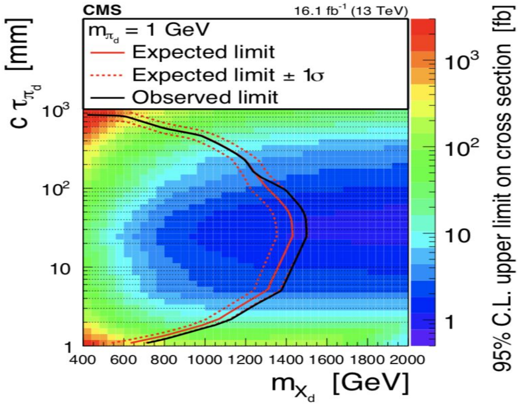
Emerging jets

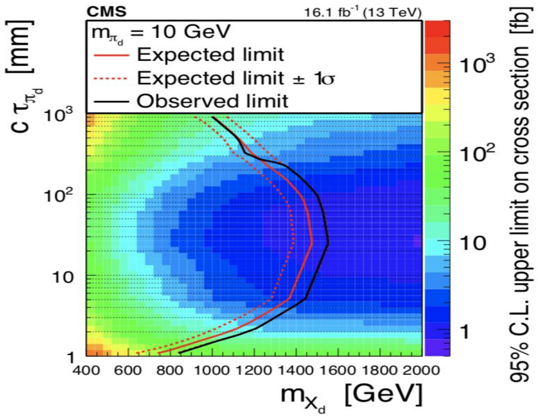
CMS EXO-18-001, arXiv 1810.10069, HepData

- ❖ **Results :**

Set number	Expected	Observed	Signal	Model parameters $m_{X_{DK}}$ [GeV]	$m_{\pi_{DK}}$ [GeV]	$c\tau_{\pi_{DK}}$ [mm]
1	$168 \pm 15 \pm 5$	131	36.7 ± 4.0	600	5	1
2	$31.8 \pm 5.0 \pm 1.4$	47	$(14.6 \pm 2.6) \times 10^2$	400	1	60
3	$19.4 \pm 7.0 \pm 5.5$	20	15.6 ± 1.6	1250	1	150
4	$22.5 \pm 2.5 \pm 1.5$	16	15.1 ± 2.0	1000	1	2
5	$13.9 \pm 1.9 \pm 0.6$	14	35.3 ± 4.0	1000	2	150
6	$9.4 \pm 2.0 \pm 0.3$	11	20.7 ± 2.5	1000	10	300
7	$4.40 \pm 0.84 \pm 0.28$	2	5.61 ± 0.64	1250	5	225

⇒ Observed events in agreement with background expectations in all 7 regions



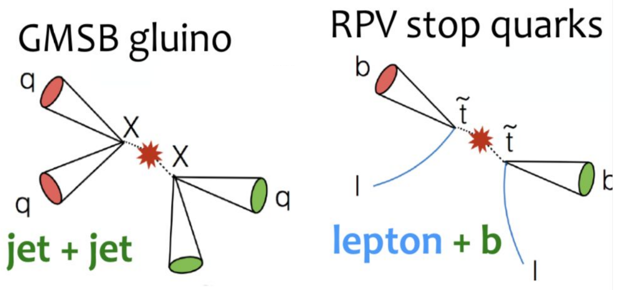


First emerging jet and dark QCD results in CMS !

Displaced jets

CMS EXO-18-007 , arXiv 1811.07991 , HepData

- *Benchmark model : theoretical motivation very rich!*
  - ❑ *RPV SUSY, GMSB SUSY, Split SUSY, Stealth SUSY, WIMP triggered Baryogenesis , etc …*
  - ❑ *Signature : 2 displaced jets, proper decay length 3 -130 mm.*



❖ *Trigger*

- *Dedicated trigger to tag displaced jets requires :*
  - ❑ *HT > 350 GeV & jet pT > 40 GeV & $|\eta| < 2.$ & max 2 prompt tracks & at least 1 displaced tracks.*

❖ *Event selection and vertexing :*

- *HT > 400 GeV & jet pT > 50 GeV & $|\eta| < 2.$*
- *Vertex reconstruction based on specific tracks.*
  - ❑ *High purity Tracks with pT > 1. GeV*
  - ❑ *Impact parameter > 0.5 mm*
  - ❑ *impact parameter significance > 5*

+

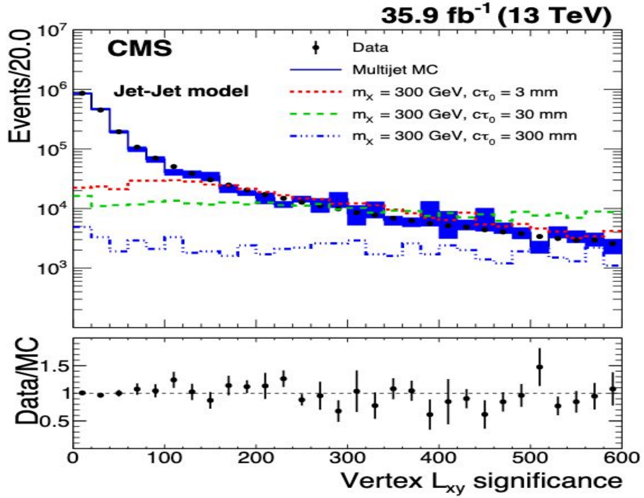
Vertex quality selections are used to minimise contamination from Background especially from B

Displaced jets

CMS EXO-18-007, *arXiv 1811.07991*, *HepData*

- *Search region divided as a function of HT.*
- *Background extracted from data in the control region, build from likelihood discriminant function.*

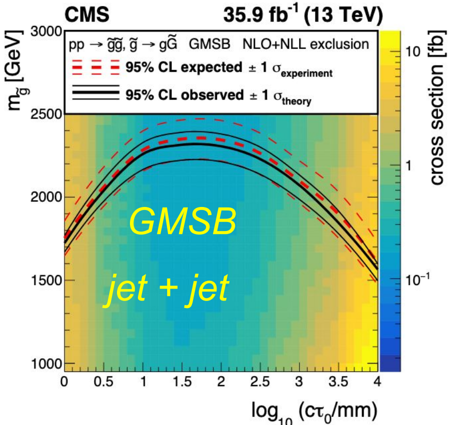
Selection on H_T	Number of dijets	Expected	Observed
$400 < H_T < 450$ GeV	1	0.42 ± 0.14 (stat) ± 0.01 (syst)	0
$450 < H_T < 550$ GeV	1	0.23 ± 0.08 (stat) ± 0.07 (syst)	0
$H_T > 550$ GeV	1	0.19 ± 0.07 (stat) ± 0.05 (syst)	1
—	>1	0.16 ± 0.11 (stat) ± 0.06 (syst)	0

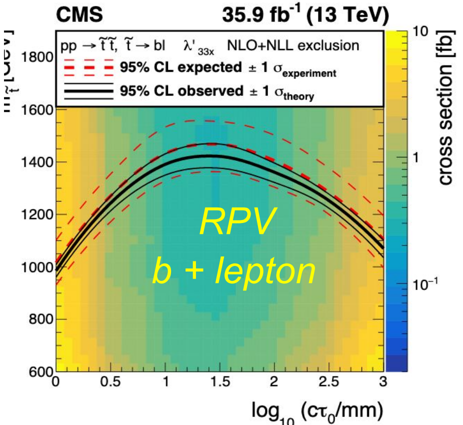


- *1 event observed in accord with the total background prediction.*
- *Event with displaced vertex of Lxy = 3.5 cm , HT = 590 GeV and track multiplicity = 10 ⇒ b quark jet.*

➢ *Limits are set for :*

- *RPV : LL top squark mass up to 1350 GeV and proper lifetime 7-110 mm are excluded.*
- *GMSB : gluino masses up 2300 GeV for proper decay length 20 -110 mm are excluded*



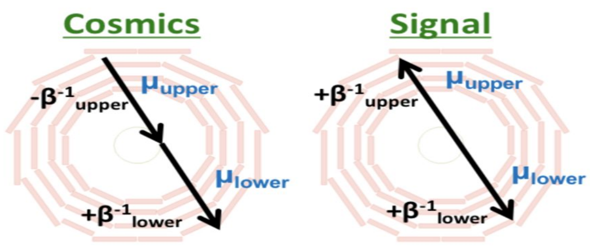


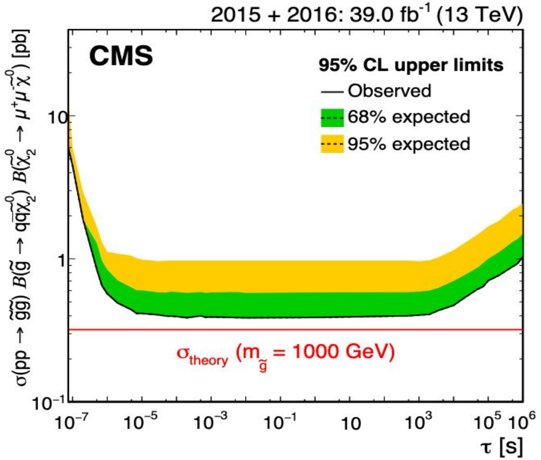
And more …

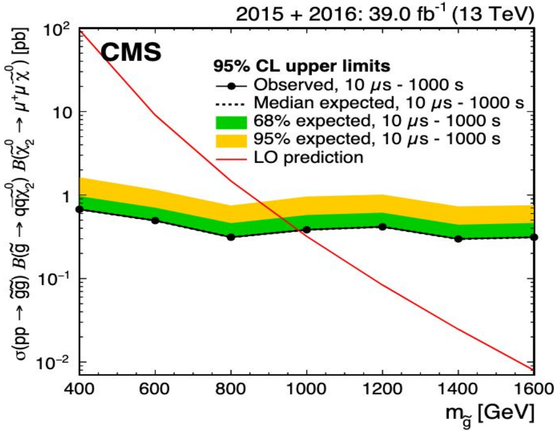
Stopped particles

CMS EXO-17-004, arXiv 1801.00359, HepData

- *Search for long lived particles that stop in the detector & decay into muons after some time.*
- *non-coincident with pp collisions 744 hours trigger lifetime in 2015/16 included in this search.*
- *Searches for long lived gluinos with delayed muons. No events observed in 2015/16*







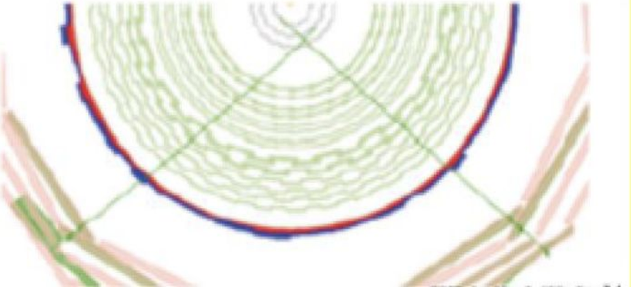
***Excluded gluinos** with mass between 400 and 970 GeV, assuming 100% BF to muons*

Displaced Lepton Pairs

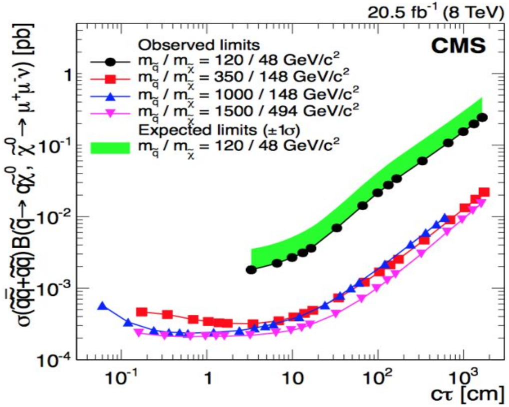
arXiv:1411.6977

❖ ***since run I ? yes !***

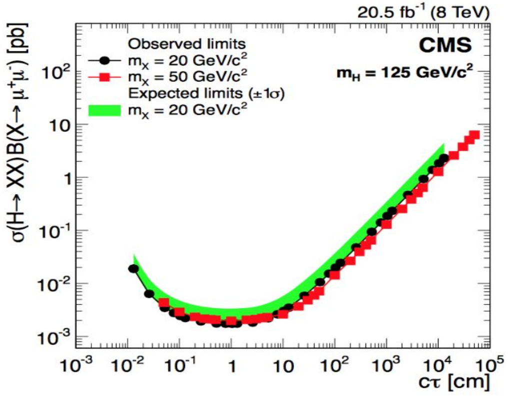
- <u>*Aim*</u> : *Search for long-lived particles that decay into final states containing two muons or two electrons.*
- *Based on the CMS tracker -Select muons pairs with pT > 26 GeV, electrons with 40/25 GeV.*
- *Models tested: non-Standard Model Higgs and SUSY squark production*



$\tilde{q} \rightarrow q\tilde{\chi}^0,\ \tilde{\chi}^0 \rightarrow \mu^+\mu^-\nu$



$H^0 \longrightarrow XX$



Summary :

- *Search for Long-Lived particles is an exciting and motivated exploration frontier.*
- *Clearly and increased interest in LLP searches at the LHC.*
- *So far this is only the tip of the iceberg, we didn't observe any signal yet.*
- *Many analysis are done, but also many others are still in progress !*
- *Systematic approach to study Long-lived particles and the strategy in*

  The LHC LLP Community white paper ! **arXiv:1903.04497**


Thank you !