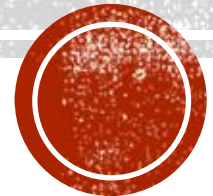
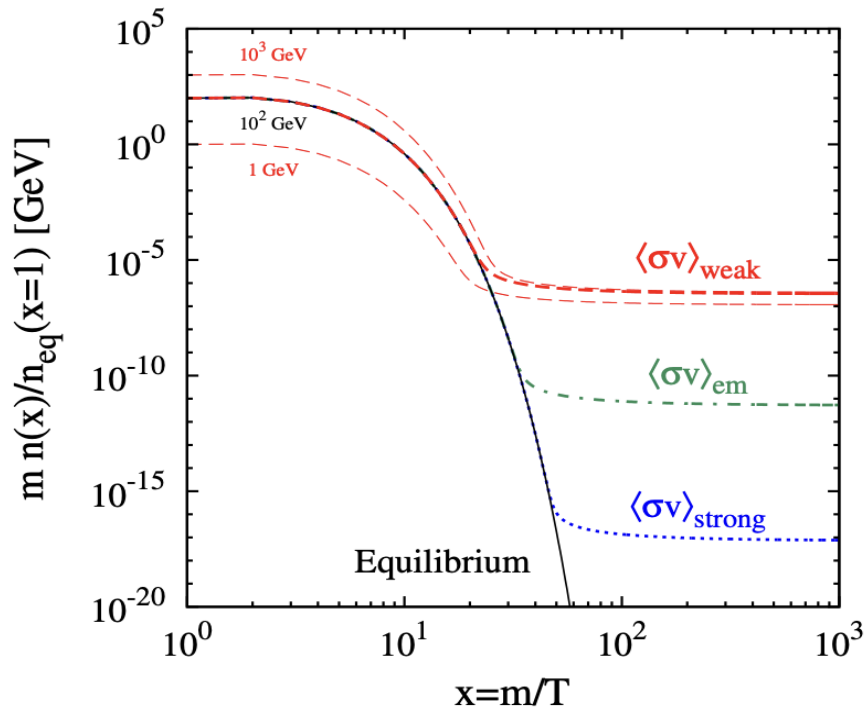


PROBING FREEZE-IN DARK MATTER AT THE LHC VIA MACHINE LEARNING

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TRADITIONAL DARK MATTER SEARCHES



■ Freeze-Out Dark Matter (assumes thermal equilibrium)

1. **Equilibrium** — production \rightleftharpoons annihilation
2. **Cooling** — production drops, annihilation dominates
3. **Freeze-out** — annihilation stops, relic density locked in

[2] Gary Steigman, Basudeb Dasgupta, and John F. Beacom. Precise relic wimp abundance and its impact on searches for dark matter annihilation. *Physical Review D*, 86(2), 2012.

No evidence so far and constraints are strong. Could DM be hiding in rare corners of the phase space?



MOTIVATION: BEYOND WIMPS

- Feebly Interacting DM has been a topic of interest
 - Slow production, no annihilation -> No thermal equilibrium
 - $\Gamma < H$, universe expands faster than DM could annihilate
 - Relic density slowly built up

The purpose of this talk is to consider a well motivated FIDM model and how to probe it at the LHC.



OUR MODEL: SPIN-2 MEDIATED PRODUCTION

- Heavy **spin-2 mediators** in many BSM theories (e.g., extra dimensions, Randall–Sundrum scenarios)
- Natural starting point — now repurposed as a **DM portal**

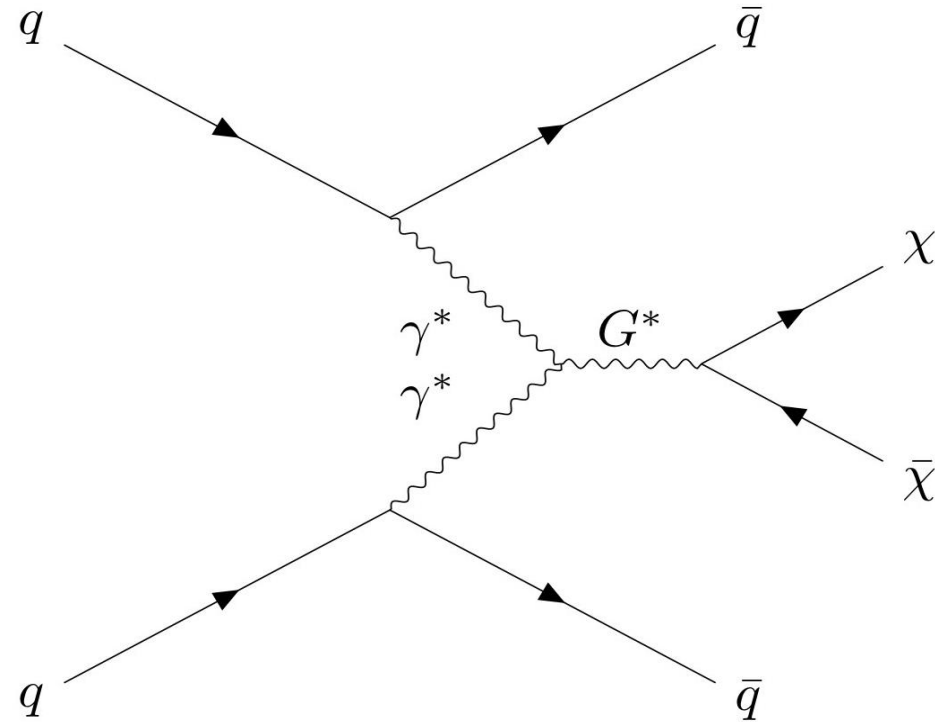
- *Lagrangian:*
$$\mathcal{L}_{\text{int}} = \frac{1}{\Lambda_\gamma} G^{\mu\nu} T_{\mu\nu}^{(\gamma)} + \frac{1}{\Lambda_\chi} G^{\mu\nu} T_{\mu\nu}^{(\chi)}$$

- Λ absorbs both coupling strength and EFT cutoff
- **Photons only:** minimal scenario that evades existing bounds on fermion searches (di-electron, di-muon)



OUR MODEL: PROBING AT THE LHC

- Existing DM searches fail in our model - No gluons/quarks coupling:
 - Mono-jet ($q\bar{q} \rightarrow \mathbf{G} \rightarrow \text{DM DM} + \text{j}$)**
 - Diphoton resonance searches**
- VBF** = rare but distinctive signature



But first: what parameter space is cosmologically viable?



PART 1: COSMOLOGICAL CONSTRAINTS



FREEZE-IN CONSTRAINT

- Freeze-in requirement: no equilibration

$$\frac{C(T)}{H(T) n_{\chi}^{\text{eq}}(T)} \ll 1, \quad n_{\chi}^{\text{eq}}(T) \simeq \frac{\zeta(3)}{\pi^2} T^3$$

- Simplifications

1. Resonance: $\text{TR} \sim m_{\text{G}}$ (mediator thermally accessible \rightarrow on-mass-shell production)

2. Off-resonance: $\text{TR} \ll m_{\text{G}}$ (mediator too heavy \rightarrow virtual exchange only)

Both translate to lower bounds on Λ



RELIC DENSITY CONSTRAINT

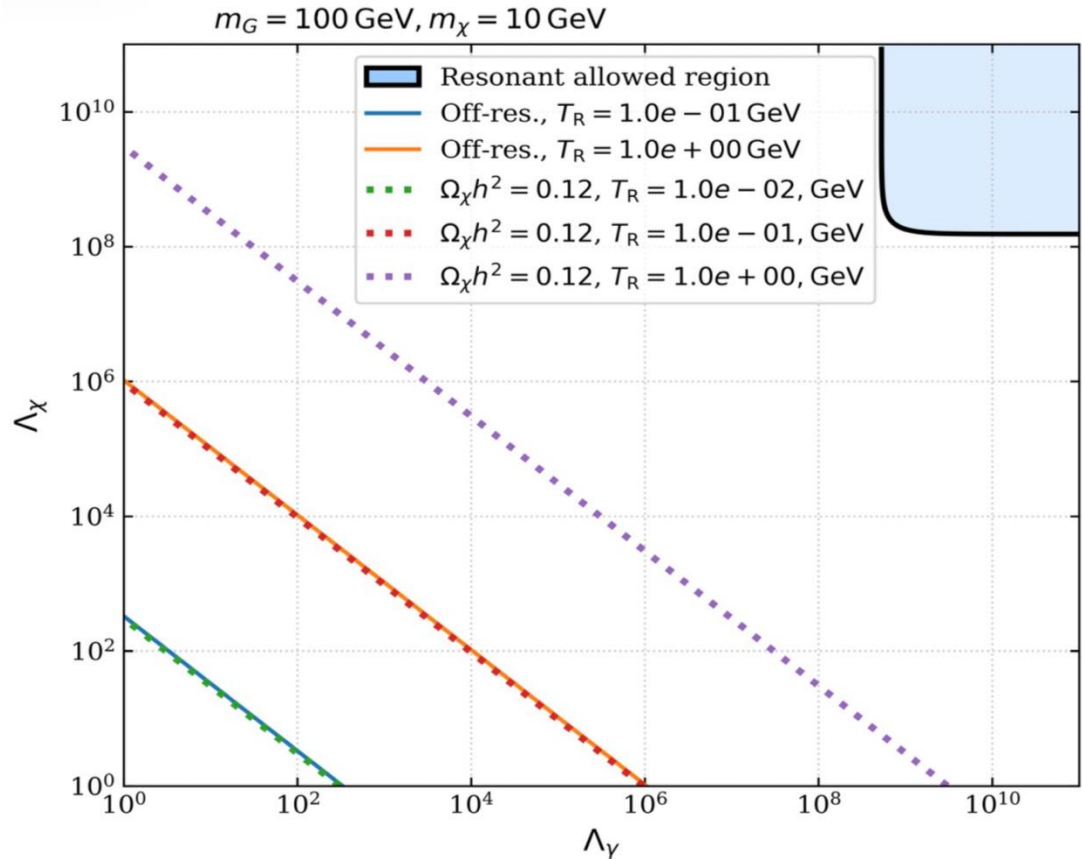
- Observed DM relic density is $\Omega_\chi h^2 = 0.12$
- Want our result to contribute less than 0.12
- Off-resonance assumption simplifies Boltzmann integral
- Lower bound on Λ

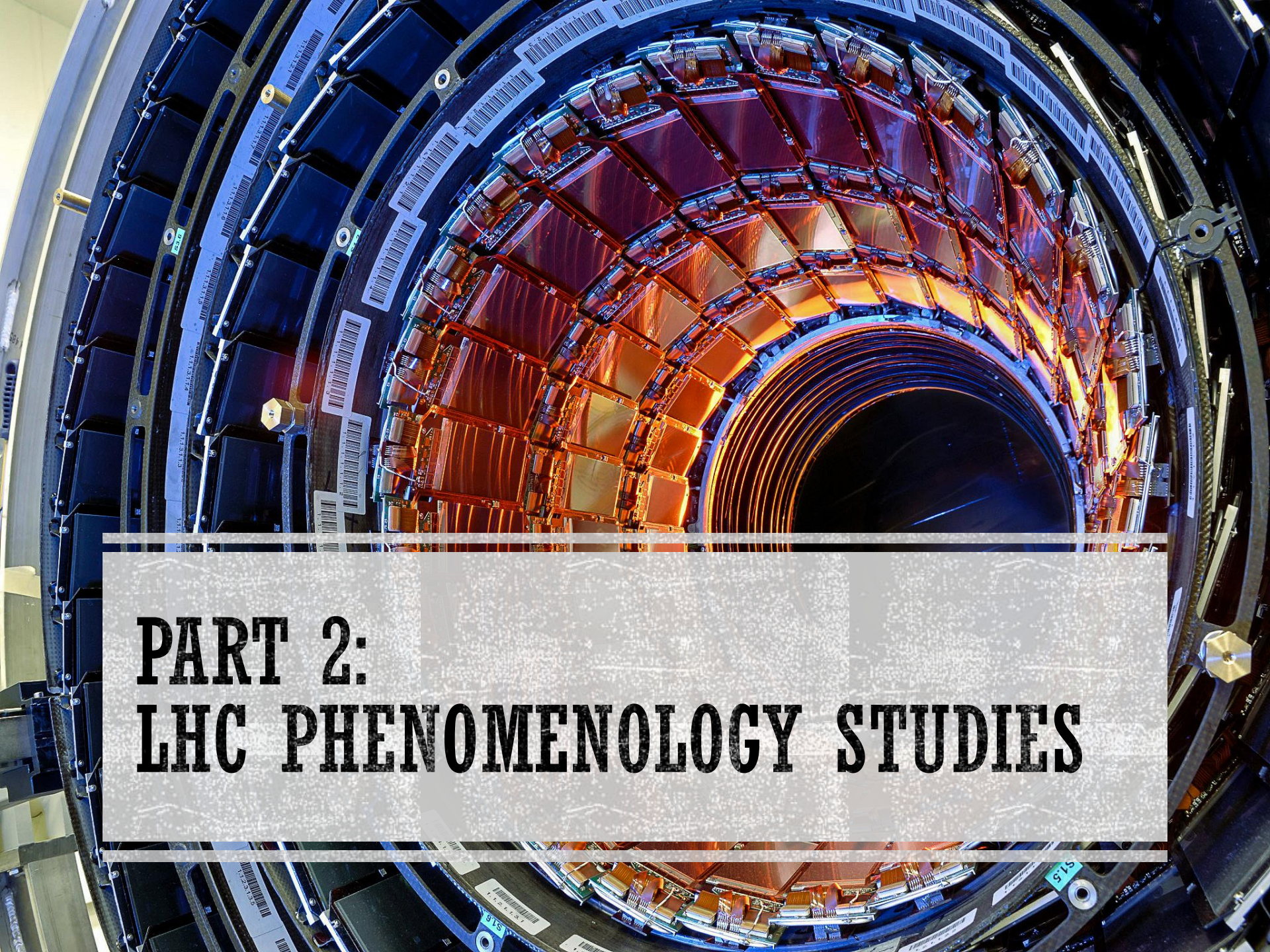
$$\Omega_\chi h^2 \simeq 2.75 \times 10^8 \left(\frac{m_\chi}{\text{GeV}} \right) Y_\chi \quad Y_\chi \simeq \kappa \frac{M_{\text{Pl}}}{g_*^{3/2}} \frac{T_R^7}{\Lambda_\gamma^2 \Lambda_\chi^2 m_G^4}$$



COSMOLOGICAL PARAMETER SPACE

- Feasible region = low T_R , off-resonance production
- Target for collider searches





PART 2: LHC PHENOMENOLOGY STUDIES

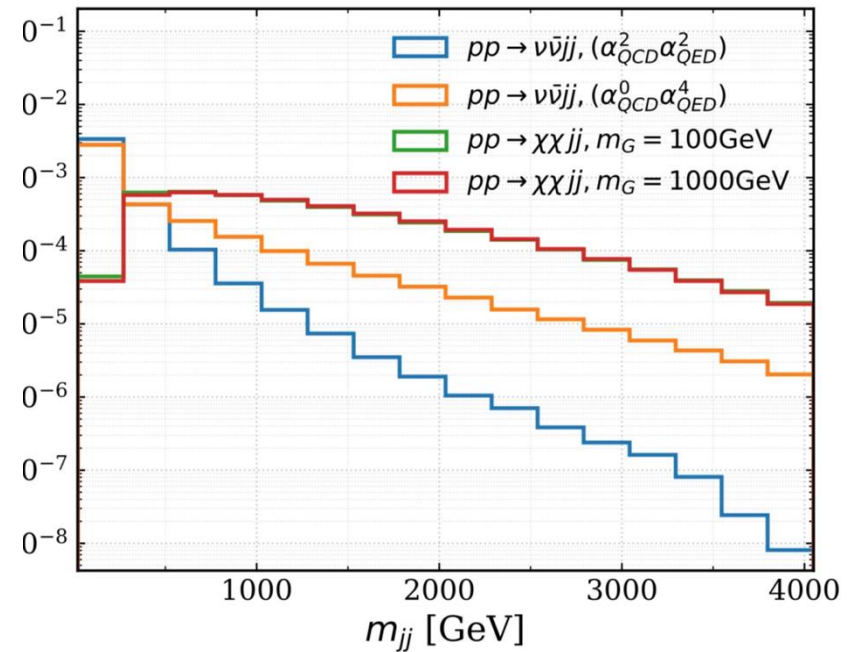
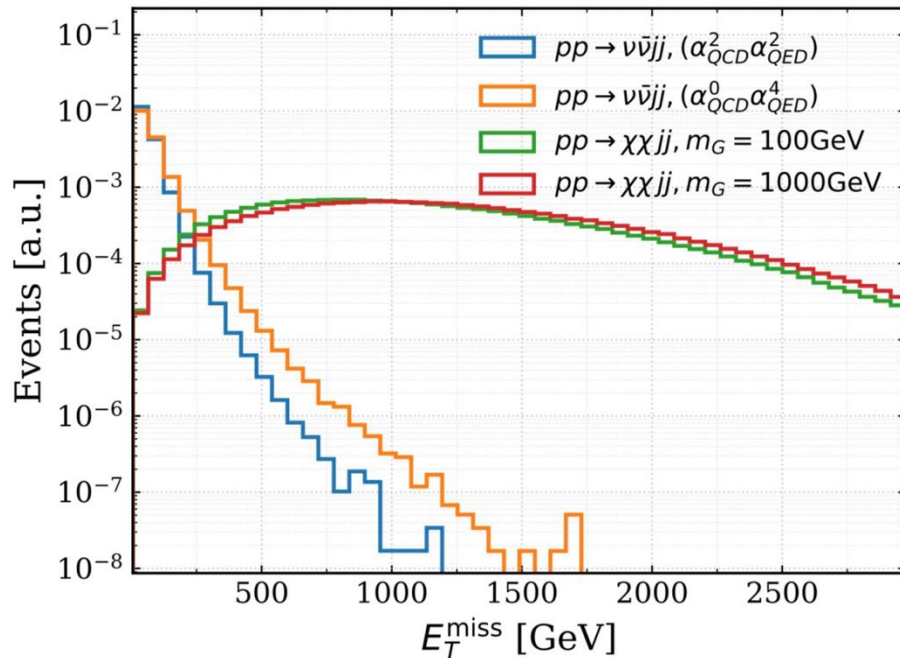
SIMULATION METHODOLOGY

- **Event Generation (MadGraph5)**
 - Signal: 1M events for each m_G mass, $m_{DM} = 10$ GeV, $m_G \in [50, 1000]$ GeV
 - Background: 10M SM events
- **Parton Shower & Hadronization:** Pythia 8 + MLM matching
- **Detector Simulation:** Delphes 3.4.1
- **HL-LHC Pileup**
 - ~ 140 simultaneous interactions per bunch crossing
 - Degrades lepton, jet, and b-tag reconstruction \rightarrow conservative efficiencies applied



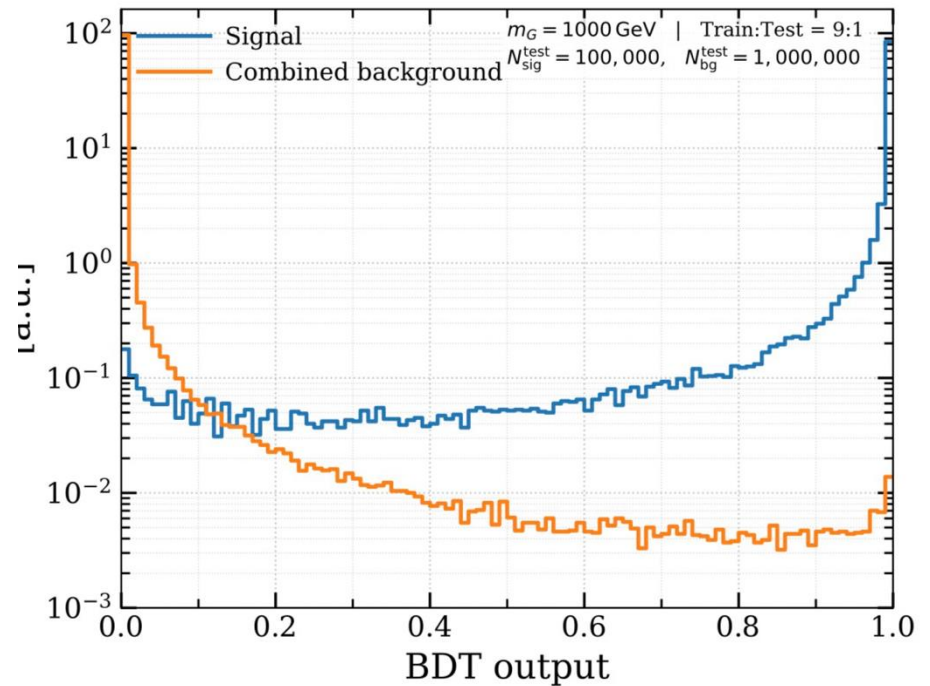
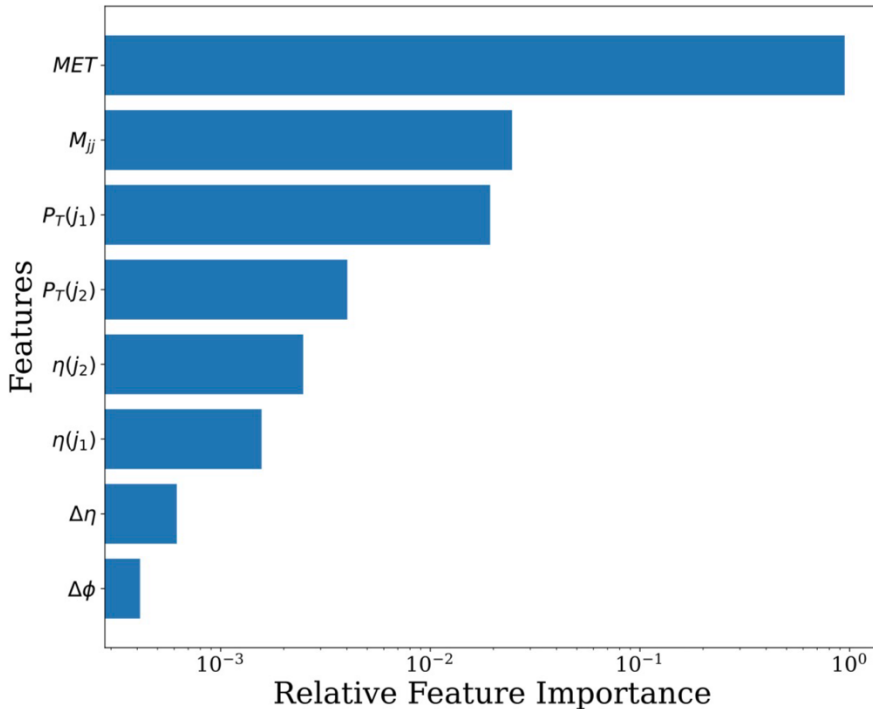
KINEMATIC FEATURES

- Signal: high m_{jj} , high MET
- Background: $pp \rightarrow \nu l \nu l + \text{jets}$ process



MACHINE LEARNING PERFORMANCE

- BDT using kinematic observables
- Use correlation to improve discrimination



HL-LHC SENSITIVITY

Profile Likelihood Fit

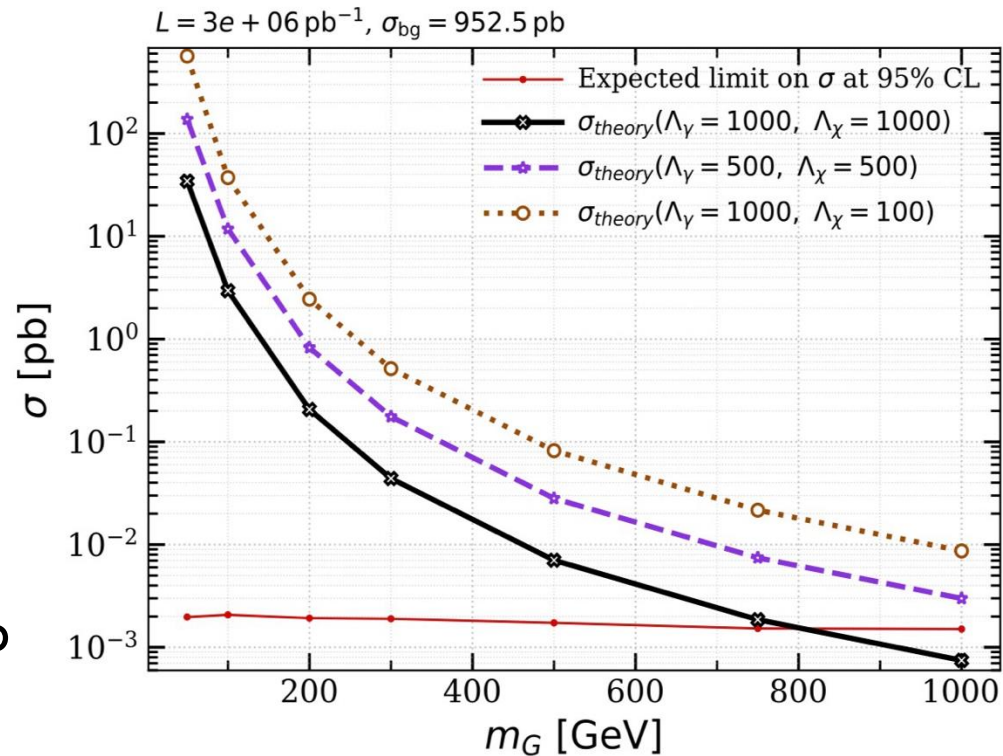
- Use full BDT shape on Poisson distribution

$$\mathcal{L}(\mu) = \prod_i \text{Poisson}(b_i | \mu s_i + b_i)$$

- Asimov (background-only) dataset → **expected 95% CL upper limits**

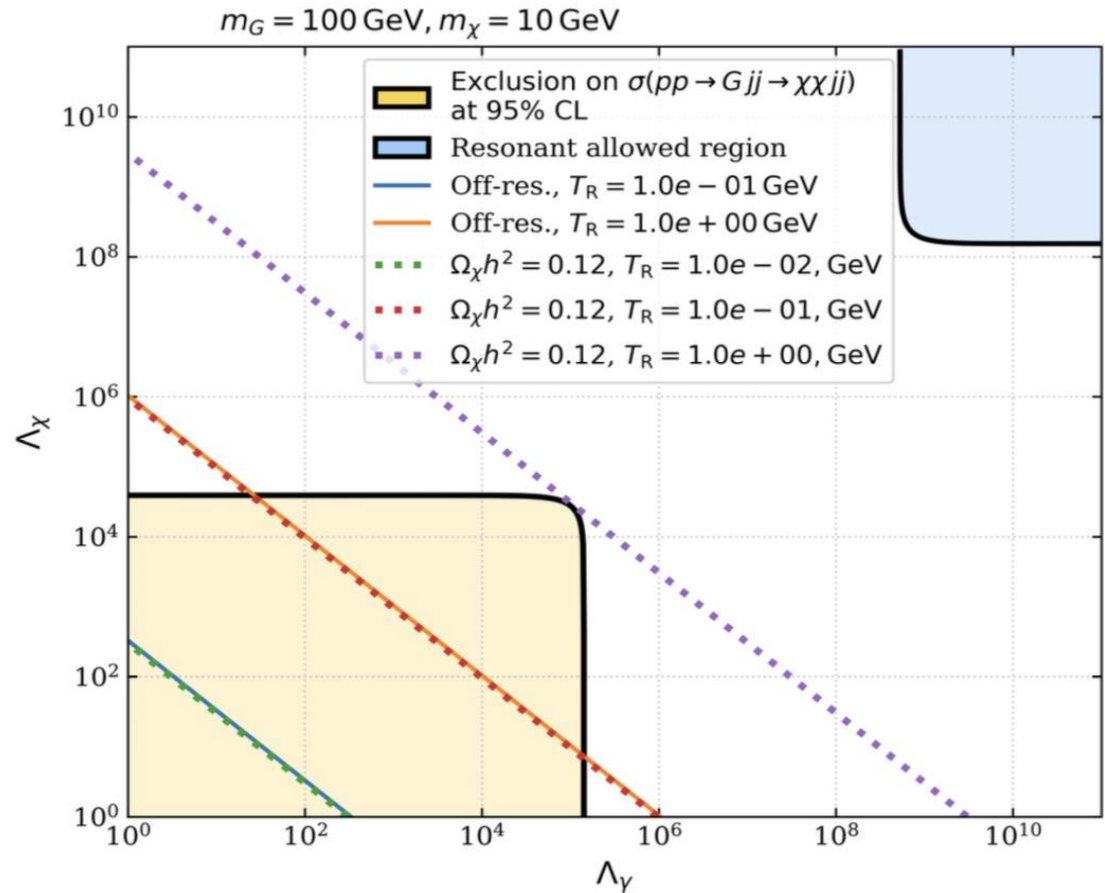
Result

- Reach cross section of $\sigma \sim 10^{-3}$ pb
- Probe mediator masses \sim TeV



COSMOLOGY VS COLLIDER

- Overlay constraints
- Partial overlap of viable + observable
- LHC probes freeze-in DM at MeV scale reheating temperature



CONCLUSION

- Freeze-in DM naturally evades traditional searches
- VBF + ML provides new sensitivity regime
- HL-LHC can probe a large section of cosmology-consistent parameter space
- Future Studies:
 - Extend beyond photon-only portal
 - Path toward ATLAS/CMS implementation



THANK YOU!

