

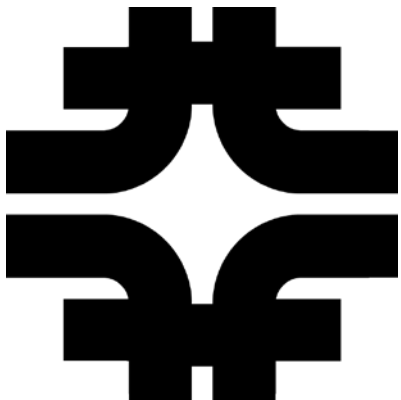
# Searches for new physics with unconventional signatures at ATLAS and CMS

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on behalf of the ATLAS and CMS Collaborations

March 26, 2019

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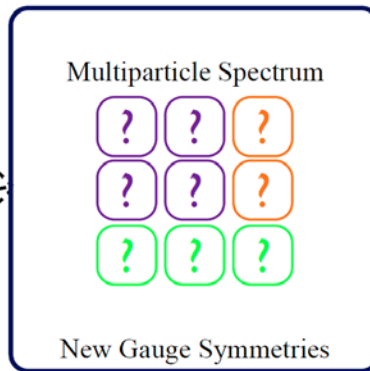
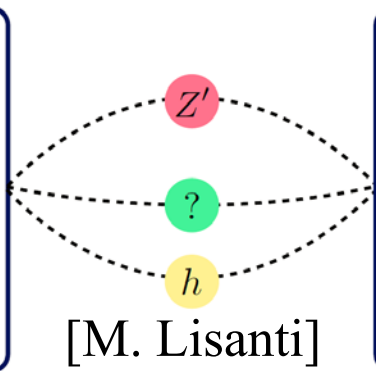
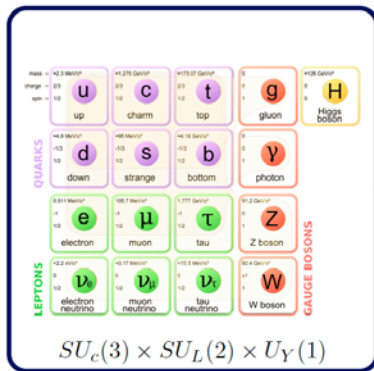


# Unconventional Models

Visible Sector

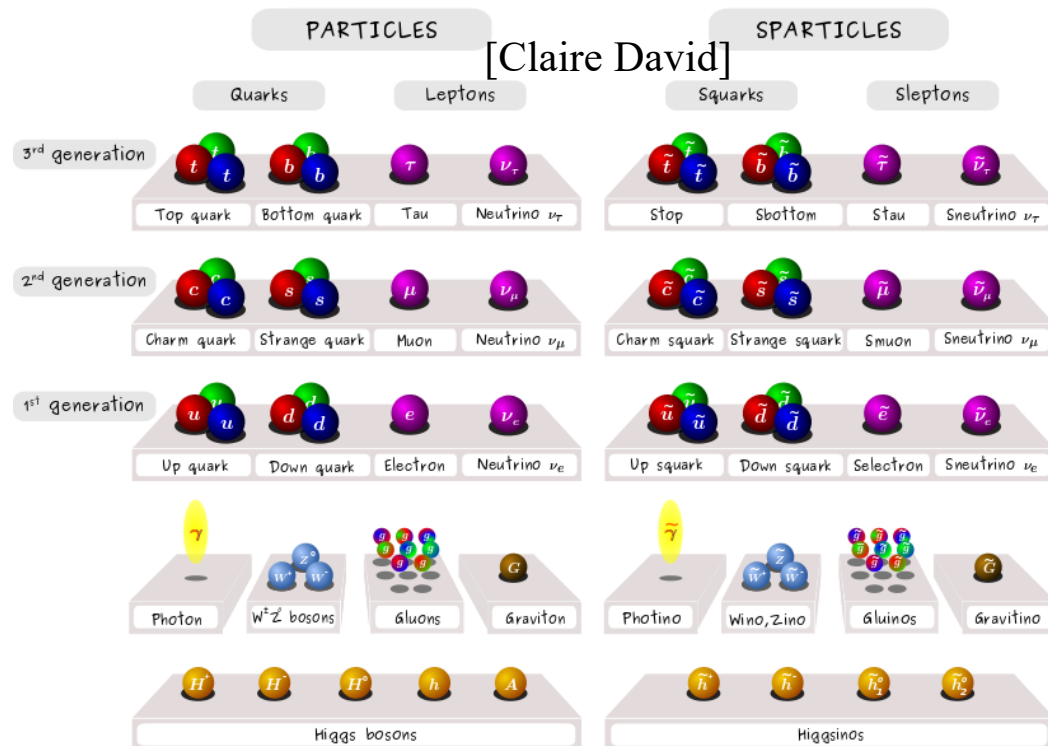
Portal

Dark Sector



- **Hidden sector:**  
new particles & forces
- Small coupling to SM  
→ long lifetime
- Unusual dynamics or striking signatures

- **Supersymmetry:**  
superpartner for each SM particle w/  $1/2$  spin difference
- R-parity violating, split, stealth, gauge- or anomaly-mediated SUSY breaking...
- Long lifetimes tend to occur in compressed scenarios (near-degenerate masses) or with suppressed decays



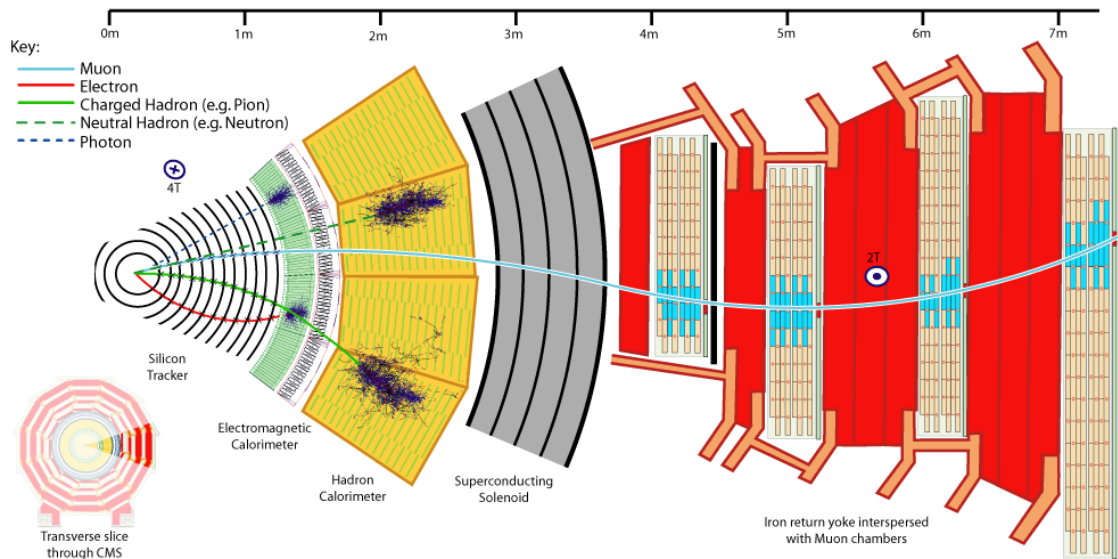
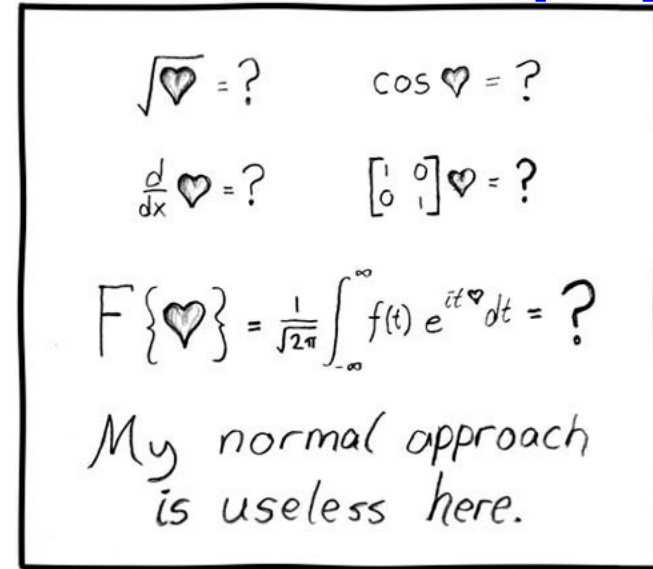
# Challenges

[xkcd]

## Reconstruction:

- “Standard” methods optimized for prompt decays  
→ may fail for long-lived particles
- Need to rely on missing energy or ionization to detect ~stable BSM particles
- Hard to trigger on many unconventional signatures

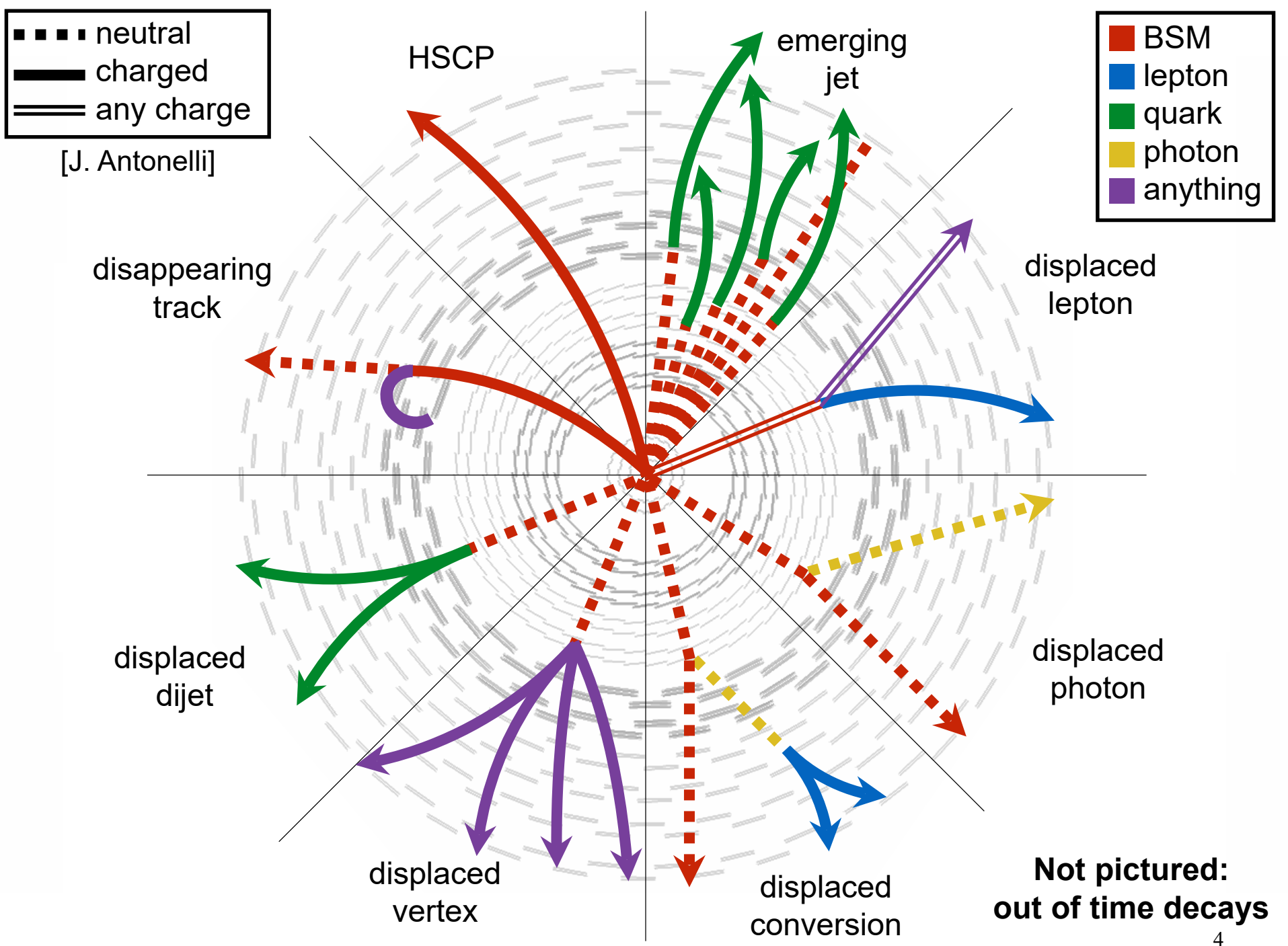
➤ Rely on low-level subdetector information



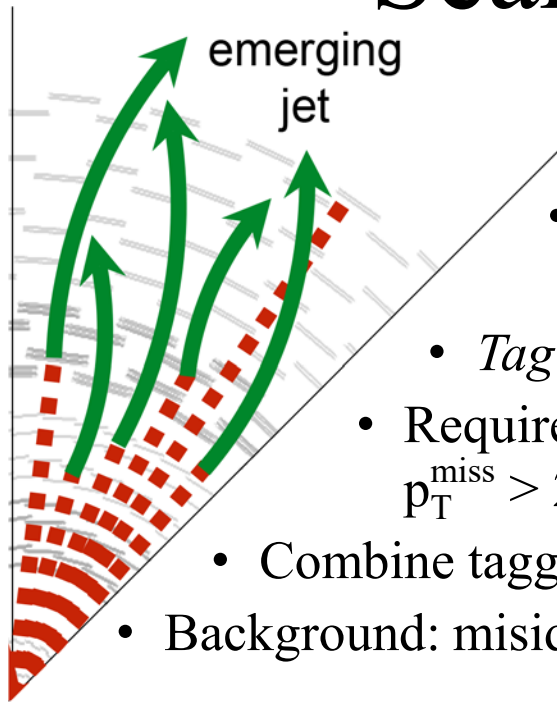
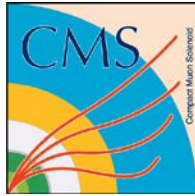
## Backgrounds:

- Mostly instrumental or other unusual sources
- Probably not simulated well (if at all)
- SM has LLPs, e.g. B hadrons

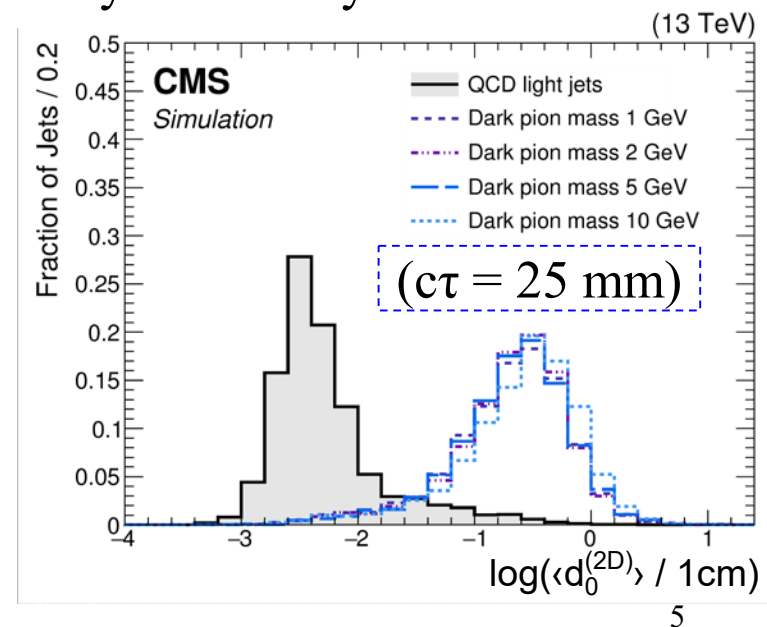
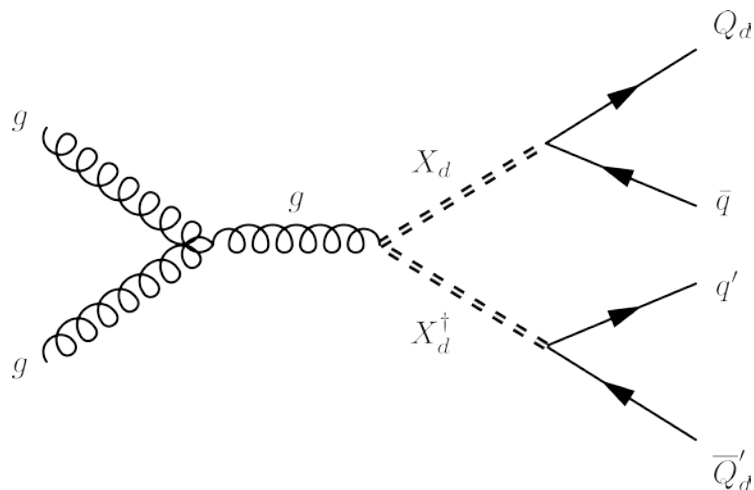
➤ Need data-driven methods



# Search for Emerging Jets



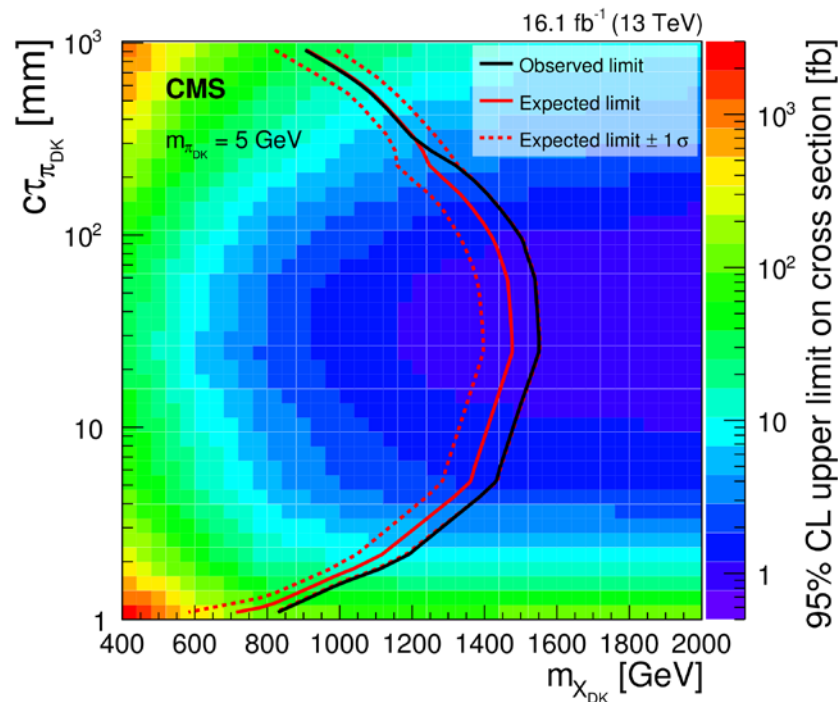
- Dark QCD force w/ dark quarks  $\rightarrow$  form dark mesons & baryons
- These decay after non-negligible lifetime to SM hadrons  $\rightarrow$  **emerging jets**
- *Tag* emerging jets using track impact parameter variables
- Require 4 jets w/ 2 tagged emerging jets (or 1 tagged and  $p_T^{\text{miss}} > 200$  GeV for large  $c\tau$ ), trigger on  $H_T = \sum p_T(j_{1,2,3,4})$
- Combine tagging WPs w/ kinematic selections  $\rightarrow$  7 signal regions
- Background: misid. rate (from  $\gamma$  CR)  $\times$  QCD CR yield = SR yield



# Emerging Jet Results



- Data:  $16.1 \text{ fb}^{-1}$ ,  $\sqrt{s} = 13 \text{ TeV}$ , 2016
- [JHEP02\(2019\)179](#), [arXiv:1810.10069](#)
- Observed data agree with background predictions (within uncertainties )
- Limits do not depend strongly on  $m_{\pi_d}$
- Exclude  $m_{X_d}$  between **400 and 1250 GeV** for  $c\tau_{\pi_d}$  between **5 and 225 mm**



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

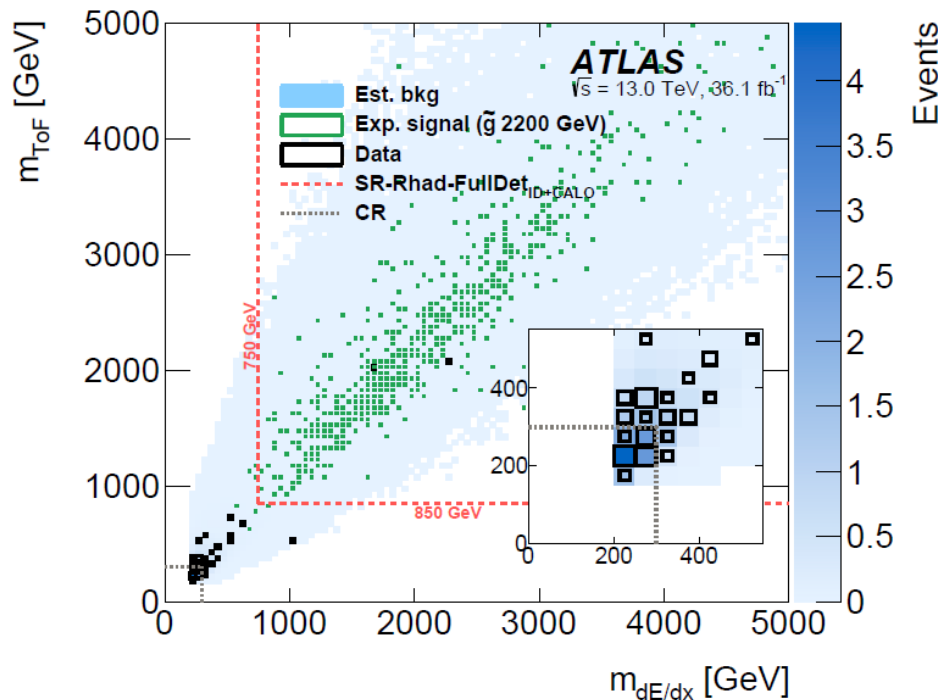
(Signal yields in table shown for largest  $m_{X_d}$  excluded by each selection set)

# Search for Heavy Charged LLPs



- **R-hadrons**: bound state of SUSY & SM colored particles
  - **Gluinos** (split SUSY) or **stops** (electroweak baryogenesis)
- Use “**full-detector**” or “**MS-agnostic**” (no muon spectrometer)
- **Electroweak SUSY**: **staus** (GMSB) or **charginos** (AMSB)
- Use both **inner detector (ID)** and **muon spectrometer (MS)**

HSCP

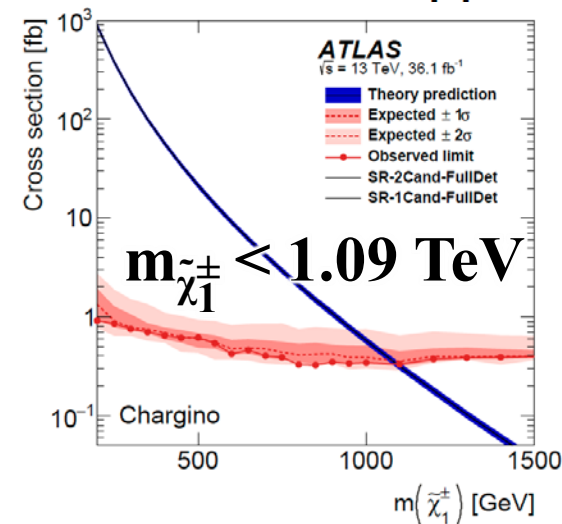
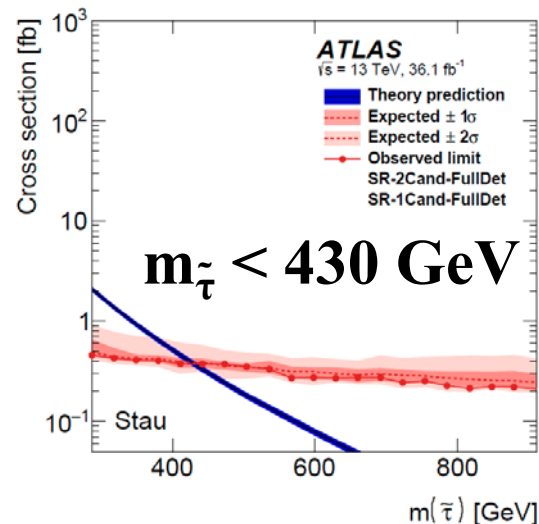
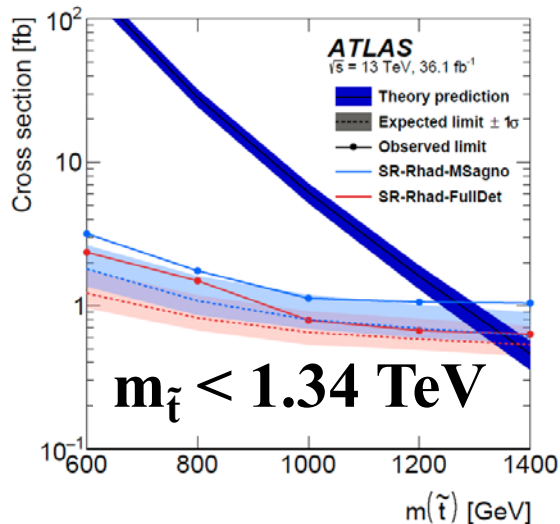
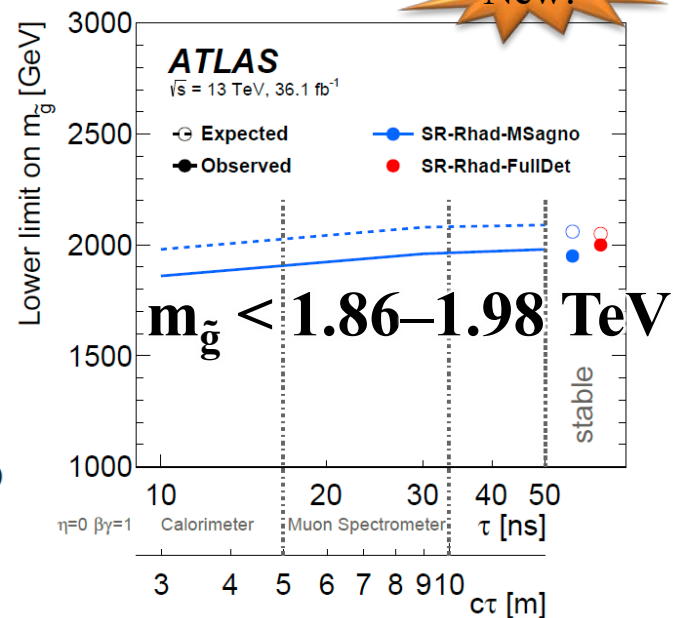
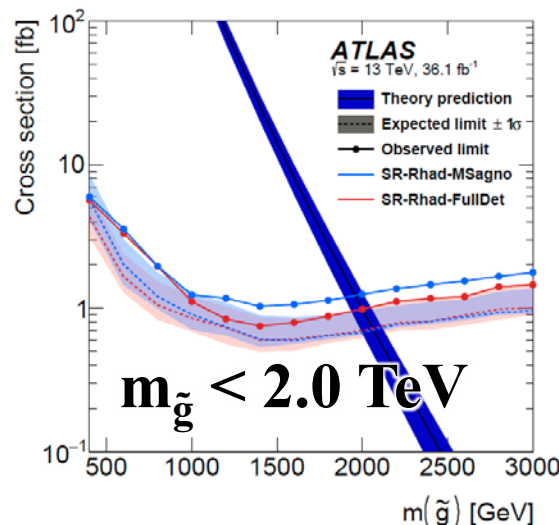


- Trigger on single muon or  $p_{\text{T}}^{\text{miss}}$
- ❖ **Measure candidate velocity ( $\beta$ ) and mass ( $m = p/\beta\gamma$ ) from  $dE/dx$  or ToF**
- Background: sample mass values from distrs. of  $p$ ,  $\beta_{\text{ToF}}$ ,  $(\beta\gamma)_{dE/dx}$

# Heavy Charged LLP Results



- Data:  $36.1 \text{ fb}^{-1}$ ,  
 $\sqrt{s} = 13 \text{ TeV}$ , 2015/16
- [arXiv:1902.01636](https://arxiv.org/abs/1902.01636)
- No significant excess observed
- Limits degrade slightly for meta-stable R-hadrons

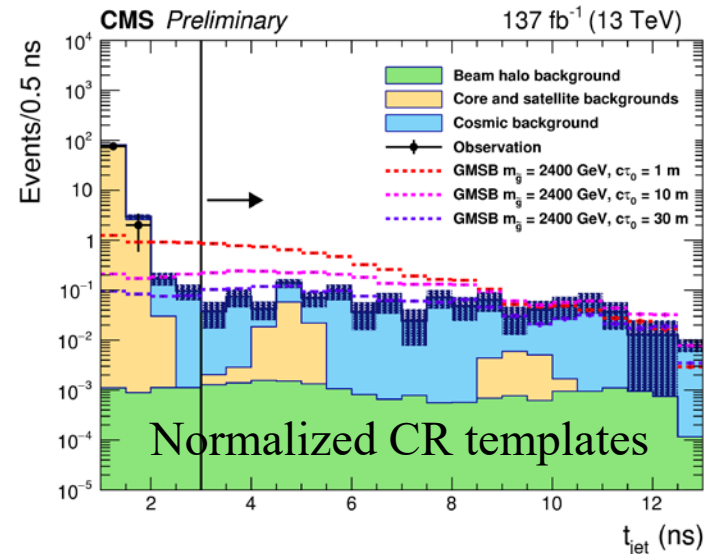
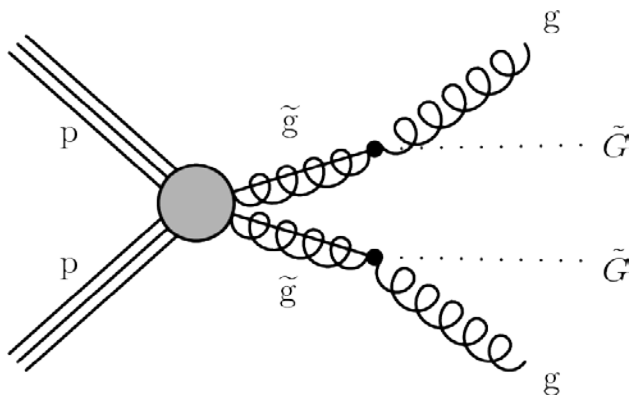


# Search for Delayed Jets



displaced  
~~dijet~~

- GMSB SUSY w/ long-lived gluinos  
→ R-hadrons decay to delayed jets +  $p_T^{\text{miss}}$
- First use of **ECAL** timing to distinguish displaced jets:  
 $t_{\text{jet}} = \text{median}(t_{\text{cell}})$ ,  $\Delta R(\text{cell}, \text{jet}) < 0.4$ ,  $t_{\text{cell}} < 20$  ns
- Calorimeter jets and  $p_T^{\text{miss}}$  (w/ out-of-time **ECAL**)
- **Cathode Strip Chambers (CSC)** & **HCAL** reject beam halo
- **Tracks** reject satellite bunches & mismeasurements
- **Drift Tubes (DT)** and **Resistive Plate Chambers (RPC)** reject cosmics
- **ECAL** rejects pileup & APD hits
- **Backgrounds:**  
invert cleaning cuts to form data CRs



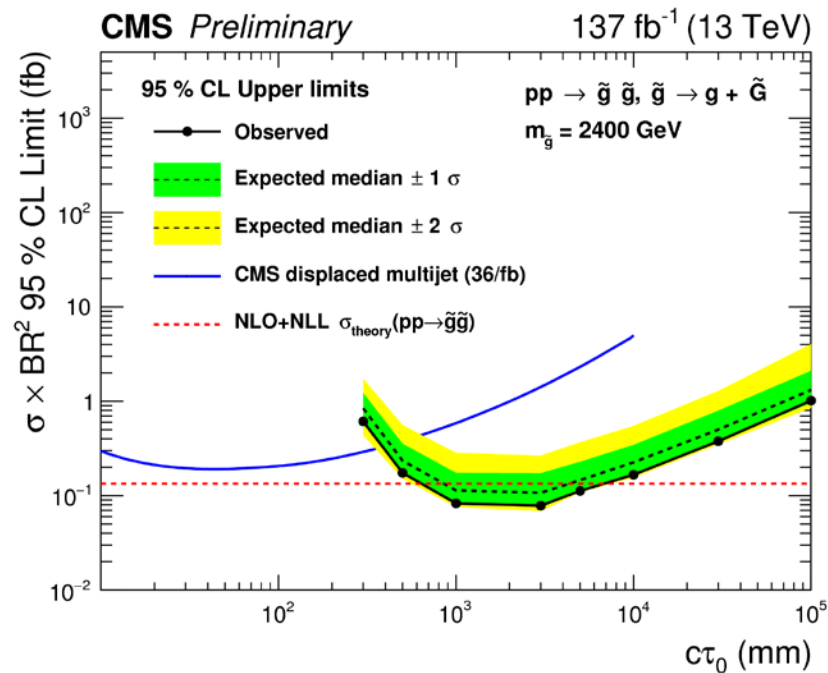
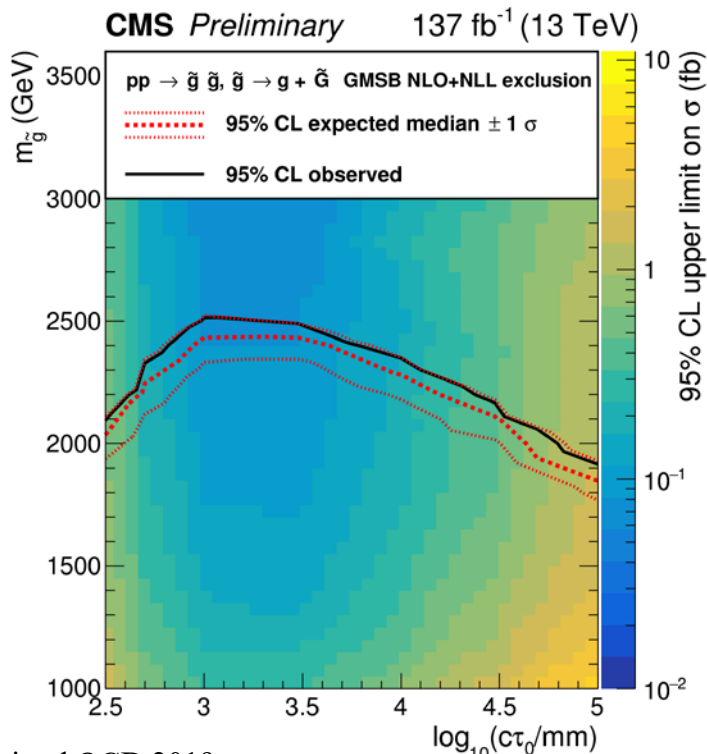
Signal region:  $N_{\text{jet}} \geq 1$ ,  $t_{\text{jet}} > 3$  ns

# Delayed Jet Results



- Data:  $137.4 \text{ fb}^{-1}$ ,  $\sqrt{s} = 13 \text{ TeV}$ , full Run 2! (2016/2017/2018)
- Observed: 0 events, in agreement w/ background prediction:  $1_{-1}^{+2.5}$
- Exclude  $m_{\tilde{g}} < 2.5 \text{ TeV}$  for  $c\tau_0 \sim 1 \text{ m}$  or  $m_{\tilde{g}} < 2.0 \text{ TeV}$  for  $c\tau_0 \sim 10 \text{ m}$
- Significantly extends reach for  $c\tau_0 \geq 1 \text{ m}$  (vs. tracker-based searches)
- [CMS-PAS-EXO-19-001](#)

Background	Prediction
Beam halo	$0.02_{-0.02}^{+0.06} \text{ (stat)}_{-0.01}^{+0.05} \text{ (syst)}$
Core and satellite bunches	$0.11_{-0.05}^{+0.09} \text{ (stat)}_{-0.02}^{+0.02} \text{ (syst)}$
Cosmics	$1.0_{-1.0}^{+1.8} \text{ (stat)}_{-1.0}^{+1.8} \text{ (syst)}$

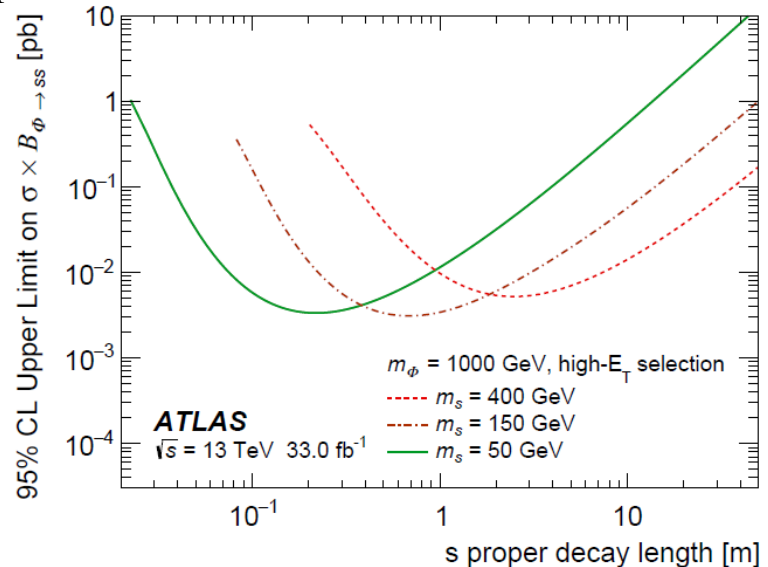
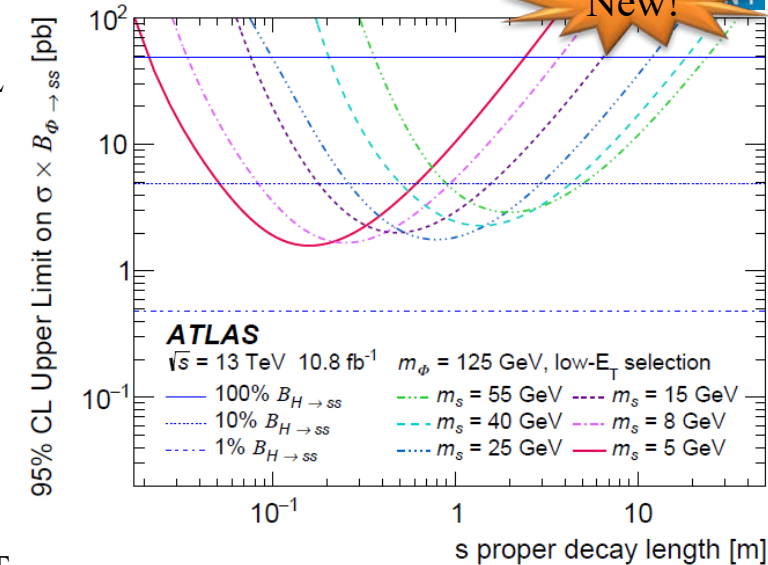


# Search for Displaced Hadronic Jets



- Simplified hidden sector,  $\Phi \rightarrow s s \rightarrow f \bar{f} f' \bar{f}'$
- **Custom triggers** using  $CalRatio = E_{HCAL}/E_{ECAL}$ 
  - High- $E_T$  and low- $E_T$  versions  
(33.0 fb<sup>-1</sup> or 10.8 fb<sup>-1</sup>,  $\sqrt{s} = 13$  TeV, 2016)
  - Separate data streams for cosmic and beam-induced background (BIB)
- ❖ **MLP** predicts jet decay position ↴
- ❖ **Jet BDT** classifies jets: signal, QCD, or BIB ↴
- ❖ **Event BDTs** optimized for high- $E_T$  and low- $E_T$
- Multijet background:
  - Use  $\sum \Delta R_{\min}(\text{jets}, \text{trk})$  and event BDT score
  - Simultaneous fit to signal and background
- [arXiv:1902.03094](https://arxiv.org/abs/1902.03094)

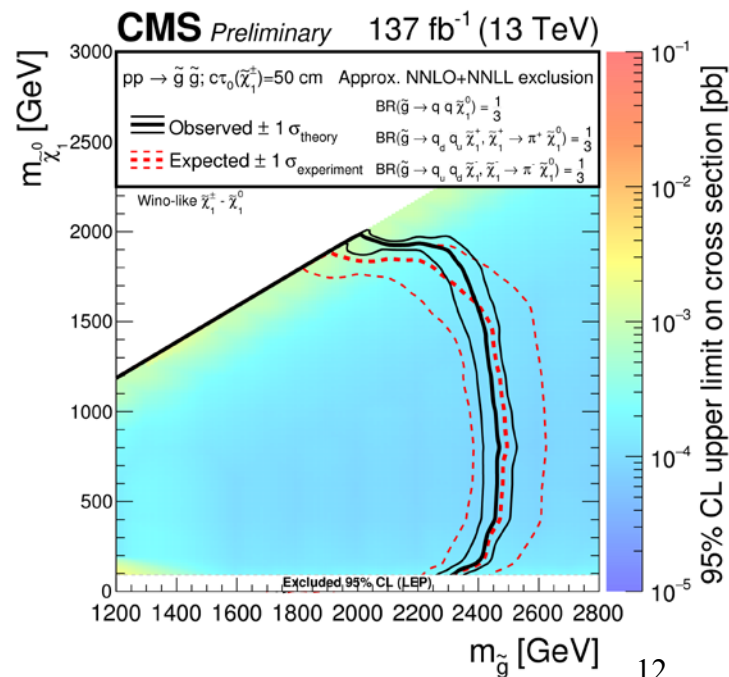
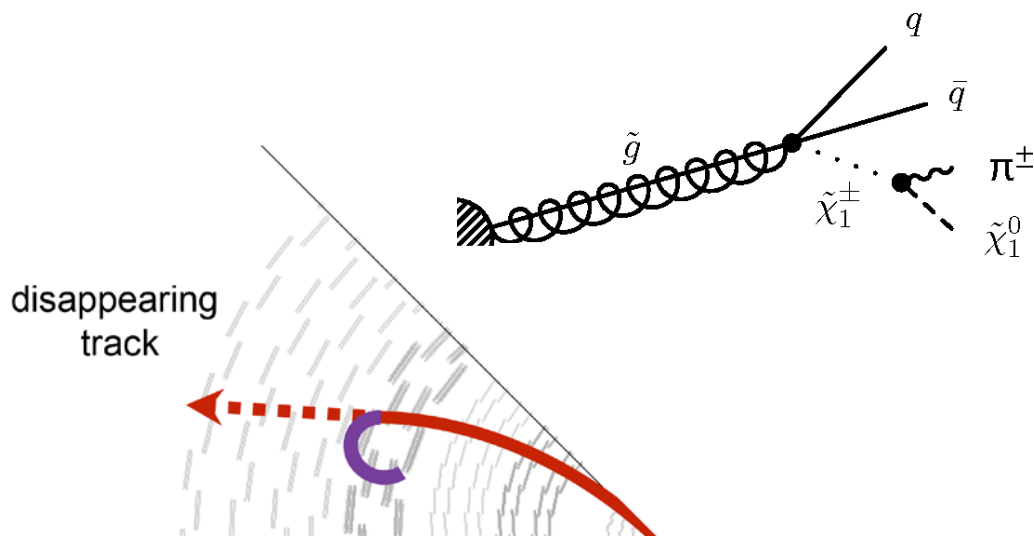
Main selections	Estim. A ( <i>a priori</i> )	Estim. A ( <i>a posteriori</i> )	A
High- $E_T$ selection	$6.7^{+3.2}_{-2.3}$	$8.5^{+2.3}_{-2.0}$	10
Low- $E_T$ selection	$2.5^{+2.5}_{-1.4}$	$5.3^{+2.1}_{-1.6}$	7



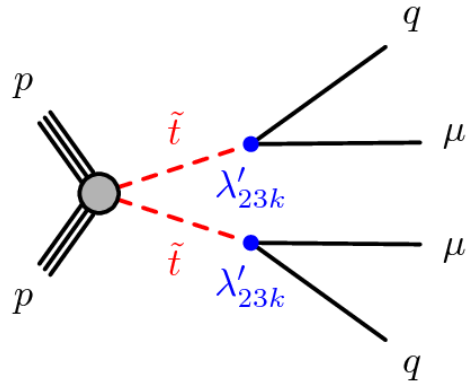
# SUSY w/ Disappearing Tracks



- Data:  $137.4 \text{ fb}^{-1}$ ,  $\sqrt{s} = 13 \text{ TeV}$ , full Run 2! (2016/2017/2018)
- Compressed SUSY w/  $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \sim 100 \text{ MeV}$ ,  $c\tau(\tilde{\chi}_1^\pm) \sim 50 \text{ cm}$
- Require  $\geq 2$  jets,  $M_{T2} > 200 \text{ GeV}$ , at least one short track (ST)
- Bin in  $N_{\text{jet}}$ ,  $H_T$ , ST length, ST  $p_T$ : 68 search regions
- Background: fake rate applied to ST “candidates” (relaxed quality, isolation req.)
- Exclude  $m_{\tilde{g}} < 2.46 \text{ TeV}$  and  $m_{\tilde{\chi}_1^0} < 2.0 \text{ TeV}$
- Improvement of 210 GeV and 525 GeV (resp.) in compressed region
- [CMS-PAS-SUS-19-005](#)

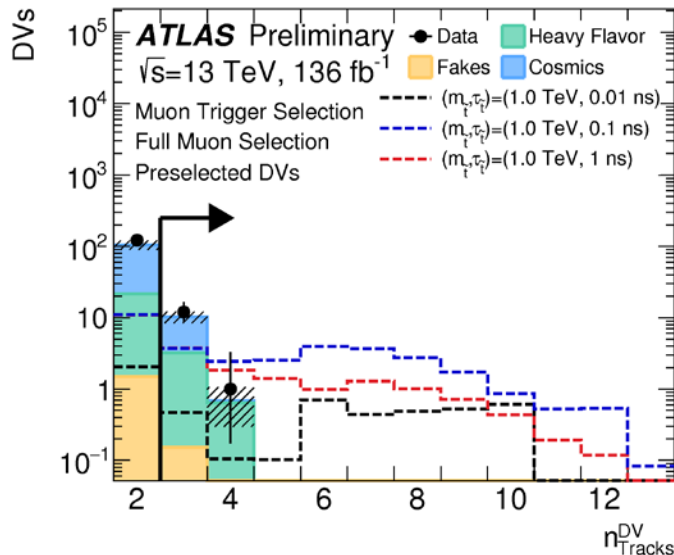


# Search for Displaced Vertex & Muon



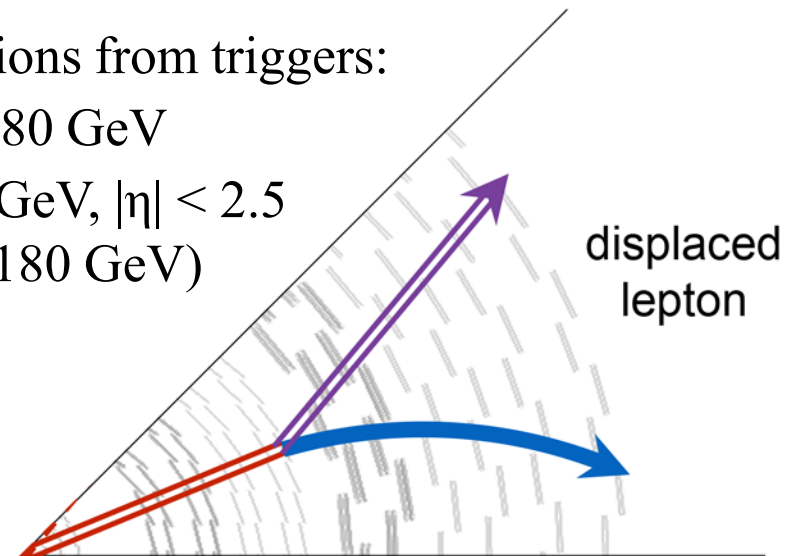
- R-parity violating SUSY w/  $\tilde{t}$  as LSP and small  $\lambda'_{23k}$  coupling  $\rightarrow$  suppressed decays, R-hadrons
- *Large-radius tracking* (LRT) improves efficiency for tracks with large impact parameters
- *Displaced vertices* (DV) reconstructed w/ secondary vertex algorithm

- **Muon spectrometer** rejects cosmic background and fake muons
- **Inner detector** rejects heavy flavor
- Backgrounds: transfer factors from DV CRs applied to muon CRs (in data)



- Signal regions from triggers:

- $p_T^{\text{miss}} > 180 \text{ GeV}$
- $p_T^\mu > 60 \text{ GeV}, |\eta| < 2.5$   
( $p_T^{\text{miss}} < 180 \text{ GeV}$ )



# Displaced Vertex & Muon Results



- Data:  $136 \text{ fb}^{-1}$ ,  $\sqrt{s} = 13 \text{ TeV}$ , full Run 2! (2016/2017/2018)

• [ATLAS-CONF-2019-006](#)

- Exclude  $m_{\tilde{t}} < 1.7 \text{ TeV}$  for  $\tau_{\tilde{t}} = 0.1 \text{ ns}$   
( $m_{\tilde{t}} < 1.3 \text{ TeV}$  for  $0.01 < \tau_{\tilde{t}} < 30 \text{ ns}$ )

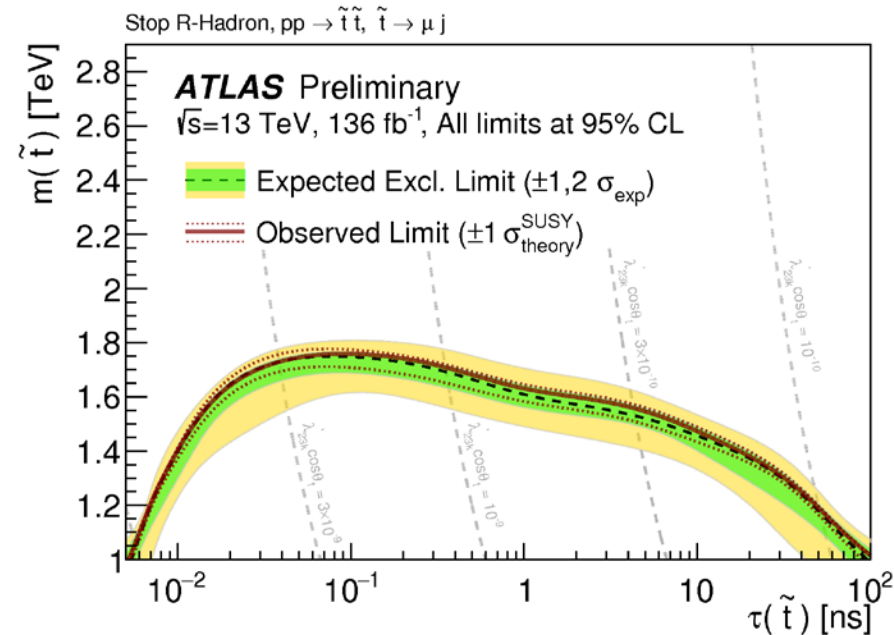
➤ Strictest limits to date

for metastable  $\tilde{t}$  decaying via  $\lambda'_{ijk}$

- Model-independent limits on # signal events and  $\sigma_{\text{vis}}$  also derived

Signal Region	$S_{\text{obs}}^{95}$	$S_{\text{exp}}^{95}$	$\langle \sigma_{\text{vis}} \rangle_{\text{obs}}^{95} [\text{fb}]$
$E_{\text{T}}^{\text{miss}}$ Trigger SR	3.1	$3.1^{+1.1}_{-0.1}$	0.023
Muon Trigger SR	3.7	$4.2^{+1.6}_{-1.0}$	0.027

	Predicted	Obs.
$p_{\text{T}}^{\text{miss}}$ Trigger SR	$0.43 \pm 0.16 \pm 0.16$	0
$\mu$ Trigger SR	$1.88 \pm 0.20 \pm 0.28$	1





Backup

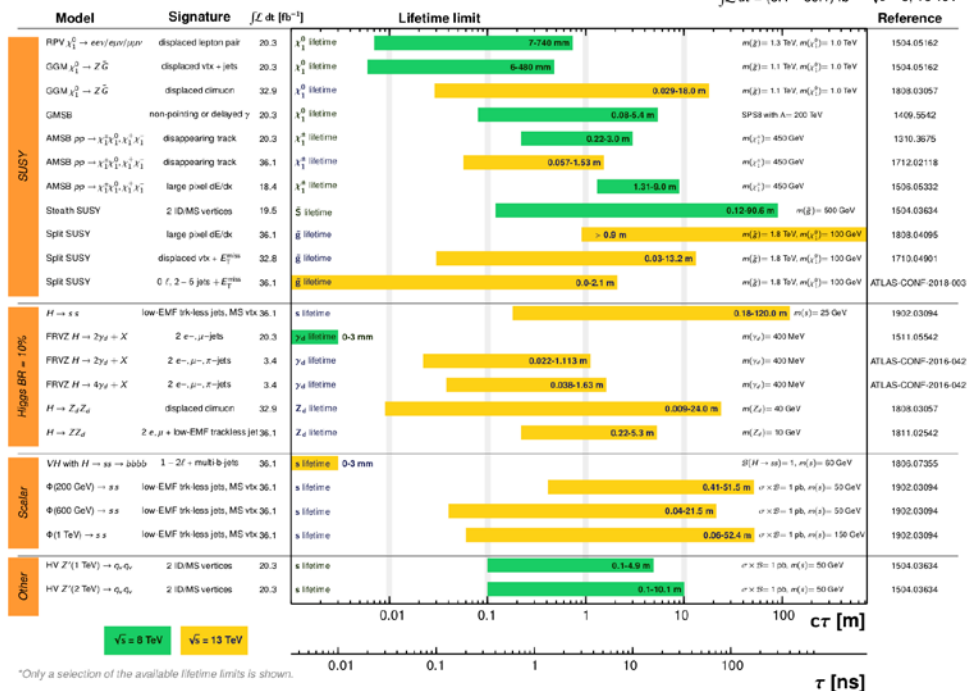
# ATLAS Summary

## ATLAS Long-lived Particle Searches\* - 95% CL Exclusion

Status: March 2019

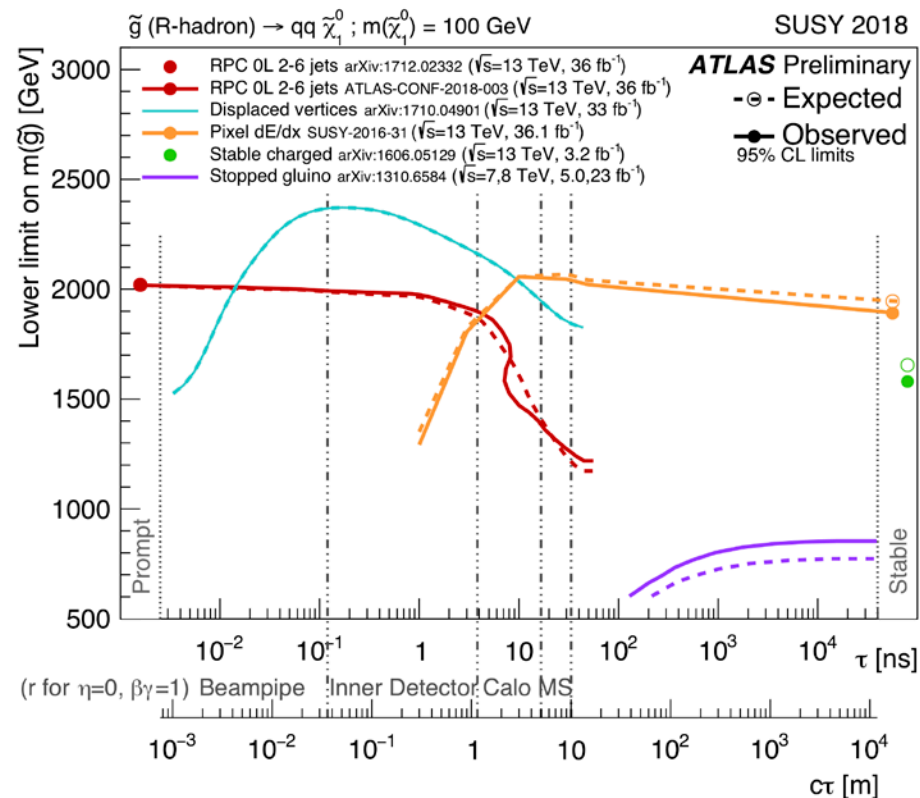
ATLAS Preliminary

$$\int \mathcal{L} dt = (3.4 - 36.1) \text{ fb}^{-1} \quad \sqrt{s} = 8, 13 \text{ TeV}$$



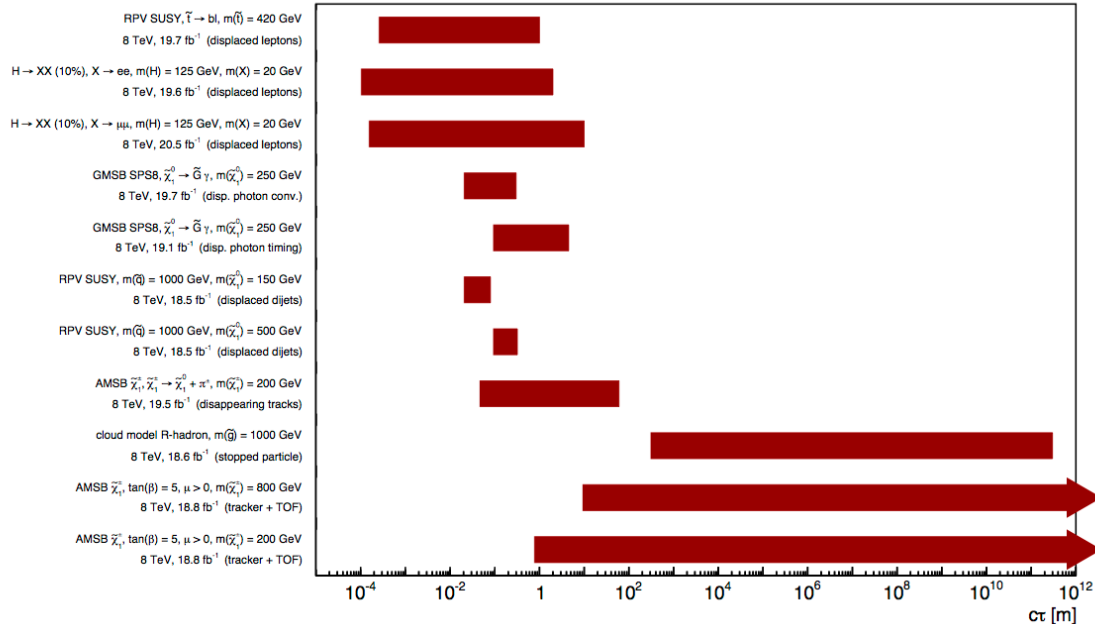
<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/>

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/>



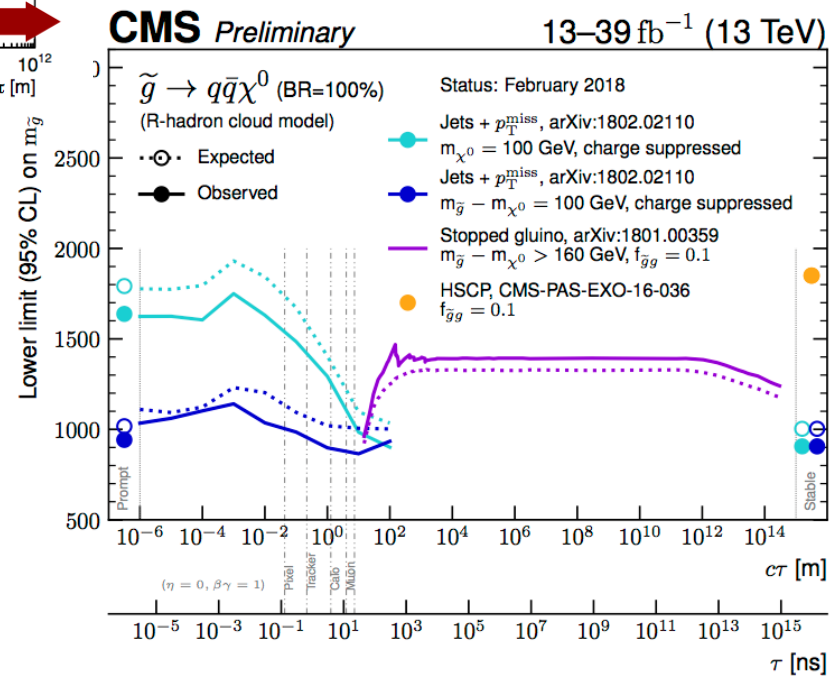
# CMS Summary

CMS long-lived particle searches, lifetime exclusions at 95% CL



<http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/index.html>

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV>



# Emerging Jet Details



## Tagging WPs

Criteria group	$\Delta z_{\text{PU}} (<) [\text{cm}]$	$D_N (<)$	$\langle d_0^{2D} \rangle (>) [\text{cm}]$	$\alpha_{3D} (<)$
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

QCD control selections

## Signal Regions

Set number	$H_T$	$p_{T,1}$	$p_{T,2}$	$p_{T,3}$	$p_{T,4}$	$p_T^{\text{miss}}$	$n_{\text{EMJ}}(\geq)$	EMJ group	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	SM QCD-enhanced
9	900	225	100	100	100	200	1	8	

## Jet Selections

- Each jet:
  - $n_{\text{trk}} \geq 1$
  - $p_T(\text{trk})/p_T(j) < 0.6$
  - $f_{\text{ch. EM}} < 0.9$
  - $f_{\text{neu. EM}} < 0.9$
- $p_T(j_1) > 225 \text{ GeV}$ ,  
 $p_T(j_{2,3,4}) > 100 \text{ GeV}$

Mis-reco

Reject ele.

# Emerging Jet Background



## Photon CRs

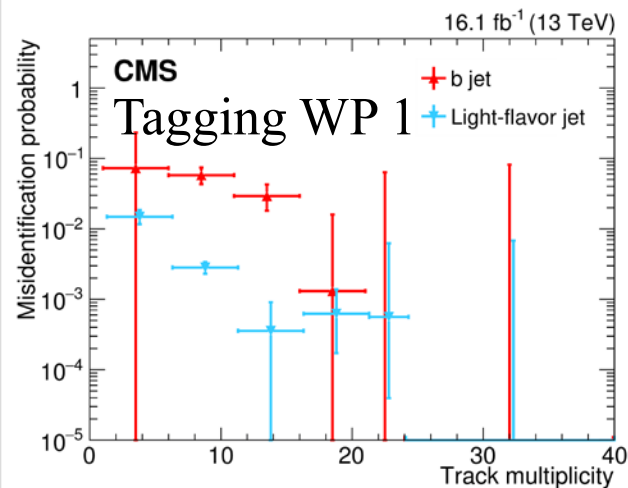
- $N_\gamma = 1, p_T > 175 \text{ GeV}, |\eta| < 1.44$
- $N_{\text{SMJ}} \geq 1, p_T > 50 \text{ GeV}, \text{CSV}_{\text{v2}} > 0.8 \text{ OR } < 0.2$

## QCD CRs

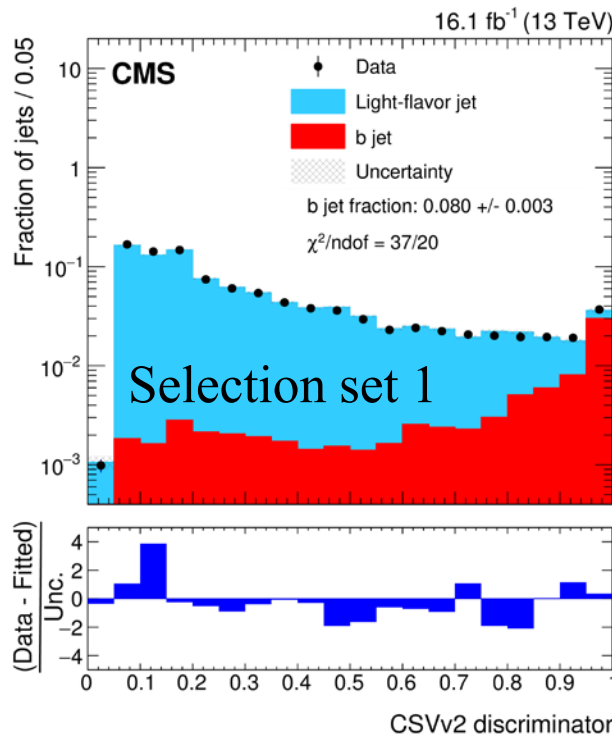
- $N_{\text{EMJ}} = 0, p_T^{\text{miss}} > 200$   
OR  $N_{\text{EMJ}} = 1, p_T^{\text{miss}} \geq 0$

➤ SM jets **misidentified** as emerging jets

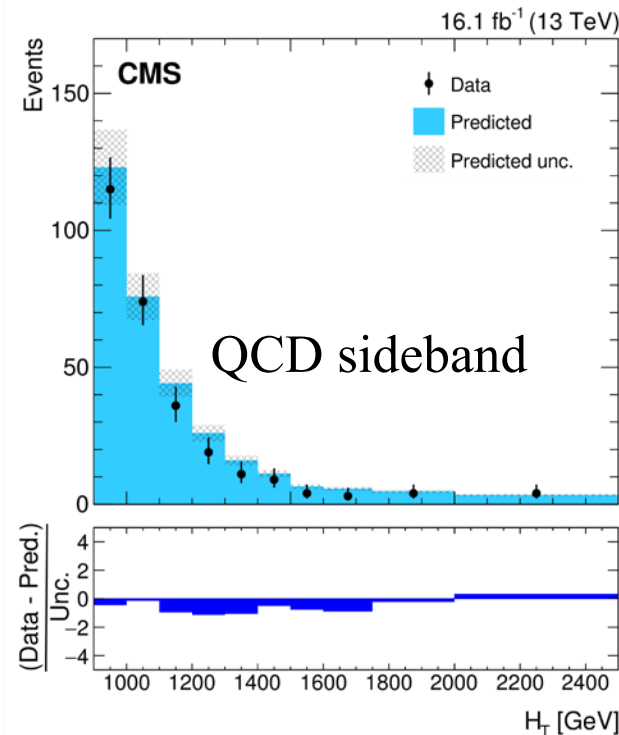
- Misid. rate (from  $\gamma$  CR)  $\times$  QCD CR yield = SR yield
- Misid. rate higher for b quarks vs. light flavor  
→ get CR flavor compositions from CSVv2 dist.
- Uncertainties: b quark fraction (0.6–5%), non-b quark composition (1.4–6.3%, 28.3% for  $p_T^{\text{miss}} > 200$ )



Moriond QCD 2019



Kevin Pedro



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# Heavy Charged LLP Details



Signal region	Trigger	Candidate selection	Candidates per event	Final requirements				
				$ \eta $	$p$ [GeV]	$\beta_{\text{ToF}}$	$(\beta\gamma)_{dE/dx}$	Mass
SR-Rhad-MSagno	$E_T^{\text{miss}}$	ID+CALO	$\geq 1$	$\leq 1.65$	$\geq 200$	$\leq 0.75$	$\leq 1.0$	ToF & $dE/dx$
SR-Rhad-FullDet	$E_T^{\text{miss}}/\mu$	LOOSE	$\geq 1$	$\leq 1.65$	$\geq 200$	$\leq 0.75$	$\leq 1.3$	ToF & $dE/dx$
SR-Rhad-FullDet	$E_T^{\text{miss}}/\mu$	ID+CALO	$\geq 1$	$\leq 1.65$	$\geq 200$	$\leq 0.75$	$\leq 1.0$	ToF & $dE/dx$
SR-2Cand-FullDet	$E_T^{\text{miss}}/\mu$	LOOSE	$= 2$	$\leq 2.00$	$\geq 100$	$\leq 0.95$	-	ToF
SR-1Cand-FullDet	$E_T^{\text{miss}}/\mu$	TIGHT	$= 1$	$\leq 1.65$	$\geq 200$	$\leq 0.80$	-	ToF

## Background:

- Distrs. of  $p$ ,  $\beta_{\text{ToF}}$ ,  $(\beta\gamma)_{dE/dx}$  from data or MC sidebands (5–6  $\eta$  bins because of correlations)
- Sample from distrs. to get background vs.  $m_{\text{ToF}}$  and  $m_{dE/dx}$
- Normalize using low-mass CRs
- Prediction uncertainties:
  - Rhad-MSagno: 33–34%
  - Rhad-FullDet: 27–53%
  - Stau/chargino: 9–34%

## Baseline Selection

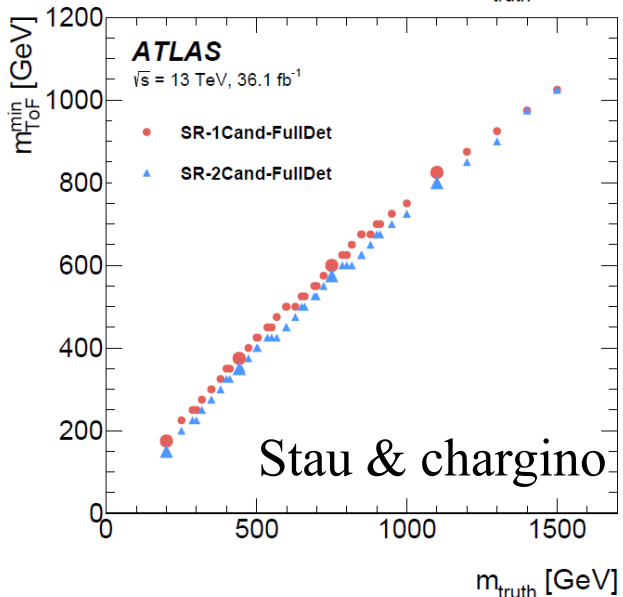
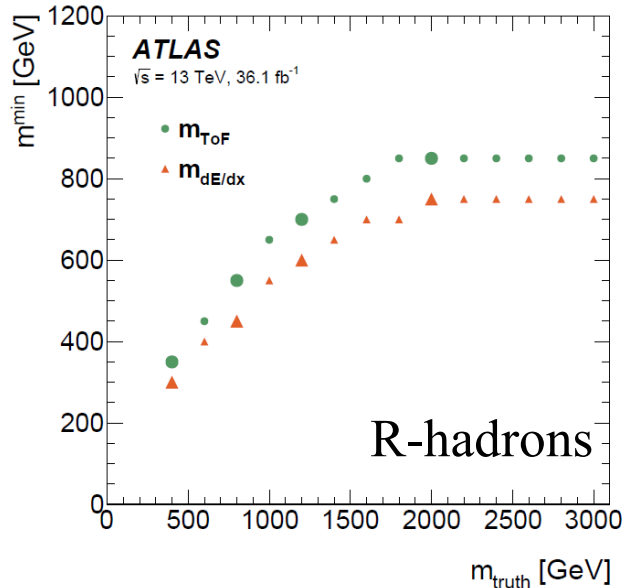
- $N_{\text{trk}} \geq 1$  ( $p_T > 50$  GeV,  $p < 6.5$  TeV)
  - pass ID req.
- PV from  $\geq 2$  trk w/  $p_T > 400$  MeV

## Common Track Selection

- $N_{\text{clusters}} > 6$ ,  $N_{\text{shared+split}} = 0$ ,  $N_{\text{SCT}} > 2$
- $L_{\text{trk}} < 5$  GeV calo. timing
- $f_{\text{ECAL}}(\text{jet}, p_T > 20) < 0.95$  ele. veto
- $E_{\text{jet}} < p_{\text{trk}}$  had. veto
- $\Delta R_{\text{cosmics}} > 0.04$  cosmic veto
- $|m_{\text{trk}, \mu_1} - 10| > m_Z$  Z veto

# Heavy Charged LLP Selections

## Discovery Regions



### Track ID+Calo

- $|\eta| < 1.65$
- $N_{\text{clusters}} > 1$
- $0 < dE/dx < 20 \text{ MeV g}^{-1} \text{ cm}^2$
- $0.2 < (\beta\gamma)_{\text{dE/dx}} < 10$
- $0.2 < \beta_{\text{tile}} < 2, \sigma(\beta_{\text{tile}}) < 0.06, P(\chi^2) > 0.01$

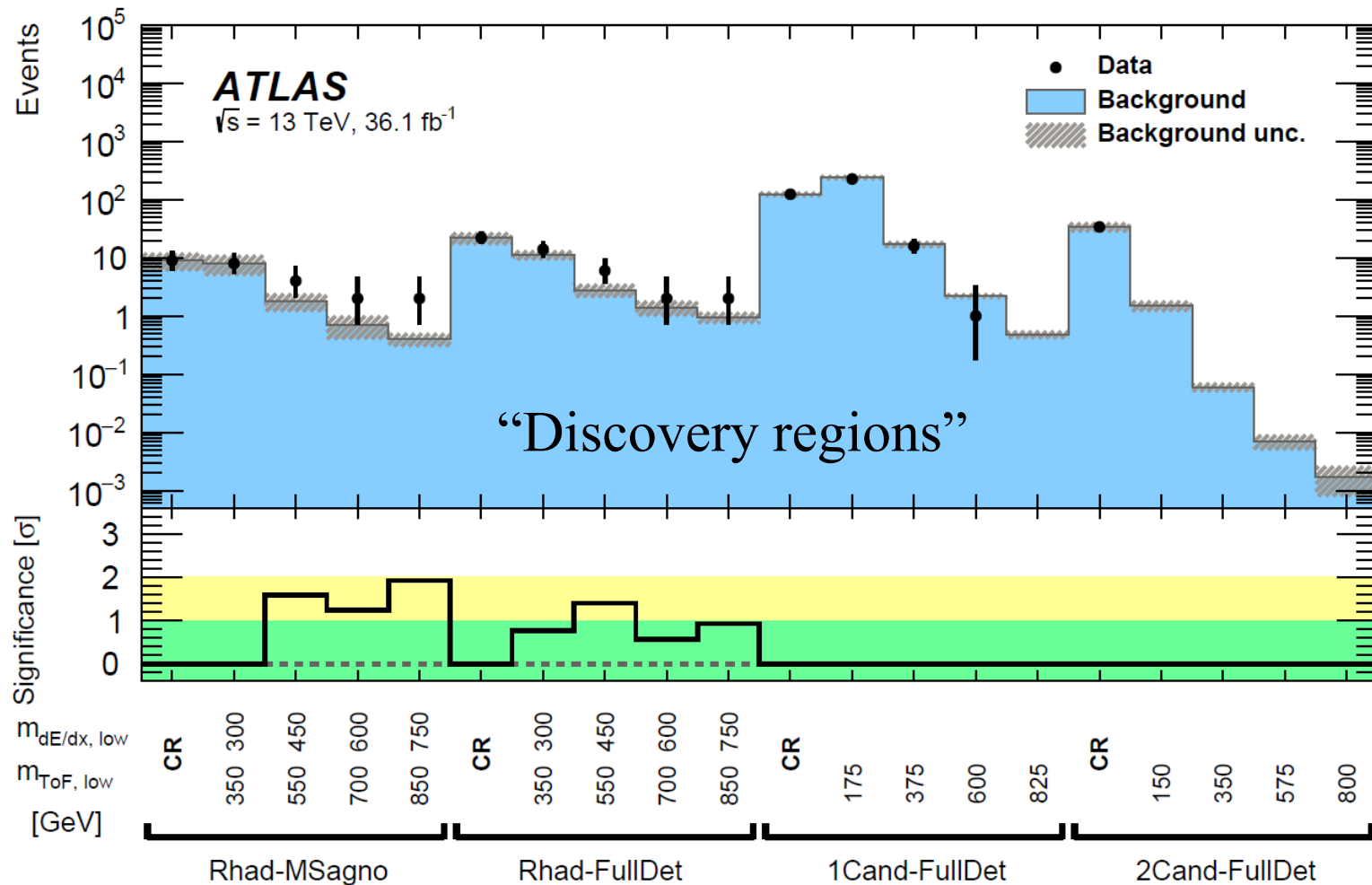
### Track Loose

- $N_{\text{time meas.}} \geq 1$
- $p_T > 70 \text{ GeV}, |\eta| < 2, N_{\text{MS hit}} \geq 2$
- All  $\beta$  measurements consistent w/in  $5\sigma$
- $0.2 < \beta_{\text{ToF}} < 2, \sigma(\beta_{\text{ToF}}) < 0.025$

### Track Tight

- Loose +  $|\eta| < 1.65$
- $1 < dE/dx < 20 \text{ MeV g}^{-1} \text{ cm}^2$
- $N_{\text{systems}} \geq 2$

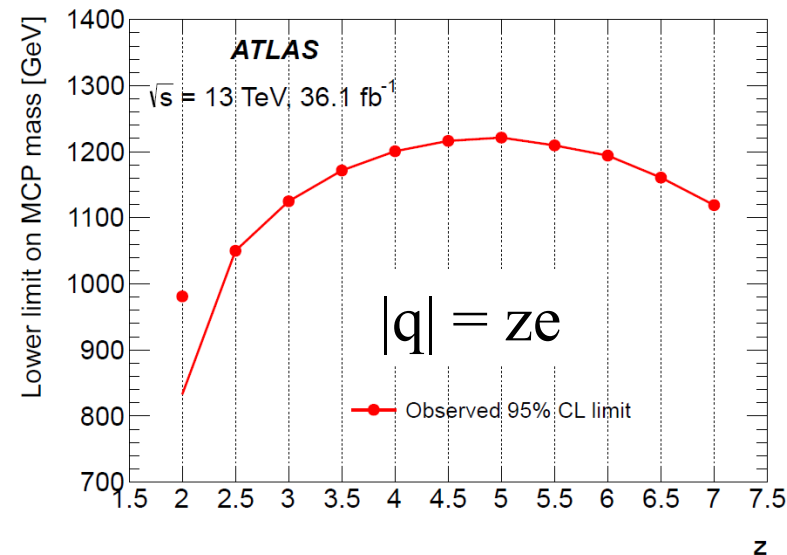
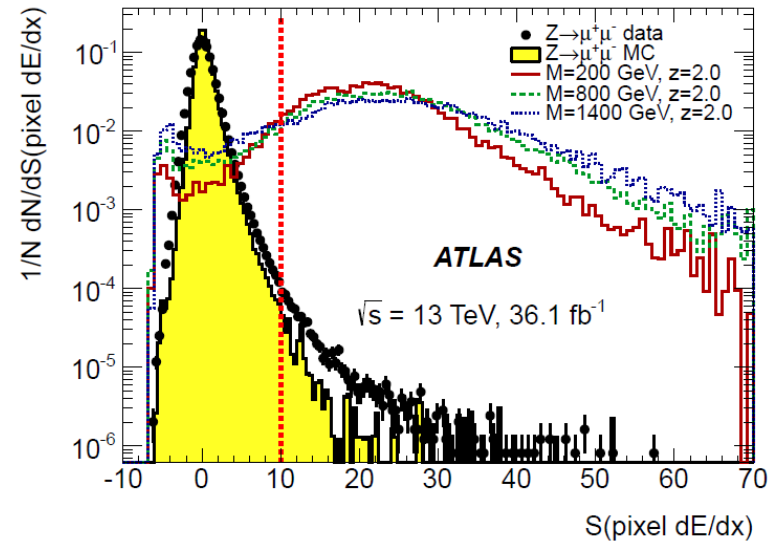
# Heavy Charged LLP Prediction



# Search for Multi-Charged LLPs



- Models: almost-commutative leptons, technibaryons, left-right supersymmetric Higgs
- Single muon and  $p_T^{\text{miss}}$  triggers
- $S(dE/dx)$  significance for **pixel**, **transition radiation tracker (TRT)**, and **monitored drift tubes (MDT)**
- Background (high- $p_T$  muons):
  - $z = 2$ :  $0.15 \pm 0.05$  (stat.)  $\pm 0.10$  (syst.)
  - $z > 2$ :  $0.029 \pm 0.004$  (stat.)  $\pm 0.002$  (syst.)
- Data:  $36.1 \text{ fb}^{-1}$ ,  $\sqrt{s} = 13 \text{ TeV}$ , 2015/16
- [arXiv:1812.03673](https://arxiv.org/abs/1812.03673)
- 0 events observed for  $z = 2$  and  $z > 2$
- Exclude  $50 < m_{\text{MCP}} < 980\text{--}1120 \text{ GeV}$ , depending on  $z$



# Delayed Jet Details



## Jet Cleaning

\*noise

- $E_{\text{ECAL}} > 20 \text{ GeV}$  pileup\*
- $N_{\text{cell}} > 25$  APD hits\*
- $\text{RMS}(t_{\text{jet}})/t_{\text{jet}} < 0.4, \text{RMS}(t_{\text{jet}}) < 2.5$  \*
- $f_{\text{PV track}} < 1/12$  mismeas., satellite
- $f_{\text{HCAL}} > 0.2, E_{\text{HCAL}} > 50$  beam halo\*
- $E_{\text{CSC}}/E_{\text{ECAL}} < 0.8$  beam halo

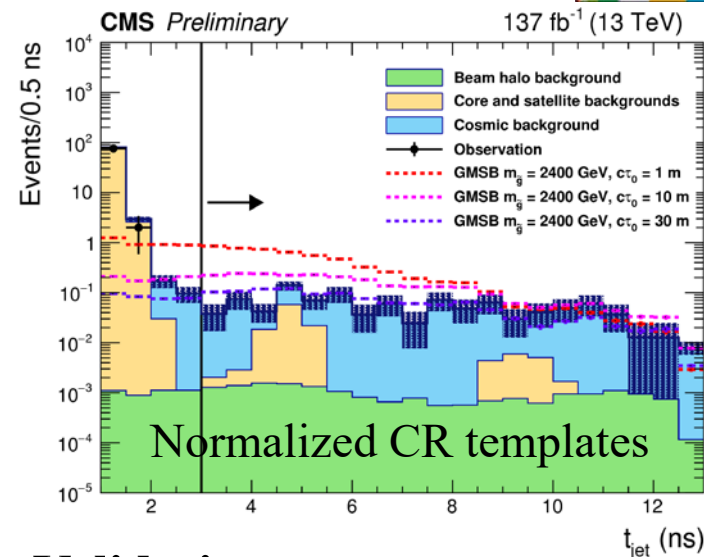
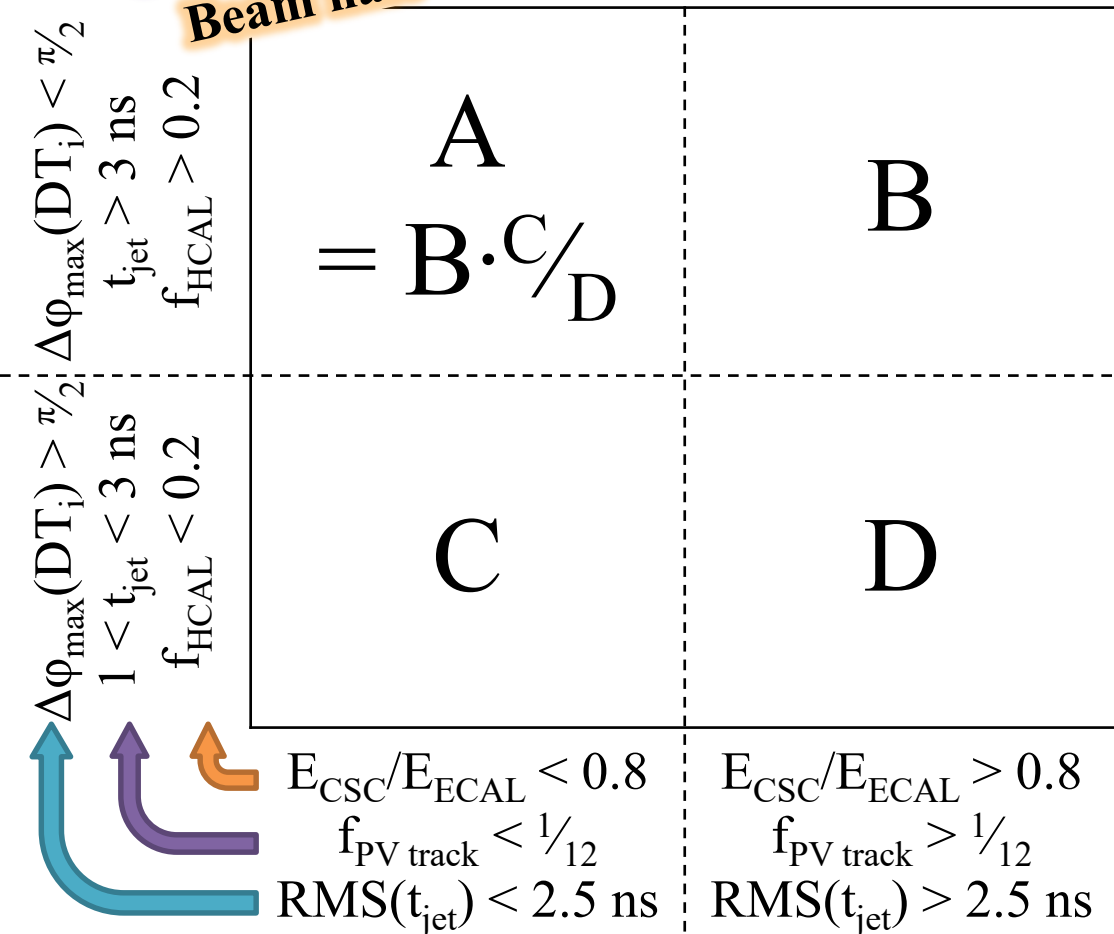
## Baseline Selection

- $N_{\text{jet}} \geq 1$  ( $p_{\text{T}} > 30 \text{ GeV}, |\eta| < 1.48$ )
  - $t_{\text{jet}} > 3 \text{ ns} + \text{cleaning}$
- $p_{\text{T}}^{\text{miss}} > 300 \text{ GeV}$  Trigger
- $\Delta\phi_{\text{max}}(\text{DT}_i, \text{DT}_j) < \pi/2$  cosmoics
- $\Delta\phi_{\text{max}}(\text{DT}_i, \text{RPC}_j) < \pi/2$
- Event quality filters

# Delayed Jet Background



**Cosmic**  
**Core & satellite collisions**  
**Beam halo**



## Validation:

- Beam halo:**

$t_{\text{jet}} < -3 \text{ ns}$  ( $|\phi_{\text{jet}}| < 0.2$  or  $\pi - 0.2$ , rej. satellite & cosmic)

- Core & satellite:**

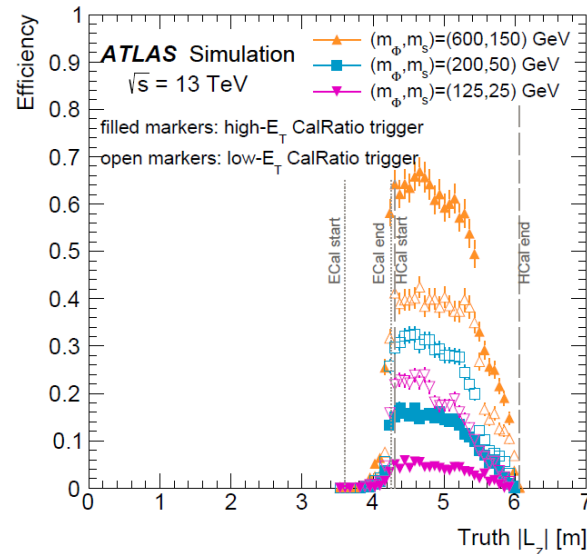
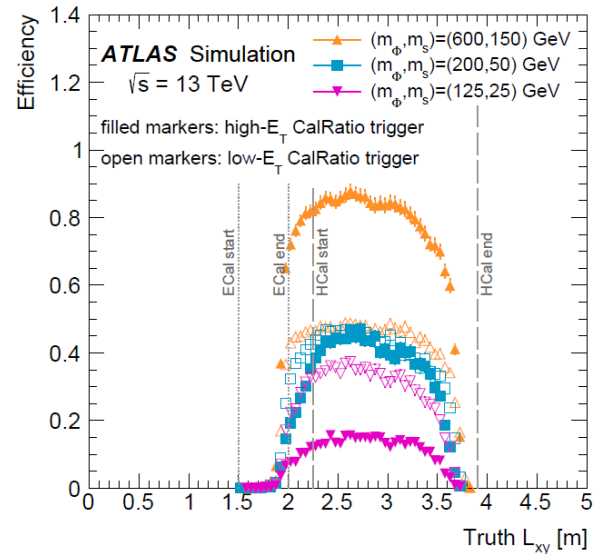
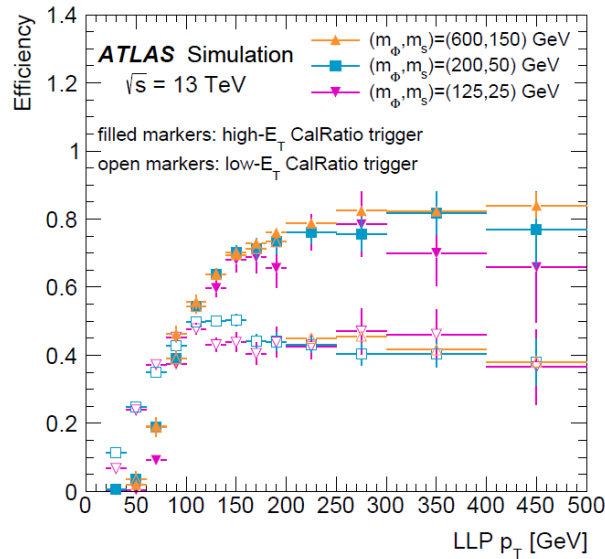
$t_{\text{jet}} < -1 \text{ ns}$ ,  
also  $p_T^{\text{miss}} < 300 \text{ GeV}$

- Cosmic:**

Invert HCAL quality filters

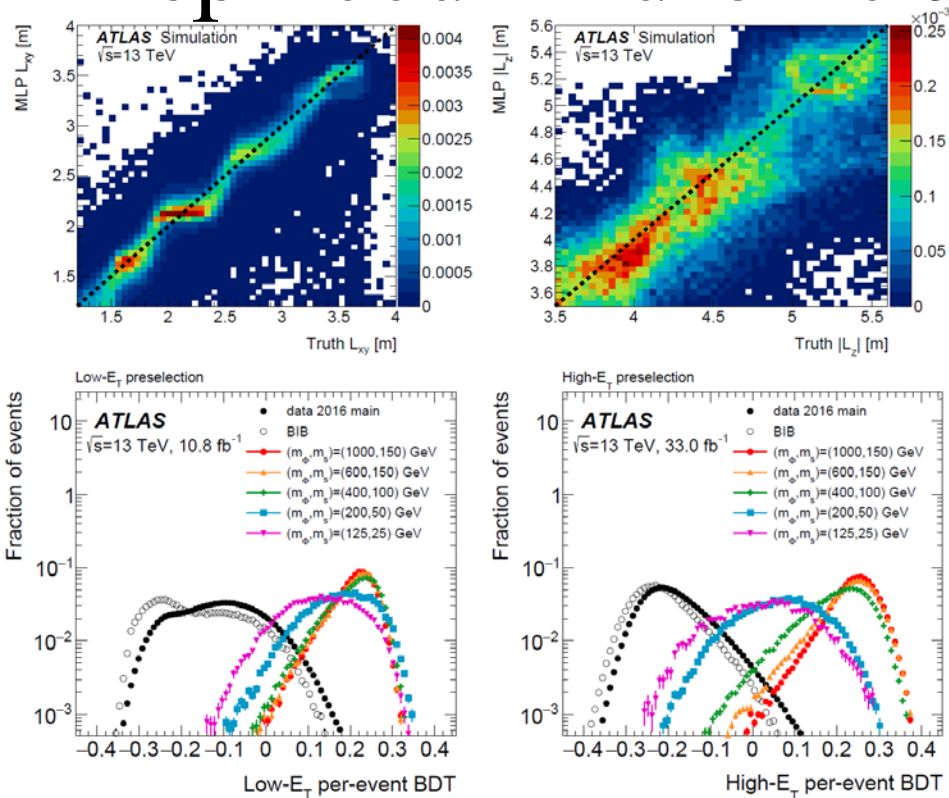
# Displaced Hadronic Jet Trigger

- L1 high- $E_T$ :
  - $E_T > 60$  GeV in  $0.2 \times 0.2$  region (ECAL + HCAL)
- L1 low- $E_T$ :
  - $E_T > 30$  GeV in HCAL
  - $E_T < 3$  GeV in ECAL ( $\Delta R < 0.2$ )
- HLT:
  - Jet  $E_T > 30$ ,  $|\eta| < 2.5$ ,  $\log_{10}(E_{\text{HCAL}}/E_{\text{ECAL}}) > 1.2$
  - no tracks w/  $p_T > 2$  GeV and  $\Delta R < 0.2$

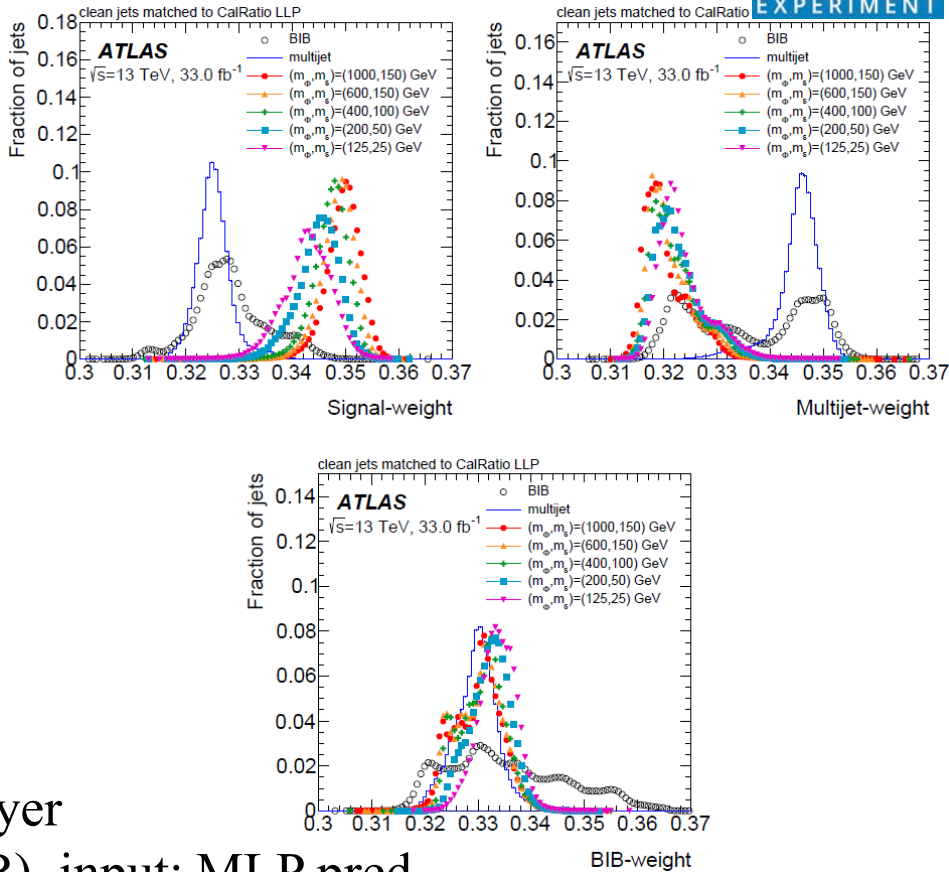


- BIB veto: 4 HCAL cells (same  $\phi$ , layer) w/ BIB-like timing  $\rightarrow$  send to BIB data stream
- Cosmic data stream: trigger on empty bunch crossings

# Displaced Hadronic Jet MLP & BDTs



- Top left: MLP (decay position), input: ECAL & HCAL energy fractions per layer
- Right: Jet BDT (signal vs. QCD vs. BIB), input: MLP pred.,  $\sum p_T(\text{trk})$ ,  $\max(p_T(\text{trk}))$ , jet radius, centroid, density & fraction in first HCAL layer of highest- $p_T$  cluster & z and xy dist. to centroid,  $p_T$ , timing
- Bottom left: Event BDT, input: highest 2 signal-weight jets & BIB-weight jets,  $H_T^{\text{miss}}/H_T$ ,  $\Delta R(j_1, j_2)$



# Displaced Hadronic Jet Details

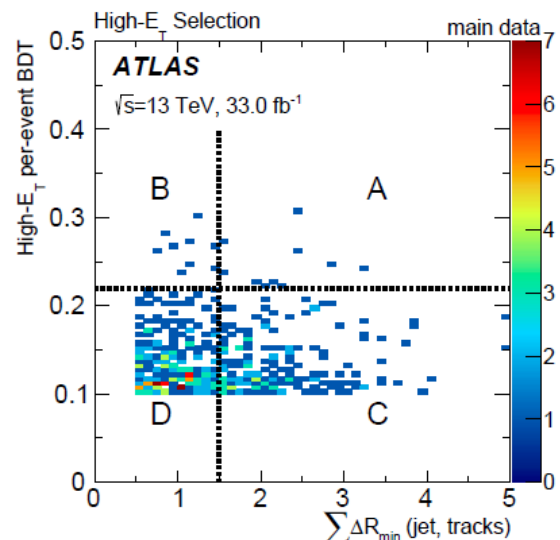
## High- $E_T$ [Low- $E_T$ ] Selection

- PV from  $\geq 2$  trk w/  $p_T > 400$  MeV
- $N_{\text{jet}} \geq 2$  ( $p_T > 40$  GeV,  $|\eta| < 2.5$ ),  
 $\log_{10}(E_{\text{HCAL}}/E_{\text{ECAL}}) > 1.2$
- $\sum_{\text{jets}} \Delta R_{\text{min}}(\text{jet, closest track}) > 0.5$ 
  - $p_T(\text{trk}) > 2$  GeV, from PV
- High- $E_T$  [Low- $E_T$ ] Event BDT  $> 0.1$
- Trigger matching ( $\geq 1$  jet)
- $-3 < t_{\text{jet}} < 15$  ns
- $\sum_{j_1, j_2} \log_{10}(E_{\text{HCAL}}/E_{\text{ECAL}}) > 1.0$  [2.5]
- $H_T^{\text{miss}}/H_T < 0.6$  [0.0]
- $p_T(j_1) > 160$  [80] GeV
- $p_T(j_2) > 100$  [60] GeV

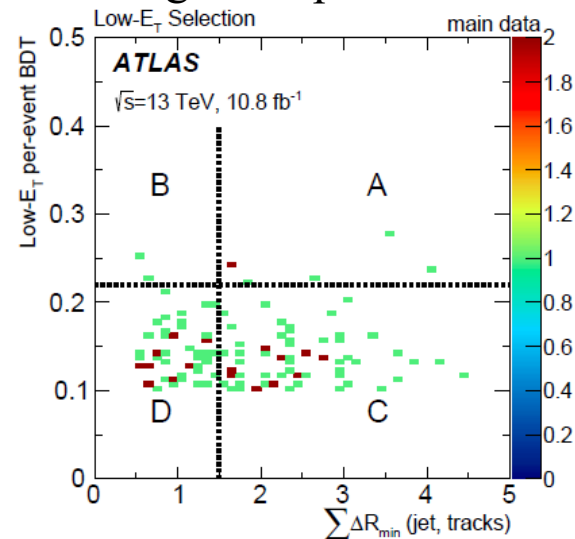
Preselection

Cleaning

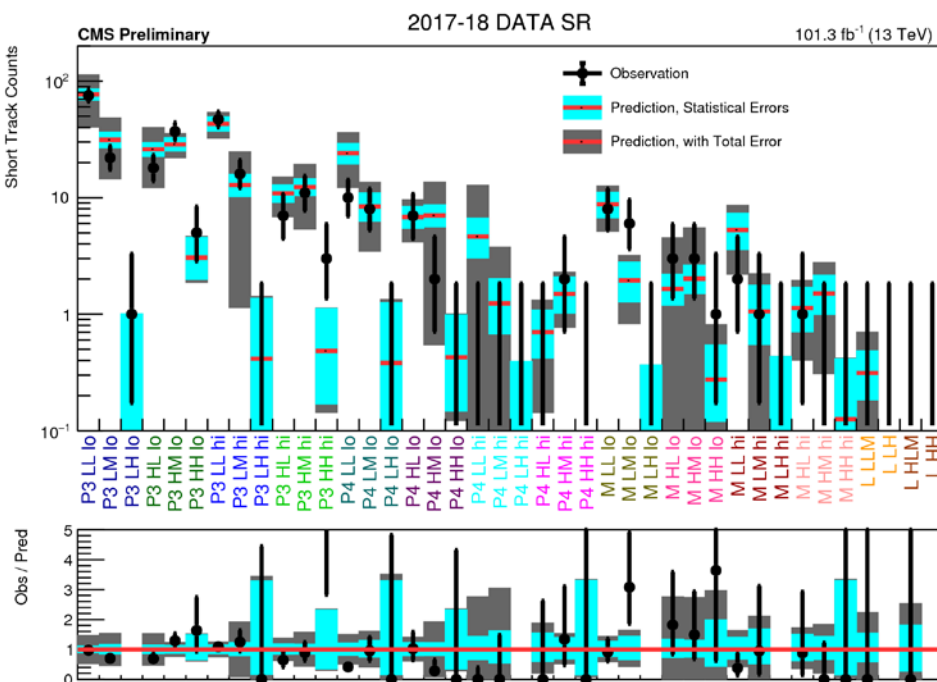
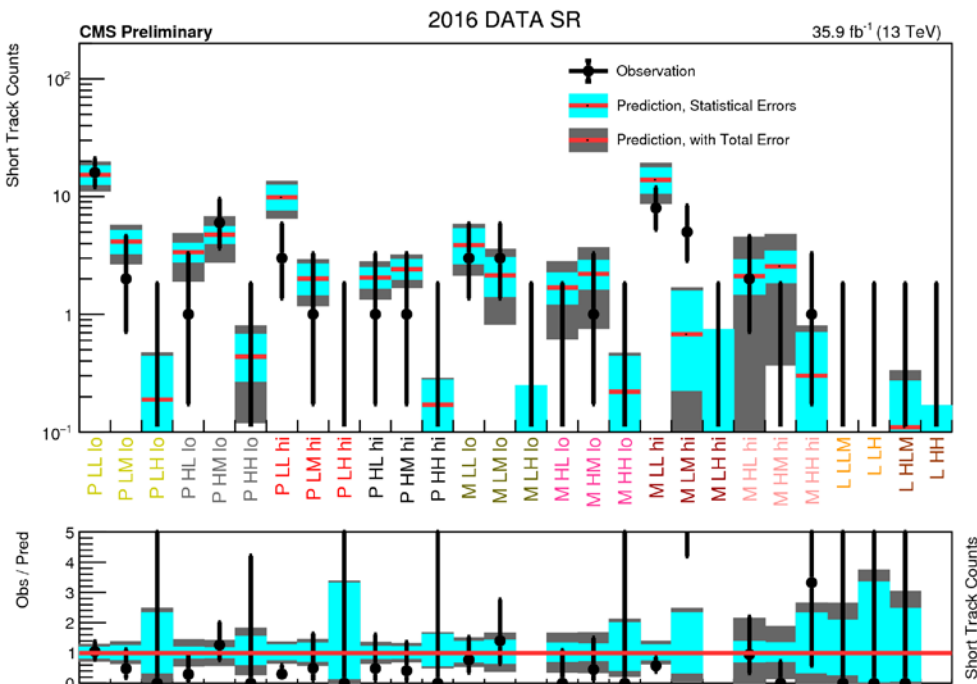
Final selection



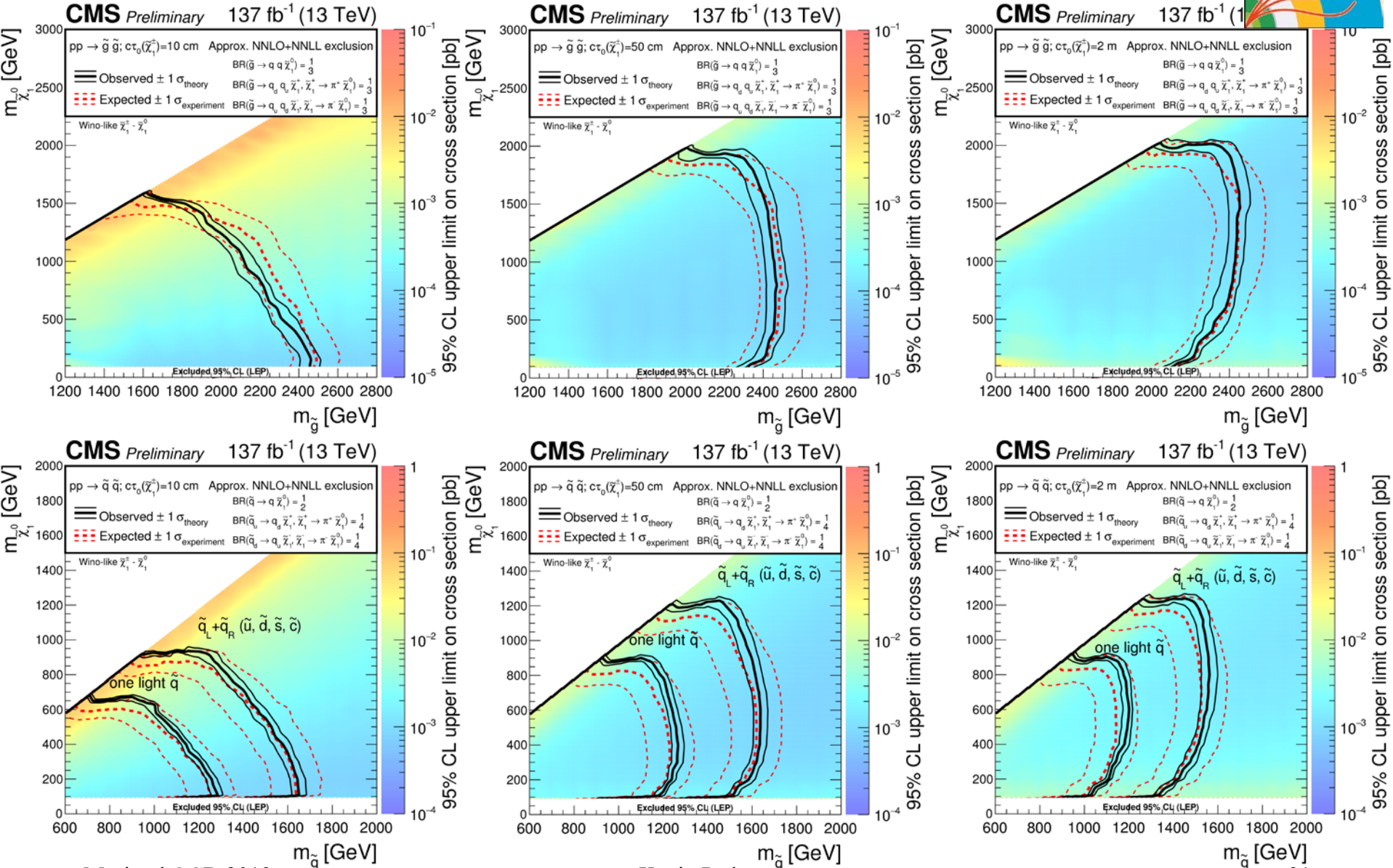
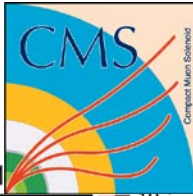
## Background predictions



# Disappearing Track Background



# Disappearing Track Limits



# Displaced Vertex & Muon Details



## Baseline Selection

- $p_T^{\text{miss}} > 180 \text{ GeV}$  XOR  $p_T^\mu > 60 \text{ GeV}, |\eta| < 2.5$  Trigger
- $N_\mu \geq 1$  ( $p_T > 25 \text{ GeV}, |\eta| < 2.5$ )
  - pass ID req. and vetoes
- $N_{\text{DV}} \geq 1$  ( $n_{\text{trk}} \geq 3, m_{\text{DV}} > 20 \text{ GeV}$ )
- PV w/  $\geq 2$  trk,  $|z_{\text{PV}}| < 200 \text{ mm}$

## DV Selection

- $r_{\text{DV}} < 300 \text{ mm}$
- $z_{\text{DV}} < 500 \text{ mm}$
- $\chi^2/\text{ndf} < 5$
- $\min(|\vec{r}_{\text{DV}} - \vec{r}_{\text{PV}}|) > 4 \text{ mm}$
- Material map veto

## Muon Selection

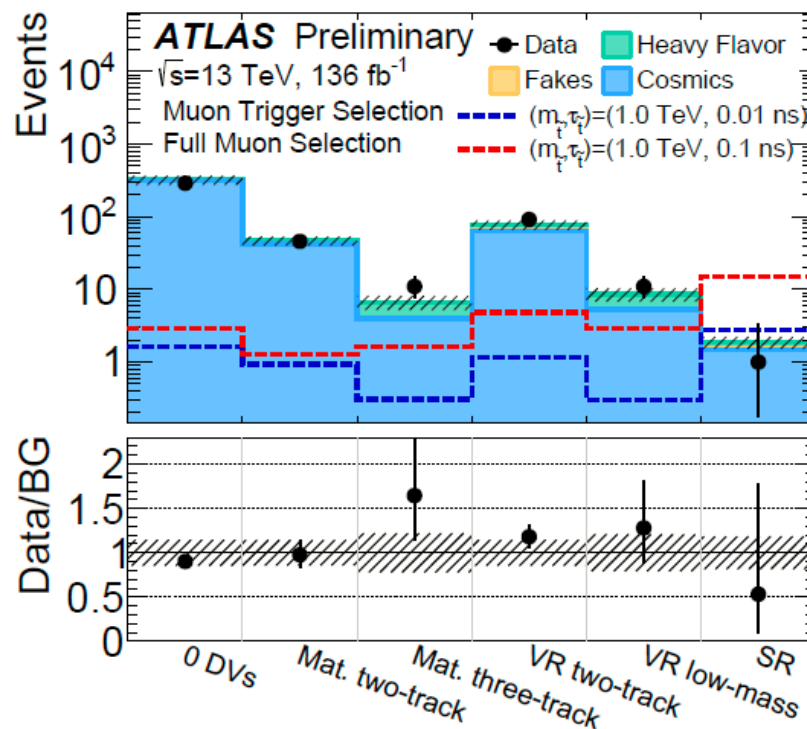
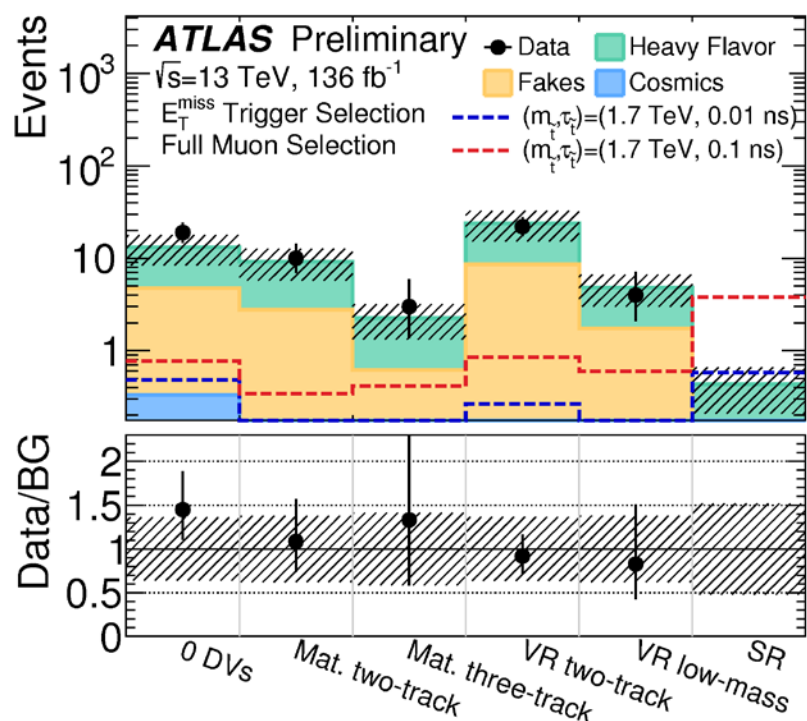
- $2 < |d_0| < 300 \text{ mm}$
- $|z_0| < 500 \text{ mm}$
- Veto  $|\eta_\mu + \eta_{\text{seg.}}| < 0.05$  and  $|\Delta\phi(\mu, \text{seg.}) - \pi| < 0.22$  Cosmic
- Veto back-to-back in  $\eta, \phi$  w/ un-instrumented MS region Cosmic
- $I_{\text{trk}}, I_{\text{calo}} < 0.06 p_T^\mu$  Heavy flavor
- $N_{\text{seg.}} > 3, \chi^2/\text{ndf} < 8$  Fakes

# Displaced Vertex & Muon Bkg.

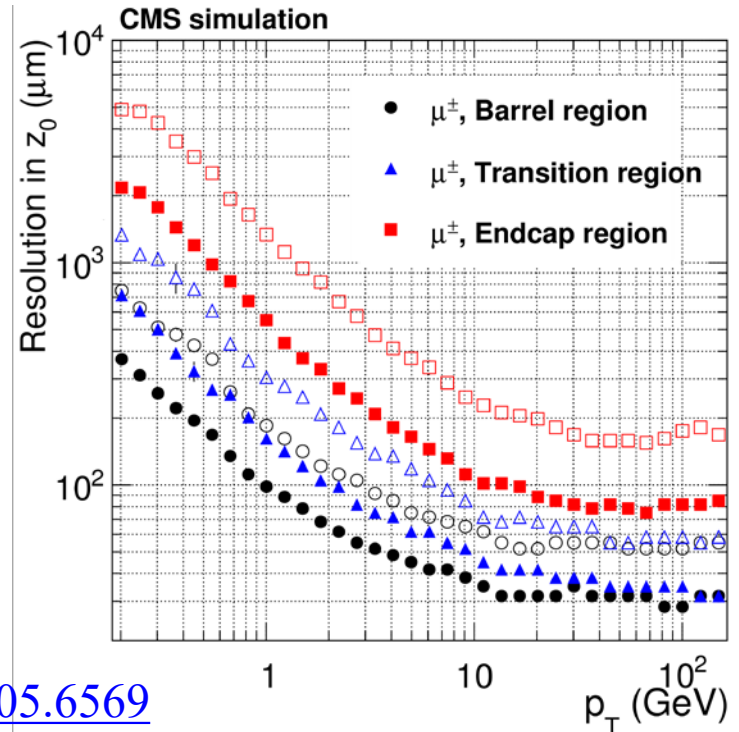
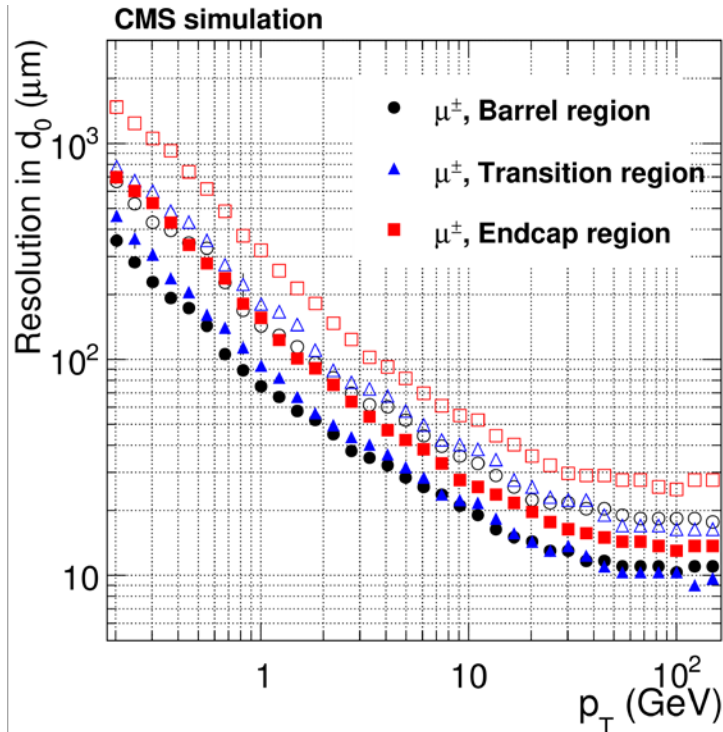
Background uncertainty:

- DV CR sub-regions
- Varying muon  $d_0$  selections

Background source ( $i$ )	Transfer factor ( $f_i$ )
Cosmic-ray muons	$(4.0 \pm 0.2 \text{ (stat.)} \pm 0.5 \text{ (syst.)}) \times 10^{-3}$
Fake muons	$(1.0 \pm 0.3 \text{ (stat.)} \pm 0.5 \text{ (syst.)}) \times 10^{-2}$
Heavy-flavor muons	$(9.1 \pm 1.6 \text{ (stat.)} \pm 4.0 \text{ (syst.)}) \times 10^{-2}$



# CMS Track Resolutions



[arXiv:1405.6569](https://arxiv.org/abs/1405.6569)

## Resolutions

( $1 < p_T < 10$  GeV,  $|\eta| < 1.4$ )

- $p_T$ : 1.5%
- transverse: 25–90  $\mu\text{m}$
- longitudinal: 45–150  $\mu\text{m}$