Time-dependent Signals of New Physics at the LHC

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Motivation

Background

- The LHC searches for BSM physics via missing energy, resonance, and other channels. Current analyses assume signal cross sections are time-invariant.
- New physics coupled to ultralight dark matter (DM) can produce time-dependent signal rates — a powerful discriminator orthogonal to kinematics.

Ultralight Dark Matter

- Ultralight bosonic DM ($m^{DM} \leq 0.1$ eV) has large phase-space occupancy and behaves as a classical oscillating background field.
- Oscillation period $T = 2\pi/m^{DM} \approx 4$ s $\times$ (10^{-15} eV / m^{DM}).
- de Broglie wavelength is macroscopic: $\lambda \approx 10^9$ km $\times$ (10^{-15} eV / m^{DM}).
- Examples: QCD axion, axion-like particles, dark photon, dilaton.

Why the LHC?

- If SM couples to DM only via a TeV-scale mediator, low-energy experiments lose sensitivity → the energy frontier is the natural place to search.
- **Timing information can improve sensitivity by up to ~2×.**

Model & Signal Processes

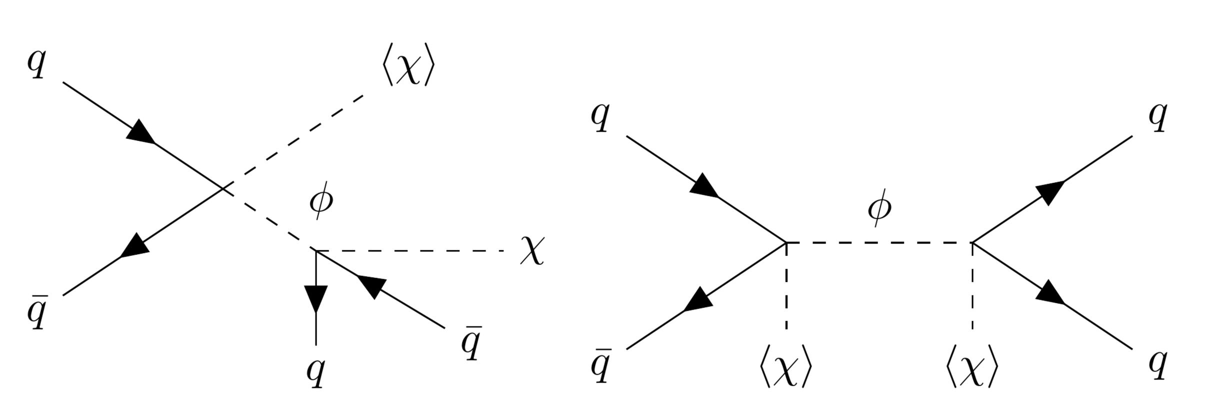
- Consider ultralight DM (χ) and a dark sector scalar (φ) coupling to SM quarks via:

$$\mathcal{L} \supset \frac{1}{\Lambda^2}\,\chi\,\partial_\mu\phi\,\bar{q}\,\gamma^\mu q$$

- The classical DM field oscillates as:

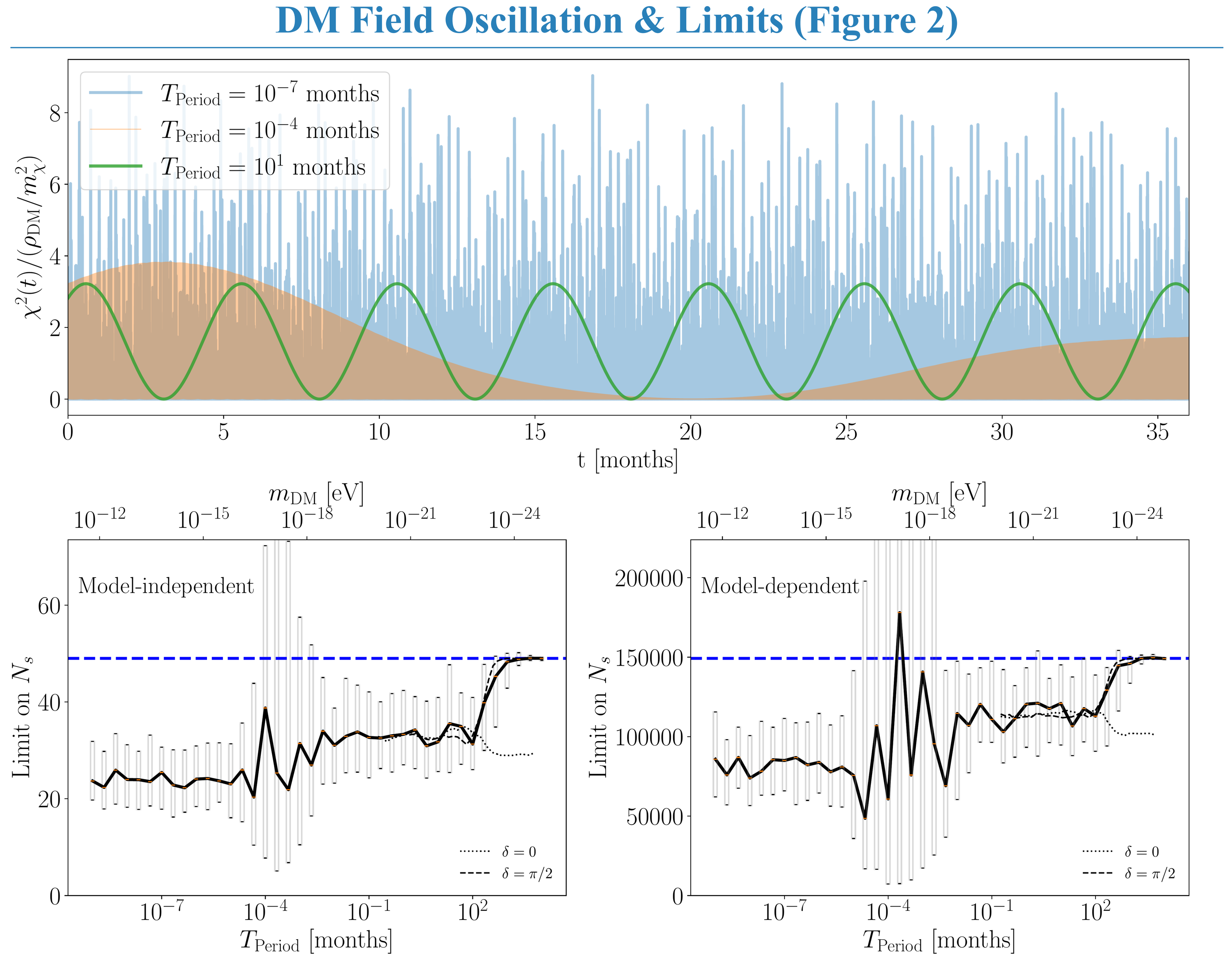
$$\chi(t) = \frac{\sqrt{f_{\rm DM}\rho_{\rm DM}}}{m_\chi}\sum_{j=1}^{N}\alpha_j\sqrt{f(v_j)\Delta v}\,\sin\left[m_\chi\left(1+\frac{v_j^2}{2}\right)t+\delta_j\right]$$

Feynman Diagrams (Figure 1)



- Left: Missing energy ($q\bar{q} \to \varphi + \chi$) with $P_s(t) \propto \chi^2(t)$.
- Right: Dijet resonance ($q\bar{q} \to \varphi \to qq$) with $P_s(t) \propto \chi^4(t)$.
- Time-independent channel ($\langle\chi\rangle \to \chi$) is phase-space suppressed for small m_χ.

DM Field Oscillation & Limits (Figure 2)



Time-dependent Missing Momentum

ATLAS Mono-jet Reinterpretation

- ATLAS jet + E_T^{miss} search: 139 fb^{-1}, ~36 months, $\sqrt{s}$ = 13 TeV.
- Highest E_T^{miss} bin (> 1200 GeV): N^b = 223 ± 19 expected, 207 observed.
- Signal rate $P_s(t) \propto \chi(t)^2$; background is uniform in time.

Extended Likelihood

$$\mathcal{L}(N_s, r) = \left[\frac{\mu^n e^{-\mu}}{n!}\prod_i f(t_i)\right] \times e^{-(r-1)^2/2\sigma_r^2}$$

- Profiled over 100 random DM field realizations. Phase δ is critical for long $T_{\rm Period}$.

Time-dependent Resonances

Known Oscillation: Likelihood-Ratio Weighting

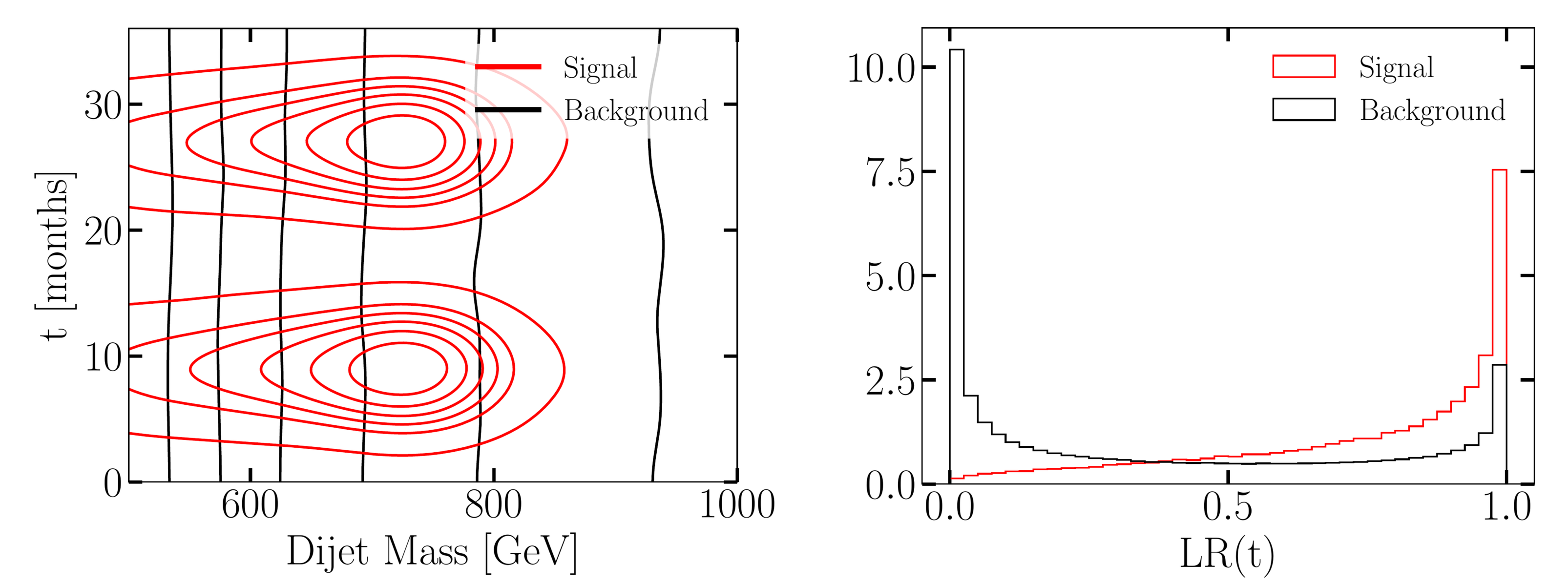
- Dijet resonance $\varphi \to jj$ at m_φ = 750 GeV (MadGraph5 + Pythia + Delphes).
- Time component of the likelihood ratio factorizes:

$$P_s(t) \propto \chi(t)^2\,, \quad {\rm LR}(t) = \frac{p_s(t)}{p_b}$$

- Weighting events by LR(t) suppresses background relative to signal in the mass distribution.

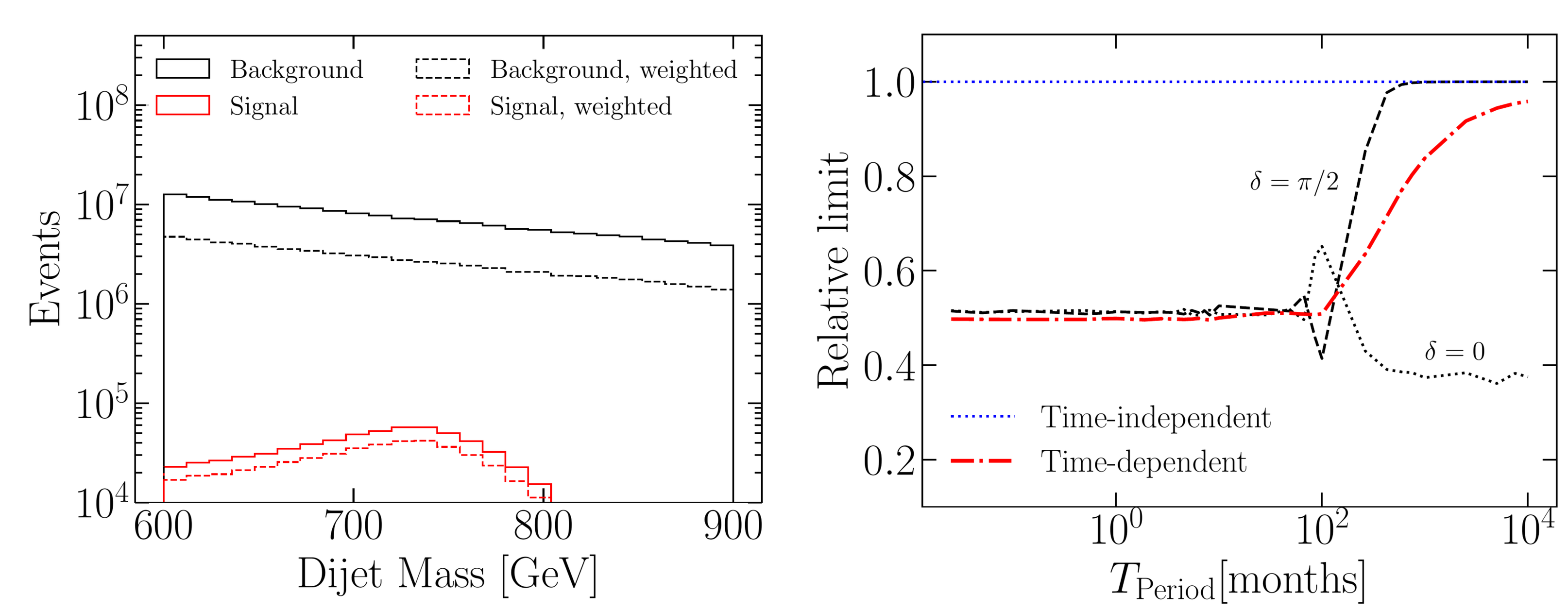
A. Known Oscillation

Figures 3: Mass–Time & LR Distributions



- Left: Signal & background contours in (m_{jj}, t) plane.
- Right: LR distributions showing expected separation.

Figures 4: LR-Weighted Mass & Limits



- Left: Mass distribution before (solid) and after (dashed) LR weighting.
- Right: ~50% improvement for $T_{\rm Period} \in$ [0.01, 1] month.

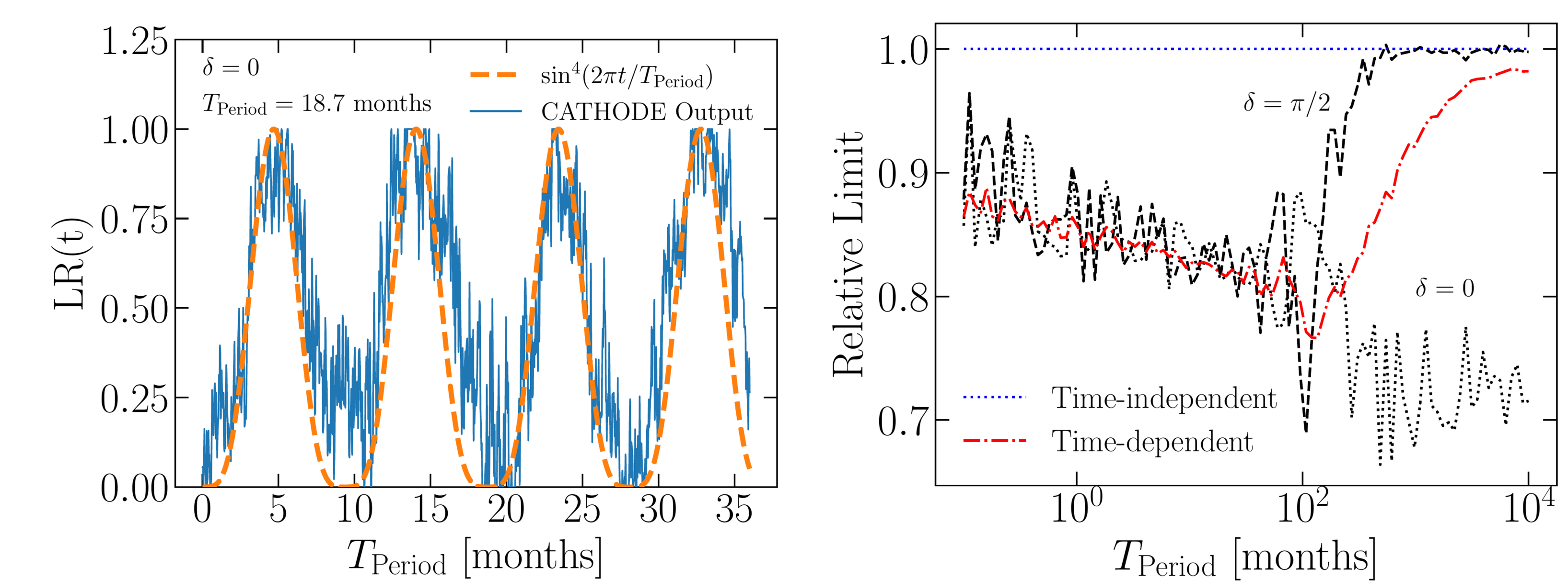
B. Learned Oscillation (CATHODE)

- When the oscillation period is unknown, use CATHODE anomaly detection to learn time dependence directly from data.
- Auxiliary Fourier feature bank (100 periods × 4 harmonics):

$$\mathbf{x}_t = \left[\frac{t}{t_{\rm exp}},\ \left\{\sin\left(2\pi h\frac{t}{T_j}\right),\ \cos\left(2\pi h\frac{t}{T_j}\right)\right\}_{j=1,\ldots,100}^{h=1,\ldots,4}\right]$$

- Motivated by $\sin^4(x) = [3 - 4\cos(2x) + \cos(4x)] / 4$.
- CATHODE learns an LR-like score without pre-specifying target period or phase.

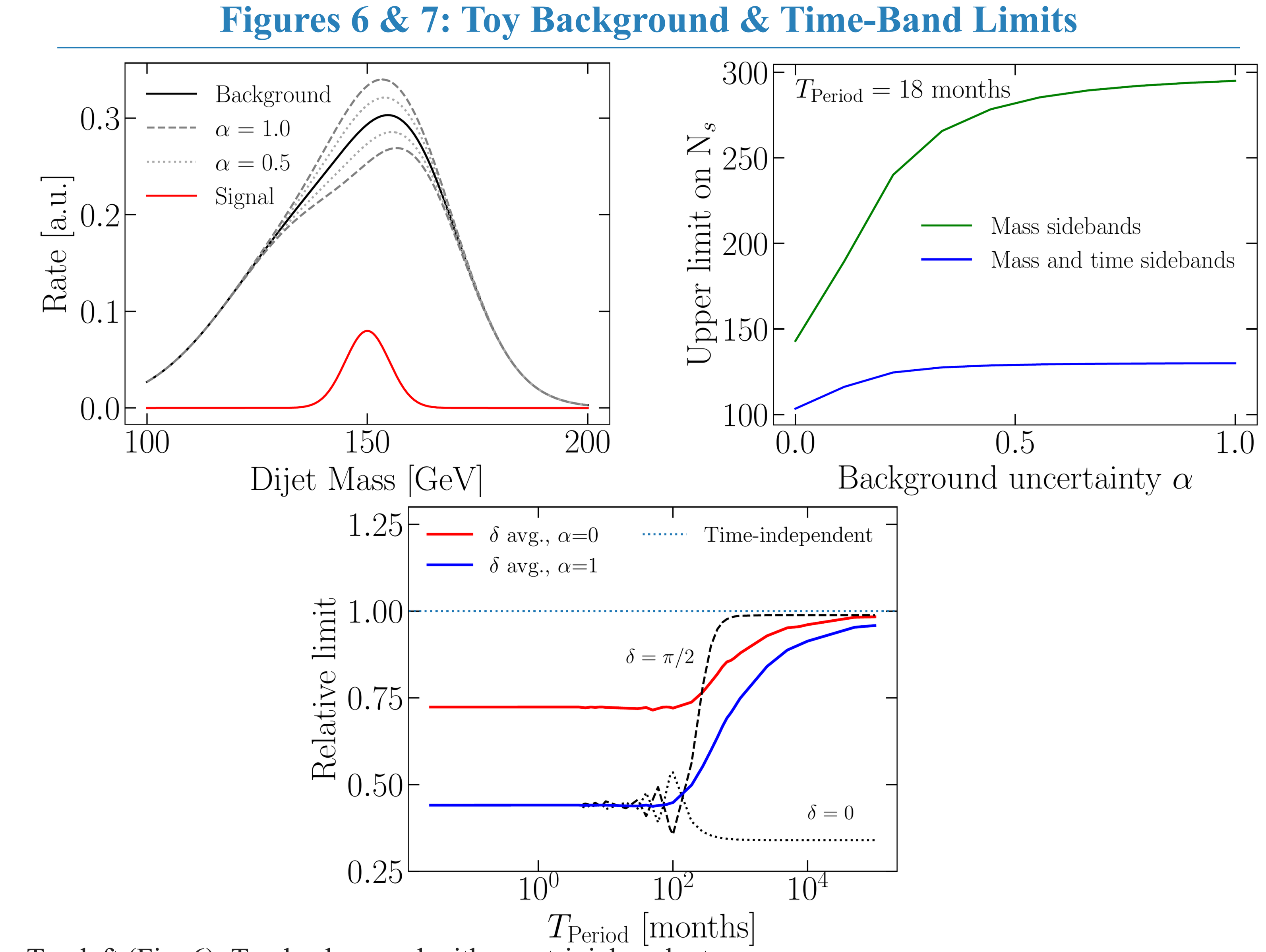
Figures 5: CATHODE Output & Limits



- Left: Learned time score (blue) captures the true modulation (dashed orange).
- Right: Relative limit vs $T_{\rm Period}$ — bounds are stronger than time-independent analysis.

C. Sidebands in Time

Figures 6 & 7: Toy Background & Time-Band Limits



- Top left (Fig. 6): Toy background with non-trivial peak at resonance mass.
- Top right (Fig. 7 top): Time sidebands maintain sensitivity even with large background uncertainty (α = 1)
- Bottom (Fig. 7 bottom): Limit scan over background uncertainty α and signal fraction.

Discussion & Conclusions

Systematics

- Time-dependent systematics (luminosity decay, beam–beam effects, dust, ground motion) are generally non-periodic → distinguishable from signal in Fourier space.

Summary

- Time-dependent signals provide a discriminator orthogonal to kinematics.
- ATLAS mono-jet: limits improve up to ~2× with timing information.
- Dijet resonances + LR weighting: ~50% stronger limits.
- CATHODE learns oscillation from data using Fourier features.
- Time sidebands directly constrain background in the signal region.
- **The LHC can function as a direct-detection experiment for ultralight DM.**

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