Search for BSM Physics Using Challenging Signatures

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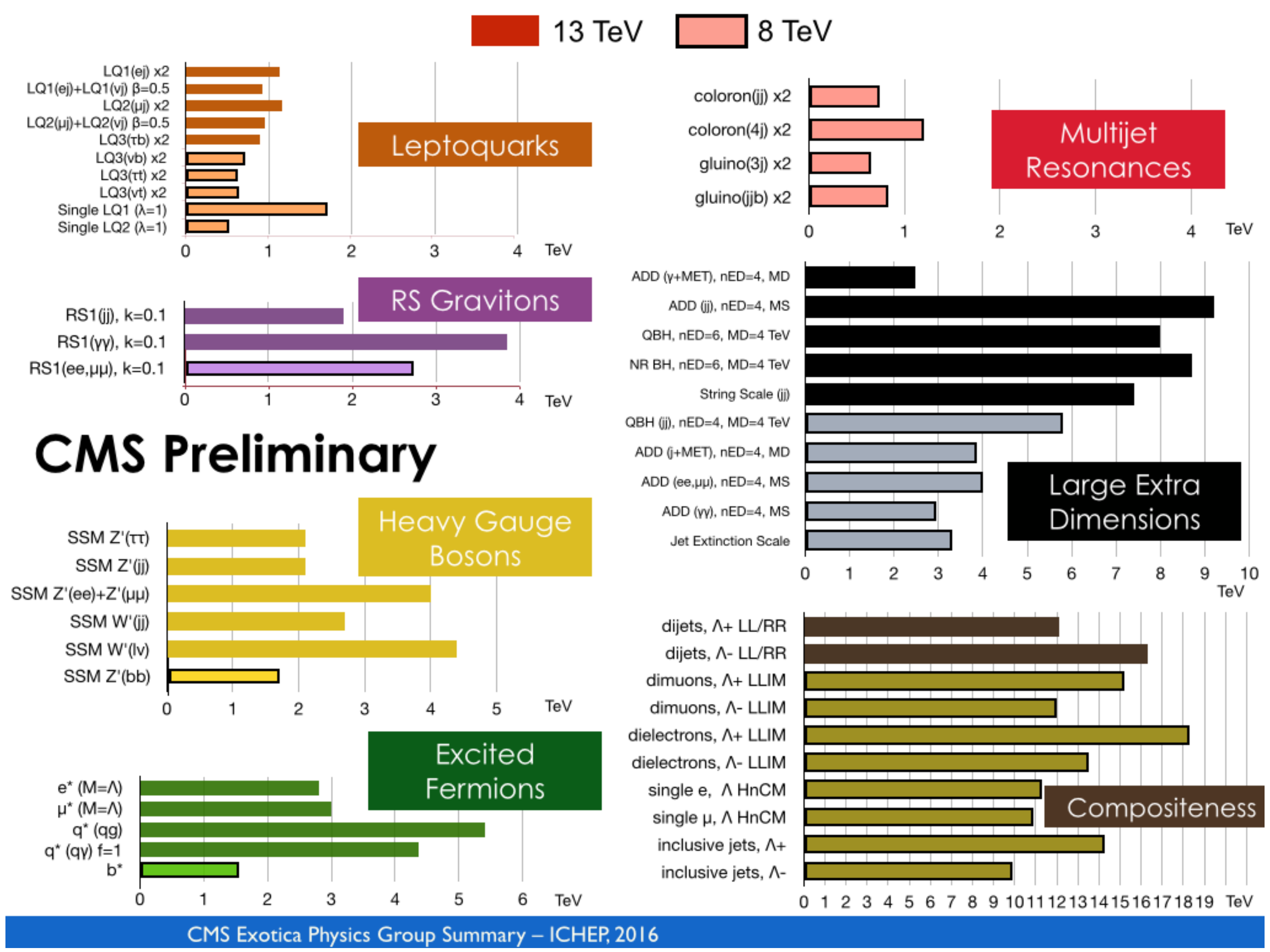
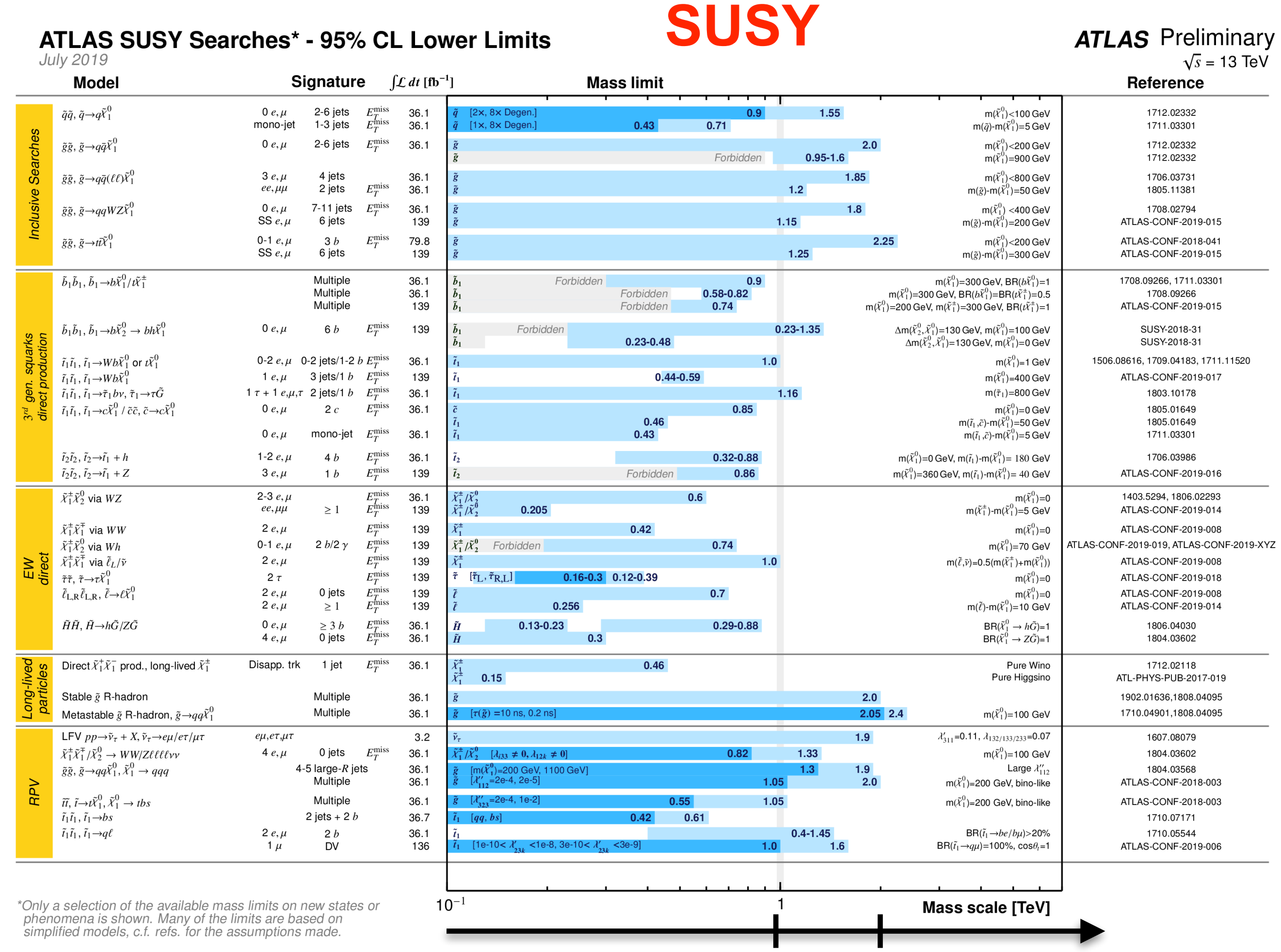
Why Search for Unusual Signatures?

- Lots of BSM ground covered in direct searches
  - no evidence using more conventional signatures

non-SUSY



SUSY



1 2 TeV
excluded masses

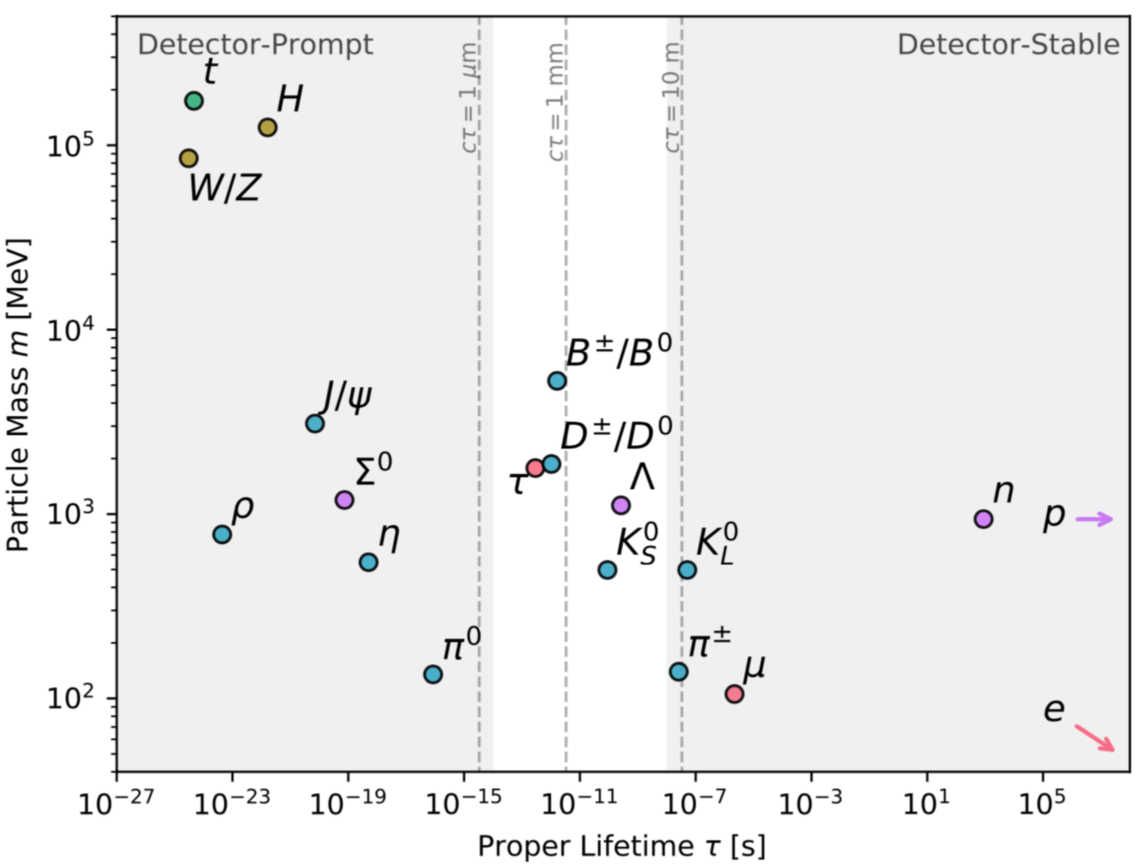
- what are conventional signatures?
  - jets and leptons (usually high p_T) from IP
  - large missing E_T (e.g. non-interacting stable particles)

What Are Unusual Signatures? (I)

- Stable or meta-stable, interacting (charged) particles
  - Dirac monopoles
  - sleptons
  - *R*-hadrons
- Meta-stable non-interacting particles
  - neutralinos
  - heavy neutrinos
  - hidden/dark-sector particles (scalar or vector)

		Small coupling	Small phase space	Scale suppression
SUSY	GMSB			✓
	AMSB		✓	
	Split-SUSY			✓
	RPV	✓		
NN	Twin Higgs	✓		
	Quirky Little Higgs	✓		
	Folded SUSY		✓	
DM	Freeze-in	✓		
	Asymmetric			✓
	Co-annihilation		✓	
Portals	Singlet Scalars	✓		
	ALPs			✓
	Dark Photons	✓		
	Heavy Neutrinos			✓

https://arxiv.org/abs/1810.12602



https://arxiv.org/abs/1810.12602

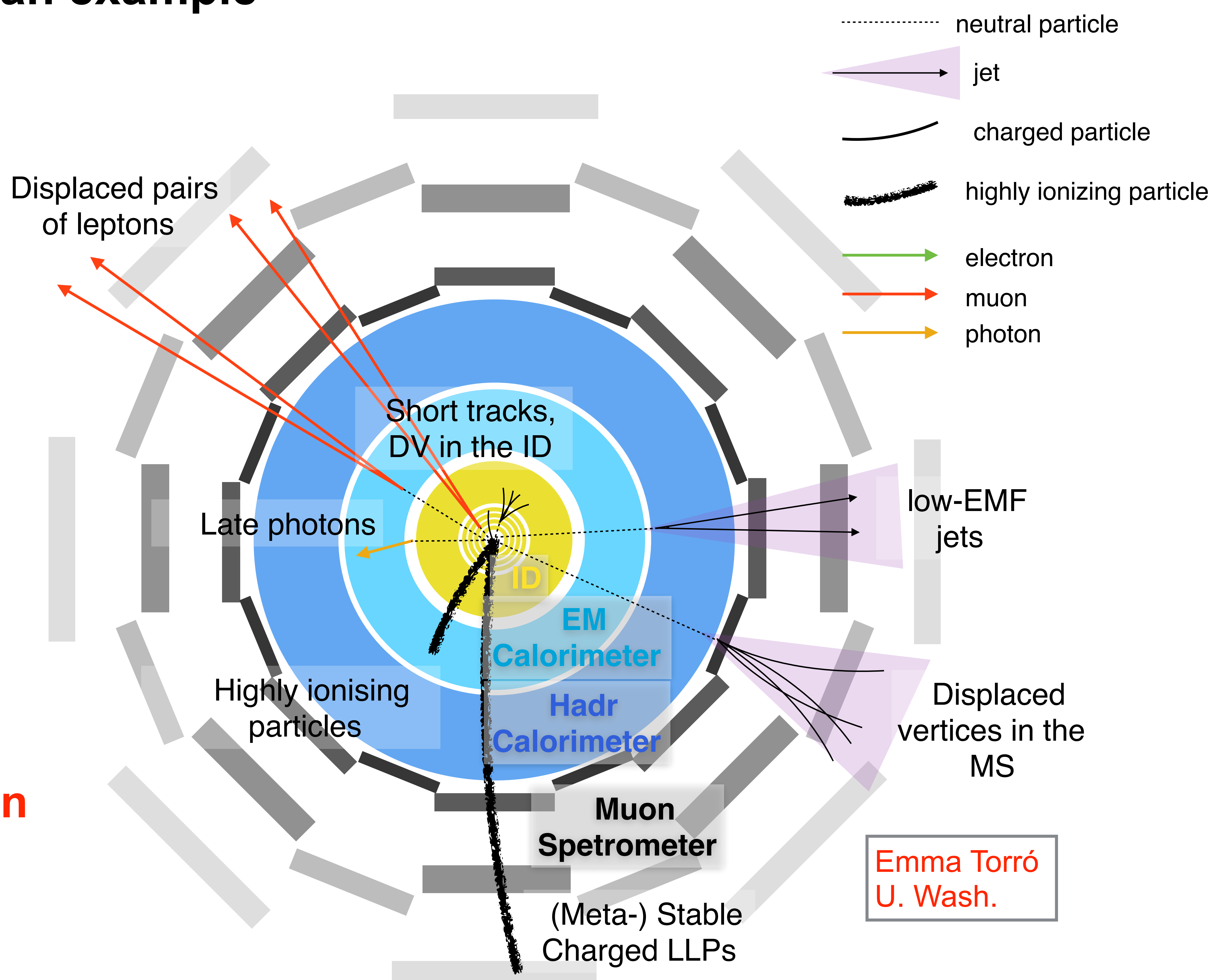
- More generally…SM itself displays wide range of lifetimes
  - near degeneracy in mass spectra
  - small couplings
  - highly virtual intermediate states

Detector Signatures: Long-Lived Particles (LLP)

- **ATLAS as an example**

Keywords:

- displaced
- delayed
- disappearing
- emergent
- late
- highly-ionizing



challenges to offline object reconstruction

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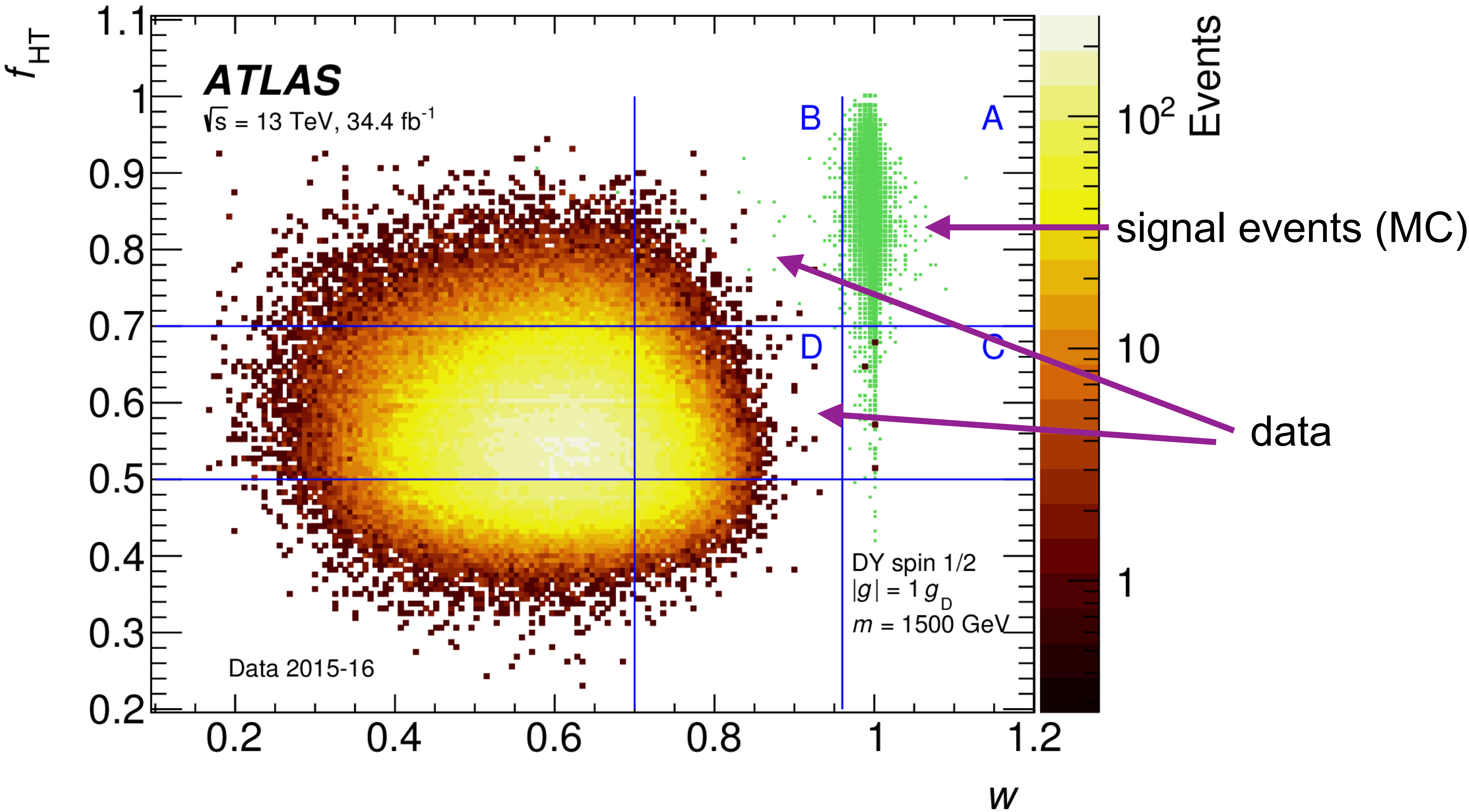
Trigger Limitations

- Special triggers dedicated to unusual signatures
  - bandwidth concerns → suppress combinatorics, SM bkgds, etc.
  - signal efficiency → detector limitations (e.g. only barrel, only part of tracking volume, etc.)
  - implications for background estimation → MC sometimes not reliable
- Trigger on something in event not directly associated with the unusual signature…associated production
  - ex. prompt hight p_T lepton/jet/γ, MET…
  - introduces model dependence

Background Estimation

- Often the MC simulation is not reliable enough for some/all bkgd
  - Detector features or measurements not used by many other analyses
  - Backgrounds not simulated at all, or rather poorly → cosmics, beam-related backgrounds, instrumental effects, etc.
- Use only/mostly data itself to provide the estimates…
  - Ex. special triggers applied to empty bunch crossings
  - “ABCD method” utilizing two independent quantities

Background Estimation: ABCD Method

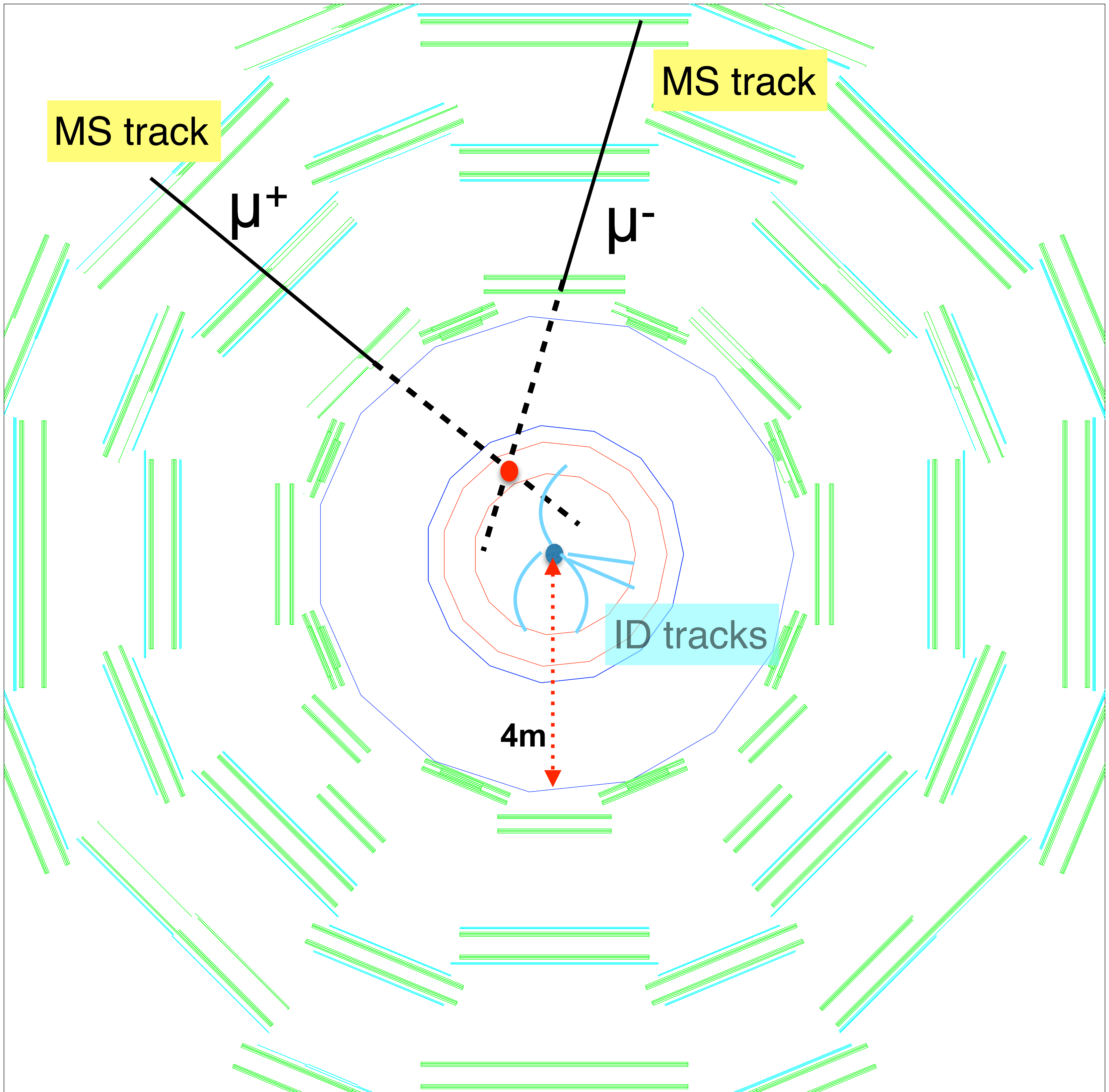


Signal Estimate: $N_A / N_C = N_B / N_D$

Displaced Dimuon Vertex

Phys. Rev. D 99 (2019) 012001

Idea ⇒ look for displaced dimuon vertices using solely MS tracks



- Simple approach using what ATLAS measures well/cleanly ⇒ muon tracks!
- Use only muon tracks not matched to an ID track
- MS tracks make a vertex

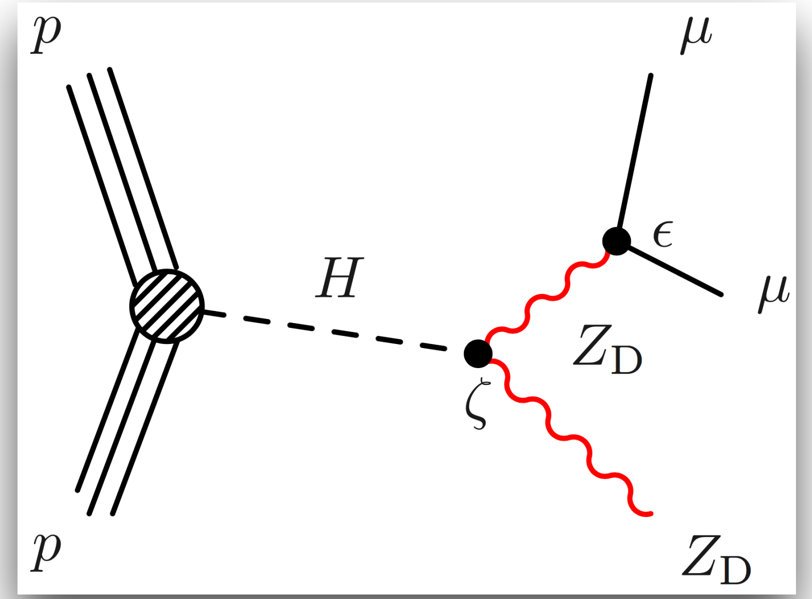
Sensitivity:
Decay lengths of ~1cm - 4m

Displaced Dimuon Vertex

Phys. Rev. D 99 (2019) 012001

Low p_T muons / low mass signal

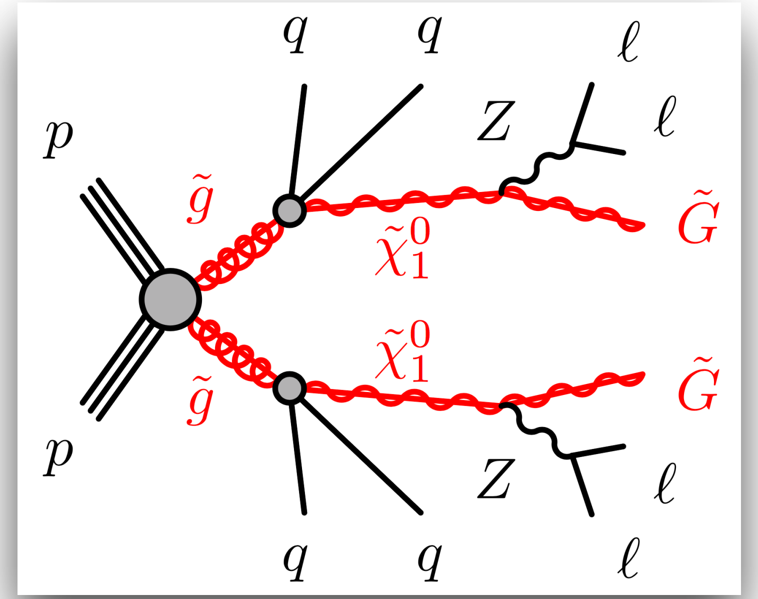
- $15 < m_{\mu\mu} < 60$ GeV
- special dimuon trigger
- backgrounds mostly processes with muons produced far from IP (cosmics, beam, pi/K decay)



- Small BF($H \rightarrow Z_D Z_D$): 1-10%
- Small Z-Z_D coupling: long-lived
- BF($Z_D \rightarrow \mu\mu$) = 10-15%
- Dimuons with $m_{\mu\mu} < m_H$

High p_T muons / high mass signal

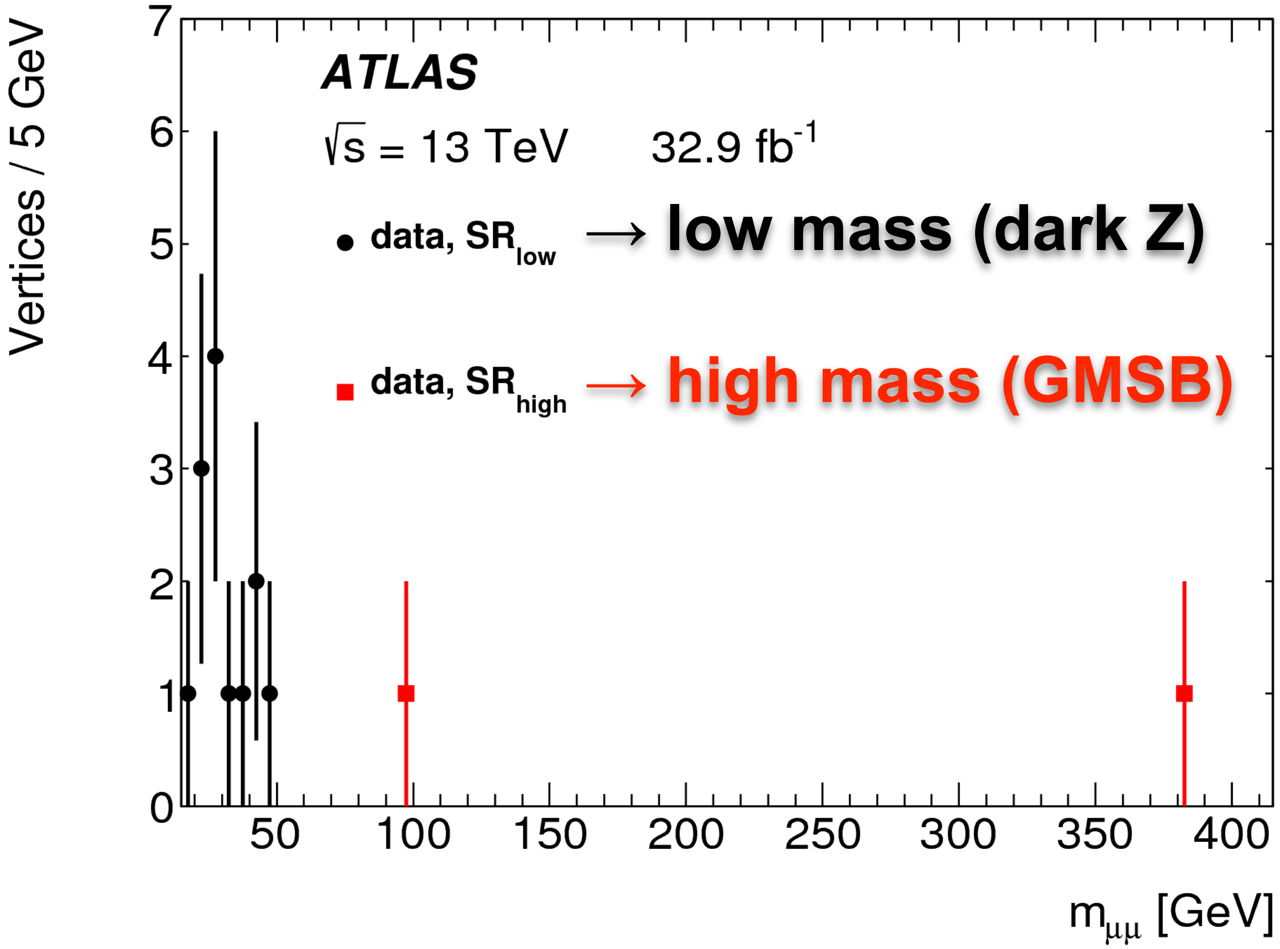
- $m_{\mu\mu} > 60$ GeV
- MET and single MS trigger
- backgrounds mostly processes with muons produced near IP (Drell-Yan/Z boson)

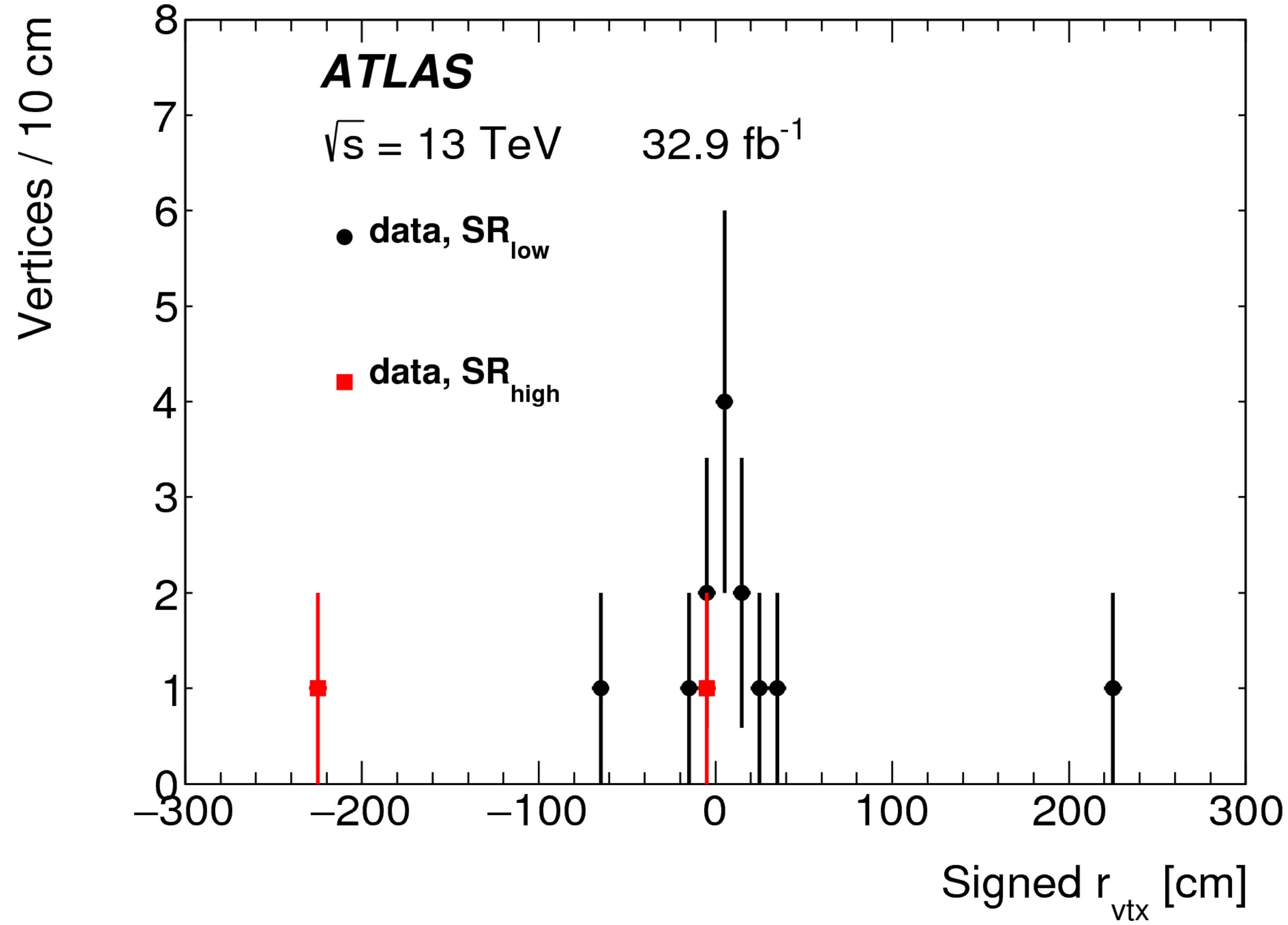


- GGM/GMSB
- Very light gravitino LSP
- Neutralino NLSP: long-lived and heavy
- Dimuons at *Z* pole

Displaced Dimuon Vertex

[Phys. Rev. D 99 (2019) 012001](https://doi.org/10.1103/PhysRevD.99.012001)



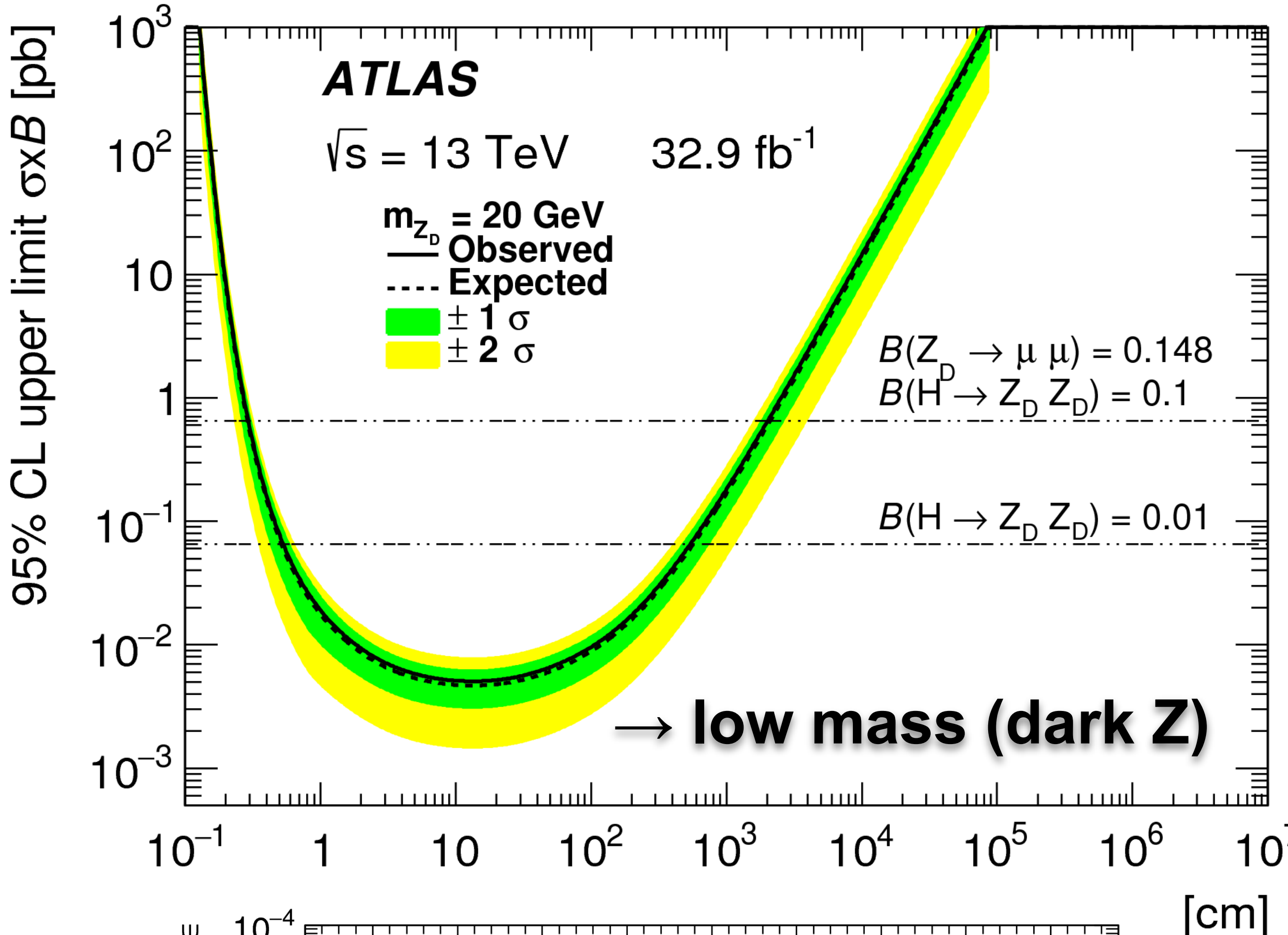


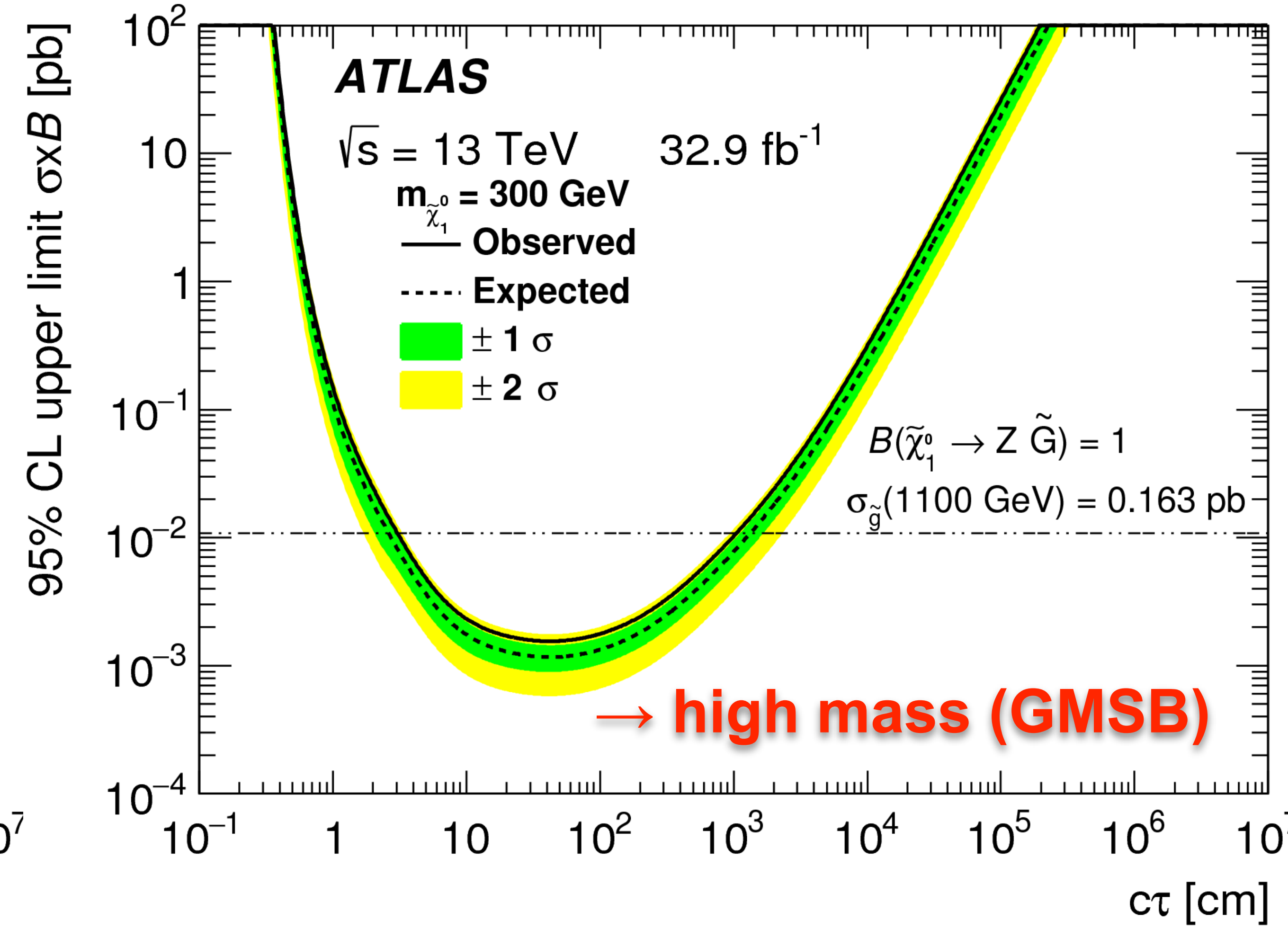
Yield	SR_{low}	SR_{high}
N^{fake}	14.9 ± 5.2	$0.0^{+1.4}_{-0.0}$
N^{prompt}	$0.1^{+1.3}_{-0.1}$	$0.5^{+4.7}_{-0.1}$
N^{bkgd}	15.0 ± 5.4	$0.5^{+4.9}_{-0.1}$
N^{obs}	23	4

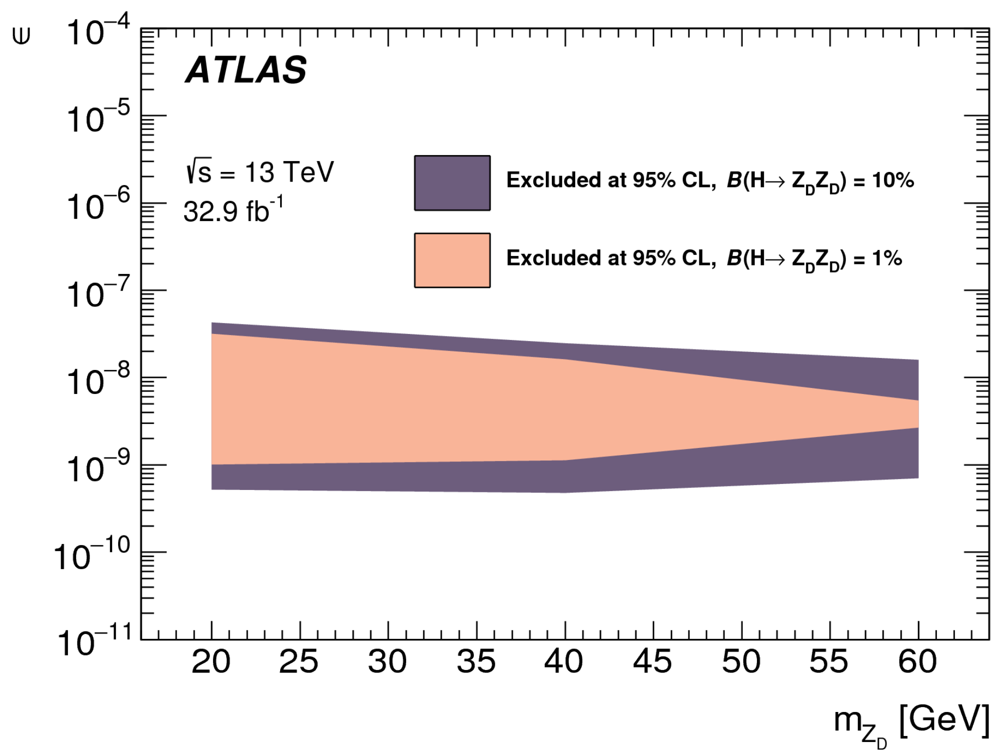
Observed number of vertices consistent with background prediction

Displaced Dimuon Vertex

[Phys. Rev. D 99 (2019) 012001](#)





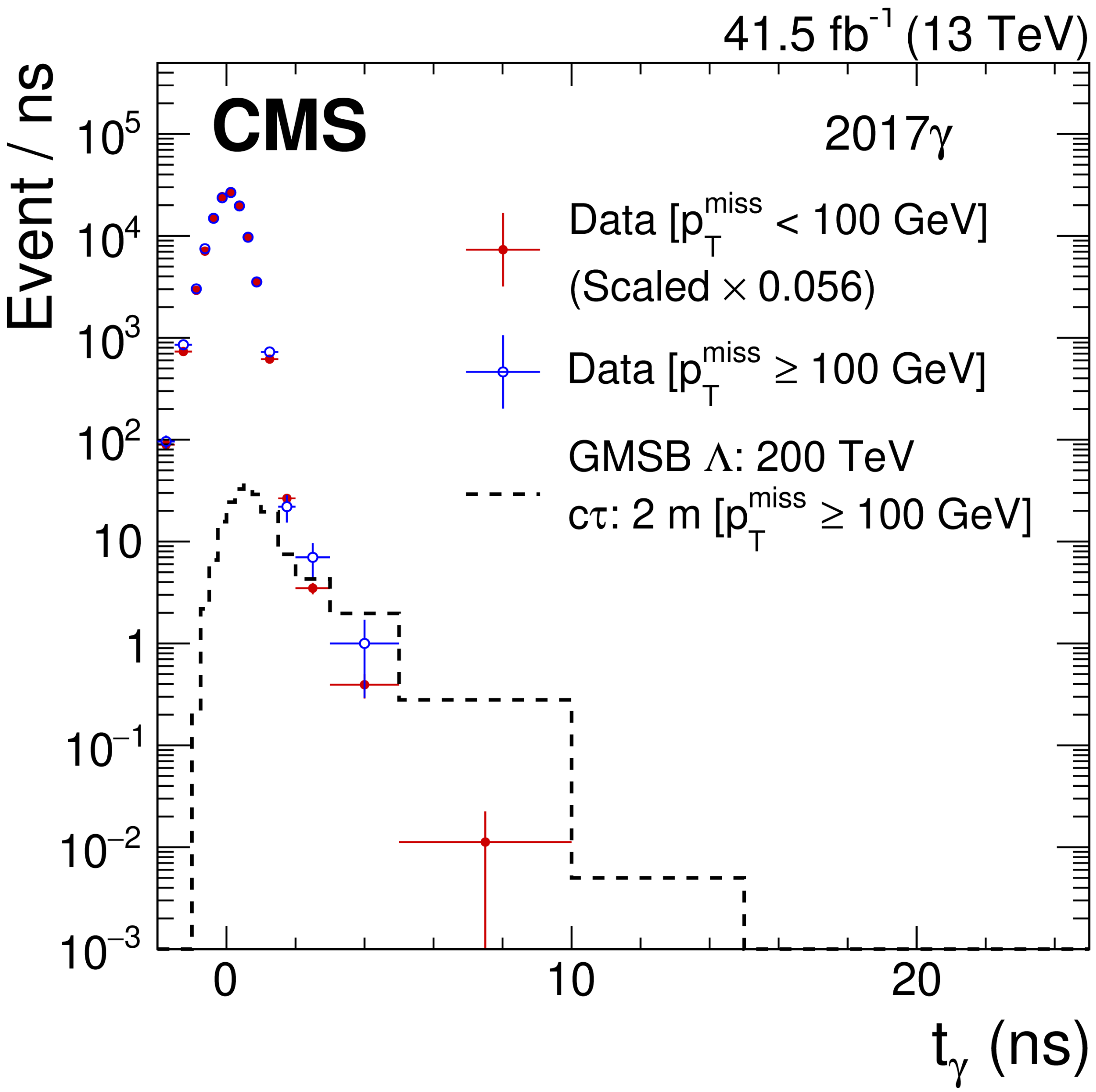


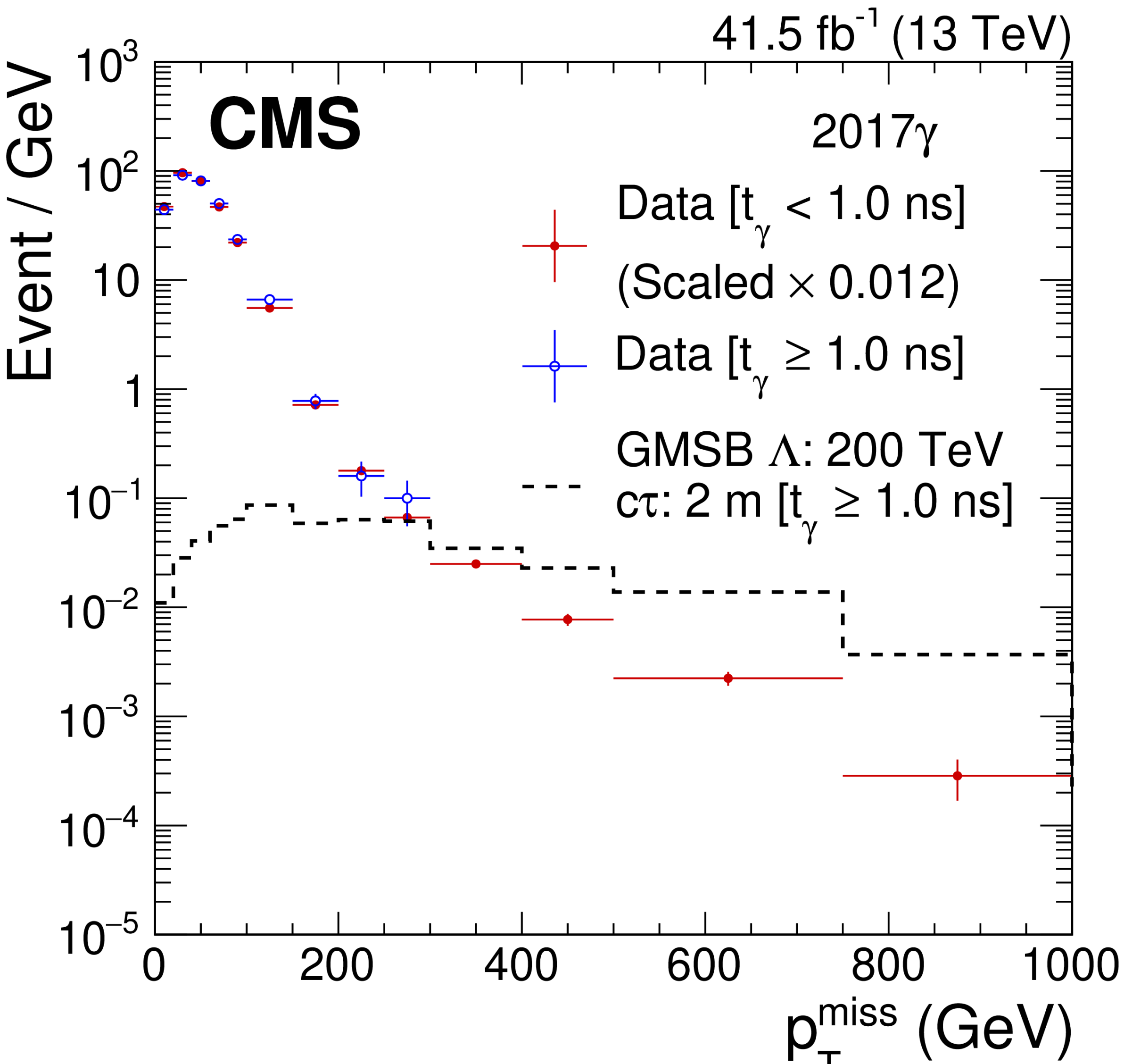
Exclude 1 < cτ < 1000 cm (approx)

Delayed Photon

- Search for neutral LLP decaying to photons
  - photons arrive "late" at the calorimeter → delayed
  - use arrival time in ECAL and MET for signal-bkgd discrimination

$\sigma_{t\gamma}$ = 400 ps

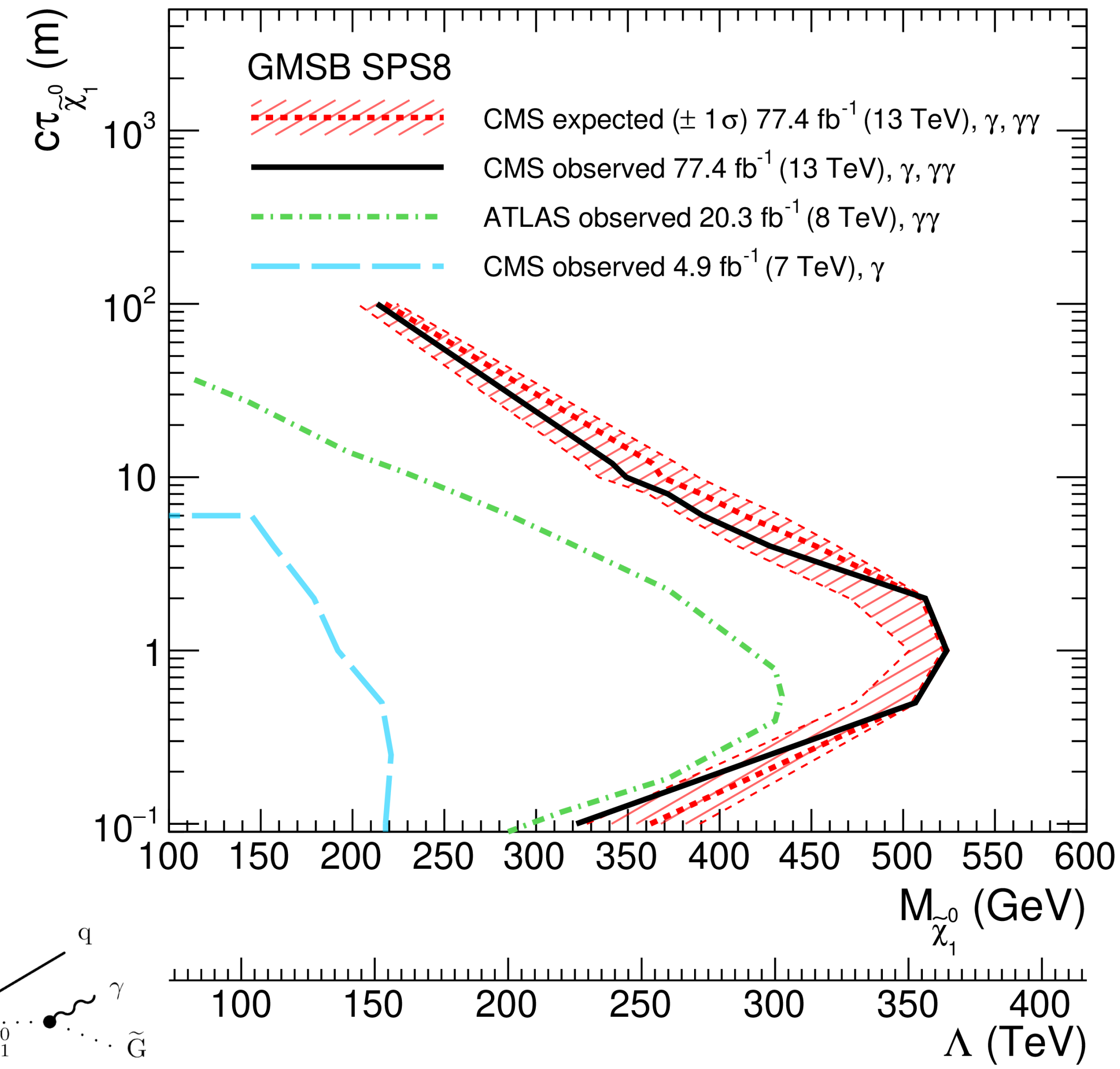


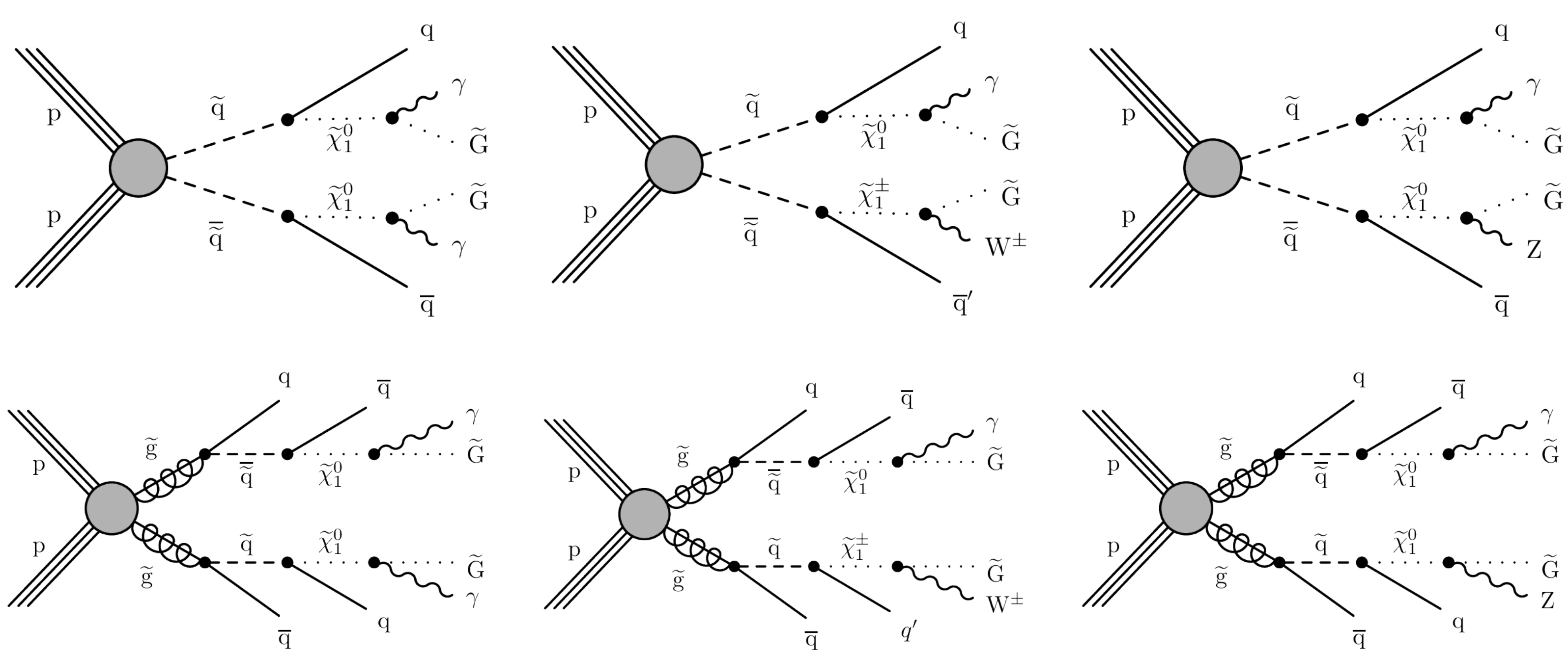


Delayed Photon

arXiv:1909.06166

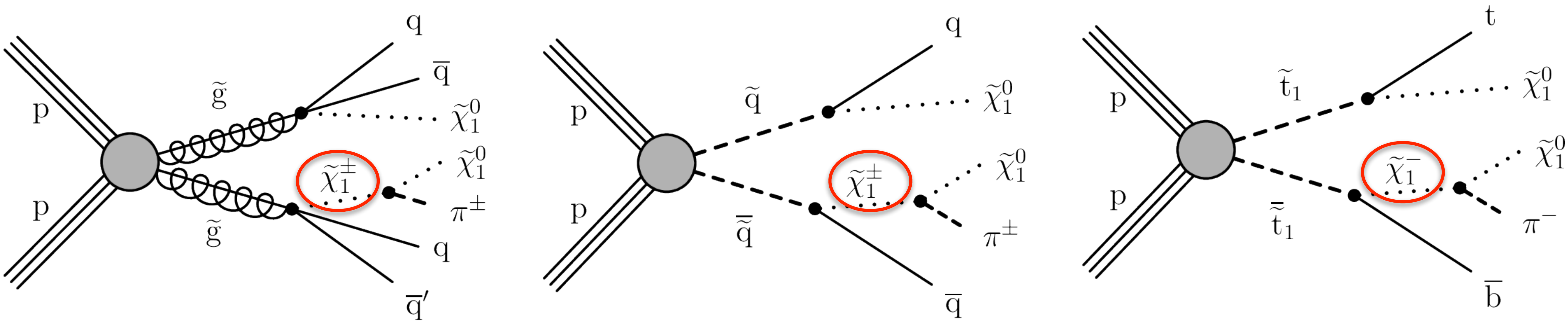
- Limits for long-lived neutralino in GMSB
  - exclude neutralino masses in 300 - 500 GeV range
  - exclude cτ in 0.1 - 100 m range





Disappearing Track + Jets

- Search for electrically-charged LLP decaying inside detector
  - track originates from IP but “disappears”
  - use isolated track (p_T > 15 GeV) → not lepton → no calo deposit → lacking outer inner detector hits

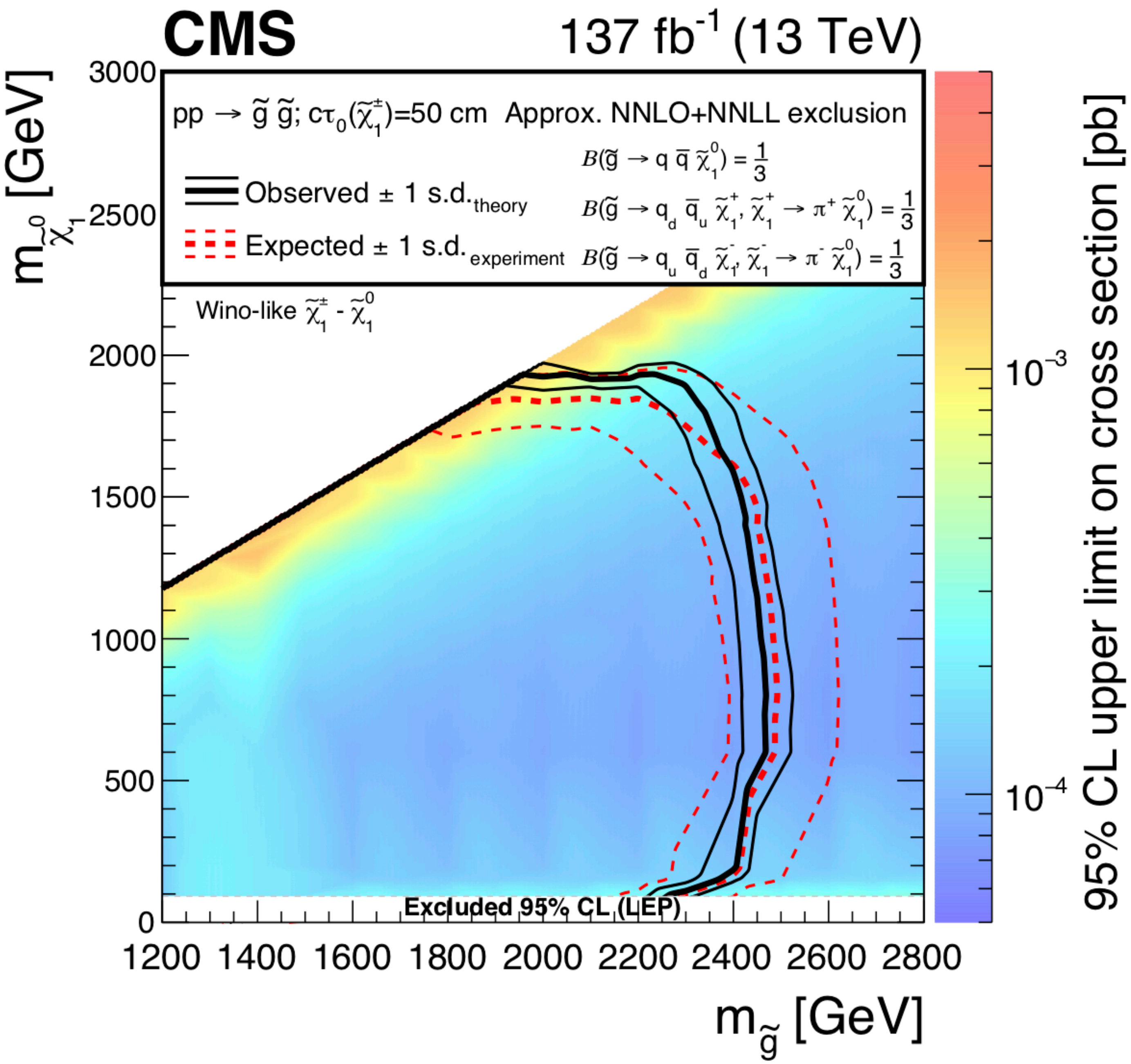


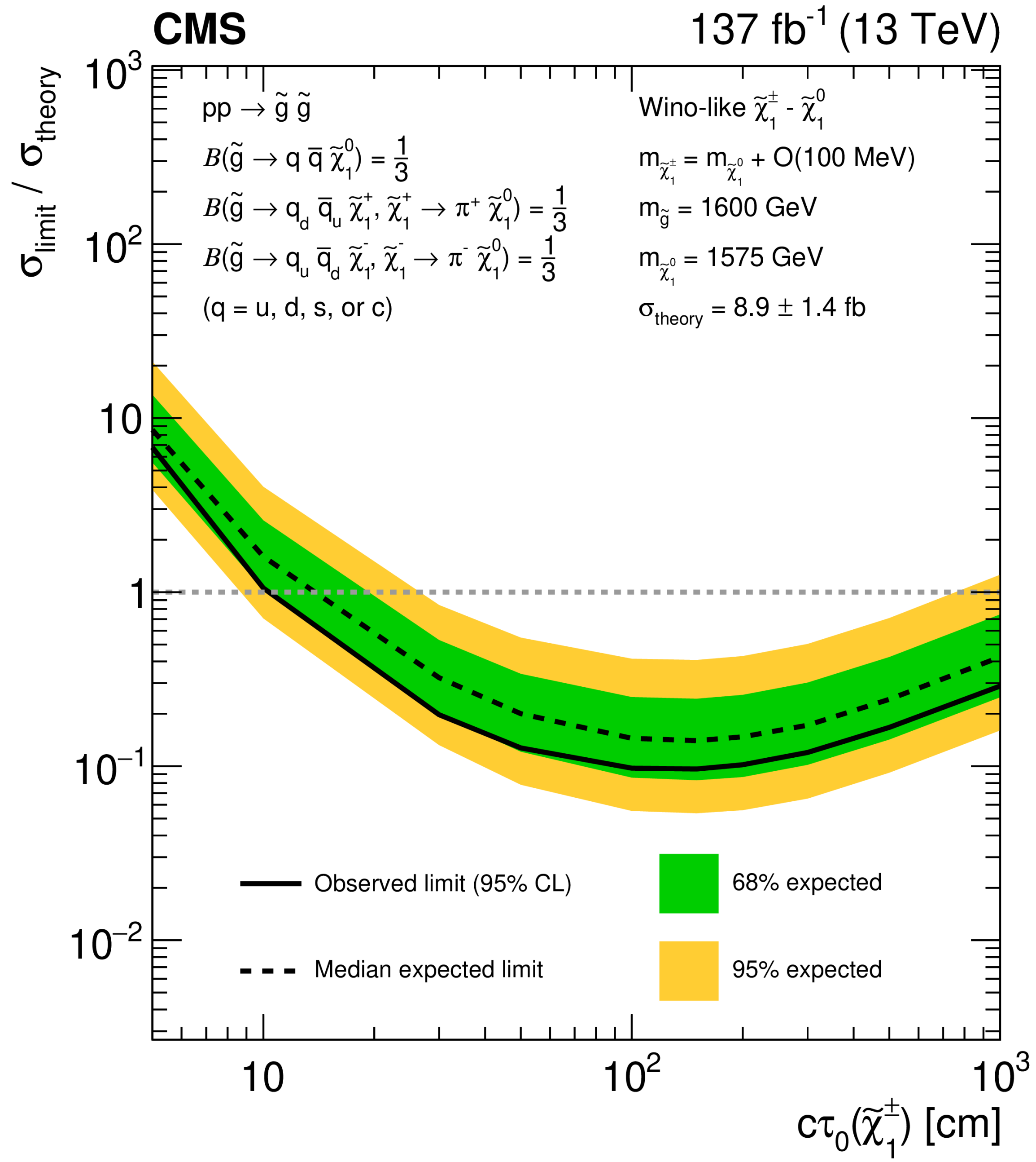
- Long-lived SUSY chargino → neutralino-chargino mass difference small (compressed phase space)

Disappearing Track + Jets

arXiv:1909.0346

- Very powerful charged LLP search…Exclude:
  - neutralino-gluino masses, 10 < cτ < 1000 cm (approx)

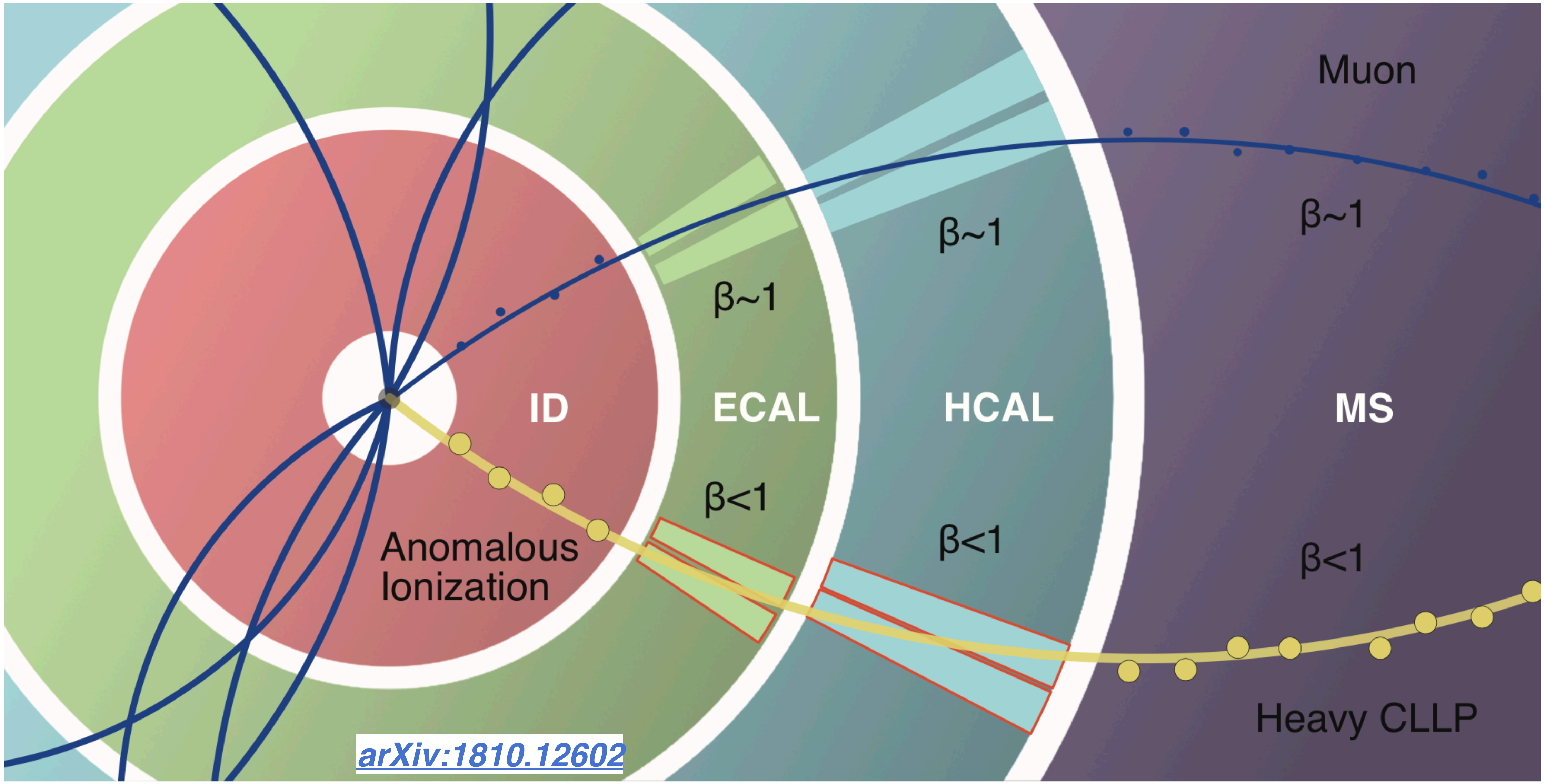




Highly-Ionizing Particles (HIPs)

arXiv:905.10130

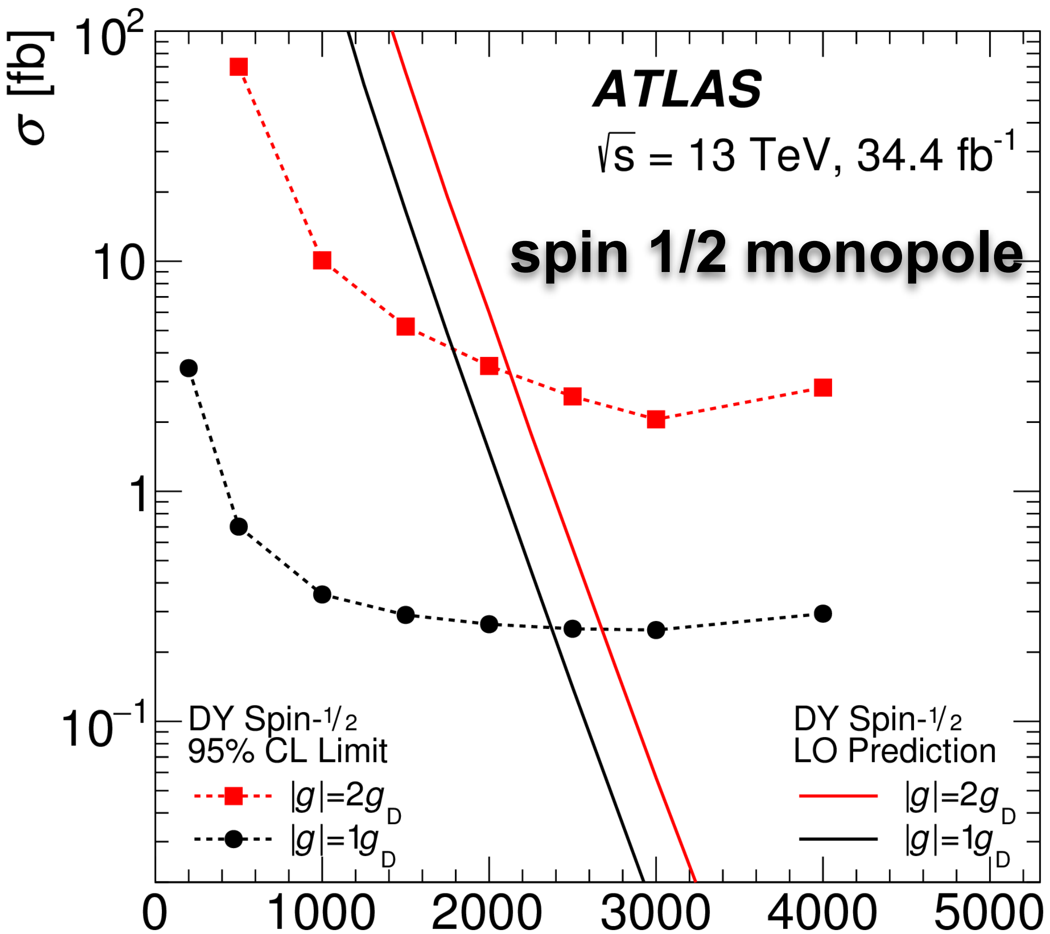
- Signature of very high energy loss in tracking detectors and electromagnetic calorimeter
  - HECOs → High-Electric-Charge-Objects (*s*-quark matter, *Q* balls, micro black hole remnants)
  - Dirac Magnetic Monopoles→ TeV-scale masses and large magnetic charge



arXiv:1810.12602

Highly-Ionizing Particles (HIPs)

- Drell-Yan production assumed
- 200 < m < 4000 GeV and 60 < $|q_{e,m}|$ < 100e
- High ionization in Transition Radiation Detector and "pencil-like" deposit of energy in the ECAL



- Background estimate: 0.2 ± 0.4
- No events observed in signal region

Lower limits on the mass of Drell–Yan magnetic monopoles and HECOs [GeV]

	$\|g\| = 1g_D$	$\|g\| = 2g_D$	$\|z\| = 20$	$\|z\| = 40$	$\|z\| = 60$	$\|z\| = 80$	$\|z\| = 100$
Spin-0	1850	1725	1355	1615	1625	1495	1390
Spin-1/2	2370	2125	1830	2050	2000	1860	1650

Conclusion

- ATLAS and CMS increasingly clever in utilizing detector information to search for non-SM phenomena
  - SUSY RPV, SUSY GMSB, dark sectors, monopoles…
- LHC Run 3 begins in 2021 → will double the Run 2 sample
  - New triggers → increase sensitivity to these exotic signatures
  - Better job of performing analyses in a way that allows for re-interpretation in terms of other models
- HL-LHC running begins in 2026 → ten times the Run 2+3 sample
  - Large improvements to the detectors!