Testing Non-thermal produced Axino at the LHC

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based on 2304.01082

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PQ symmetry: solution to strong CP problem

$$\mathcal{L}_{\theta QCD} = \frac{\theta_{QCD}}{32\pi^2} \mathrm{Tr}\, G_{\mu\nu} \tilde{G}^{\mu\nu},$$

where $\tilde{G}^{\mu\nu} = \epsilon^{\mu\nu\alpha\beta} G_{\alpha\beta}$, $\bar{\theta} = \theta_{QCD} + Arg\ detM \lesssim 10^{-10}$. **CP symmetry is kept? Why?**

1. Axion solve the strong CP problem: $\bar{\theta}_{QCD} = \mathcal{C}\varphi/f_a \simeq 0$.
   A generic Lagrangian to SM particles:

$$\mathcal{L}_{int} = -\frac{g_{\varphi\gamma}}{4}\varphi F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{g_{\varphi N}}{2m_N}\partial_\mu\varphi\left(\bar{N}\gamma^\mu\gamma_5 N\right) + \frac{g_{\varphi e}}{2m_e}\partial_\mu\varphi\left(\bar{e}\gamma^\mu\gamma_5 e\right) - \frac{i}{2} g_d \varphi \bar{N}\sigma_{\mu\nu}\gamma_5 N F^{\mu\nu} + g_{\varphi G}\varphi G\tilde{G} + \dots$$

   with $g_{\varphi\gamma}$, $g_{\varphi N}/2m_N$, $g_{\varphi e}/2m_e$, $g_d^{\frac{1}{2}} \propto 1/f_a$.
2. The lightest SUSY particle, Axino: **Hot/Warm/Cold DM candidate.**
   Inherited from axion couplings that are suppressed by a factor of $\frac{1}{f_a}$, the axino is unlikely to be produced by scattering of ordinary SM/SUSY particles.

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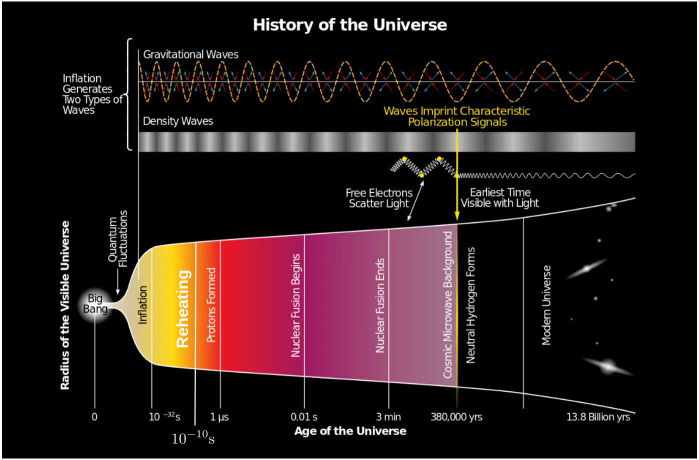
A Long Story back to the Early Universe



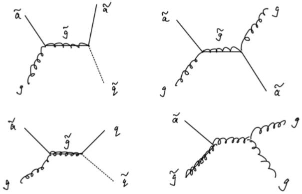
- Big Bang, Inflation, Reheating, Freeze-out temperature...

KSVZ Axino in the early universe:Thermal Relic

Axino production in the early universe is model dependent.

Three key words: Axino freeze-out temperature $T_f^{\tilde{a}}$, PQ symmetry breaking scale f_a and Universe reheating T_R.

1. Axino as Thermal Relic: $T_f^{\tilde{a}} < T_R$. The $\tilde{a}$ is in equalibrium with other SM/SUSY particles.

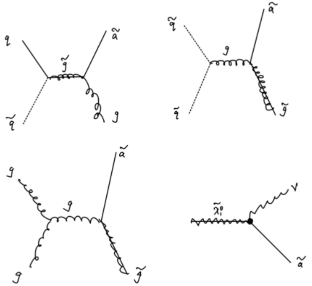


$$\Omega_{\tilde{a}}^{thermal} h^2 = 0.05 \left(\frac{230}{g_{*S}(T_f^{\tilde{a}})}\right) \left(\frac{m_{\tilde{a}}}{100eV}\right) \simeq m_{\tilde{a}}/2KeV$$

Catelysed to "hot" DM: $m_{\tilde{a}} \lesssim 37$ eV.

KSVZ Axino in the early universe: TP Axino

2. Thermally produced (TP) axino: $T_f^{\tilde{a}} > T_R > T_f^{\tilde{f}}$. The $\tilde{a}$ is nevel in equalibrium in the plasma, but it can be produced by the scattering/decay of ordinary particles that are in equalibrium, e.g. $\tilde{g} - g$, $\tilde{q}q$ scattering.



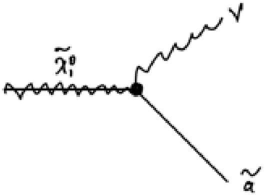
$$\Omega_{\tilde{a}}^{TP} h^2 = 5.5 g_s^6(T_R) \ln\left(\frac{1.211}{g_s(T_R)}\right)\left(\frac{m_{\tilde{a}}}{0.1 GeV}\right)\left(\frac{10^{11}\text{GeV}}{f_a}\right)\left(\frac{T_R}{10^4\text{GeV}}\right)$$

Catelysed to "warm" DM: 12 **KeV** $\lesssim m_{\tilde{a}} \lesssim 100$ **KeV.**
Catelysed to "cold" DM: $m_{\tilde{a}} \gtrsim 100$ **KeV.**

KSVZ Axino in the early universe: NTP Axino

3. Non-thermally produced **(NTP) axino: $T_f^{\tilde{a}} \gg T_R$.**
The NTP $\tilde{a}$ comes from the lightest ordinary supersymmetric particles (LOSP) decay..
The relic density of NTP $\tilde{a}$ is determined by the density of LOSP.

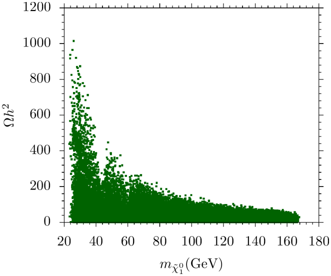
$$\Omega_{\tilde{a}}^{NTP} h^2 = \frac{m_{\tilde{a}}}{m_{LOSP}} \Omega_{LOSP} h^2$$

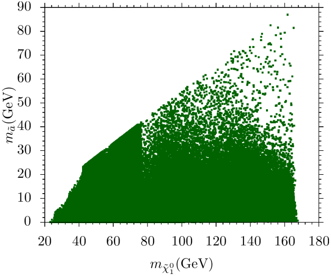


KSVZ Axino in the early universe: NTP Axino

$$\Omega_{\tilde{a}}^{NTP} h^2 = \frac{m_{\tilde{a}}}{m_{LOSP}} \Omega_{LOSP} h^2$$

Save $\tilde{B}$-like LOSP models?





arXiv:2304.01082, W.Zhang, W.Ahmad, I.Khan, T.Li, S.Raza

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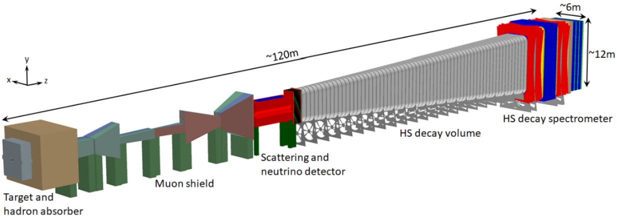
Light axino search with a fixed target: SHiP...



Overview of a fixed target experiment, SHiP. *Eur.Phys.J.C 82 (2022) 5, 486*

A brand new search for light axino: experiment with a fixed target.

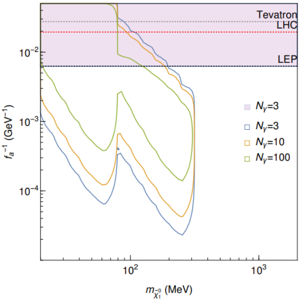
- Beam energy: 400 GeV $\simeq$ **27** GeV pp collision.

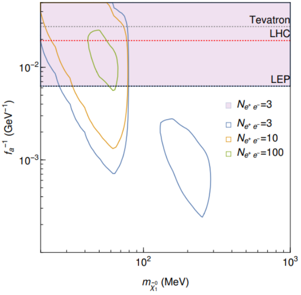
$$pp \to Meson + X_{SM}$$
$$\hookrightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 + X'_{SM}$$
$$\hookrightarrow \tilde{a}\gamma / \tilde{a} e^+ e^-$$

Light axino searches with a fixed target

- Fixed target experiment: CHARM, NOMAD, SHiP, SeaQuest...

$$\tau(\tilde{\chi}_1^0 \to \tilde{a}+\gamma) = 0.49\times10^{-9}\text{sec}\left(\frac{1/128}{\alpha_{em}}\right)^2\left(\frac{f_a}{10^5\ \text{GeV}}\right)^2\left(\frac{10\ \text{GeV}}{m_{\tilde{\chi}_1^0}}\right)^3\left(1-\frac{m_{\tilde{a}}^2}{m_{\tilde{\chi}_1^0}^2}\right)^{-3}$$





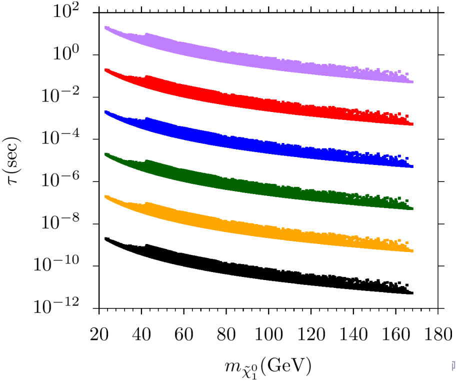
Expected observed events given by SHiP. *Phys.Dark Univ. 27 (2020) 100460*

NTP axino production/searches at the LHC

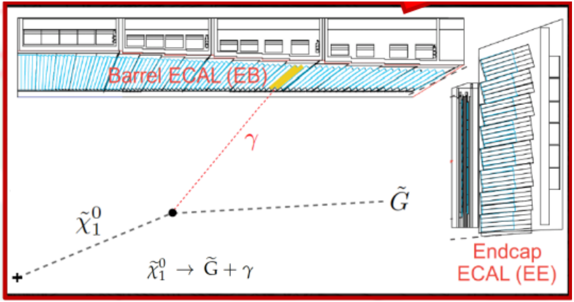
As the LSP, the axino can be produced via decay of Bino-like LOSP.

$$\Gamma(\tilde{\chi}_1^0 \to \tilde{a}\gamma) = \frac{\alpha_{em}^2 C_{aYY}^2 v_4^{(1)2}}{128\pi^3 \cos^2\theta_W} \frac{m_{\tilde{\chi}_1^0}^3}{(f_a/N)^2} \left(1 - \frac{m_{\tilde{a}}^2}{m_{\tilde{\chi}_1^0}^2}\right),$$

With $f_a/N = 10^7, 10^8, 10^9, 10^{10}, 10^{11}$ and 10^{12} GeV from the bottom to the top, we have:



Long-lived neutralino search with timing sensor in the ECAL



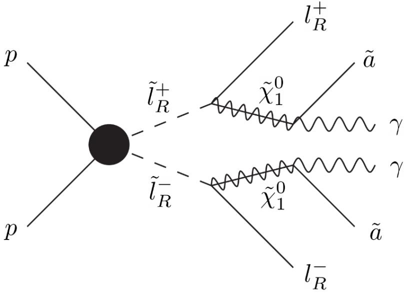
Time resolution: $\mathcal{O}(100)ps$-$\mathcal{O}(10)ps$.

Delayed photon significant MET: **Clean Background!**

NTP axino production at the LHC

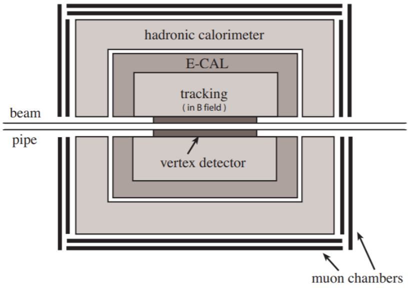
The coupling between the $\tilde{a}$ and the SM particle is highly suppressed by a factor $\propto 1/f_a$.

It's unlikely to produce a axino as a direct production of proton collision.



NTP Axino production at the LHC.

NTP axino production at the LHC

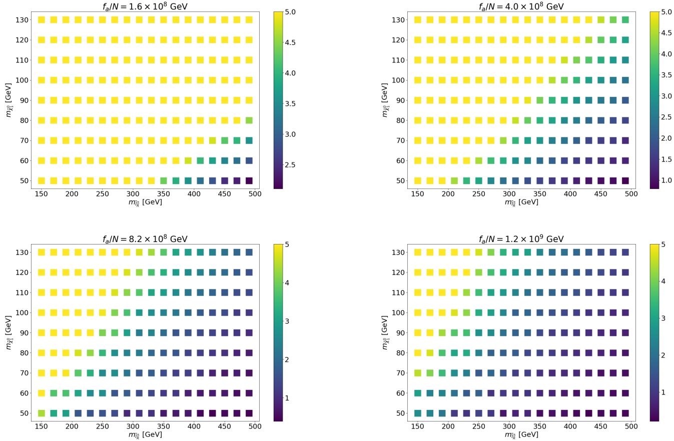


Key point: Detect the delayed photon!

Using the possibility that the LOSP, $\tilde{\chi}_1^0$ decay inside the ECAL:

$$p = \frac{1}{4\pi}\int_{\Delta\Omega} d\Omega \int_{L_1}^{L_2} \frac{1}{d} e^{-L/d},$$

NTP axino detection at ATLAS



The signal significance for the NTP axino $\tilde{a}$ to be detected by the ECAL.

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Summary

- In talk, we give a short introduction to three kinds of Axinos, catelysed by the production mode in the early universe, which are thermal relic, thermally produced axino, non-thermally produced axino.
- Axino search is an old topic, but now it has new chance as the development of experimental technology reaches the region of light DM mass.
- A small contribution is given by my new work about $\mathcal{O}(100)$ GeV Axino searches using the timing layer in the ECAL.