ATLAS Searches With Unconventional Signatures and Long-Lived Particles

Andrew Smith

On behalf of the ATLAS Collaboration

ICHEP July 20th, 2024

ATLAS EXPERIMENT

NEVIS LABORATORIES
COLUMBIA UNIVERSITY

Unconventional Signatures and LLPs

- Beyond Standard Model (BSM) physics may look quite different than what we have been **expecting…**
- BSM decays can produce **unconventional signatures** with challenging backgrounds (e.g. Lepton Jets)
- Well-motivated scenarios lead to **Long Lived Particles** (LLPs) due to weak couplings, compressed mass spectra
  - ATLAS projective geometry + prompt reconstruction not designed to efficiently target LLPs
- Searches for these signatures push the limits of detector performance!
  - Often require special reconstruction, dedicated triggers, data-driven background estimation

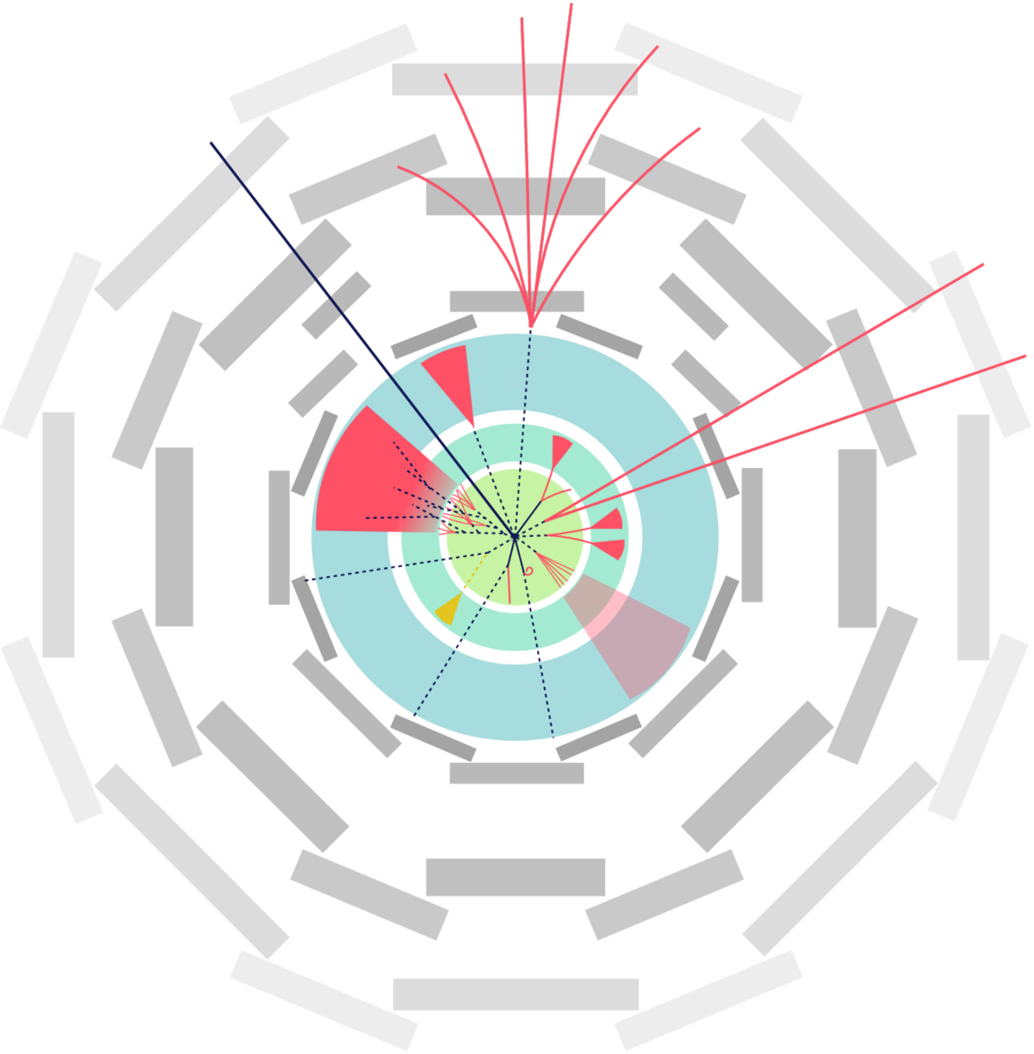


Image by Heather Russell

Recent ATLAS Unconventional/LLP Search Program

NEW for ICHEP!

Reference	Title	Publication	Date
ATLAS-CONF-2024-011	**Displaced Leptons Run 2 + Run 3**	Conf. Note	20 July 2024
EXOT-2022-04	**Hadronic LLPs w/ Associated leptons or jets**	Submitted to JHEP	12 July 2024
EXOT-2018-55	**Dark Photons (Prompt Lepton Jets)**	Submitted to EPJC	12 July 2024
ATL-PHYS-PUB-2024-009	**Pixel dE/dx + β-calo chargino interpretation**	Pub. Note	31 May 2024
ATL-PHYS-PUB-2024-007	**RPC-to-RPV LLP di-tau re-interpretation**	Pub. Note	6 May 2024
EXOT-2021-32	**Hadronic LLPs using Displaced Vertices**	Submitted to PRL	22 March 2024
EXOT-2022-15	**Dark Photons (Displaced Lepton Jets)**	Accepted by EPJC	30 November 2023
ATLAS-CONF-2023-044	**Pixel dE/dx + β-calo**	Conf. Note	8 September 2023
EXOT-2019-33	**Magnetic Monopoles**	JHEP 11 (2023) 112	9 August 2023

- Extensive search program in ATLAS, not enough time today to cover everything!
- Results in **blue** will be covered in this talk

Overview

mean LLP decay length

Unconventional prompt signatures

- Dark Photons (Lepton Jets) **NEW**

LLPs in the inner detector (ID)

- Hadronic LLPs using displaced vertexing
- Displaced Leptons search Run 2 + **Run 3** **NEW**

LLPs in the calorimeters / muon system

- Neutral LLPs + leptons or jets **NEW**

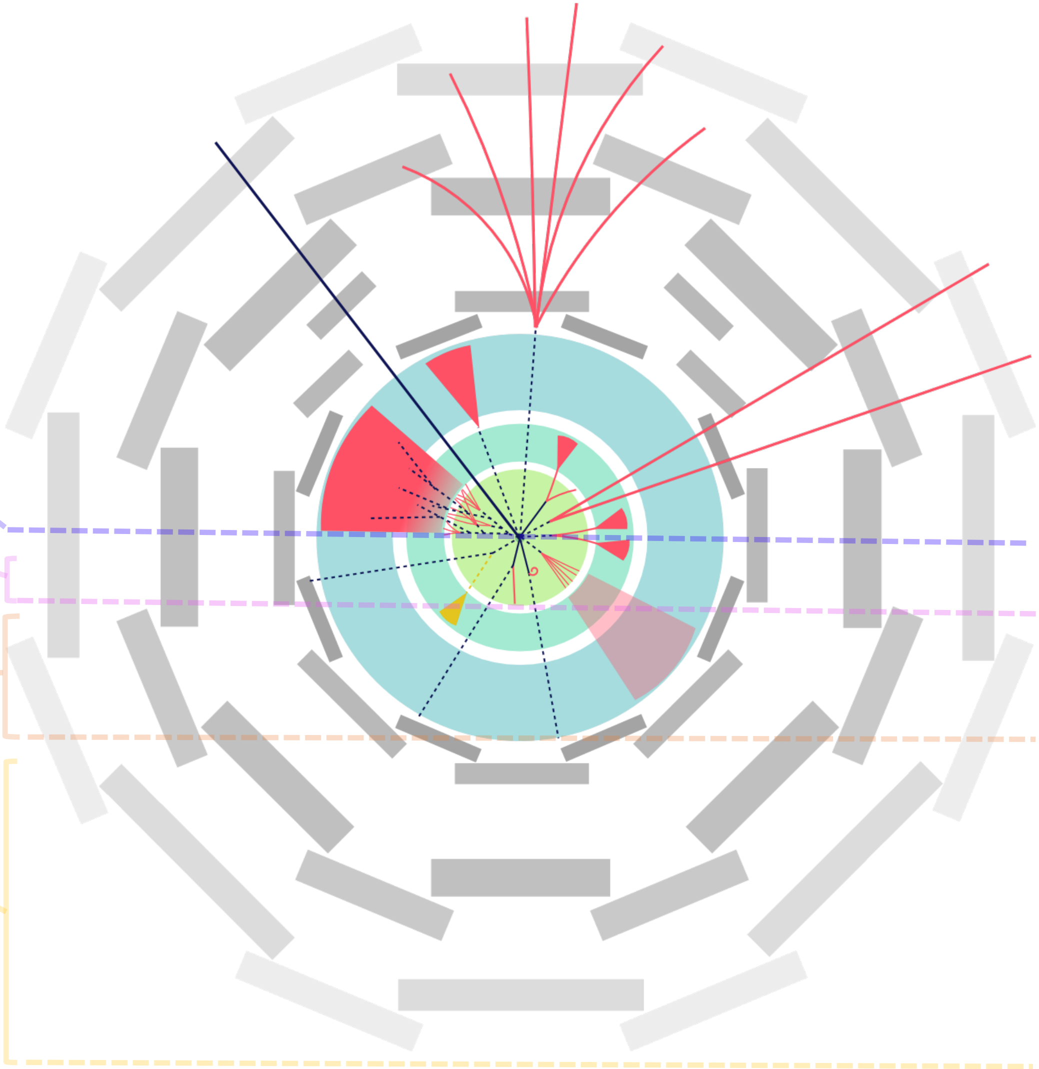


Image by Heather Russell

Dark Photon (Lepton Jets)

New for ICHEP

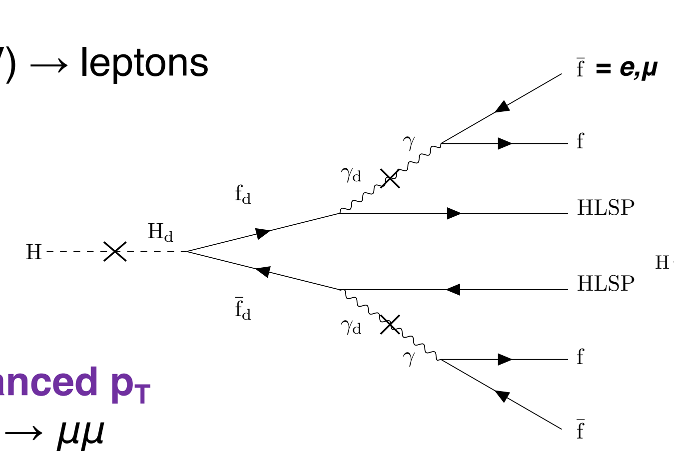
$$c\tau = \frac{1}{\Gamma_{tot}} \propto \frac{1}{\epsilon^2}$$

Benchmark: Neutral γ_d decays to collimated SM fermions. m(γ_d) ~ O(10GeV) → leptons

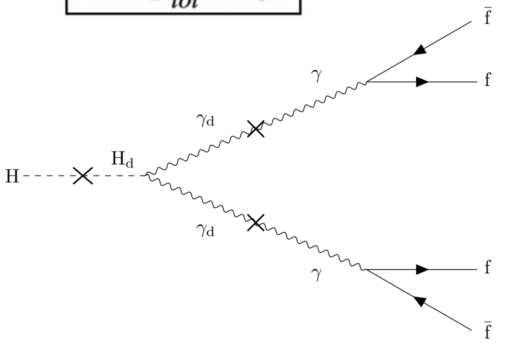
- Kinetic mixing coupling (ϵ) to SM γ related to γ_d lifetime
- Target $\epsilon > 10^{-5}$ → **prompt γ_d**

Expect two collimated "Lepton Jets" (LJs) with zero sum of charges

- Trigger on single or multi-lepton events
- ***μ*LJs:** ≥2μ in ΔR < 0.4 cone (no e)
- ***e*LJs:** ≥1*e* with multiple associated tracks → **wide showers + balanced p_T**
- ***μ*LJ Backgrounds** – virtual $\gamma \to \mu\mu$; pair-produced SM resonance → $\mu\mu$
- ***e*LJ Backgrounds** – (SM *e* from Z or $t\bar{t}$) + (random track)

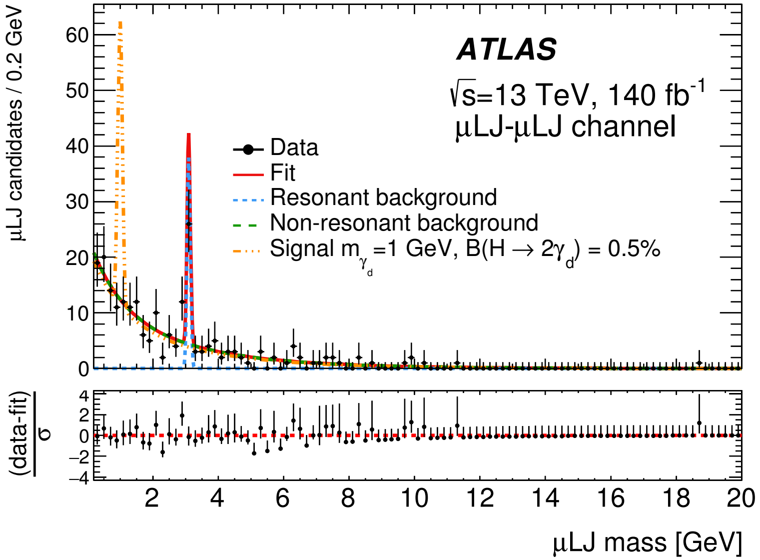


Falkowsky, Ruderman, Volansky, Zupa (FRVZ) Model

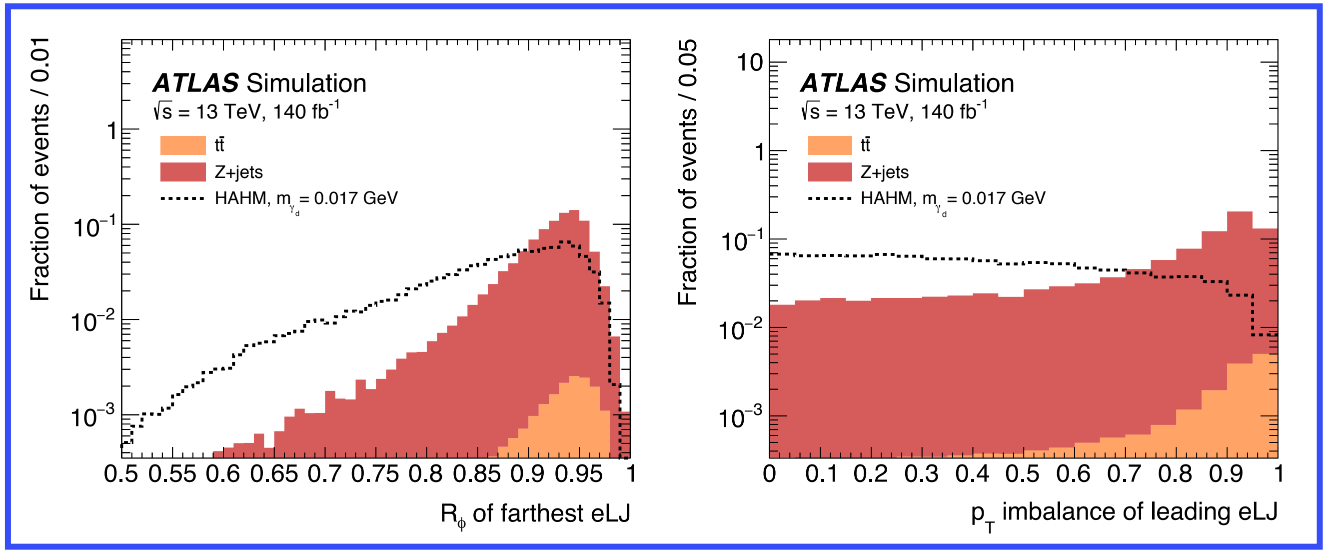


Hidden Abelian Higgs Model (HAHM)

≥1 *μ*LJ: fit LJ jet invariant mass



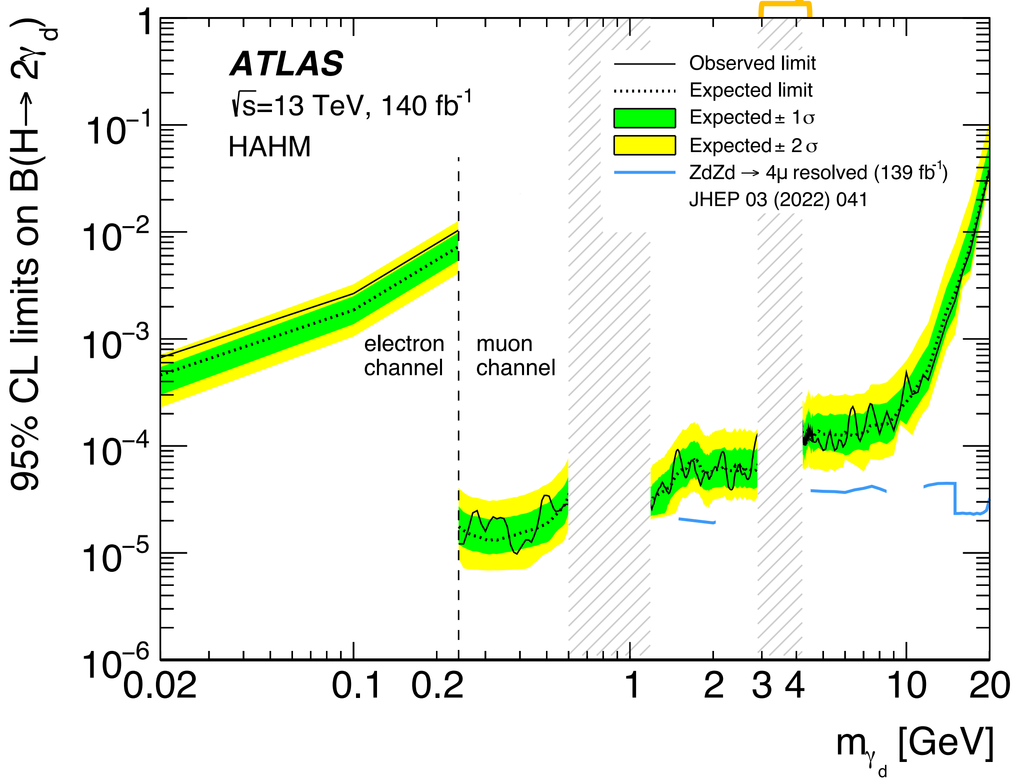
*e*LJ-*e*LJ: ABCD (width of shower ϕ, p_T imbalance of LJ tracks)



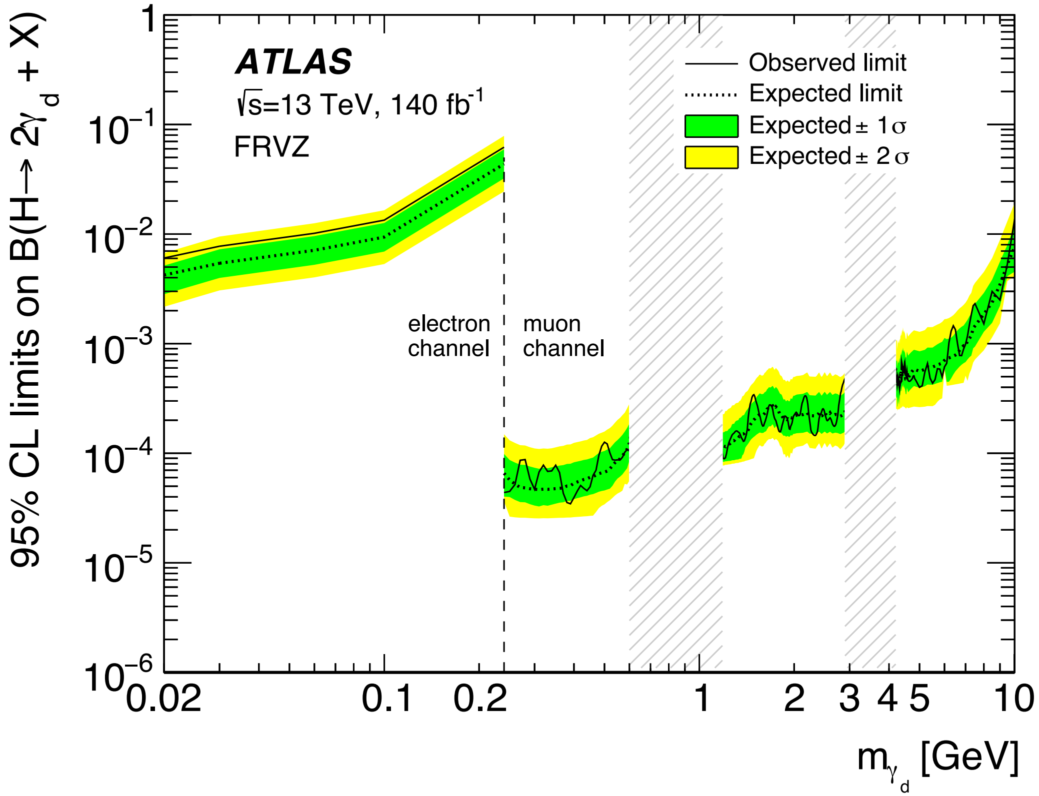
Dark Photon (Lepton Jets) Results

Veto SM resonances

HAHM



FRVZ

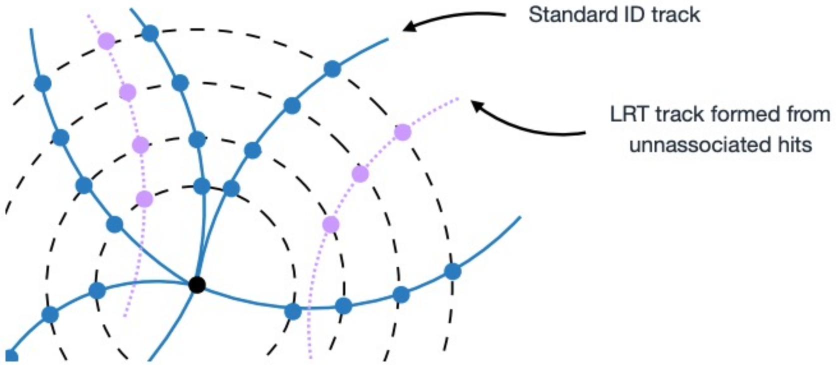


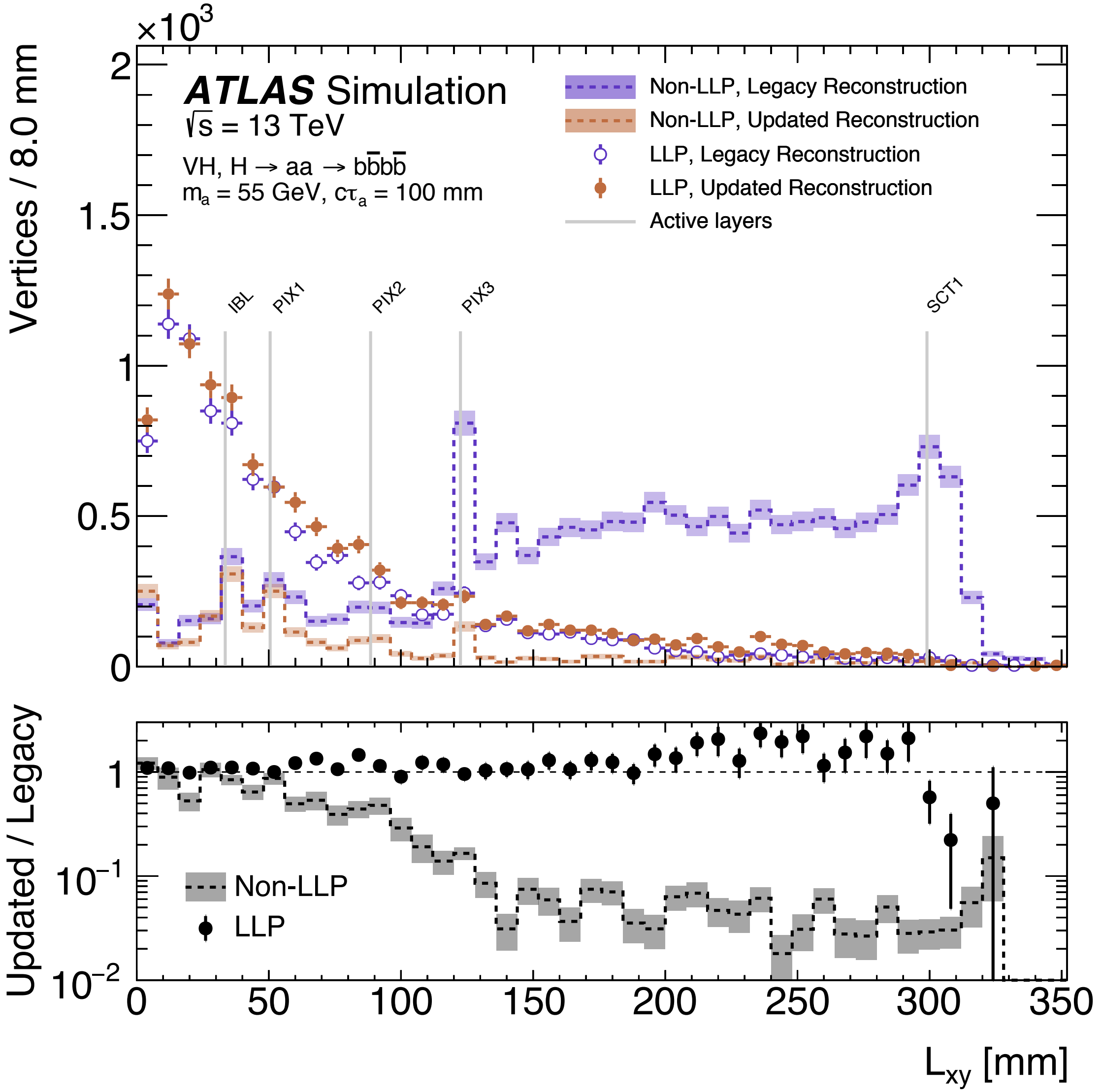
- **No deviation from Standard Model** → set limits on Higgs BR to γ_d between 0.05% and 1% excluded, depending on m(γ_d)
- New sensitivity w.r.t. ATLAS Run 1 result [JHEP02(2016)062], driven by new shape fit technique
- **m(γ_d) = .4GeV, FRVZ model:** BR(H $\rightarrow 2\gamma_d + X$) limits **improve x50** (x13, accounting for added lumi + higher cross-section)

Special Reconstruction: Large Radius Tracking

- Standard track reconstruction in ATLAS designed for tracks pointing back to Primary Vertex (PV)
- Large Radius Tracking (LRT) – additional tracking pass on unused hits after initial tracking pass, relaxing some requirements (e.g. impact parameters)
- Difficult computational problem – high pileup, many random hits in the tracker

Improvements in LRT [IDTR-2021-03]
- Run on all events, rather than prev. ~10%
- In Run 2: can now look at LRT with full dataset!
- **In Run 3:** [new LRT triggers] **increase sensitivity to LLP decays!**

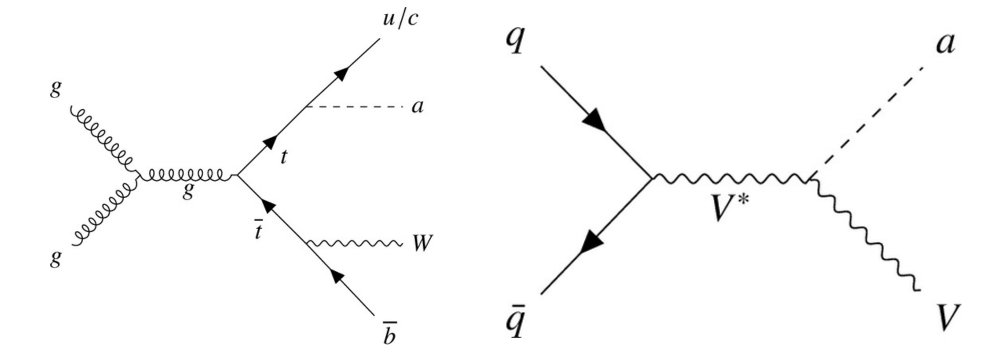




Hadronic LLPs Using Displaced Vertices

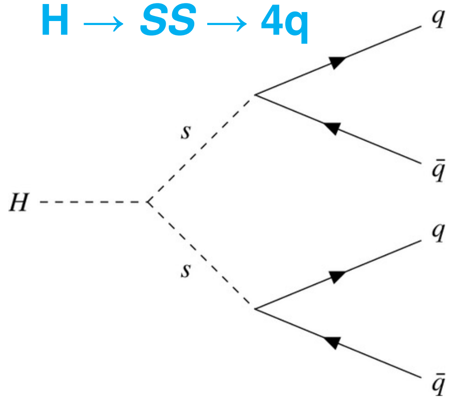
Target: LLPs (5-55GeV) decaying hadronically in inner detector

Expect ≥ 2 hadronic jets originating from ≥1 Displaced Vertices (DVs)



Axion Like Particle (ALP) t → aq or aV

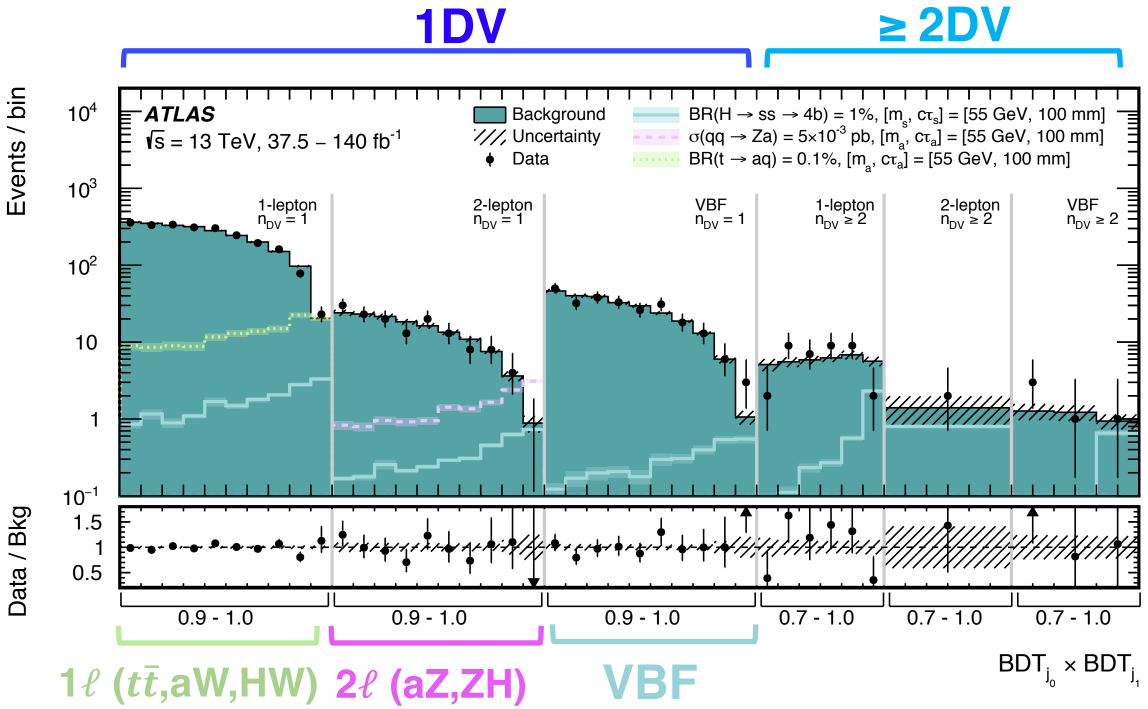
VBF H or H+(W/Z)
H → *SS* → 4q



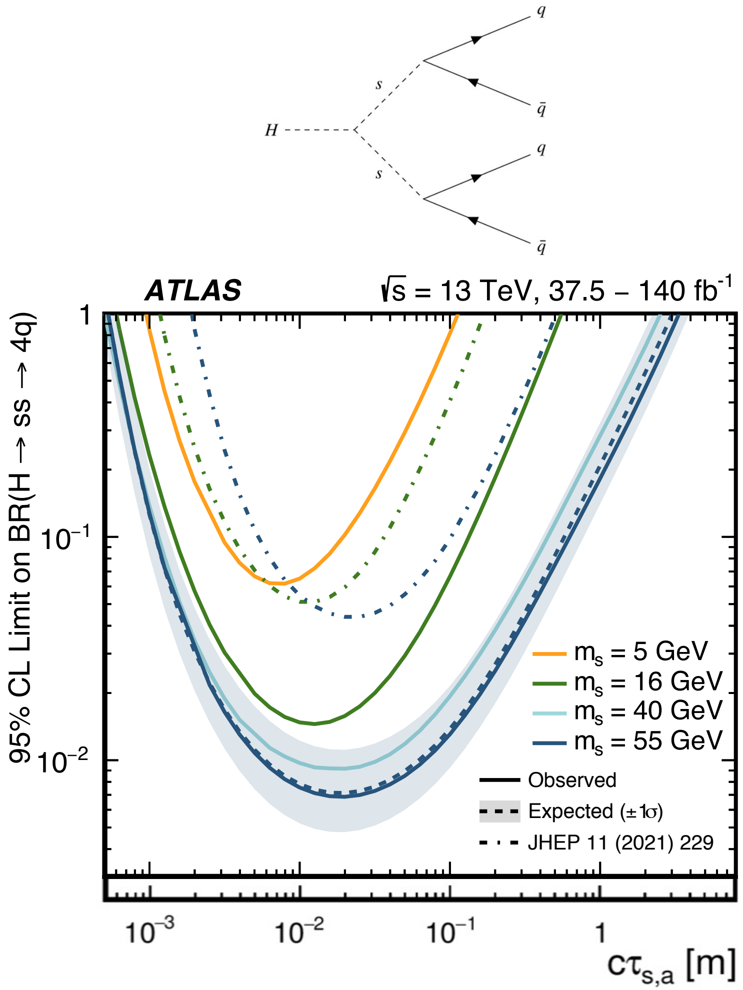
- 1ℓ , 2ℓ regions: single + dlipeton triggers
- VBF region: dedicated trigger for jets consistent with VBF

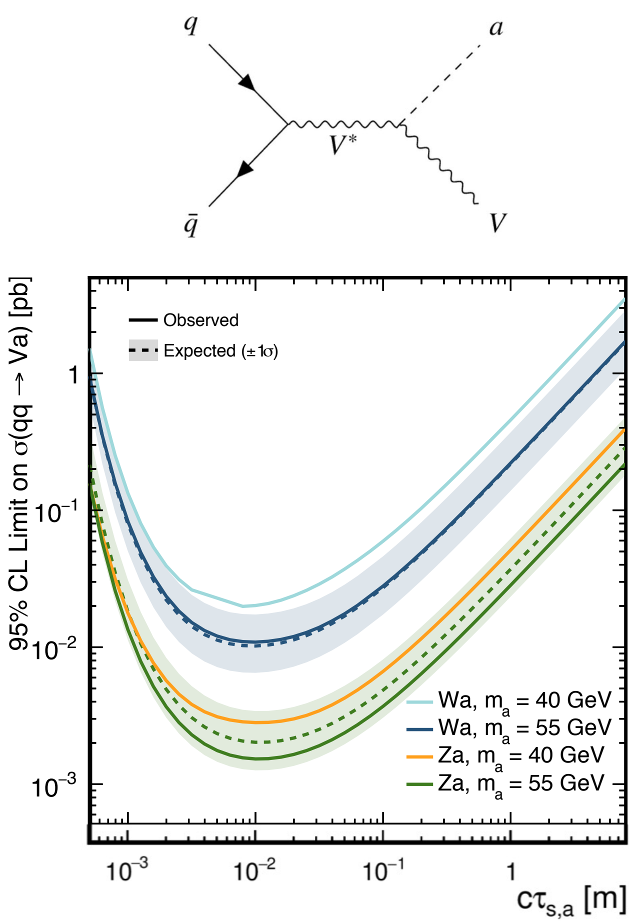
- Reconstruct DVs from combined standard **+ LRT tracks**
- Per-jet BDT to target jets with displaced tracks
  - Trained on simulated $t\bar{t}$, W+jets, Z+jets + signal
  - Discriminant – **BDT_{j0} × BDT_{j1}** from highest scoring jets

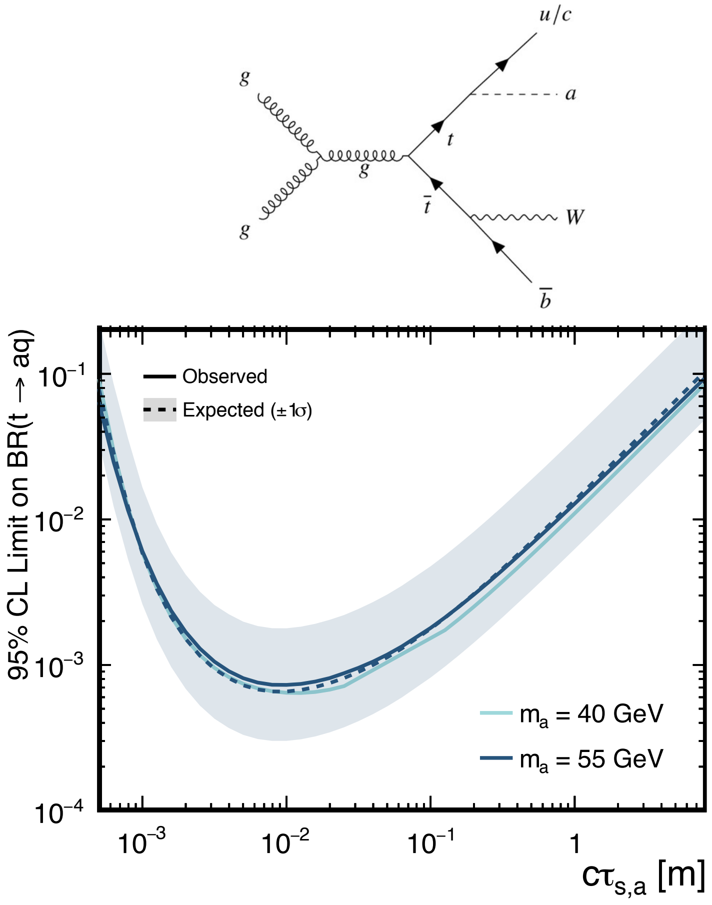
- Predict background from P(jet matched to DV) in low BDT_{j0} × BDT_{j1} region → per-event weights applied in search regions



LLPs w/ Displaced Vertices Results



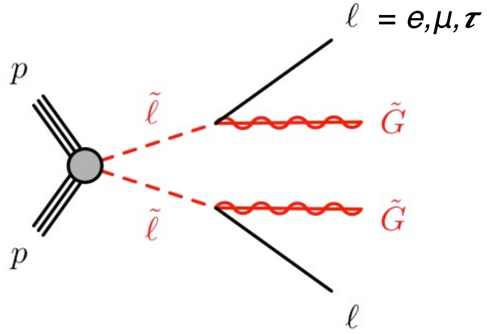




First limits on ALPs w/ photon coupling suppressed at LHC!

- **No Excess w.r.t SM predictions. BR(H → SS → 4*c*) > 10% excluded** for m_S = 5 GeV, 3mm < $c\tau$ < 20mm
- New LRT, New VBF, 1ℓ, 1DV regions deliver sensitivity w.r.t. previous [JHEP 11 (2021) 229] ATLAS Run 2 result!

Displaced Leptons In Run 2 + Run 3



Slepton-pair production

Benchmark: slepton pair production via Gauge-Mediated Supersymmetry Breaking (GMSB)

- Next-to-lightest Supersymmetric Particle (NLSP) is LLP ($\tau \sim .01$-100ns)

Expect displaced pairs of SM leptons

- Reconstruct *e/μ* using standard and LRT tracks
- Can look in 1e, $e\gamma$, $\gamma\gamma$, where one decay is outside ATLAS or displaced e reco'd as γ

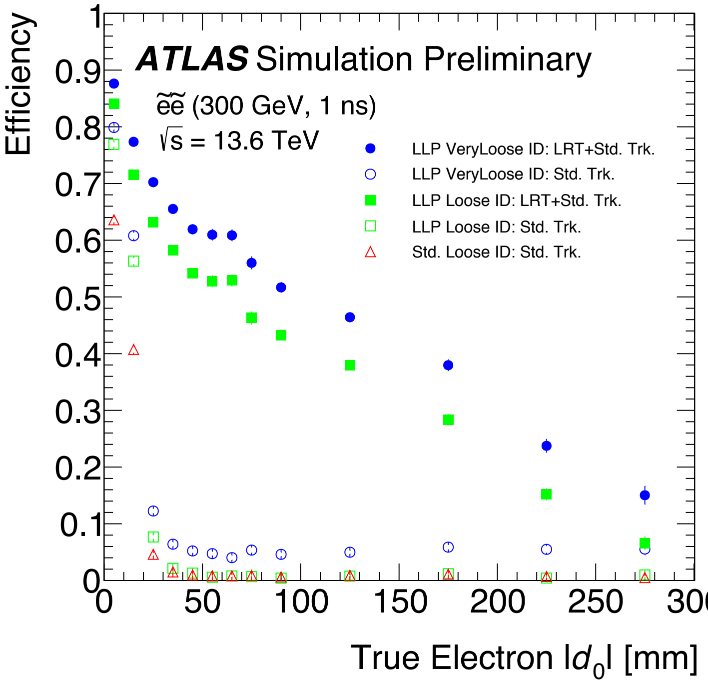
First result exploiting new LRT triggers in Run 3, designed for displaced e/μ

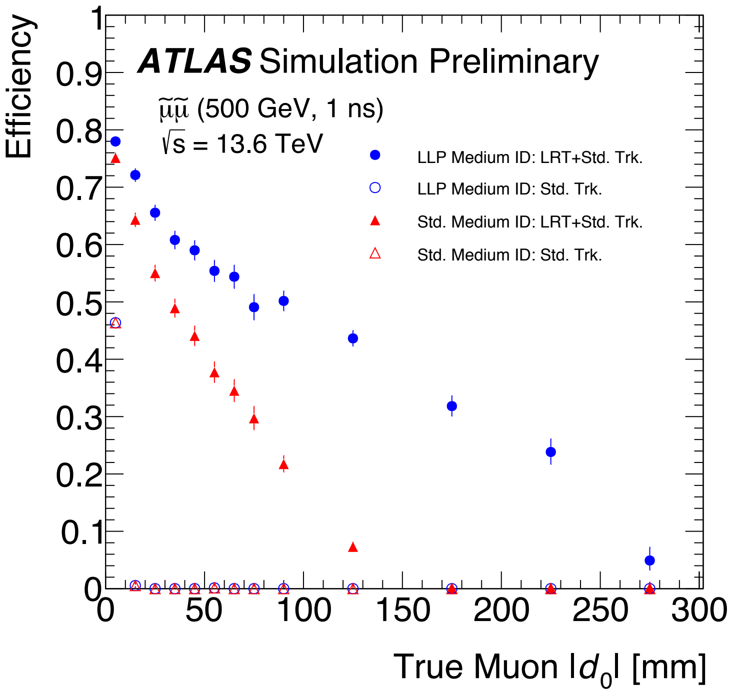
(ee,eμ,μμ) Run 2 + 3

- ABCD (ℓ_1 track quality,ℓ_2 track quality)
- Near zero-background search

(1e,eγ,$\gamma\gamma$) Run 3 BDT for final states with e,γ

- Lower lepton multiplicity, higher backgrounds to cope with
  → Displaced electron tagger using tracker + calorimeter info (+BDT targeting $\gamma\gamma$)





New for ICHEP

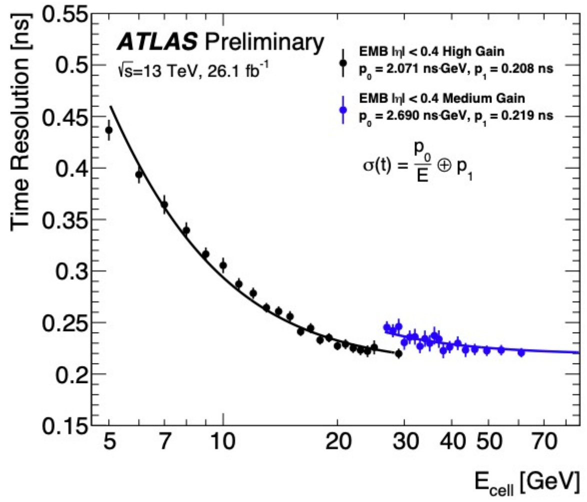
Displaced Leptons Strategy

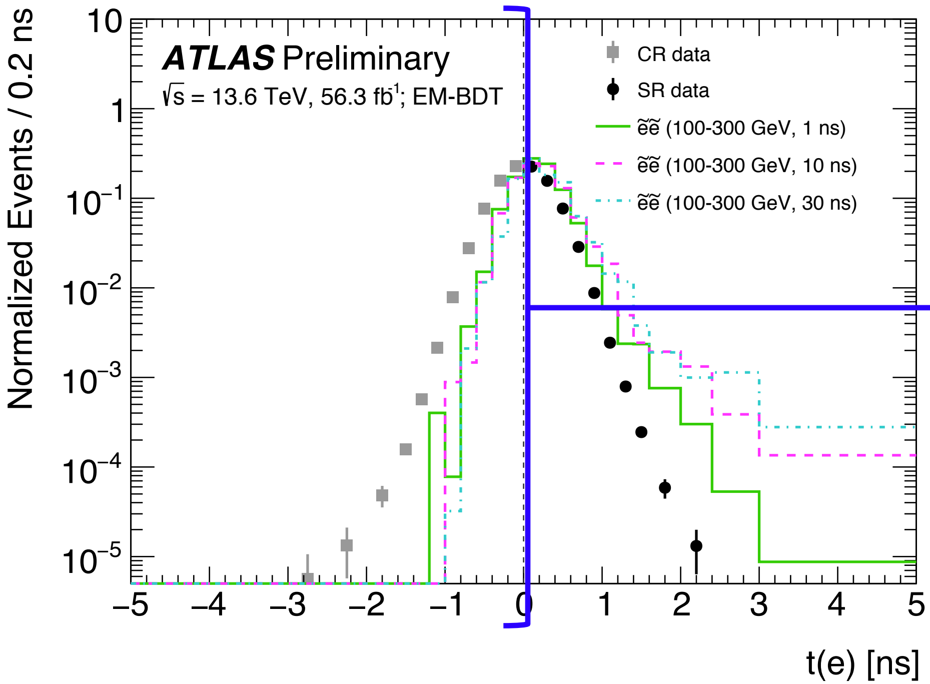
Liquid Argon (LAr) Calorimeter precision timing can be exploited to target LLPs

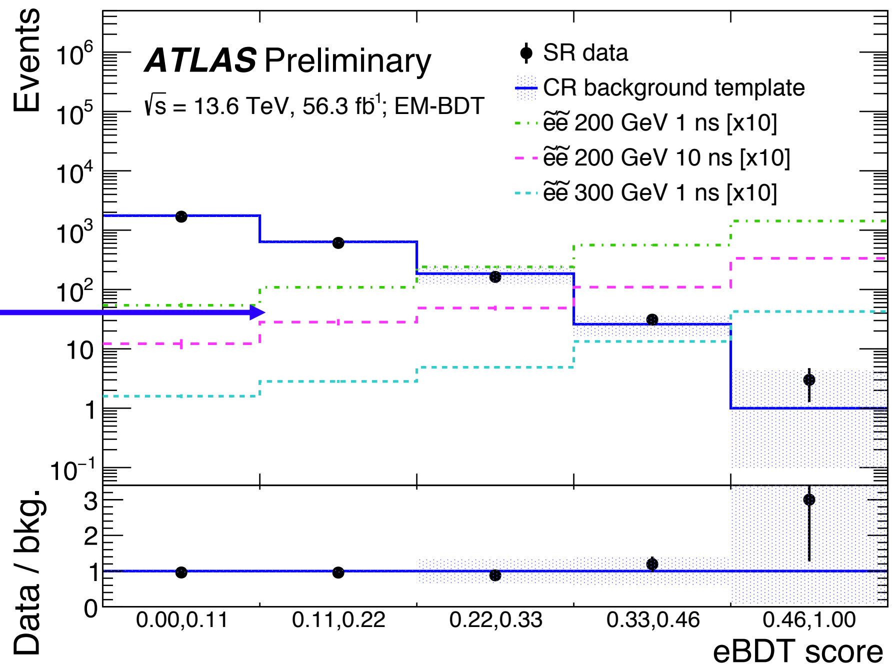
- O(200ps) resolution for energetic *e/γ* (limited by beamspread)
- Enough to resolve "late" *e/γ* from LLP decays against prompt SM background

BDT utilizes timing symmetry of prompt background for prediction in search region

- Train on data with $ToF_{cal} < 0$, signal $ToF_{cal} > 0$ to predict scores in $ToF_{cal} > 0$ data
- Validated by applying BDT to events enriched in SM W/Z

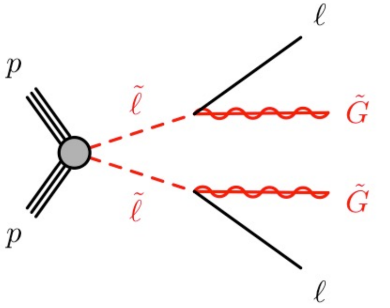






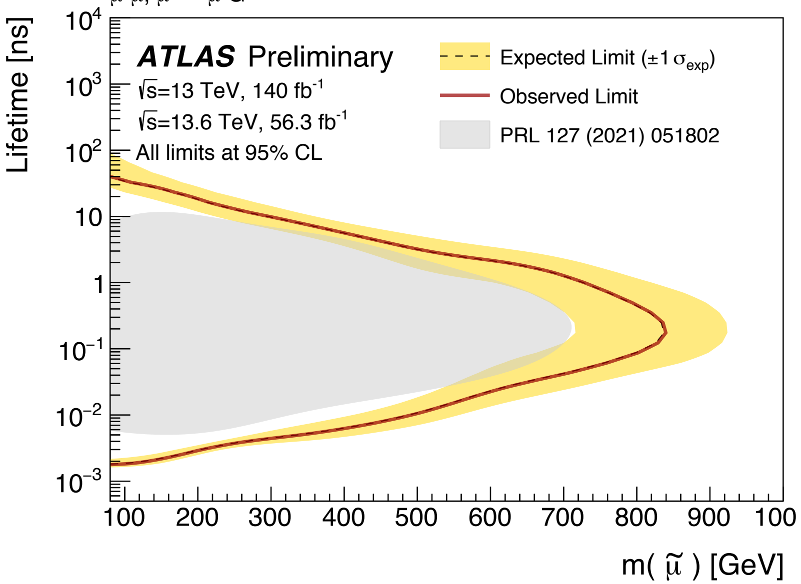
New for ICHEP

Displaced Leptons In Run 2 + Run 3

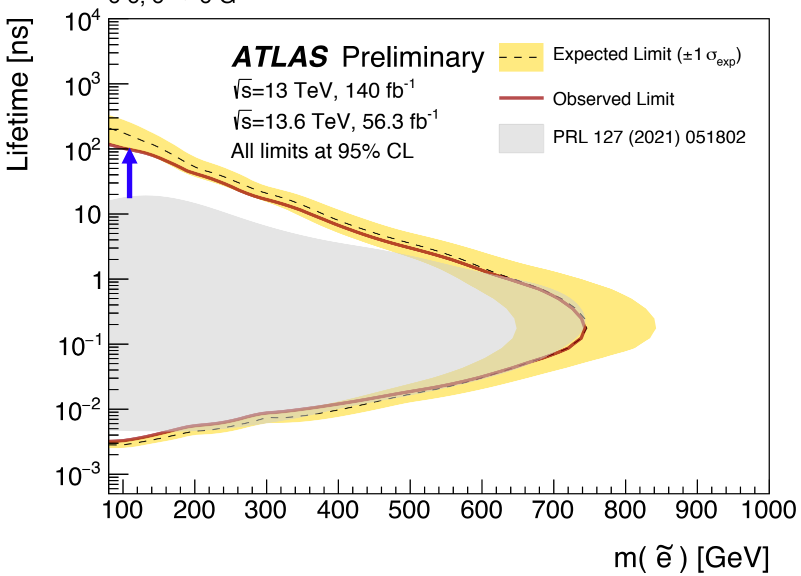


New sensitivity for long-lived decays to electrons from BDT
~5x for selectrons, ~3x for staus

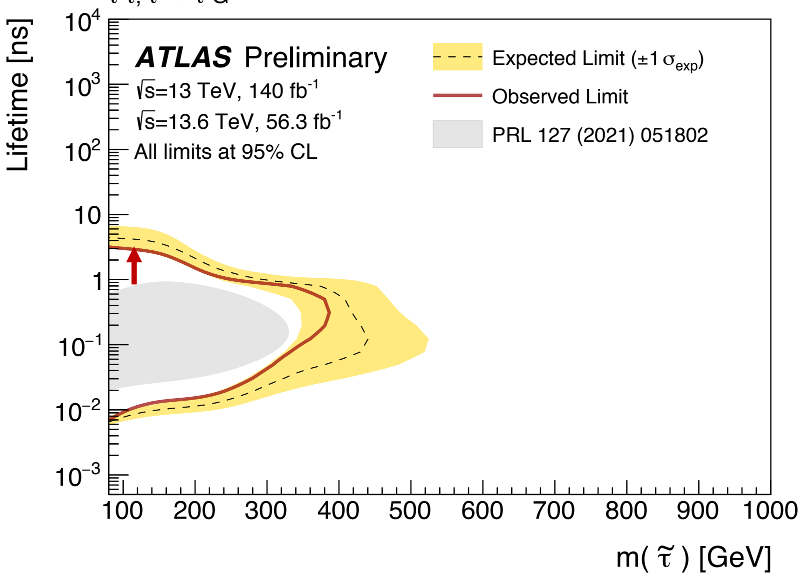
Smuons



Selectrons



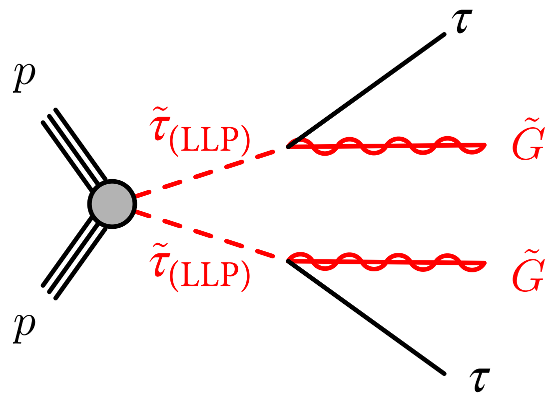
Staus

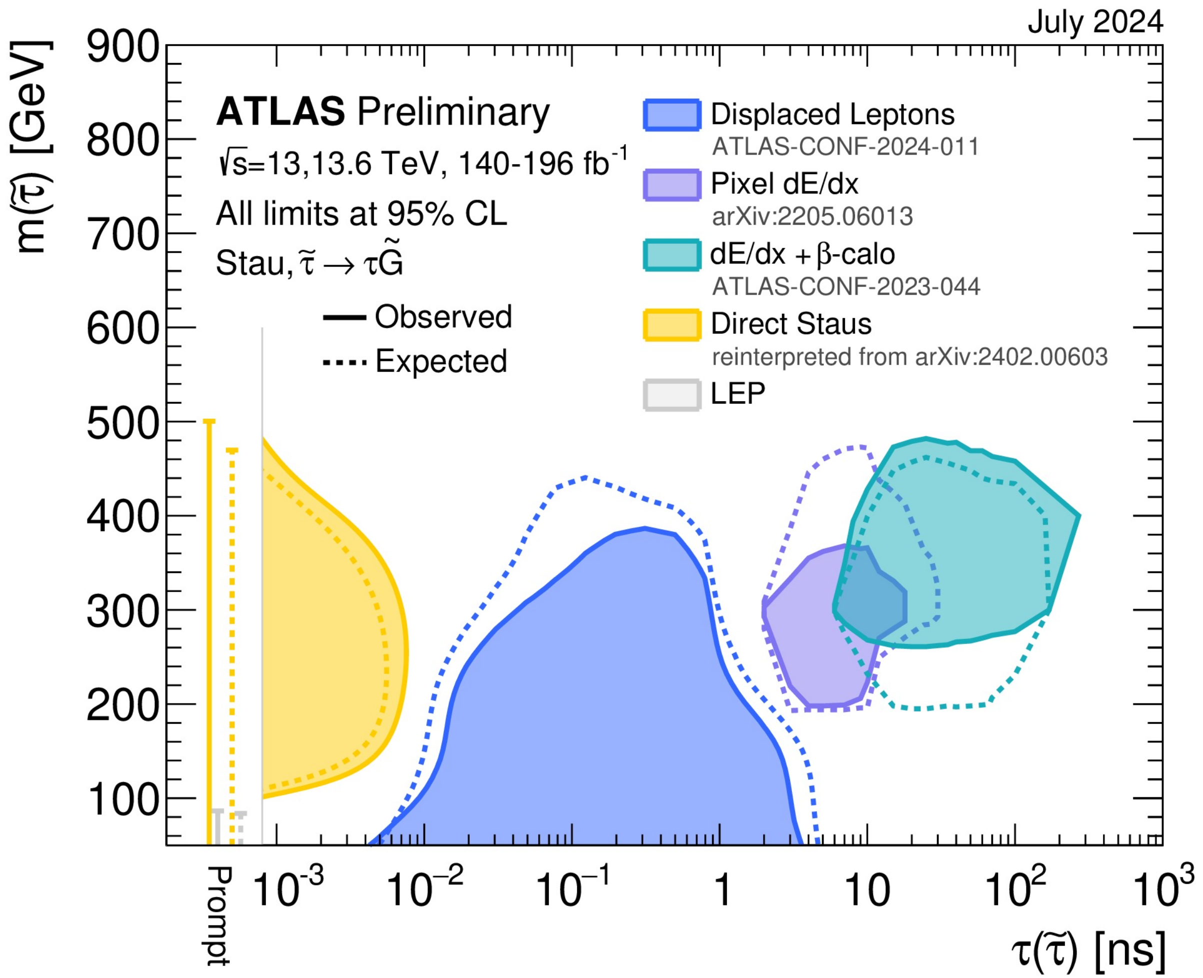


- **First ATLAS Search Result at $\sqrt{s}$ = 13.6 TeV, No significant deviation from SM expectation**
- Largest local significance 2.2σ in LRT-enriched ee final state (1 event observed, $0.0016^{+0.0029}_{-0.0016}$ expected)
- Adding early Run 3 data + **new triggers** improves sensitivity w.r.t. previous search [PRL 127 051802]
  - Smuon limits for $\mu\mu$ final states only – gains here driven by Run 3 LRT triggers
  - BDT region probes new final states, allows exclusion at higher lifetimes

New for ICHEP

Displaced Leptons: Big Picture





- New results from re-interpretation of **prompt direct staus** [ATL-PHYS-PUB-2024-007] + **Displaced Leptons** offer new sensitivity to staus **(but gaps still remain!)**

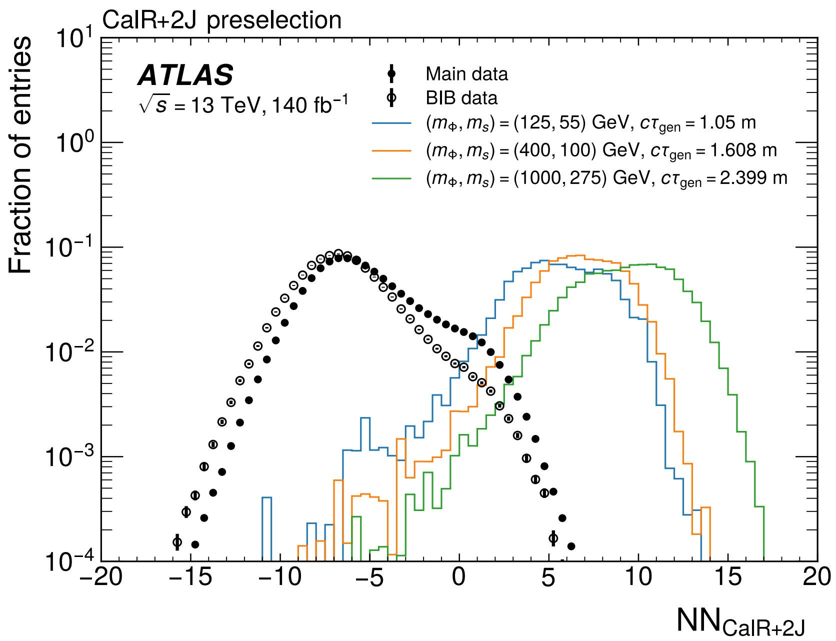
Hadronic LLPs + Leptons/Jets

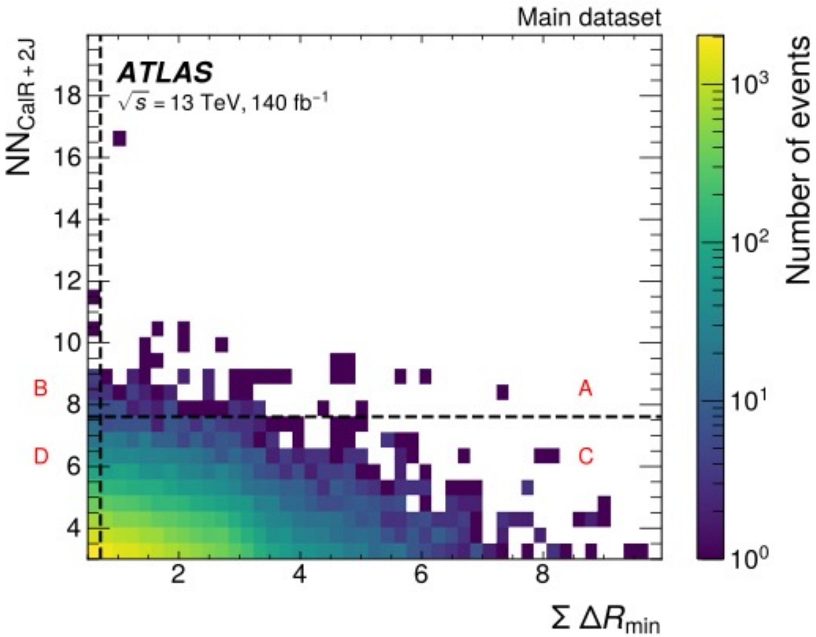
Target pair-produced LLPs, LLP + Standard Model W/Z

Expect jets with low energy fraction in electromagnetic calorimeter due to displacement
→ Exploit hadronic/electromagnetic calorimeter energy fraction ≡ "CalRatio" jets

- Trigger on ***e/μ* from W/Z** → CalRatio + W/Z channels
- Trigger on jets from LLP (**CalRatio triggers**) → CalRatio + 2J channel
- Suppress multijet, beam-induced background with per-jet NN, then use ABCD method

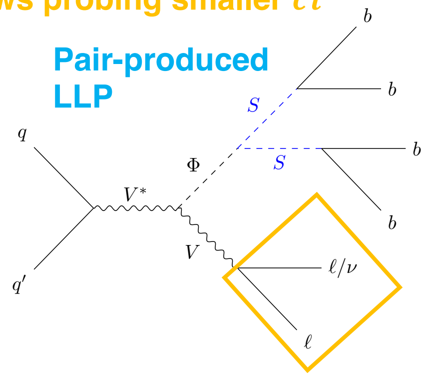
ABCDisCo: Train NN discriminant, explicitly decorrelate with $\Sigma(\Delta R_{min})$ to build ABCD plane



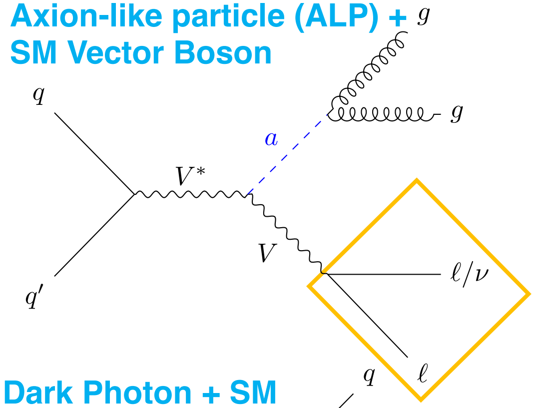


prompt "handle" for triggering allows probing smaller $c\tau$

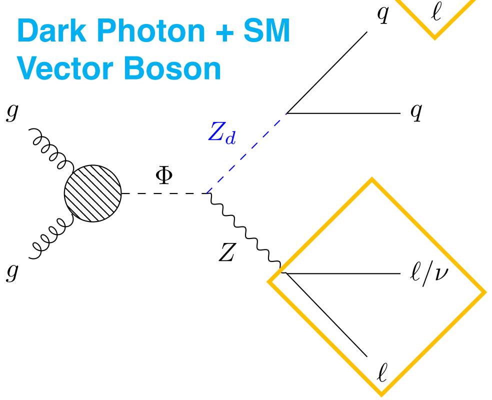
Pair-produced LLP



Axion-like particle (ALP) + SM Vector Boson

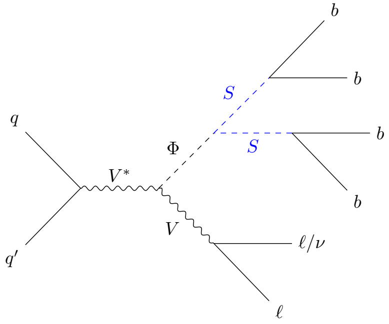


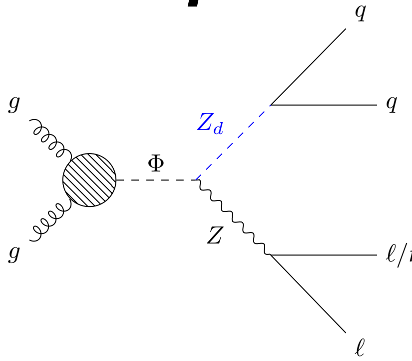
Dark Photon + SM Vector Boson

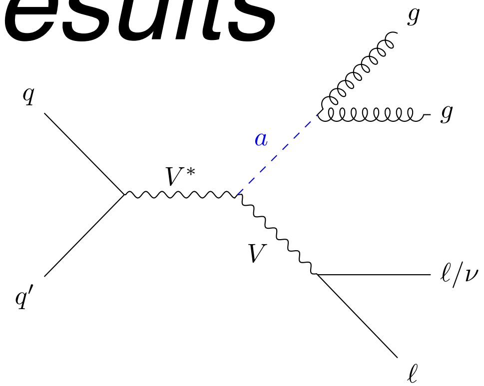


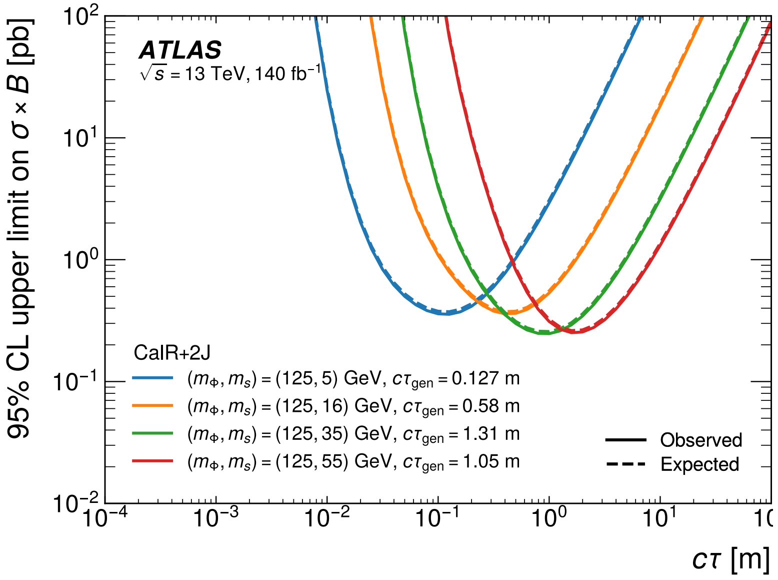
New for ICHEP

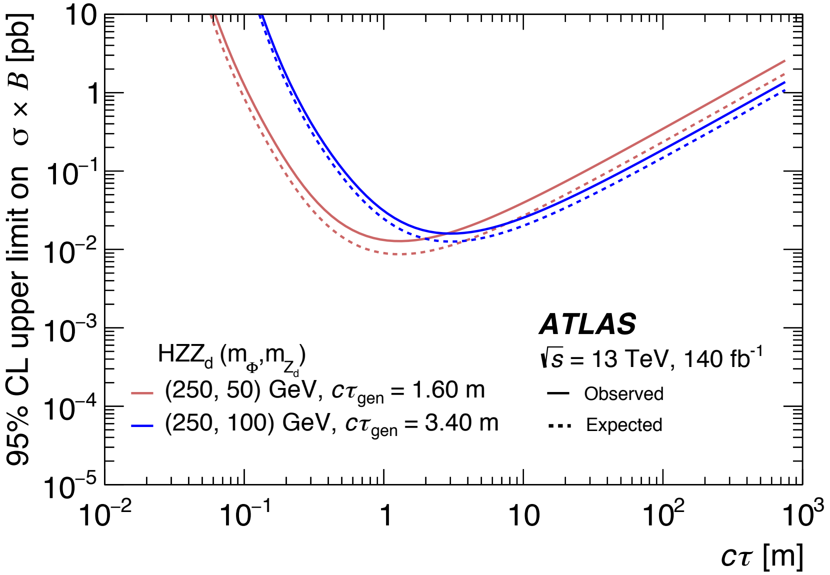
Hadronic LLPs + Leptons/Jets Results

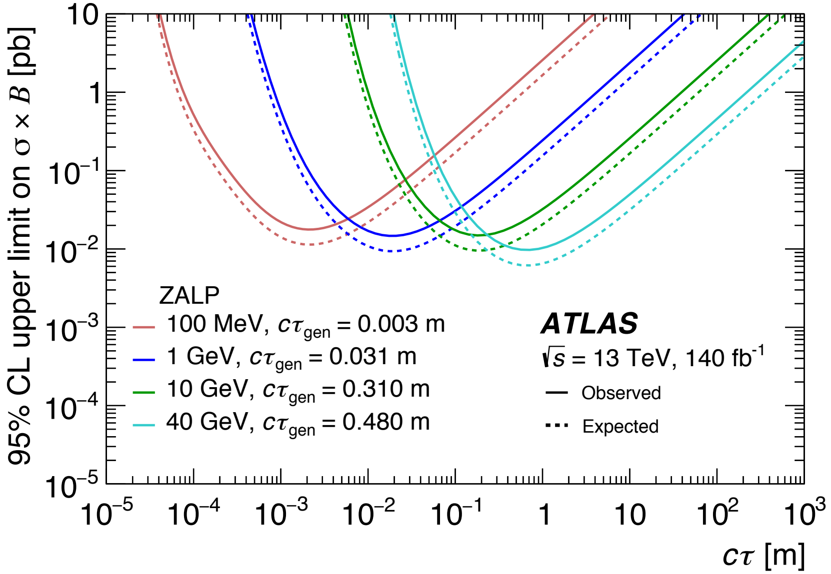












3x improvement for BR(H → SS → 4b) w.r.t previous search [JHEP06(2022)005]

HZZ_d σ > 0.1 pb for Z_d with cτ ∈ 0.1mm-10m (**10x** improvement w.r.t previous search [PRL122(2019)151801]: more stats + per-jet NN)

Photo-phobic ALP σ > 0.1 pb excluded for cτ ∈ 0.1mm-10m

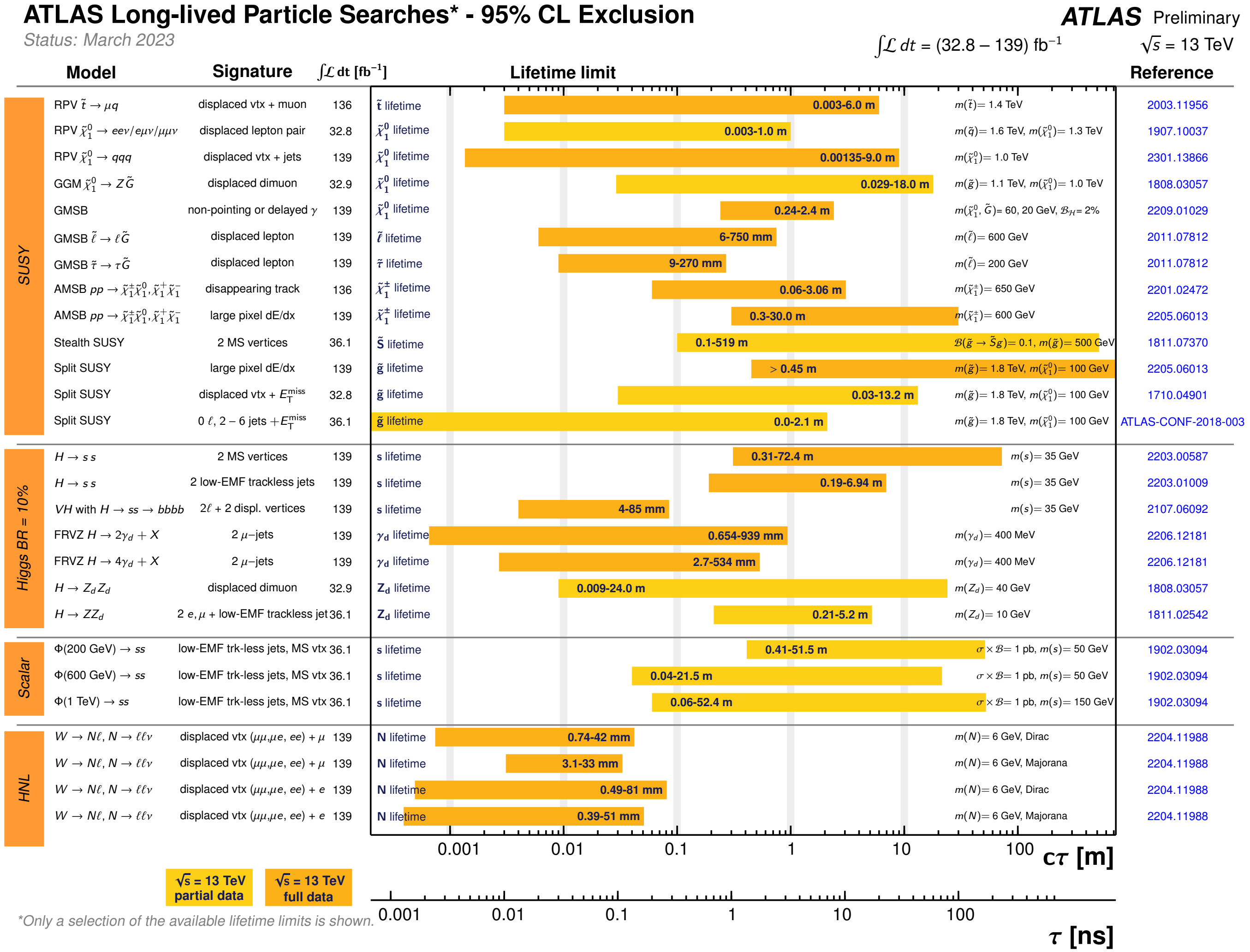
Conclusion

If BSM manifests as an LLP…

- Could escape "standard" search methods
- So far setting limits, expanding to meet prompt regime and cover out to detector-stable LLPs
- Require custom variables, dedicated triggers, special reconstruction…

→ LRT in Run 2 and (with triggers) in Run 3

- Extensive search program in ATLAS, not enough time to cover everything!
- See [ATLAS Public Results Page]()



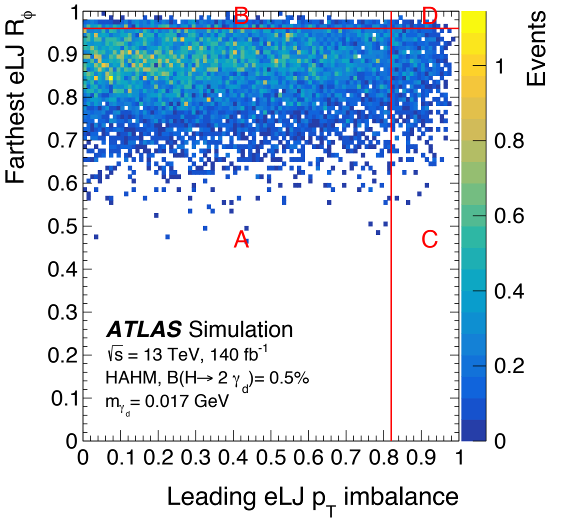
→ First ATLAS Search Result at $\sqrt{s}$ = 13.6 TeV

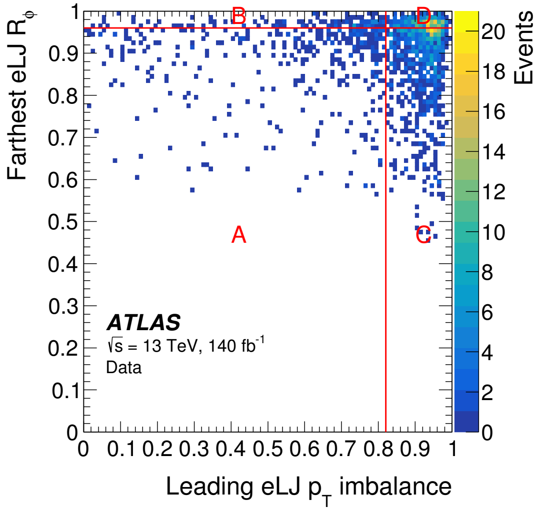
→ More exciting results as Run 3 continues

BACKUP

Prompt Lepton Jets Extra

*e*LJ channel ABCD:



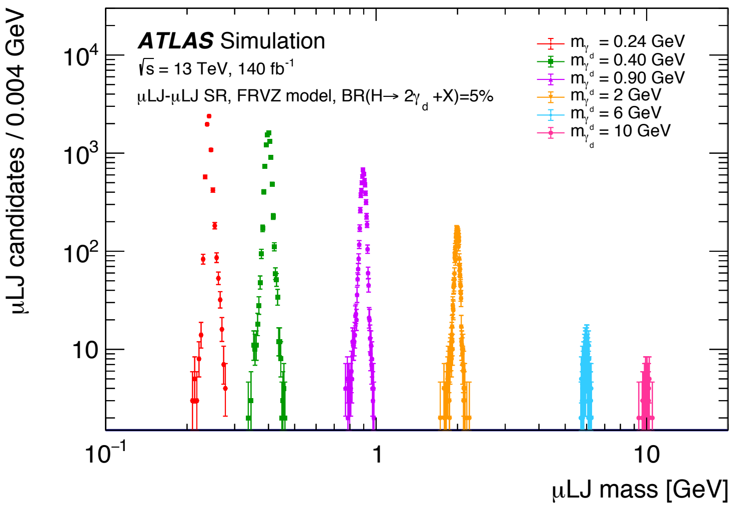


Selection	CR B	CR C	CR D	SR expected	SR observed
*e*LJ–*e*LJ	125	862	356	303 ± 33	351

*e*LJ channel region definitions:

Requirement / Region	SR	CR B	CR C	CR D	VR_Z
Applied to both leading and farthest *e*LJ					
N. of EM clusters in *e*LJ			1		
*e*LJ mass imbalance			< 0.8		
Selection on event-level variables					
$\Delta\phi(eLJ,eLJ)$			> 2.5		
N. of Jets (p_T > 40 GeV)			0		
$m(eLJ,eLJ) \notin [80, 100]$ GeV	yes	yes	yes	yes	veto
Leading *e*LJ p_T^{imb}	< 0.8	< 0.8	> 0.8	> 0.8	–
Farthest *e*LJ R_ϕ	< 0.96	> 0.96	< 0.96	> 0.96	–

$m_{\mu\mu}$ for selected $m(\gamma_d)$



*μ*LJ channel background shape parameterization:

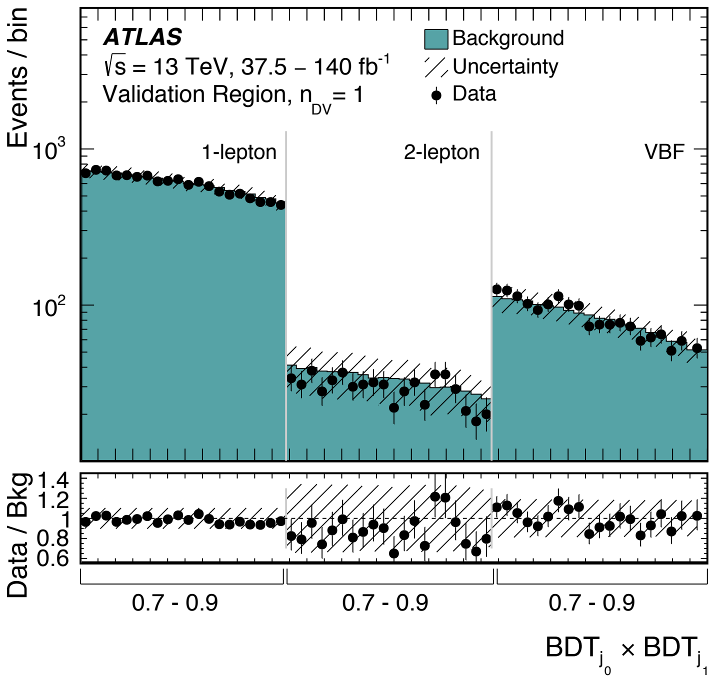
$$B(m_{\mu LJ}) = \left(1 - f_{\exp} - f_{J/\psi} - f_{\phi(1020)} - f_{\psi(2S)}\right) e^{-m_{\mu LJ}/\tau_2} + f_{\exp} e^{-m_{\mu LJ}/\tau} + f_{J/\psi} e^{-\left(\frac{m_{\mu LJ}-\mu_{J/\psi}}{\sigma_{J/\psi}}\right)^2} + f_{\psi(2S)} e^{-\left(\frac{m_{\mu LJ}-\mu_{\psi(2S)}}{\sigma_{\psi(2S)}}\right)^2} + f_{\phi(1020)} e^{-\left(\frac{m_{\mu LJ}-\mu_{\phi(1020)}}{\sigma_{\phi(1020)}}\right)^2},$$

- Double exponential + Gaussian probabilities for SM resonances

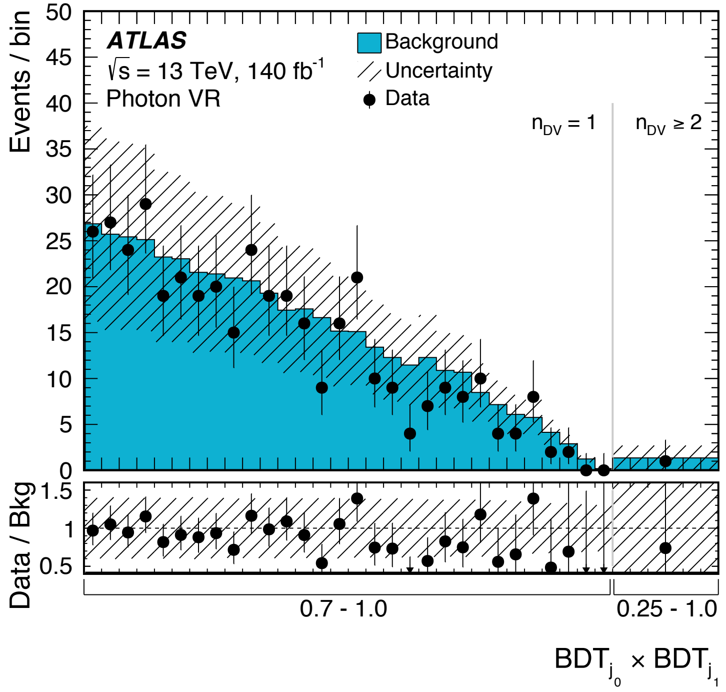
Hadronic LLPs Using DVs Extra

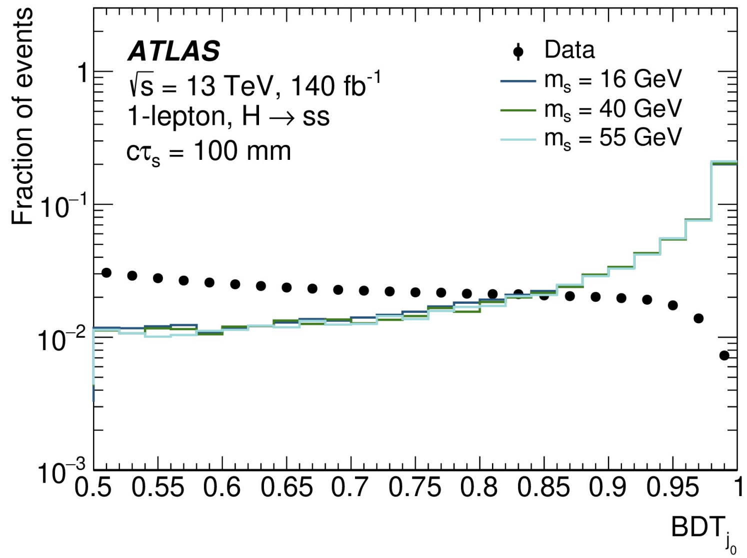
- Validate extrapolation of per-jet probabilities to event-level weights for background prediction in $BDT_{j0} \times BDT_{j1} < 0.7$ using
  - $BDT_{j0} \times BDT_{j1} < 0.7 \rightarrow 0.7 < BDT_{j0} \times BDT_{j1} < 0.9$ for $n_{DV} = 1$
  - Events with high-p_T photon, 2 jets, 0 leptons for $n_{DV} \geq 2$

Low-score validation region

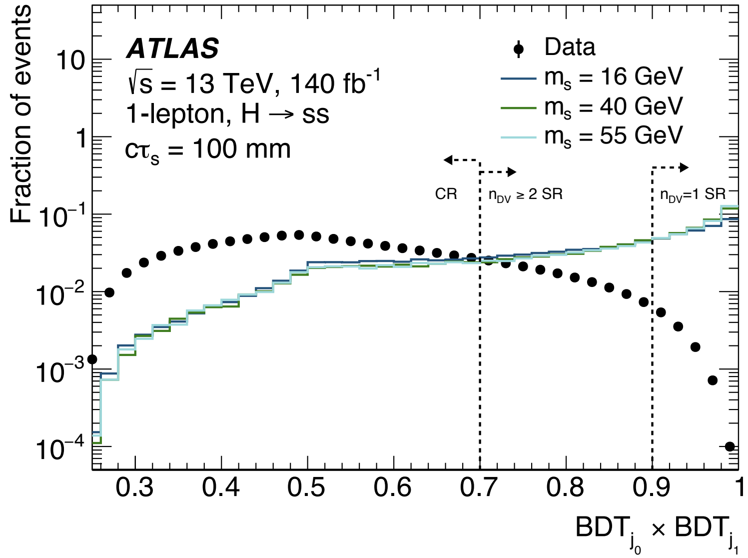


Photon Validation Region





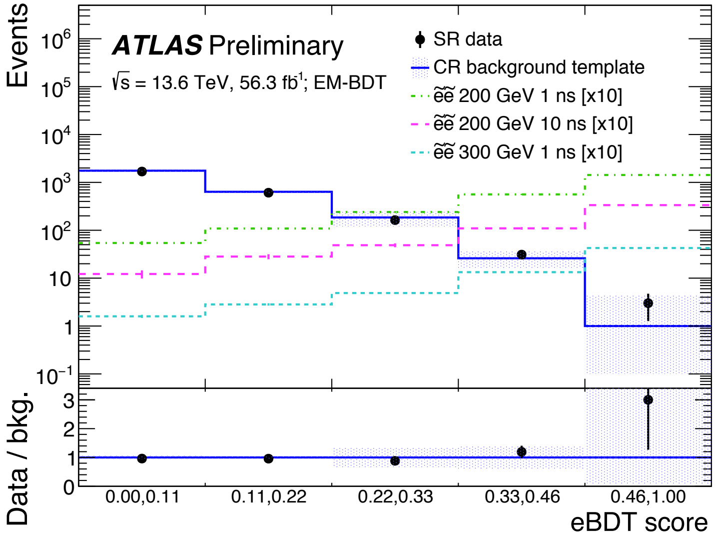
$BDT_{j0} \times BDT_{j1}$ showing region definiton



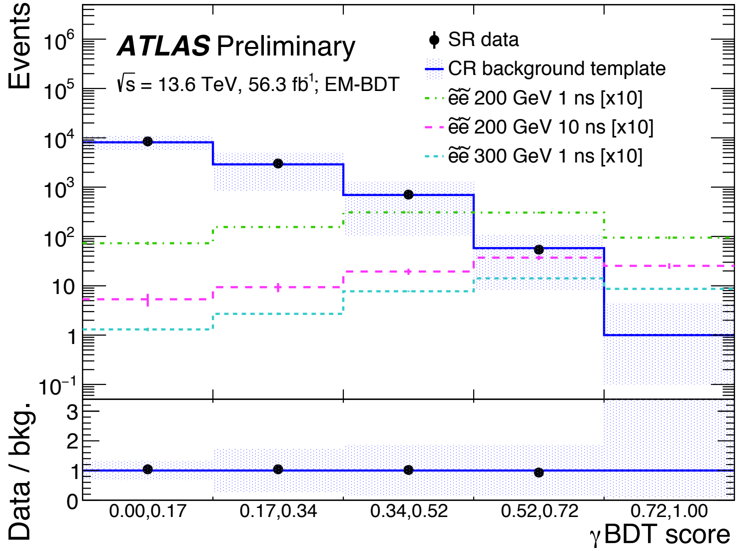
Displaced Leptons Extra

- Exclusion results from combined fit across nine ABCD regions and EM-BDT region
- EM-BDT non-closuse shape systematic from disagreement in extrapolation across (t = 0) in W/Z enriched events

electron BDT



photons BDT



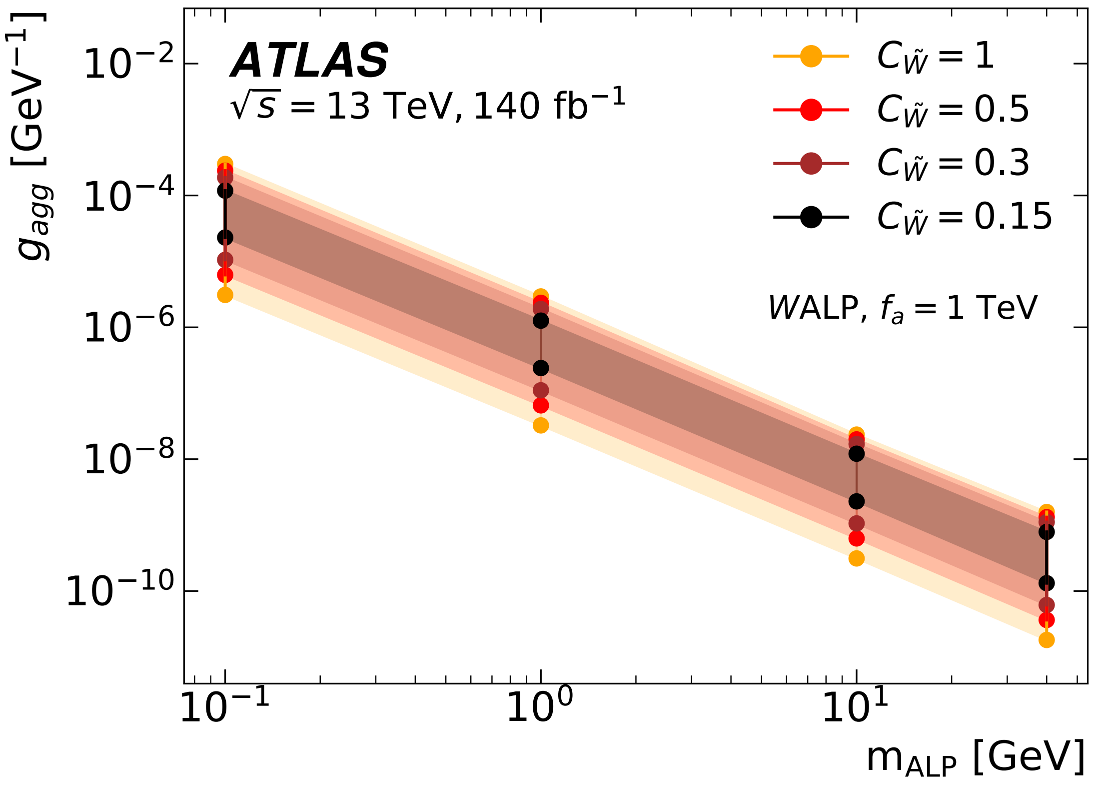
Results across all signal regions

Signal Region	Total Bkg.	Data	$\langle A\epsilon\sigma\rangle^{95}_{\text{obs}}$ [fb]	S^{95}_{obs}	S^{95}_{exp}	CL_b	$p(s=0)$ (Z)
SRee-high-p_T-Run2	0.031 ± 0.031	0	0.02	3.0	$3.0^{+0.0}_{-0.0}$	0.46	0.5 (0)
SRee-high-p_T-Run3	0.06 ± 0.05	0	0.05	3.0	$3.0^{+0.0}_{-0.1}$	0.45	0.5 (0)
SRee-LRT	$0.0016^{+0.0029}_{-0.0016}$	1	0.07	4.1	$3.1^{+0.0}_{-0.1}$	0.97	0.01 (2.2)
SR$\mu\mu$-high-p_T-Run2	$0.02^{+0.22}_{-0.02}$	0	0.02	3.0	$3.0^{+0.0}_{-0.0}$	0.49	0.5 (0)
SR$\mu\mu$-high-p_T-Run3	$0.01^{+0.11}_{-0.01}$	0	0.05	3.0	$3.0^{+0.0}_{-0.0}$	0.48	0.5 (0)
SR$\mu\mu$-LRT	$0.02^{+0.04}_{-0.02}$	0	0.05	3.0	$3.0^{+0.0}_{-0.0}$	0.49	0.5 (0)
SR$e\mu$-high-p_T-Run2	$0.0016^{+0.0033}_{-0.0016}$	0	0.02	3.0	$3.0^{+0.0}_{-0.1}$	0.50	0.5 (0)
SR$e\mu$-high-p_T-Run3	$0.004^{+0.010}_{-0.004}$	0	0.05	3.0	$3.1^{+0.0}_{-0.0}$	0.50	0.5 (0)
SR$e\mu$-LRT	$0.2^{+0.4}_{-0.2}$	0	0.05	3.0	$3.0^{+0.1}_{-0.1}$	0.45	0.5 (0)
SR-EMBDT	$1.0^{+2.3}_{-0.9}$	3	0.13	7.1	$5.7^{+1.9}_{-0.8}$	0.77	0.2 (0.9)

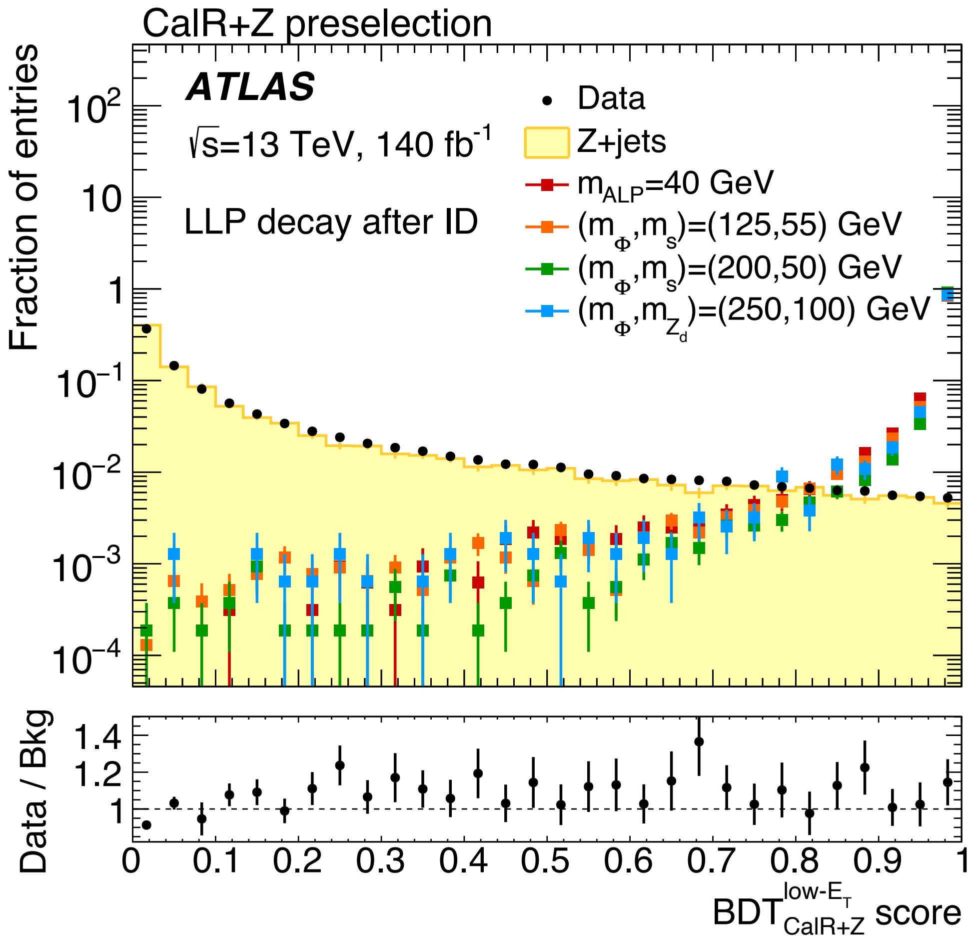
Hadronic LLPs + Leptons/Jets Extra

$$\Gamma_{agg} = \frac{2}{\pi f_a^2} C_{\tilde{G}}^2 m_{\mathrm{ALP}}^3$$

$$g_{agg} = 4C_{\tilde{G}}/f_a$$



BDT CalR+Z performance:



- Gluon coupling proportional to cτ, SM weak sector coupling proportional to σ, → can set limits on $C_{\tilde{W}}, C_{\tilde{G}}$