LLP Experimental Overview

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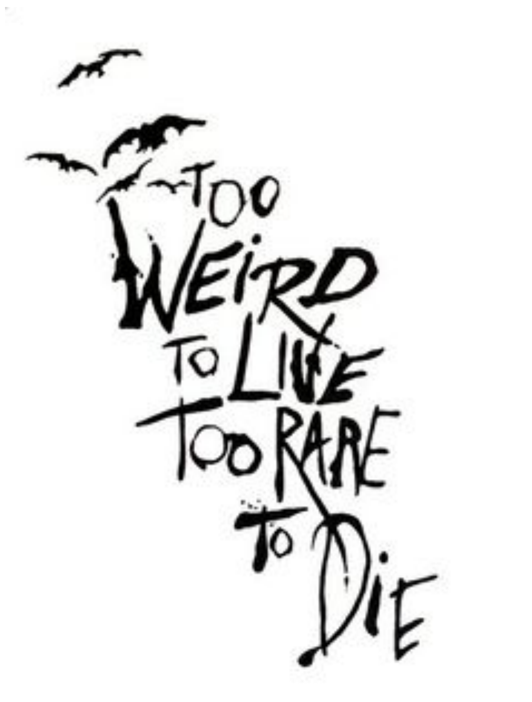
11/20/19

Overview

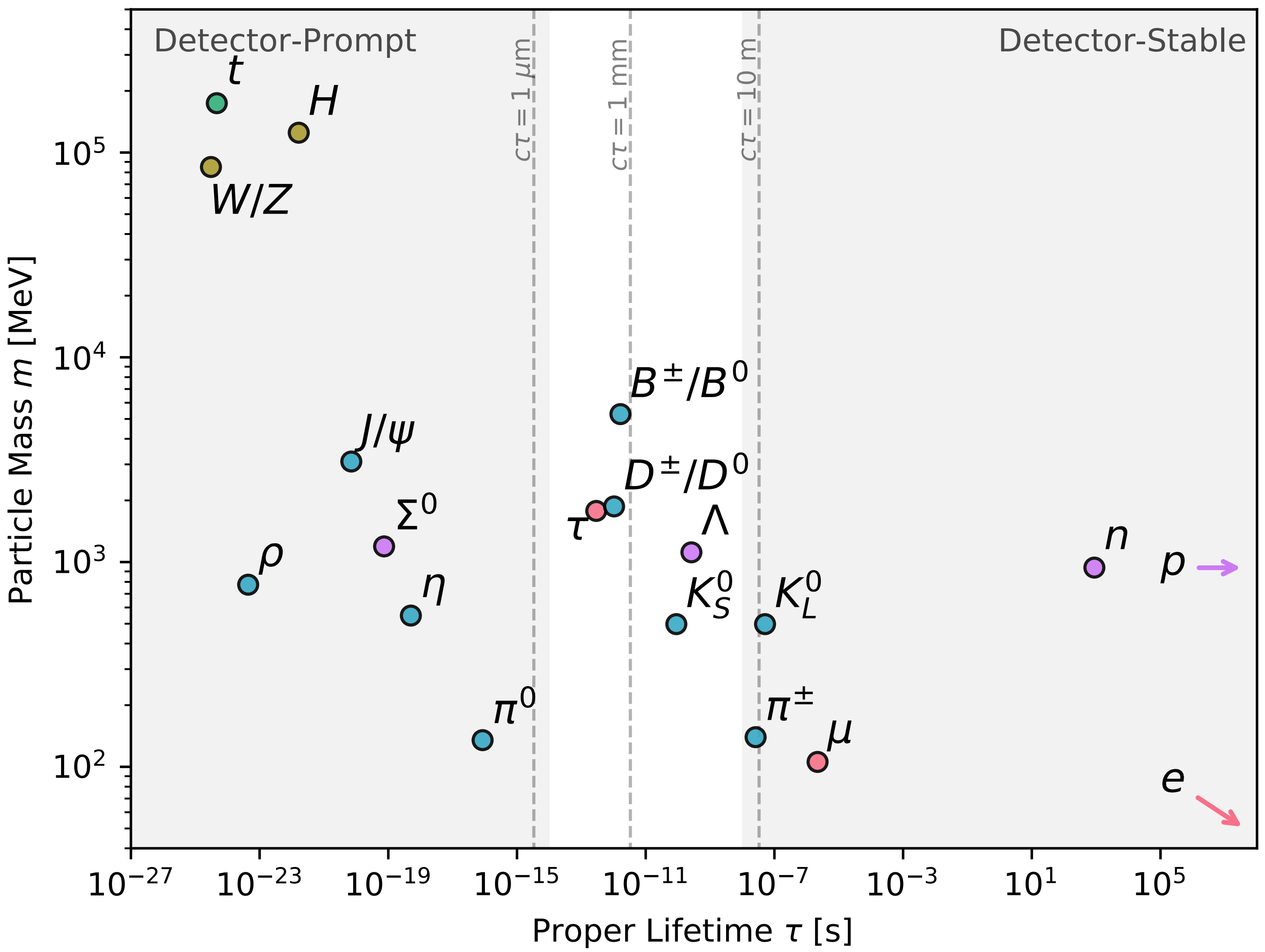
- Introduction
- Search results
  - Indirect detection
  - Direct detection
- Summary
- Future prospects
- Conclusion



"There he goes. One of God's own prototypes. A high-powered mutant of some kind never even considered for mass production. Too weird to live, and too rare to die."
-Hunter S. Thompson

Introduction

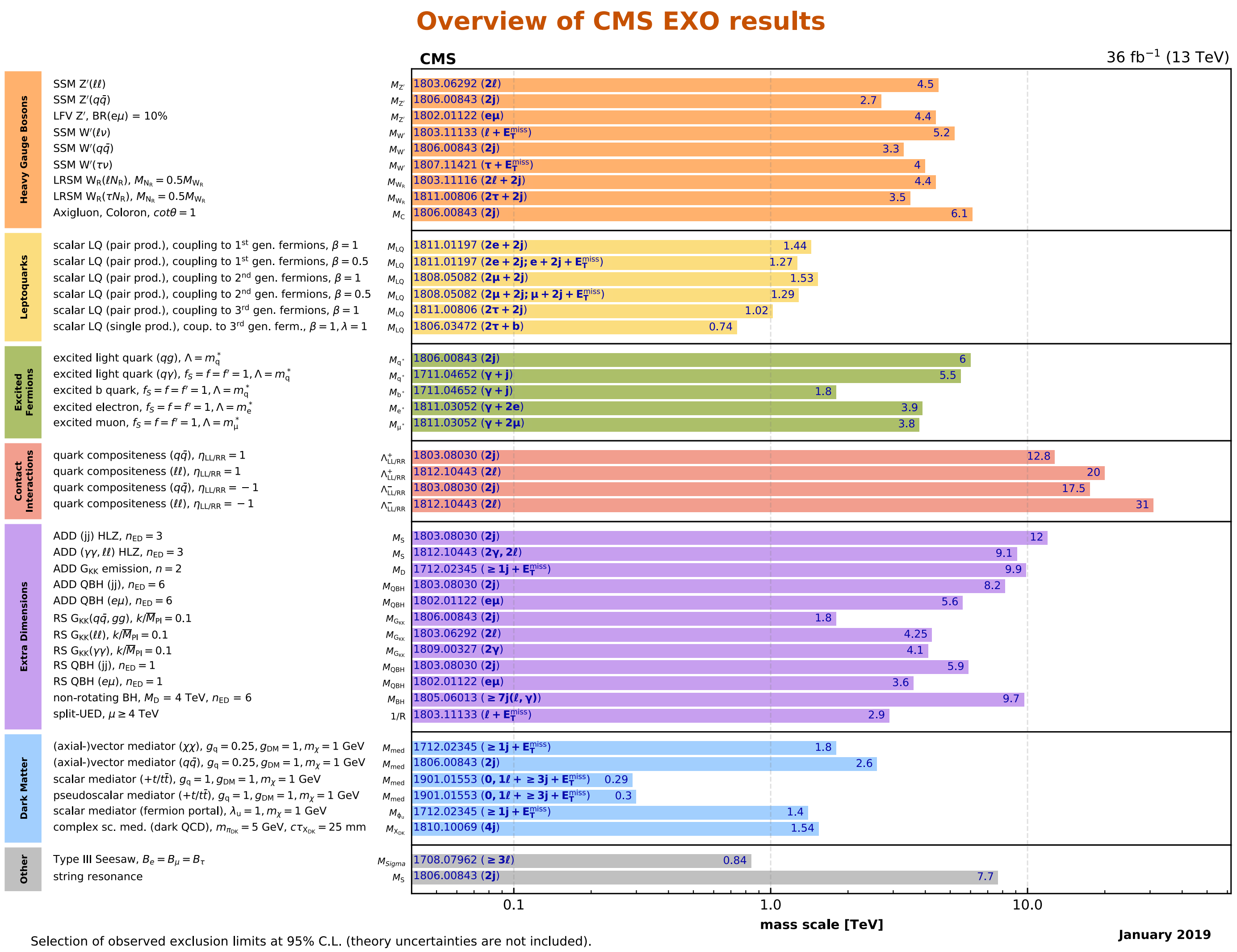
Experimentalist's motivation for LLPs searches

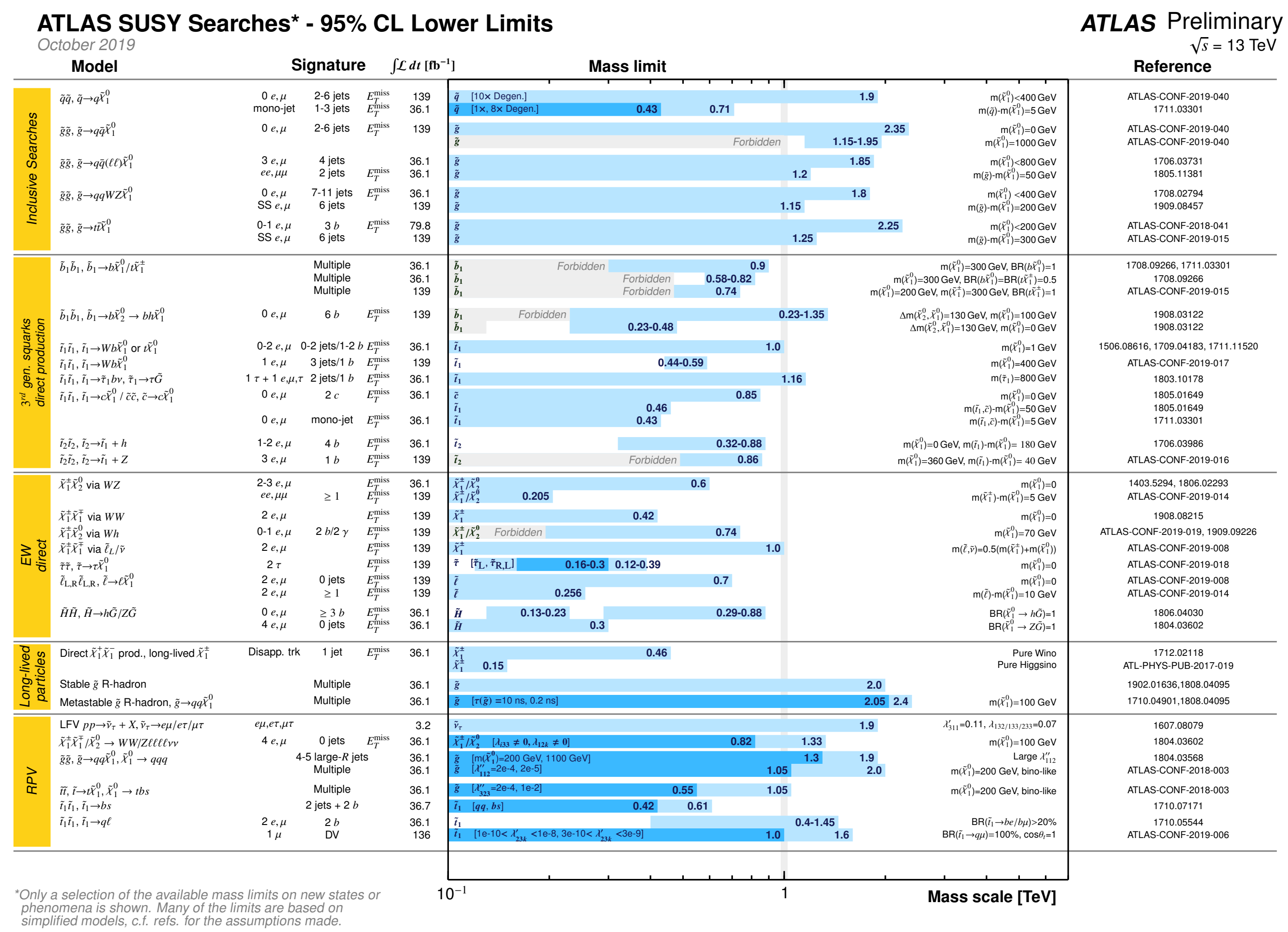


[1810.12602]

Introduction

Experimentalist's motivation for LLPs searches

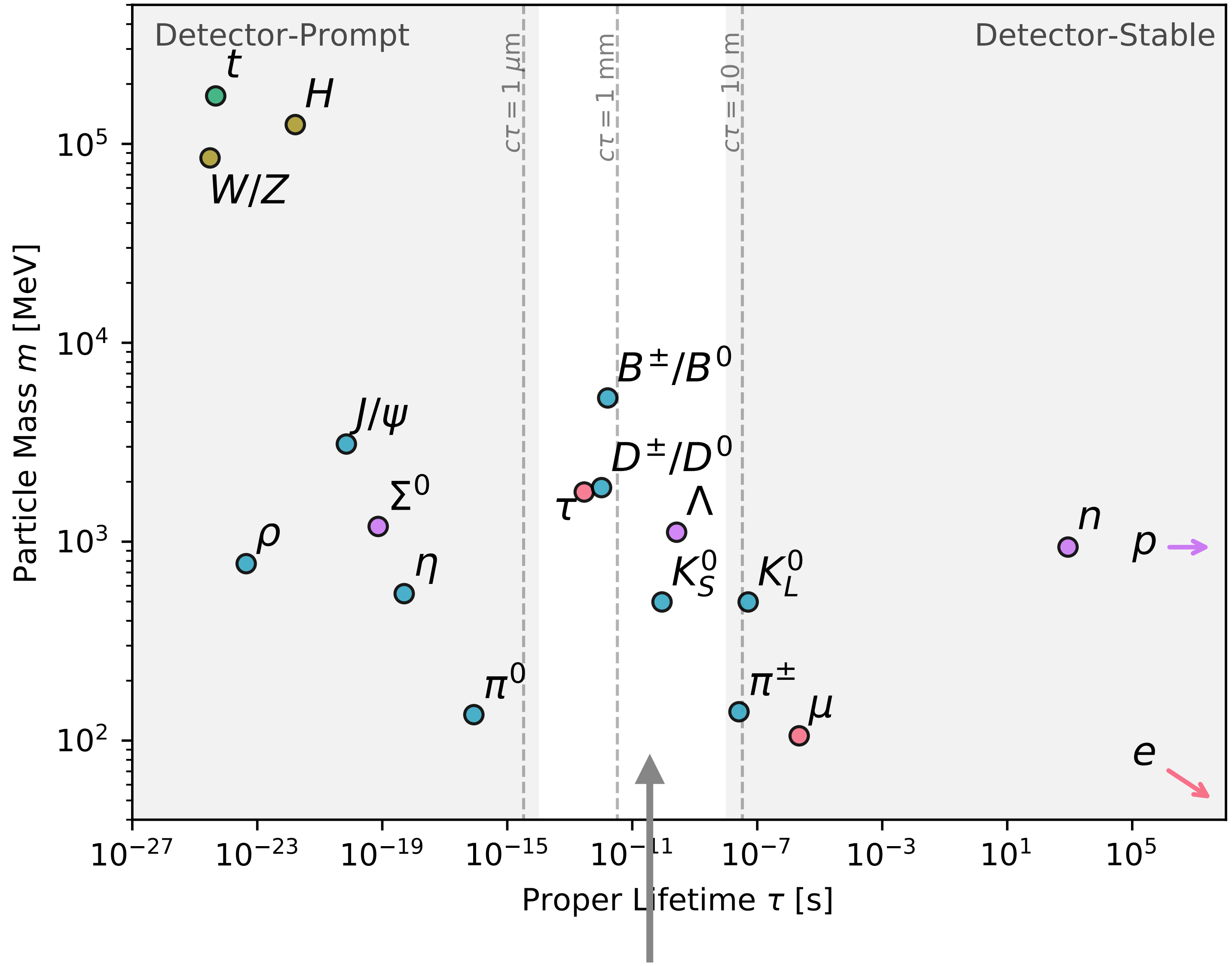




Very extensive program of searches for prompt and stable particles

Introduction

Experimentalist's motivation for LLPs searches

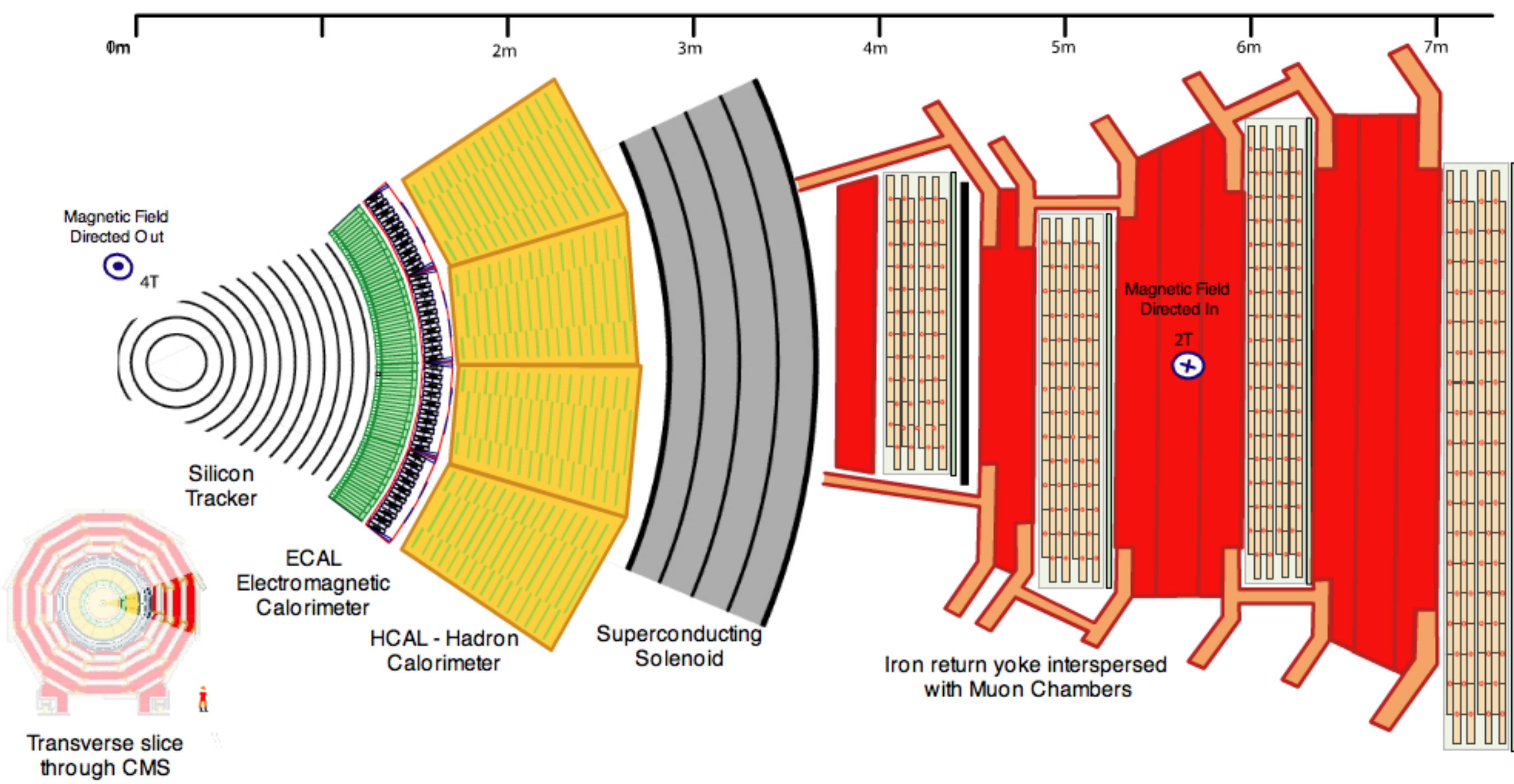


[1810.12602]

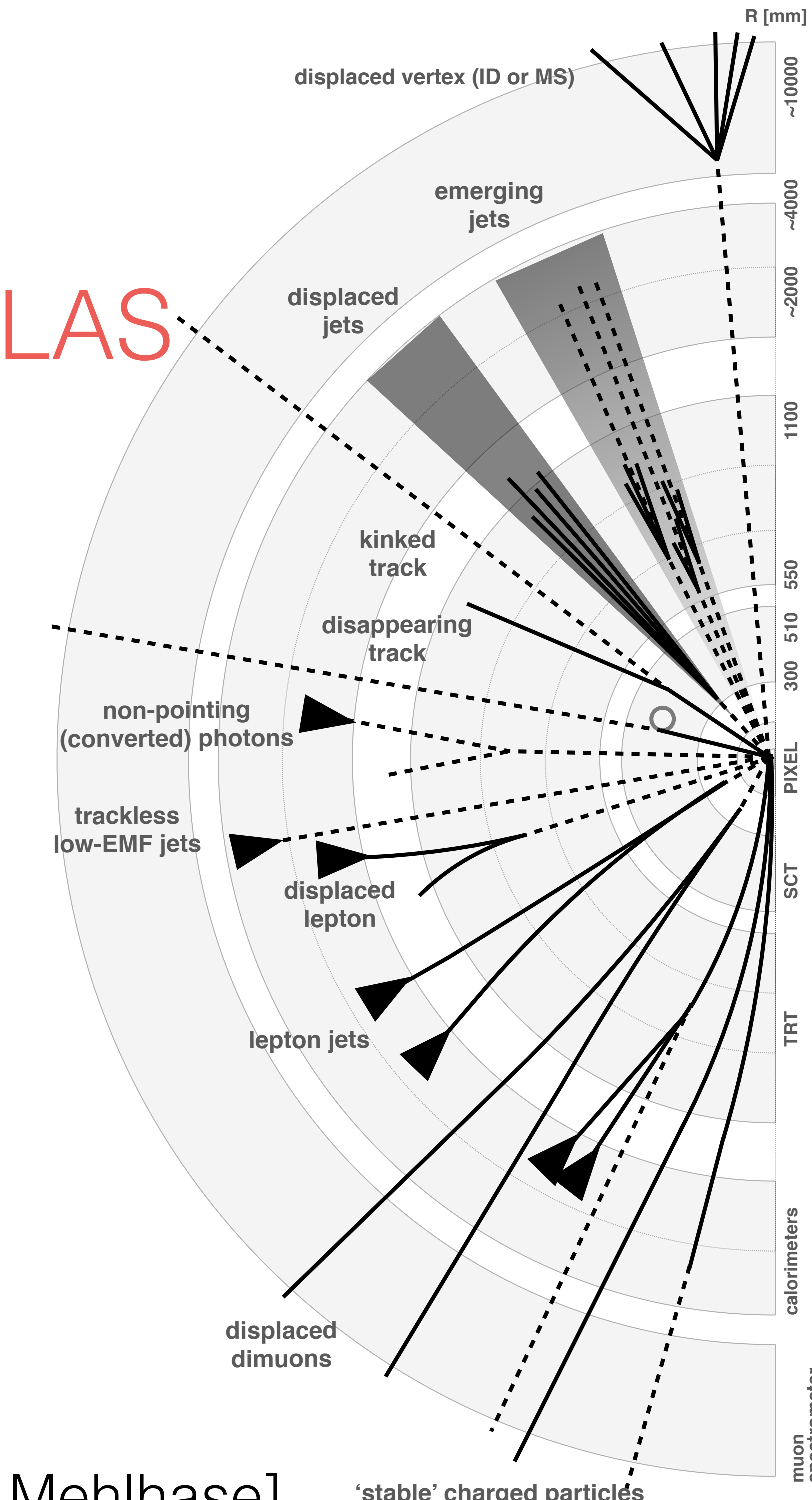
Maybe new physics is hiding here?

Introduction

CMS



ATLAS

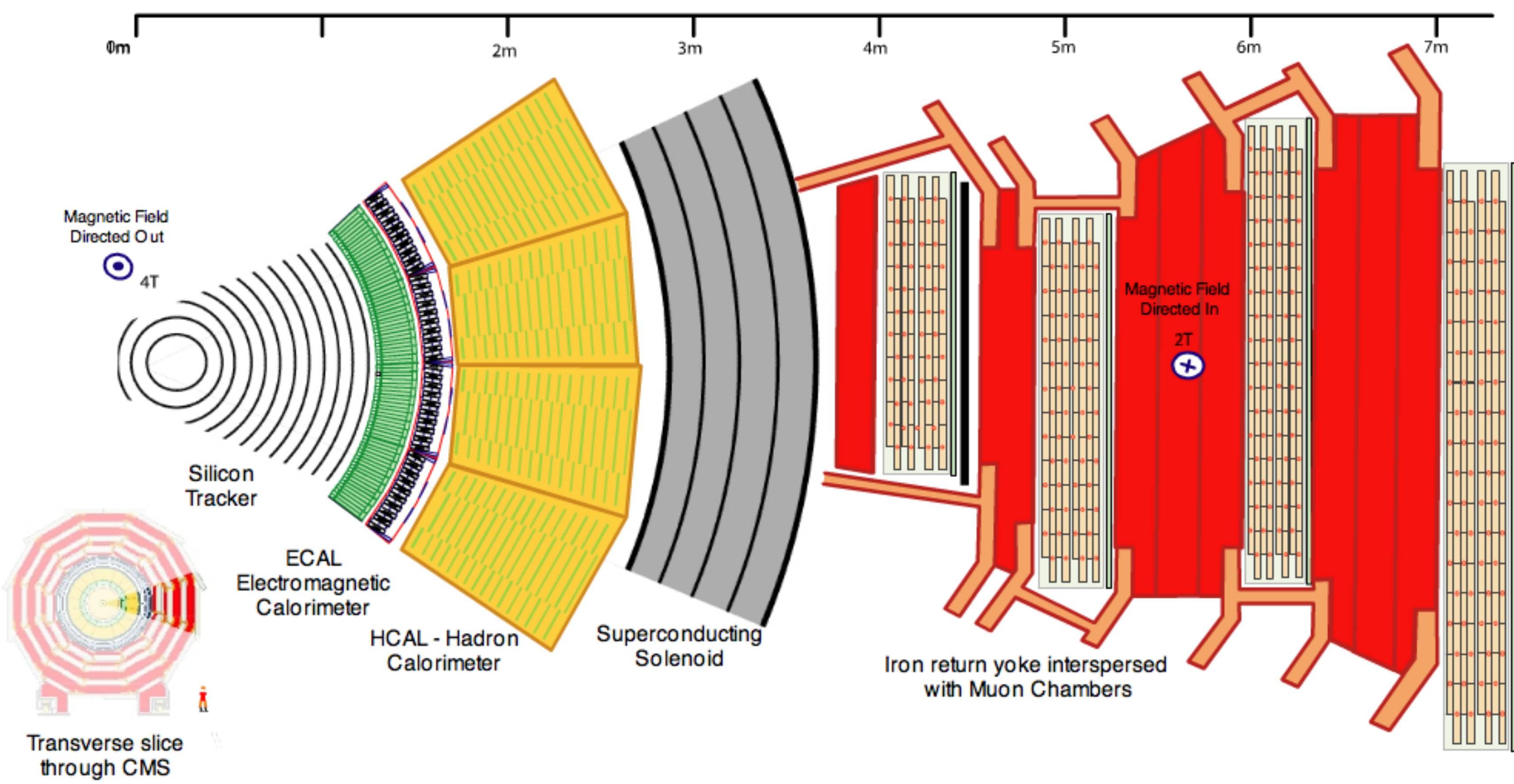


similar long-lived signatures investigated by CMS

[Sascha Mehlhase]

Introduction

CMS



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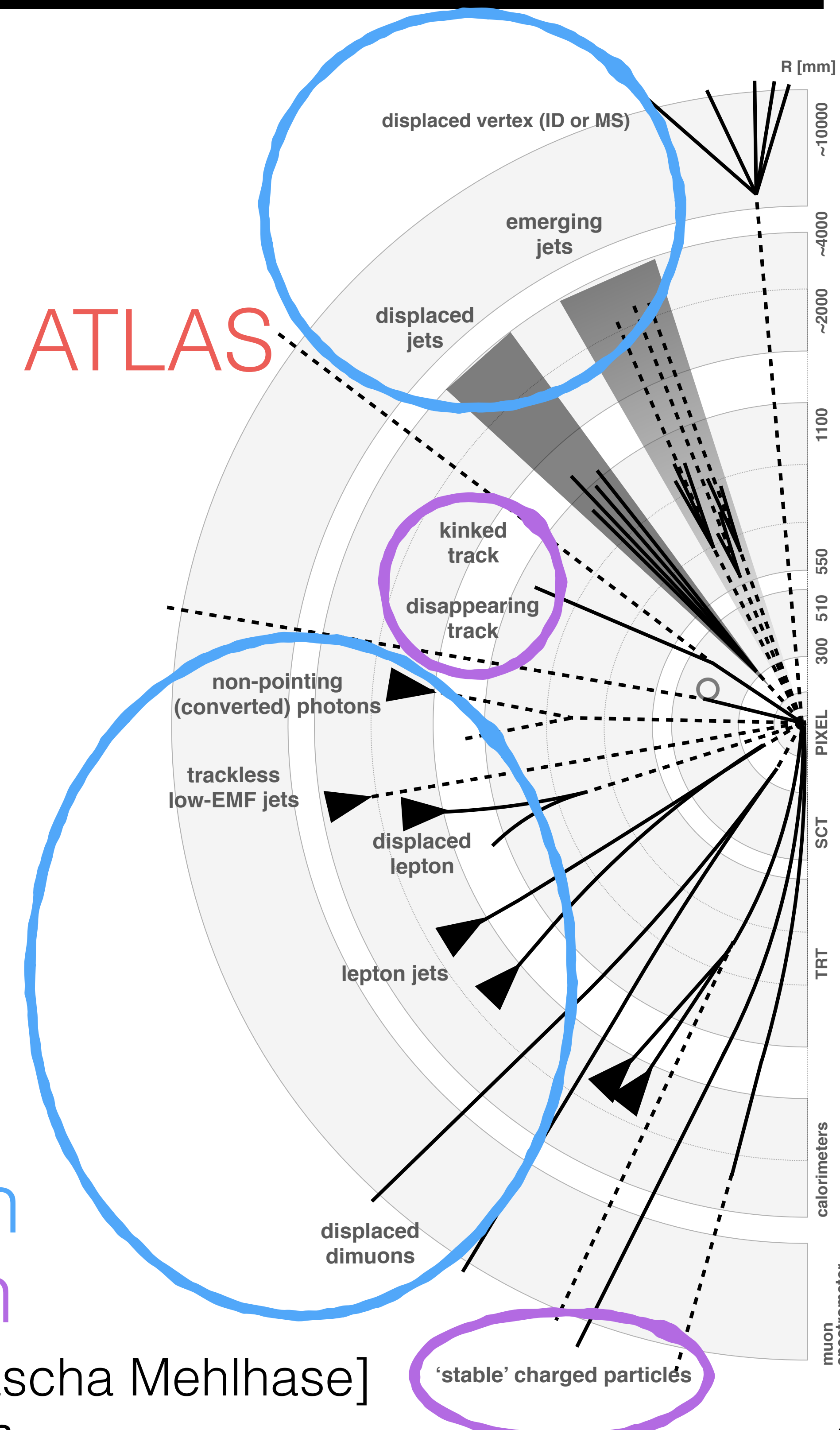


similar long-lived signatures investigated by CMS

Indirect Detection
Direct Detection

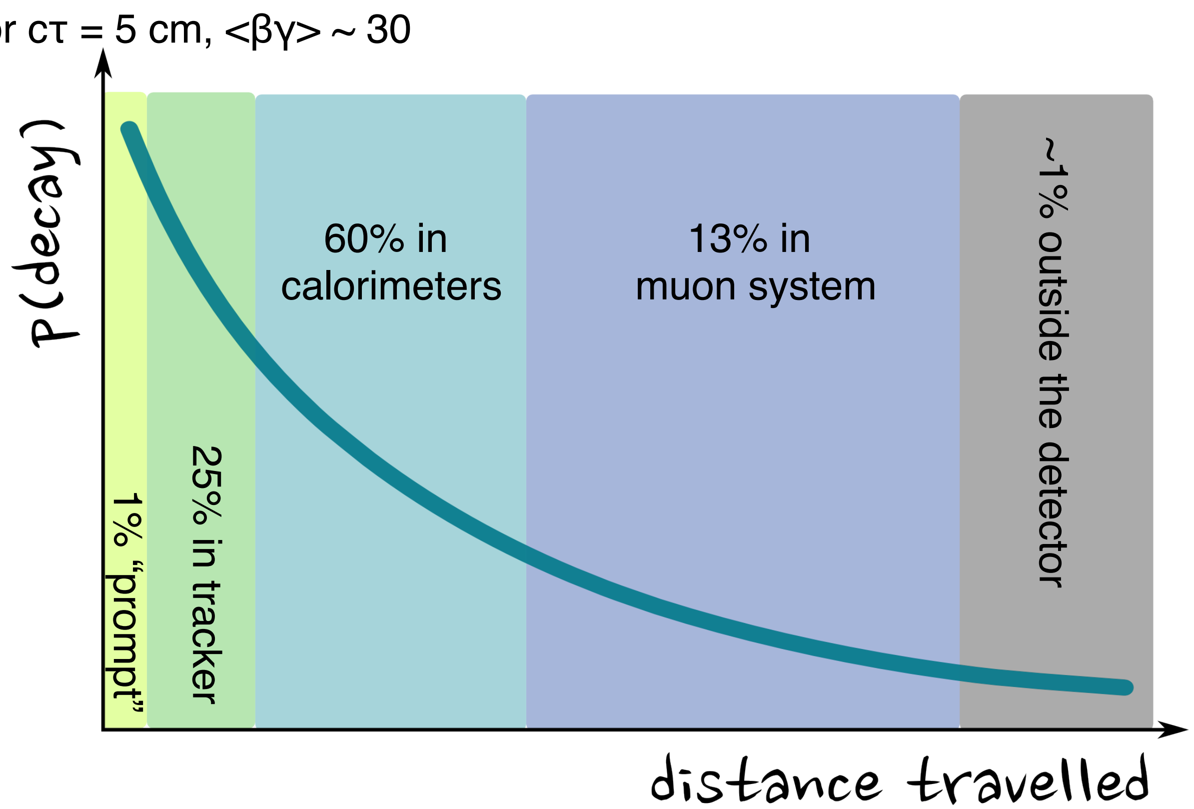
[Sascha Mehlhase]

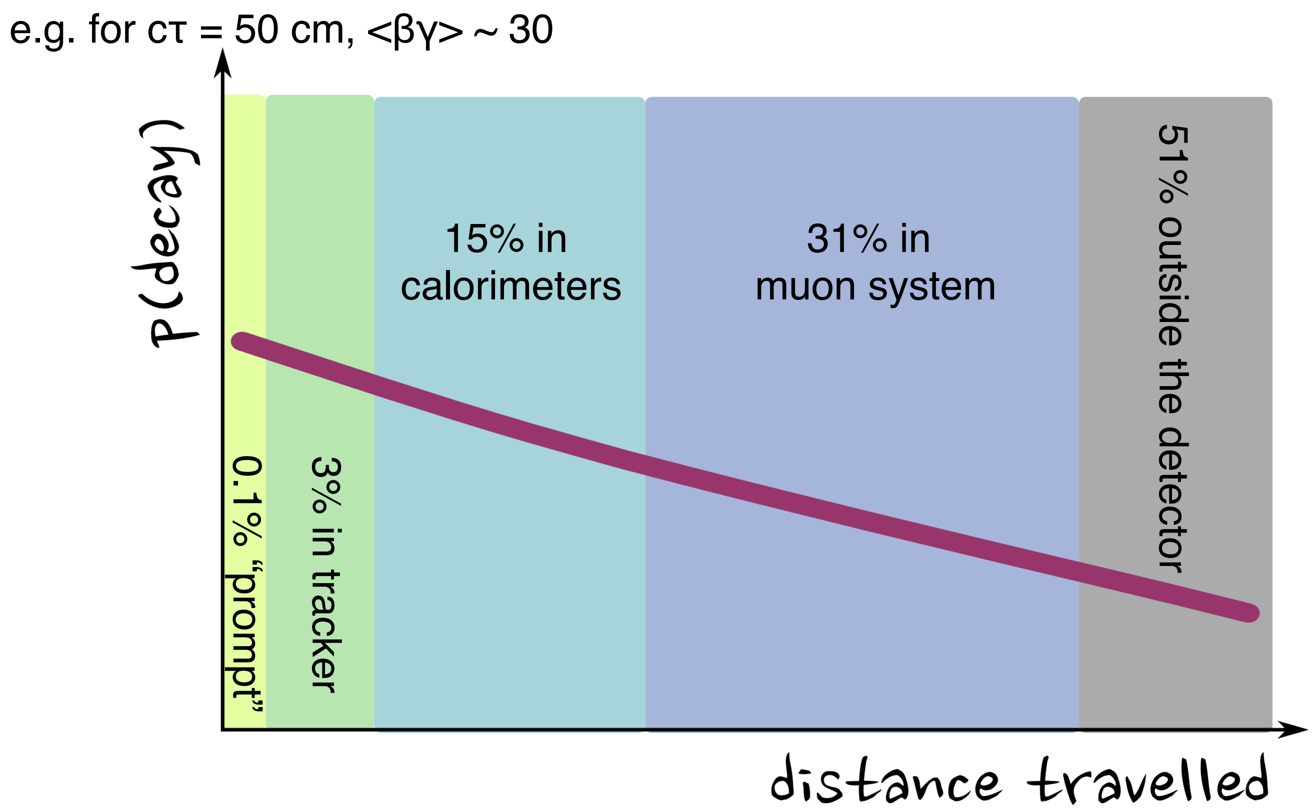
Introduction

- Long-lived particles often have striking signatures with no irreducible SM backgrounds
  - For ~zero background searches, sensitivity scales with L_{int}
- Backgrounds are generally from non-collision sources or instrumental effects (typically quite rare)
  - Monte Carlo not appropriate
  - Data-driven techniques required
- Triggering and reconstruction of unconventional signatures can be highly non-trivial

Decay Position

For a given proper lifetime, LLP decays occur in variety of detector systems



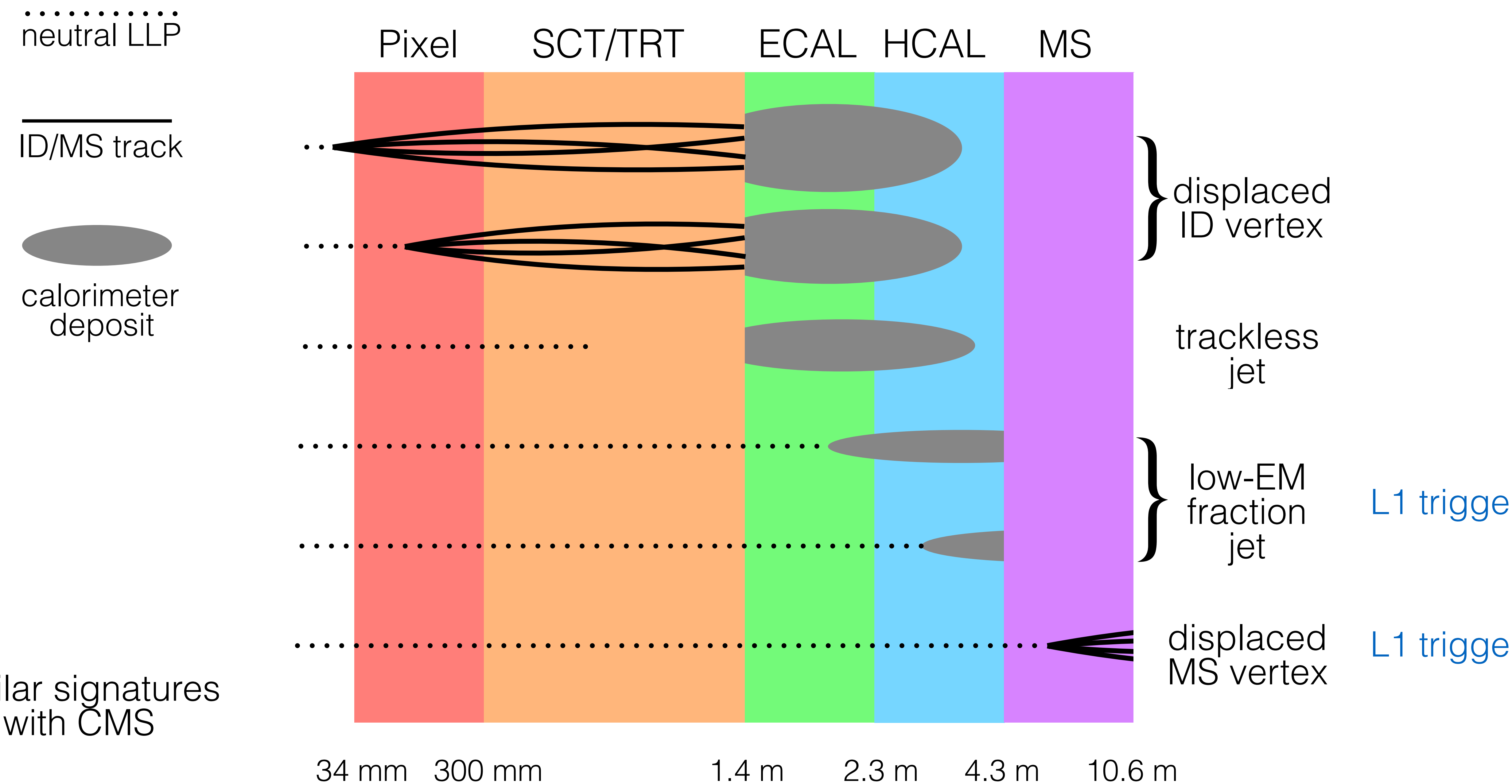


[Heather Russell]

Detector Signatures

Each subsystem has a different signature

Flavors of displaced jets:



similar signatures with CMS

Recent LLP Results

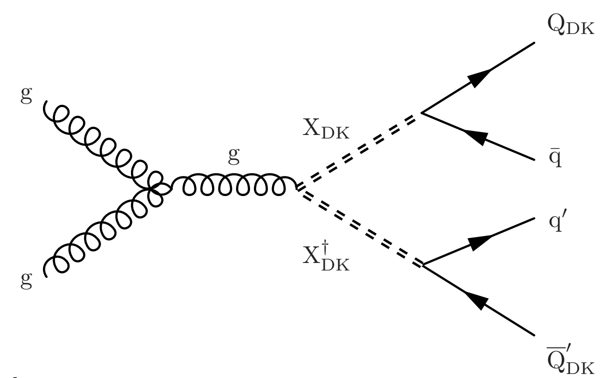
Date	Experiment	Reference	LLP	Signature
10/19	LHCb	1910.06926	dark photon	dimuon DV
9/19	CMS	1909.06166	neutralino	non-pointing photon (elliptical shower and delayed arrival in ECAL)
9/19	ATLAS	1909.01246	dark photon	displaced lepton jet
7/19	ATLAS	1907.10037	gluino/squark R-hadron	dilepton ID DV
6/19	CMS	1906.06441	gluino R-hadron	displaced jet (delayed arrival in ECAL)
5/19	ATLAS	1905.10130	monopole/multi-charged particle	high-ionization (TRT, ECal)
5/19	ATLAS	1905.09787	heavy neutral lepton	dilepton ID DV
3/19	ATLAS	ATLAS-CONF-2019-006	stop R-hadrons	displaced jet (ID DV) + displaced muon
2/19	ATLAS	1902.03094	dark scalar	displaced jet (low EM-fraction)
2/19	ATLAS	1902.01636	gluino/squark R-hadron, chargino, stau	high-ionization (pixel) and delayed arrival (HCal, MS)
12/18	ATLAS	1812.03673	multi-charged particle	high-ionization (pixel, HCal, MS)
11/18	CMS	1811.07991	gluino/stop R-hadron	displaced jet (ID DV)
11/18	ATLAS	1811.07370	dark scalar, singlino	displaced jet (MS DV)
11/18	ATLAS	1811.02542	dark vector	Z(ll) + displaced jet (low EM-fraction)
10/18	CMS	1810.10069	dark pion	emerging jets
8/18	ATLAS	1808.06358	gluino R-hadron	high-ionization (pixel)
9/18	CMS	1808.03078	neutralino, gluino, stop R-hadron	displaced jet (2 ID DVs)
8/18	ATLAS	1808.03057	dark vector, neutralino	dimuon MS DV
6/18	ATLAS	1806.07355	dark scalar	V + displaced jet (b-tagging)
4/18	CMS	1804.07321	chargino	disappearing track

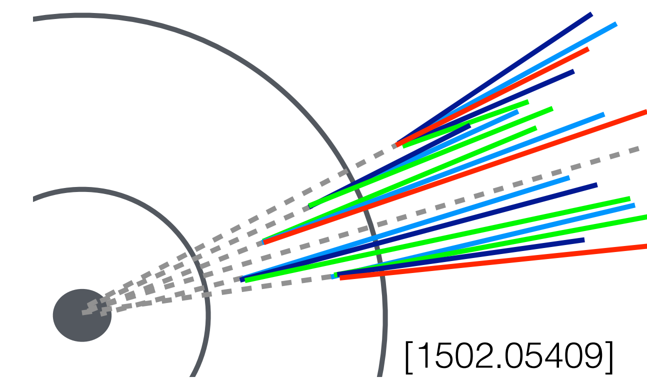
Indirect Detection

Emerging Jets

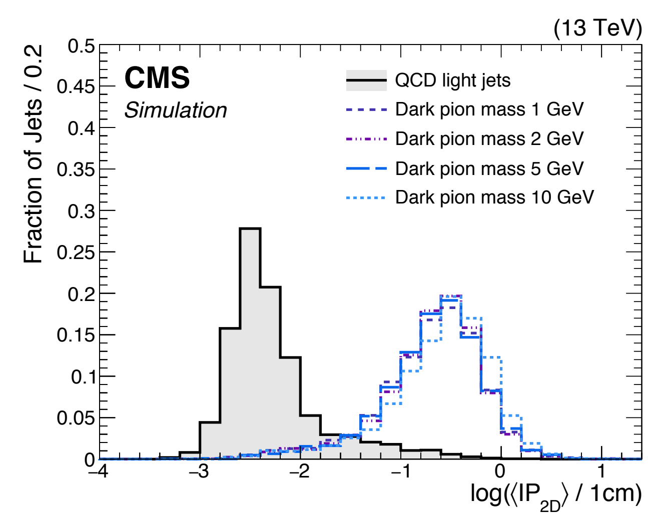
[1810.10069]

- Search for heavy mediator between SM and hidden sector with QCD-like confining force
- Dark quark showers and hadronizes in the hidden sector before gradually decaying back to the SM
  - Many displaced vertices (+ MET)
- Strategy
  - Conventional trigger: H_T > 900 GeV
  - Exploit large impact parameter of signal tracks
  - Define 8 sets of emerging jet tagging criteria
    - 7 SRs and 2 VRs (non-orthogonal)





[1502.05409]



$$\sqrt{\left[\frac{z^{PV}-z_0^{track}}{0.01\ \mathrm{cm}}\right]^2+\left[\frac{d_0}{\sigma_{d_0}}\right]^2} \qquad \frac{\sum_{\text{prompt tracks}} p_T}{\sum_{\text{all tracks}} p_T}$$

$z^{PV} - z_0^{track}$ → PU_{dz}; median(d_0) → $\langle IP_{2D}\rangle$

Criteria group	PU_{dz} (<) [cm]	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

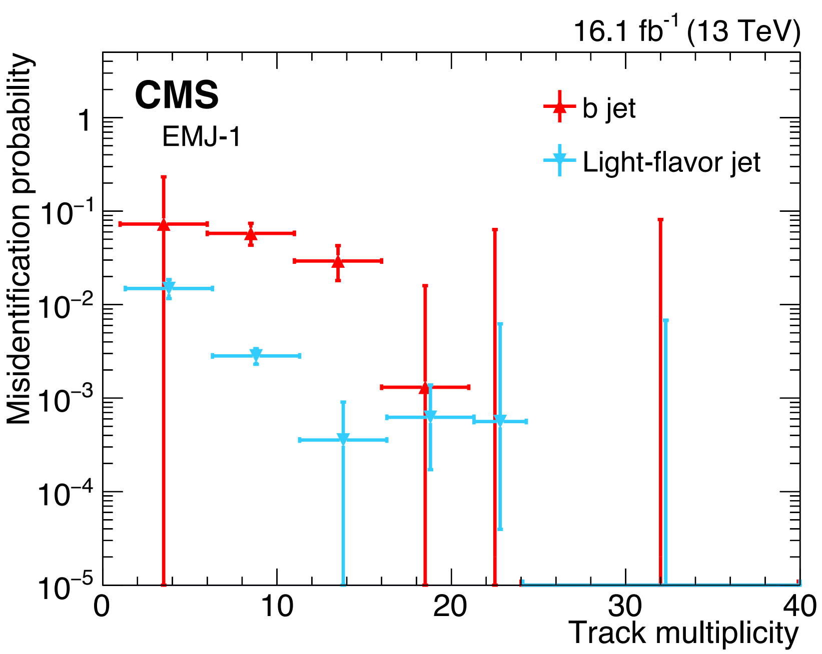
	Set number	H_T	$p_{T,1}$	$p_{T,2}$	$p_{T,3}$	$p_{T,4}$	p_T^{miss}	$n_{EMJ}(\geq)$	EMJ group	no. models
SRs	1	900	225	100	100	100	0	2	1	12
	2	900	225	100	100	100	0	2	2	2
	3	900	225	100	100	100	200	1	3	96
	4	1100	275	250	150	150	0	2	1	49
	5	1000	250	150	100	100	0	2	4	41
	6	1000	250	150	100	100	0	2	5	33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

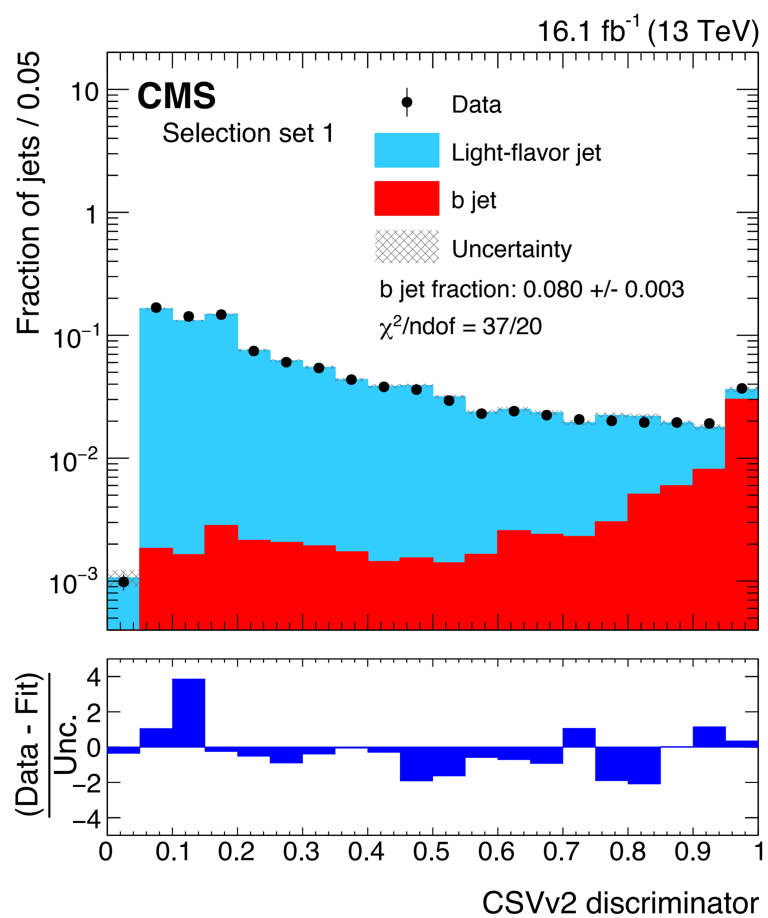
Emerging Jets

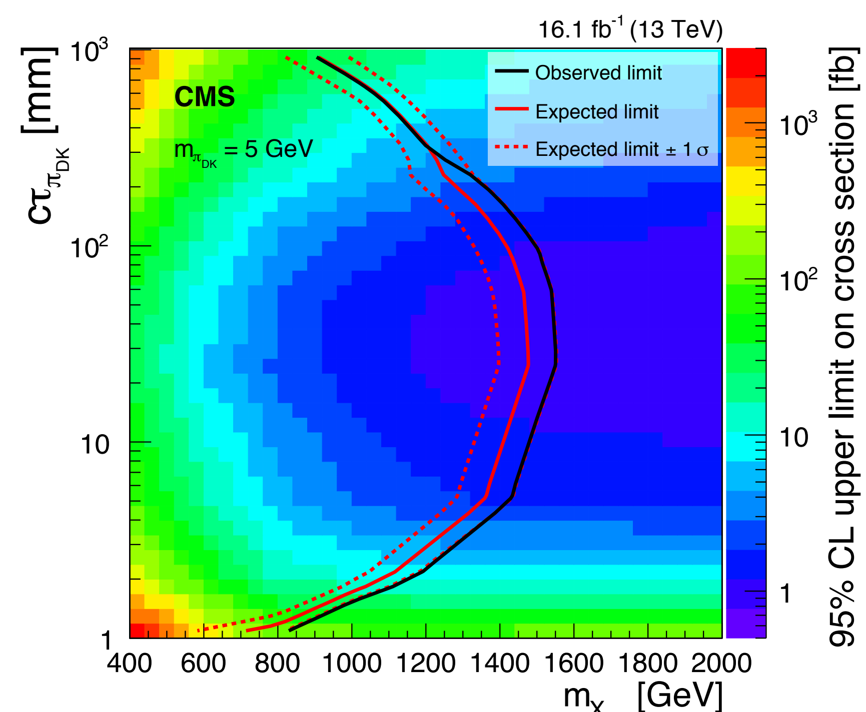
[1810.10069]

- Dominant background: QCD multi-jet events with long-lived B mesons or track mis-measurement
  - Separate light- and heavy-flavor enhanced γ+jet samples used to determine mistag rates $\varepsilon_{\text{light}}(N_{\text{track}})$ and $\varepsilon_b(N_{\text{track}})$ for each emerging jet definition
  - CR defined for each SR/VR (same requirements, except N-1 emerging jet tags)
    - Heavy flavor fraction f_b determined with fit to b-tag discriminant templates
    - Apply mistag rates to jets in CR: $\varepsilon_f = \varepsilon_b f_b + \varepsilon_{\text{light}}(1 - f_b)$

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



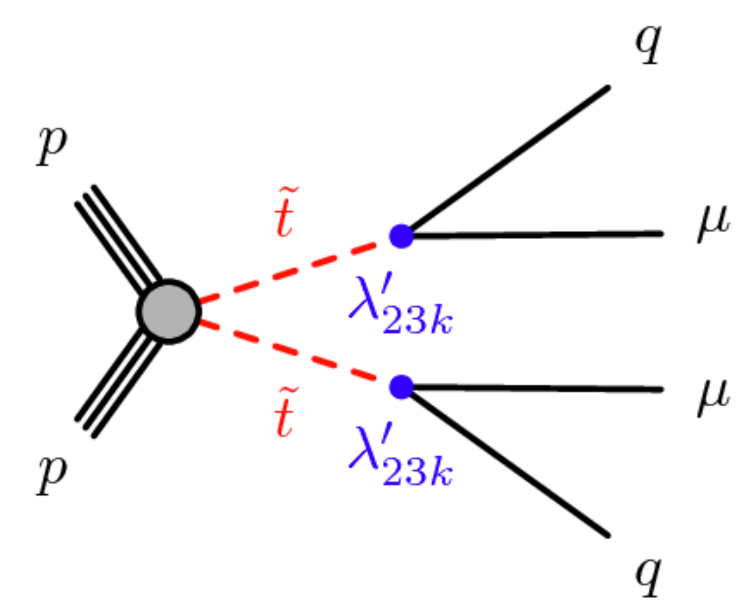




[ATLAS-CONF-2019-006]

Displaced Jet (ID DV)

- Search for RPV stop → qμ decays
  - First LLP result to analyze 2018 data
- Selects events with displaced ID vertex and displaced muon (ID+MS)
  - Conventional triggers: μ and calorimeter-based MET

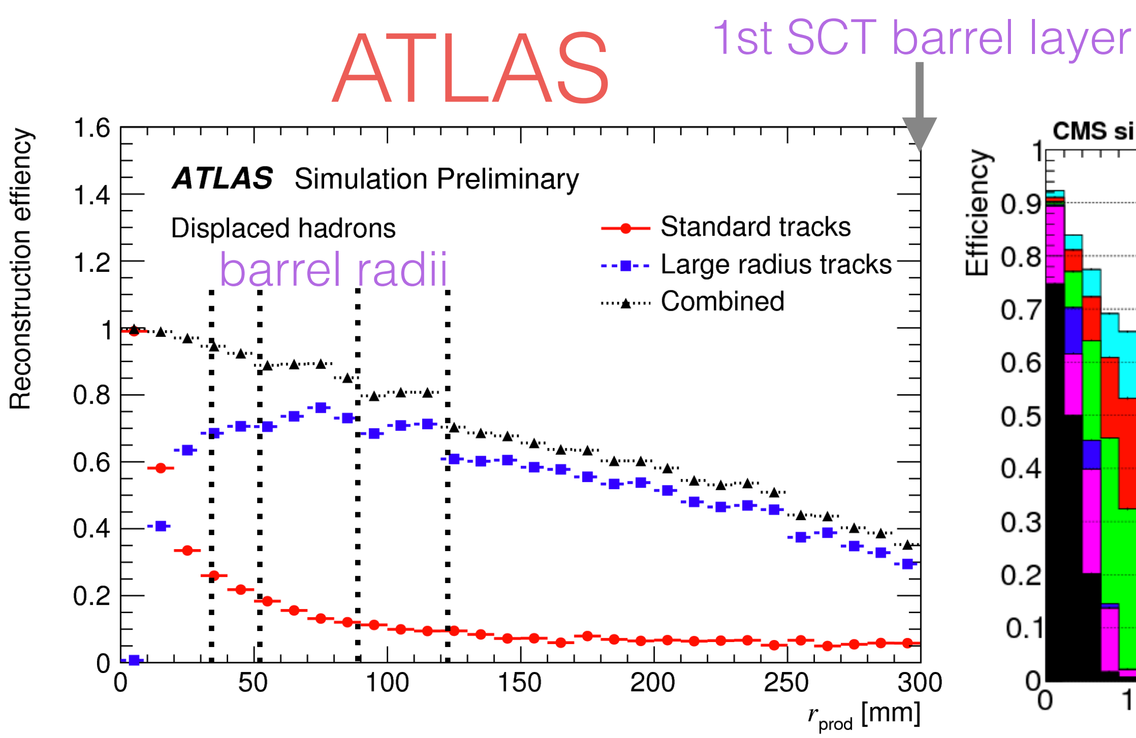


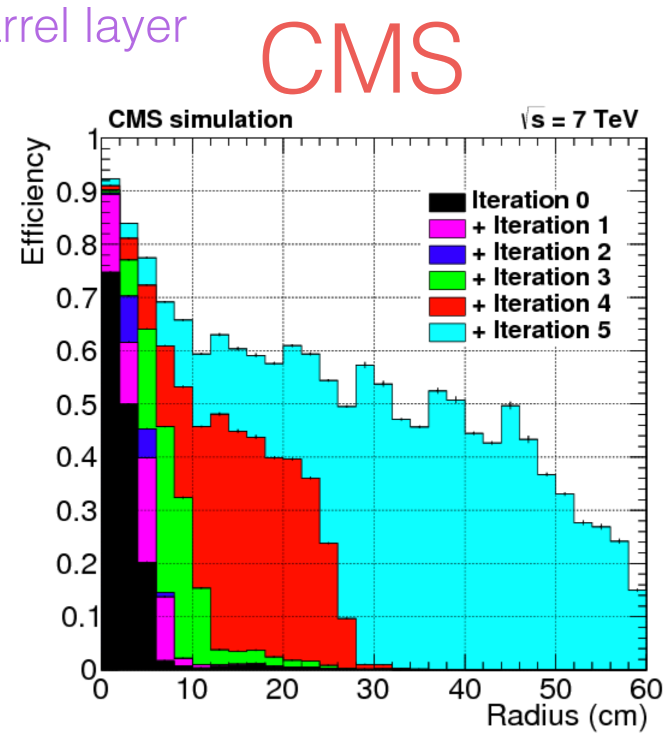
[ATL-PHYS-PUB-2017-014, ATL-PHYS-PUB-2019-013]

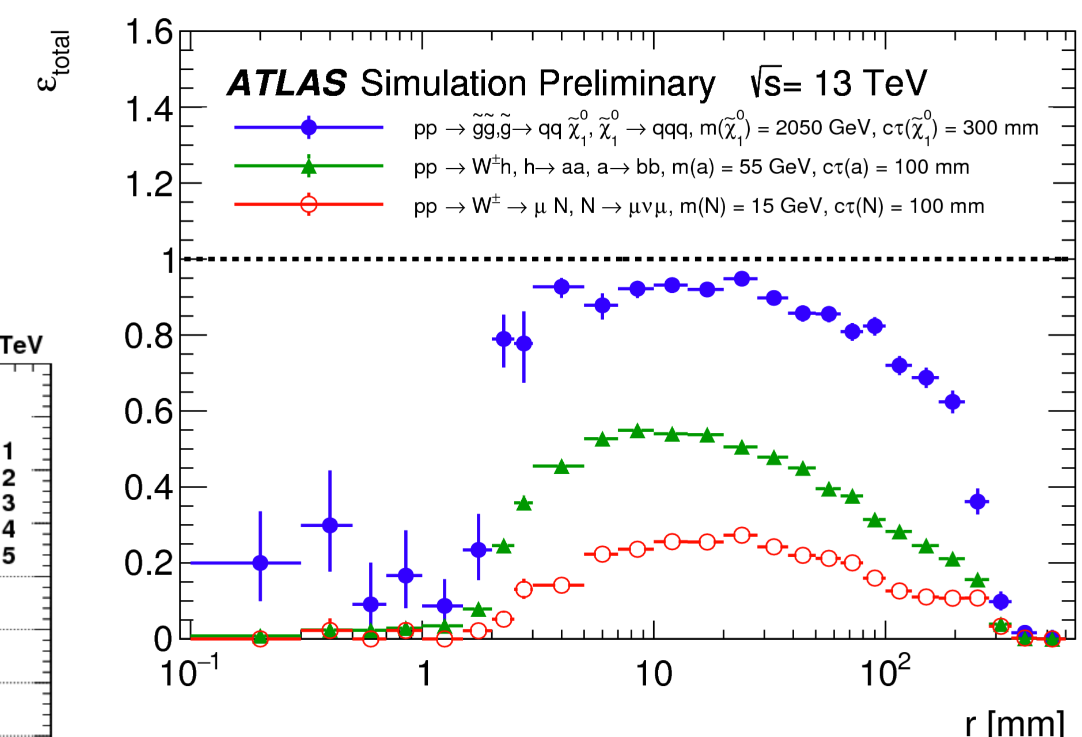
ATLAS Large Radius Tracking

- Standard ATLAS track reconstruction efficiency falls steeply for R_{prod} > 10 mm (not so for CMS)
- Large Radius Tracking (LRT) largely recovers this inefficiency
  - Computationally intensive → select *O*(few %) of data for this special processing with signature-specific filters
- Run DV reconstruction algorithm on the combined standard + large-radius track collection

	Standard	Large radius
Maximum d_0 (mm)	10	300
Maximum z_0 (mm)	250	1500
Maximum $\lvert\eta\rvert$	2.7	5
Maximum shared silicon modules	1	2
Minimum unshared silicon hits	6	5
Minimum silicon hits	7	7
Seed extension	Combinatorial	Sequential







[ATLAS-CONF-2019-006]

Displaced Jet (ID DV)

- LRT filter:
  - MS μ w/ p_T > 60 GeV OR MET > 180 GeV

Selection level	Muon selection	Displaced vertex selection
Preselection	$p_T > 25$ GeV, $\lvert\eta\rvert < 2.5$, 2 mm $< \lvert d_0\rvert <$ 300 mm, $\lvert z_0\rvert <$ 500 mm	$r_{DV} <$ 300 mm, $\lvert z_{DV}\rvert <$ 300 mm, $\min(\lvert\vec{r}_{DV} - \vec{r}_{PV}\rvert) >$ 4 mm, $\chi^2/N_{DoF} < 5$, Pass material map veto
Full selection	Pass cosmic-muon, fake-muon, and heavy-flavor vetoes	$n^{DV}_{Tracks} \geq 3$, $m_{DV} >$ 20 GeV

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matched opposite-side MS segment(s)

non-isolated

poor χ^2/NDF

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Full selection	Pass cosmic-muon, fake-muon, and heavy-flavor vetoes	$n^{DV}_{Tracks} \geq 3$, $m_{DV} >$ 20 GeV

random track crossings

material interactions

[ATLAS-CONF-2019-006]

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2 orthogonal channels

Selection level	E_T^{miss} Trigger SR	Muon Trigger SR
Preselection	Selected by E_T^{miss} trigger, Cluster-based E_T^{miss} > 180 GeV, Selected PV, preselected muon,	Selected by muon trigger, Cluster-based E_T^{miss} < 180 GeV, Selected PV, preselected muon, Highest-p_T muon matches trigger muon
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[ATLAS-CONF-2019-006]

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[ATLAS-CONF-2019-006]

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- Background sources of displaced muons and vertices are uncorrelated

preselected events

DV control region	DV validation region	DV signal region
no preselected DVs	preselected DV(s), no selected DVs	selected DV(s)

[ATLAS-CONF-2019-006]

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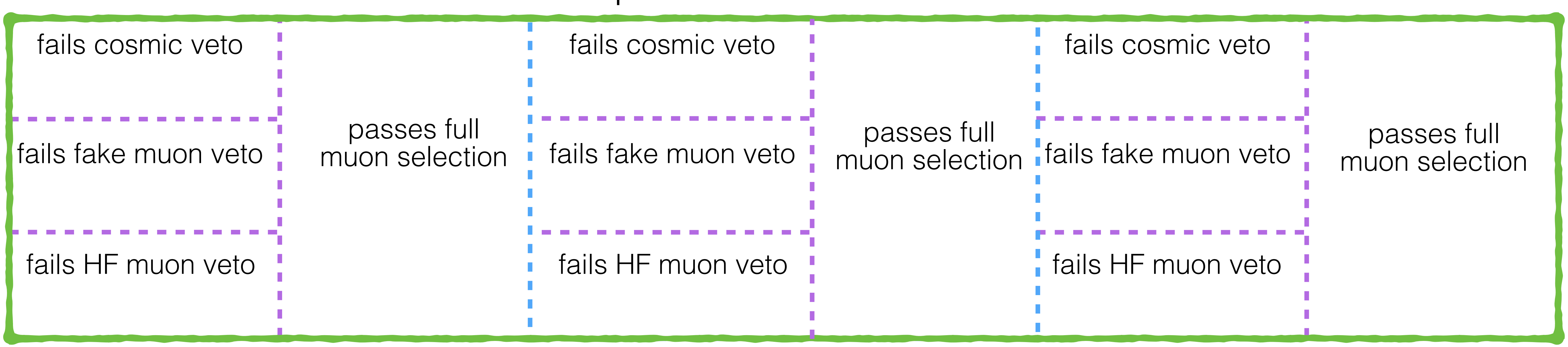
preselected events



[ATLAS-CONF-2019-006]

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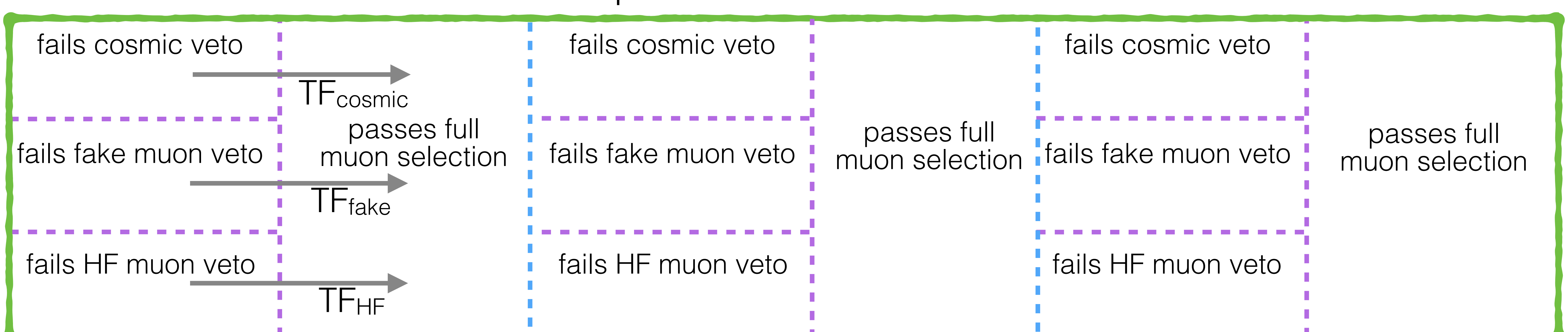
preselected events



measure transfer factors in DV CR

Displaced Jet (ID DV)

[ATLAS-CONF-2019-006]

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  - MS μ w/ p_T > 60 GeV OR MET > 180 GeV

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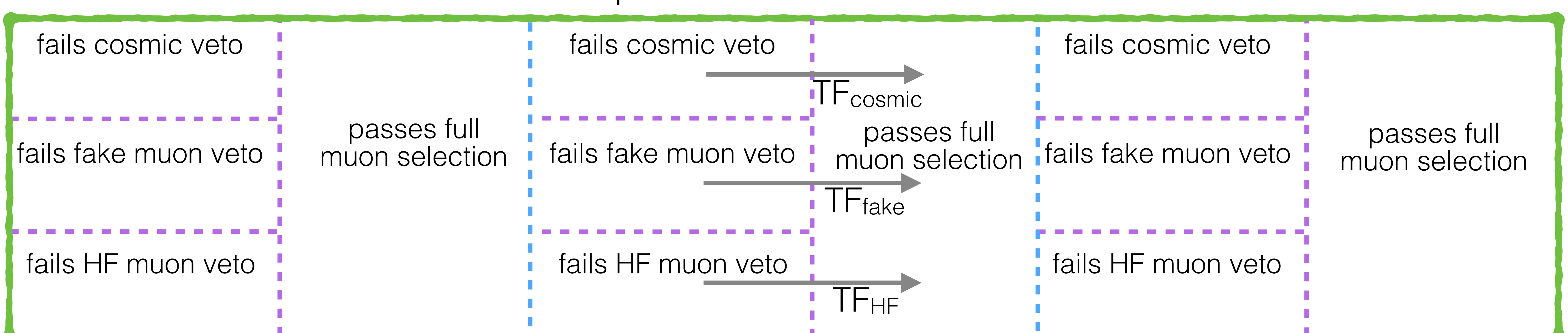
preselected events



validate in DV VR

[ATLAS-CONF-2019-006]

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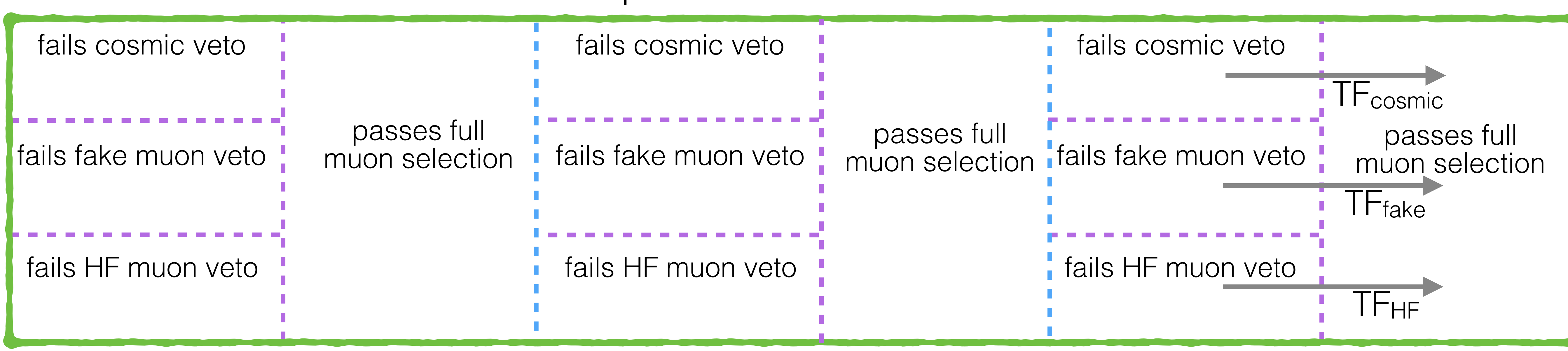
Full selection	≥ 1 full-selection muon, ≥ 1 full-selection DV	

- Background sources of displaced muons and vertices are uncorrelated

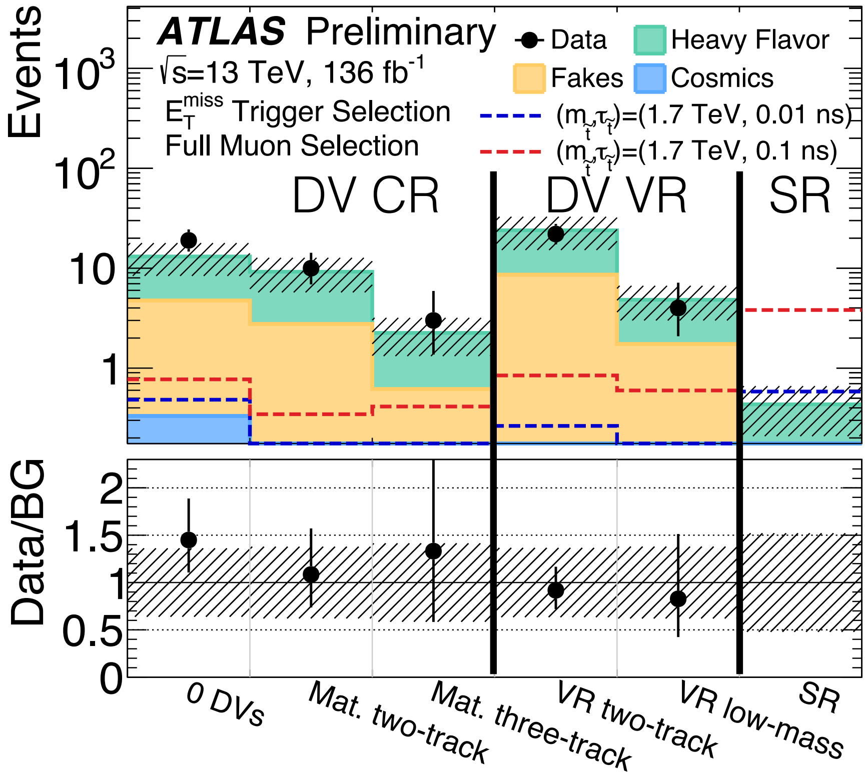
preselected events

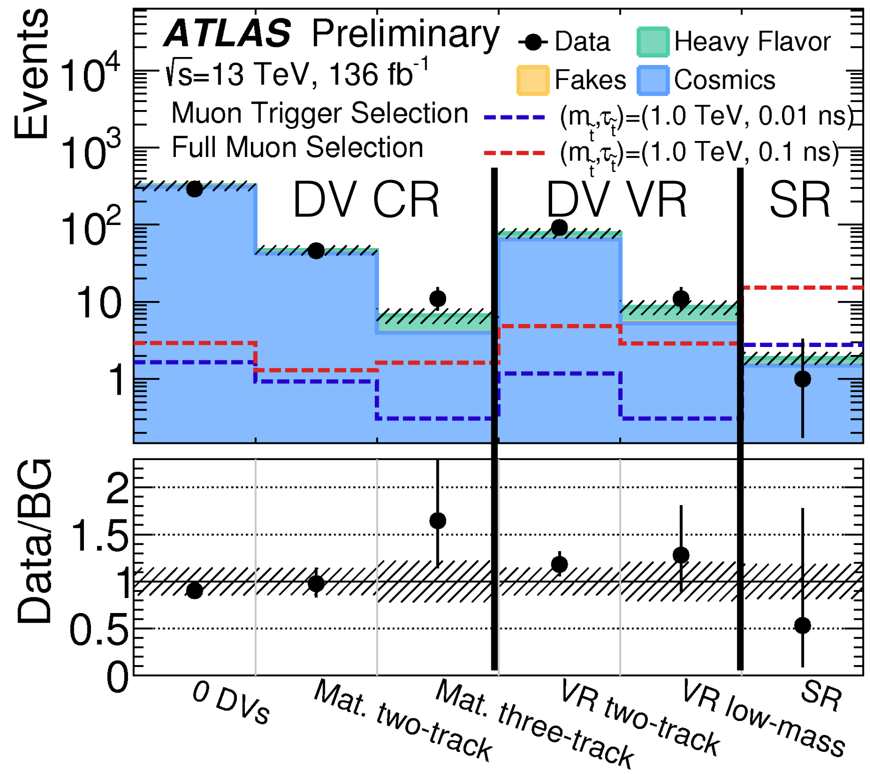


apply in DV SR

[ATLAS-CONF-2019-006]

Displaced Jet (ID DV)





good agreement between observations and expected background

	N_{exp}	N_{obs}
MET-triggered channel	0.34 ± 0.16 (stat) ± 0.16 (syst)	0
Muon-triggered channel	1.88 ± 0.20 (stat) ± 0.28 (syst)	1

[ATLAS-CONF-2019-006]

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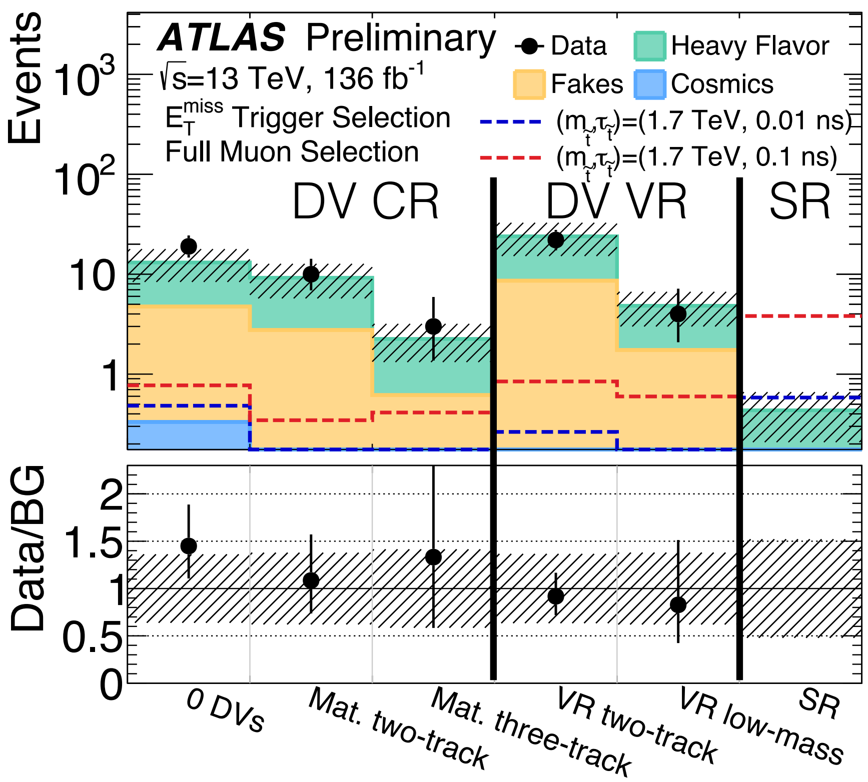

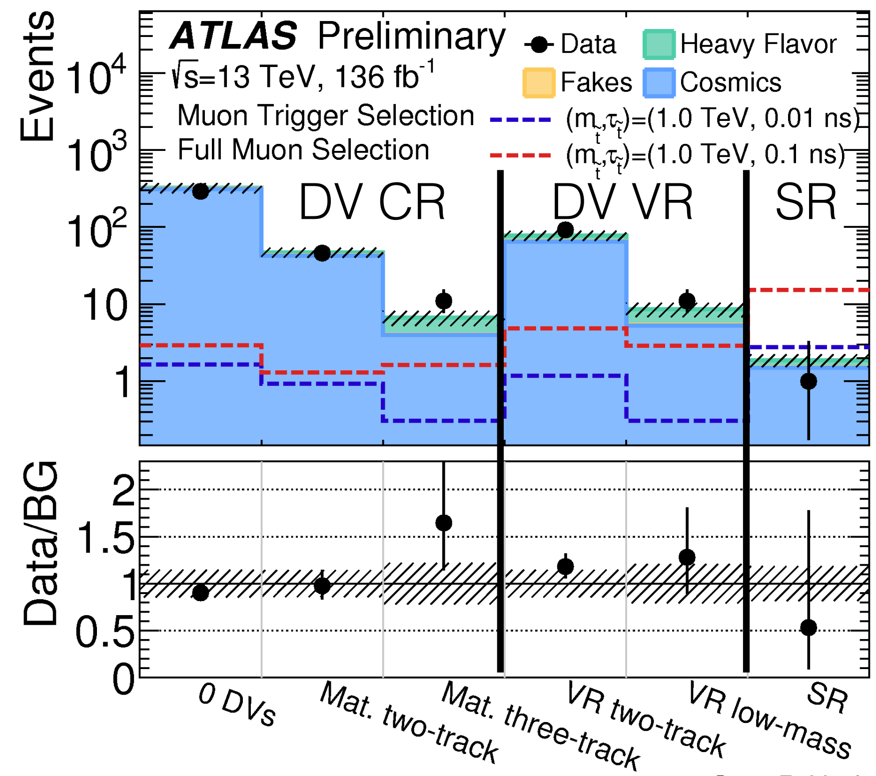

stronger than prompt stop limits

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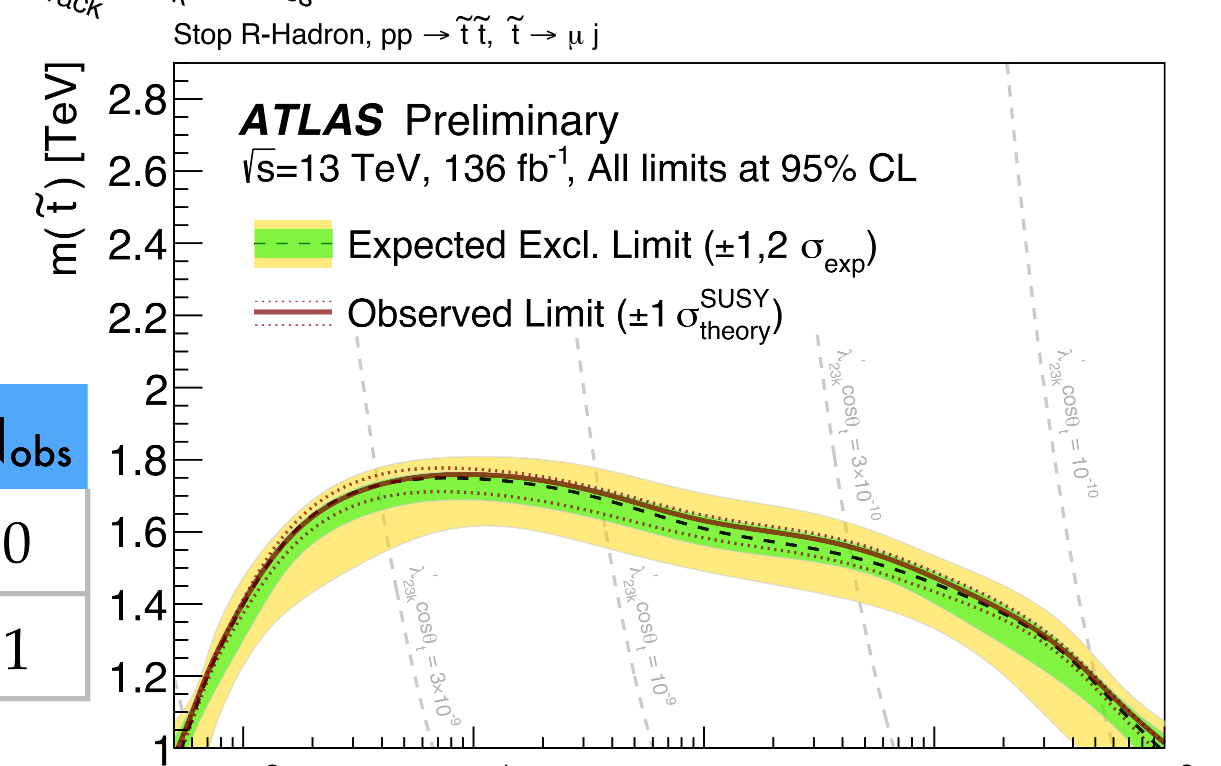
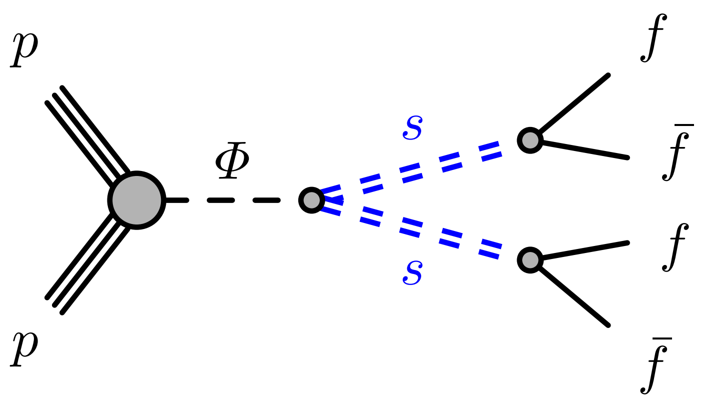


[1902.03094]

Displaced Jet (Low EM-Fraction)

- Search for LLP decays in the HCal
  - Low EMCal/HCal energy ratio (EM fraction)
  - No associated tracker activity
  - Narrow energy deposits
- Main backgrounds:
  - Jets composed of mostly neutral hadrons
  - Beam-induced background (BIB)
    - Muons (traveling parallel to the beam) undergo hard bremsstrahlung in HCAL



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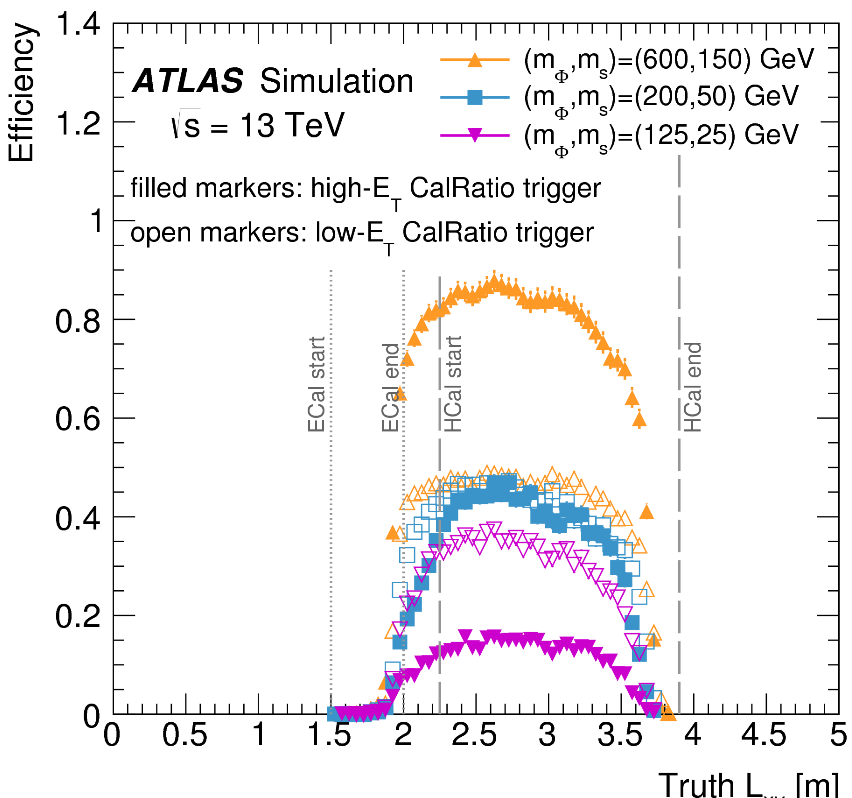
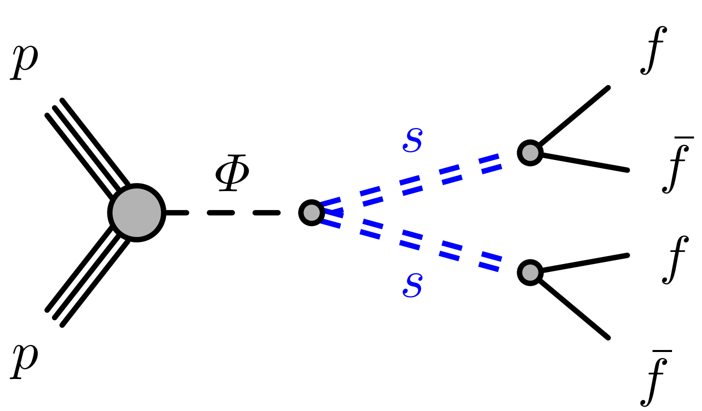
dedicated L1 and HLT trigger





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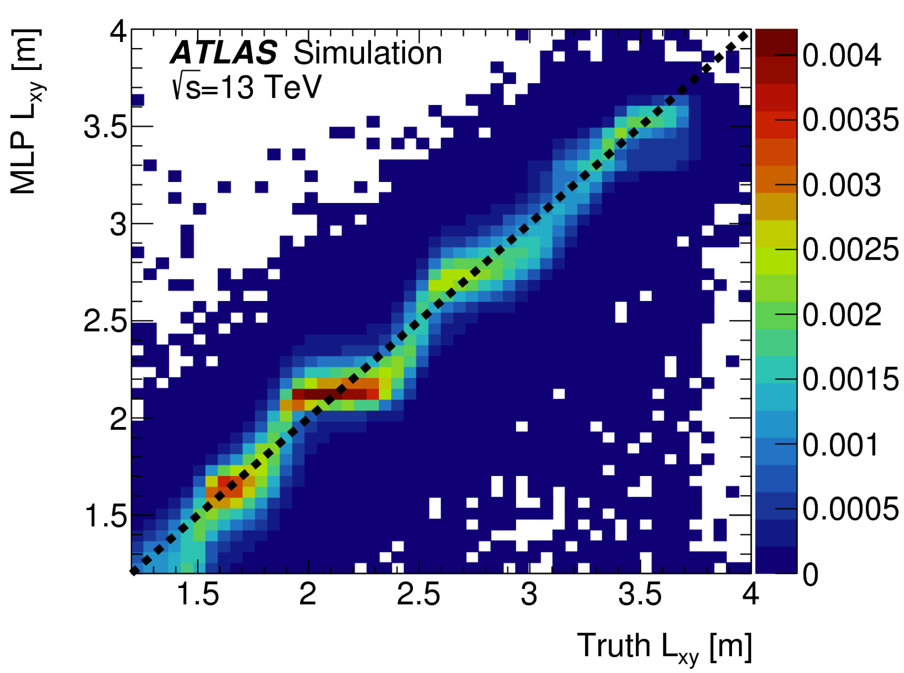
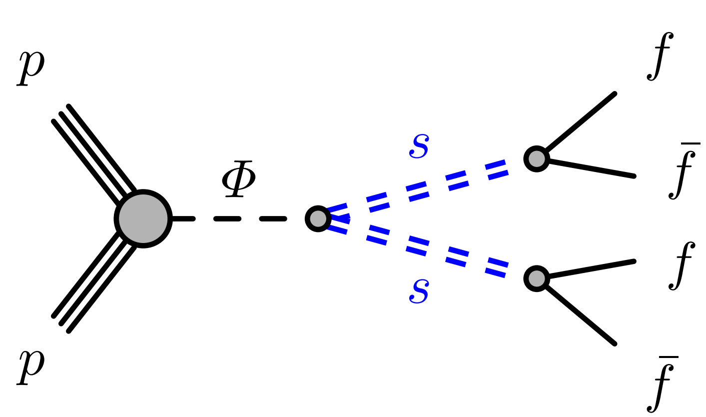
dedicated L1 and HLT trigger

↓

multilayer perceptron
(estimate LLP decay position)





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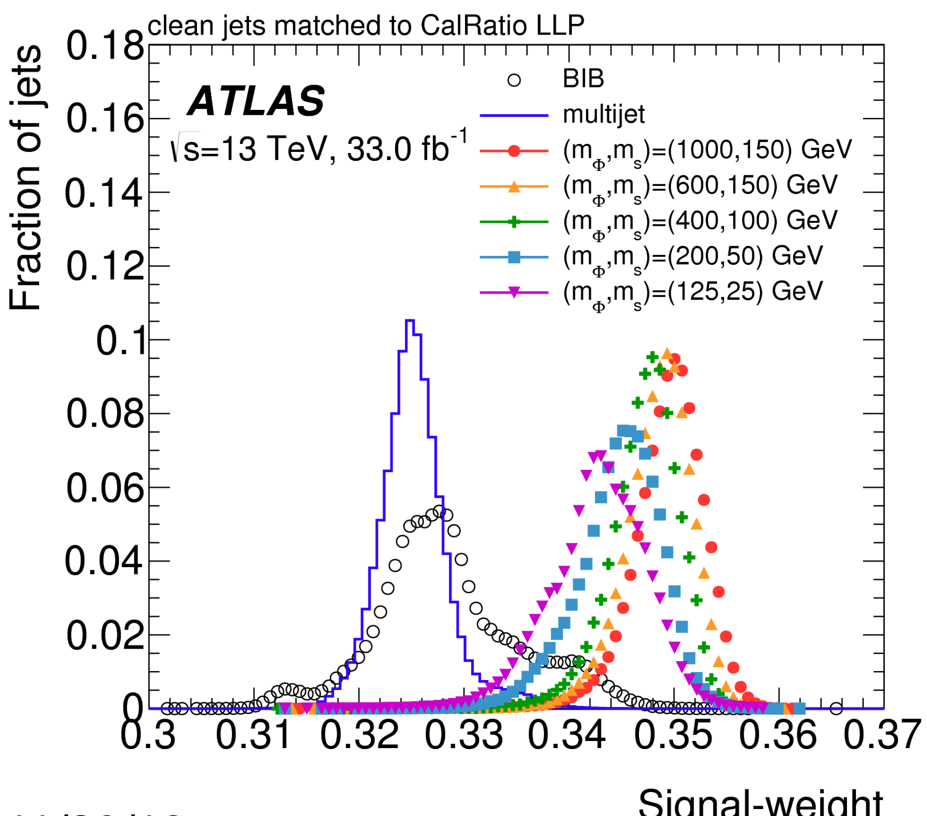

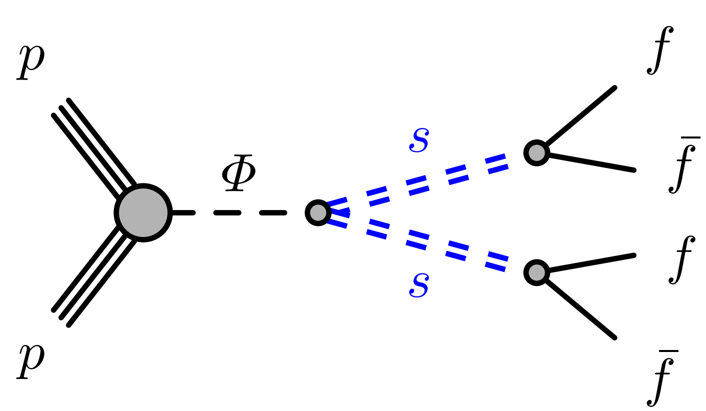

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dedicated L1 and HLT trigger

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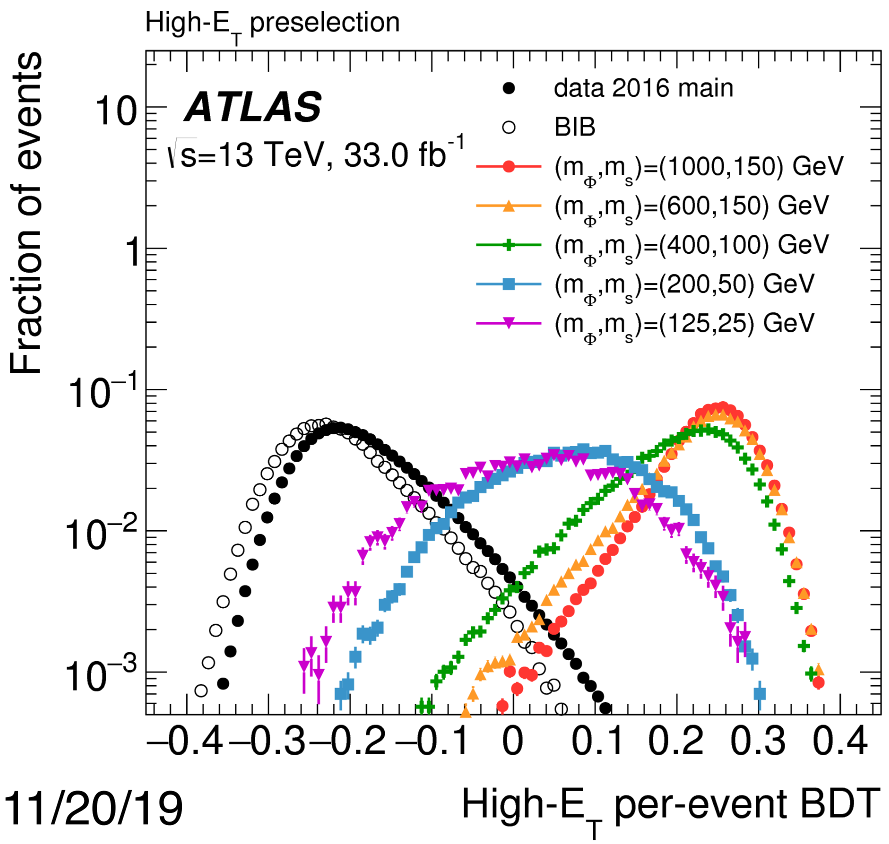
multilayer perceptron
(estimate LLP decay position)

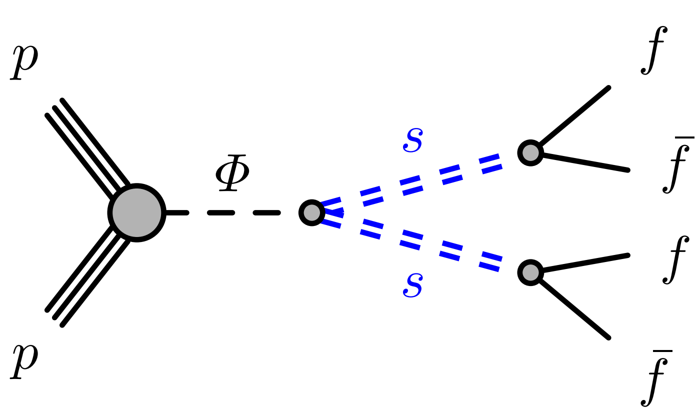
↓

per-jet BDT
(classify as signal, QCD, BIB)

↓

cut on per-event BDT
(remove BIB)



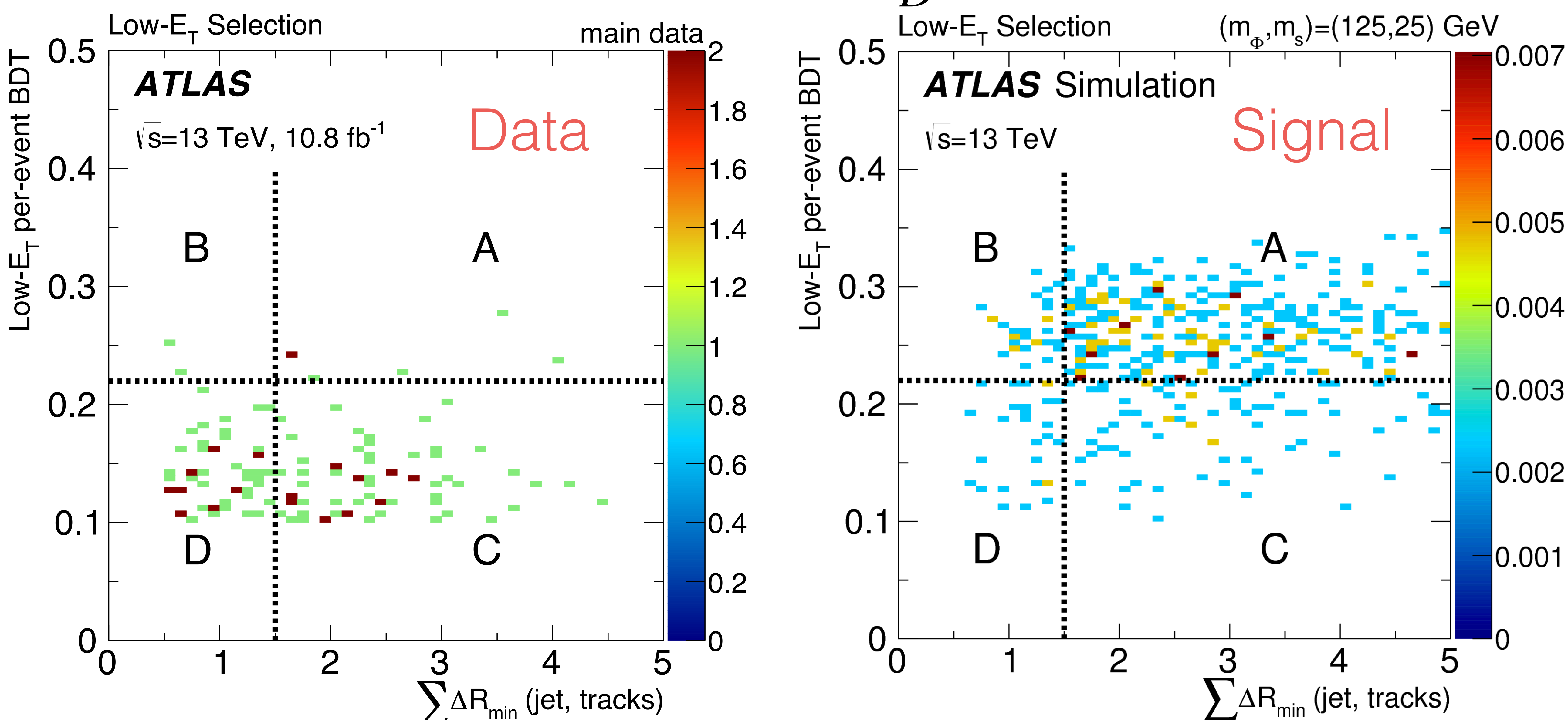


[1902.03094]

Displaced Jet (Low EM-Fraction)

- ABCD method used to estimate residual QCD background:

$$N_A = N_B \frac{N_C}{N_D}$$



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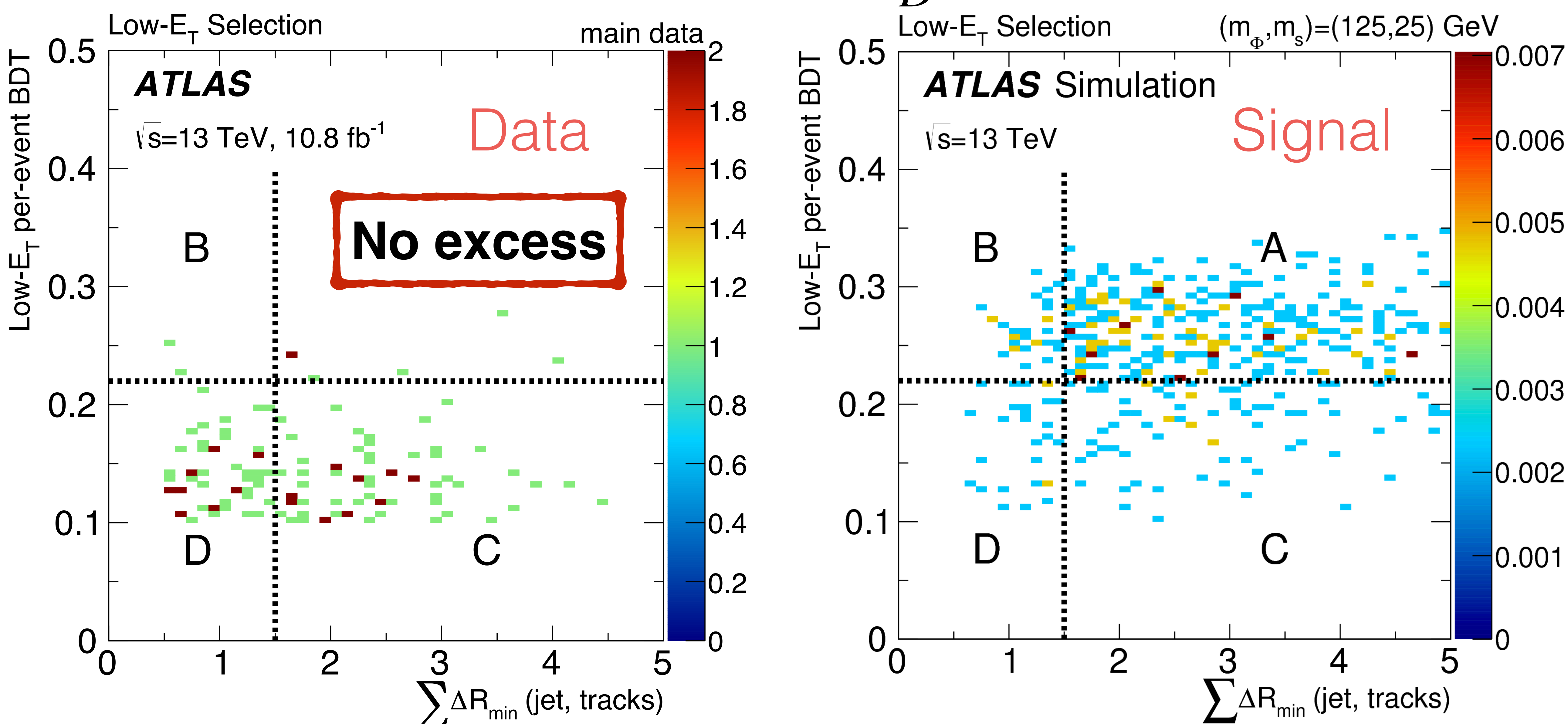
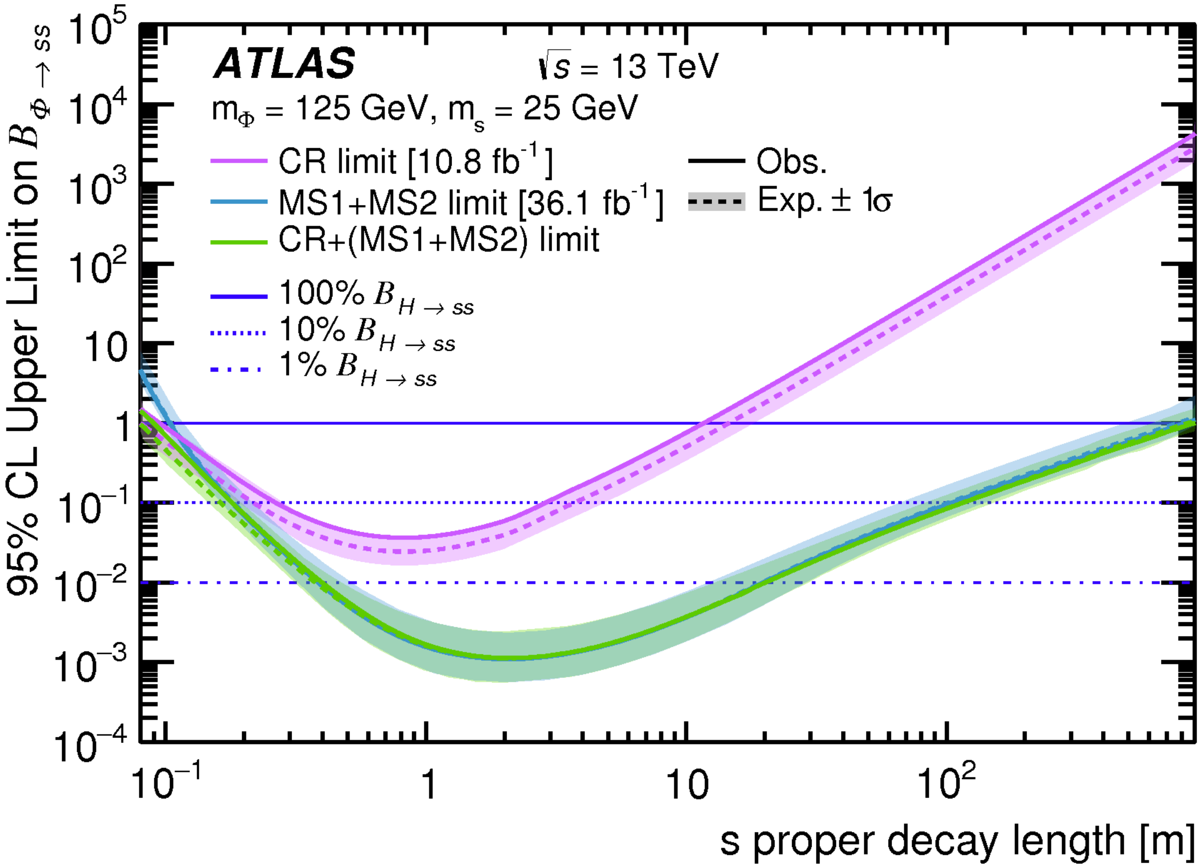


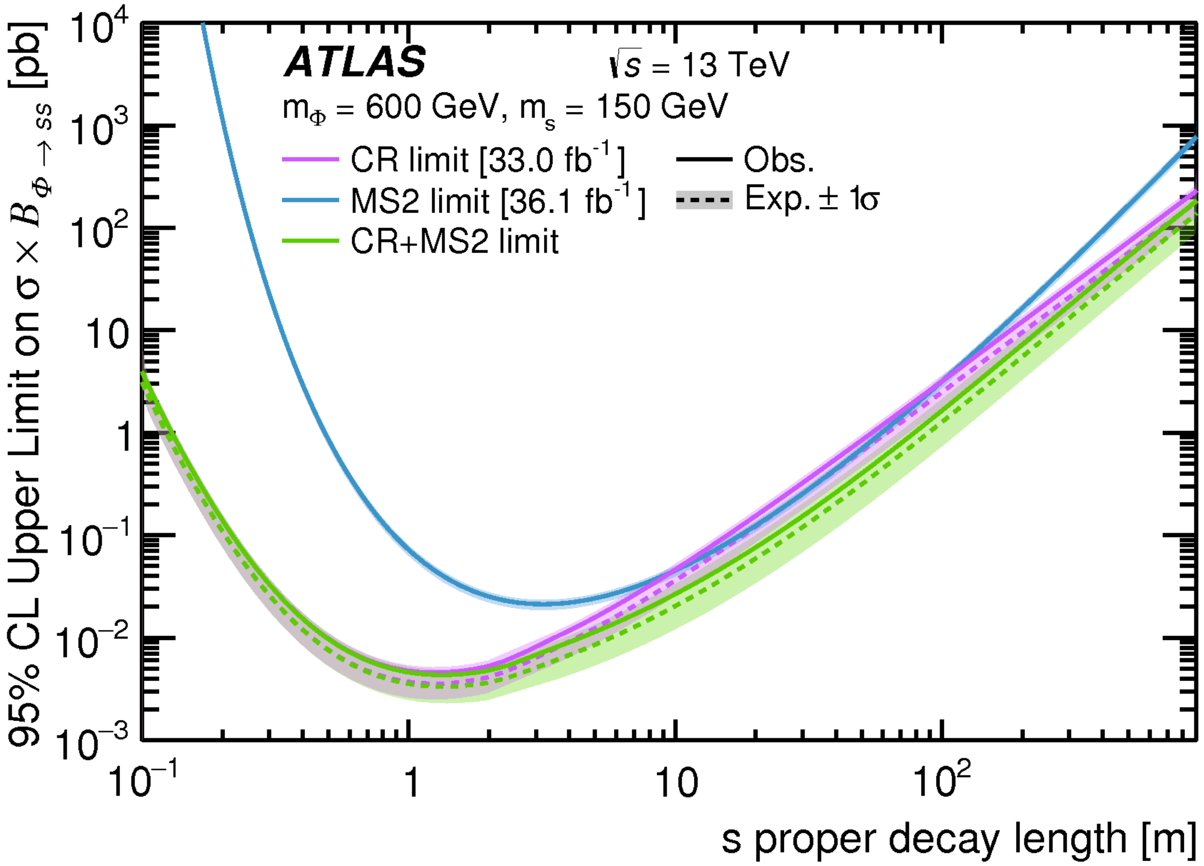
[1902.03094]

Displaced Jet (Low EM-Fraction)

H(125)



H(600)

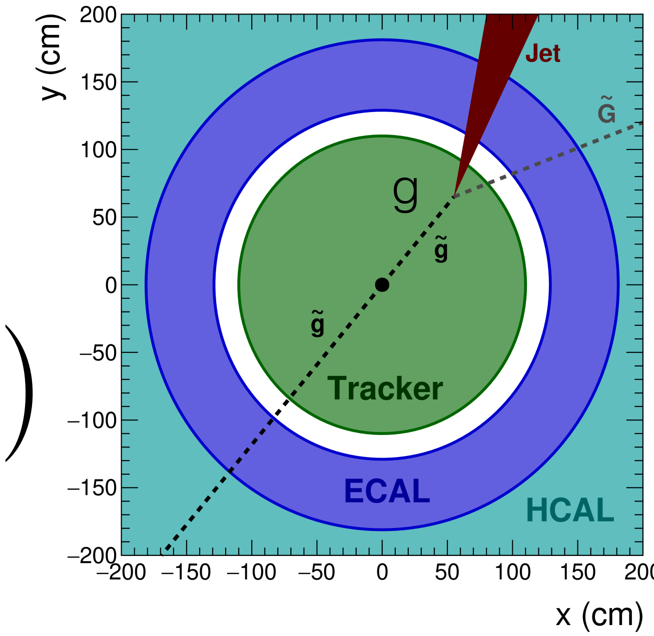


Displaced Jet (Timing)

[1906.06441]

- Search for delayed jets (due to slow/heavy LLP and indirect path)
  - Few ns for TeV scale LLP with L ≈ 1 m
  - First search to use ECal timing to identify delayed jets
- Backgrounds
  - ECal time resolution tails (inter-calibration uncertainty, crystal-dependent scintillator rise time variations, run-by-run shifts associated with readout electronics)
  - Electronic noise
  - Direct APD hits (~11 ns faster than scintillation light)
  - In-time PU (spread in collision time, varying flight paths)
  - Out-of-time PU
  - Satellite bunches (RF buckets separated by 2.5 ns)
  - Beam halo
  - Cosmic muons

$$t_{\mathrm{jet}} = \mathrm{median}\left(t^{i}_{\mathrm{crystal}}\right)$$



$E_{\mathrm{ECAL}} > 20\,\mathrm{GeV}$
$N^{\mathrm{cell}}_{\mathrm{ECAL}} > 25$
$\mathrm{HEF} > 0.2$ and $E_{\mathrm{HCAL}} > 50\,\mathrm{GeV}$
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$E^{\mathrm{CSC}}_{\mathrm{ECAL}} / E_{\mathrm{ECAL}} < 0.8$
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Event level selection

At least one signal jet
$p^{\mathrm{miss}}_{\mathrm{T}} > 300\,\mathrm{GeV}$ ← trigger
Quality filters
$\max(\Delta\phi_{\mathrm{DT}}) < \pi/2$
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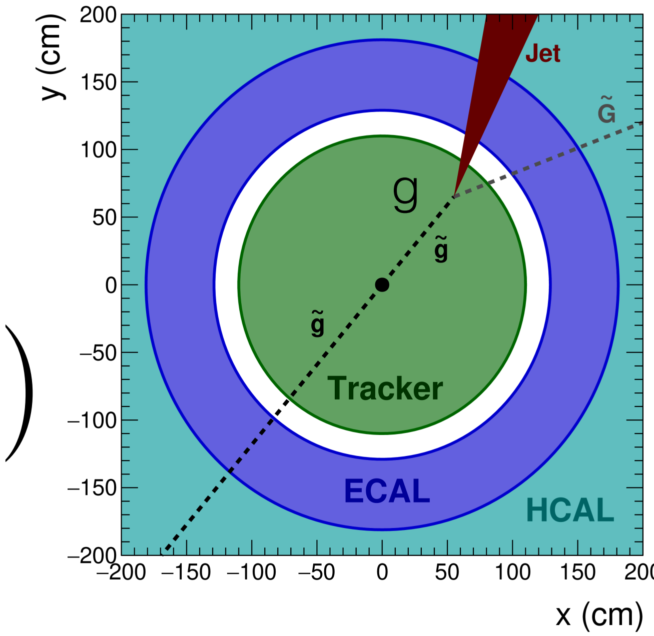

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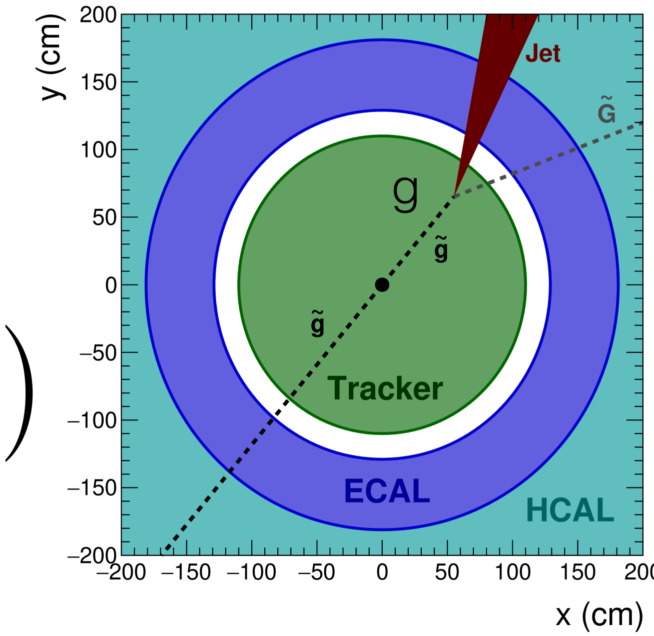

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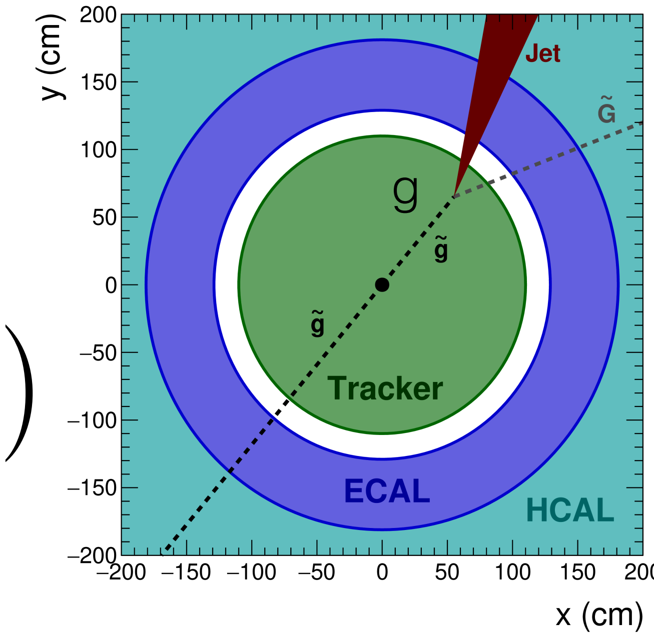

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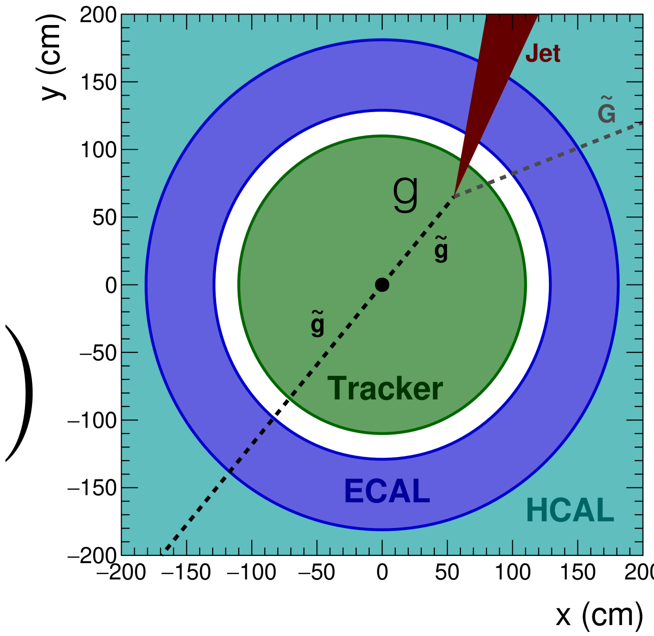

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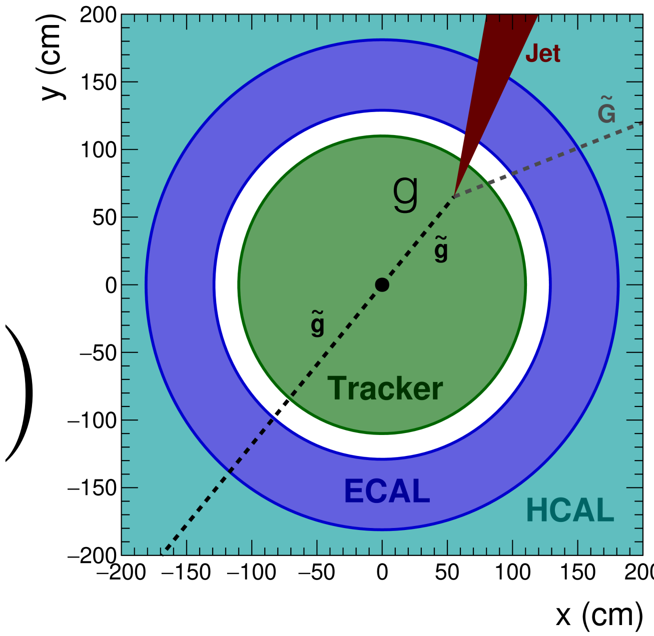

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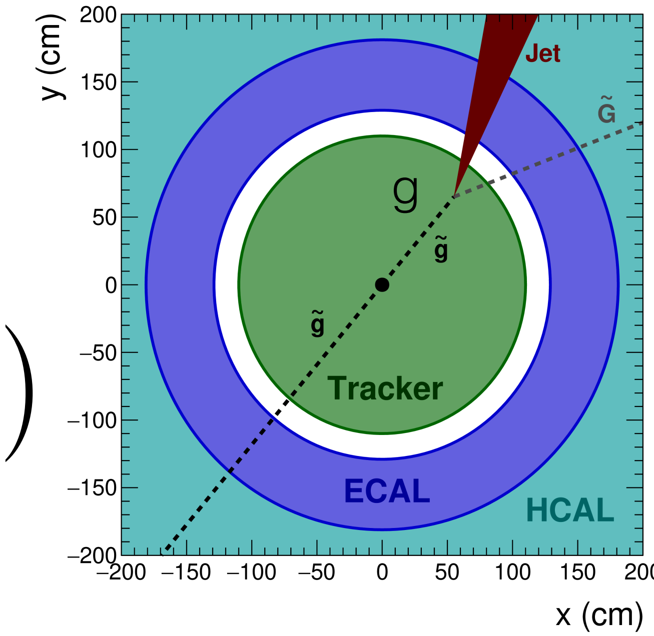

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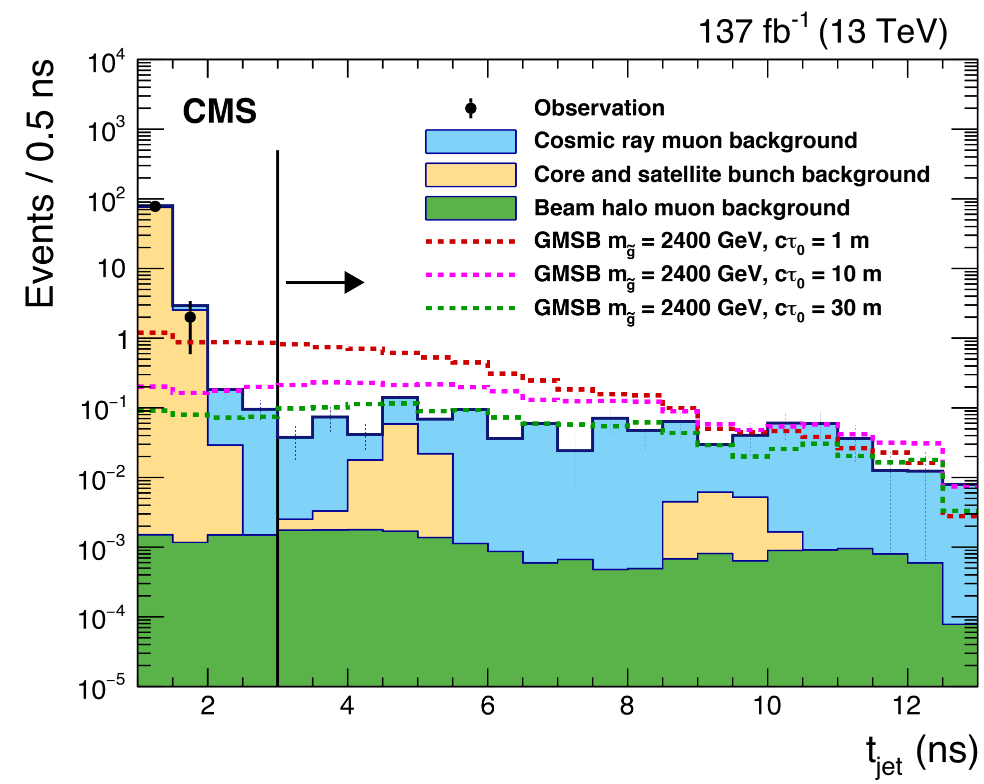
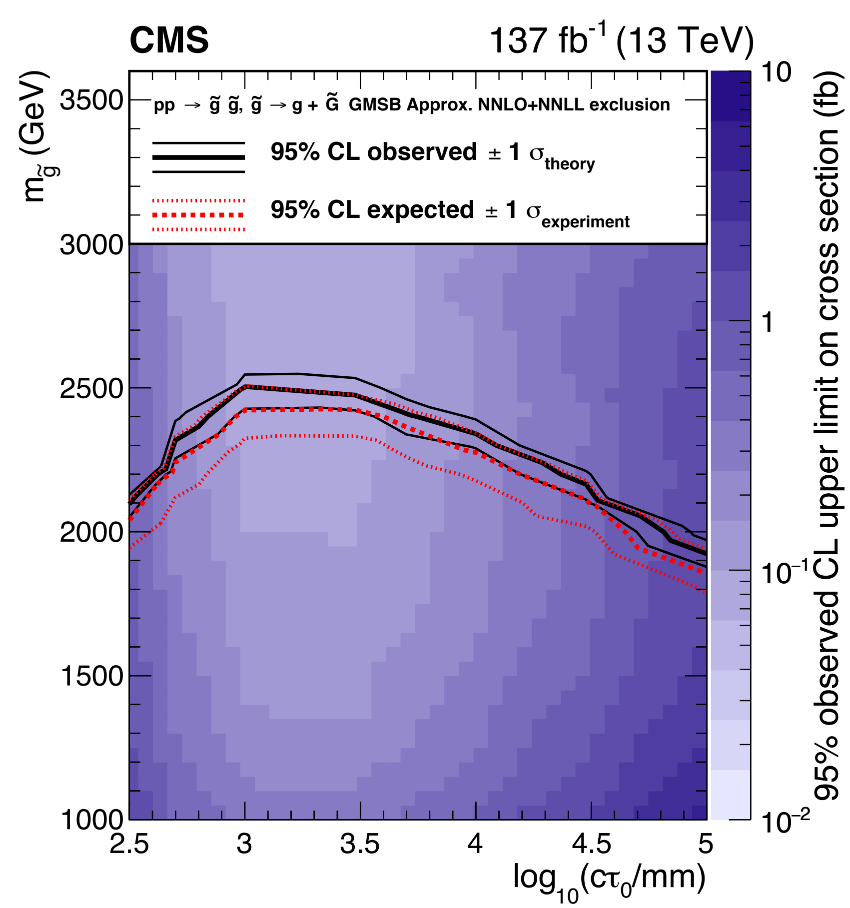
Displaced Jet (Timing)

[1906.06441]

- Background predictions from ABCD method (3x)

Background source	Events predicted
Beam halo muons	$0.02^{+0.06}_{-0.02}\,(\text{stat})^{+0.05}_{-0.01}\,(\text{syst})$
Core and satellite bunch collisions	$0.11^{+0.09}_{-0.05}\,(\text{stat})^{+0.02}_{-0.02}\,(\text{syst})$
Cosmic ray muons	$1.0^{+1.8}_{-1.0}\,(\text{stat})^{+1.8}_{-1.0}\,(\text{syst})$





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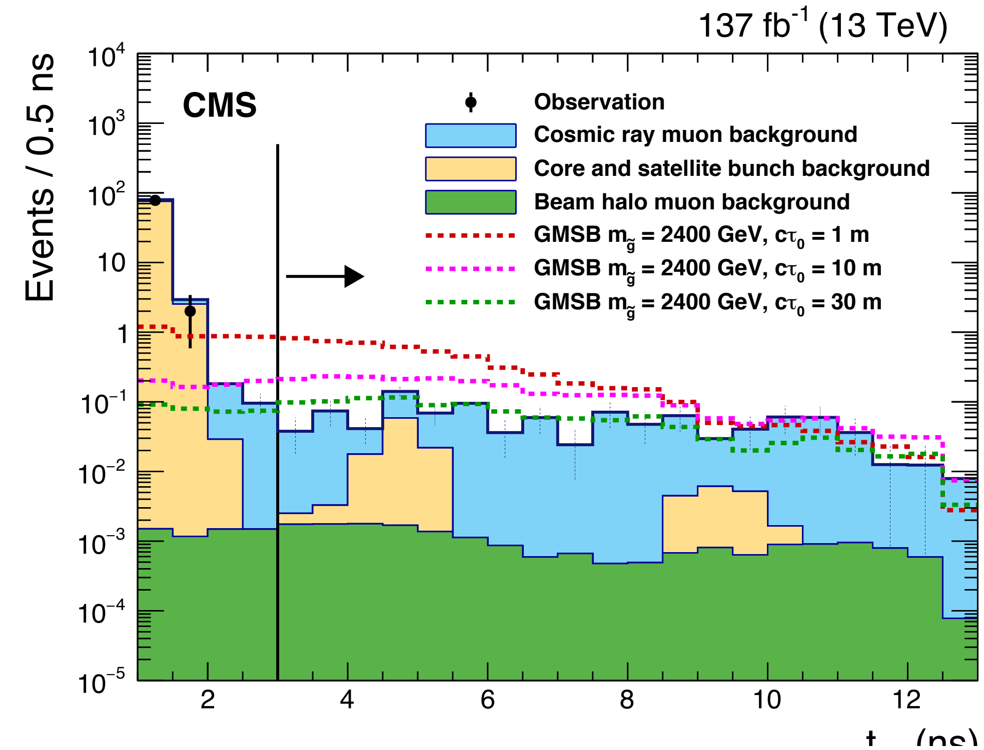
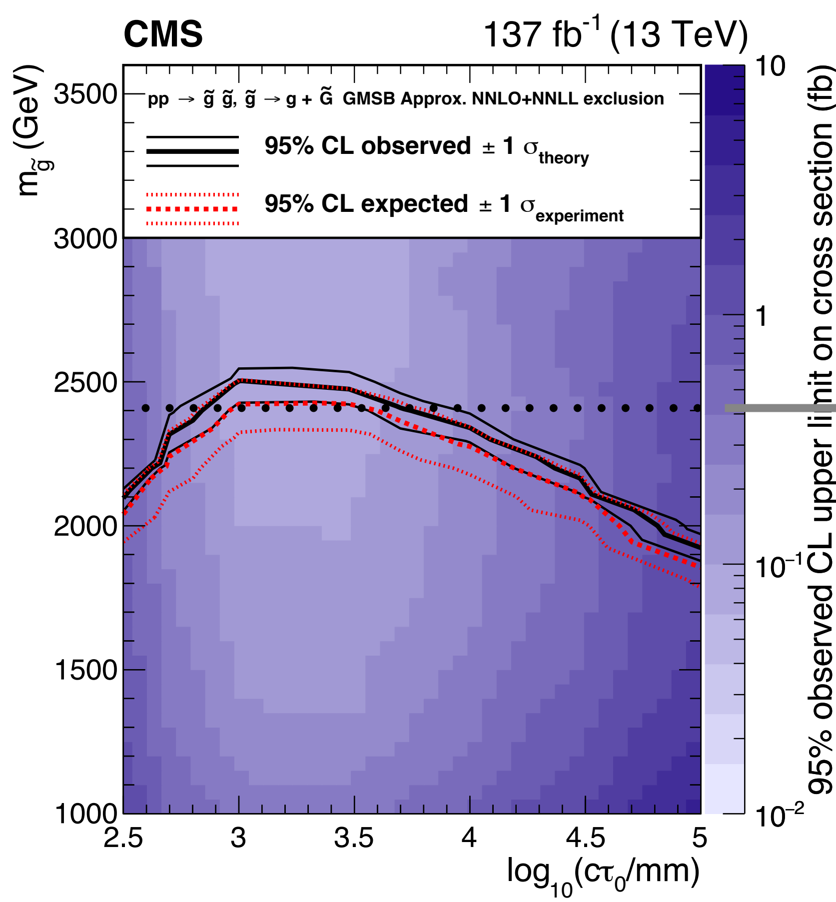
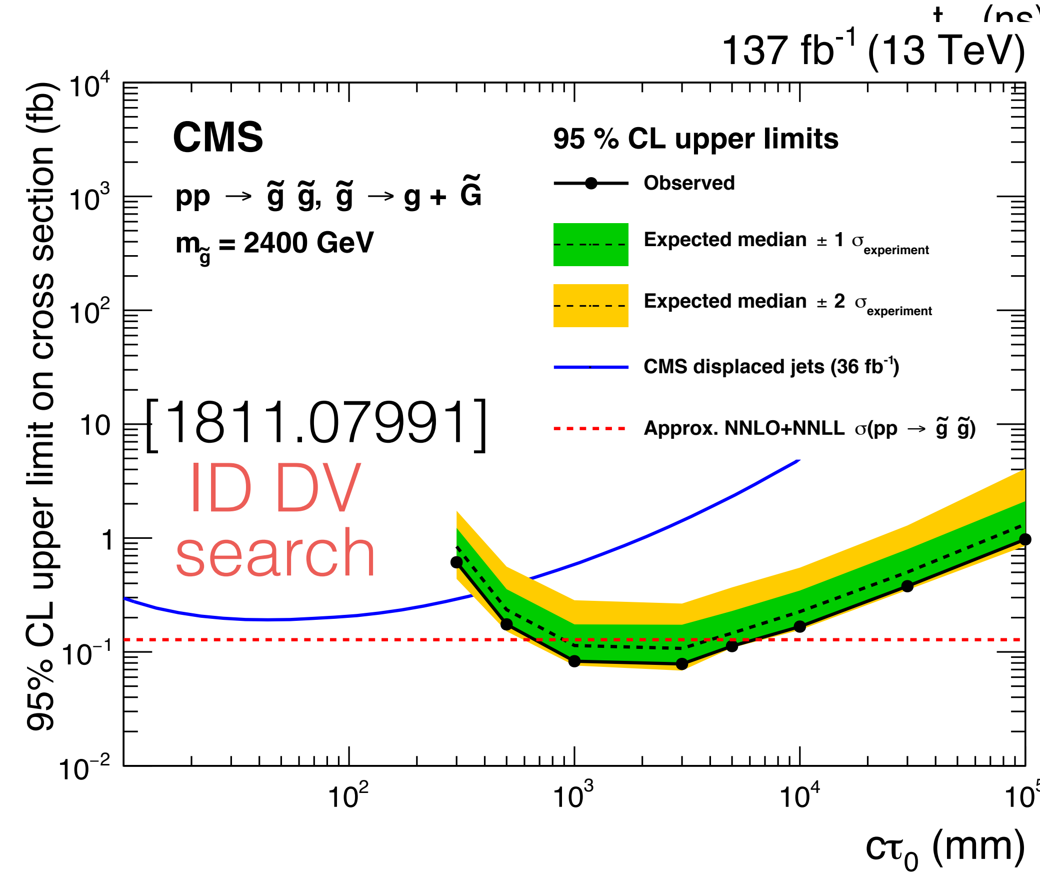


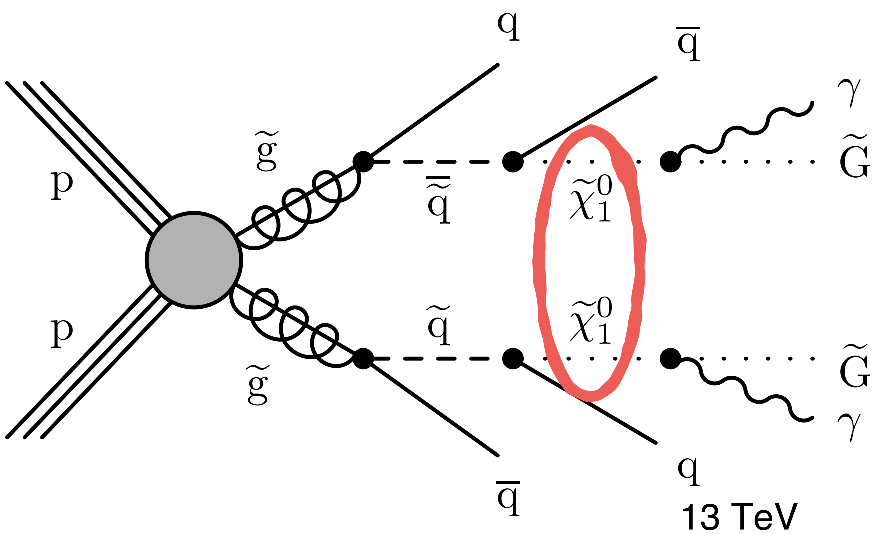


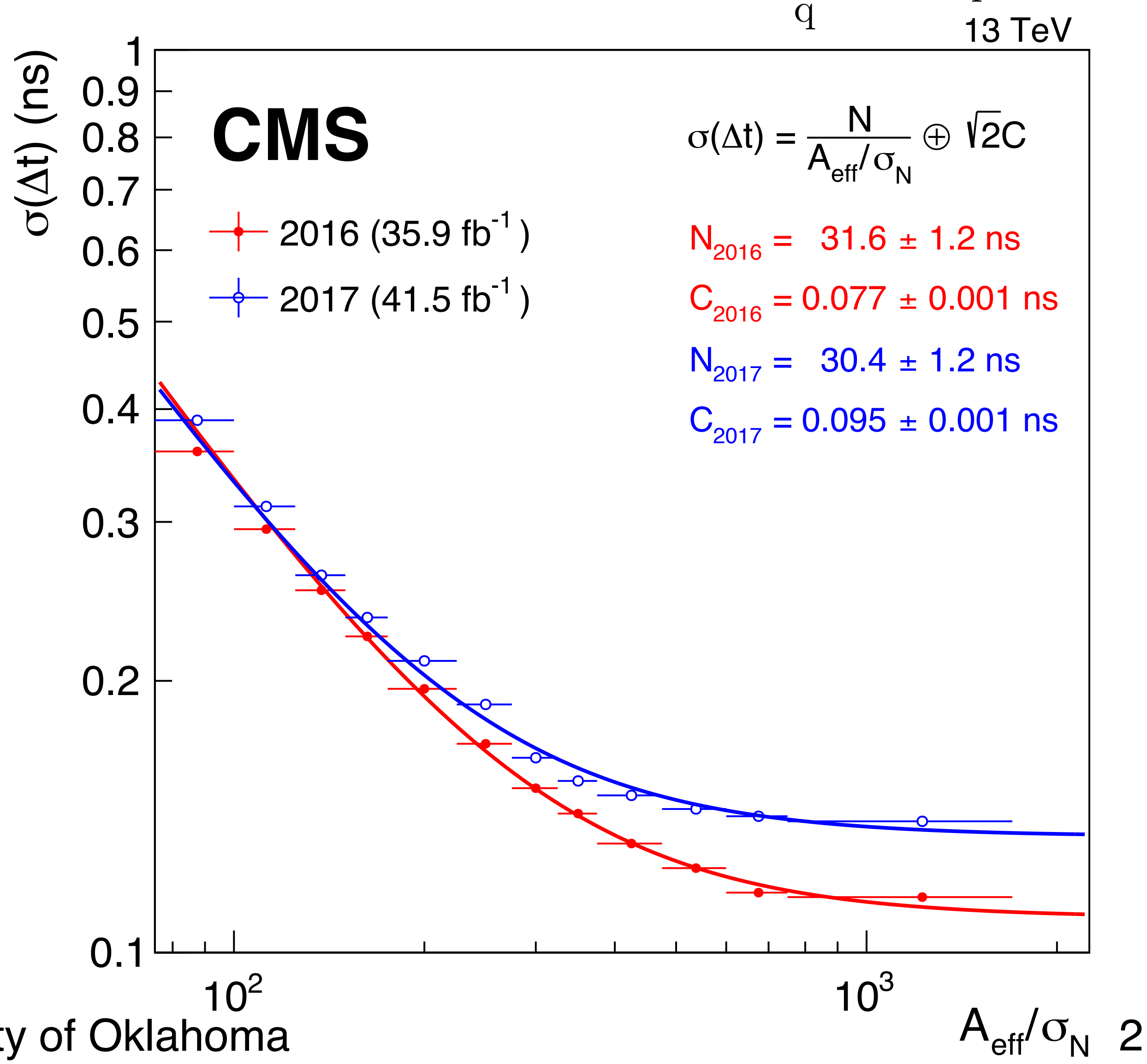


[1909.06166]

Delayed/Non-Pointing Photon

- Search for LLP decays to a photon
- Similar few ns delay (up to ~10)
  - Utilizes dedicated out-of-time photon reconstruction
  - Exploits non-normal ECal incidence angle → elliptical shower
- Trigger:
  - 2016 - conventional $\gamma\gamma$ (p_T > 42, 25 GeV)
  - 2017 - $\gamma\gamma$ OR dedicated γ (p_T > 60 GeV, elliptical shower) + H_T > 350 GeV
- Offline:
  - ≥ 3 jets plus:
    - 2016: 2 displaced photons
    - 2017: 2 displaced photons OR 1 displaced photon + H_T

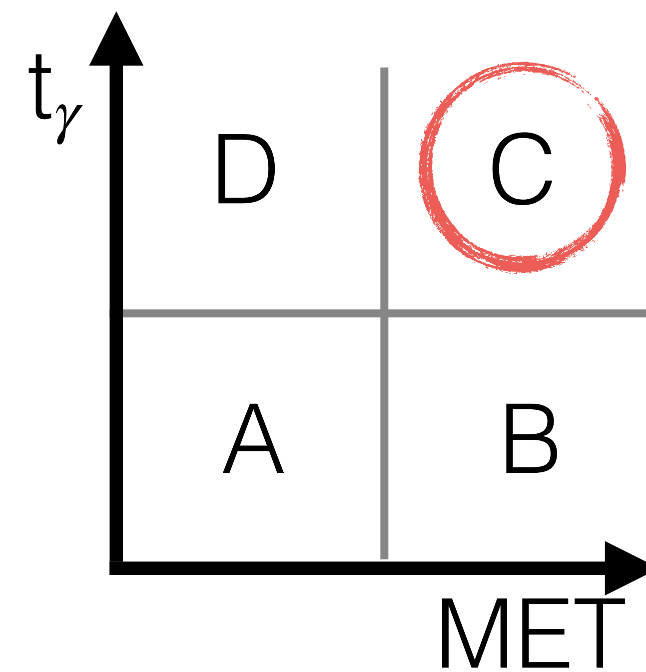




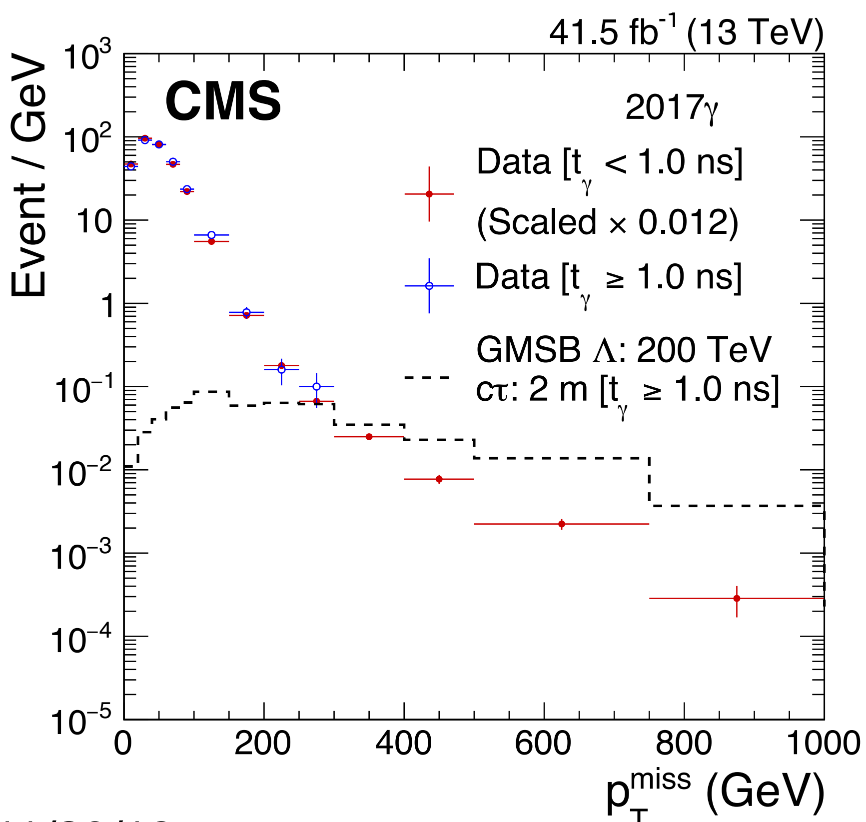
[1909.06166]

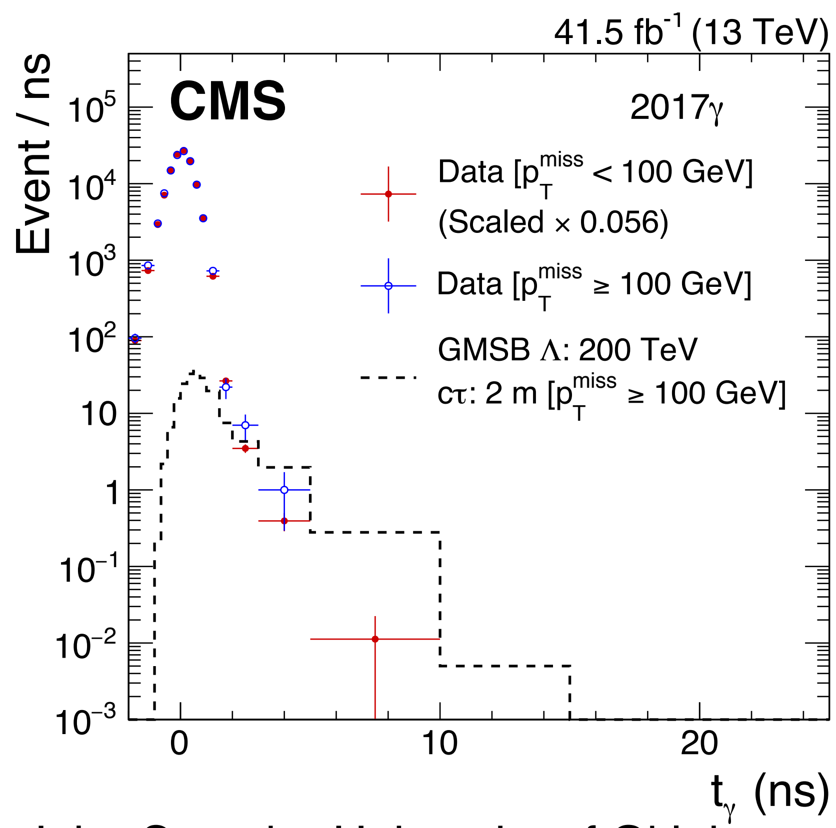
Delayed/Non-Pointing Photon

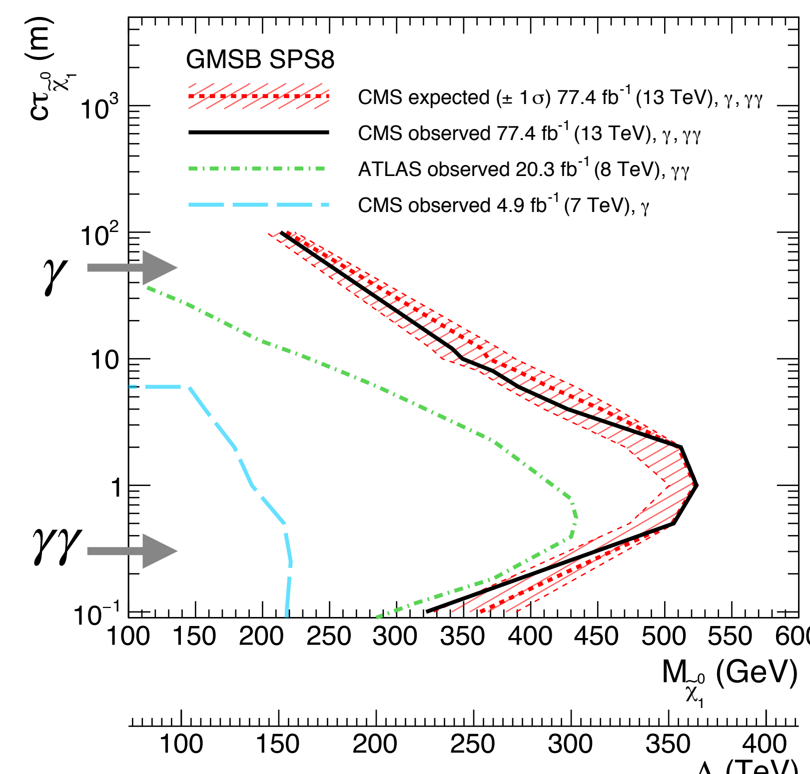
- Dominant backgrounds: γ+jet and QCD
  - Jet and photon requirements ~eliminate non-collision backgrounds
- Background predicted with ABCD method



$$N_C = N_B \frac{N_D}{N_A}$$





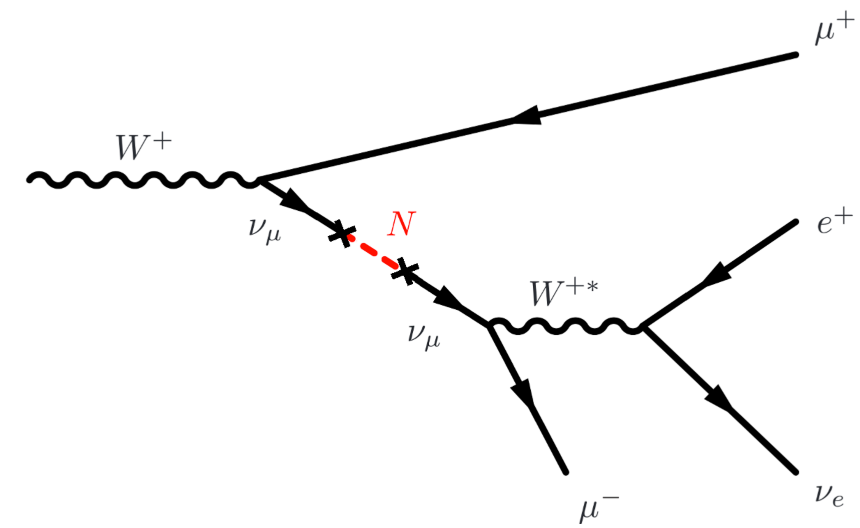


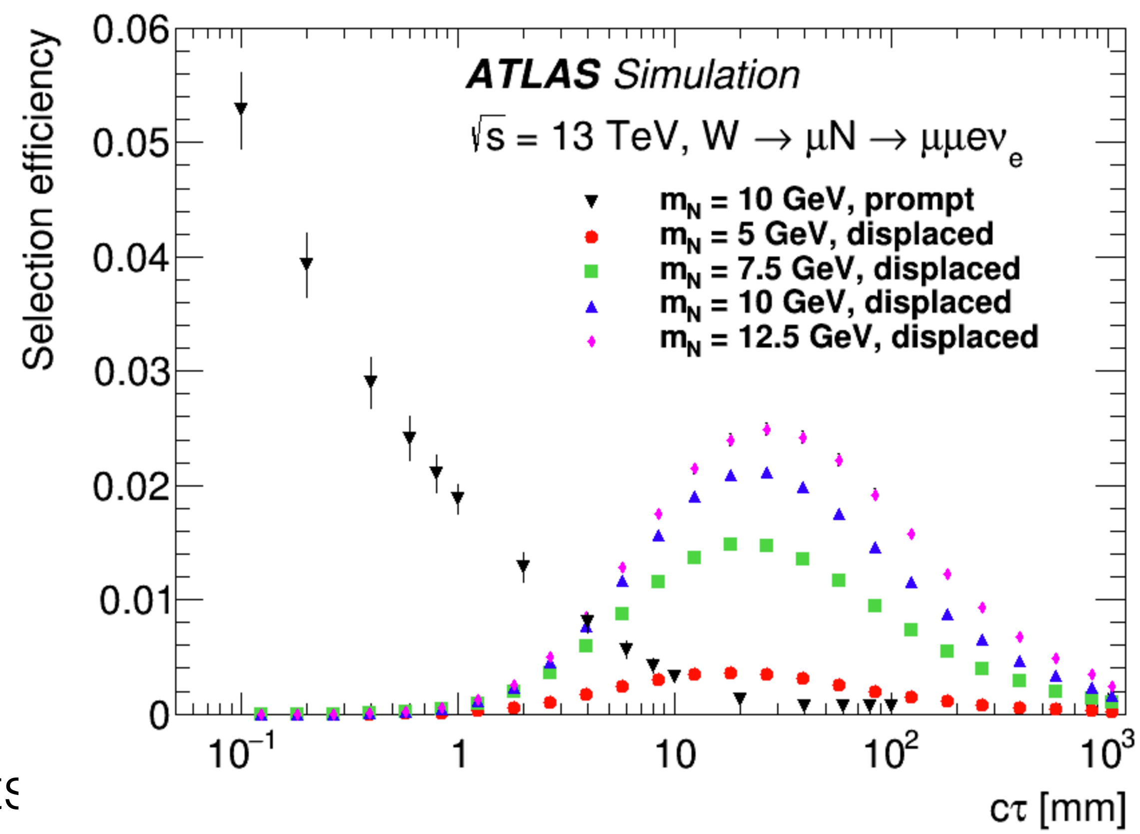
SUSY breaking scale

Dilepton DV

[1905.09787]

- Search for LL Heavy Neutral Lepton (HNL) with small mixing with muon neutrino
- Utilizes LRT and same DV reconstruction algorithm as the displaced jet search
  - LRT filter: 1 prompt and 1 displaced muon
- SR requires DV with:
  - Exactly 2 OS tracks
    - Tight* muon
    - Tight* electron or muon
  - $m > 4$ GeV
  - $4 < R < 300$ mm



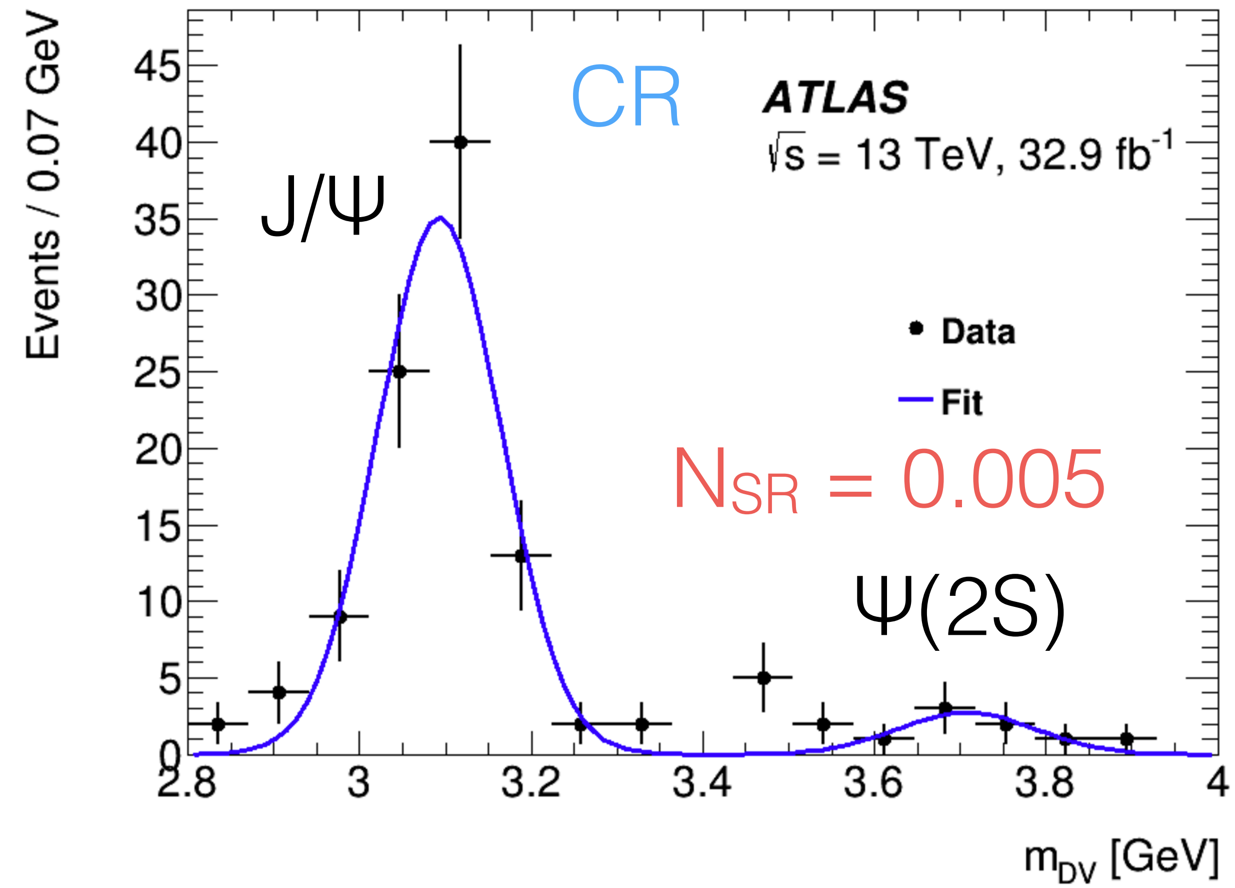


*minus usual requirement on number of pixel hits

Dilepton DV

[1905.09787]

- Backgrounds
  - Material intersections and metastable states studied in CR
    - Found to be negligible for $m_{DV} > 4$ GeV
  - Random track crossing background modeled with ABCD method
    - N_ℓ in DV vs. SS/OS DV tracks



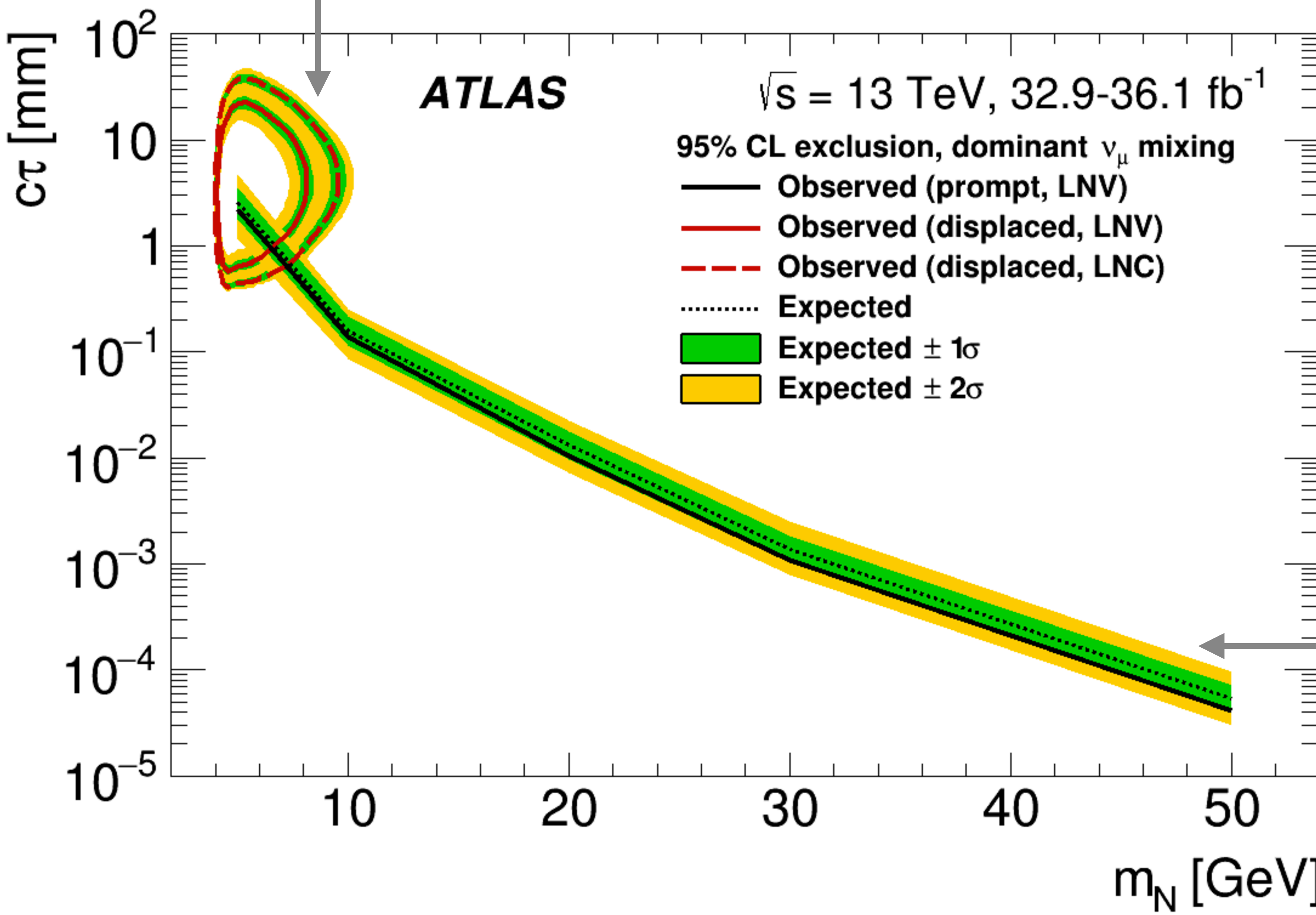
$$N_A = N_B \frac{N_C}{N_D}$$

leptons in DV	same-charge DV	opposite-charge DV	opposite-charge DV estimated
2	B 0	0 (signal region) A	< 2.3 at 90% CL
0	D 169254	168037 C	

Dilepton DV

[1905.09787]

LL exclusion (decay lengths ≈ 1-30 mm)



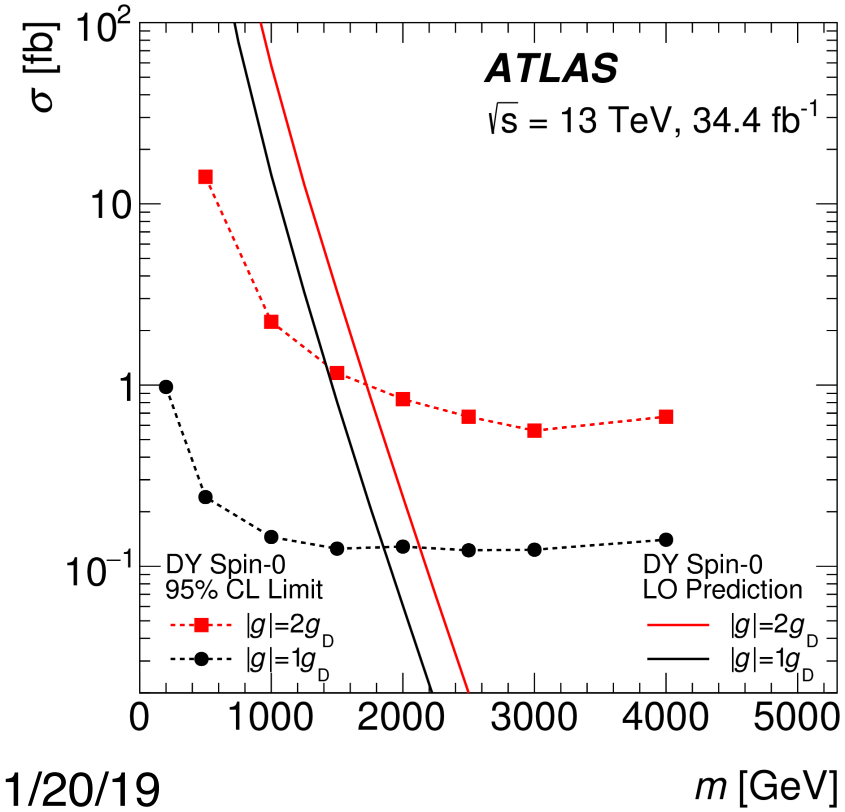
prompt exclusion

Direct Detection

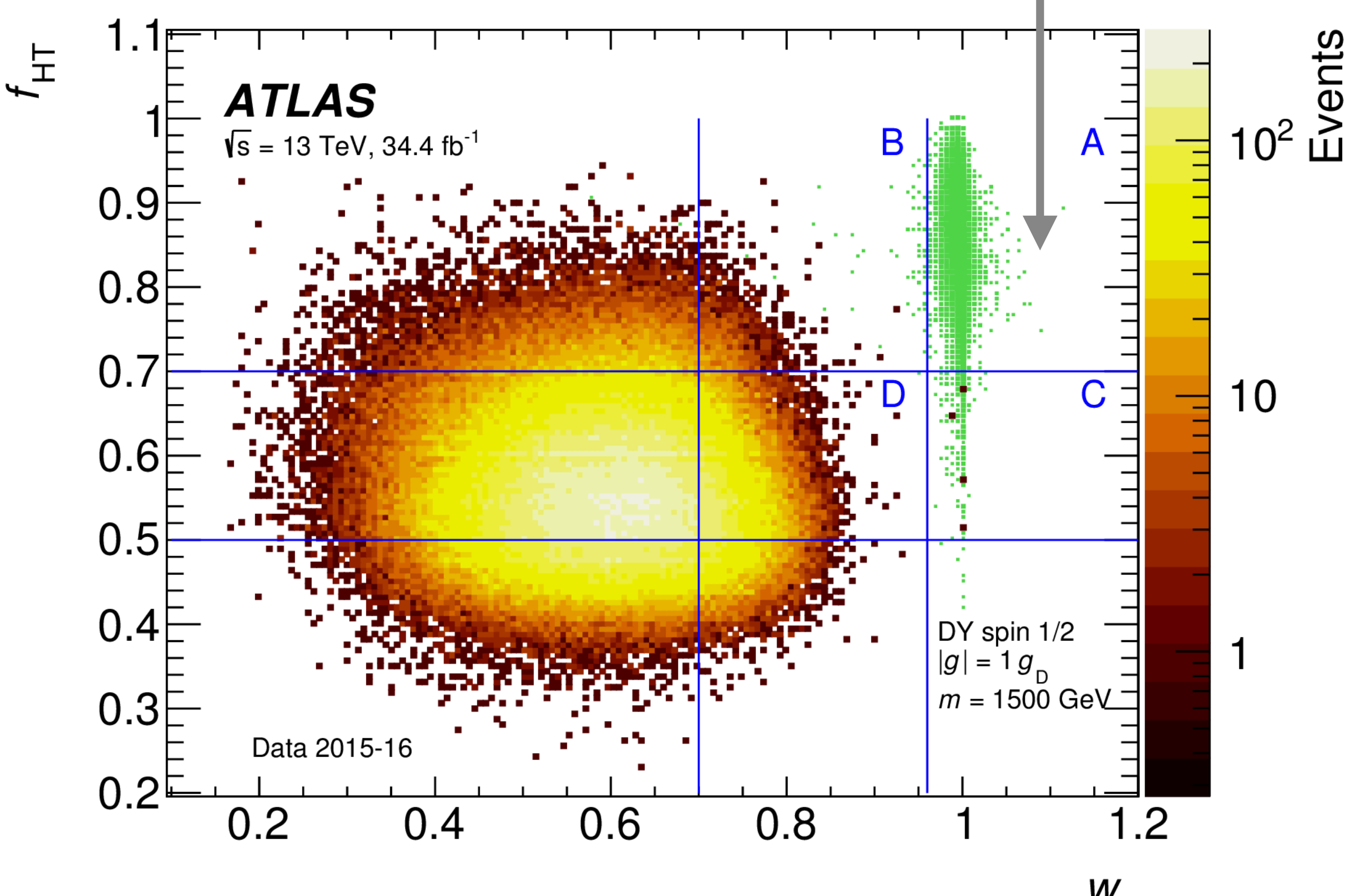
Magnetic Monopole

[1905.10130]

- Monopoles are extremely highly-ionizing particles
  - Produce many high-threshold hits in TRT
  - Stop in ECal, after leaving a pencil-shaped energy deposit
- Dedicated trigger: Based on number and fraction of high-threshold (HT) hits in TRT RoI (w/ HCal energy veto)
- Offline selection: EM cluster seed with E_T > 18 GeV
- Background modeling: ABCD method
  - Fraction of nearby HT TRT hits
  - EM cluster energy dispersion



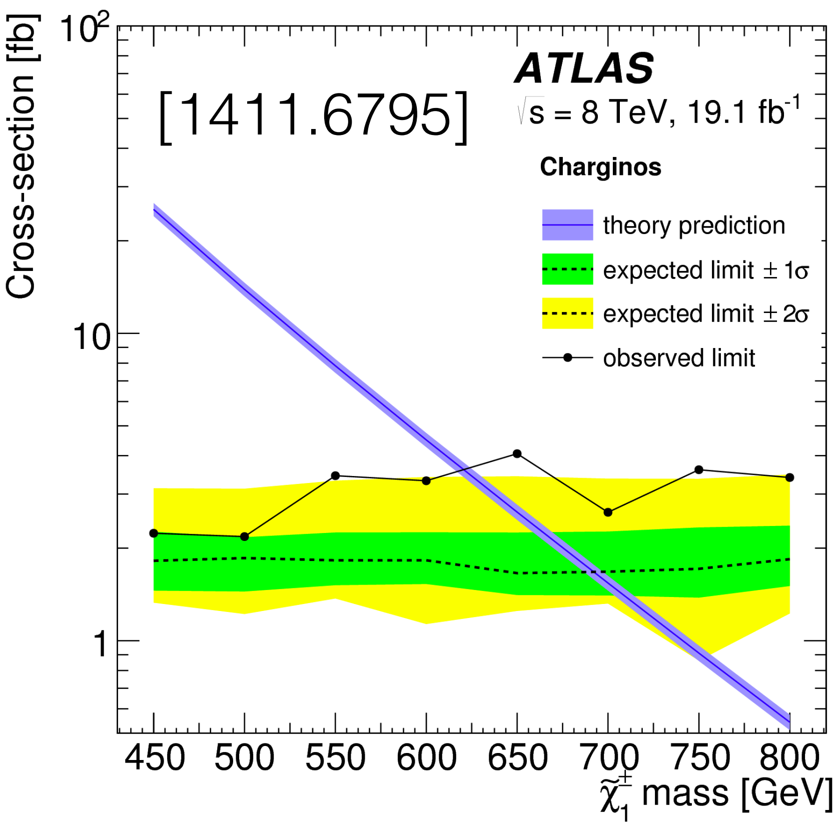
0 events observed

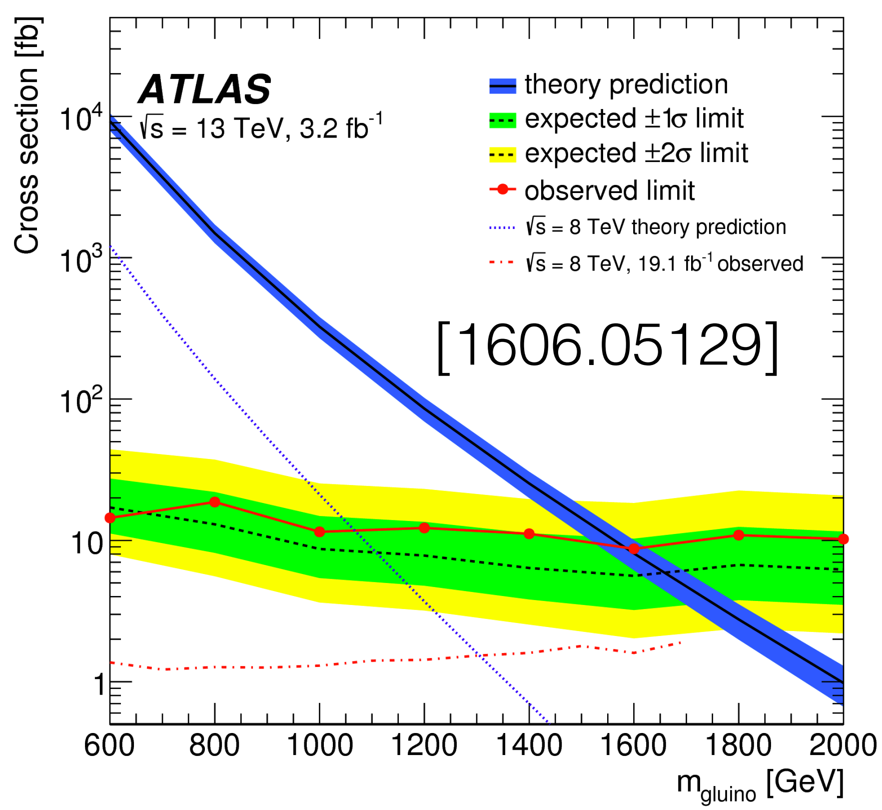


Heavy Stable Charged Particle

[1902.01636]

- Search for several varieties of heavy stable charged particles (HSCP:) squark/gluino R-hadron, chargino, stau
  - Slow, muon-like particle
- Earlier searches from ATLAS and CMS show intriguing trend





CMS: 12.9 fb^{-1} @ 13 TeV

	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

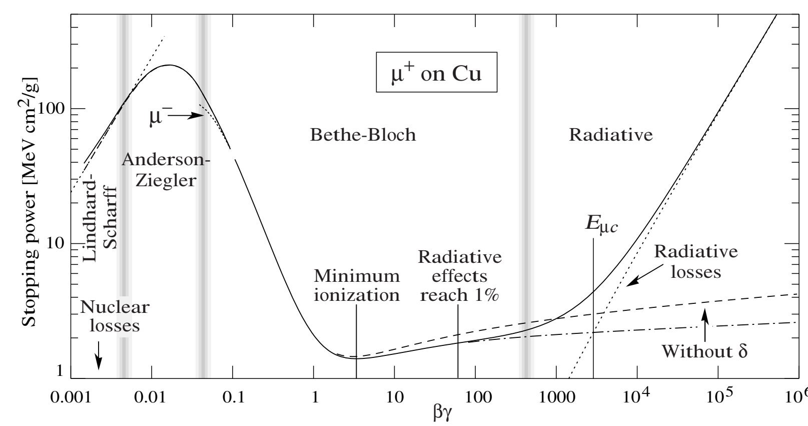
[CMS PAS EXO-16-036]

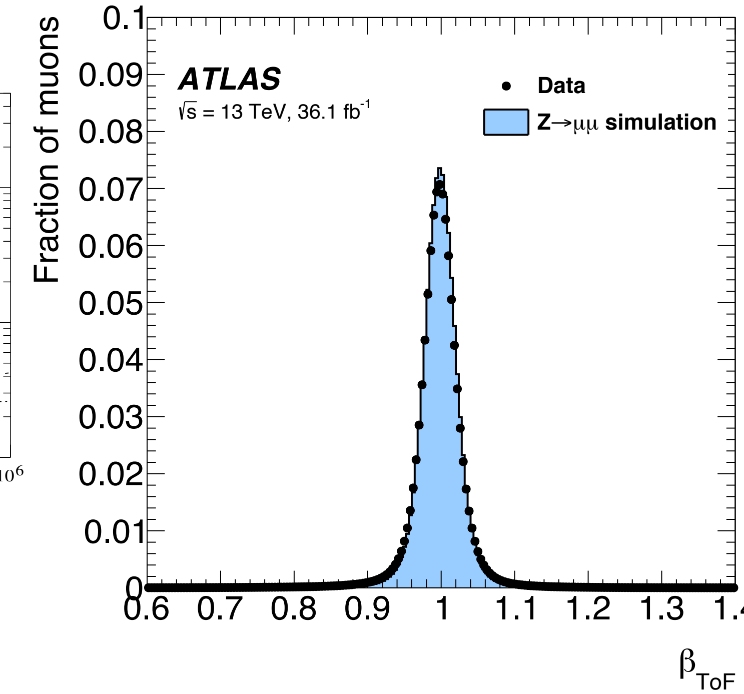
Admittedly, a bit of cherry picking here

[1902.01636]

Heavy Stable Charged Particle

- Conventional triggers: muon and calorimeter-based MET
- Pixel detector: dE/dx ➞ βγ
  - Calibration via low-momentum *p*, $\pi^{\pm}$, $K^{\pm}$
  - Resolution ≈ 14%
- HCal + MS: time of flight ➞ β
  - Calibration via high-momentum μ
  - HCal resolution ≈ 0.07
  - Combined resolution ≈ 0.02
- Candidate mass calculated separately from dE/dx and ToF info using: $m = p/\beta\gamma$





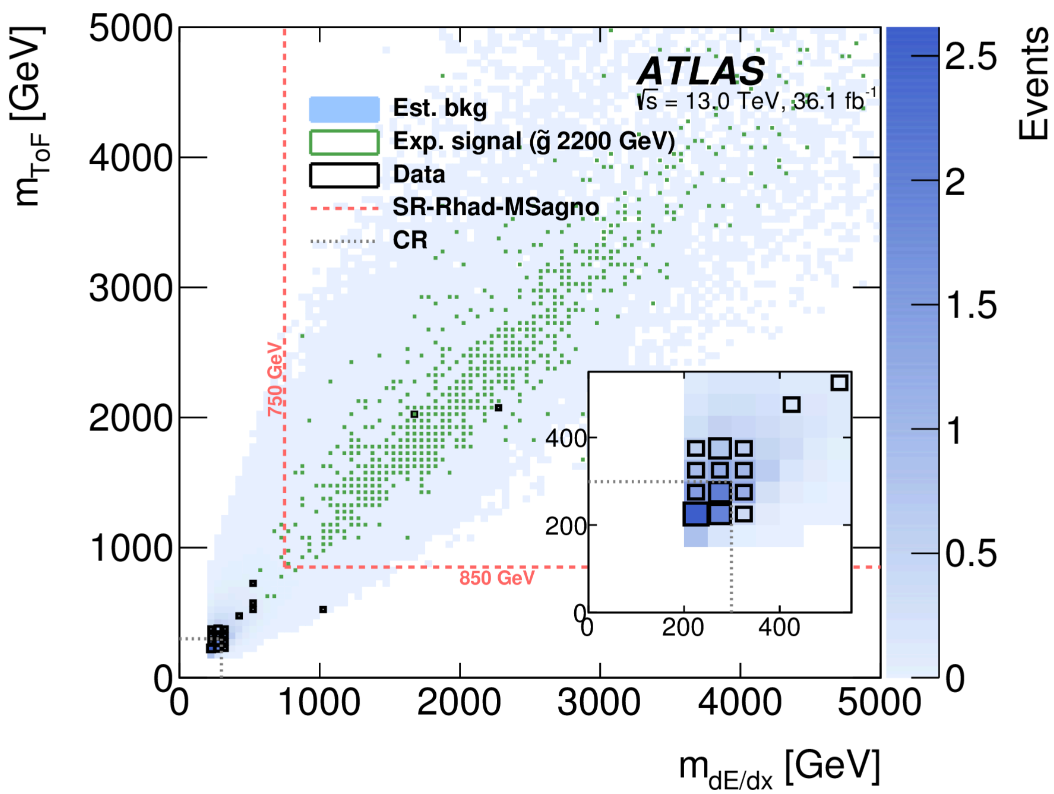
Signal region	Trigger	Candidate selection	Candidates per event	Final requirements				
				$\lvert\eta\rvert$	p [GeV]	β_{ToF}	$(\beta\gamma)_{dE/dx}$	Mass
SR-Rhad-MSagno	$E_{\mathrm{T}}^{\mathrm{miss}}$	ID+CALO	≥ 1	≤ 1.65	≥ 200	≤ 0.75	≤ 1.0	ToF & dE/dx
SR-Rhad-FullDet	$E_{\mathrm{T}}^{\mathrm{miss}}/\mu$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

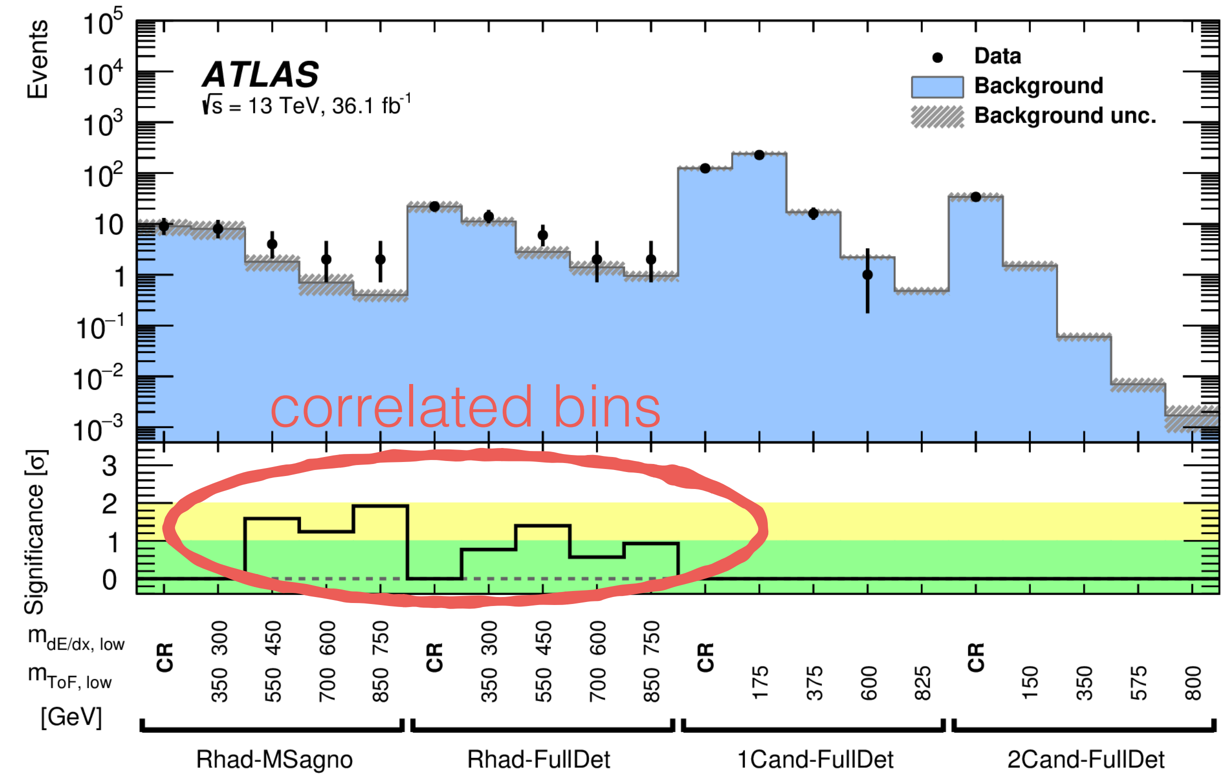
ID+calo does not use MS information

[1902.01636]

Heavy Stable Charged Particle

- Background modeling
  - Probability distribution functions derived for momentum, β_{ToF}, and $(\beta\gamma)_{dE/dx}$ in data sidebands
    - Randomly sampled to determine m_{ToF} (and $m_{dE/dx}$) shape
  - Normalized to data in low mass CR



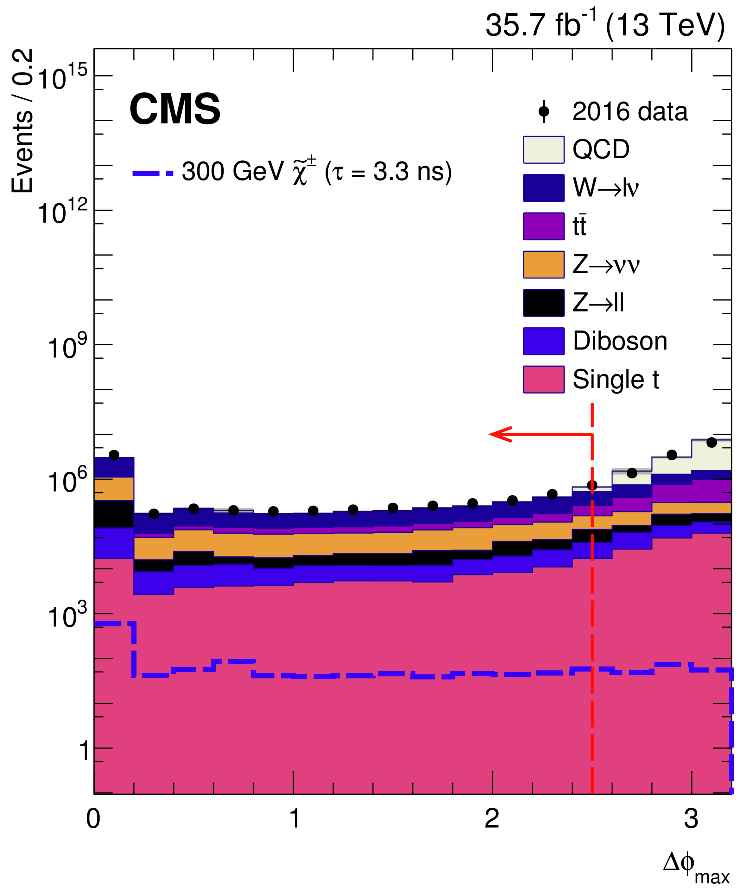


Something to keep an eye on

Disappearing Track

[1804.07321]

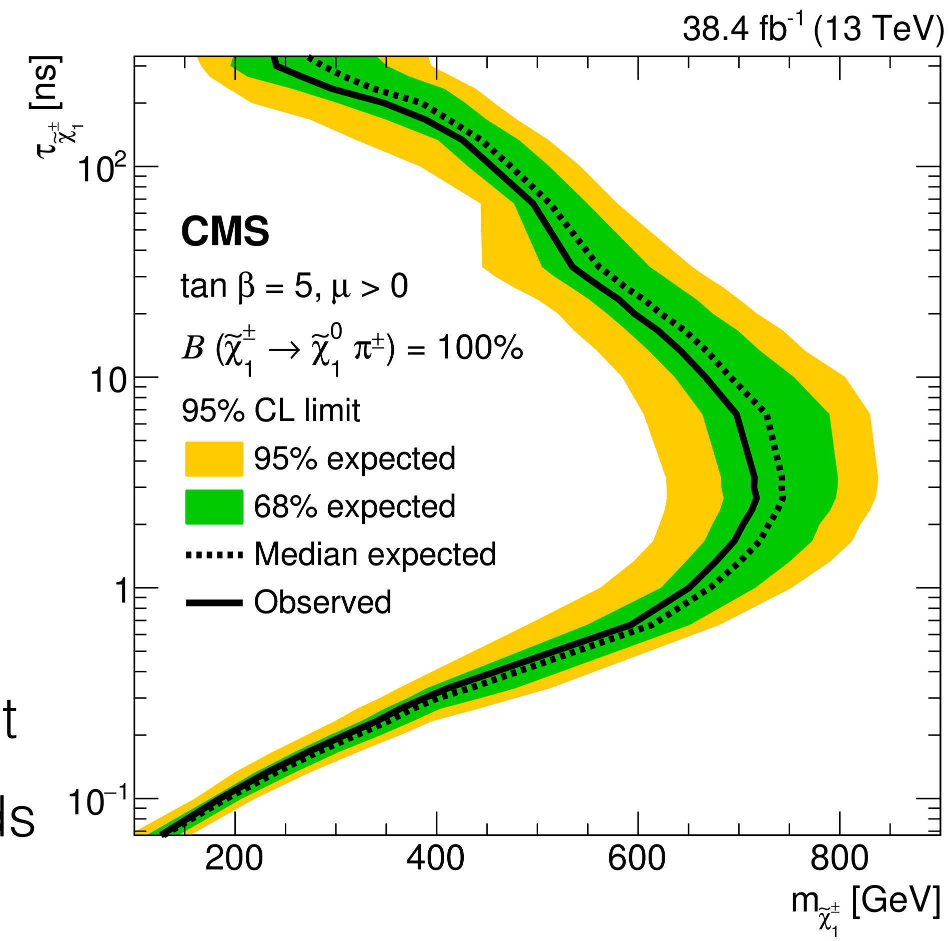
- Search for charged particles which decay within the tracker → "disappearing" track
  - Motivated by anomaly mediated SUSY breaking:
    - Small chargino/neutralino mass gap: chargino → neutralino + soft $\pi^{\pm}$
- Trigger: exploit ISR to create MET
  - Dedicated: MET > 75 GeV + isolated track with p_T > 50 GeV
  - Conventional: Higher MET threshold w/o track requirement
- Offline event selection:
  - MET > 100 GeV
  - Jet w/ p_T > 110 GeV
    - Back to back with MET
  - $\Delta\phi_{max}(j_i,j_k) < 2.5$



Disappearing Track

[1804.07321]

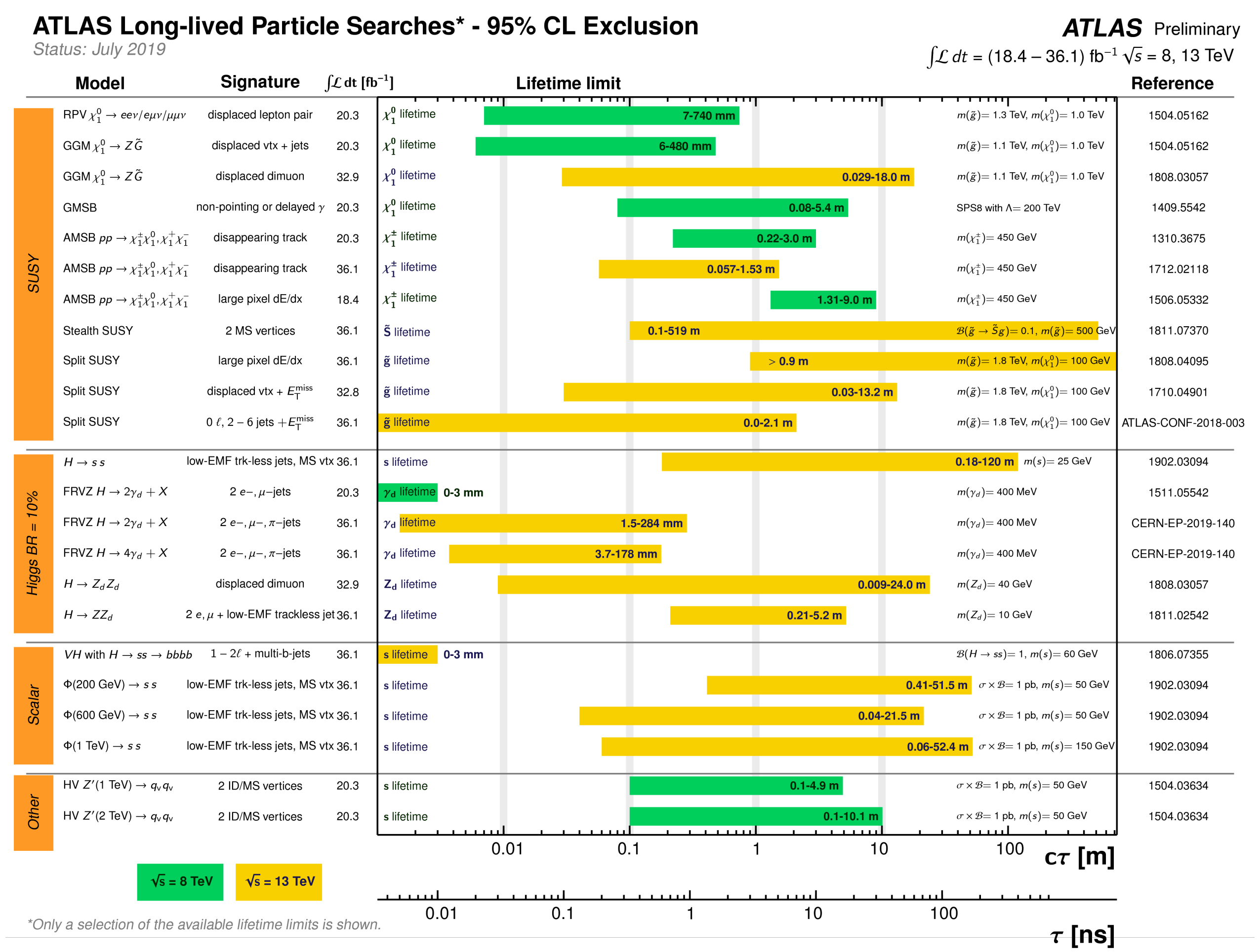
- Disappearing track selection:
  - ≥7 consecutive hits in innermost tracker layers (13 total)
  - ≥3 missing hits in outer tracker layers
  - Isolated from calorimeter deposits
  - Tight impact parameter requirements (combinatorial fakes)
- Dominant backgrounds:
  - Tracks from *e* (τ_h) which undergo hard bremsstrahlung (material interaction)
  - Fake tracks - naturally no corresponding calorimeter deposit
  - Both backgrounds estimated using fully data-driven methods

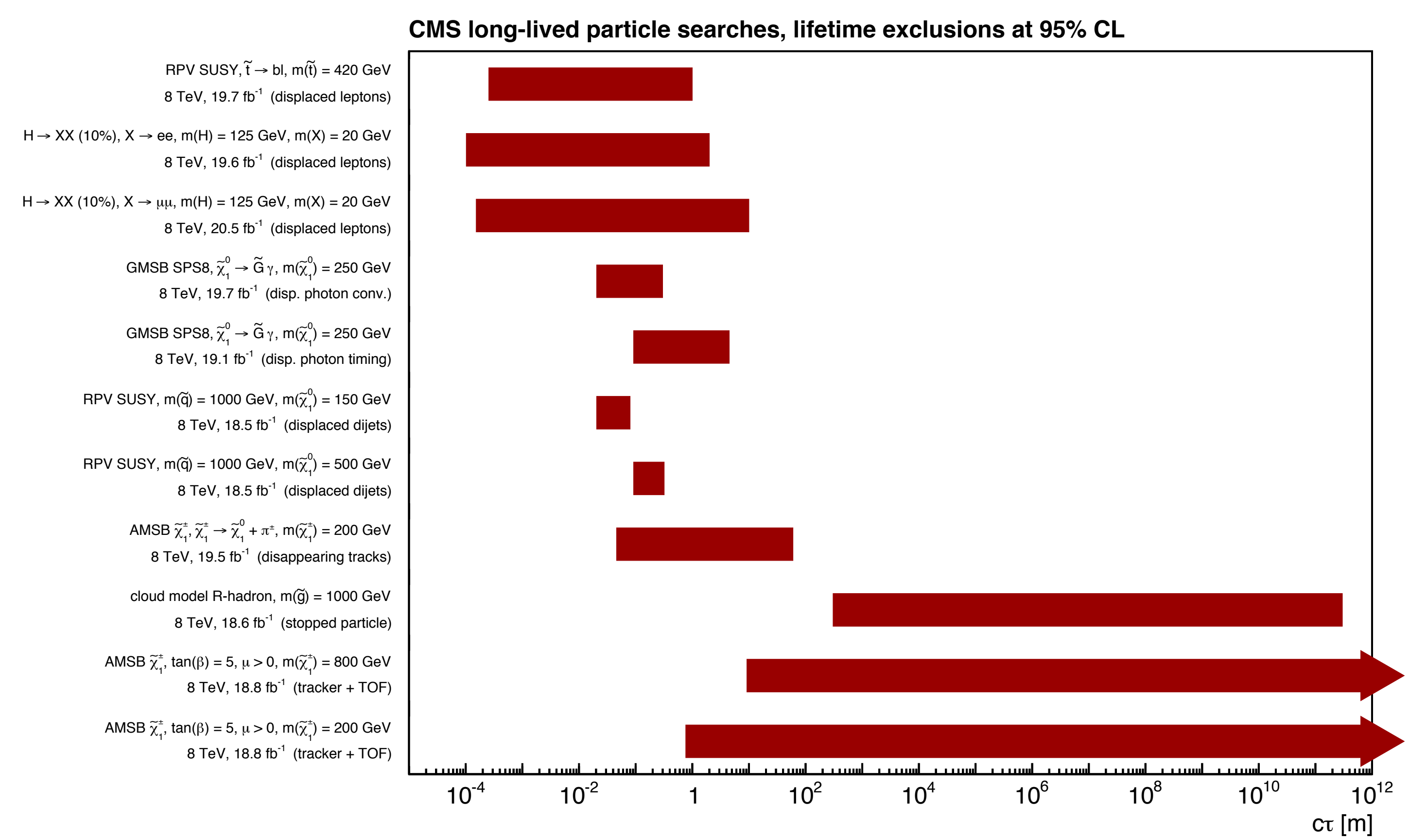


Run period	Estimated number of background events			Observed events
	Leptons	Spurious tracks	Total	
2015	0.1 ± 0.1	$0^{+0.1}_{-0}$	0.1 ± 0.1	1
2016A	$2.0 \pm 0.4 \pm 0.1$	$0.4 \pm 0.2 \pm 0.4$	$2.4 \pm 0.5 \pm 0.4$	2
2016B	$3.1 \pm 0.6 \pm 0.2$	$0.9 \pm 0.4 \pm 0.9$	$4.0 \pm 0.7 \pm 0.9$	4
Total	$5.2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

Summary of Results

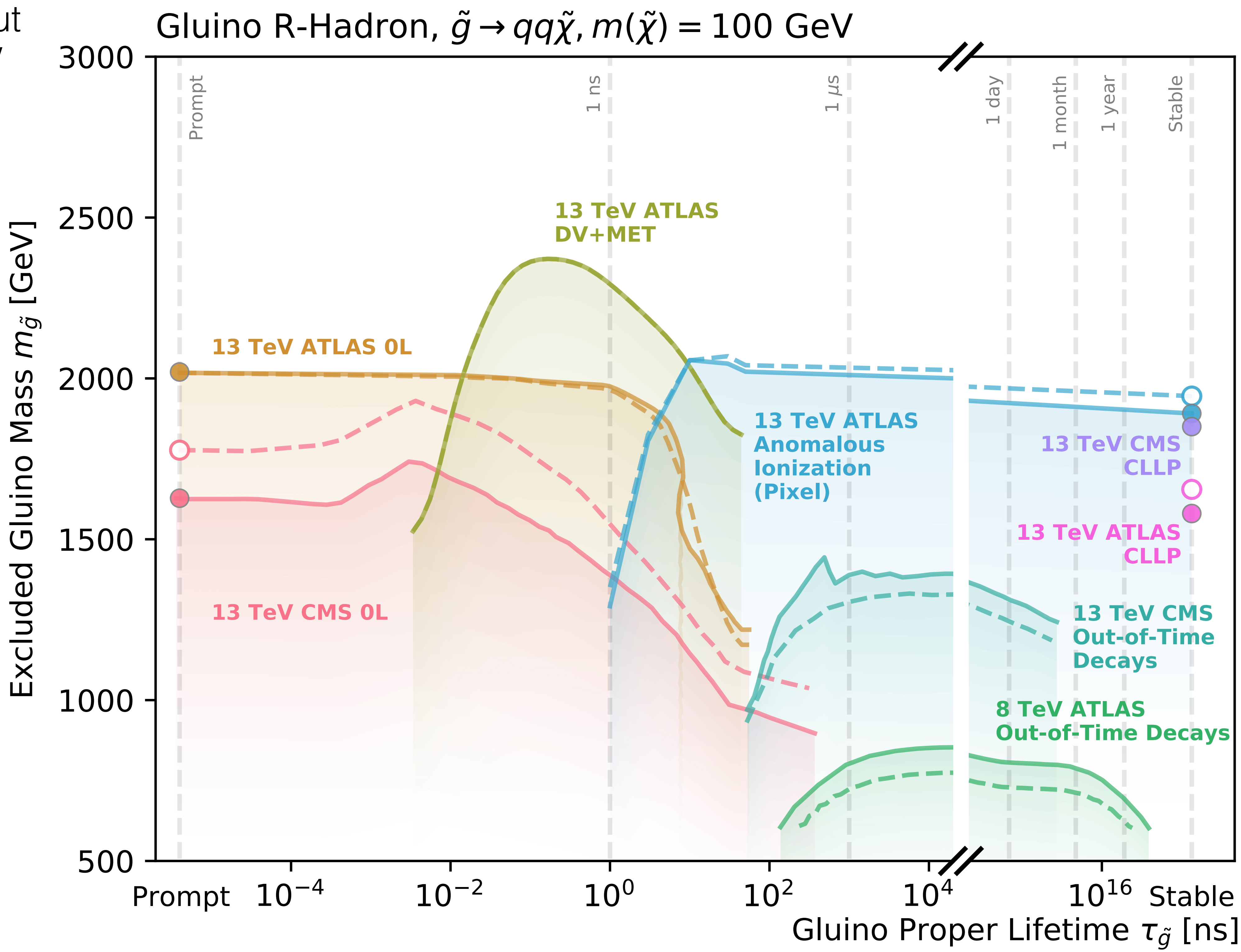
Summary of Results





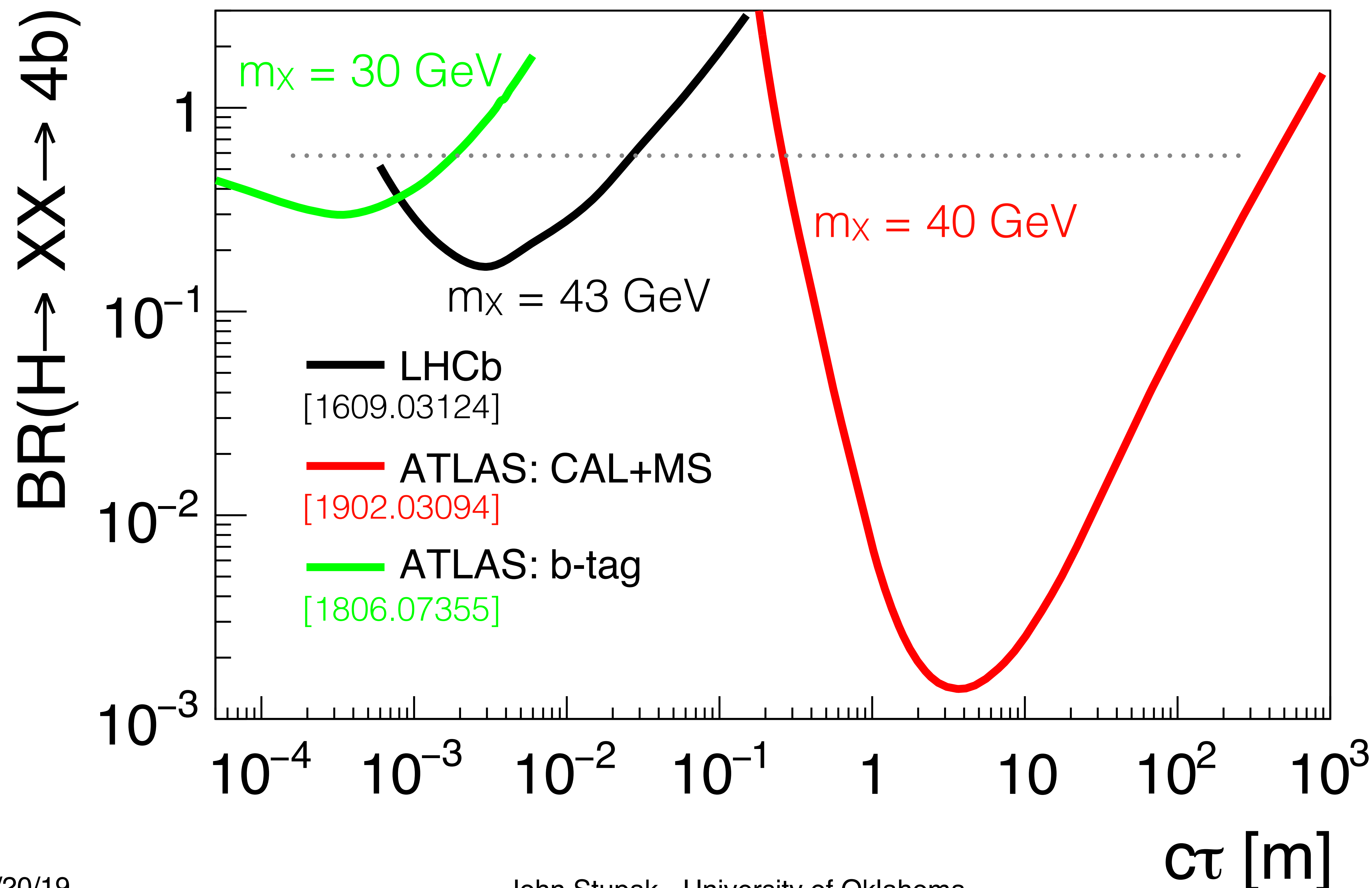
Gluino R-Hadron

somewhat out of date now



[1810.12602]

H→XX→4b



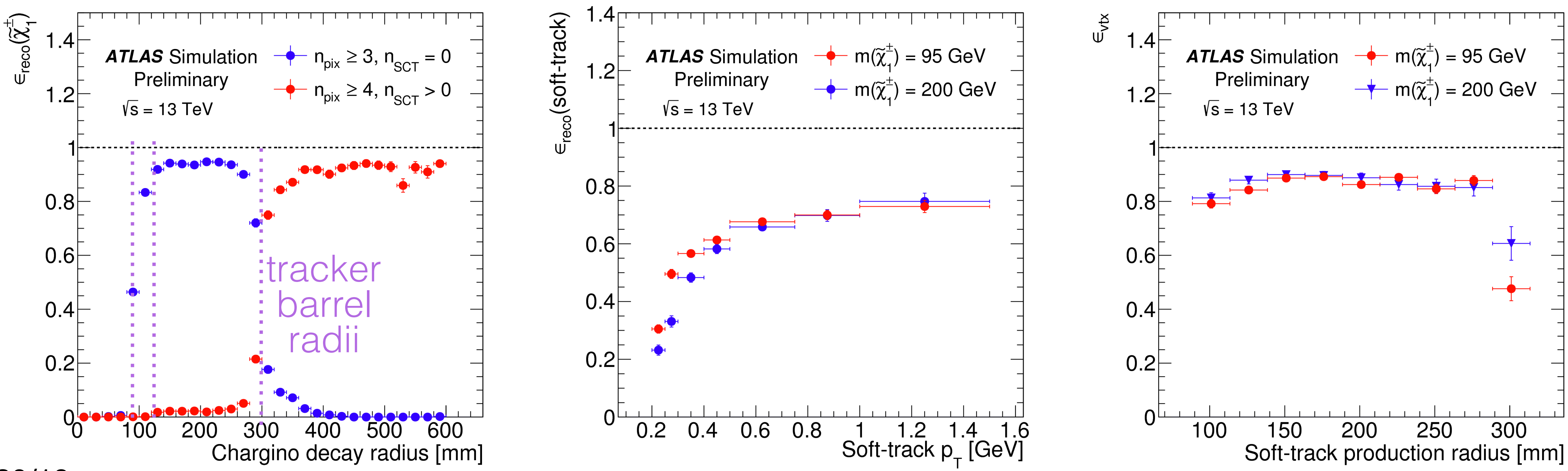
BR(H→ XX→ 4b)
1
10⁻¹
10⁻²
10⁻³
mX = 30 GeV
mX = 43 GeV
mX = 40 GeV
LHCb
[1609.03124]
ATLAS: CAL+MS
[1902.03094]
ATLAS: b-tag
[1806.07355]
10⁻⁴
10⁻³
10⁻²
10⁻¹
1
10
10²
10³
cτ [m]

Future Prospects

[ATL-PHYS-PUB-2019-011]

Disappearing Track

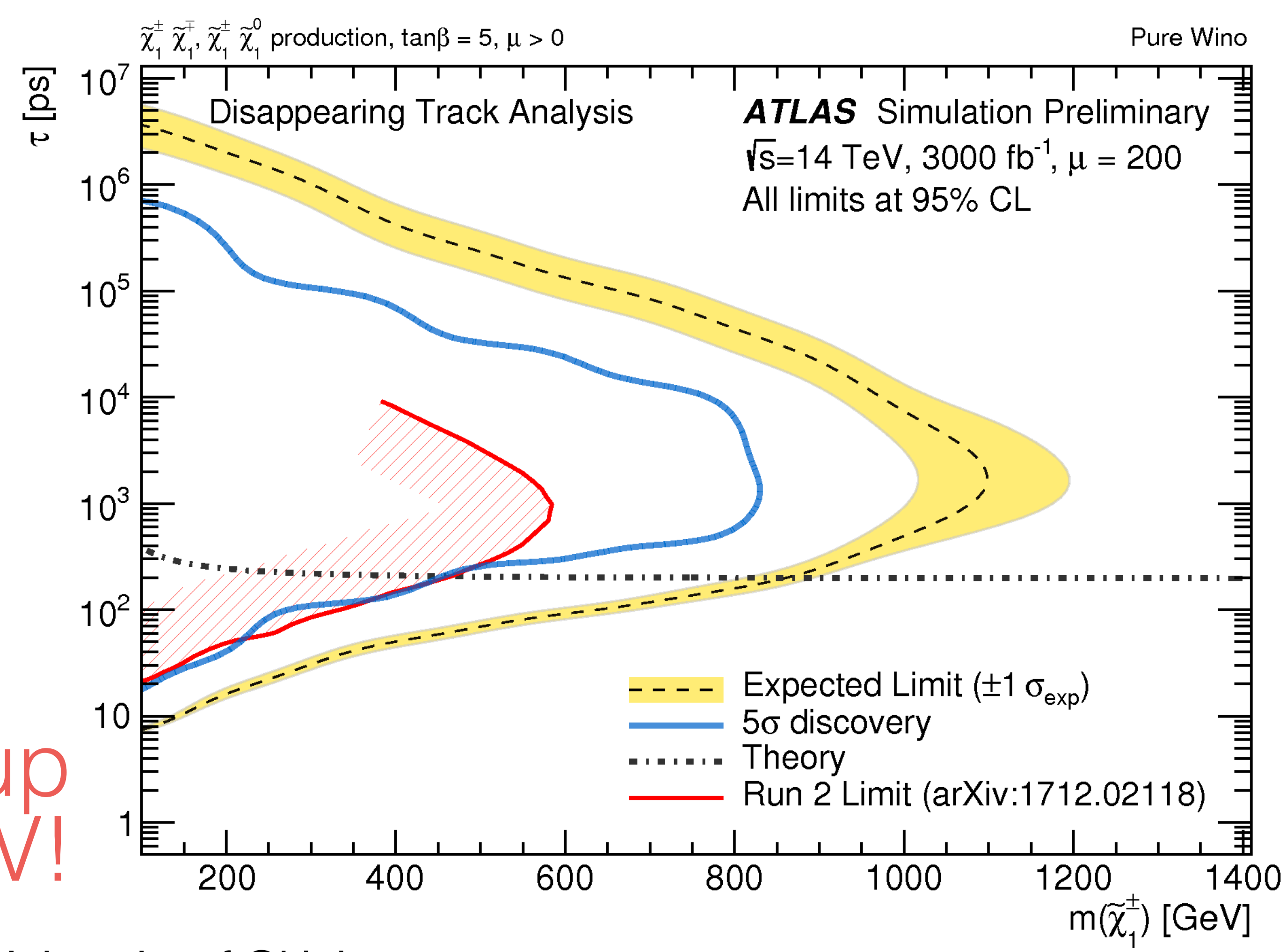
- ATLAS disappearing track reconstruction requires hits on all 4 pixel layers, vetoes hits in SCT
- In pure Higgsino scenario, chargino proper lifetime is just 7 mm ≲ $c\tau$ ≲ 14 mm
    - Use 3-hit "tracklets"
        - Fake rate increases drastically
            - Reconstruct soft (p_T ≳ 300 MeV) $\pi^\pm$ with dedicated algorithm in RoI around tracklet
            - Require consistency with 2 track DV
        - Ready for Run 2 data reprocessing (imminent)



[ATL-PHYS-PUB-2018-031]

Disappearing Track

- For HL-LHC, ATLAS tracker will be replaced
  - 5 pixel layers
  - 4 double-sided silicon strip layers
  - $|\eta| < 4$
- Compared to Run 2 PU, tracklet fake rate will increase by factor ~200
  - Totally dominates the background

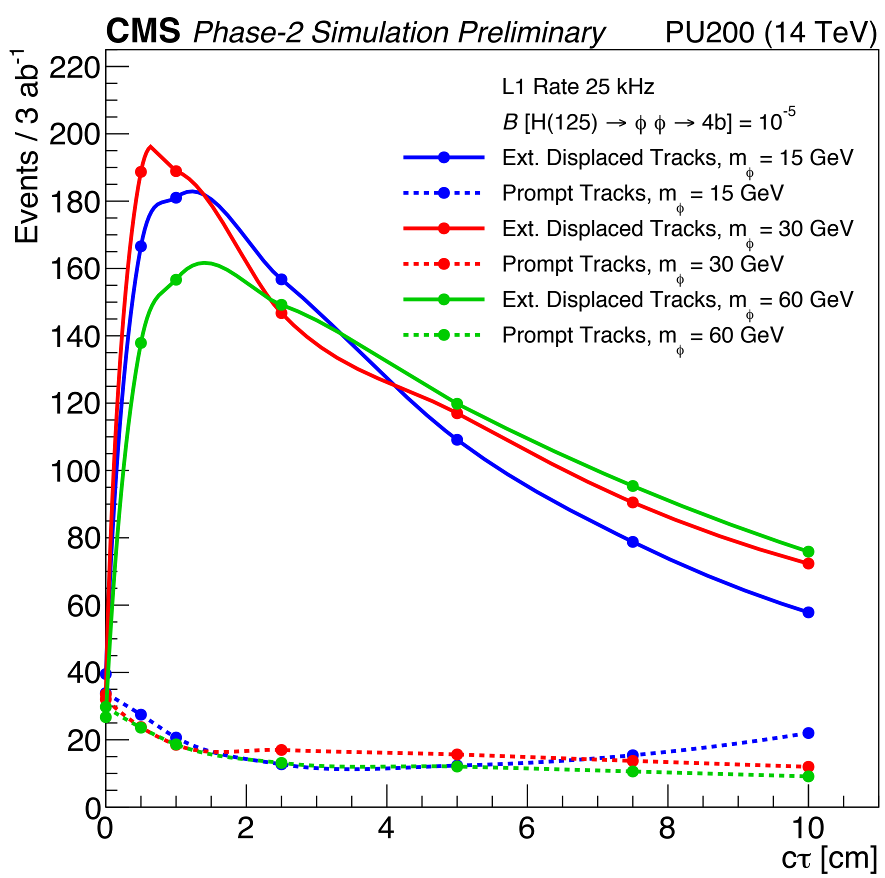


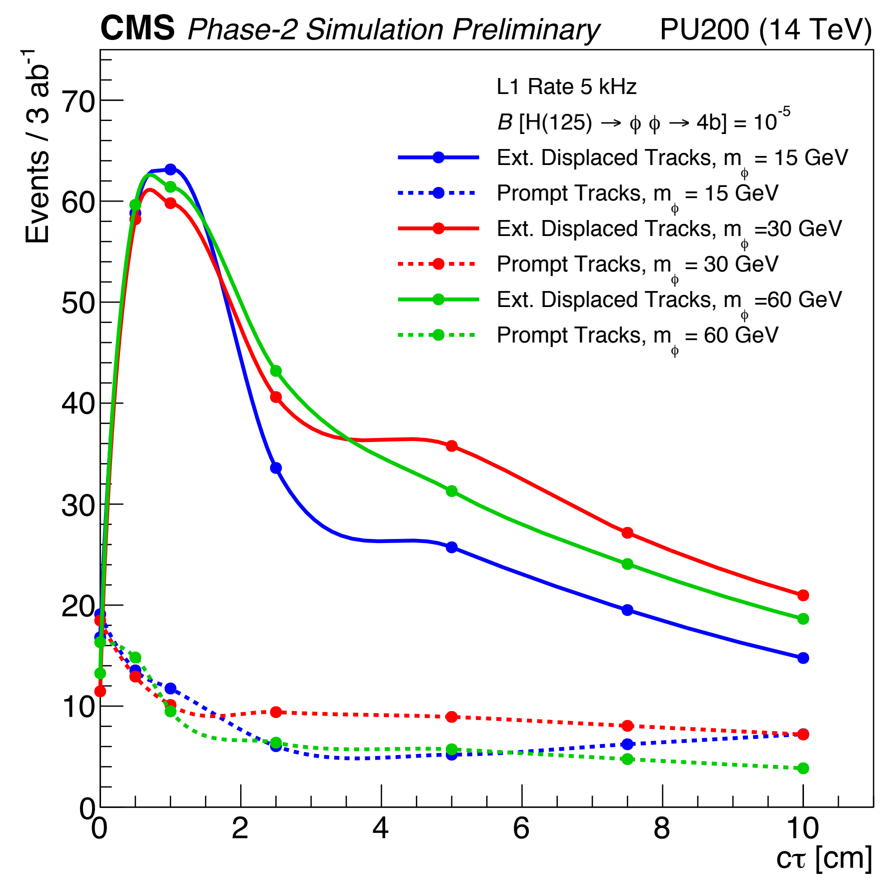
sensitivity up to m ≳ 1 TeV!

L1 Trigger

[CMS PAS FTR-18-018]

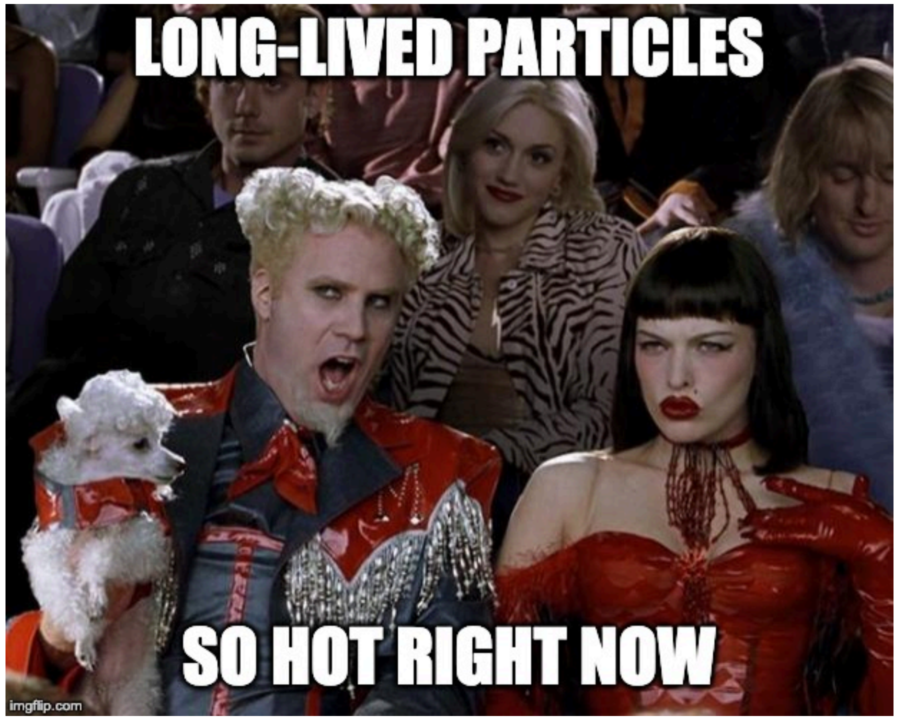
- Triggering for H(125)→XX→4j signal with X proper lifetimes cτ = O(10 mm) is a significant challenge
- CMS plans to have L1 track trigger for HL-LHC
  - Baseline design could be extended to reconstruct tracks with impact parameters in few cm range
  - Track jet clustering can be done in firmware, enabling displaced jet tagging at L1!





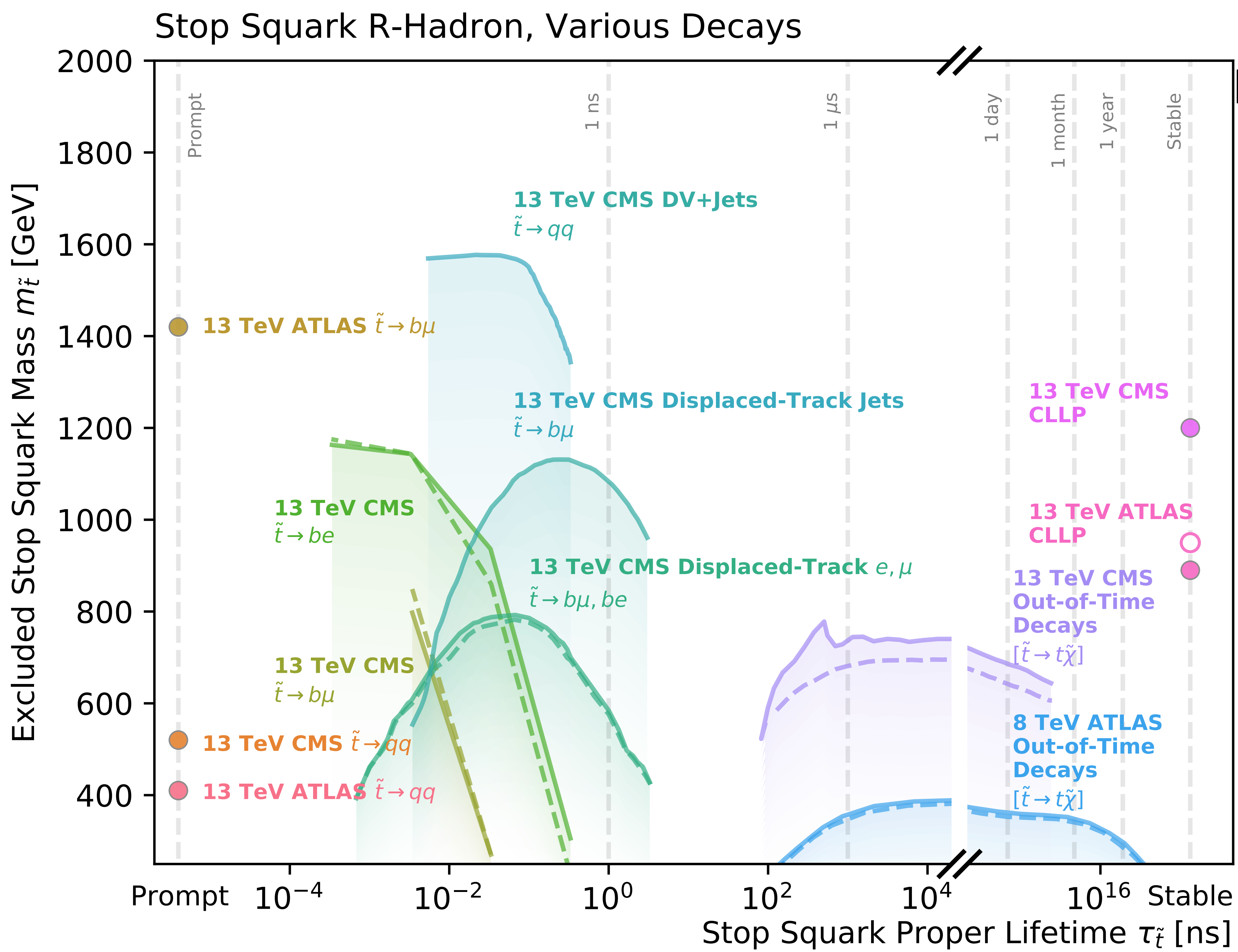
Conclusion

- Many recent/ongoing searches for LLPs at the LHC
  - Interest only likely to grow as conventional searches continue to come up null, and data doubling time increases
- A wide variety of LLP signatures currently covered at the LHC
  - But certainly plenty of gaps and/or room for improvement



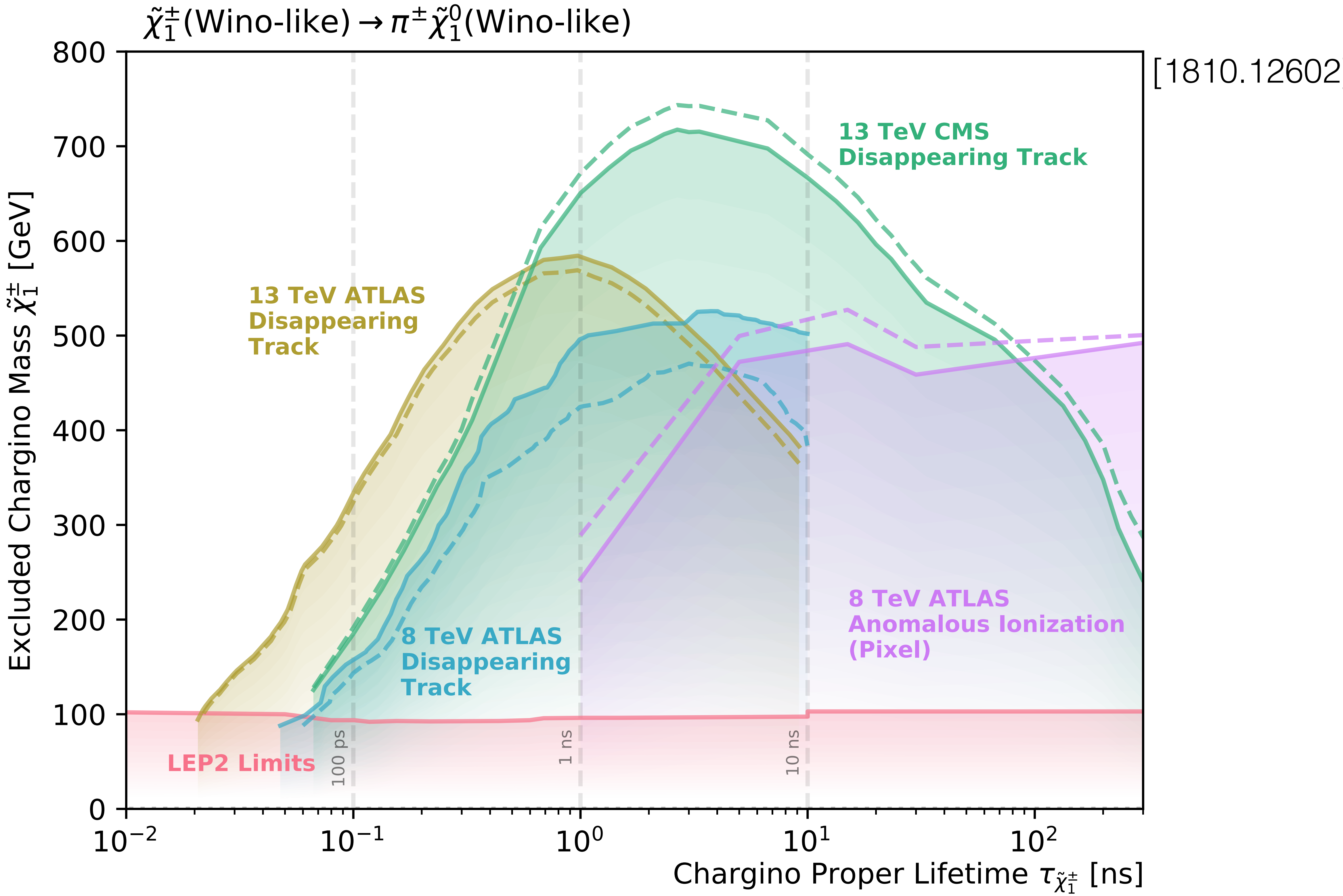
Backup

Stop R-Hadron



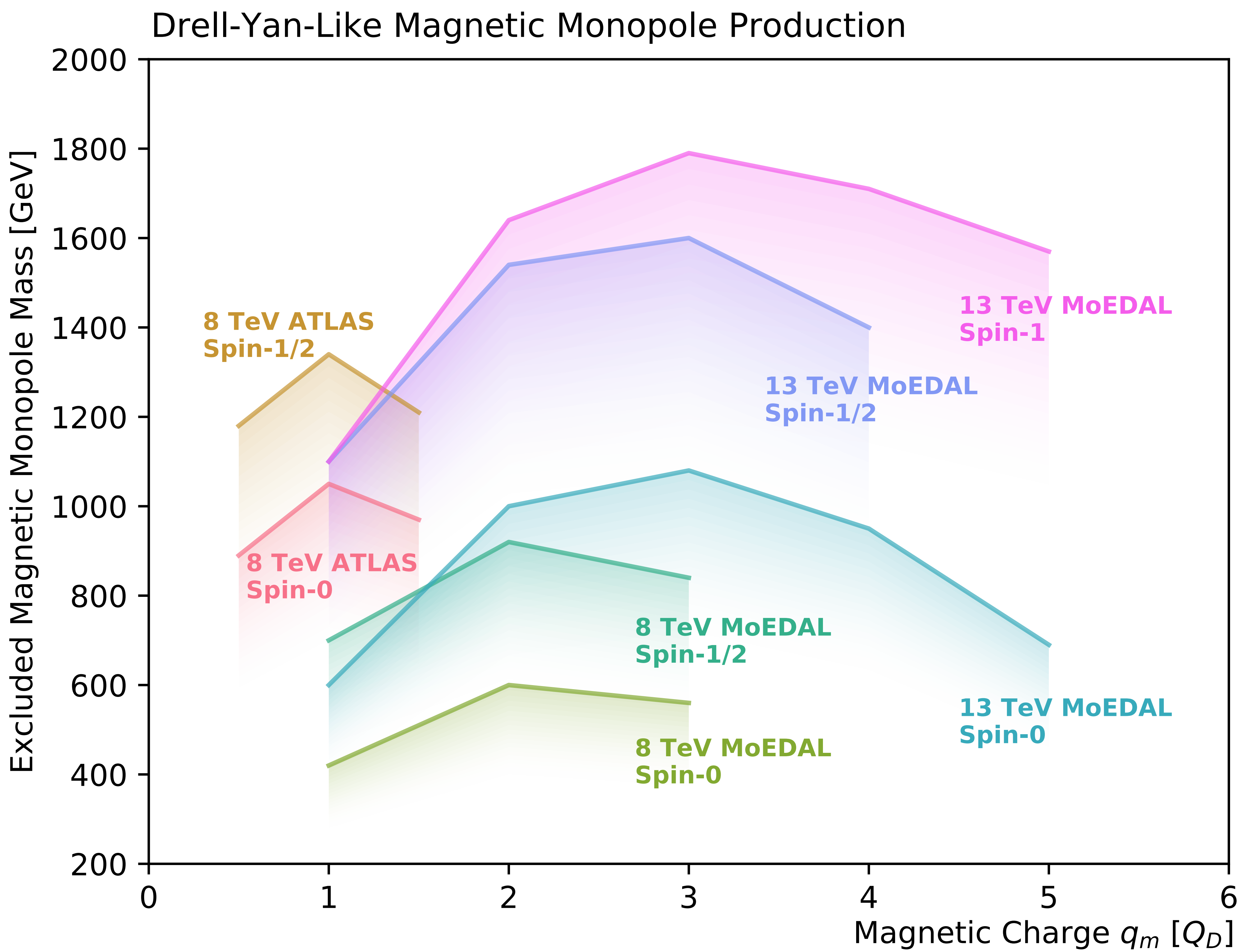
[1810.12602]

Chargino



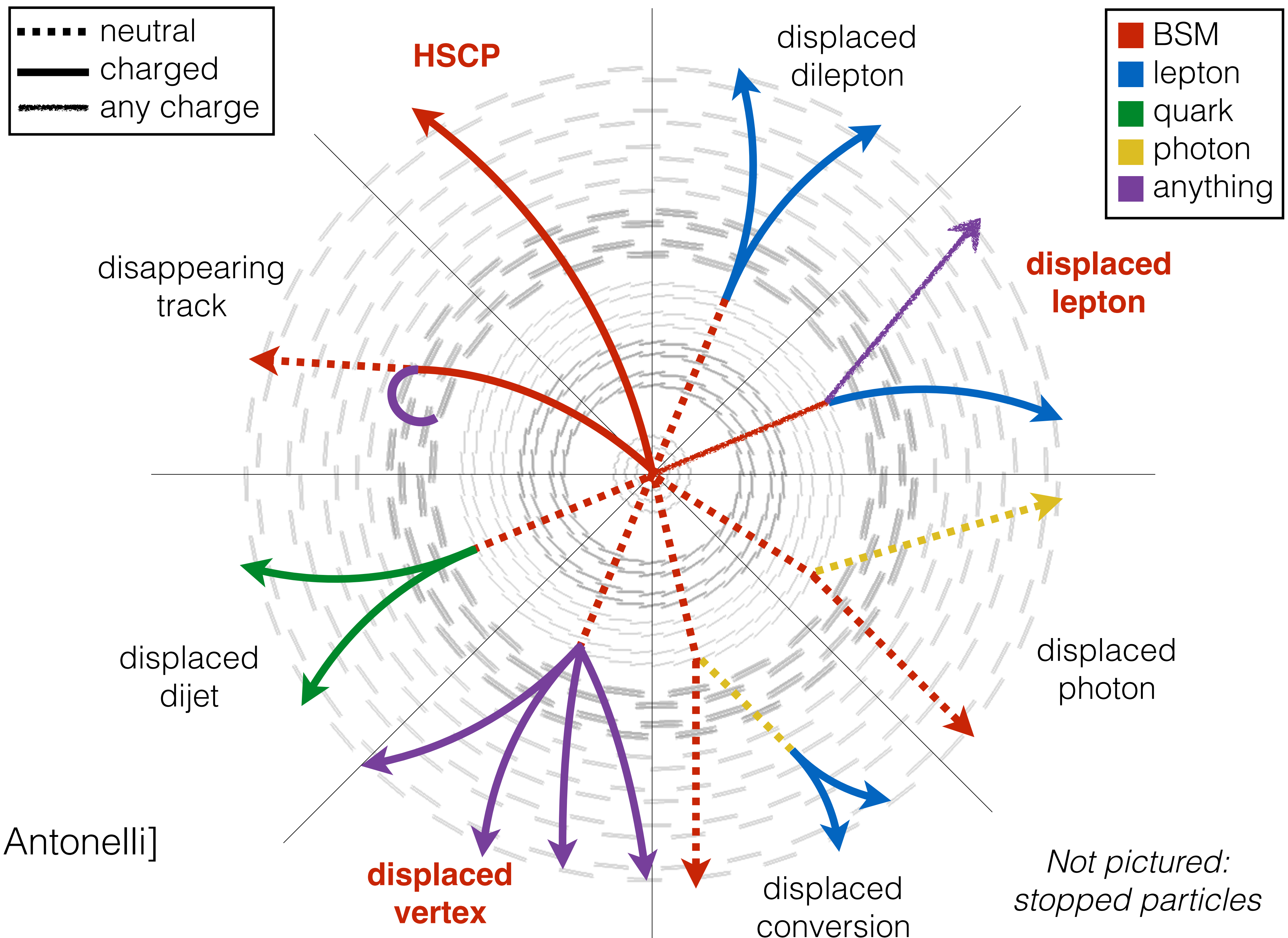
$\tilde{\chi}_1^{\pm}$(Wino-like) → $\pi^{\pm}\tilde{\chi}_1^0$(Wino-like)
[1810.12602]
Excluded Chargino Mass $\tilde{\chi}_1^{\pm}$ [GeV]
Chargino Proper Lifetime $\tau_{\tilde{\chi}_1^{\pm}}$ [ns]
0
100
200
300
400
500
600
700
800
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
100 ps
1 ns
10 ns
13 TeV CMS Disappearing Track
13 TeV ATLAS Disappearing Track
8 TeV ATLAS Disappearing Track
8 TeV ATLAS Anomalous Ionization (Pixel)
LEP2 Limits

Monopole



[1810.12602]

LLP Schematic



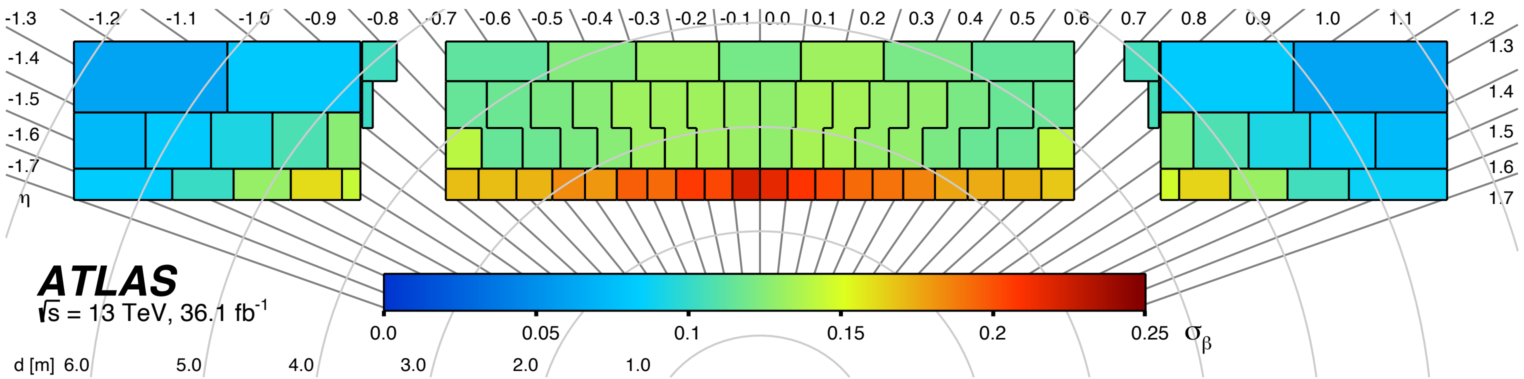
[Jamie Antonelli]

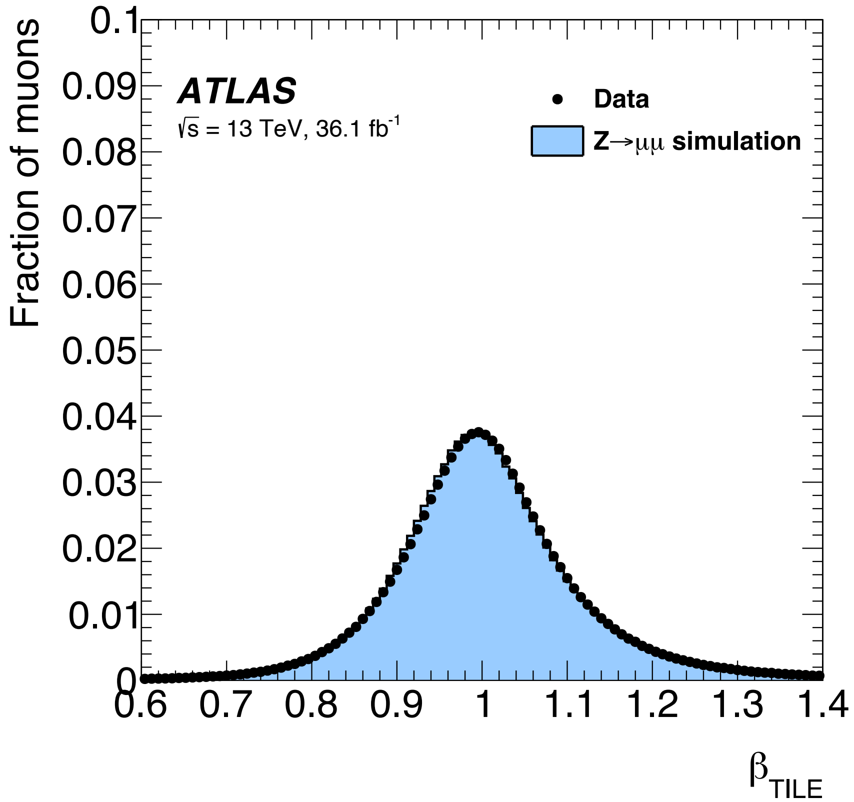
Not pictured:
stopped particles

2

[1902.01636]

Heavy Stable Charged Particle

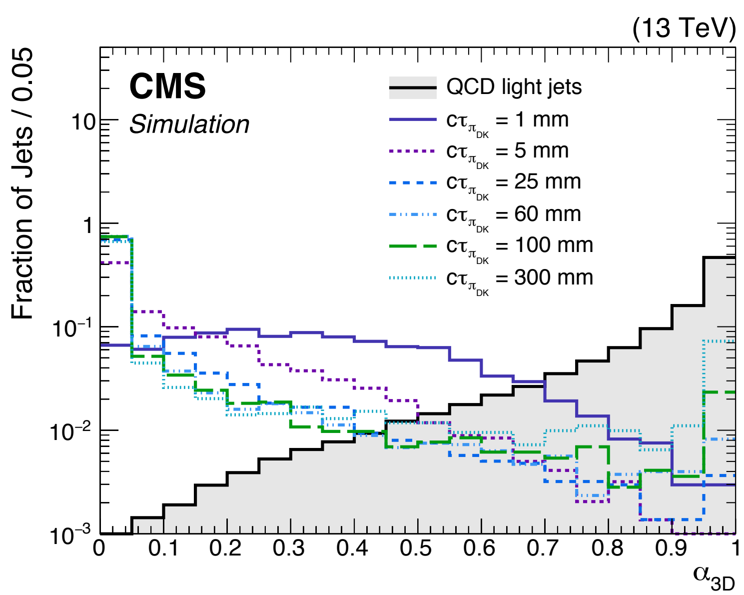


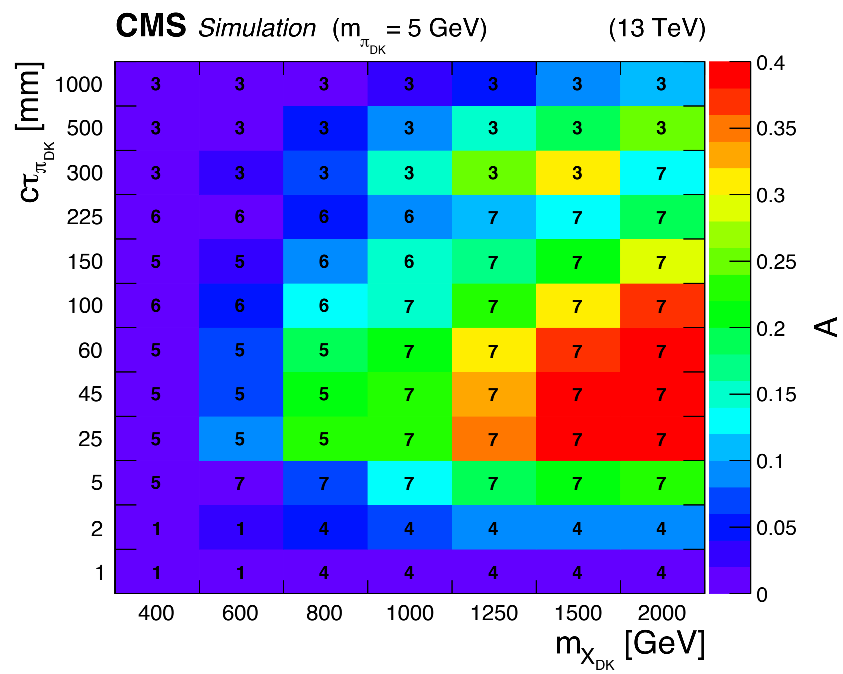


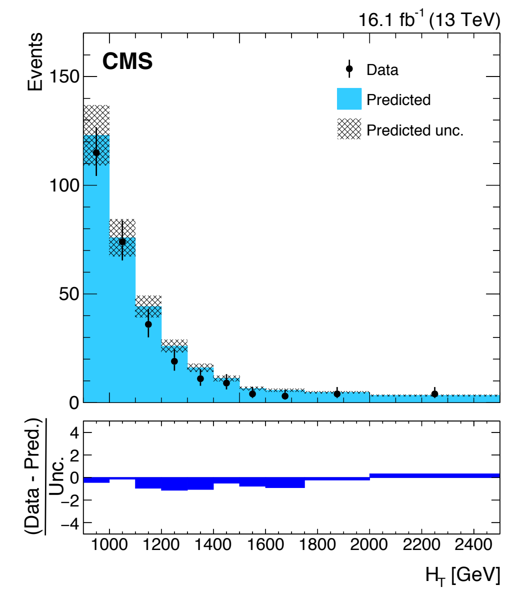
Selection	Lower mass requirements $m_{\text{ToF}}^{\text{min}}$ [GeV]	$m_{dE/dx}^{\text{min}}$ [GeV]	$N_{\text{est.}} \pm \sigma_{N_{\text{est.}}}$	$N_{\text{obs.}}$	p_0	Significance
SR-Rhad-MSagno	350	300	8.0±3.0	8	0.5	
	550	450	1.8±0.6	4	0.056	1.59
	700	600	0.7±0.3	2	0.11	1.24
	850	750	0.4±0.1	2	0.028	1.92
SR-Rhad-FullDet	350	300	11±2	14	0.22	0.77
	550	450	2.8±0.7	6	0.081	1.40
	700	600	1.4±0.4	2	0.28	0.57
	850	750	0.95±0.2	2	0.18	0.93
SR-1Cand-FullDet	175		240±20	227	0.5	
	375		17±2	16	0.5	
	600		2.2±0.2	1	0.5	
	825		0.48±0.07	0	0.5	
SR-2Cand-FullDet	150		1.5±0.3	0	0.5	
	350		0.06±0.01	0	0.5	
	575		0.007±0.002	0	0.5	
	800		0.0017±0.0009	0	0.5	

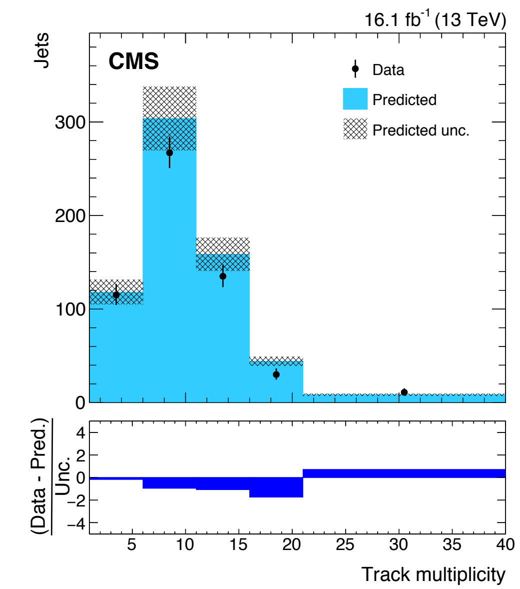
Emerging Jets

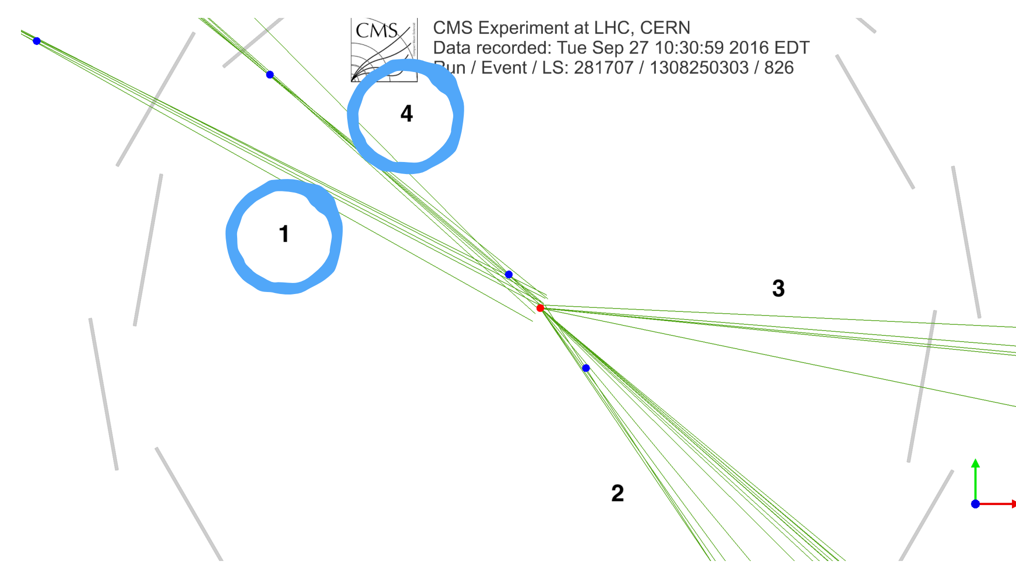
[1810.10069]









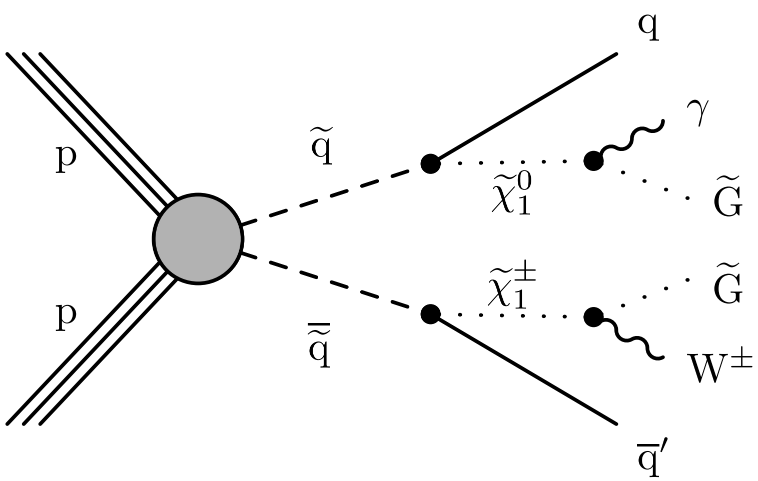


Set number	Source of uncertainty (%)	
	b quark fraction	non-b quark composition
1	2.8	1.4
2	0.6	4.4
3	2.9	28.3
4	5.0	4.4
5	0.9	4.0
6	1.6	2.1
7	1.0	6.3

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	$(14.6 \pm 2.6)\times10^2$	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

Source	Uncertainty (%)
Track modeling	<1 – 3
MC event count	2 – 17
Integrated luminosity	2.5
Pileup	<1 – 5
Trigger	6 – 12
JES	<1 – 9
PDF	<1 – 4

Delayed/Non-Pointing Photon



optimized ABCD boundaries:

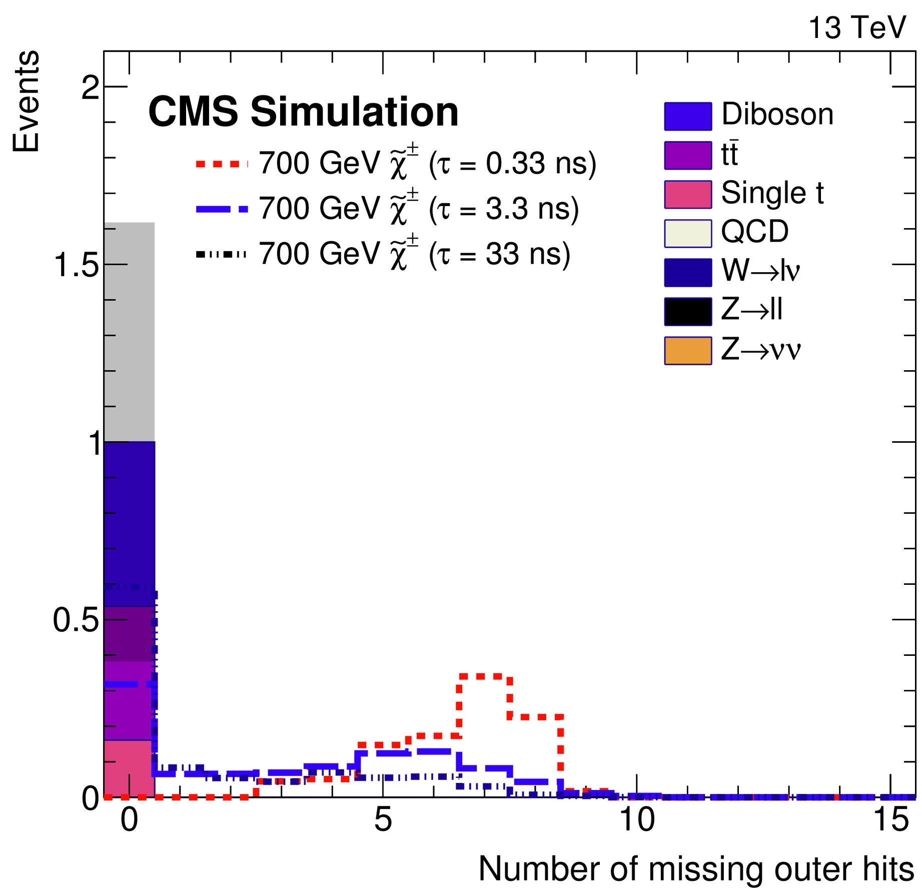
$c\tau$ (m)	$\Lambda \leq 300$ TeV 2016	$\Lambda \leq 300$ TeV 2017γ	$\Lambda \leq 300$ TeV 2017$\gamma\gamma$	$\Lambda > 300$ TeV 2016	$\Lambda > 300$ TeV 2017γ	$\Lambda > 300$ TeV 2017$\gamma\gamma$
(0, 0.1)	0 , 250	0.5 , 300	0.5 , 150	0 , 250	0.5 , 300	0.5 , 200
(0.1 , 100)	1.5 , 100	1.5 , 200	1.5 , 150	1.5 , 150	1.5 , 300	1.5 , 200

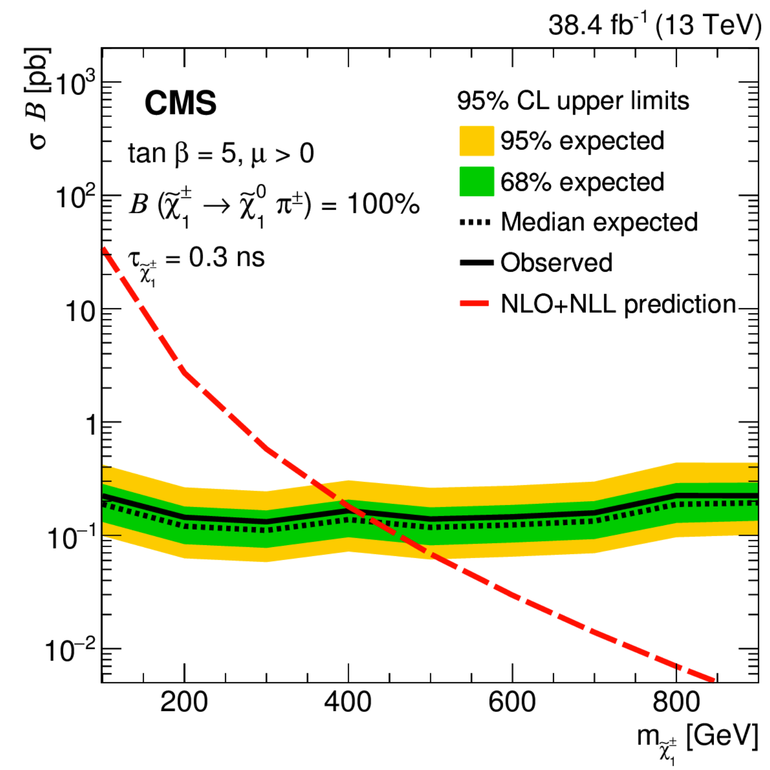
Systematic uncertainty	Sig/Bkg	Bins	2016	2017	Correlation
Integrated luminosity	Sig	A,B,C,D	2.5%	2.3%	Uncorrelated
Photon energy scale	Sig	A,B,C,D	1%	2%	Correlated
Photon energy resolution	Sig	A,B,C,D	1%	1%	Correlated
Jet energy scale	Sig	A,B,C,D	1.5%	2%	Correlated
Jet energy resolution	Sig	A,B,C,D	1.5%	1.5%	Uncorrelated
Photon time bias	Sig	A,B,C,D	1.5%	1%	Correlated
Photon time resolution	Sig	A,B,C,D	0.5%	0.5%	Correlated
Trigger efficiency	Sig	A,B,C,D	2%	<1%	Uncorrelated
Photon identification	Sig	A,B,C,D	2%	3%	Correlated
Closure in bin C ($c\tau \leq 0.1$ m)	Bkg	C	2%	3.5%	Correlated
Closure in bin C ($c\tau > 0.1$ m)	Bkg	C	90%	90%	Correlated

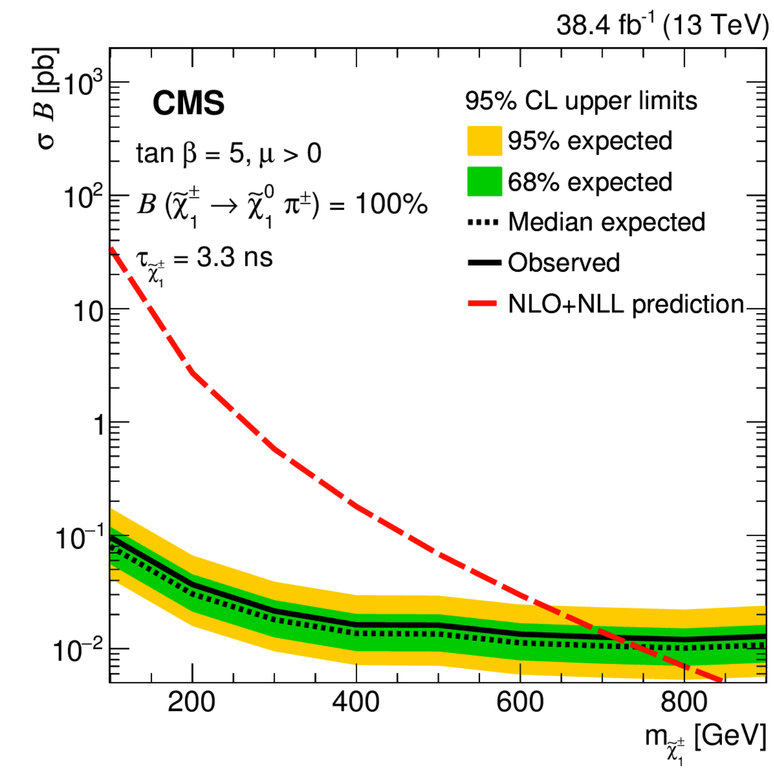
Bin boundary [t_γ (ns), p_T^{miss} (GeV)]		A	B	C	D
2017γ category					
(0.5, 300)	N_{obs}^{data}	458 372	281	41	67 655
	$N_{bkg}^{post\text{-}fit}$	458 370 ± 660	281 ± 15	41.4 ± 2.4	67 660 ± 280
	$N_{bkg(no\ C)}^{post\text{-}fit}$	460 369 ± 660	281 ± 16	41.5 ± 2.7	67 660 ± 280
(1.5, 200)	N_{obs}^{data}	524 652	1364	1	332
	$N_{bkg}^{post\text{-}fit}$	524 650 ± 710	1364 ± 36	0.9 ± 0.8	330 ± 20
	$N_{bkg(no\ C)}^{post\text{-}fit}$	524 650 ± 700	1364 ± 35	0.9 ± 1.0	330 ± 20
(1.5, 300)	N_{obs}^{data}	525 694	322	0	333
	$N_{bkg}^{post\text{-}fit}$	525 690 ± 700	322 ± 17	0.19 ± 0.21	330 ± 20
	$N_{bkg(no\ C)}^{post\text{-}fit}$	525 690 ± 700	322 ± 17	0.20 ± 0.24	330 ± 20
2017$\gamma\gamma$ category					
(0.5, 150)	N_{obs}^{data}	21 640	362	56	3201
	$N_{bkg}^{post\text{-}fit}$	21 640 ± 140	364 ± 17	54.0 ± 3.0	3200 ± 60
	$N_{bkg(no\ C)}^{post\text{-}fit}$	21 640 ± 140	362 ± 18	53.6 ± 3.3	3200 ± 60
(0.5, 200)	N_{obs}^{data}	21 863	139	24	3233
	$N_{bkg}^{post\text{-}fit}$	21 860 ± 140	142 ± 11	21.1 ± 1.7	3240 ± 60
	$N_{bkg(no\ C)}^{post\text{-}fit}$	21 860 ± 140	139 ± 11	20.6 ± 1.8	3230 ± 60
(1.5, 150)	N_{obs}^{data}	24 824	418	0	17
	$N_{bkg}^{post\text{-}fit}$	24 820 ± 150	420 ± 20	0.25 ± 0.28	16.7 ± 4.4
	$N_{bkg(no\ C)}^{post\text{-}fit}$	24 820 ± 150	420 ± 20	0.29 ± 0.36	17.0 ± 4.4
(1.5, 200)	N_{obs}^{data}	25 079	163	0	17
	$N_{bkg}^{post\text{-}fit}$	25 080 ± 150	163 ± 12	0.11 ± 0.12	16.9 ± 4.4
	$N_{bkg(no\ C)}^{post\text{-}fit}$	25 080 ± 150	163 ± 12	0.11 ± 0.14	17.0 ± 4.4

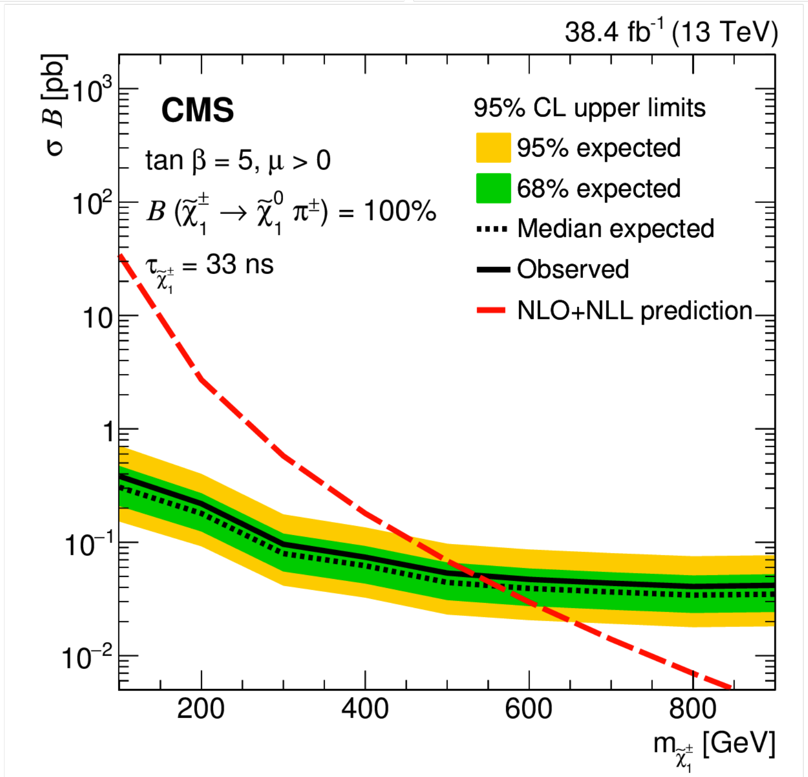
Disappearing Track

[1804.07321]



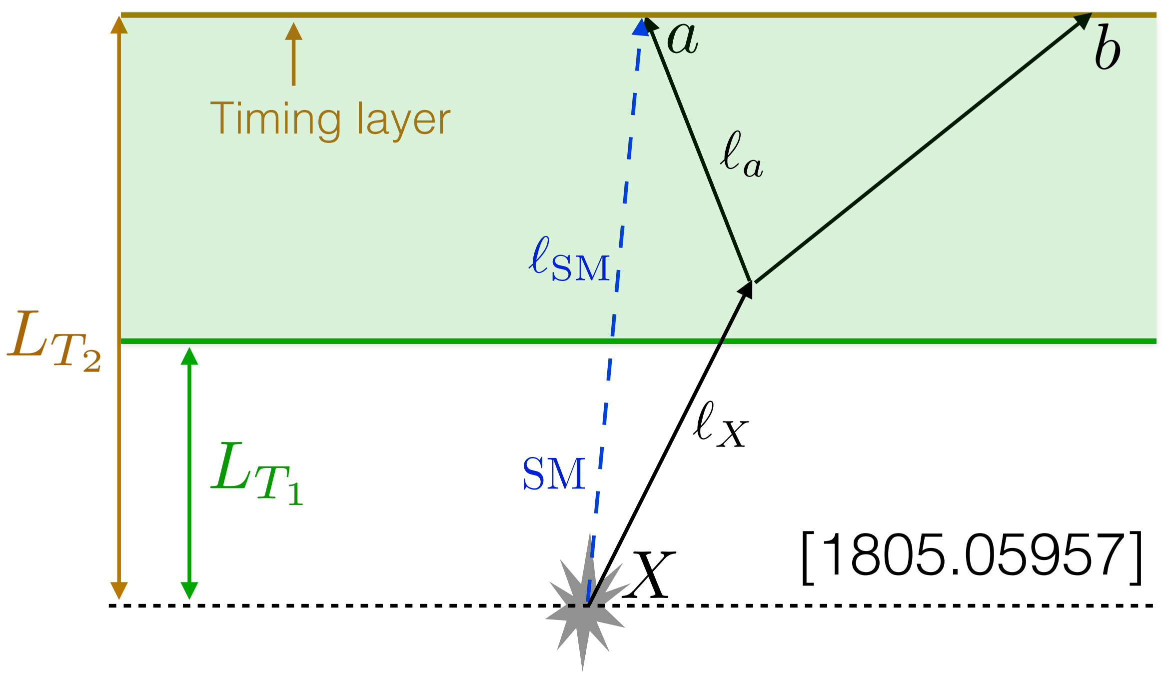


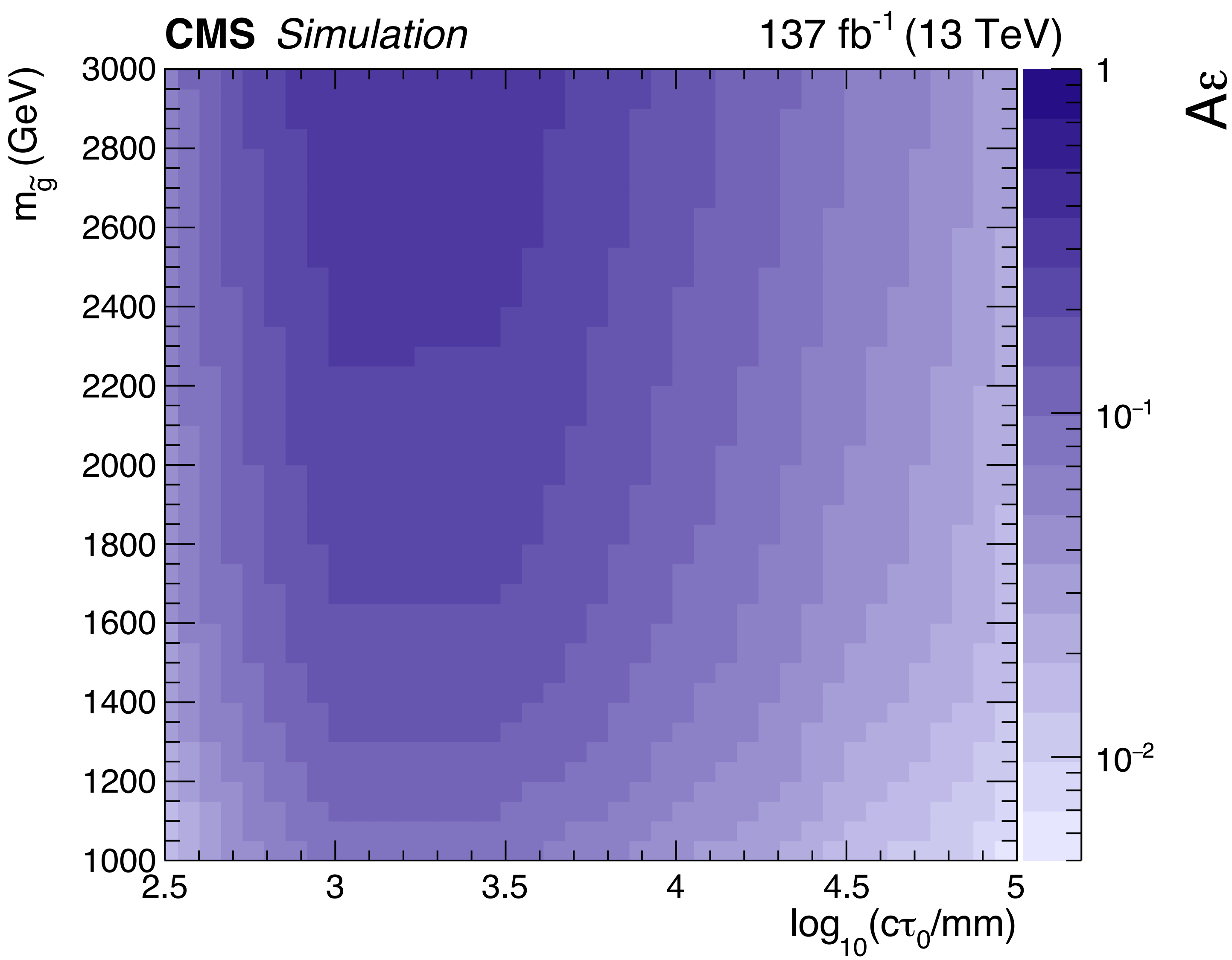




Source of uncertainty	Range [%]
Theory	3–9
Integrated luminosity	2.3–2.5
Pileup	2–3
ISR	8–9
Jet energy scale/resolution	2–6
p_T^{miss} modeling	0.4
Missing inner hits	1–3
Missing middle hits	0.3–3
Missing outer hits	0–3
E_{calo} selection	0.6–1
Trigger efficiency	4–6
Track reconstruction efficiency	1.5–4.5
Total	10–18

Displaced Jet (Timing)

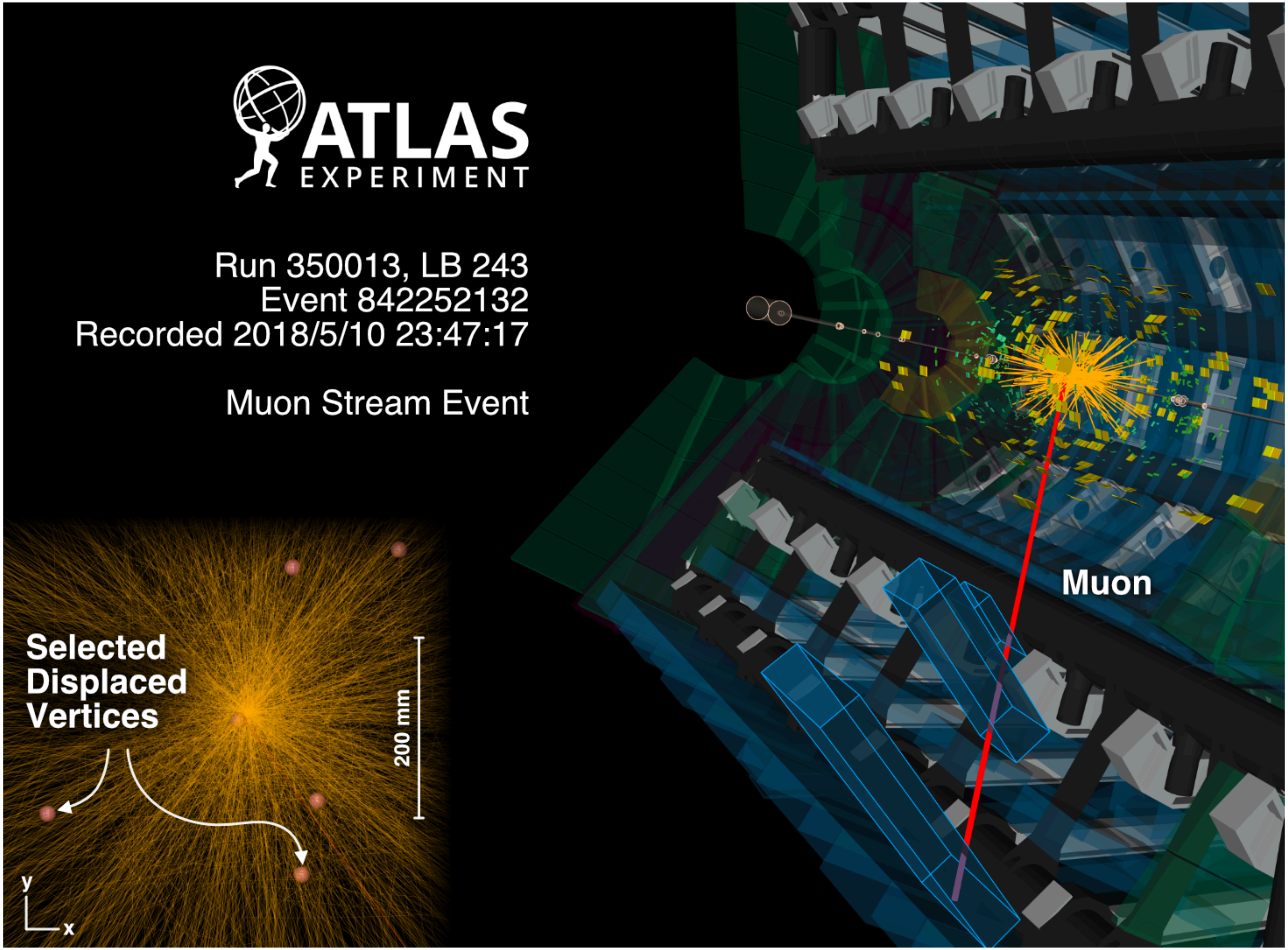




Variable	Derived uncertainty (%)	
	$c\tau_0 = 1\,\mathrm{m}$	$c\tau_0 = 10\,\mathrm{m}$
$PV_{track}^{fraction}$	0.01	0.03
N_{ECAL}^{cell}	3.2	4.2
HEF	2.8	2.5
$E_{ECAL}^{CSC} / E_{ECAL}$	0.9	0.9
t_{jet}^{RMS}	22	15

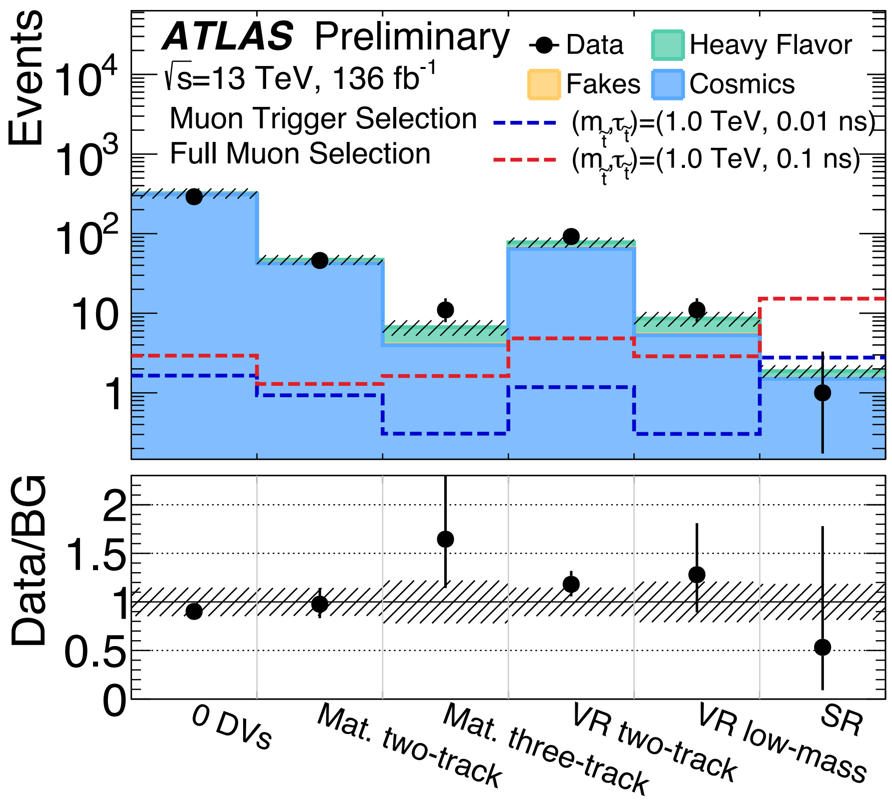
[ATLAS-CONF-2019-006]

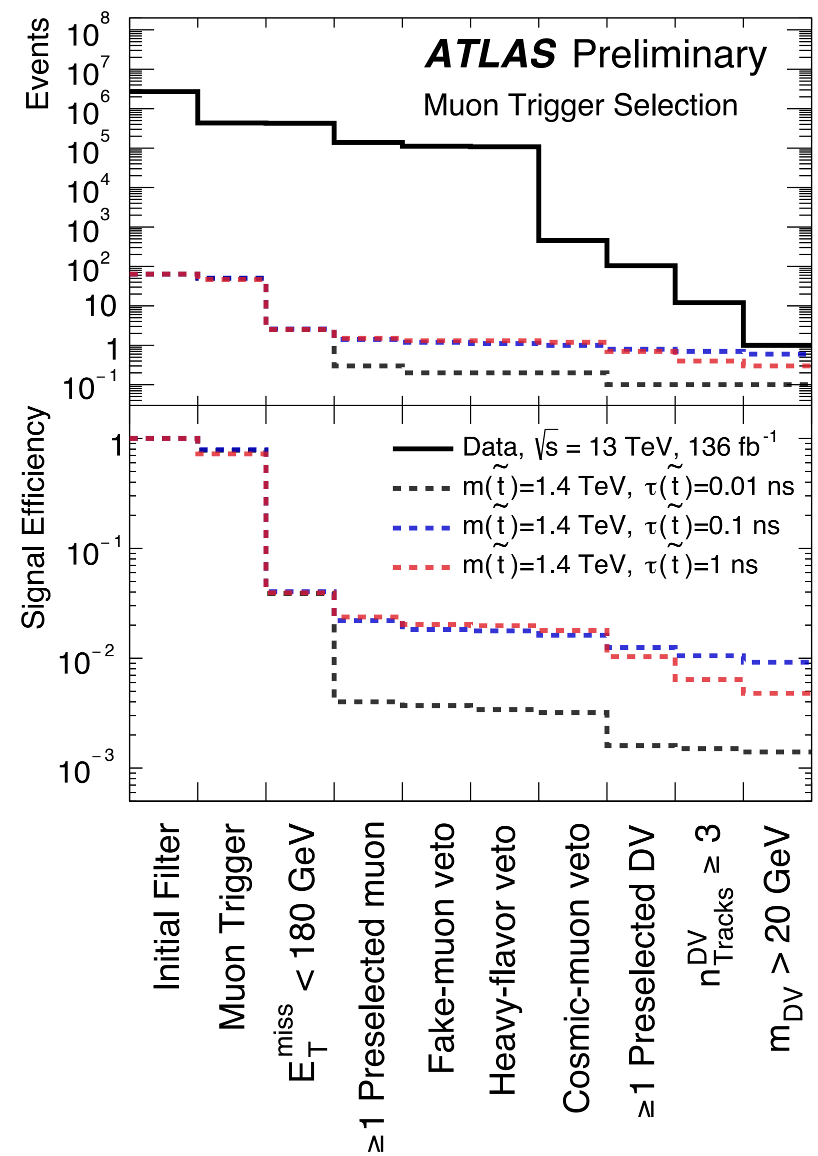
Displaced Jet (ID DV)

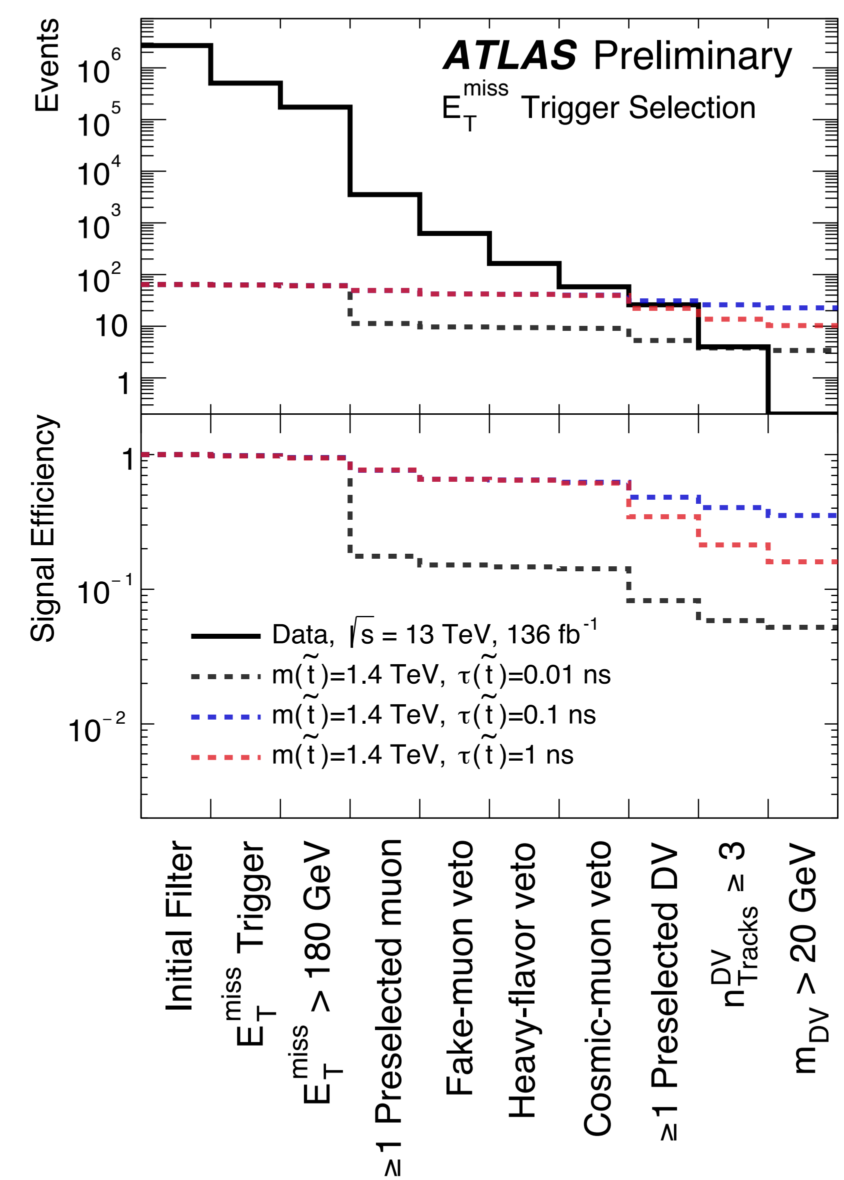


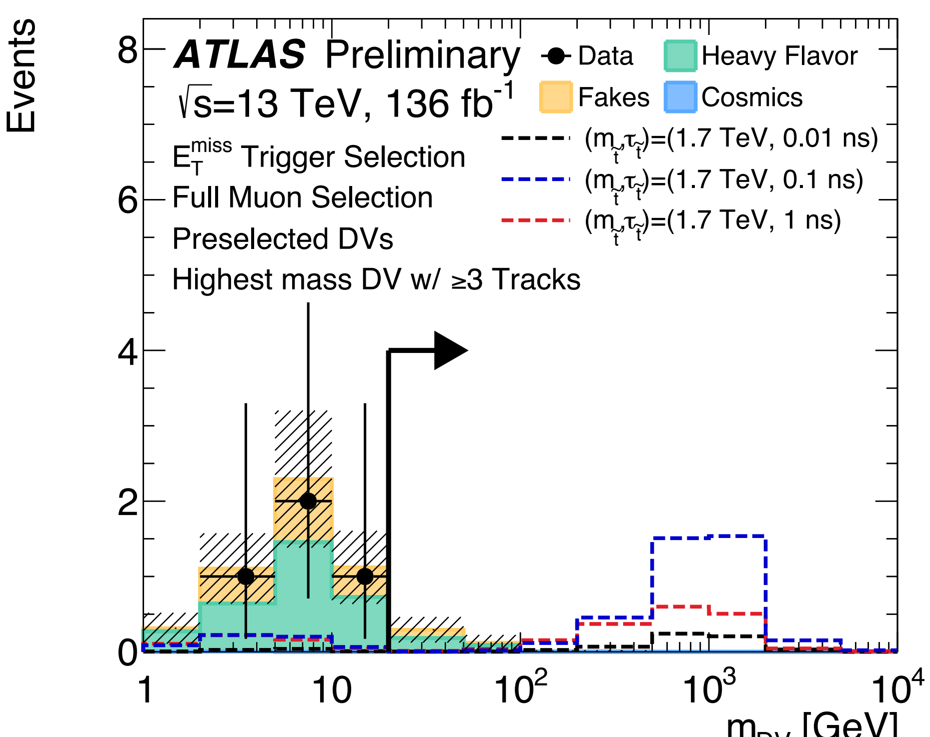
[ATLAS-CONF-2019-006]

Displaced Jet (ID DV)







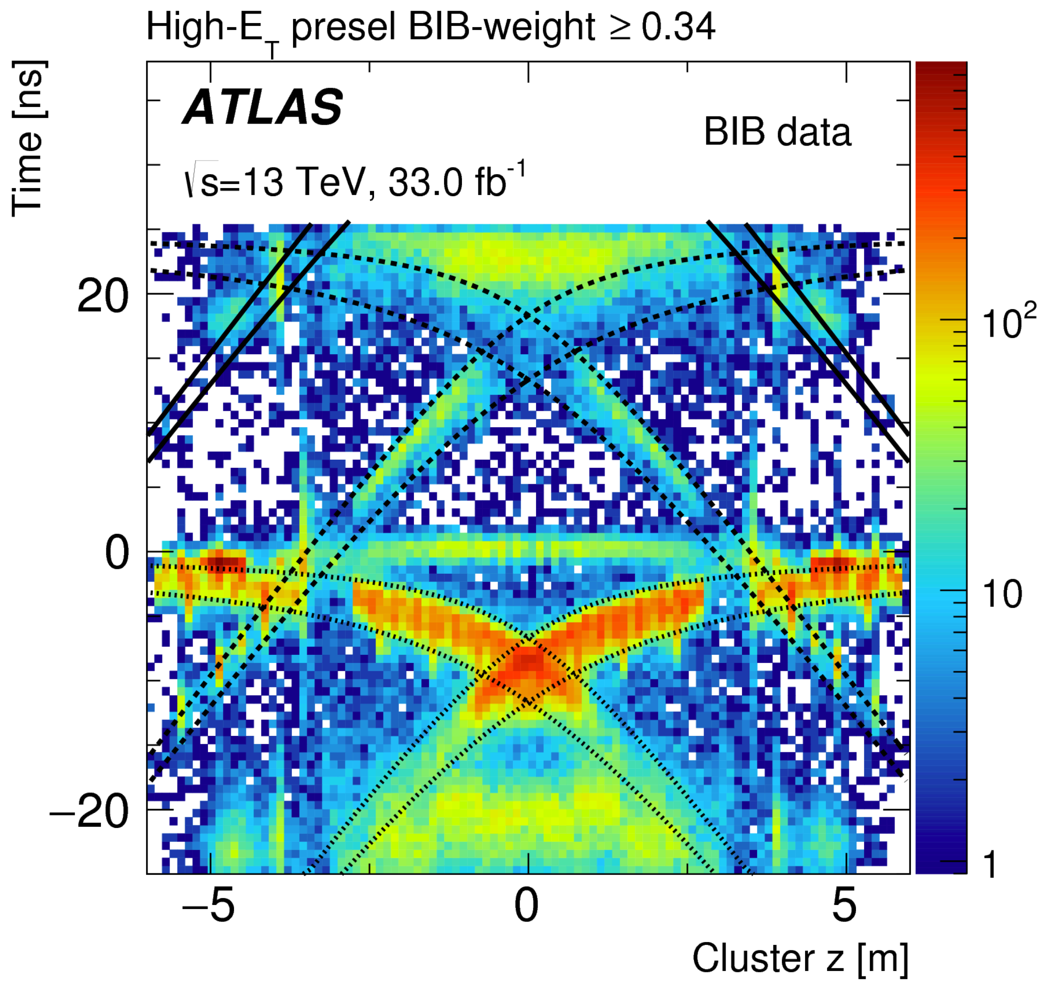


Source of uncertainty	Relative impact on ϵ_{sel} for signal events [%]
Total	18 – 20
Tracking and vertex reconstruction	15
Displaced muon efficiency	10 – 12
Prompt muon efficiency	$(0.01 - 0.7) \oplus (0.9 - 4.0)$
Radiation modeling in MC simulation	3
Pileup modeling	0.37 – 2.2
Hadronic energy scale and resolution (affecting E_T^{miss})	2.1
Integrated luminosity of dataset	1.7
E_T^{miss} trigger efficiency	< 0.2

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

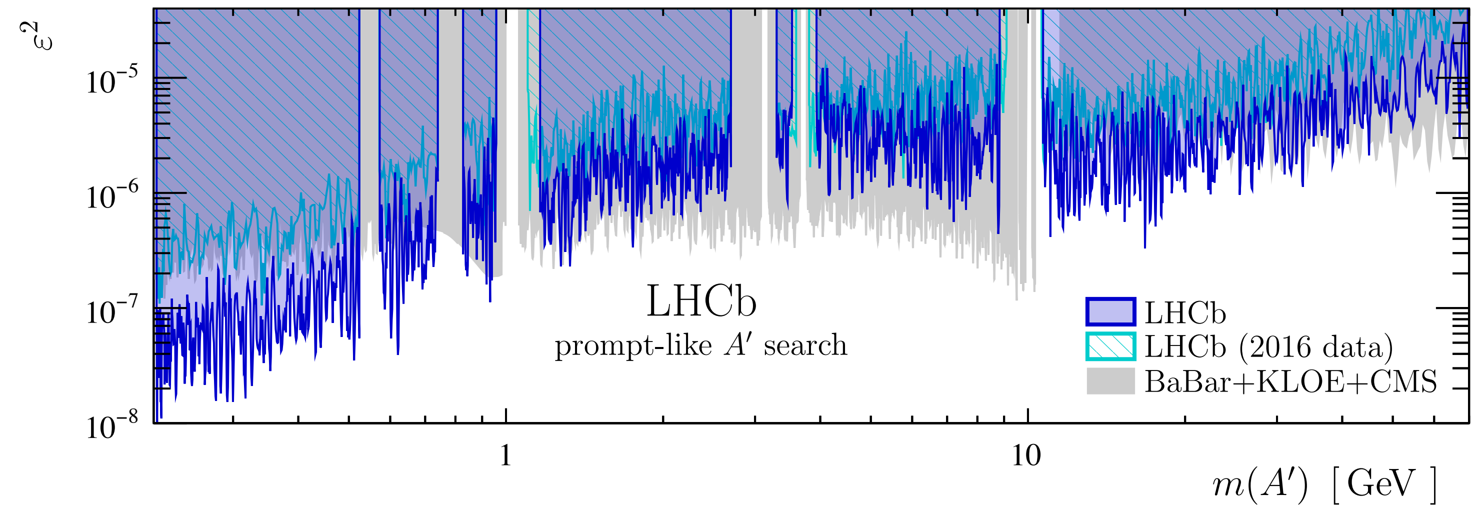
Displaced Jet (Low-EM Fraction)

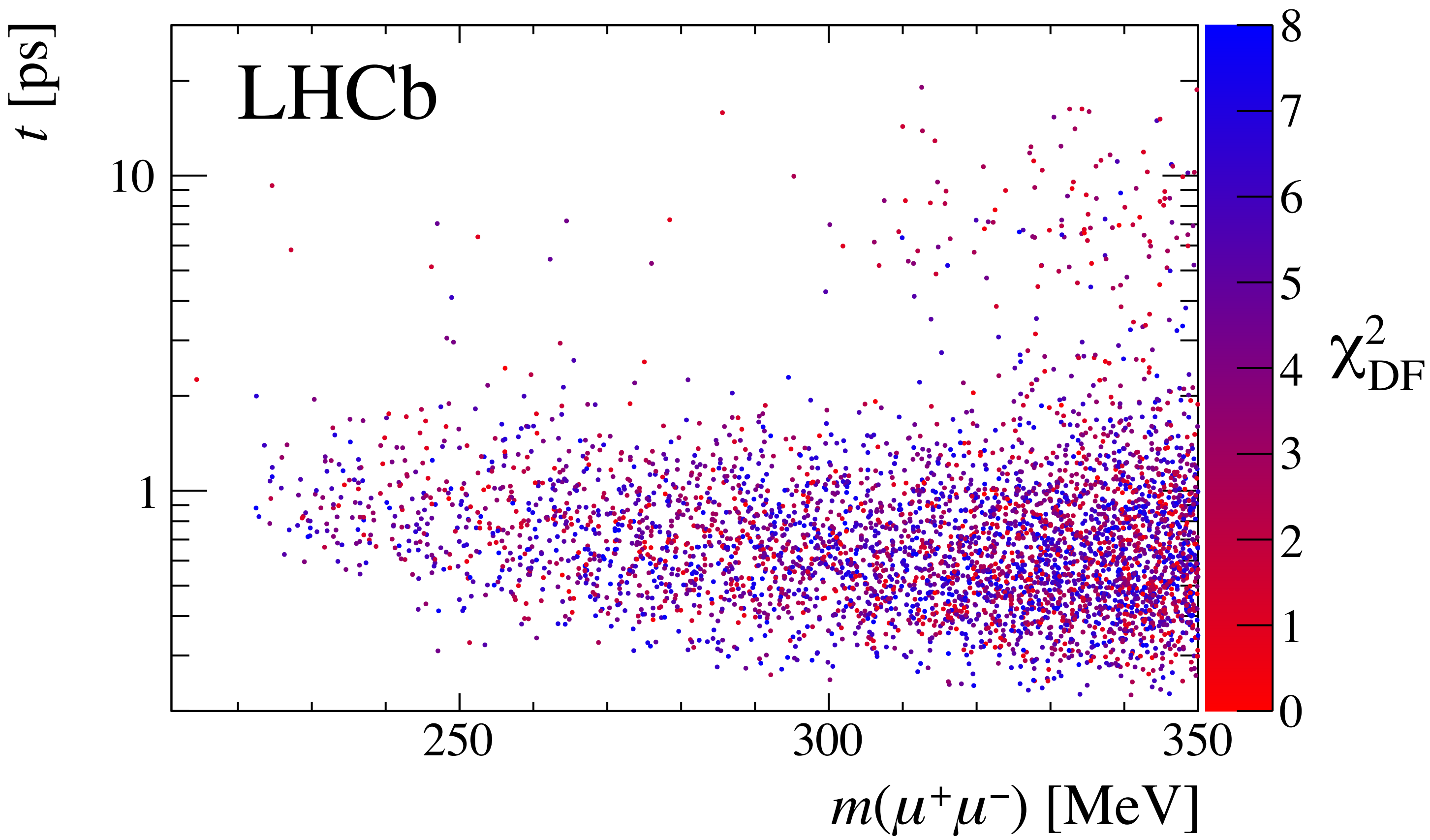
BIB enriched data

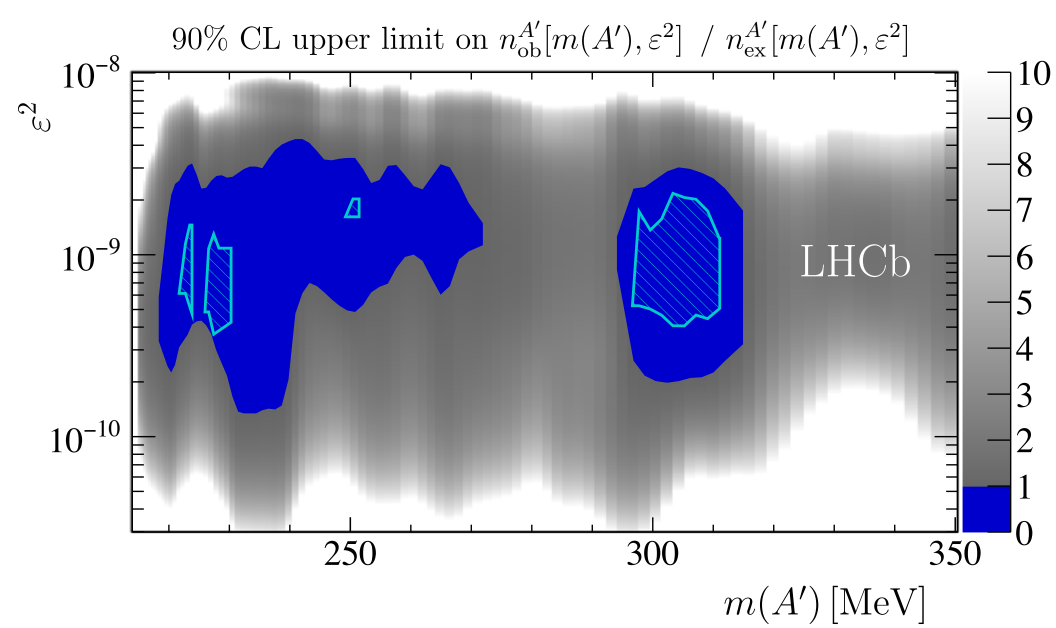


Dilepton DV

[1910.06926]

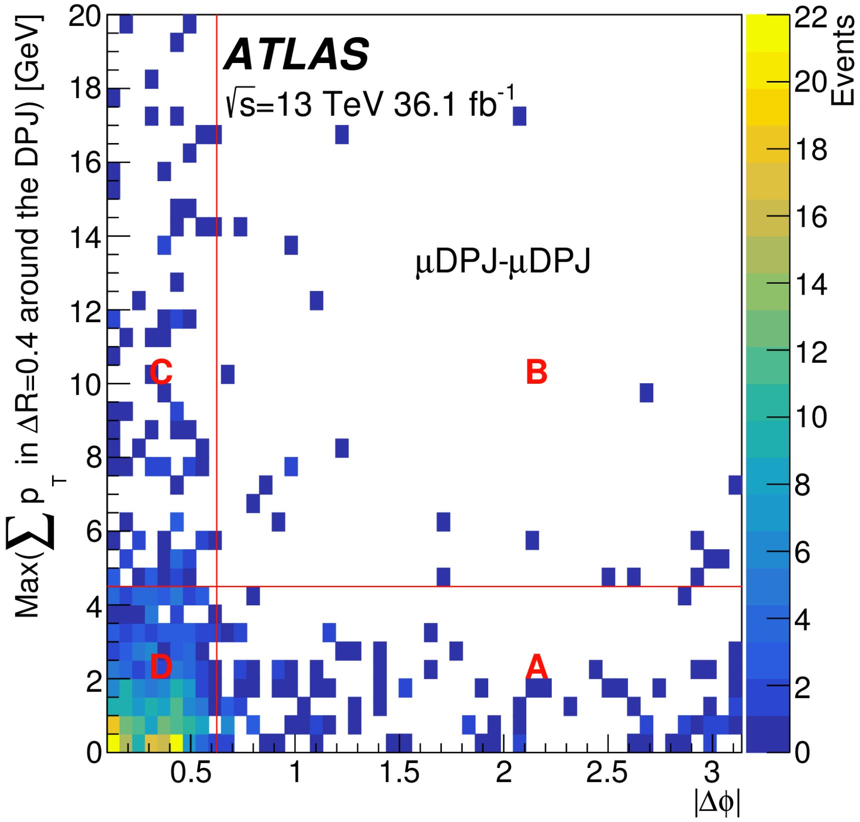


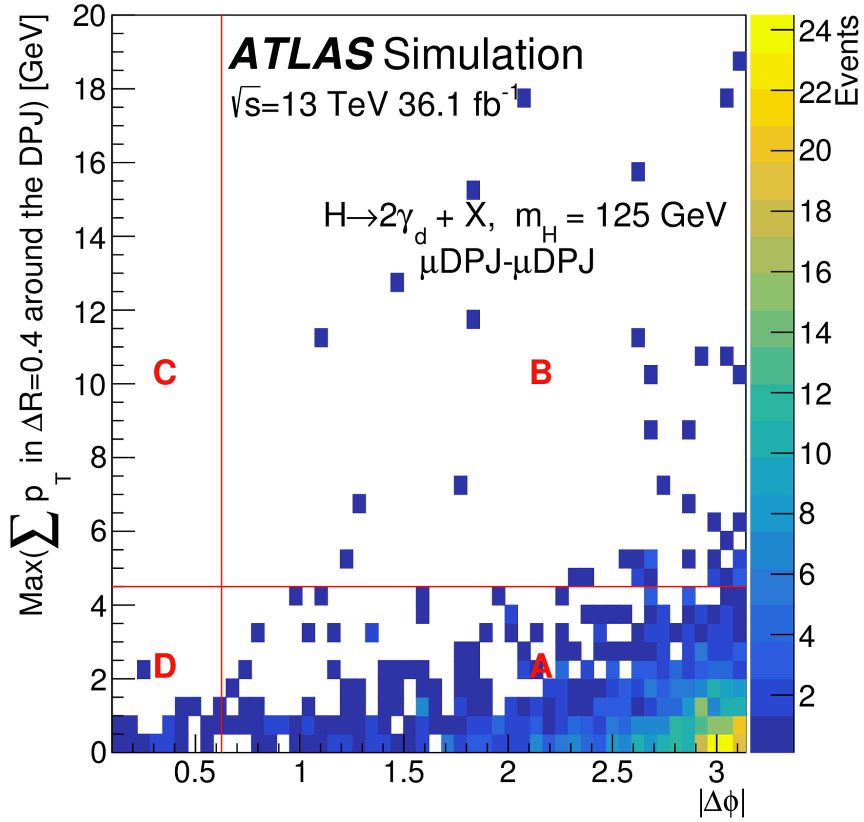


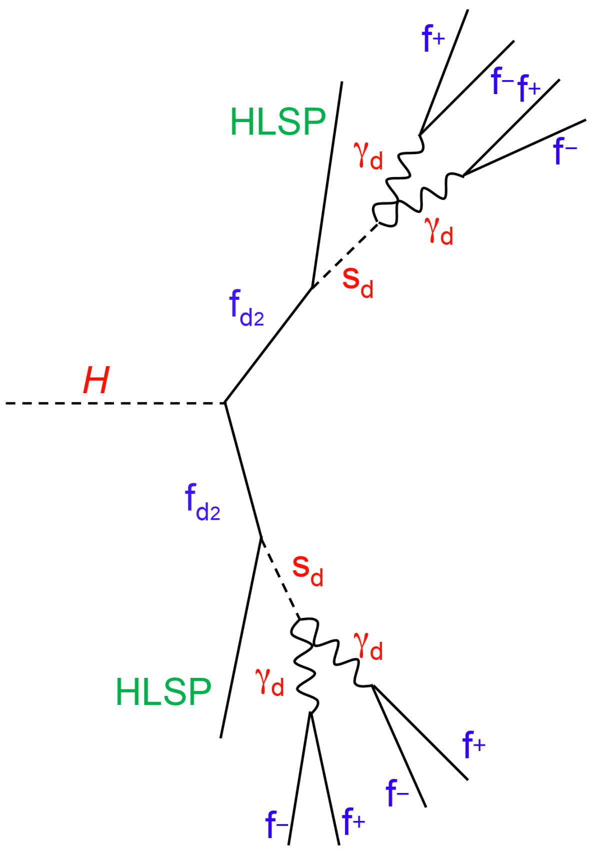


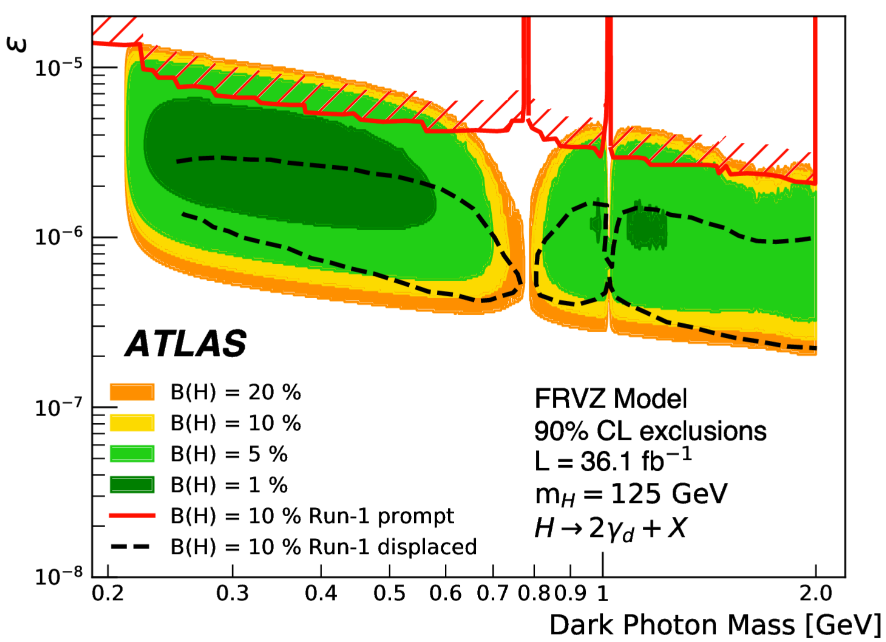
[1909.01246]

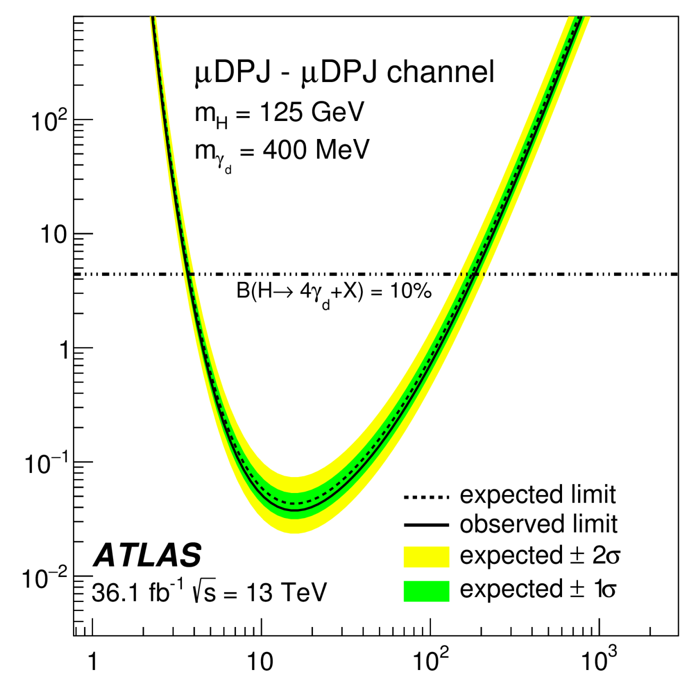
Displaced Lepton Jet



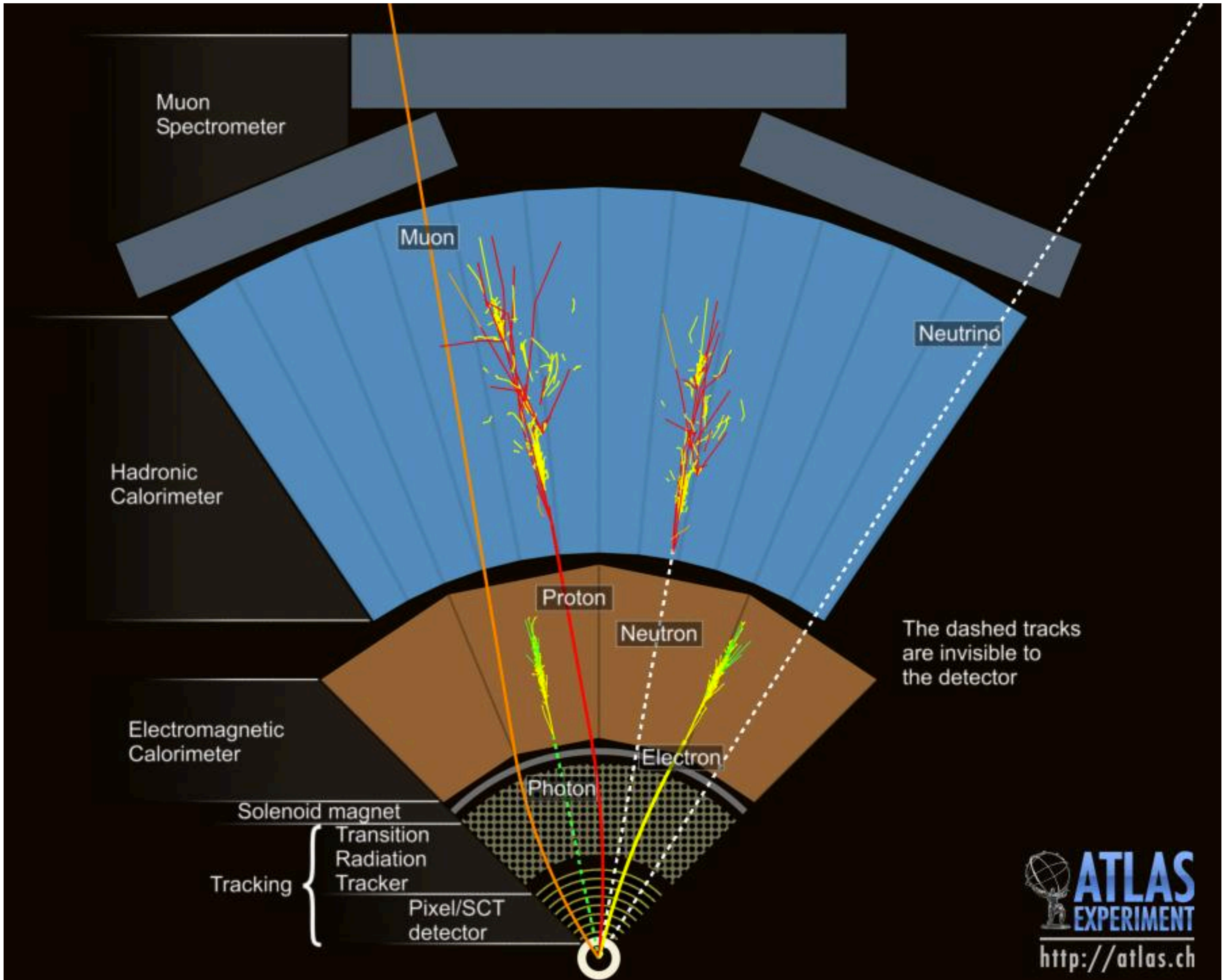








ATLAS Detector



ABCD

- Info from Will Buttinger: https://twiki.cern.ch/twiki/bin/view/Main/ABCDMethod
    - Including info on likelihood-based approach (which can account for signal contamination)
        - Simultaneous signal and background fit
            - Signal normalization controlled by μ
            - Background constrained to obey ABCD relation (within uncertainty)

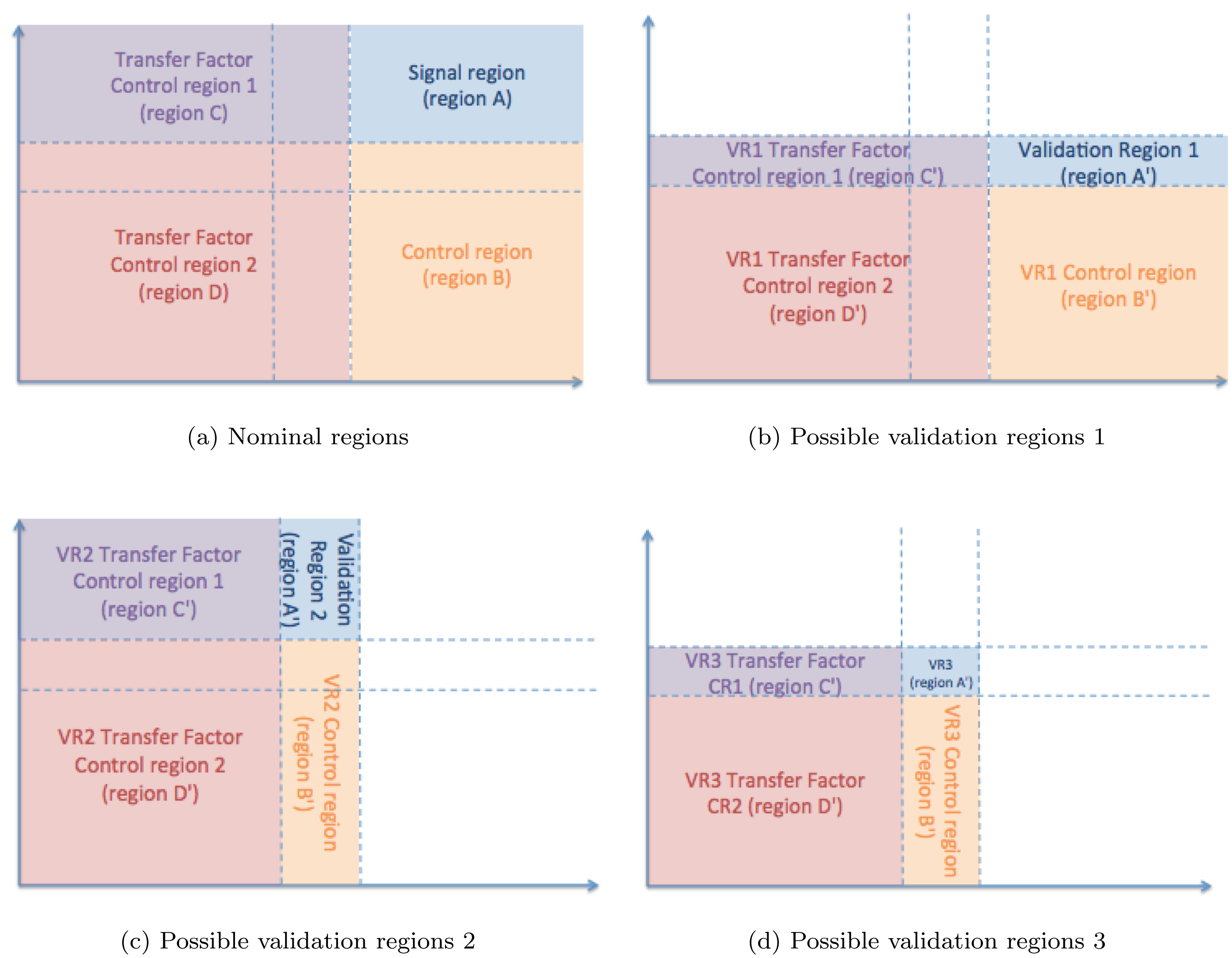


Figure 10: Illustrations of the nominal signal and control regions, and possible validation and accompanying control regions. The ability to define the validation regions depends on the discreteness of the observables defining the plane.