Searches for BSM physics using challenging and long-lived signatures with the ATLAS detector

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ATLAS EXPERIMENT

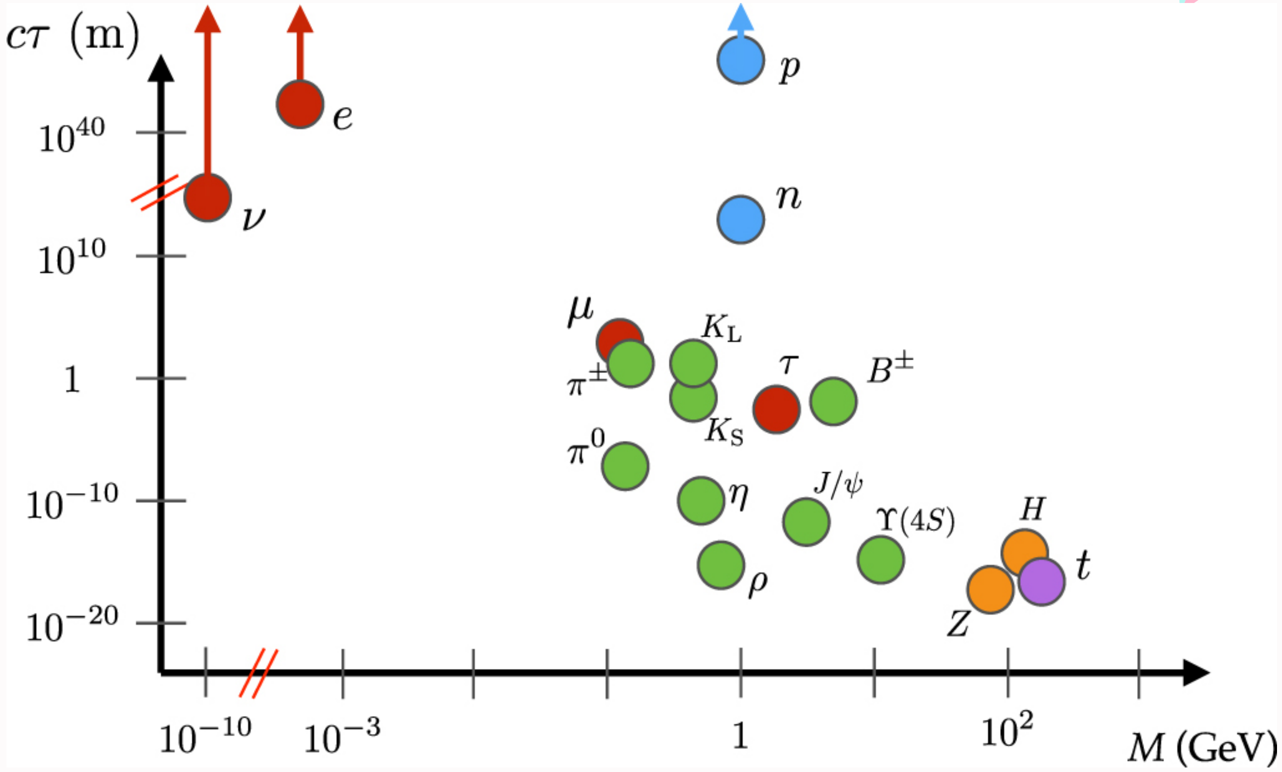
Long-Lived Particles (LLPs) in the Standard Model

Particle lifetimes in the SM range from

- Z boson ($\tau \sim 2 \times 10^{-25}$s)
- Proton ($\tau \gtrsim 10^{34}$ years)

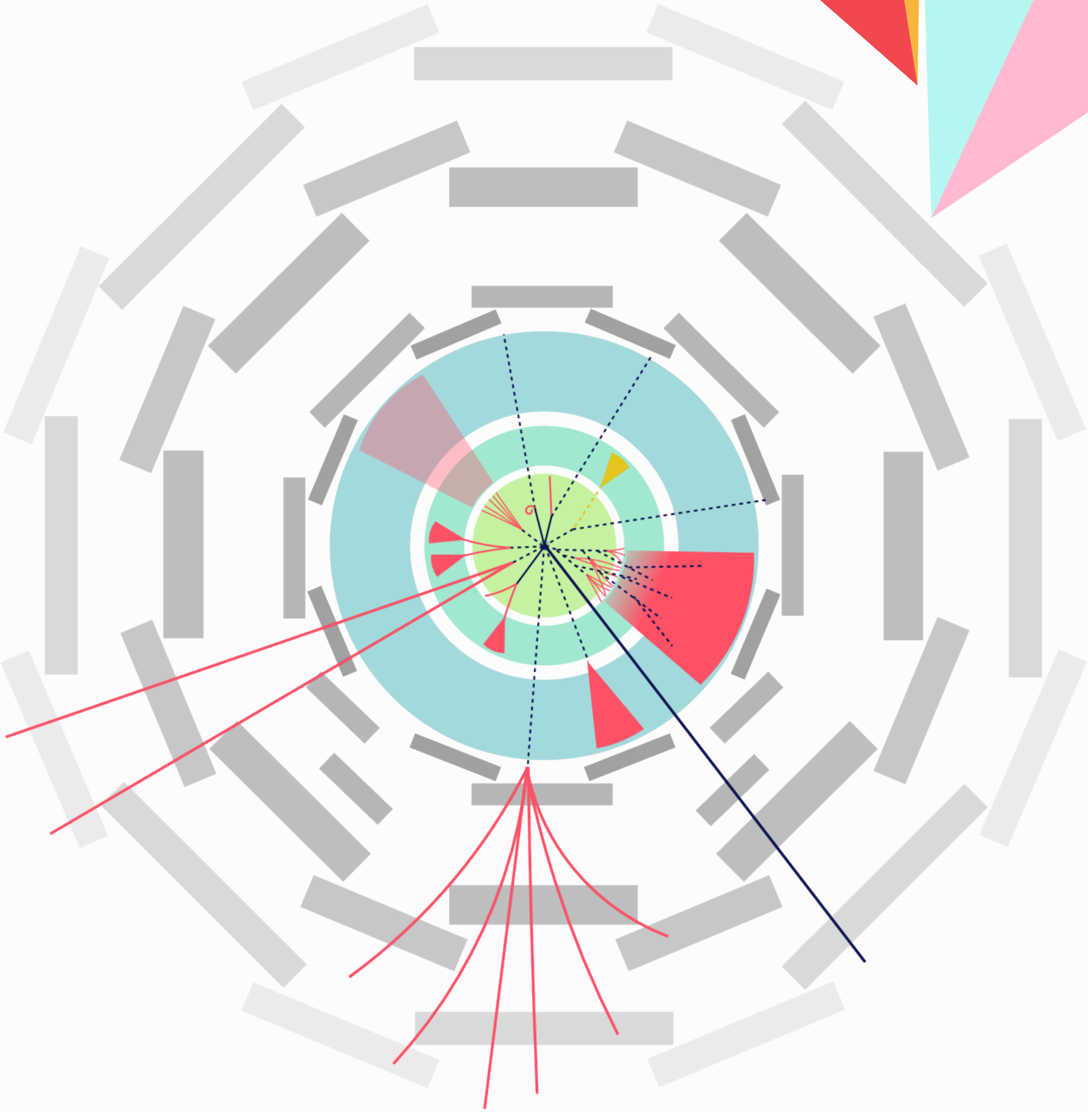
Long lifetimes can result from

- Heavy off-shell particles
  - Ex. Muons and kaons
- Phase space suppression
  - Ex. Neutron
- Very small coupling constants from approximate symmetries
- Knapen and Lowette arxiv: 2212.03883



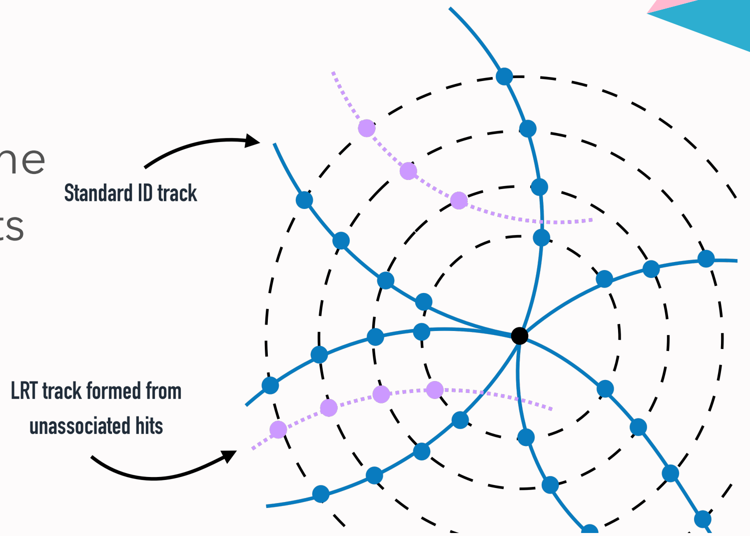
LLPs Beyond the Standard Model (BSM)

- Many complete searches for BSM have assumed that they would be prompt, without success
- Continued searches for new physical processes are expanding the range of hypothetical BSM models and their observable signatures
- Similarly to their presence in the SM, LLPs are predicted in a wide variety of BSM scenarios, including
  - Supersymmetry
  - Hidden sectors
  - Dark matter models



Challenges with reconstructing LLP signatures in ATLAS

- Standard ATLAS track reconstruction applies strict pointing requirements that limit the sensitivity of charged particles originating from the interaction point
- Reconstruction of displaced tracks to a vertex other than the primary vertex (PV) is historically computationally expensive
- Non-standard tracking algorithm:
  - Large-radius tracking (LRT) recovers tracks from LLPs within the tracking detector volume by loosening pointing requirements and running over unused hits
  - Previous version of LRT algorithm ran on only 10% of events
- Vertexing displaced tracks to a secondary, displaced vertex
  - Algorithmic challenges in reconstructing displaced vertices
- Differentiating displaced energy deposits from prompt deposits

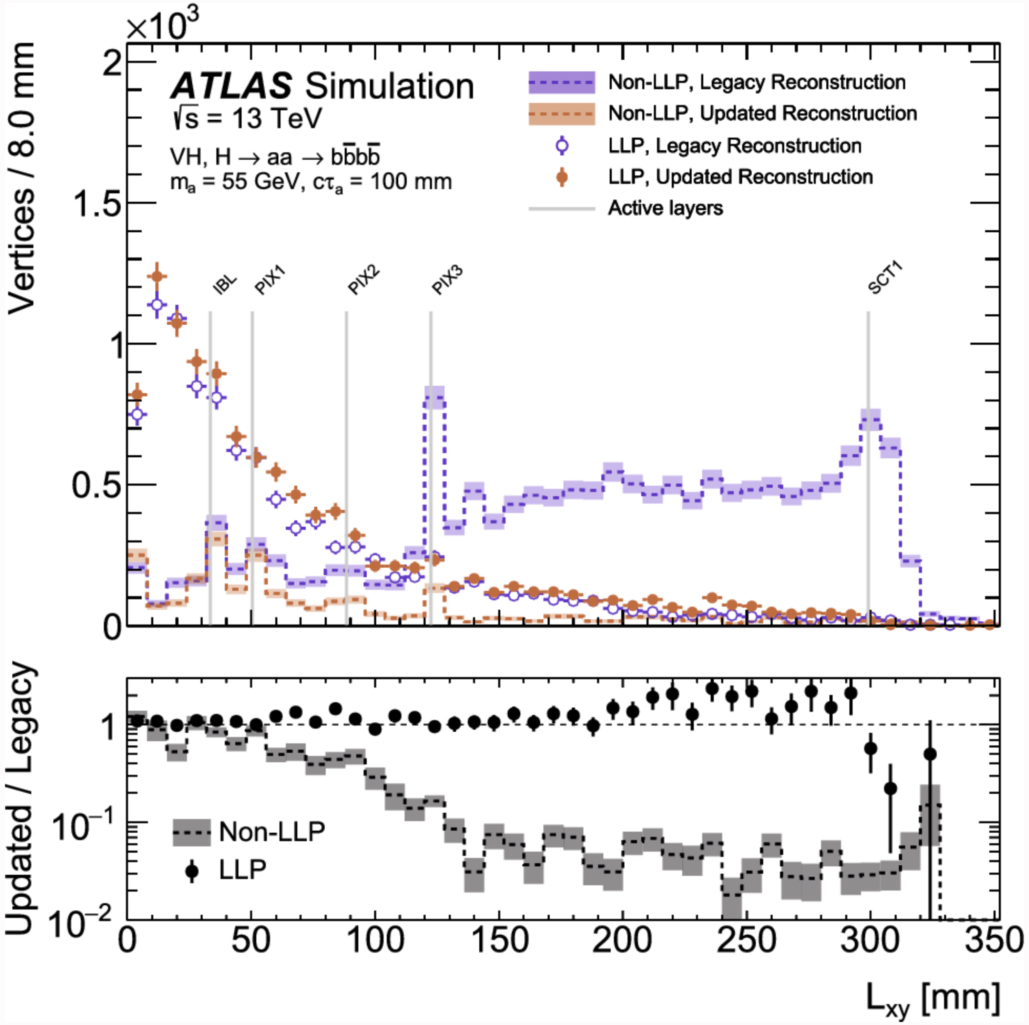


Recent ATLAS search program for LLPs

	ATLAS Reference	Title	Date	Publication	Targeted LLP Mass and lifetimes
🟢	ATLAS-CONF-2024-011	Displaced Leptons Run 2 + Run 3	18 July 2024	Conf. Note CDS:ATLAS-CONF-2024-011	Leptons m: 0 - $\mathcal{O}$(100) GeV $c\tau$:$\mathcal{O}$(1) mm - $\mathcal{O}$(10) m
🔷	EXOT-2021-32	Light hadronic LLPs using displaced vertices	22 March 2024	Submitted to EPJC arXiv:2403.15332	Hadrons m ~ 5 - 55 GeV $c\tau$: $\mathcal{O}$(1) mm - $\mathcal{O}$(1) m
🔺	EXOT-2022-04	Hadronic LLPs with associated leptons or jets	12 July 2024	Submitted to JHEP arXiv:2407.09183	Hadrons m : 10 - $\mathcal{O}$(100) GeV $c\tau$: $\mathcal{O}$(1) cm - $\mathcal{O}$(10) m

The complete list of ATLAS LLP searches can be found on the **Exotics** and **SUSY** ATLAS public results pages

Reconstructing LLPs in ATLAS with non-standard tracking



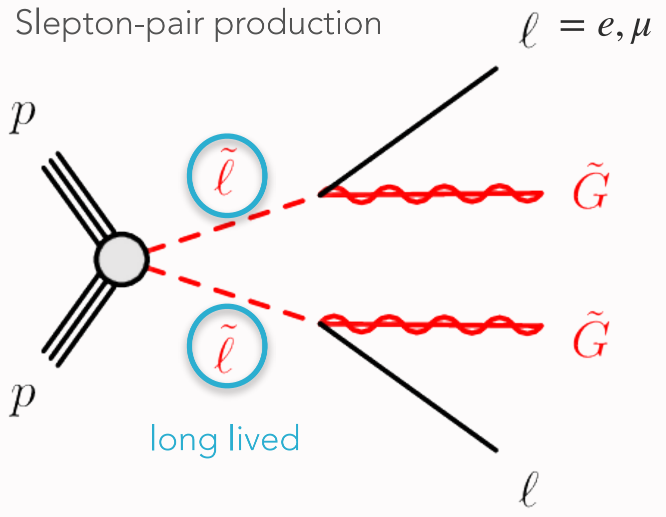
- Recent improvements in LRT algorithm
  - Less computationally expensive
  - Can now run on **all events**
    - Previously only 10%
  - Fewer fake vertices
- New LRT triggers in Run 3

Newest configuration results in ~10 times fewer fake vertices!

Displaced leptons: Run 2 + partial run 3 analysis

- **Goal:** Search for two leptons (electrons + muons) displaced from the primary vertex
  - Reconstructing e and μ using standard and LRT tracks
- **Physics targeted:** Slepton pair production via Gauge-Mediated Supersymmetry Breaking (GMSB)
  - LLP is the next-to-lightest supersymmetric particle (NLSP) : $c\tau \sim \mathcal{O}(1)$mm - $\mathcal{O}(10)$m
  - Decaying in the inner detector or the calorimeters
- Using a boosted decision tree BDT with electromagnetic *calorimeter timing information* to separate displaced e and γ from prompt SM deposits
- First result using new LRT triggers designed for displaced e and μ!

Slepton-pair production

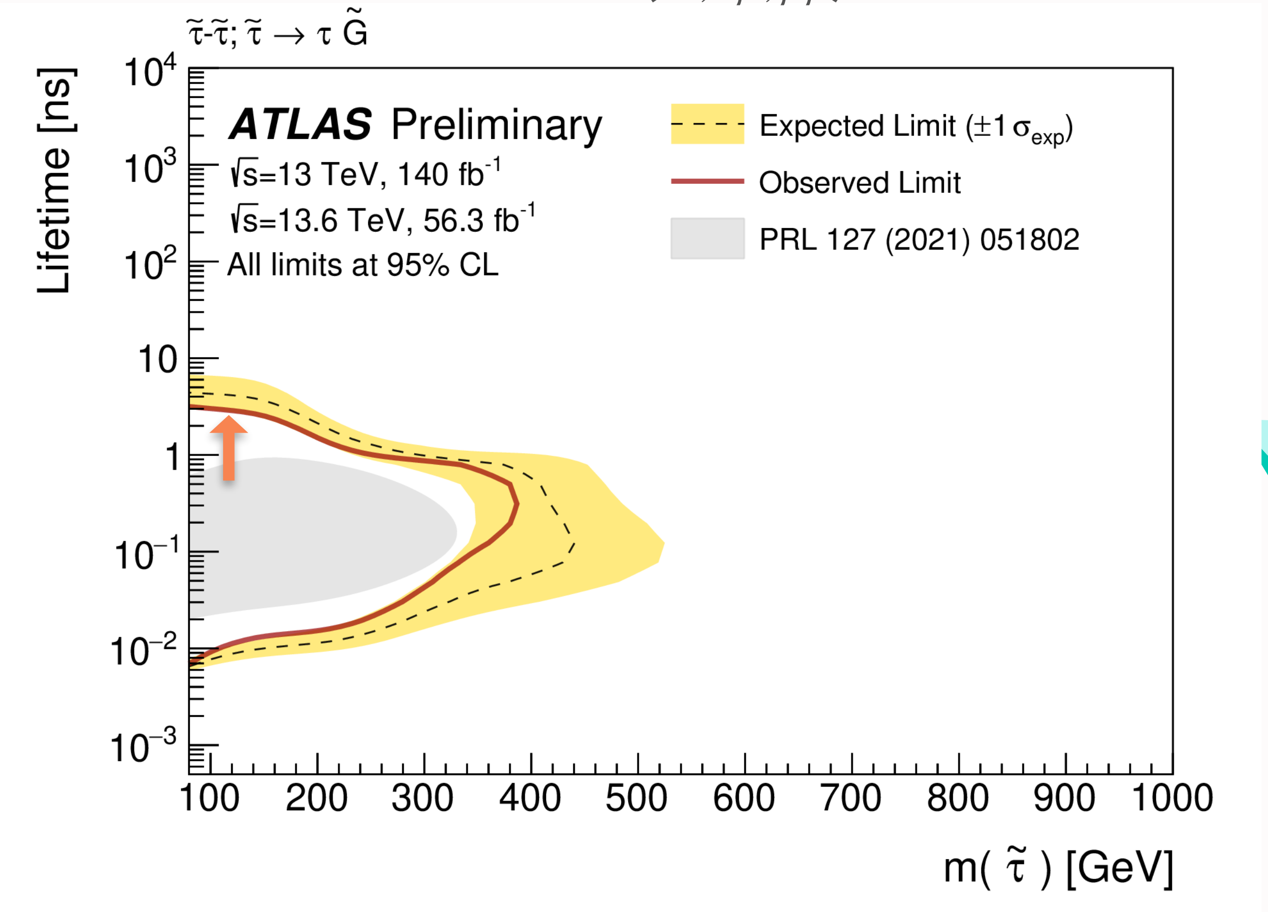


Extension of Run-2-only analysis by adding LRT triggers and EM-BDT using calorimeter timing [Phys. Rev. Lett. 127 (2021) 051802]

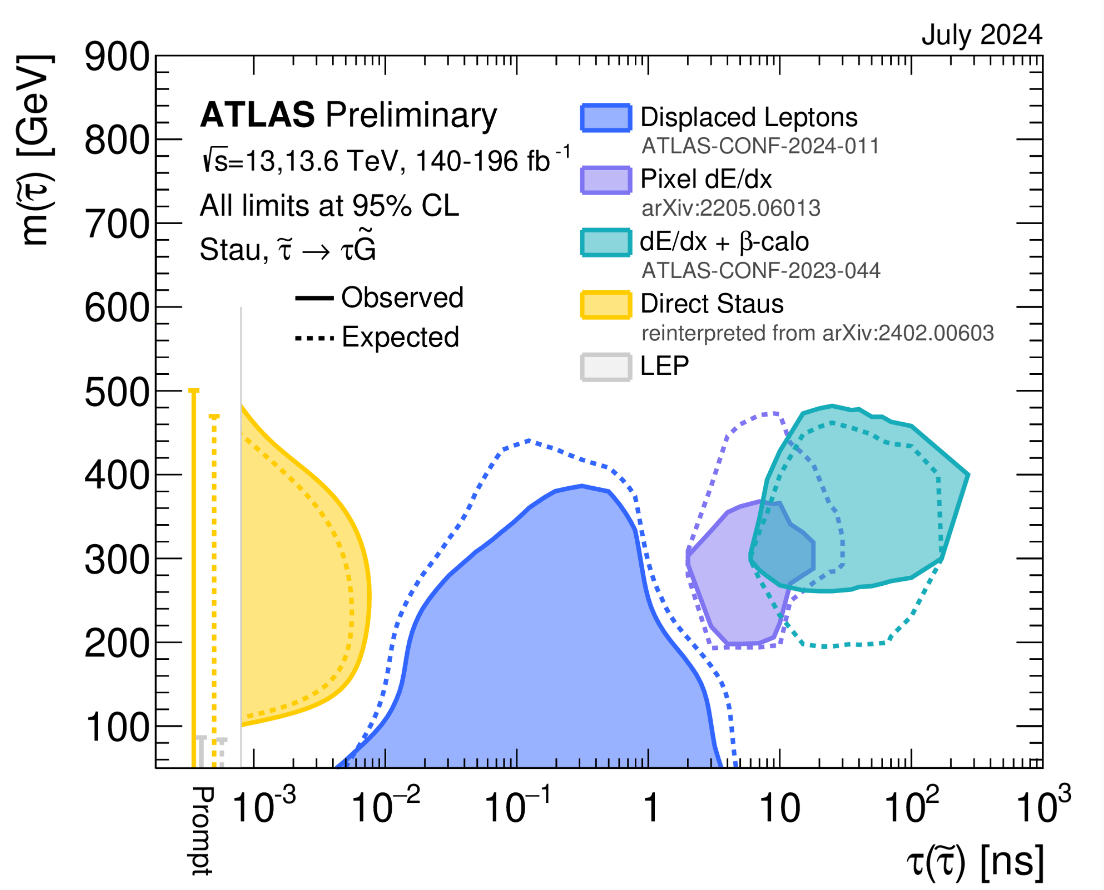
Displaced leptons: results

- Adding early Run 3 data + new triggers improves sensitivity from run-2-only-search [**Phys. Rev. Lett. 127 (2021) 051802**]
- Improvement is largest at low mass where new LRT triggers most dramatically improve acceptance
- No significant deviation from SM expectation

Staus $(ee, e\mu, \mu\mu)$



Displaced leptons: big picture

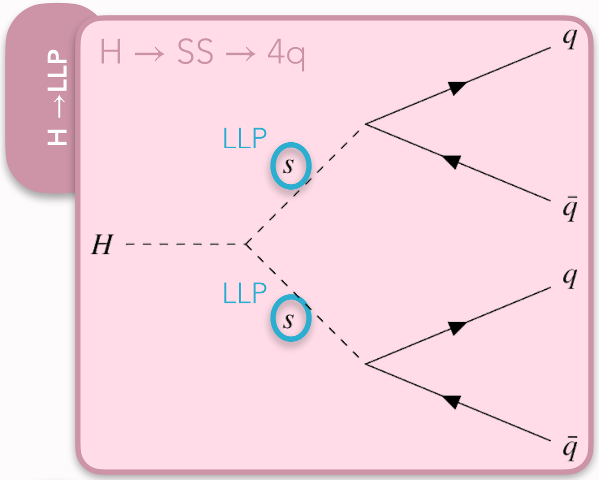


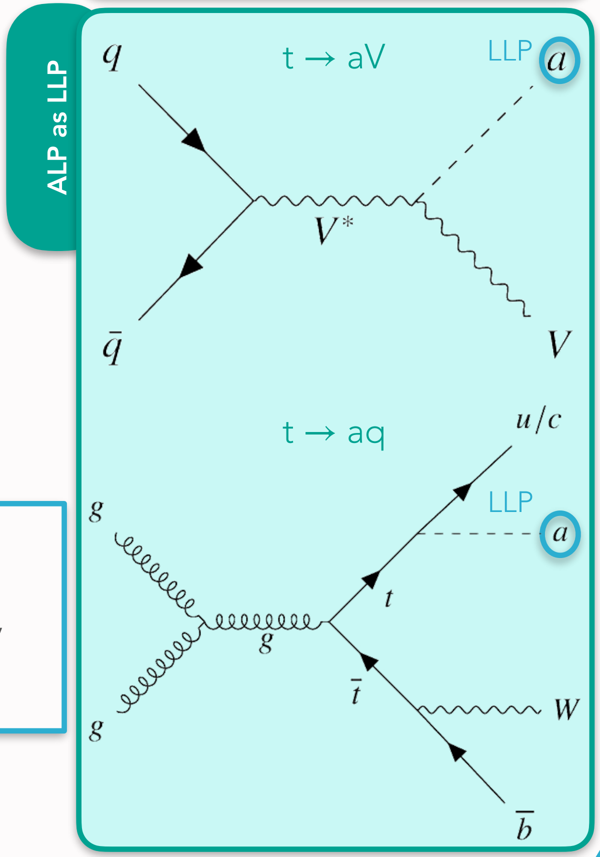
New results from re-interpretation of prompt Direct Staus search [ATL-PHYS-PUB-2024-007] and Displaced Leptons [ATLAS-CONF-2024-011] offer new sensitivity to staus

Light hadronic LLPs using displaced vertices

- **Goal:** Search for BSM neutral LLPs decaying hadronically in the inner detector
  - Targeted masses below 55 GeV
  - Hadronic jets displaced from LLP with $c\tau \sim \mathcal{O}(1)$mm - $\mathcal{O}(1)$m
- **Physics targeted:**
  - Exotic decays of Higgs boson to pairs of long-lived particles
  - Axion-like-particles (ALPs) as LLPs produced with SM vector bosons
- Search channels:
  - VBF region: dedicated triggers for jets consistent with VBF
  - $1l$, $2l$ regions: single and dilepton triggers
- Method overview:
  - Reconstruct DVs from standard and LRT tracks
  - Per-jet BDT to find jets with displaced tracks
  - Trained on $t\bar{t}$, W+jets, Z + jets + signal
- First ATLAS result to make use of updated LRT!

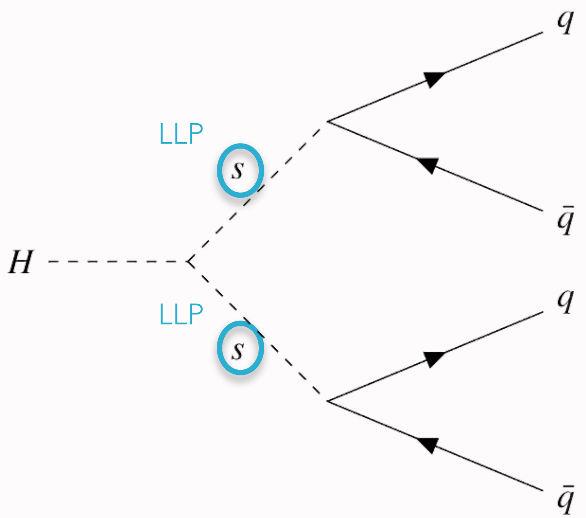
Extension of [**JHEP 11 (2021) 229**] VH4b analysis with new displaced jet BDT & single DV SR



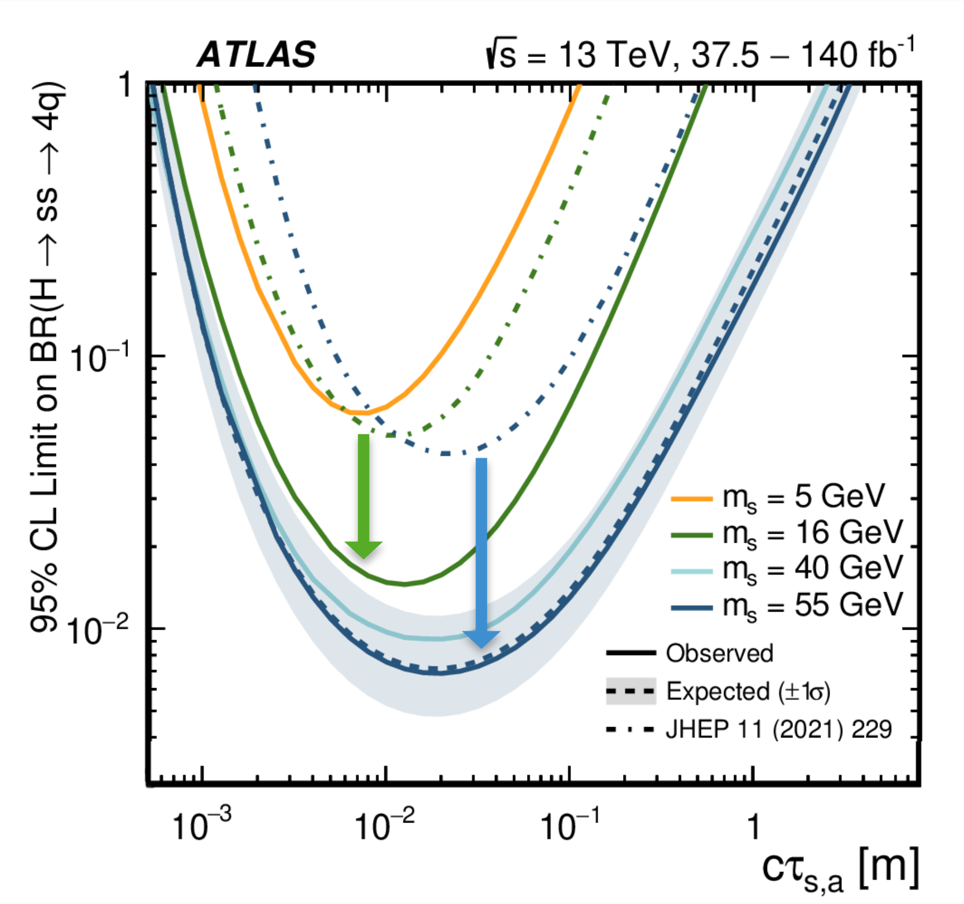


Light hadronic LLPs using displaced vertices: results

- No significant deviation from SM expectation
- New improved upper limits set for H → LLP channel relative to the previous result [**EXOT-2018-57**]
- First ATLAS result to make use of updated LRT!

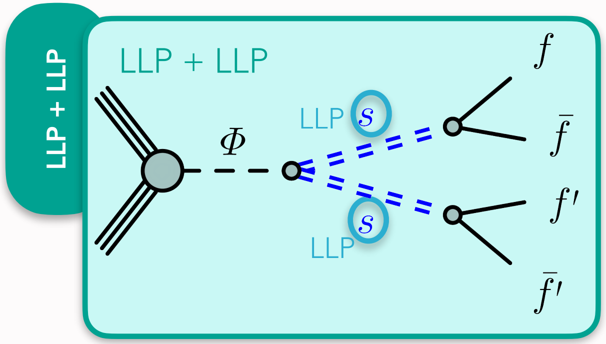


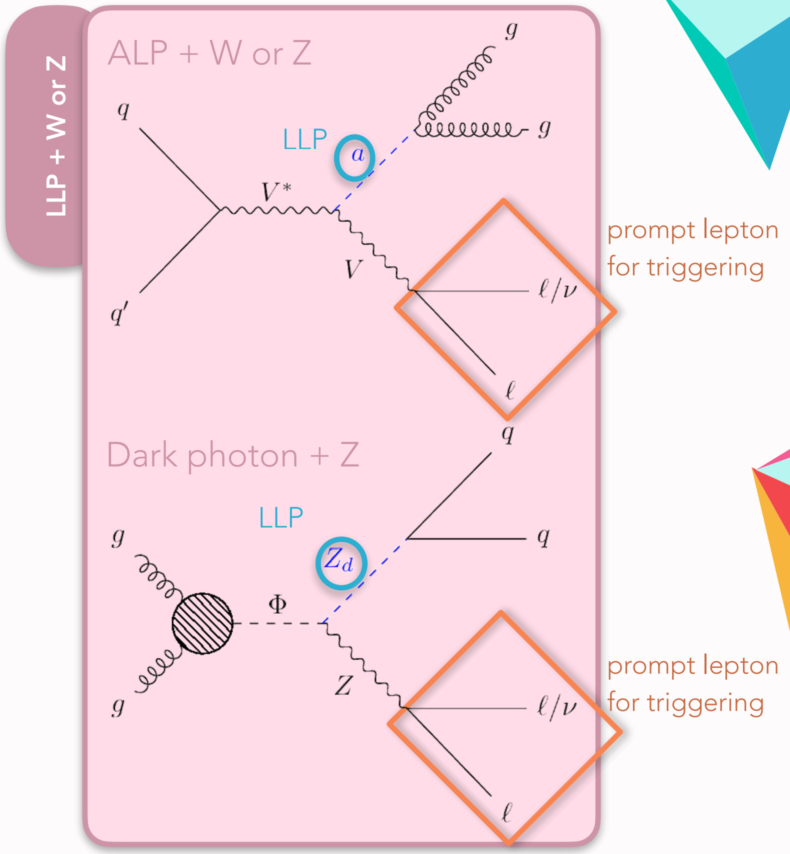
H → SS → 4q



Hadronic LLPs with associated leptons or jets

- **Goal:** Search for neutral BSM LLPs decaying hadronically
  - Observe energy deposits in HCAL
  - No tracks in the inner detector from neutral LLPs
  - $c\tau$ for LLP ranges from $\mathcal{O}(1)$cm - $\mathcal{O}(10)$m
- **Unique jet distribution**:
  - Expect LLP to decay to jets with low energy fraction in the EM calorimeter due to their displacement
  - LLPs decaying within the calorimeter system produce jets that are typically discarded by jet cleaning due to unusual energy distributions
  - *Exploit calorimeter energy ratio*
- **Channels:**
  - Pair-produced LLPs
    - Selected by one displaced jet, and two resolved jets
  - LLP is produced in association with W or Z bosons that decay leptonically
    - Use high-efficiency lepton triggers
    - Search for axion-like particles (ALPs)





Extension of past analysis [**JHEP 06 (2022) 005**] looking for pair-produced LLPs with additional prompt lepton tagging

Hadronic LLPs with associated leptons or jets: CalRatio jets

- If an LLP decays after the first EM calorimeter layer, then the ratio of energy deposited in the HCAL to ECAL will be greater than a typical jet
- CalRatio triggers are used specifically to collect these displaced jets

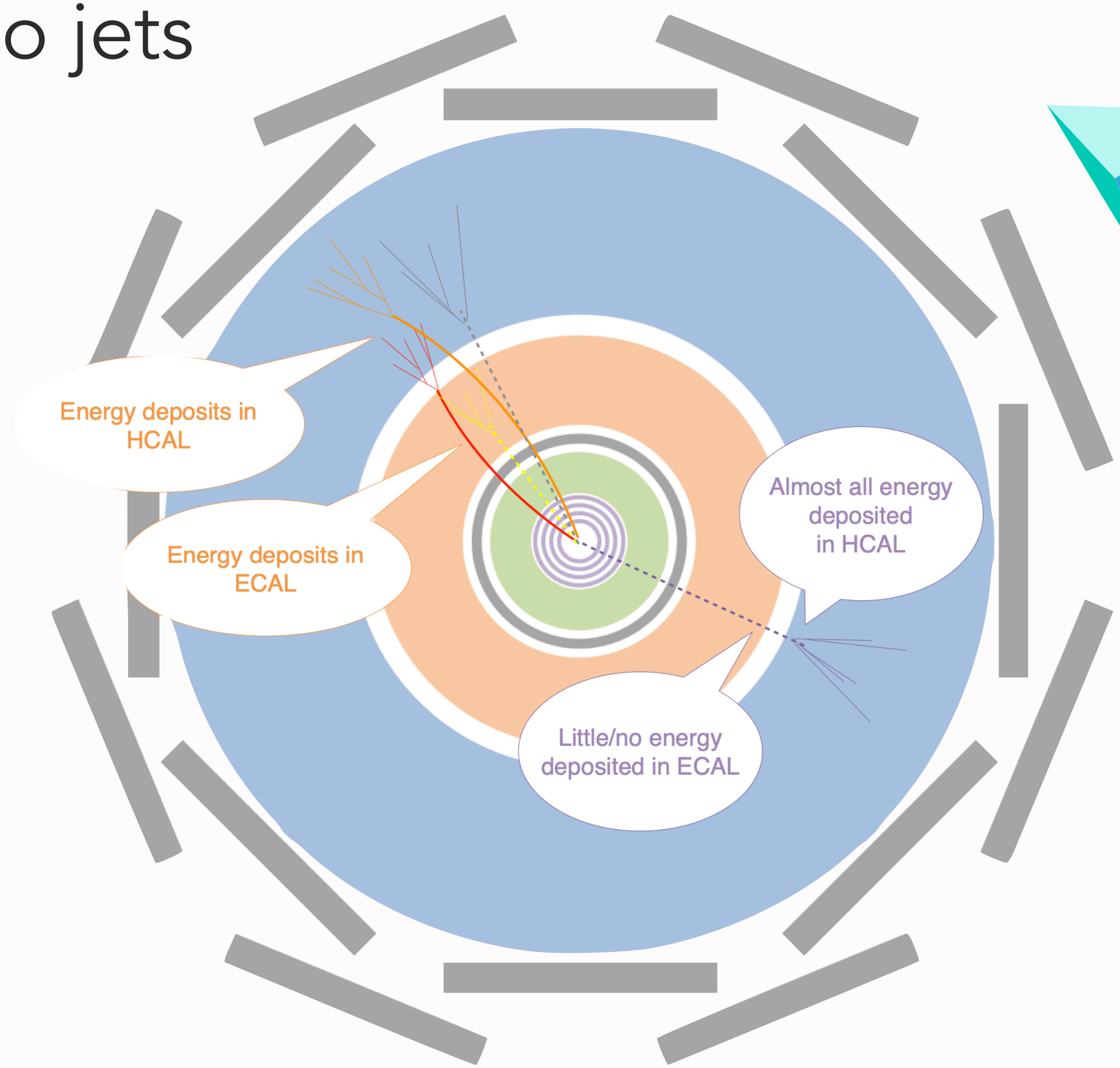
$$\text{CalRatio} \equiv \log_{10}\left(\frac{E_{HCAL}}{E_{ECAL}}\right)$$

SM Jets:
- 30% - 40% energy in ECAL
- 60% - 70% energy in HCAL

-1 < CalRatio < 0

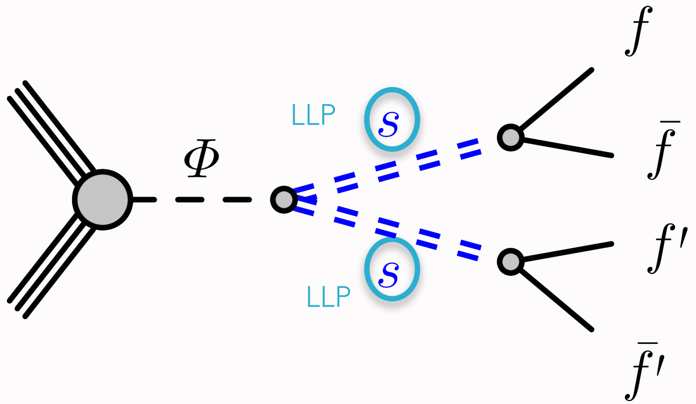
LLP → Jets:
- Late decays, less opportunity to deposit energy in ECAL
- Neutral LLP won't interact with ECAL before decay

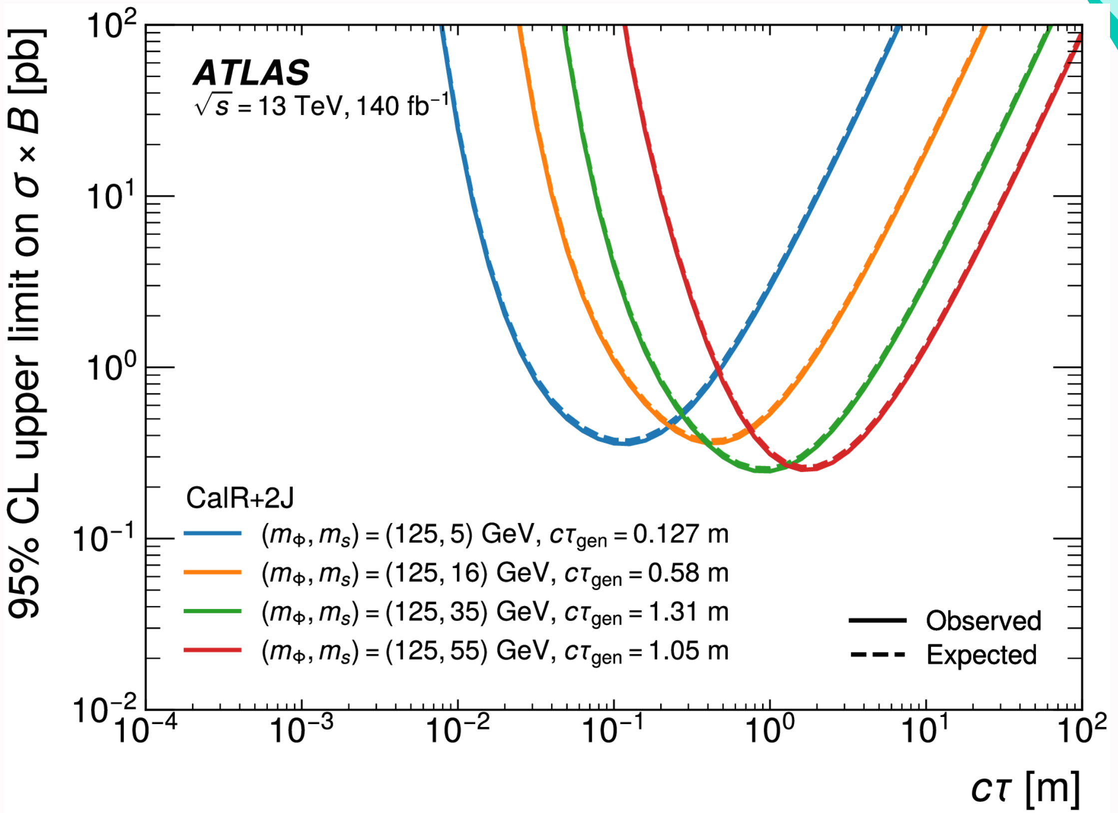
CalRatio > 1



Hadronic LLPs with associated leptons or jets: results

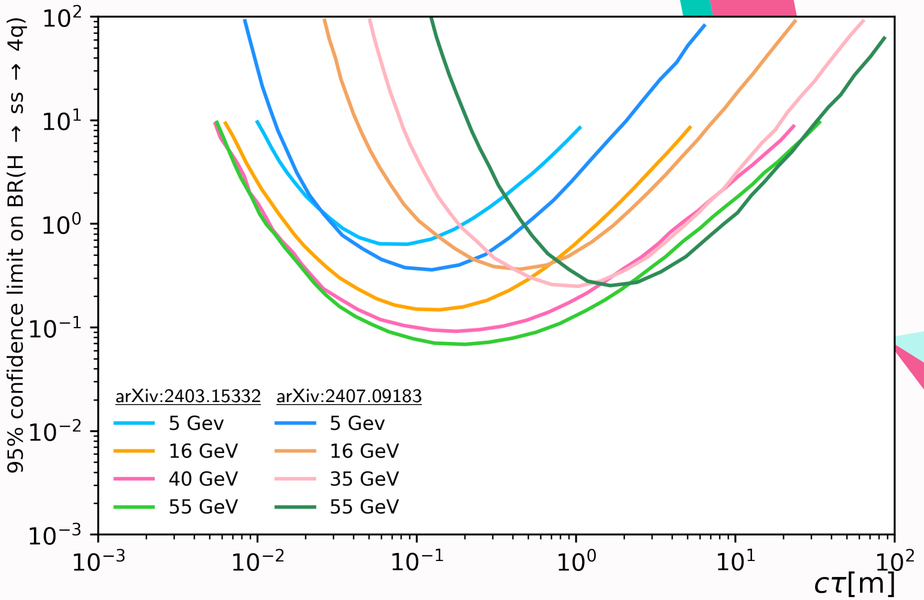
- No significant deviation from SM expectation
- New or improved upper limits set in each channel
- Complimentary results, expanding the mass ranges of the light hadronic LLP with displaced vertices search

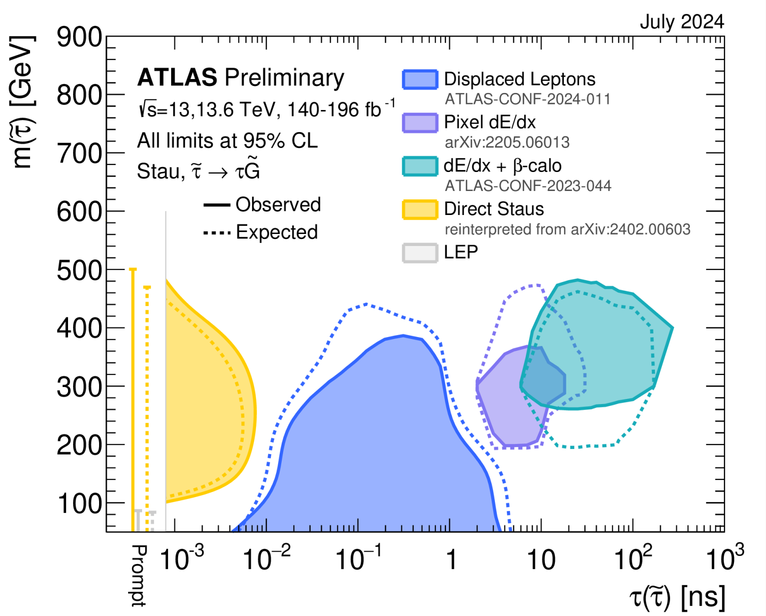




Conclusions

- LLPs are a promising method to search for BSM but challenging
- ATLAS is optimized for reconstructing tracks back to the pp collision point
  - New algorithms for prompt and displaced particle differentiation
  - New triggers developed to save events with LLPs present
  - Searches using many novel methods to differentiate prompt and displaced energy deposits
- Looking forward:
  - Continue the LLP search program during run 3
  - In the upcoming HL-LHC era we planning to collect 10x the data (3000 fb^{-1}) increasing cross-section sensitivity
- Major detector upgrades to tolerate increased collisions
  - Tracker (ITk) and trigger systems upgrades, will allow for improving sensitivity to these signatures further
  - Snowmass white paper for details [**ATL-PHYS-PUB-2022-018**]



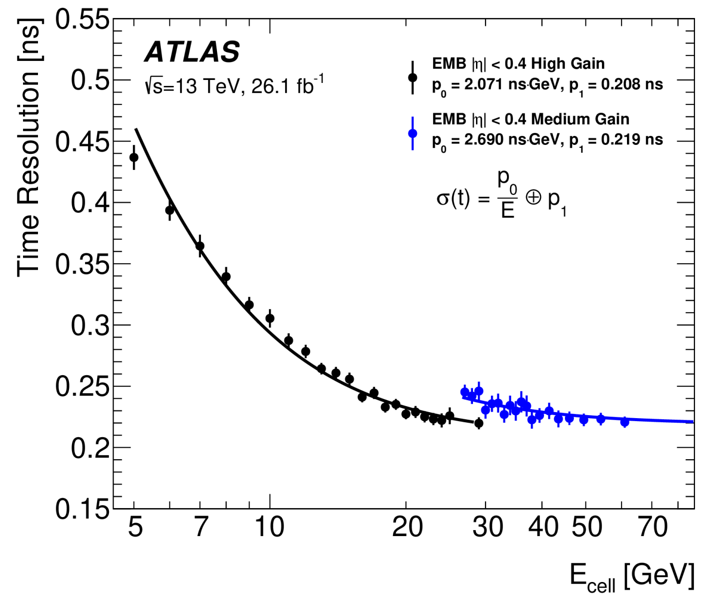


Backup

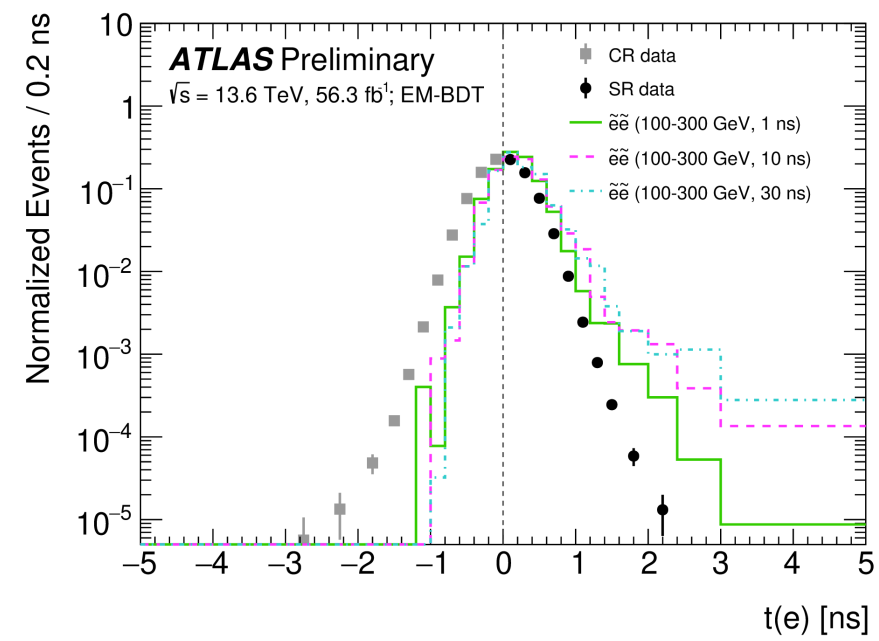
Displaced leptons: backup

- Liquid Argon (LAr) electromagnetic calorimeter precision timing used to target LLPs
  - $\mathcal{O}(200)$ ps resolution for energetic electrons & photons
  - Enough to resolve "late" e and γ from LLP decays relative to prompt SM backgrounds
- BDT uses timing symmetry of prompt background for prediction in the search region
  - According to time of flight (ToF_{cal}) in the calorimeter
  - Trained on data with $ToF_{cal} < 0$ and signal with $ToF_{cal} > 0$
  - Predict $ToF_{cal} > 0$
  - BDT validated against control sample events with SM W and Z bosons

Time resolution obtained with LAr EM calorimeter as a function of E_{cell}, the energy in the second layer cell with the largest energy deposit
Figure from **SUSY-2019-14**

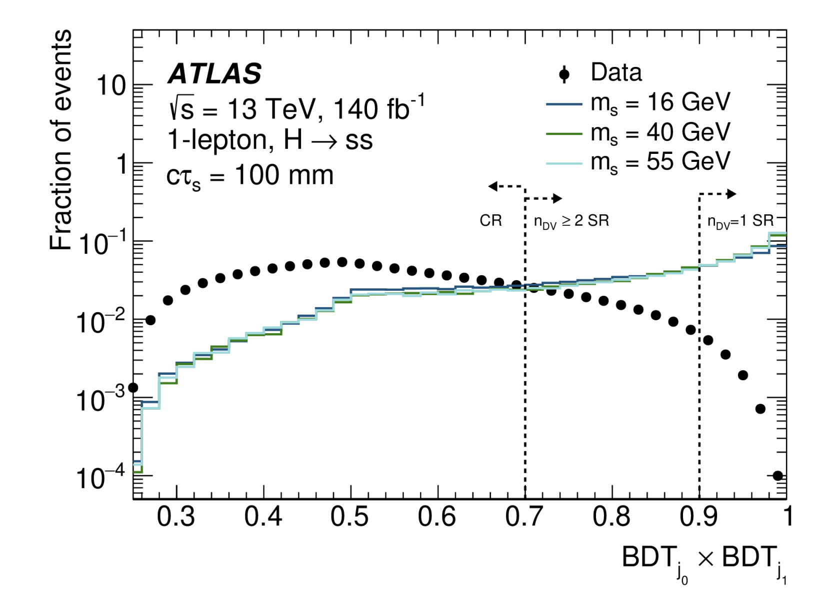


Representative data and signal model distribution for LAr timing distribution. LAr timing is calibrated to zero for promptly produced particles. Negative times represent the background region, and positive times represent the signal region.



Light hadronic LLPs using displaced vertices: backup

- Displaced Jet BDT
  - To distinguish displaced jets from prompt jets
- 5 Ovserables used as input to train the per-jet BDT using XGBoost Framework
  - Charged hadron fraction (CHF)
    - $\mathrm{CHF} = \frac{(\sum_{\text{prompt tracks}} \vec{p}_T)}{p_T^{\text{jet}}}$ for prompt track with $d_0 < 0.5\text{mm}$
    - A displaced jet will have fewer prompt tracks associated to the jet, and a small CHF
  - Displaced charged hadron fraction (dCHF)
    - $\mathrm{dCHF} = \frac{(\sum_{\text{displaced tracks}} \vec{p}_T)}{p_T^{\text{jet}}}$ for diplaced track with $d_0 > 0.5\text{mm}$
    - A displaced jet will have more displaced tracks associated to the jet, and a larger dCHF
  - $\alpha_{\max}$
    - per primary vertex define - $\alpha_i = \frac{(\sum_{\text{tracks matched to PV}_i} \vec{p}_T)}{\sum_{\text{tracks in jet}} p_T}$, then discriminate on $\max\{\alpha_i\}$
    - A prompt jet originating from PV_0 will have a large α_0, a pileup jet originating from PV_i will have a large α_i
    - A displaced jet will have fewer tracks matched to any PV, and therefore have a small $\alpha_{\max}$
  - Impact parameter significance (IPSIG)
    - $\mathrm{IPSIG} = \mathrm{median}[\log_{10}(\frac{d_0^{\text{track}}}{\sigma(d_0^{\text{track}})})]$
    - Prompt tracks have $d_0 \approx \sigma(d_0)$, so prompt jet IPSIG = 0. Well-measured displaced tracks have $d_0 \gg \sigma(d_0)$, so IPSIG > 0 for displaced tracks
  - $d_0^{\max}$
    - Maximum d_0 of all tracks in the jet
    - a displaced jet will have more displaced tracks with larger d_0 , and larger IPSIG and larger $d_0^{\max}$



Product of BDT scores of 2 jets in an event with large BDT scores.