



XII International Conference on New Frontiers in Physics

10-23 July 2023, OAC, Kolymbari, Crete, Greece

Searches for BSM physics using challenging and Long-Lived signatures with that ATLAS detector

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IFIC - Valencia

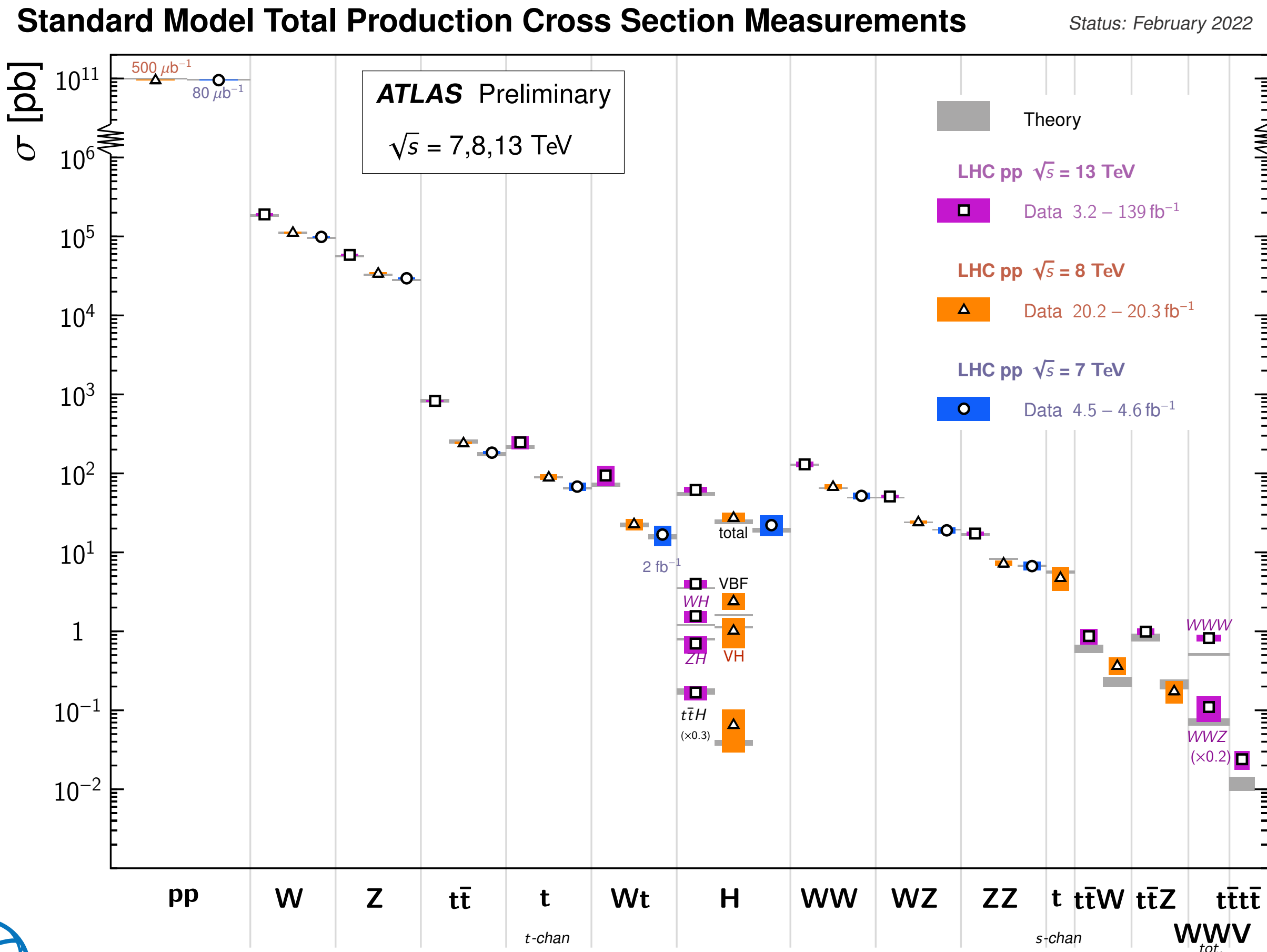
PID2021-124912NB-I00



Introduction

- **Standard Model (SM):** very successful theory
- Precise predictions, verified by experiment with impressive agreement with theory across orders of magnitude

- Cannot be the ultimate theory
- Several open questions in HEP



- What is Dark Matter?
- Neutrinos have a mass $\neq 0$
- Matter and antimatter are not symmetric
- ...

Introduction

To date, **O(100) ATLAS, CMS, LHCb papers** on BSM searches with full Run 2 dataset!

Still, no evidence of new physics...

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: July 2022

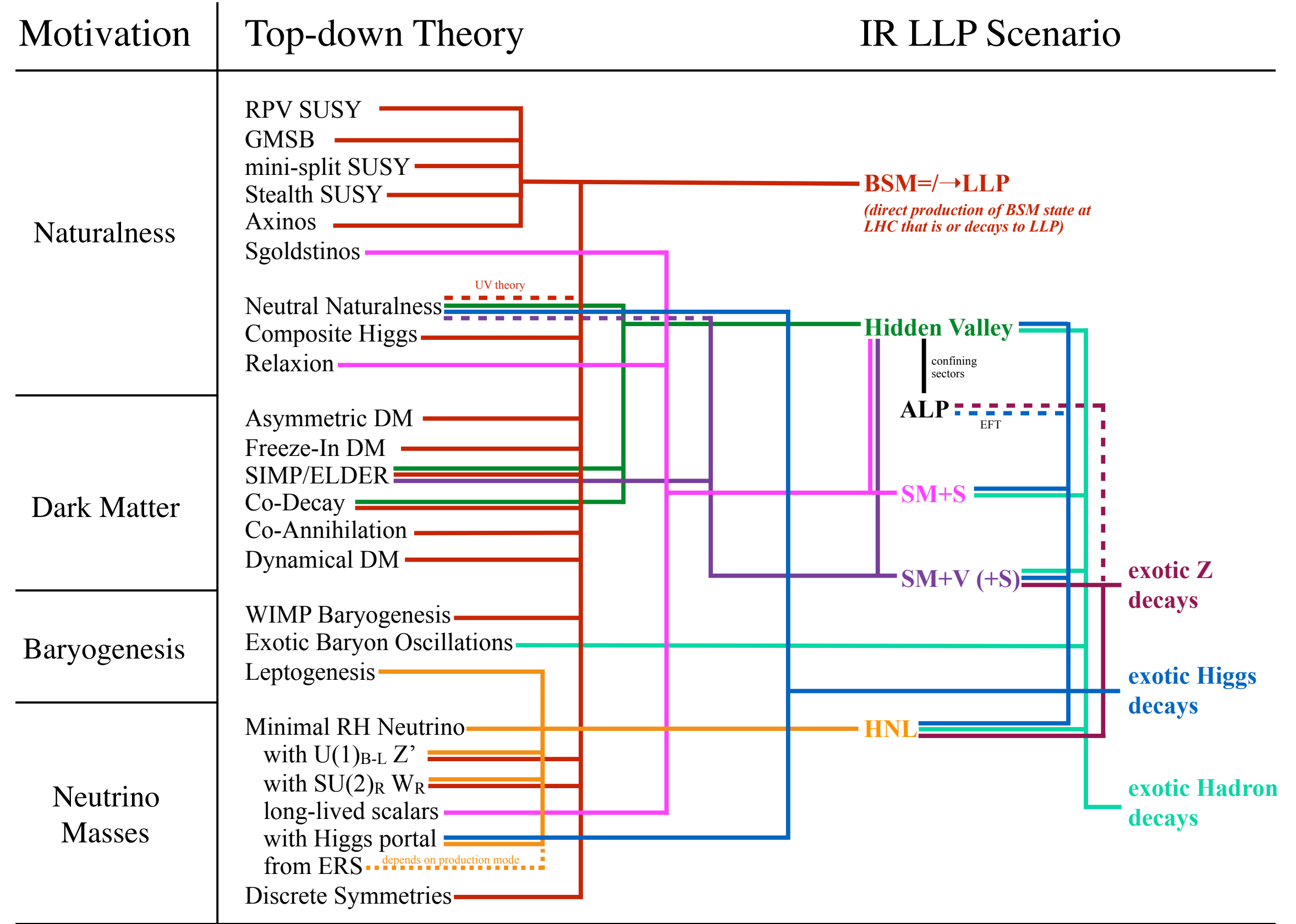
$\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$ $\sqrt{s} = 8, 13 \text{ TeV}$

ATLAS Preliminary

Model	ℓ, γ	Jets†	$E_{\text{T}}^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0 e, \mu, \tau, \gamma$	$1 - 4 j$	Yes	139	M_D 11.2 TeV, $n=2$
	ADD non-resonant $\gamma\gamma$	2γ	-	-	36.7	M_S 8.6 TeV, $n=3$ HLZ NLO
	ADD QBH	-	$2 j$	-	139	M_{th} 9.4 TeV, $n=6$
	ADD BH multijet	-	$\geq 3 j$	-	3.6	M_{th} 9.55 TeV, $n=6, M_D=3 \text{ TeV, rot BH}$
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	139	G_{KK} mass
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	G_{KK} mass 2.3 TeV, $k/M_{\text{Pl}}=0.1$
	Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell\nu qq$	$1 e, \mu$	$2 j / 1 J$	Yes	139	G_{KK} mass 2.0 TeV, $k/M_{\text{Pl}}=1.0$
	Bulk RS $g_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1 J/2$	Yes	36.1	g_{KK} mass 3.8 TeV, $k/M_{\text{Pl}}=1.0$
	ZUED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	36.1	KK mass 1.8 TeV, $\Gamma/m=15\%$
						Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	139	Z' mass 5.1 TeV
	SSM $Z' \rightarrow \tau\tau$	2τ	-	-	36.1	Z' mass 2.42 TeV
	Leptophobic $Z' \rightarrow bb$	-	$2 b$	-	36.1	Z' mass 2.1 TeV
	Leptophobic $Z' \rightarrow tt$	$0 e, \mu$	$\geq 1 b, \geq 2 J$	Yes	139	Z' mass 4.1 TeV, $\Gamma/m=1.2\%$
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	-	-	139	W' mass 6.0 TeV
	SSM $W' \rightarrow \tau\nu$	1τ	-	-	139	W' mass 5.0 TeV
	SSM $W' \rightarrow tb$	-	$\geq 1 b, \geq 1 J$	-	139	W' mass 4.4 TeV
	HVT $W' \rightarrow WZ \rightarrow \ell\nu qq$ model B	$1 e, \mu$	$2 j / 1 J$	Yes	139	W' mass 340 GeV, $g_V=3$
	HVT $W' \rightarrow WZ \rightarrow \ell\nu \ell' \ell'$ model C	$3 e, \mu$	$2 j$ (VBF)	Yes	139	W' mass 4.3 TeV, $g_V=3$
	HVT $W' \rightarrow WH \rightarrow \ell\nu bb$ model B	$1 e, \mu$	$1-2 b, 1-0 J$	Yes	139	W' mass 3.3 TeV, $g_V=3$
	HVT $Z' \rightarrow ZH \rightarrow \ell\nu bb$ model B	$0, 2 e, \mu$	$1-2 b, 1-0 J$	Yes	139	Z' mass 3.2 TeV, $m(N_R)=0.5 \text{ TeV, } g_L=g_R$
	LRSB $W_R \rightarrow \mu N_R$	2μ	$1 J$	-	80	W_R mass 5.0 TeV
CI	CI $qqqq$	-	$2 j$	-	37.0	Λ 21.8 TeV, η_{LL}
	CI $\ell\ell qq$	$2 e, \mu$	-	-	139	Λ 35.8 TeV, η_{LL}
	CI $eebs$	$2 e$	$1 b$	-	139	$g_s=1, g_1=1, m(\chi)=1 \text{ GeV}$
	CI $\mu\mu bs$	2μ	$1 b$	-	139	$g_s=1, g_1=1, m(\chi)=100 \text{ GeV}$
	CI $ttbs$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$\tan\beta=1, g_z=0.8, m(\chi)=10 \text{ GeV}$
DM	Axial-vector med. (Dirac DM)	$0 e, \mu, \tau, \gamma$	$1 - 4 j$	Yes	139	m_{med} 2.1 TeV
	Pseudo-scalar med. (Dirac DM)	$0 e, \mu, \tau, \gamma$	$1 - 4 j$	Yes	139	m_{med} 376 GeV
	Vector med. Z' -2HDM (Dirac DM)	$0 e, \mu$	$2 b$	Yes	139	m_{med} 3.1 TeV
	Pseudo-scalar med. 2HDM+a	multi-channel	-	-	139	m_{med} 560 GeV
LQ	Scalar LQ 1 st gen	$2 e$	$\geq 2 j$	Yes	139	LQ mass 1.8 TeV, $\beta=1$
	Scalar LQ 2 nd gen	2μ	$\geq 2 j$	Yes	139	LQ mass 1.7 TeV
	Scalar LQ 3 rd gen	1τ	$2 b$	Yes	139	$LQ_{\text{up}}^{\text{mass}}$ 1.2 TeV, $\mathcal{B}(LQ_{\text{up}}^{\text{mass}} \rightarrow b\tau) = 1$
	Scalar LQ 3 rd gen	$0 e, \mu$	$\geq 2 j, \geq 2 b$	Yes	139	$LQ_{\text{up}}^{\text{mass}}$ 1.24 TeV, $\mathcal{B}(LQ_{\text{up}}^{\text{mass}} \rightarrow t\nu) = 1$
	Scalar LQ 3 rd gen	$\geq 2 e, \mu, \geq 1 \tau, \geq 1 j, \geq 1 b$	-	-	139	$LQ_{\text{up}}^{\text{mass}}$ 1.43 TeV, $\mathcal{B}(LQ_{\text{up}}^{\text{mass}} \rightarrow t\tau) = 1$
	Scalar LQ 3 rd gen	$0 e, \mu, \geq 1 \tau, 0 - 2 j, 2 b$	-	-	139	$LQ_{\text{up}}^{\text{mass}}$ 1.26 TeV, $\mathcal{B}(LQ_{\text{up}}^{\text{mass}} \rightarrow b\nu) = 1$
	Vector LQ 3 rd gen	1τ	$2 b$	Yes	139	$LQ_{\text{up}}^{\text{mass}}$ 1.77 TeV, $\mathcal{B}(LQ_{\text{up}}^{\text{mass}} \rightarrow b\tau) = 0.5, \text{ Y-M coupl.}$
Vector-like fermions	VLQ $TT \rightarrow Zt + X$	$2e/2\mu/\geq 3e, \mu$	$\geq 1 b, \geq 1 j$	-	139	T mass 1.4 TeV, SU(2) doublet
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV, SU(2) doublet
	VLQ $T_{5/3} T_{5/3} T_{5/3} \rightarrow Wt + X$	$2(SS)/\geq 3e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV, $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} Wt) = 1$
	VLQ $T \rightarrow Ht/Zt$	$1 e, \mu$	$\geq 1 b, \geq 3 j$	Yes	139	T mass 1.8 TeV, SU(2) singlet, $\kappa_T = 0.5$
	VLQ $Y \rightarrow Wb$	$1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Y mass 1.85 TeV, $\mathcal{B}(Y \rightarrow Wb) = 1, c_R(Wb) = 1$
	VLQ $B \rightarrow Hb$	$0 e, \mu$	$\geq 2b, \geq 1 j, \geq 1 J$	-	139	B mass 2.0 TeV, SU(2) doublet, $\kappa_B = 0.3$
	VLL $\tau' \rightarrow Z\tau/H\tau$	multi-channel	$\geq 1 j$	Yes	139	τ' mass 898 GeV, SU(2) doublet
Excited fermions	Excited quark $q^* \rightarrow qg$	-	$2 j$	-	139	q^* mass 6.7 TeV, only u' and d' , $\Lambda = m(q^*)$
	Excited quark $q^* \rightarrow q\gamma$	1γ	$1 j$	-	36.7	q^* mass 5.3 TeV, only u' and d' , $\Lambda = m(q^*)$
	Excited quark $b^* \rightarrow bg$	-	$1 b, 1 j$	-	139	b^* mass 3.2 TeV, $\Lambda = 3.0 \text{ TeV}$
	Excited lepton ℓ^*	$3 e, \mu$	-	-	20.3	ℓ^* mass 3.0 TeV, $\Lambda = 1.6 \text{ TeV}$
	Excited lepton ν^*	$3 e, \mu, \tau$	-	-	20.3	ν^* mass 1.6 TeV, $\Lambda = 1.6 \text{ TeV}$
Other	Type III Seesaw	$2, 3, 4 e, \mu$	$\geq 2 j$	Yes	139	N^0 mass 910 GeV, $m(W_R) = 4.1 \text{ TeV, } g_L = g_R$
	LRSB Majorana ν	2μ	$2 j$	-	36.1	N_q mass 3.2 TeV, DY production
	Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm} W^{\pm}$	$2, 3, 4 e, \mu$ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV, DY production
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2, 3, 4 e, \mu$ (SS)	-	-	139	$H^{\pm\pm}$ mass 1.08 TeV, DY production, $\mathcal{B}(H^{\pm\pm} \rightarrow \ell\tau) = 1$
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3 e, \mu, \tau$	-	-	20.3	$H^{\pm\pm}$ mass 400 GeV, DY production, $ q = 5e$
	Multi-charged particles	-	-	-	139	multi-charged particle mass 1.59 TeV, DY production, $ g = 1g_D, \text{ spin } 1/2$
	Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 TeV

*Only a selection of the available mass limits on new states or phenomena is shown.

† Small-radius (large-radius) jets are denoted by the letter j (J).



Curtin et al, 1806.07396

New physics could have long lifetimes

Signatures in ATLAS and CMS not visible in standard searches!!

How can we look for LLPs in collider experiments?

That depends on:

LLP lifetime

Standard HEP detector structure

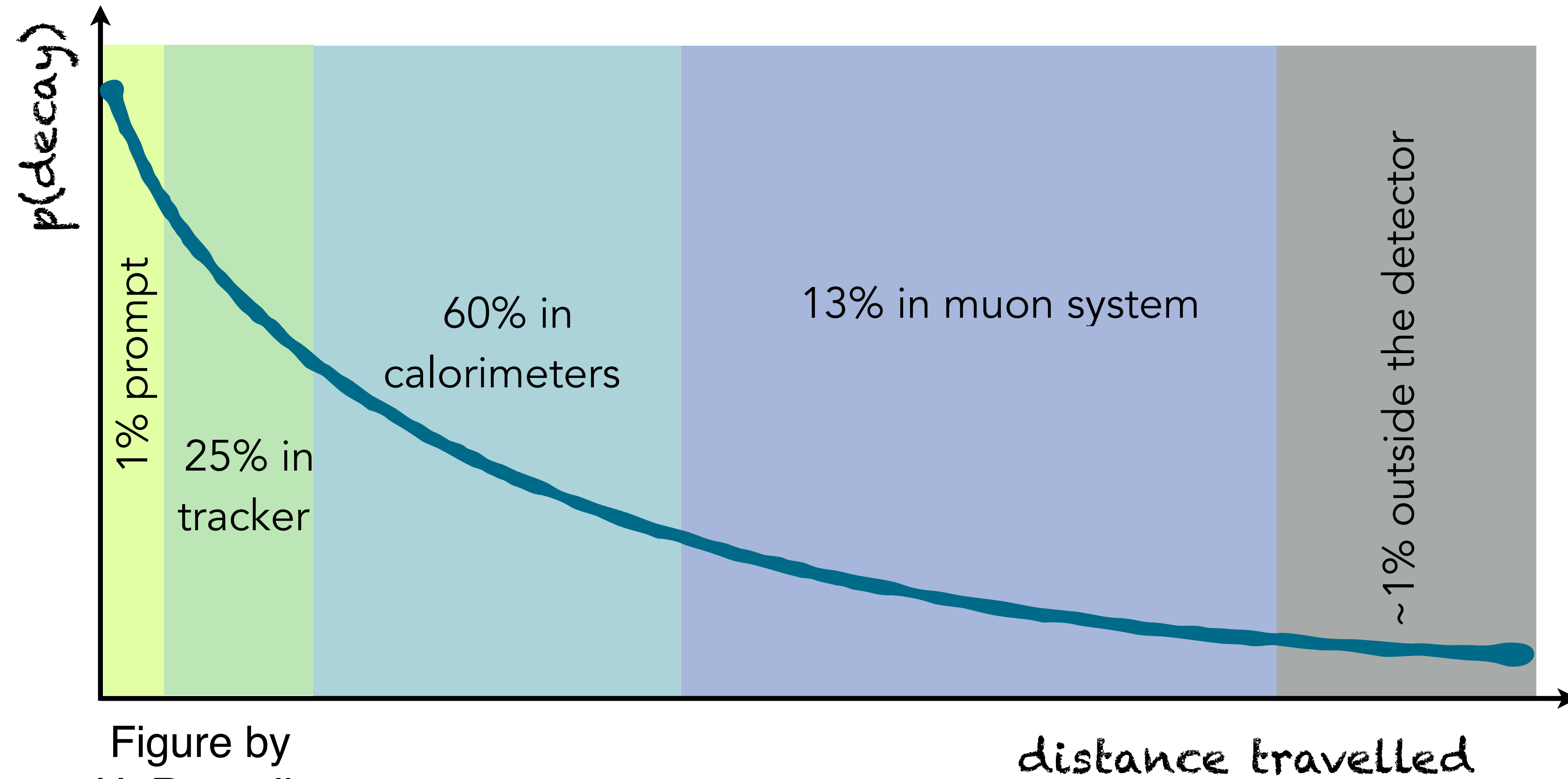
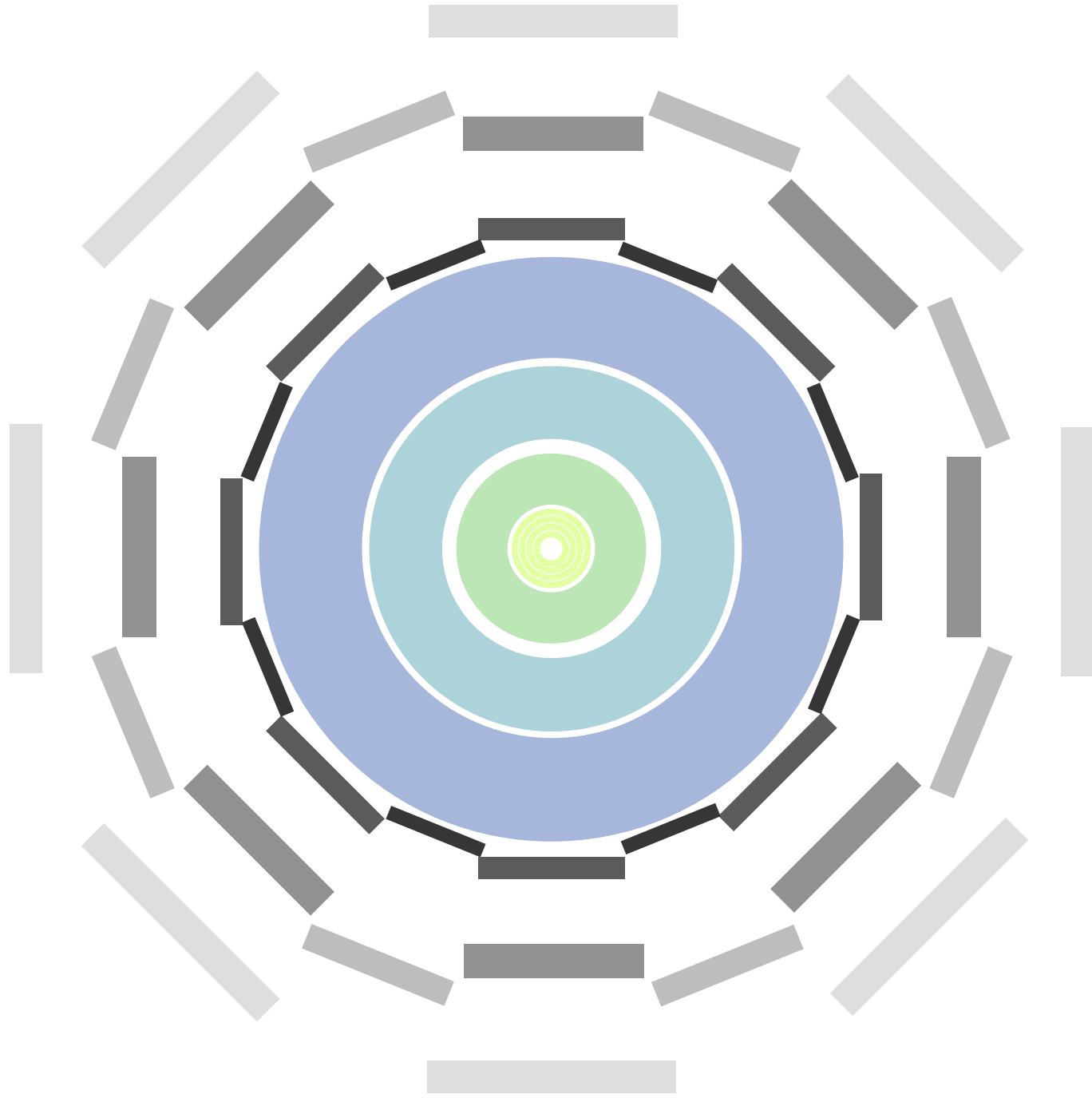


Figure by H. Russell

distance travelled

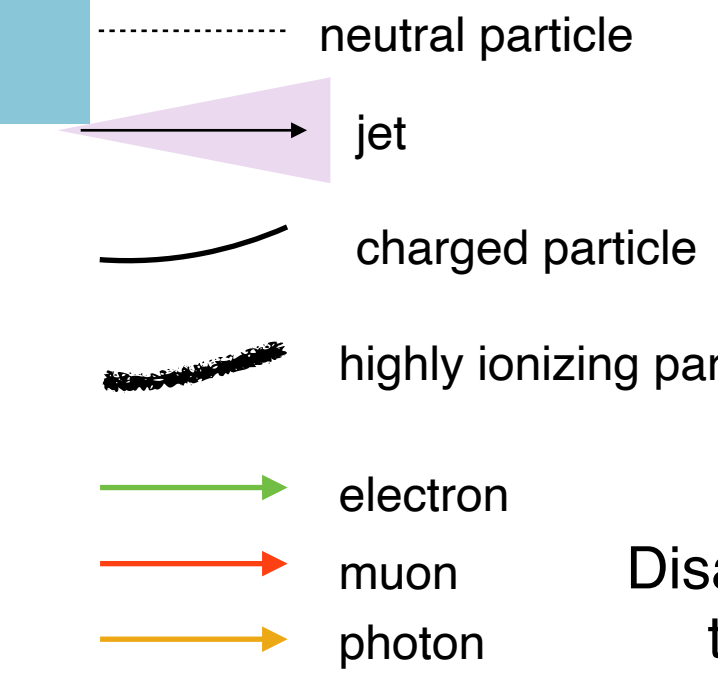
How can we look for LLPs in collider experiments?

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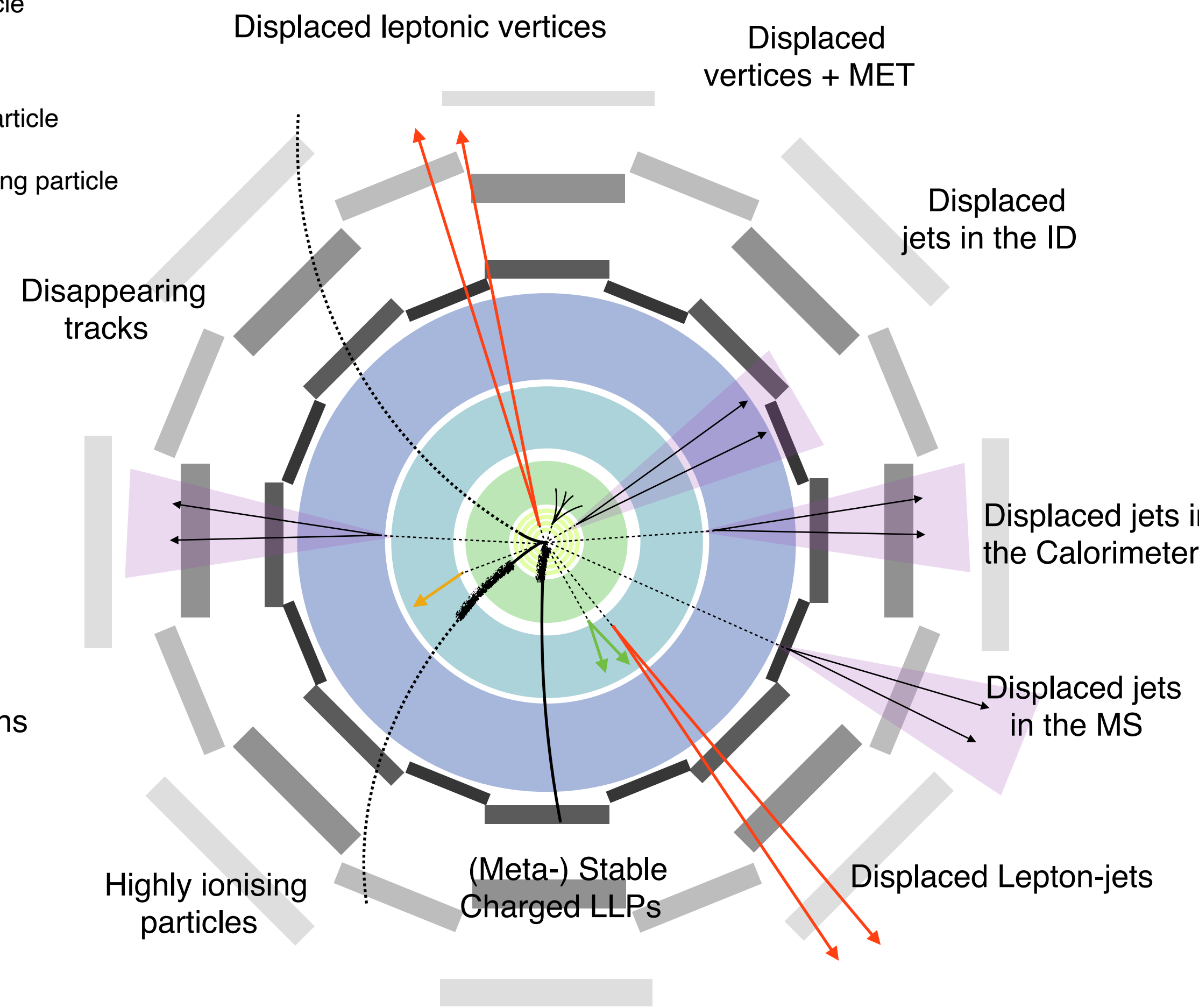


- Is it charged?
 - Does it leave a standard track?
 - Is it highly ionising?
- Is it neutral?
 - which decay mode (hadronic, leptonic, photons, invisible)?

• None of these signatures would be “seen” by a standard HEP search!



Stopped LLPs NOT IN FILLED BUNCH CROSSING



How can we look for LLPs in collider experiments?

That depends on:

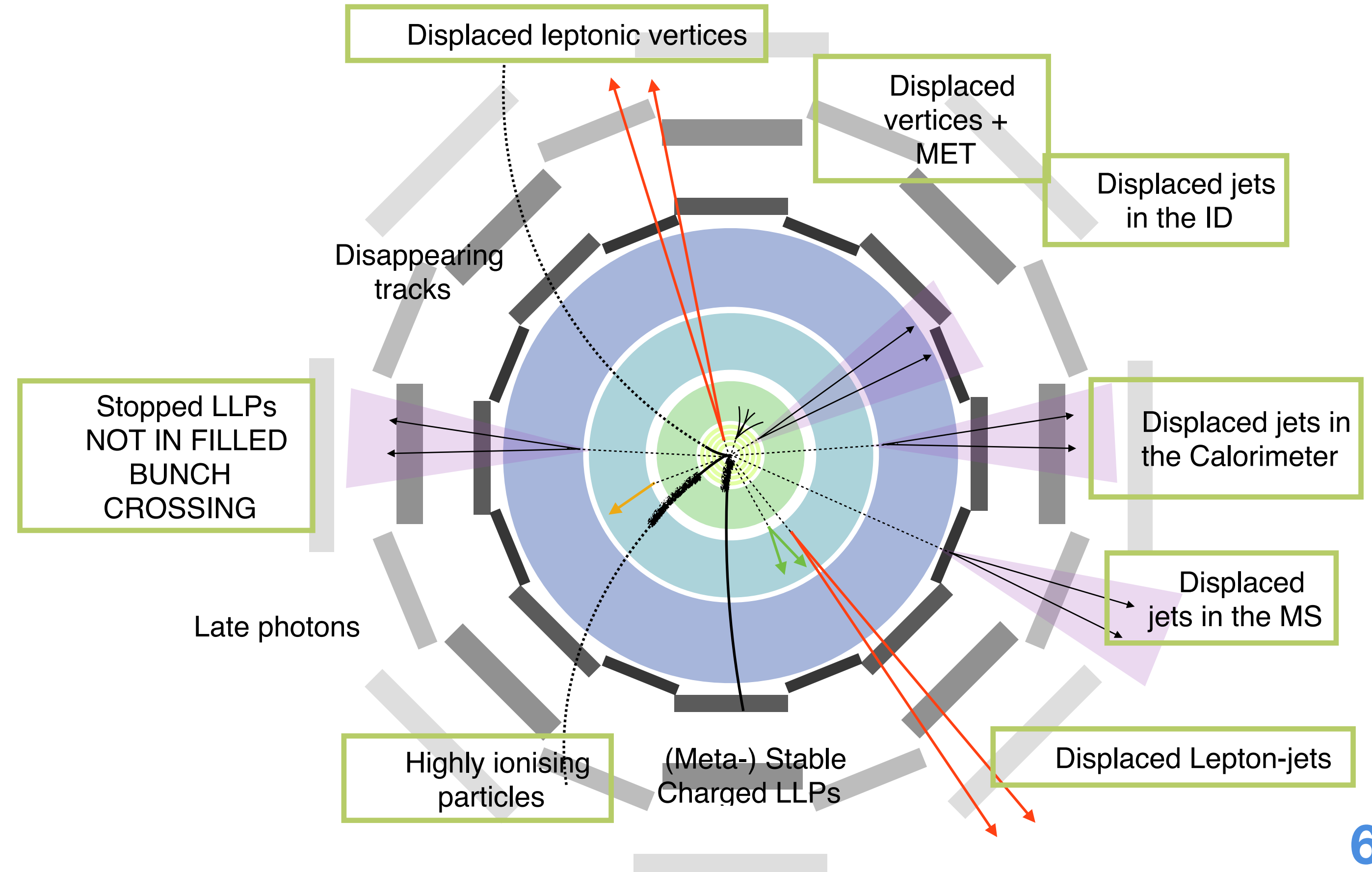
LLP lifetime

LLP nature

object identification

trigger

- **Trigger**: combination of hardware + software that must decide very quickly whether to save an event or lose it forever
- Standard triggers have no sensitivity to LLPs
- Develop **dedicated triggers**



How can we look for LLPs in collider experiments?

That depends on:

LLP lifetime

LLP nature

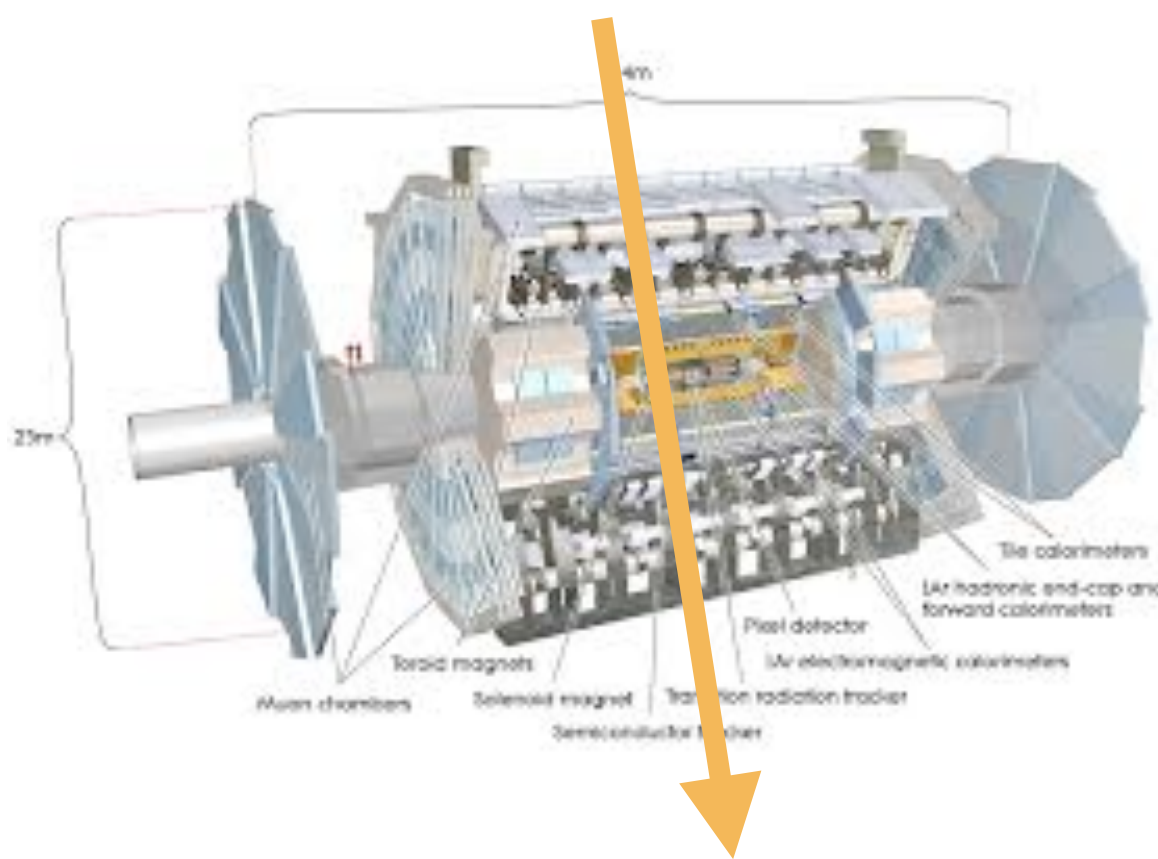
object identification

trigger

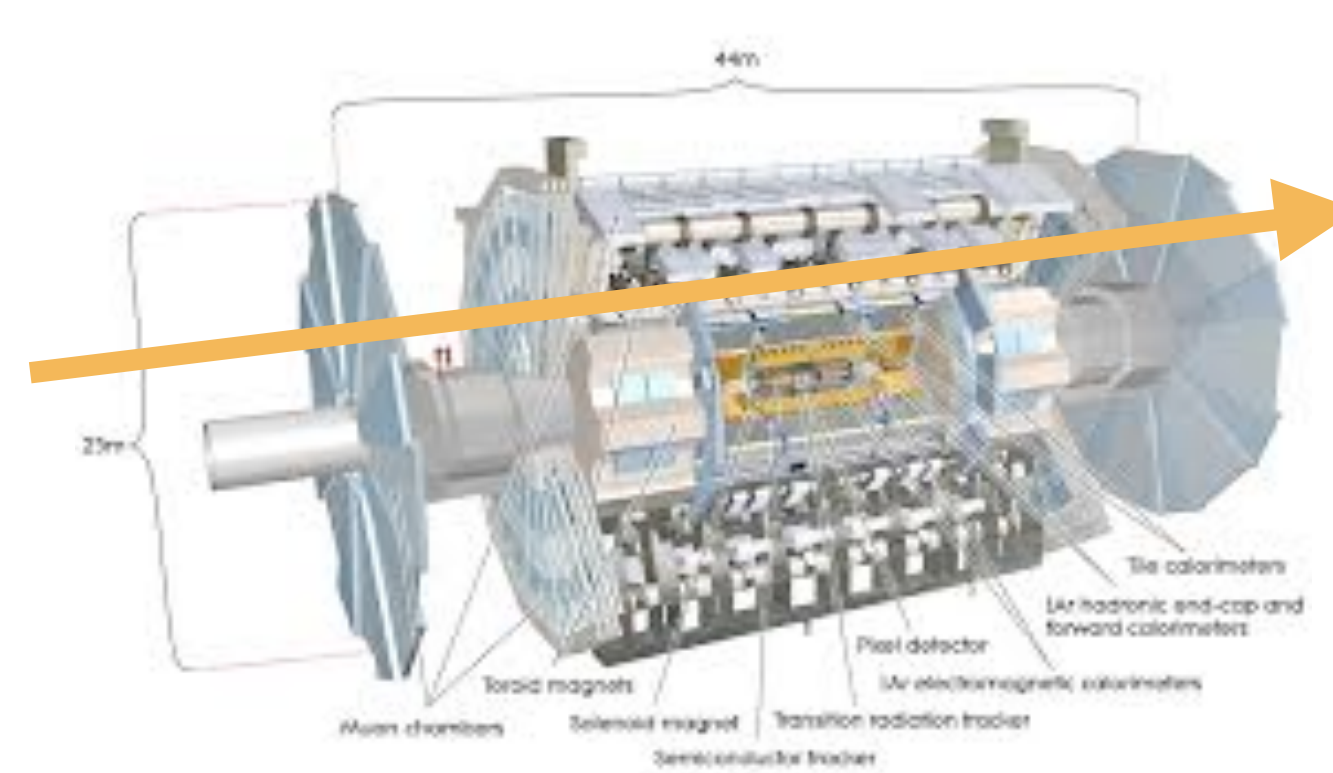
background rejection

- Small or unusual backgrounds play a key role:

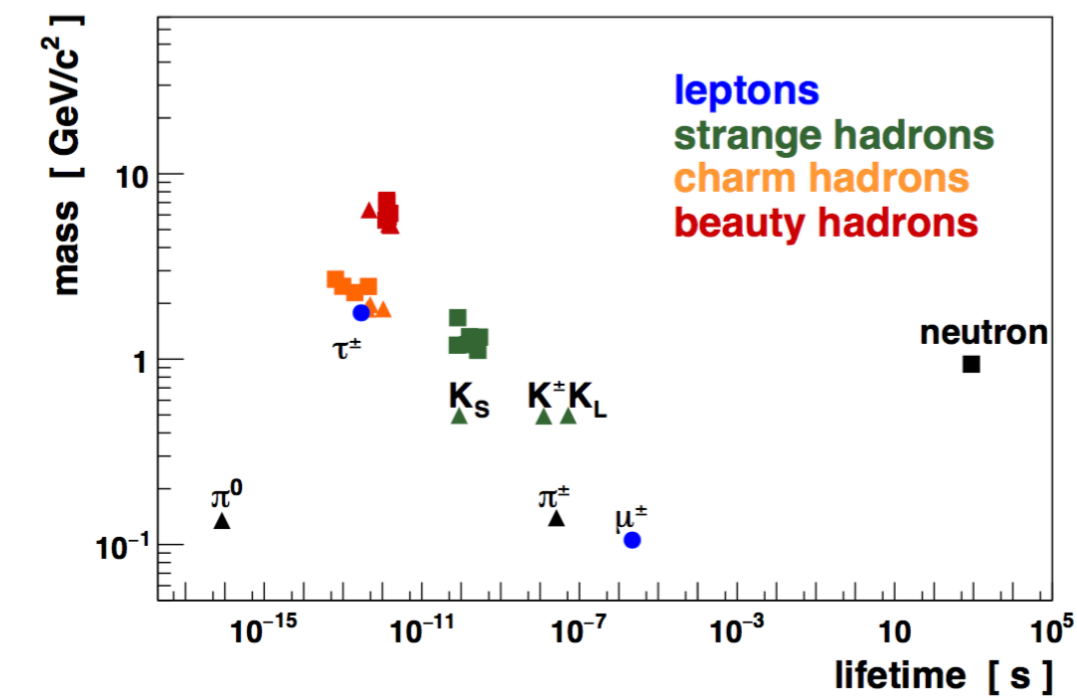
cosmic muons



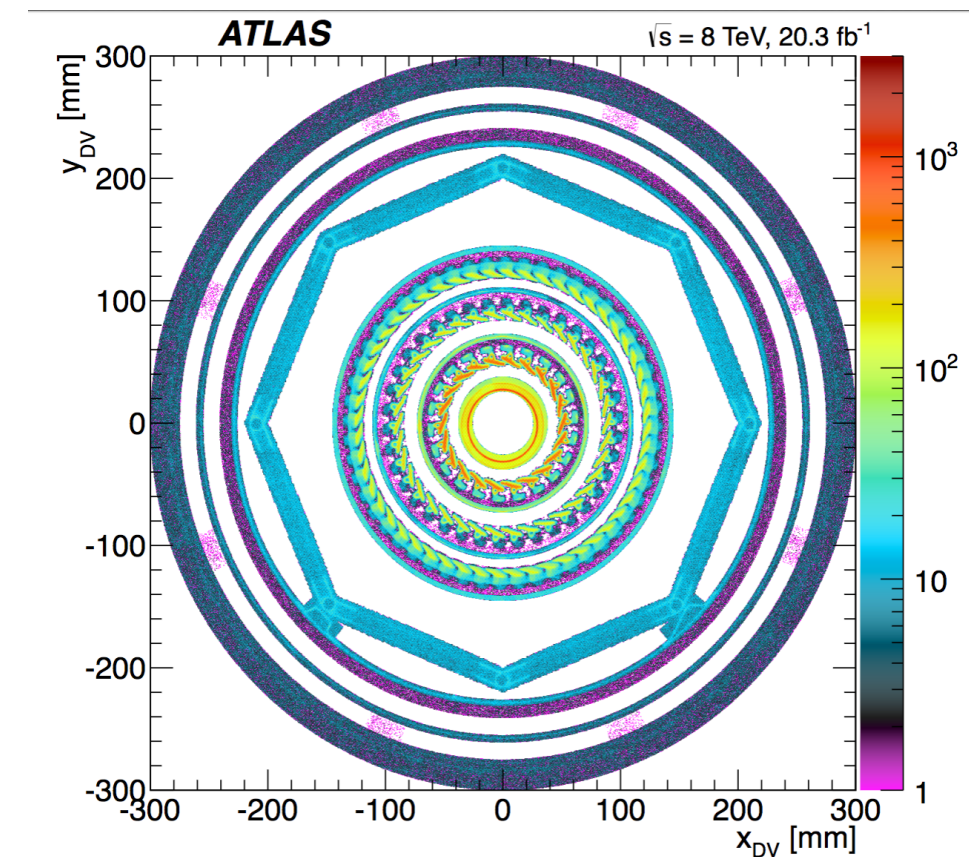
beam halo muons



SM particles with relatively long lifetime



material interactions



- For most of them, no good simulations
 - All searches rely on data-driven methods

LLP lifetime

LLP nature

object identification

trigger

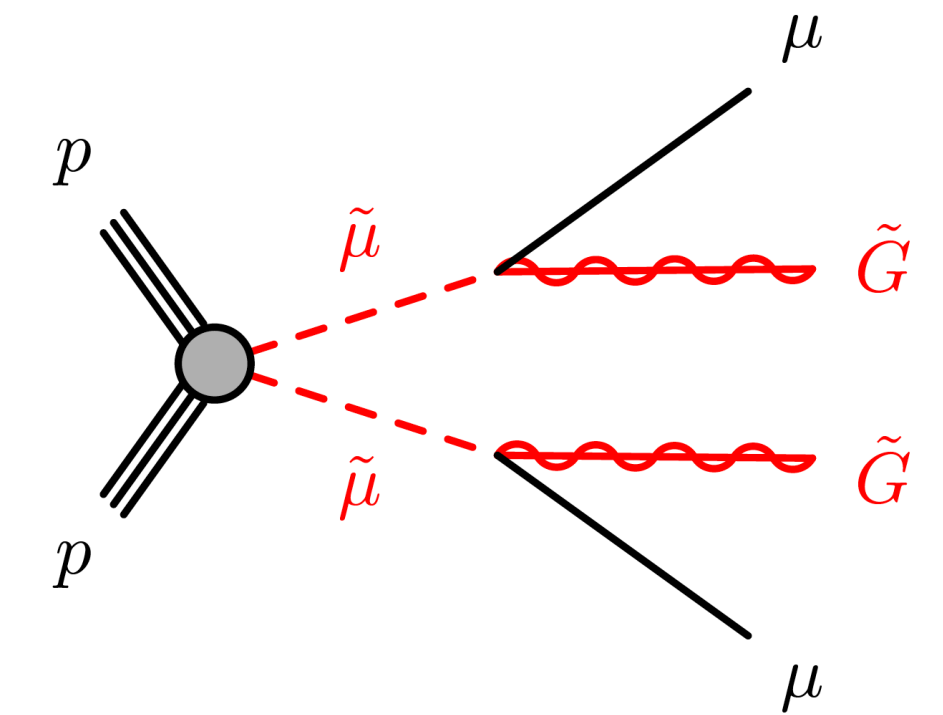
background rejection

Latest results on Searches for LLPs in ATLAS

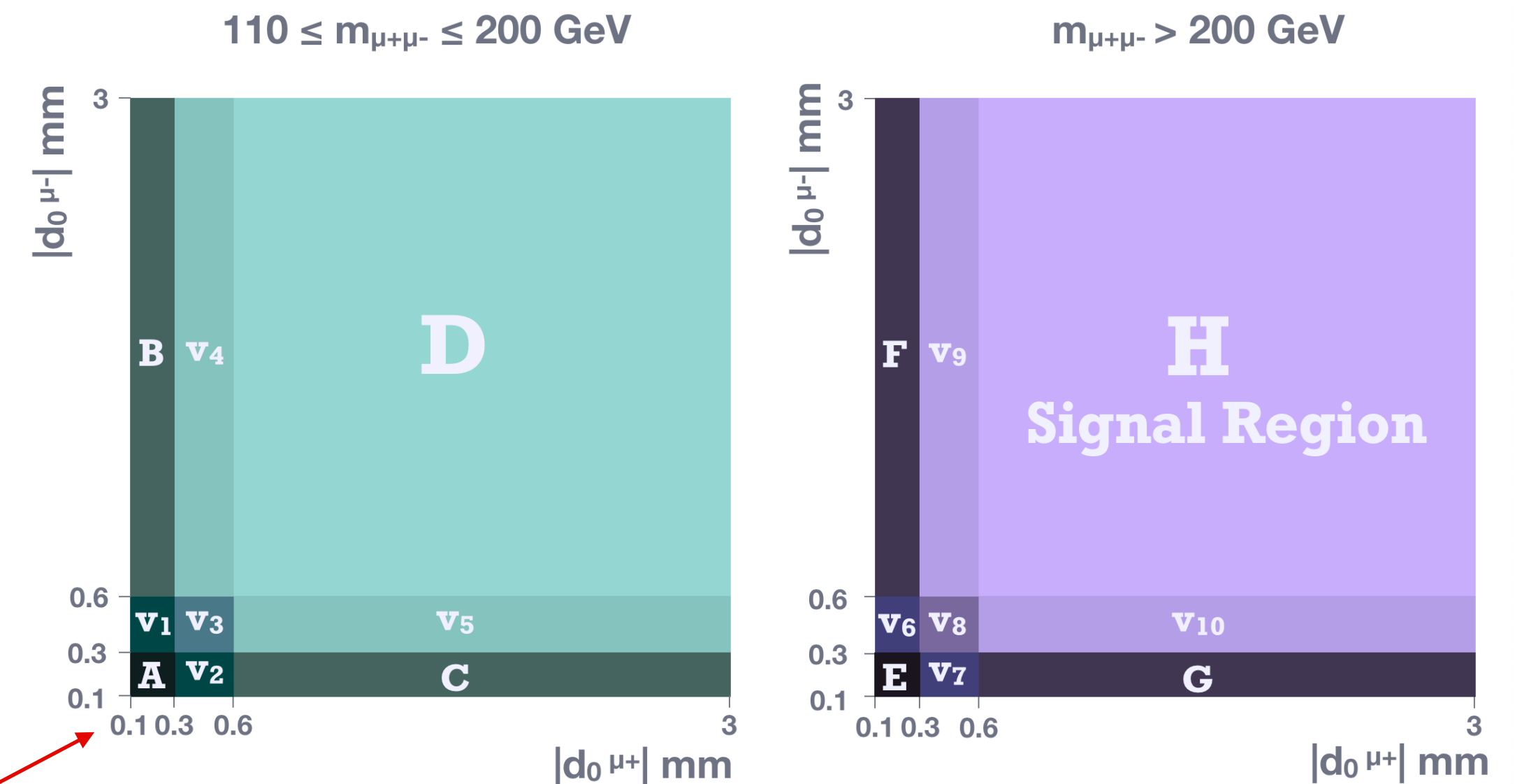
Micro-displaced muons



- Search for pairs of opposite charge muons with O(mm) impact parameter
- GMSB SUSY with nearly massless gravitino LSP and long-lived slepton ($\tilde{\tau}, \tilde{e}, \tilde{\mu}$ NLSP) due to small coupling to the LSP
- Di-muon trigger
- Very simple Signal Region selection: two muons with large transverse impact parameter $|d_0| > 0.6$ mm



- Dominant SM background: semileptonic B -hadron decays, $bb \rightarrow \mu\mu$
 - Data driven background ABCD method
- Other SM processes with prompt leptons are negligible (Z/W +jets, tt , single top, di-boson)

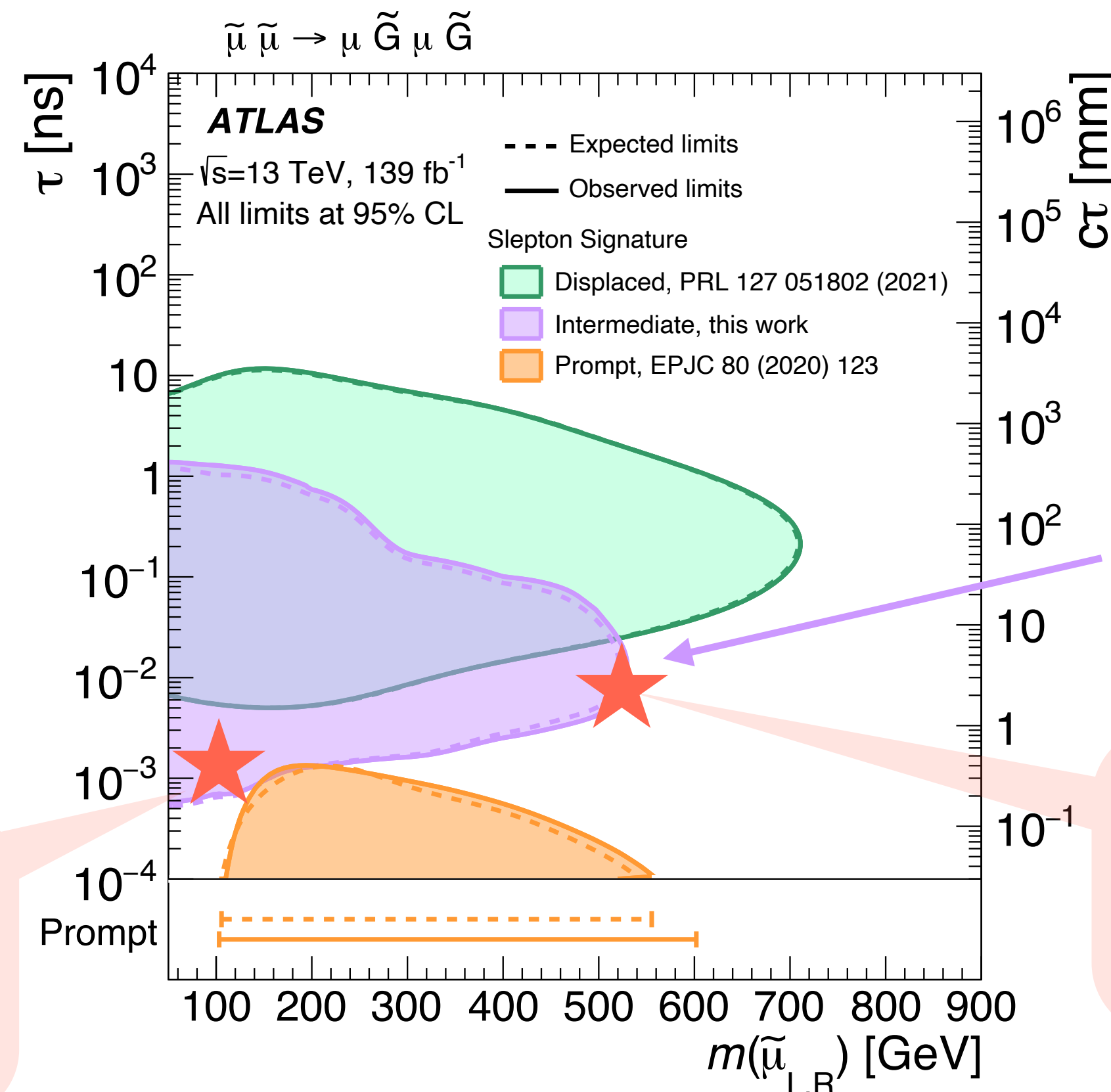
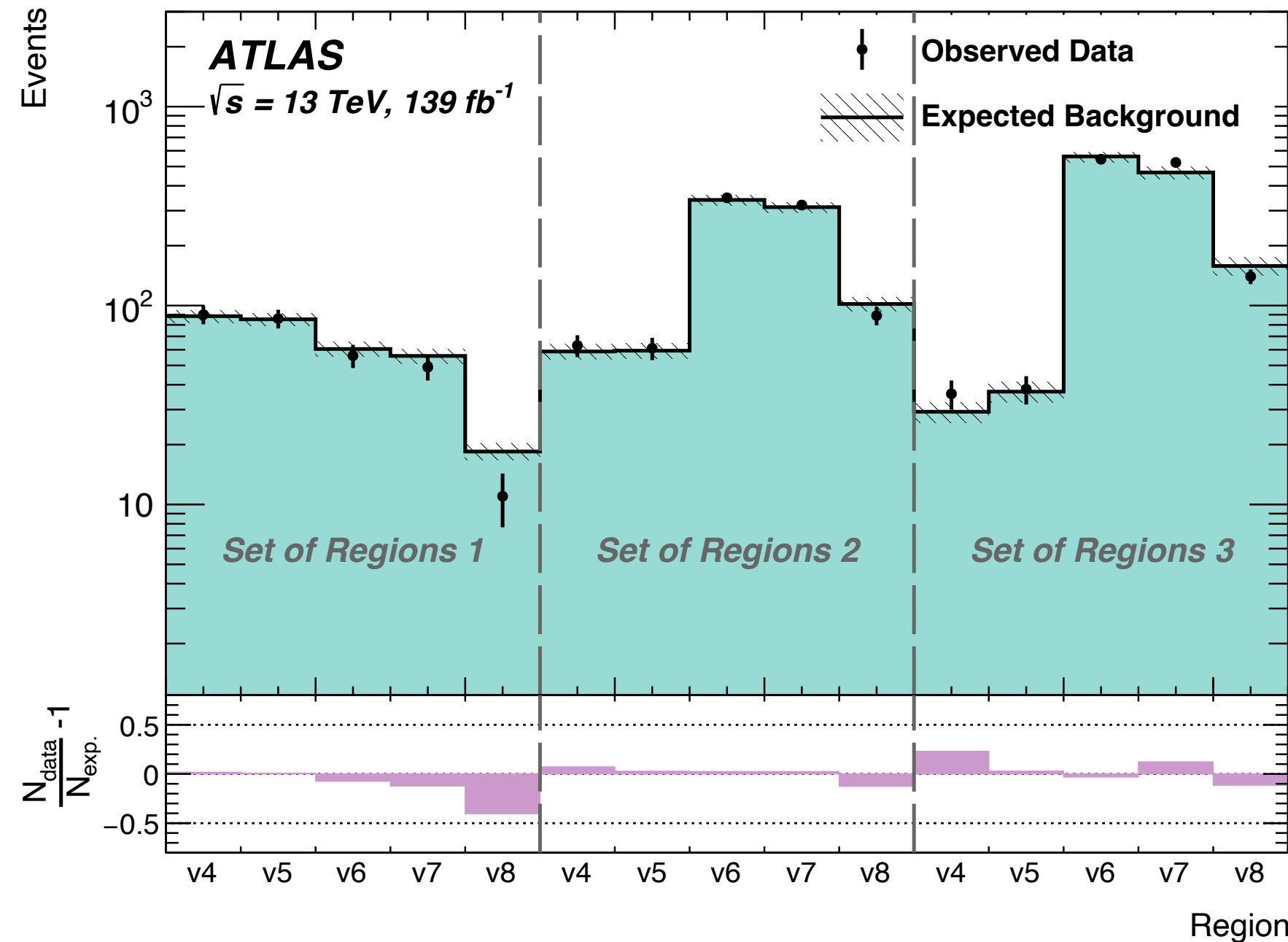
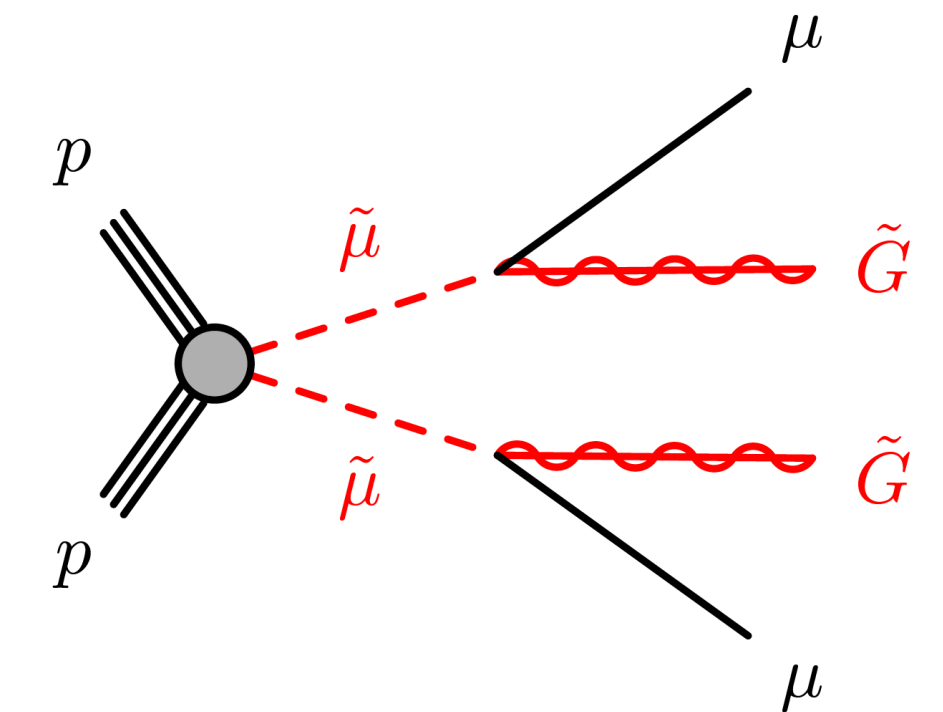


$|d_0| > 0.1$ mm to reduce SM processes

Micro-displaced muons

- 15 Validation regions to test the ABCD method
 - General good agreement
 - One region has a 2σ non-closure
 - Systematic uncertainty assigned in the signal region.

- No excess observed



Closing the gap between prompt (reinterpretation) and large displacement searches

Excluded lifetimes down to 1 ps for $m(\tilde{\mu}) \sim 100$ GeV

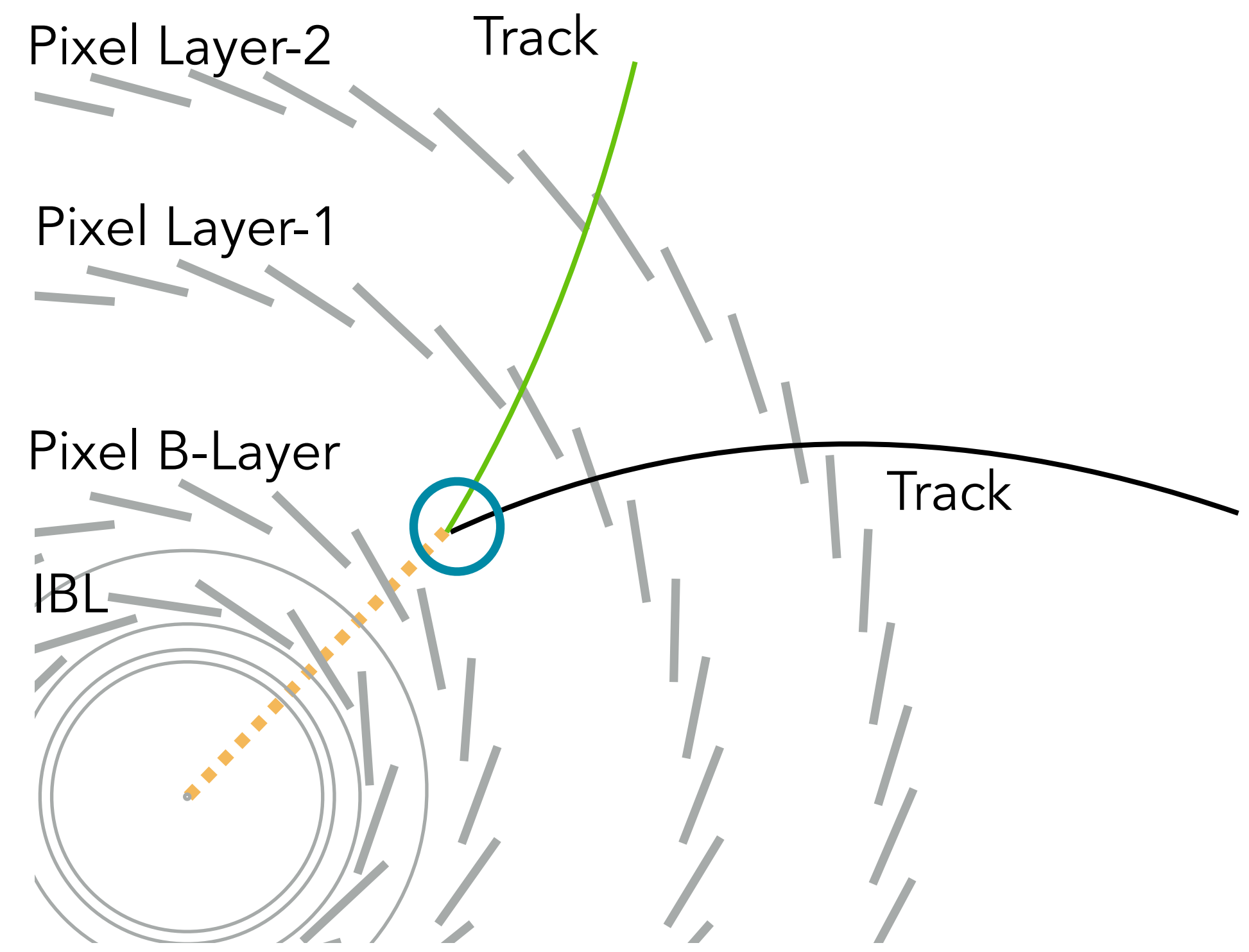
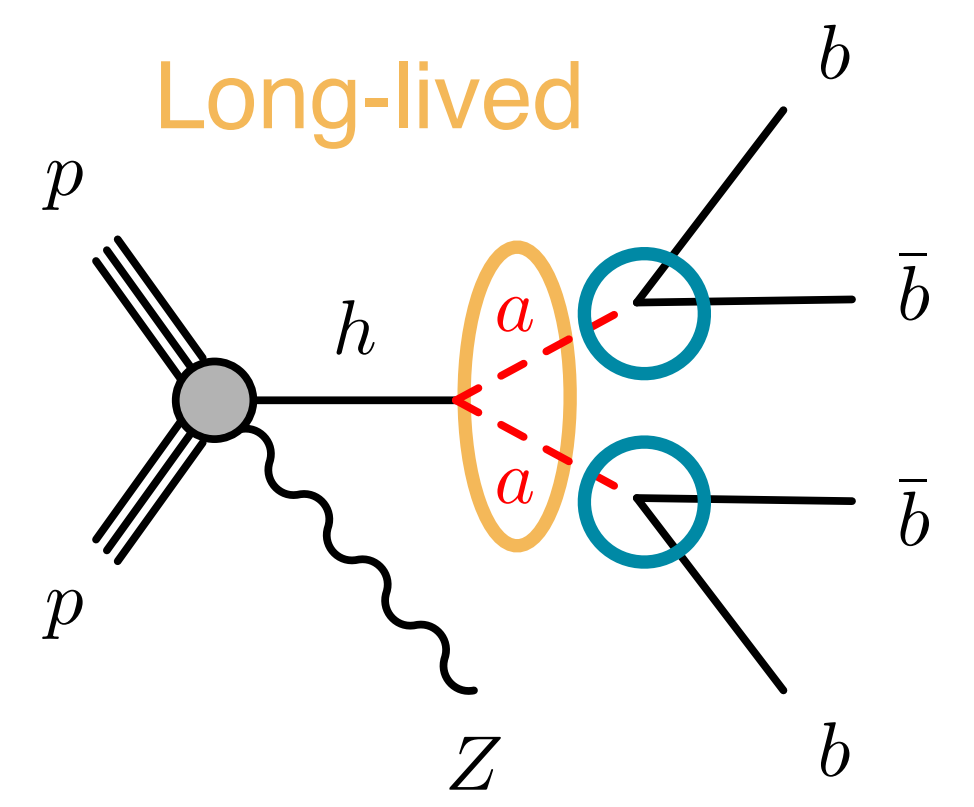
Excluded lifetimes down to 10 ps for $m(\tilde{\mu}) \sim 520$ GeV

Large-Radius Tracking



- Standard tracking in ATLAS optimized for particles pointing back to IP
 - tight requirements in number of silicon hits and impact parameter
 - would reject tracks from displaced decays

IDTR-2021-03

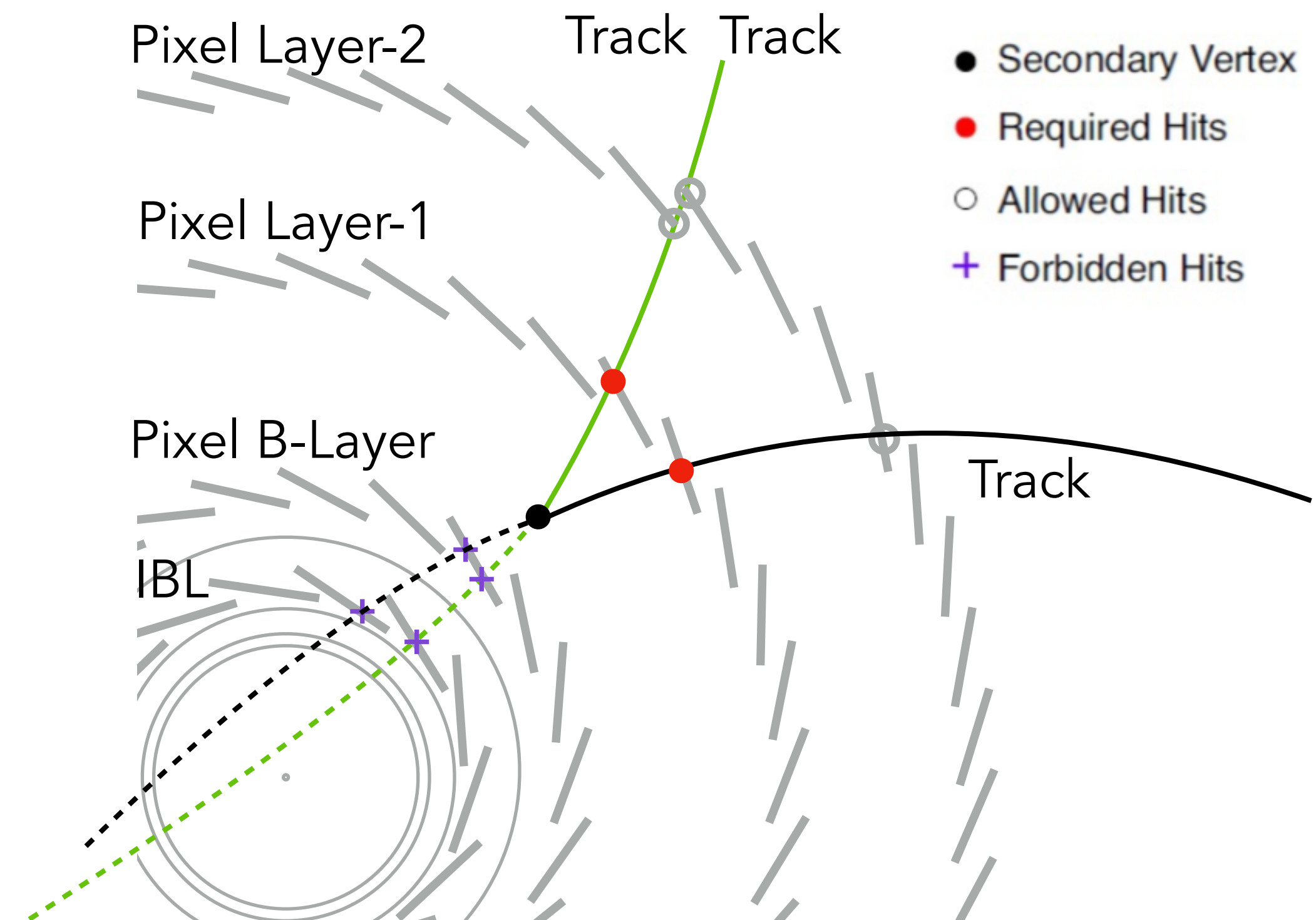
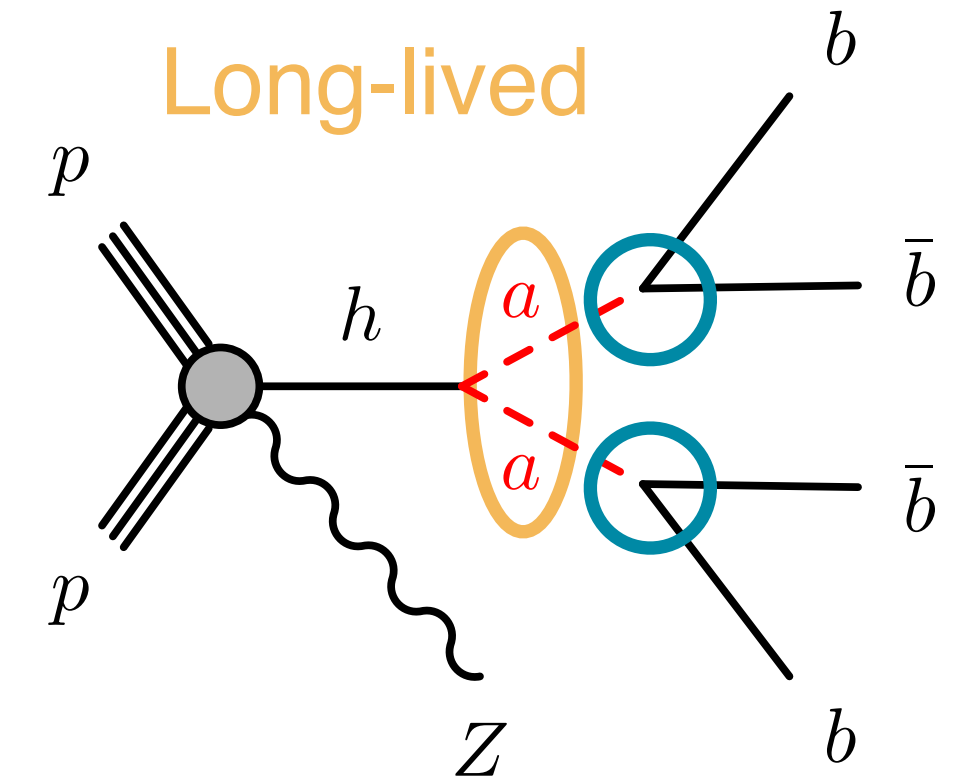


Large-Radius Tracking

IDTR-2021-03



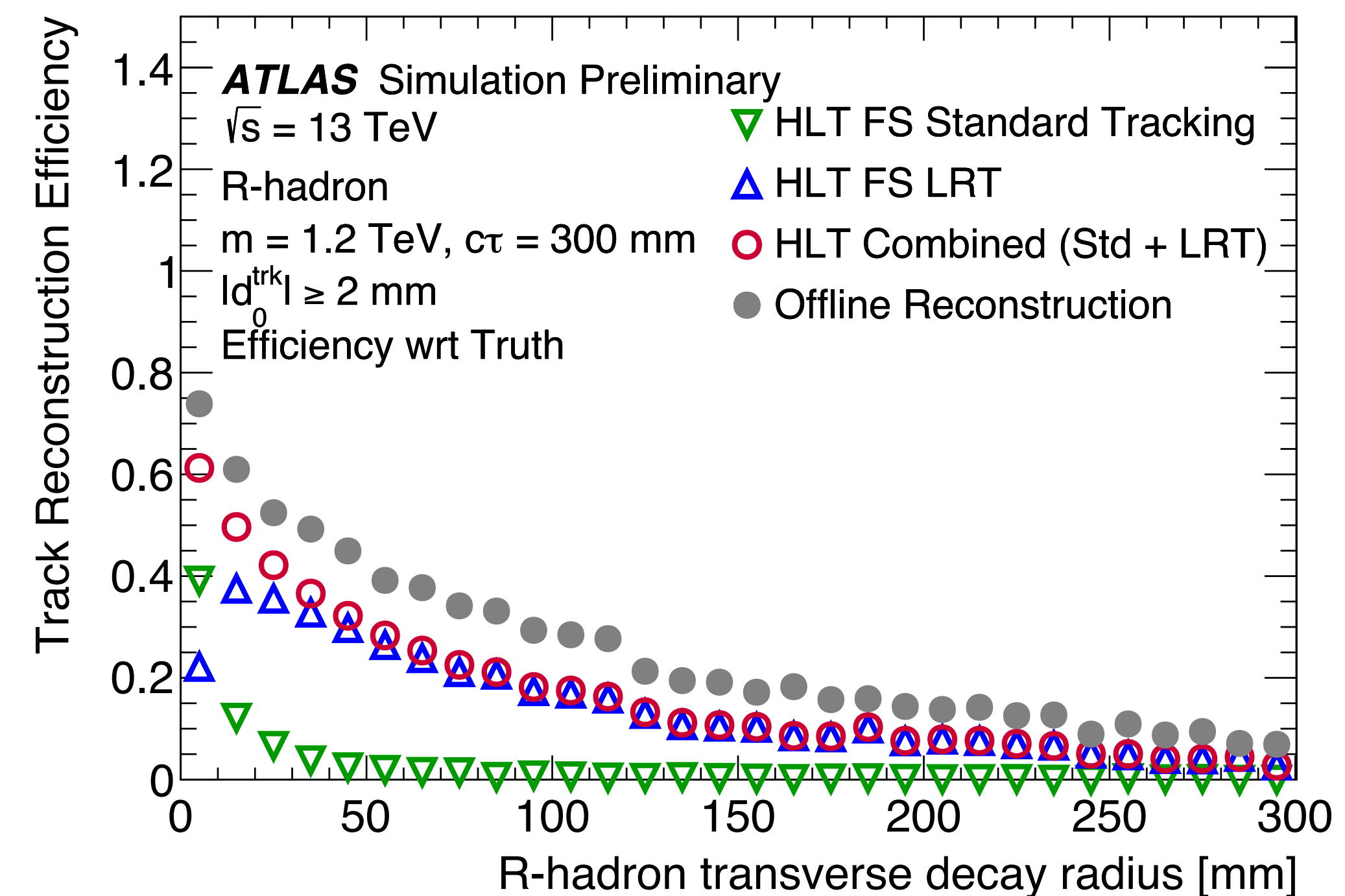
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- Large radius tracking (LRT)
 - Relax requirements in number of hits and impact parameter
 - Re-run with hits not associated with standard tracks



Large-Radius Tracking



- Standard tracking in ATLAS optimized for particles pointing back to IP
 - tight requirements in number of silicon hits and impact parameter
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- Large radius tracking (LRT)
 - Relax requirements in number of hits and impact parameter
 - Re-run with hits not associated with standard tracks
 - Improves reconstruction for displacements up to 300 mm
- LRT running at HLT trigger level in Run 3!!

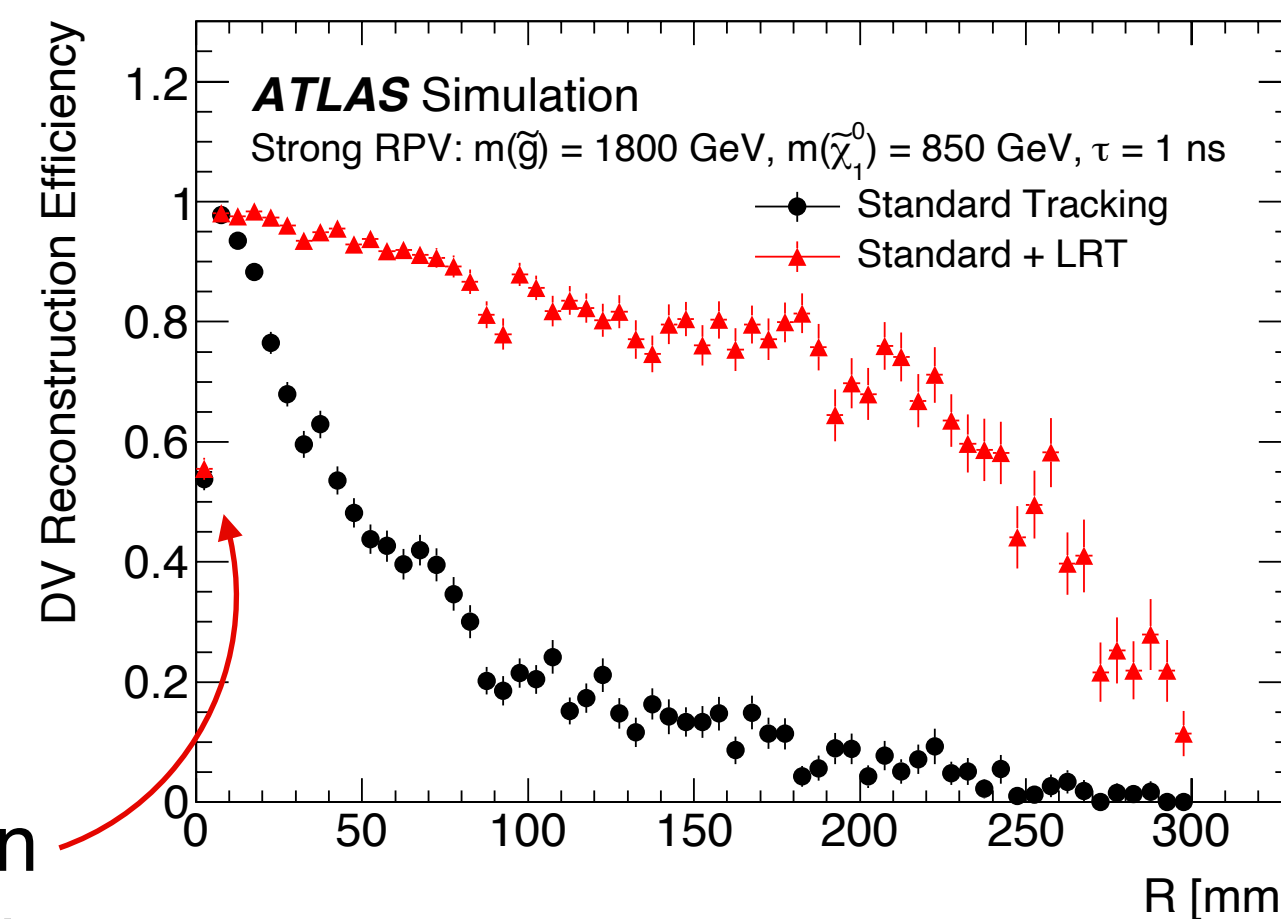
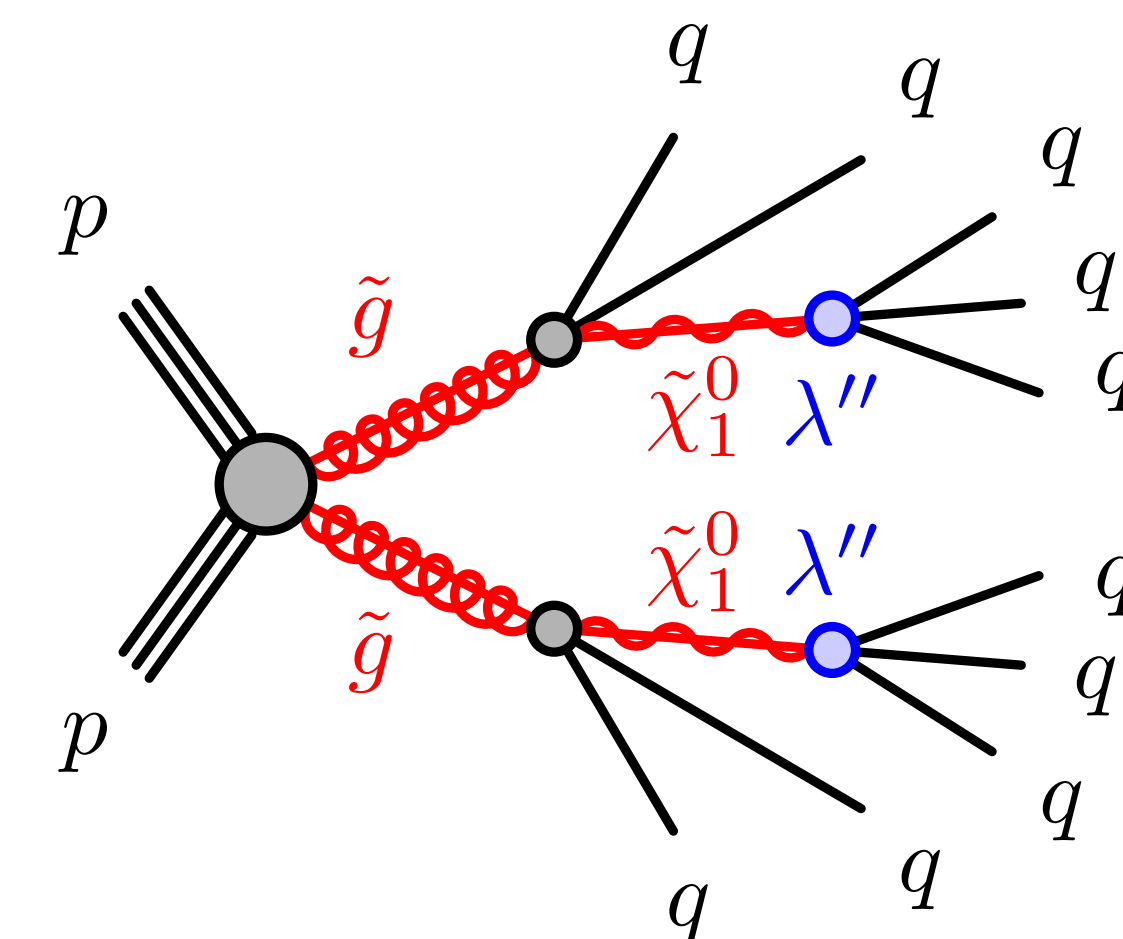


Efficiency to reconstruct displaced electrons, muons and disappearing tracks in backup

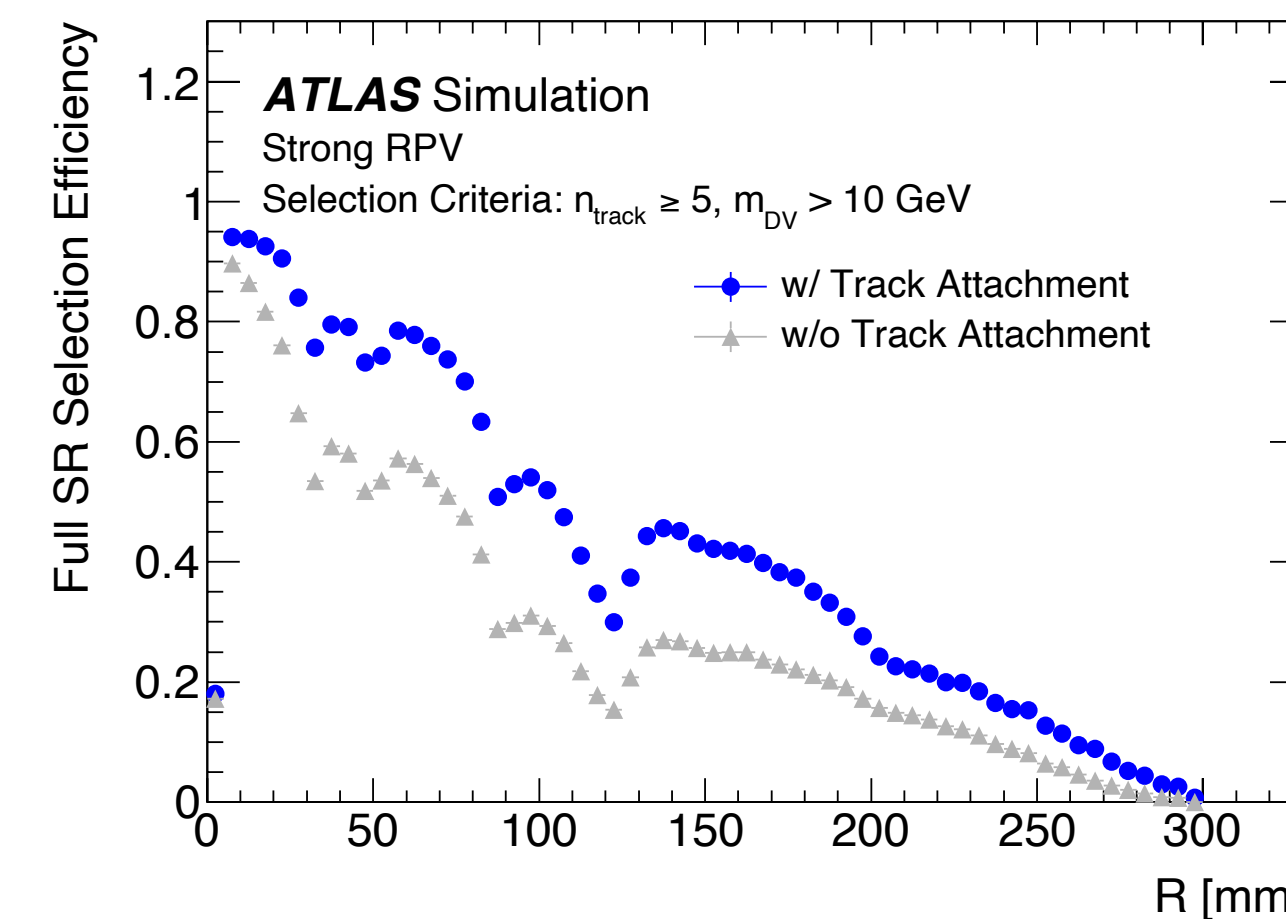
Displaced vertices + jets



- Long-lived particles decaying into hadrons in the ATLAS inner detector
- SM (MSSM) R -parity-violating (RPV)
 - mean proper lifetimes τ up to $O(10)$ ns
- Using **LRT** in events with multiple energetic jets and a displaced vertex
- Vertexing:
 1. two-track seed vertices, where at least one track with $|d_0| > 2$ mm
 - iteratively merged to form n -track vertices
 2. additional tracks with looser selection criteria are **attached** to the reconstructed vertices



requirement on
two-track seed
vertices must have
 $|d_0| > 2$ mm



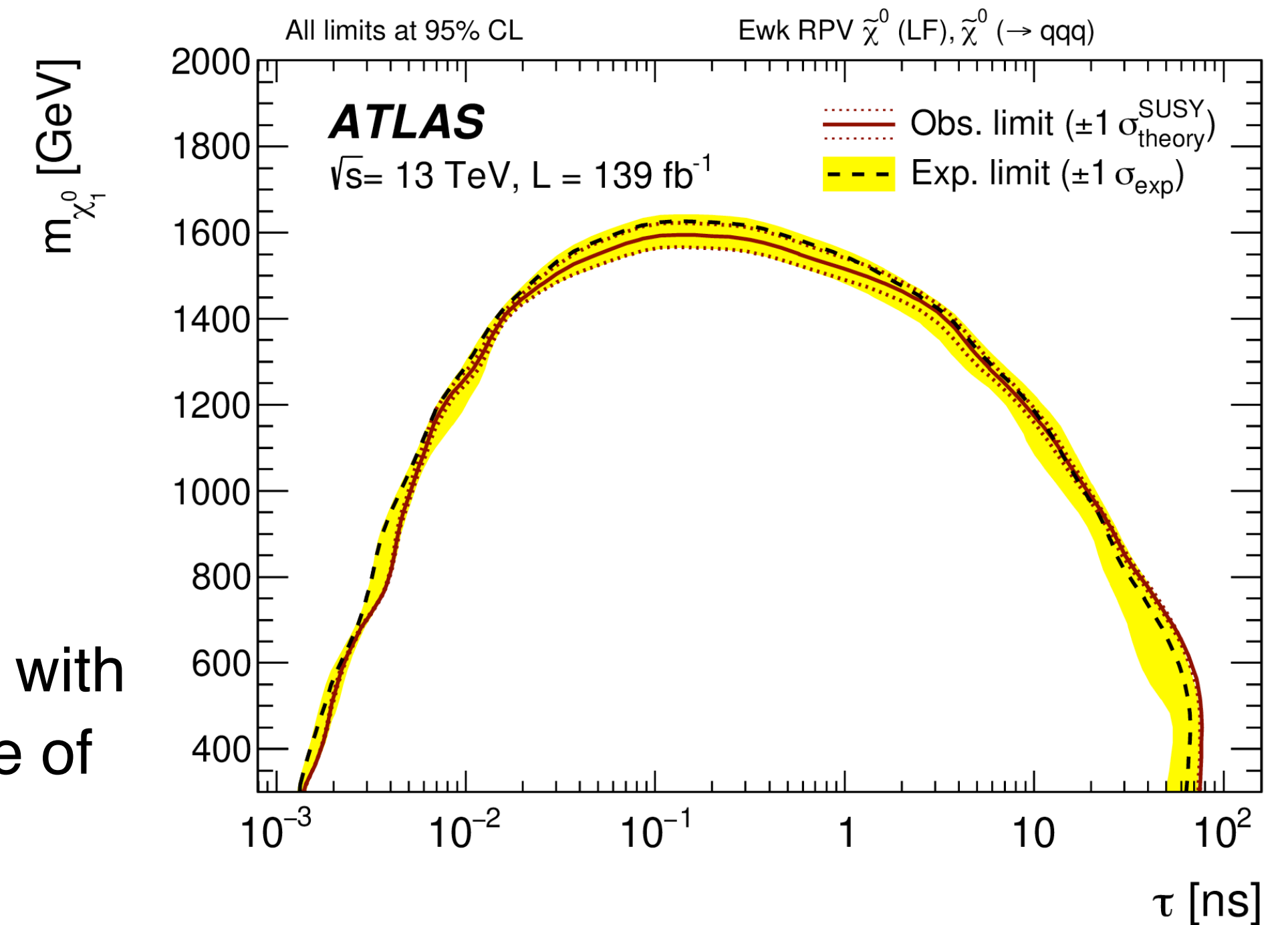
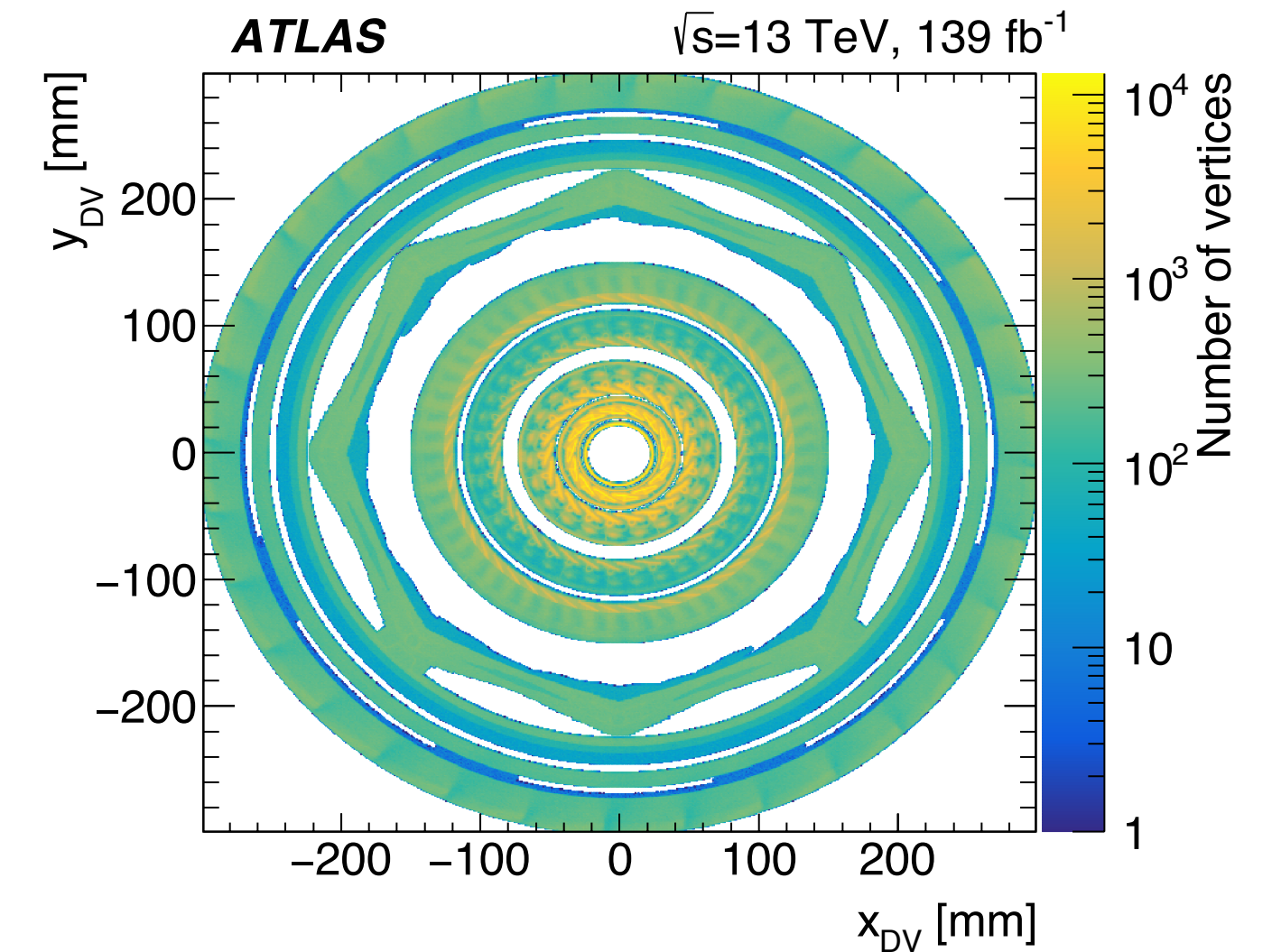
Displaced vertices + jets

SUSY-2018-13

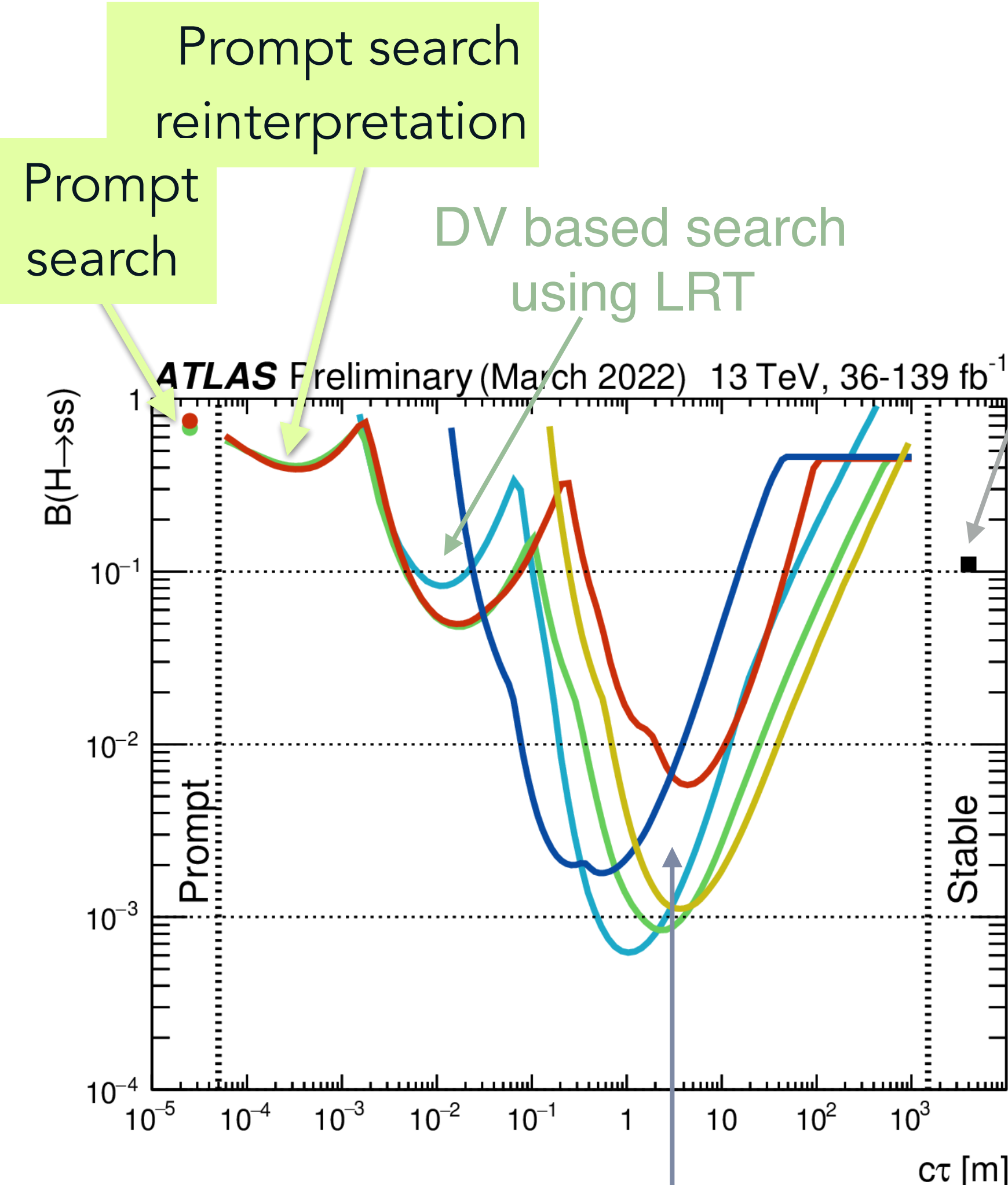
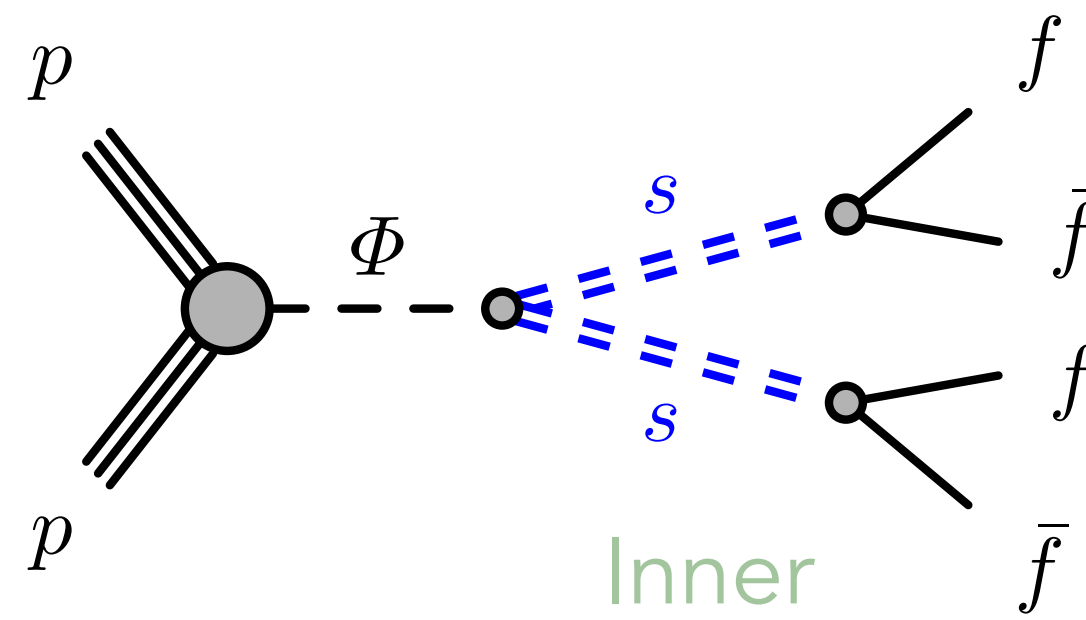


- Three main sources of background:
 - hadronic interactions: detector material
 - accidental crossings: low-mass displaced vertices crossed by an unrelated track
 - merged vertices: close-by low-mass displaced vertices
- Reject them with DV selection:
 - DV at least 4 mm away from any collision vertex
 - DVs must satisfy a material map veto
 - DVs must have at least five tracks
 - $m_{DV} > 10$ GeV
- Data-driven technique that predicts the rate of DVs from all three sources above
- Reach \sim zero background analysis

- Neutralinos with $m=1.5$ TeV excluded with lifetimes in the range of 0.02 ns to 4 ns



Displaced jets



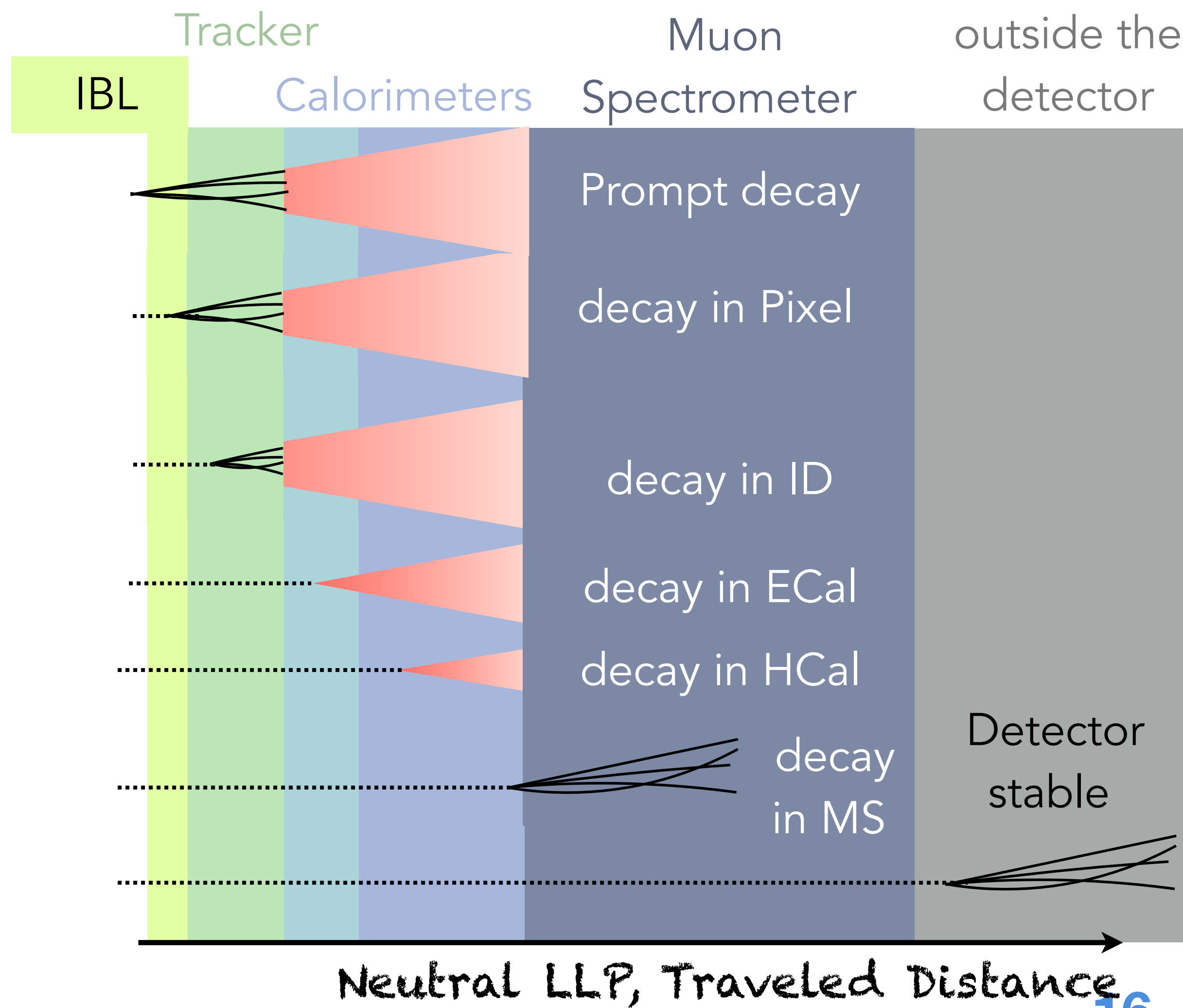
Hidden Sector, $m_H = 125$ GeV
 Selected **ATLAS** results
 95% CL observed limits

Contributing searches:

- **Muon System (2 Vtx Only), 139 fb⁻¹**
arXiv:2203.00587
- **Muon System (1 Vtx + 2 Vtx), 36 fb⁻¹**
Phys. Rev. D 99 (2019) 052005
- **Calorimeter, 139 fb⁻¹**
arXiv:2203.01009
- **Tracker+Muon System, 36 fb⁻¹**
Phys. Rev. D 101 (2020) 052013
- **Tracker (LRT), 139 fb⁻¹**
JHEP 11 (2021) 229
- **Tracker (b-tag), 36 fb⁻¹**
JHEP 10 (2018) 031
- **Monojet, 139 fb⁻¹**
ATL-PHYS-PUB-2021-020
- **H→ inv, 7-8-13 TeV combination**
ATLAS-CONF-2020-052

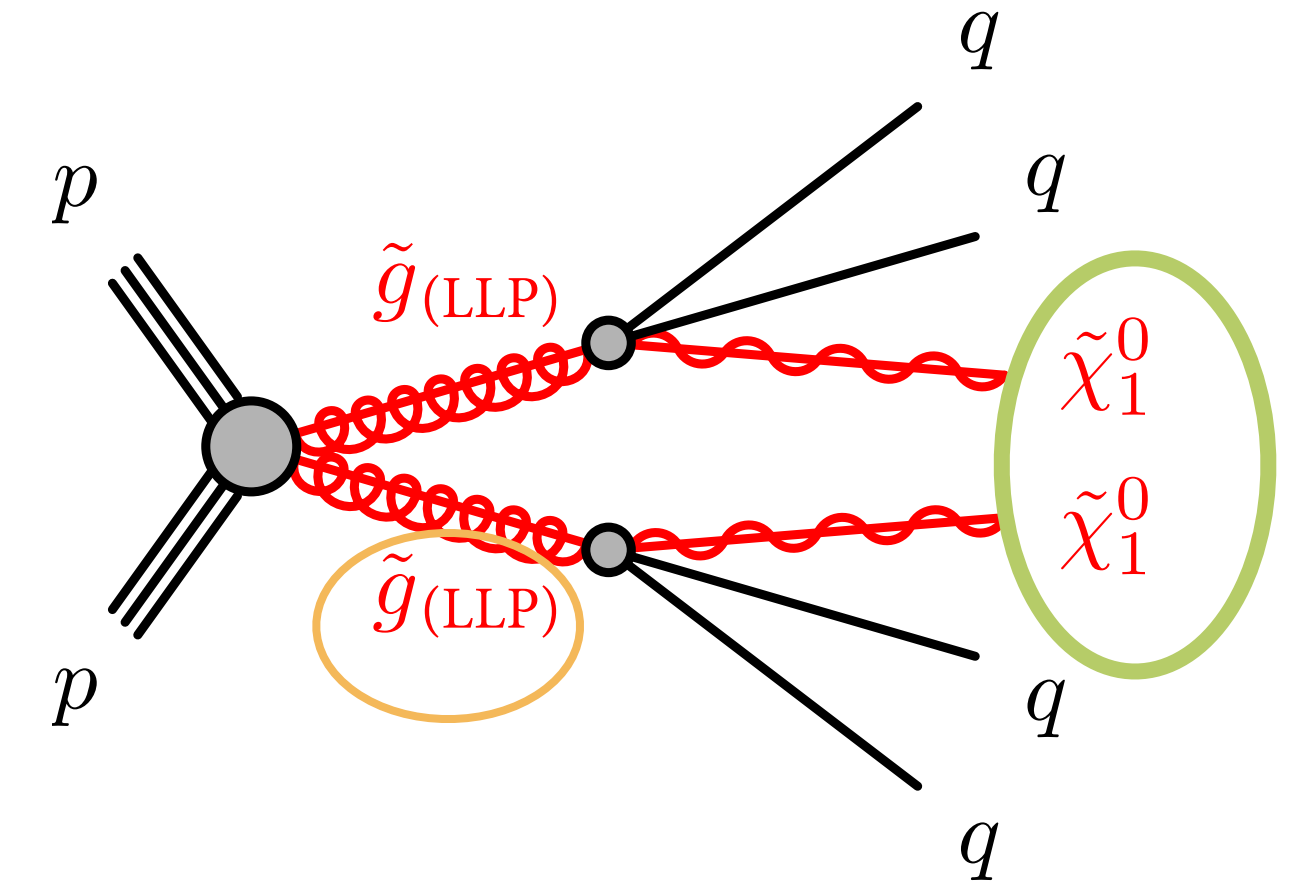
LLP masses:

- 5-8 GeV
- 15-20 GeV
- 25-35 GeV
- 40 GeV
- 45-60 GeV
- Any



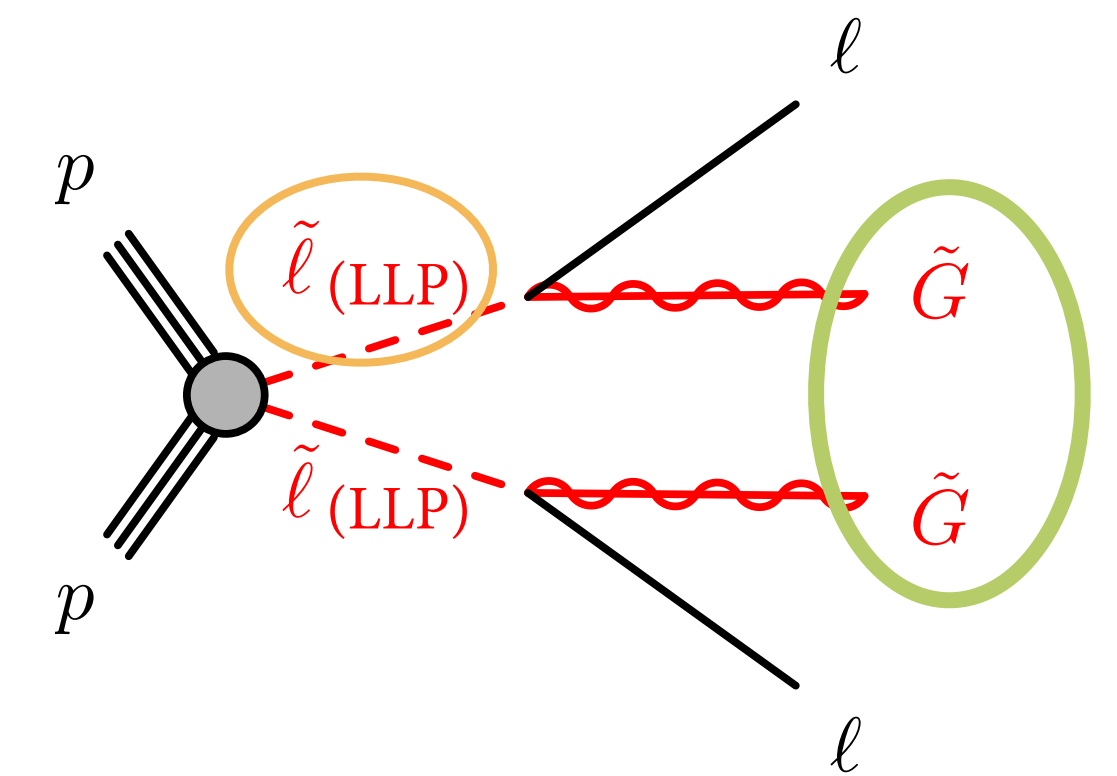
Charged LLPs Large dE/dx

- Pair production of different long-lived sparticles of charge $|q| = 1$
- isolated tracks with high transverse momenta (p_T) and anomalously large specific ionisation losses (dE/dx)
- particles are **expected to move significantly slower than the speed of light**
- Use **MET triggers**
- Fully data-driven background estimation!



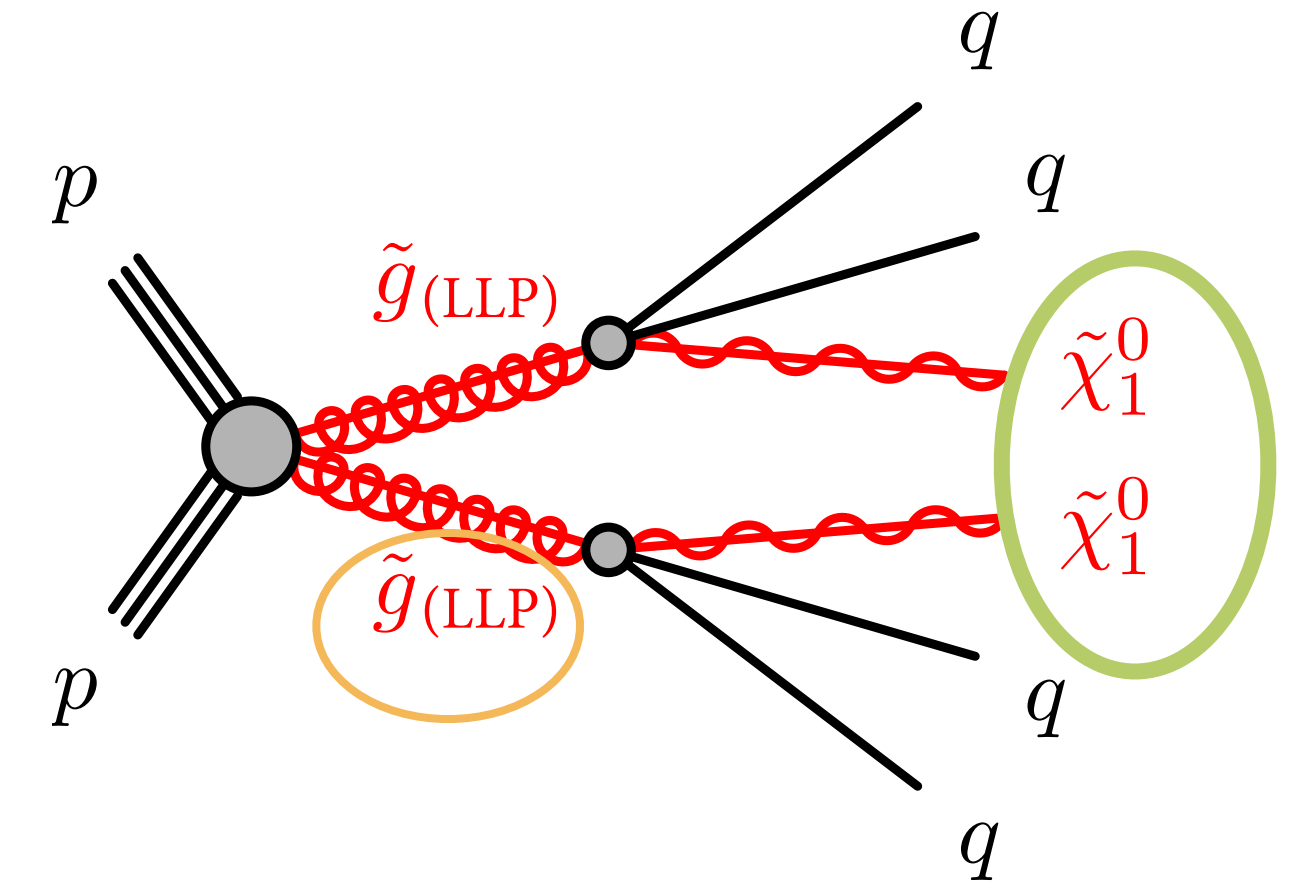
High p_T track with large dE/dx

LSP = MET

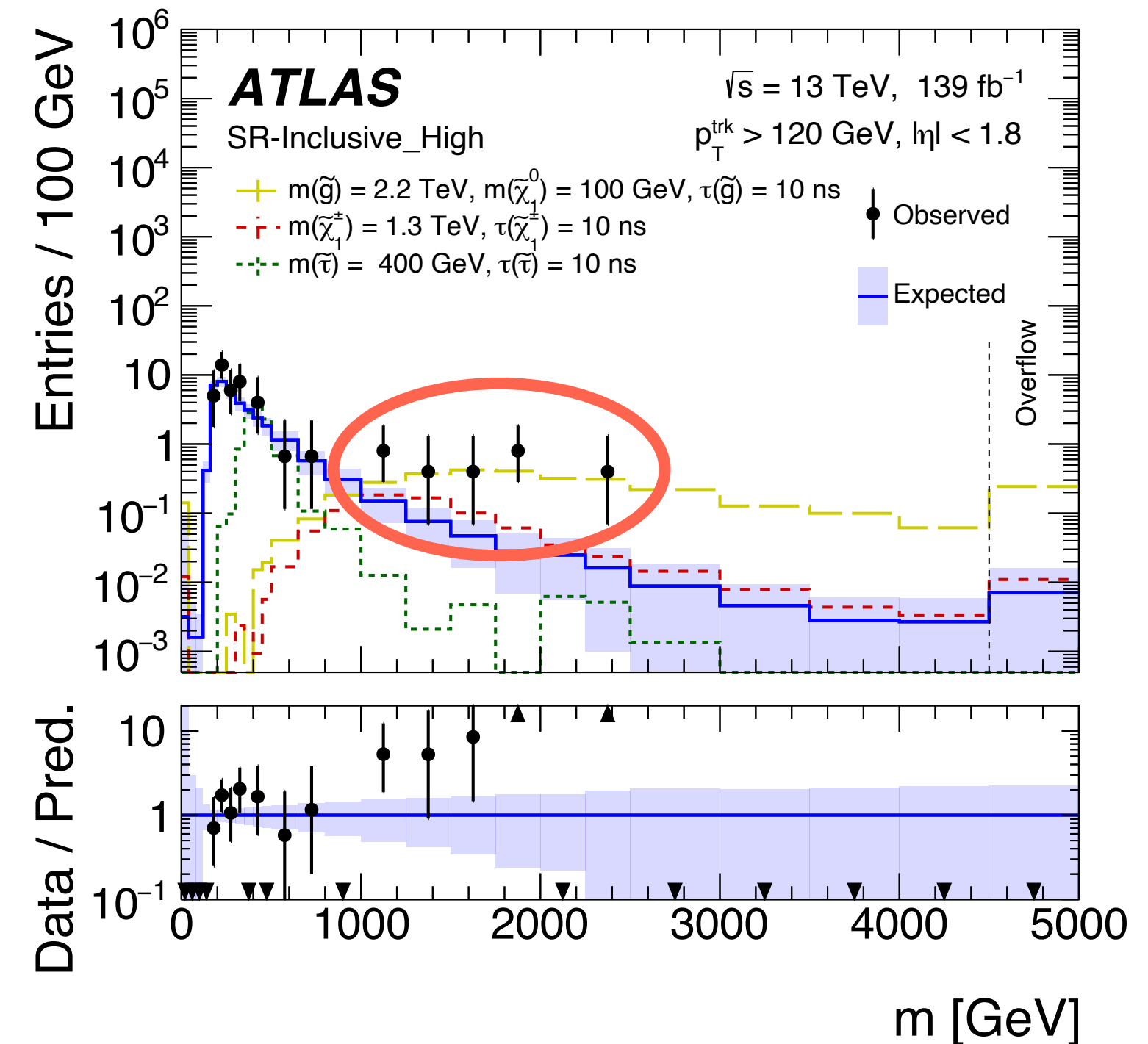


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- **3.3 σ global excess!!**
- Is this New Physics???
- Maybe, though... from TOF measurements: **none of the candidate tracks** are from charged particles moving significantly **slower than the speed of light** 😞
- Analysis ongoing in Run 3!

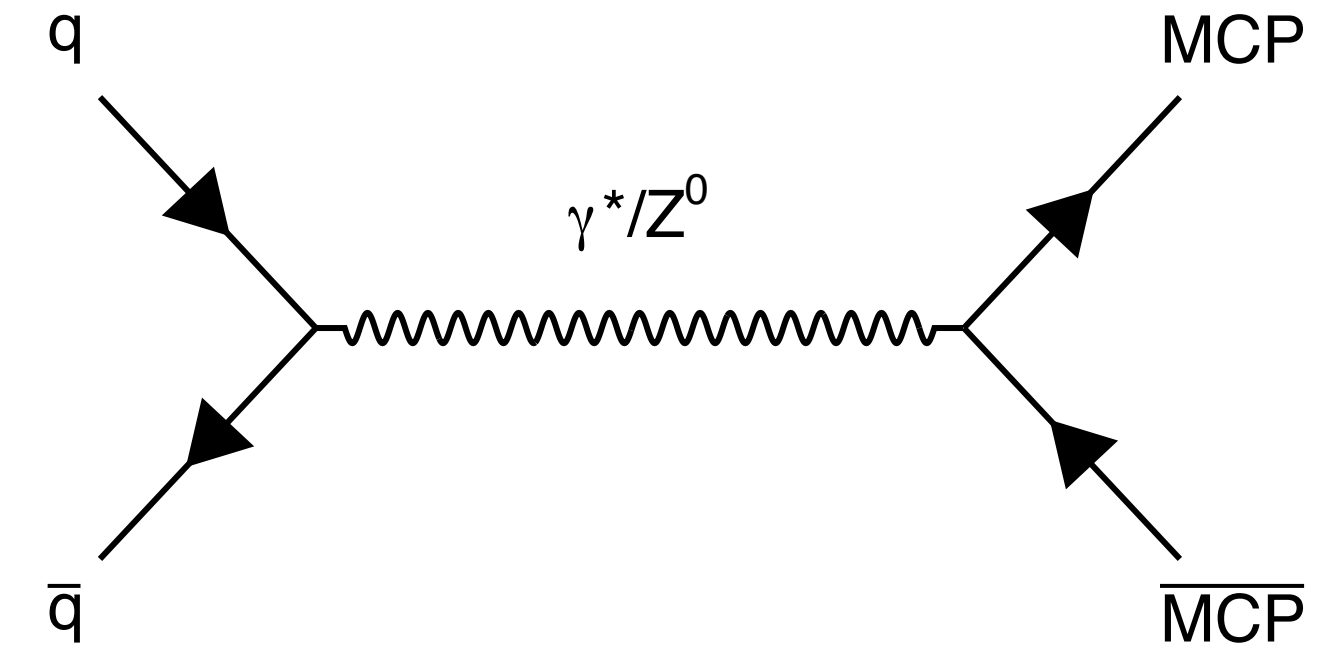


Multicharged particles

EXOT-2018-54

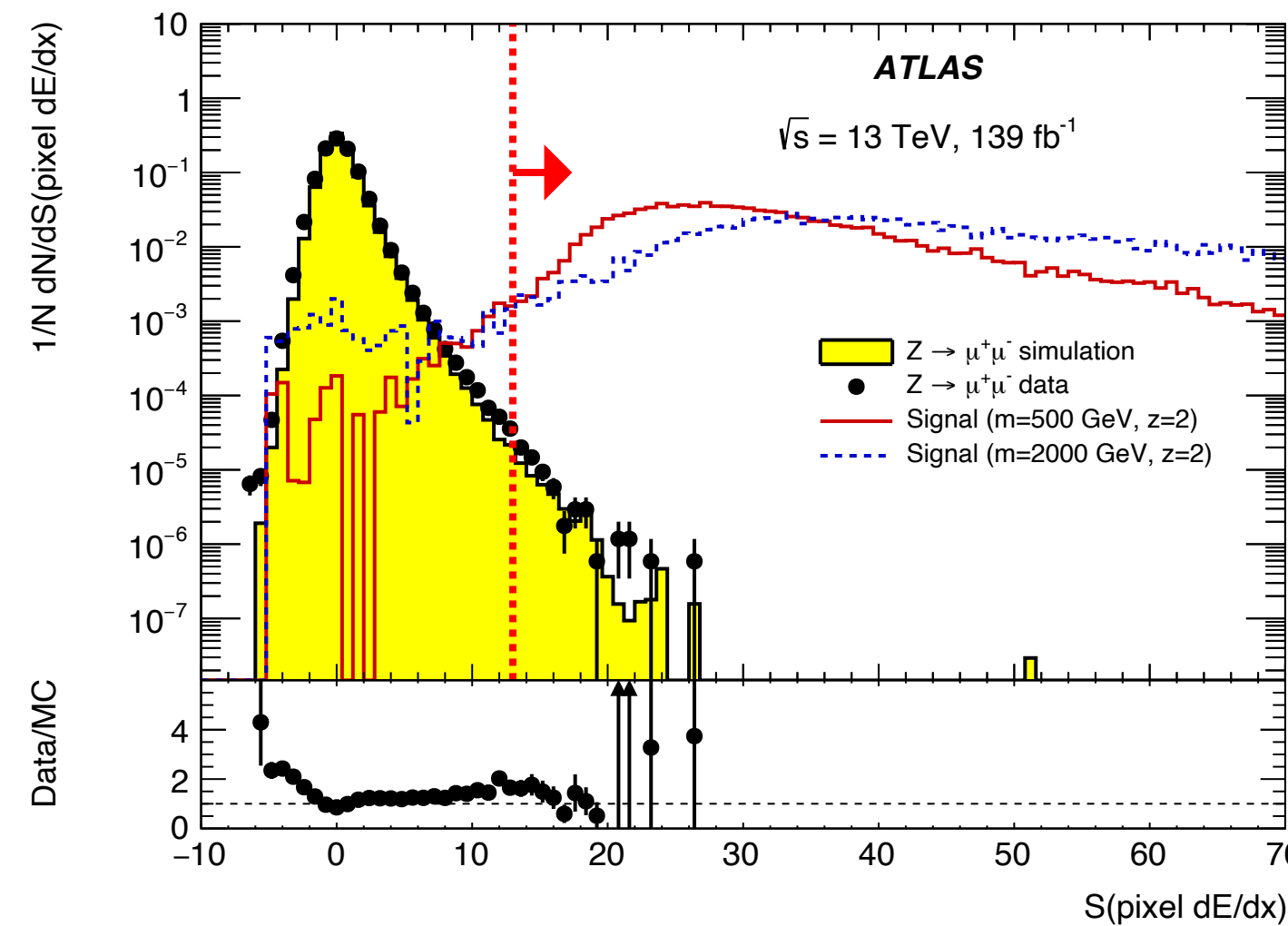


- Search for heavy long-lived multi-charged particles (MCP) with high ionization (higher electric charges and lower velocities)
 - range of electric charges from $|q| = 2e$ to $|q| = 7e$
 - live long enough to traverse the entire ATLAS detector

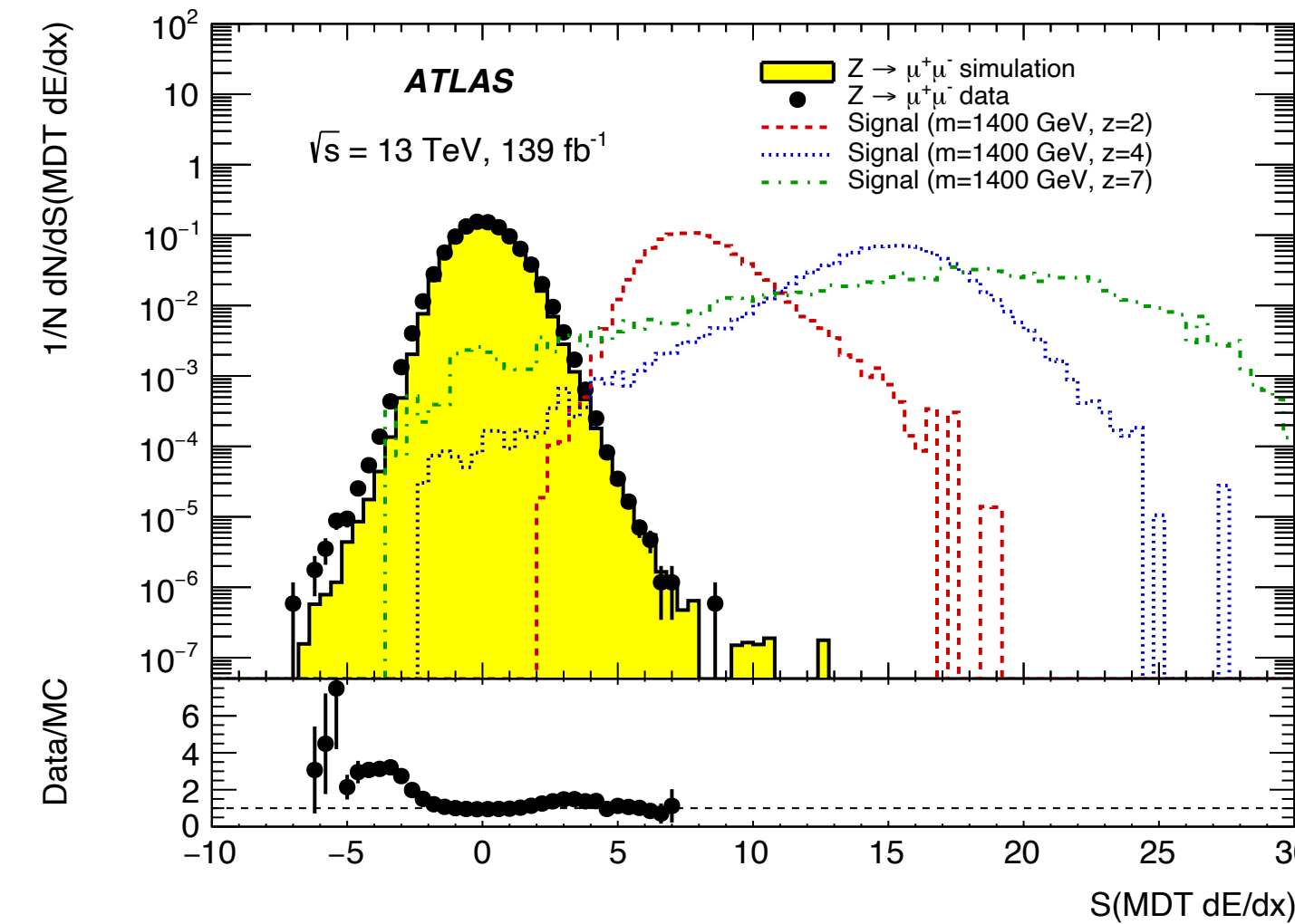


- Triggers: Muon, MET, late-muon trigger
- Select high- p_T muon-like tracks with high dE/dx values in several subdetector systems: pixel ID, TRT, MDT

$z=2$



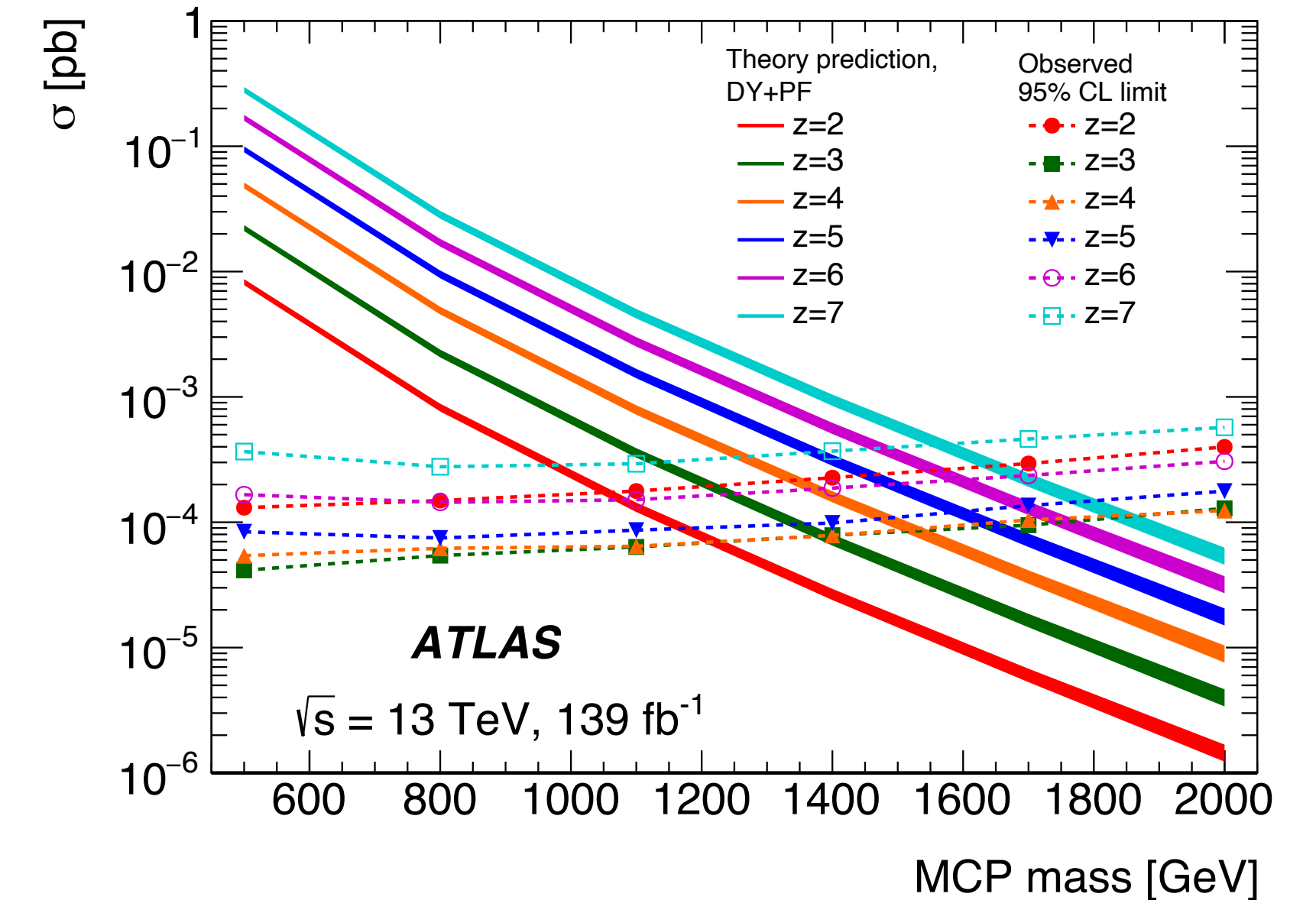
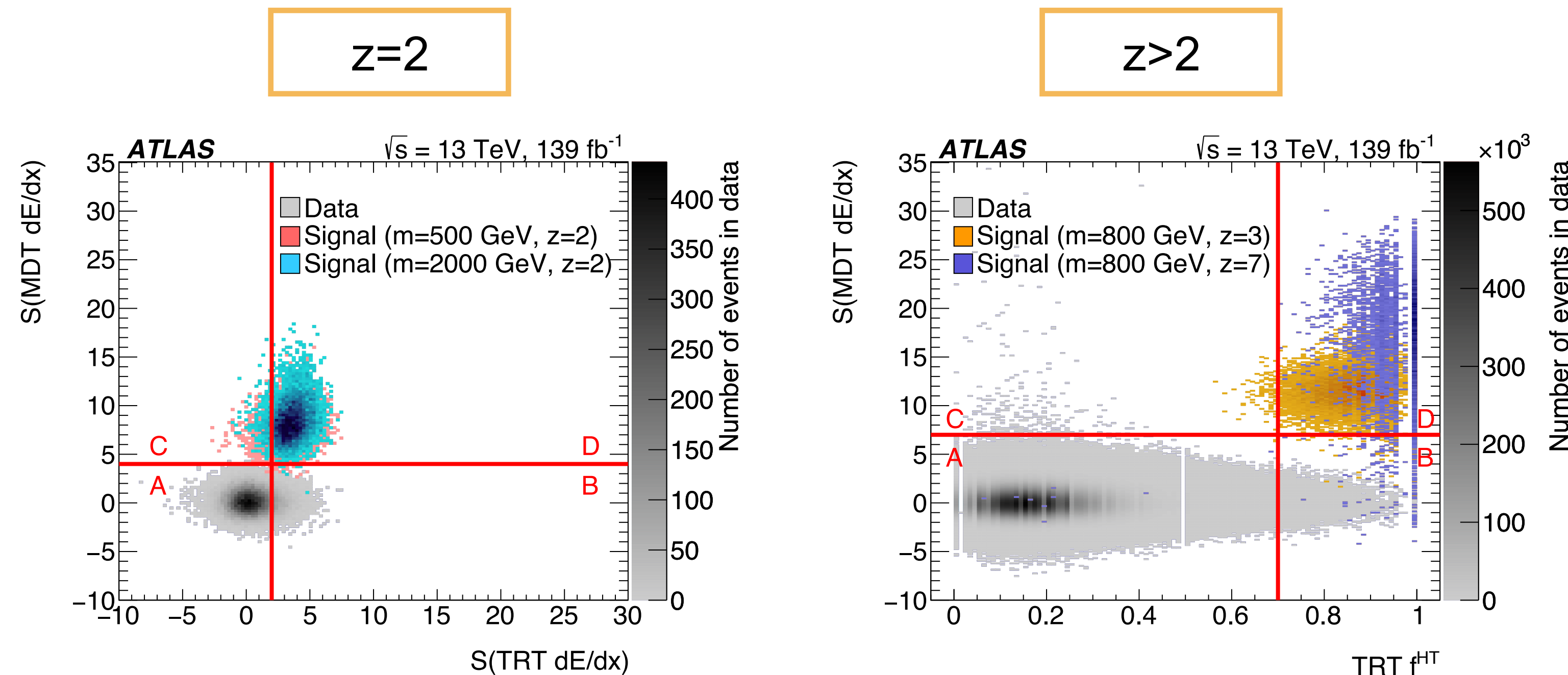
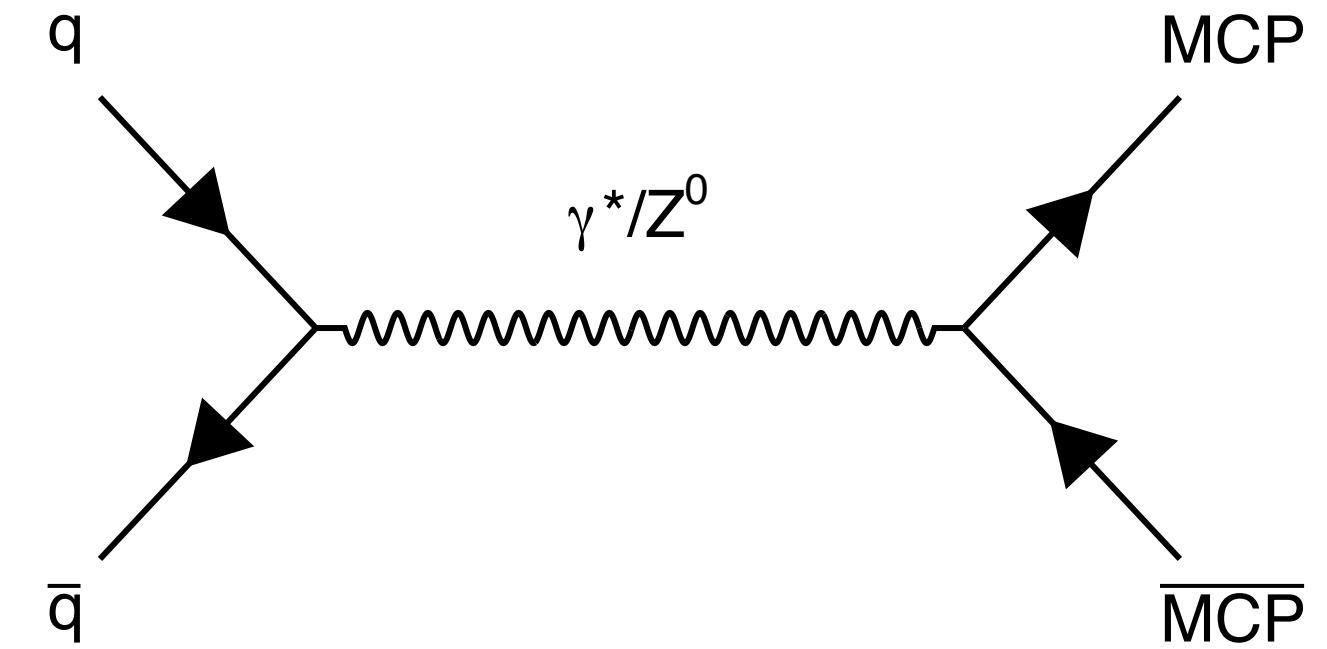
$z>2$



Multicharged particles

EXOT-2018-54

- Background mainly consists of:
 - high-pT muon reconstructed from several muons losing their energy in the same detector elements
 - sporadic-noise
- All background estimated by using a data-driven technique.



- $|q| = 2e$ particles excluded for $m < 1060\ \text{GeV}$
- $|q| = 6e$ particles excluded for $m < 1600\ \text{GeV}$

Simulation

$\sqrt{s} = 13 \text{ TeV}$

Strong RPV: $\tilde{g} \rightarrow qq\tilde{\chi}^0$ ($\rightarrow qqg$)
 $m(\tilde{g}) = 1.8 \text{ TeV}, m(\tilde{\chi}^0) = 200 \text{ GeV}, \tau = 0.1 \text{ ns}$

DV properties

(x, y, z) : (26.9, 19.0, 51.4) mm
mass : 107.1 GeV (14 tracks)

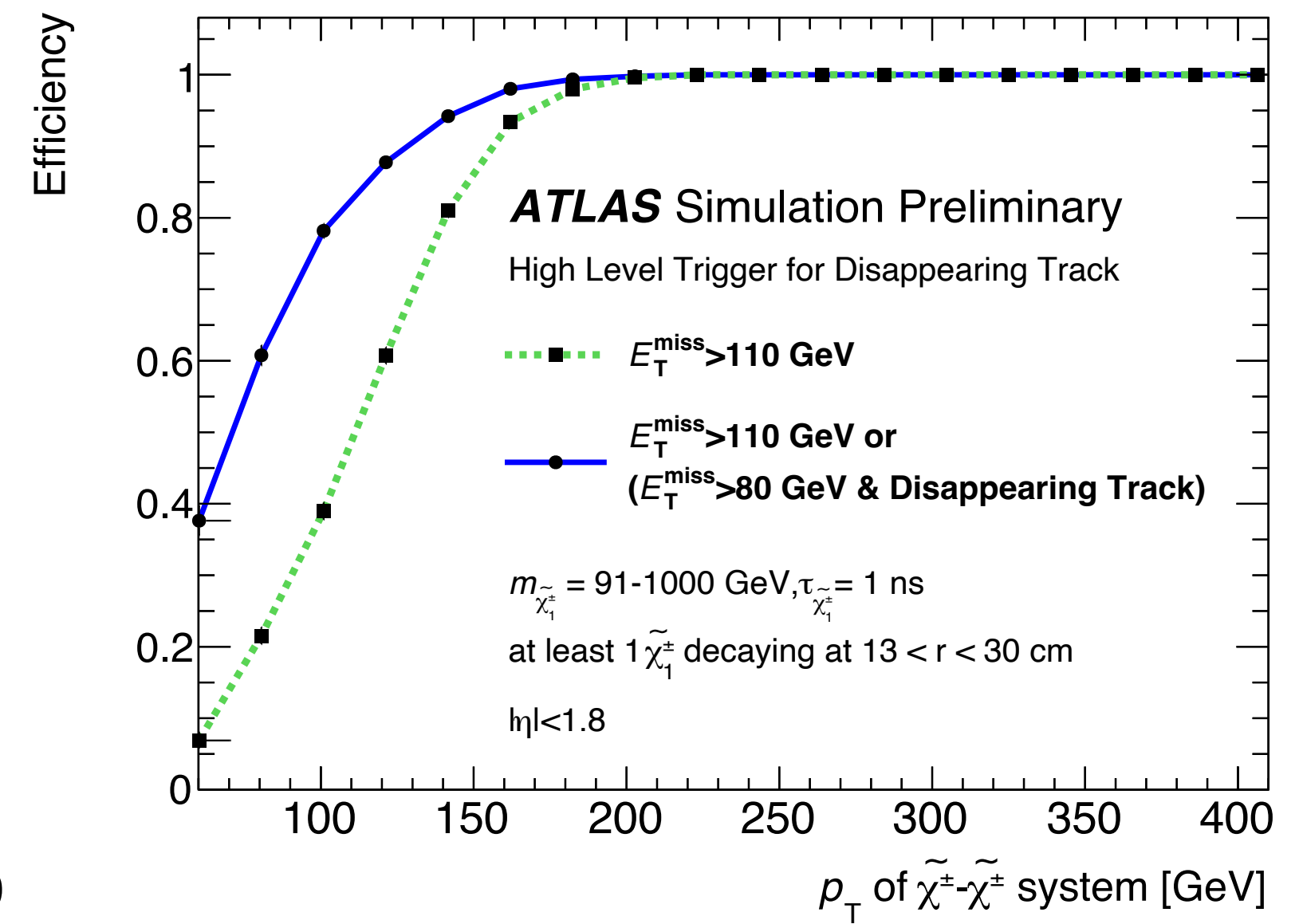
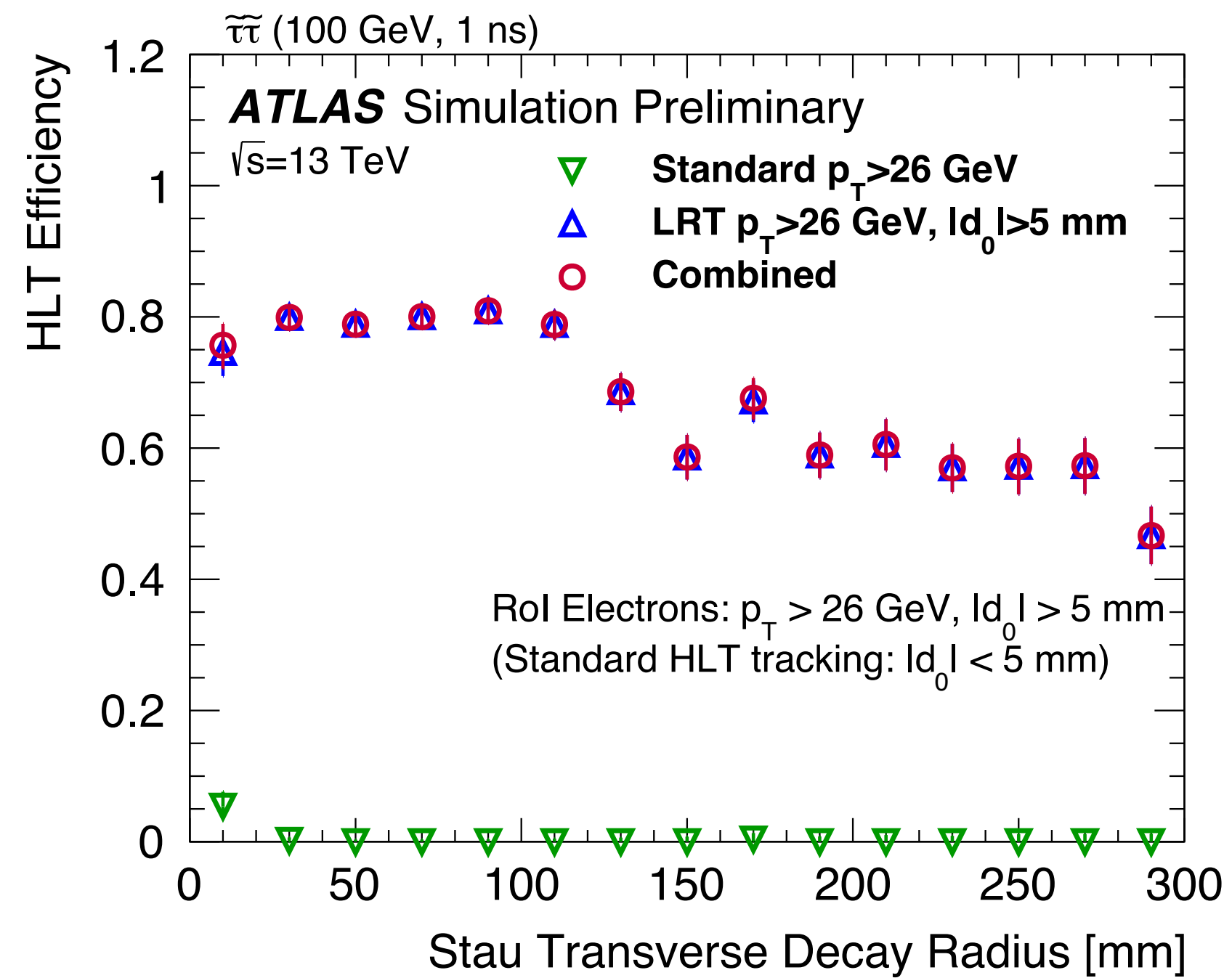
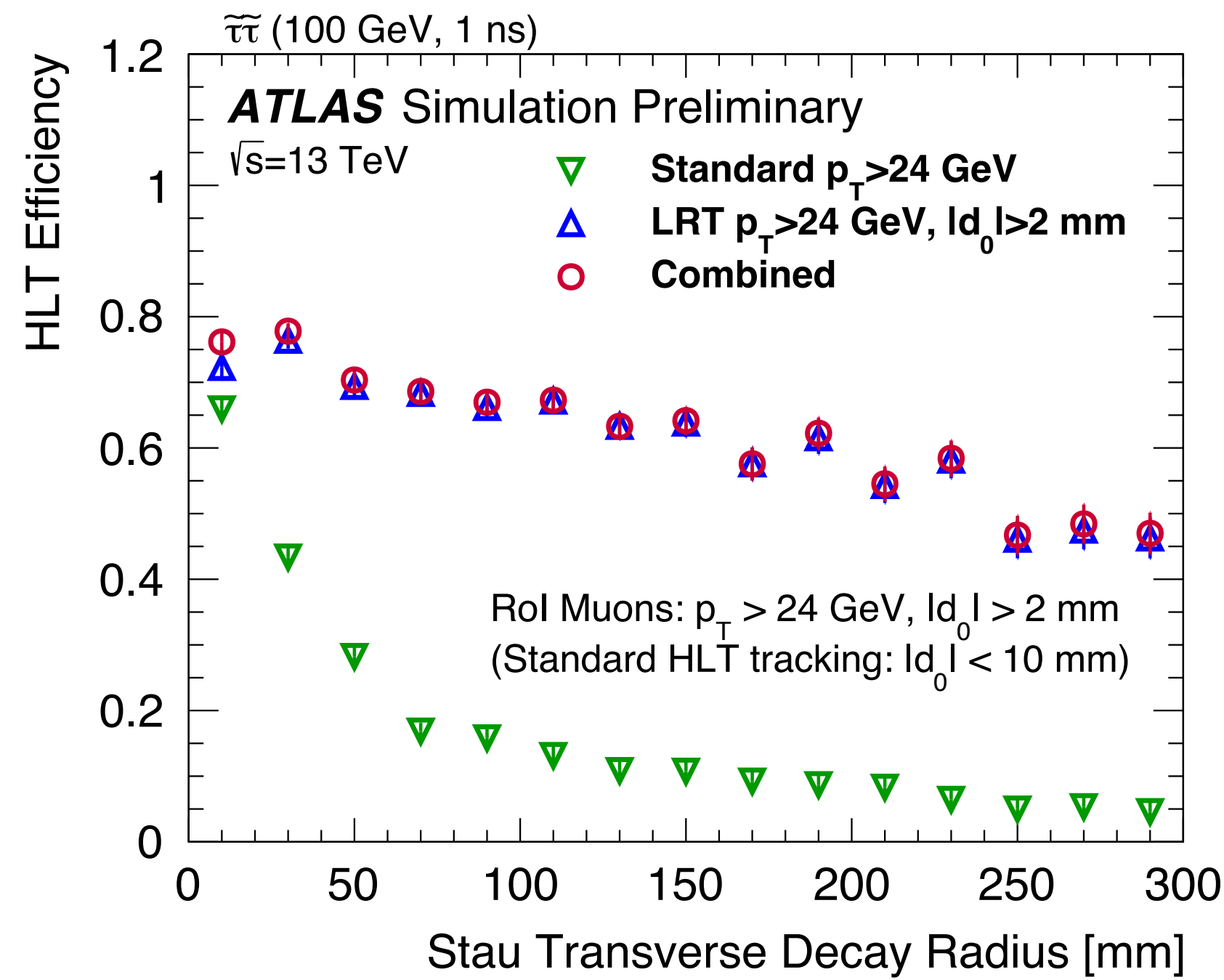
CONCLUSIONS

- LLPs might be the key for finding BSM physics
- LLPs are gaining interest!
- Great effort at the LHC experiments to search for LLPs...

BUT! still some signatures to be exploited

- Development of new tools and strategies to improve identification of LLPs, pushing the detector beyond its original design capabilities
- Run 3 and HL-LHC offer a great opportunity to innovate and plan for new unconventional searches

LRT at HLT trigger level



Multicharged particles

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