In this talk, we present our work on investigating light NMSSM pseudoscalar states with boosted ditau tagging. Our research is based on the paper by Eric Conte, Benjamin Fuks, Jun Guo, Jinmian Li, and Anthony G. Williams, published in JHEP 05(2016)100.

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Based on
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| Outline   | Light pseudoscalar in NMSSM | Di-$\tau$ jet tagging | Benchmark | Conclusion |
|----------|-----------------------------|-----------------------|-----------|------------|
| 1.       | Light pseudoscalar in NMSSM |                       |           |            |
| 2.       | Di-$\tau$ jet tagging       |                       |           |            |
| 3.       | A benchmark point at 13 TeV LHC |                   |           |            |
| 4.       | Conclusion                  |                       |           |            |
The Higgs sector of NMSSM

\[
W \supset \lambda S H_u \cdot H_d + \frac{\kappa}{3} S^3
\]

\[
-\mathcal{L}_{\text{soft}} \supset \lambda A \lambda H_u \cdot H_d S + \frac{1}{3} \kappa A \kappa S^3 + \text{h.c.}
\]

- There are 3 CP-even and 2 CP-odd neutral scalar fields in NMSSM.
- The singlet-like scalar/pseudoscalar only couple to SM particles through their small mixing with the Higgs doublets, can be as light as a few GeV while consistent with data.
- Peccei-Quinn symmetry limit of the NMSSM solves the strong CP-problem indicating a like singlet scalar.
LHC searches for light $A_1$

- $\sigma(gg \rightarrow H) Br(H \rightarrow A_1A_1) Br^2(A_1 \rightarrow \tau^+\tau^-) \lesssim 4.5 - 10.3 \text{ pb}^{CMS:1510.06534}$
- $\sigma(gg \rightarrow H) Br(H \rightarrow A_1A_1) Br(A_1 \rightarrow \mu^+\mu^-) Br(A_1 \rightarrow \tau^+\tau^-) \lesssim 7 \text{ fb}^{ATLAS:1505.01609(\text{at least one } \tau \rightarrow e/\mu)}$

\[
\frac{\Gamma(a \rightarrow \mu\mu)}{\Gamma(a \rightarrow \tau\tau)} = \frac{m_{\mu}^2}{m_{\tau}^2 \sqrt{1 - (2m_\tau/m_a)^2}} \sim 0.3%
\]

\[
\text{Br}(a \rightarrow \mu\mu) + \text{Br}(a \rightarrow \tau\tau) = 1
\]
LHC searches for light $A_1$

- $\sigma(gg \to H) \text{Br}(H \to A_1A_1) \text{Br}^2(A_1 \to \mu^+\mu^-) \lesssim 1 \text{fb}$ CMS:1506.00424

- $\chi_i^0 \to A_1\chi_j^0$
NMSSM parameter space

Scanning the NMSSM parameter space in the following range:

| $M_0$/GeV   | $M_{1/2}$/GeV | $A_0$/GeV | $A_\lambda$/GeV | $A_\kappa$/GeV |
|------------|--------------|-----------|-----------------|----------------|
| [400,2000] | [1000,2000]  | [-5000,-1000] | [-500,500] | [0,300]        |

$\lambda$, $\kappa$, $\tan \beta$, $\mu$/GeV

- $M_0$, $M_{1/2}$, $A_0$, $A_\lambda$, $A_\kappa$ being defined at the grand unification scale and the last four parameters being defined at the electroweak scale.
- Theoretical constraints including converged RGE running, no tachyons, no Landau pole below the GUT scale, physical global minimal, et.al.
- Higgs and SUSY search bounds at the LEP and Tevatron.
\( H_2 \) is identified as the \( H_{SM} \), consistent with LHC observation

\[
(M_S^2)_{33} = \lambda A \lambda \frac{v^2 \sin 2\beta}{2v_s} + \frac{\kappa v_s}{\sqrt{2}} (A_\kappa + 2\sqrt{2}\kappa v_s)
\]

\[
(M_P^2)_{33} = \lambda A \lambda \frac{v^2 \sin 2\beta}{2v_s} + \frac{\kappa v_s}{\sqrt{2}} \left( \frac{\sqrt{2}\lambda v^2 \sin 2\beta}{v_s} - 3A_\kappa \right)
\]

- We focus on the scenarios in which the lightest pseudoscalar state \( A_1 \) is mostly singlet-like and \( m_{A_1} \in [2m_\tau, 2m_b] \).
- Without miracle cancellation in \((M_P^2)_{33}\), the mass of the lightest singlet-like scalar state in the absence of a too large mixing will be smaller than 125 GeV.
**NMSSM parameter space** (Grey points $m_{A_1} < 30$ GeV; green points $m_{A_1} \in [2m_\tau, 2m_b]$)

\[
(M^2_P)_{33} = \lambda A \frac{v^2 \sin 2\beta}{2v_s} + \frac{\kappa v_s}{\sqrt{2}} \left( \frac{\sqrt{2}\lambda v^2 \sin 2\beta}{v_s} - 3A\kappa \right)
\]

Small $\lambda$ and $\kappa$ values are generally favored.

\[
\frac{H_u}{S} \sim \frac{\lambda v}{\sqrt{2}} \left( 2\mu_{\text{eff}} - (A\lambda + \sqrt{2}\kappa v_s) \sin 2\beta \right)
\]

\[
A\lambda \sim \frac{2\mu_{\text{eff}}}{\sin 2\beta} - \frac{2\kappa \mu_{\text{eff}}}{\lambda} & \sin 2\beta \ll \lambda/\kappa
\]
NMSSM parameter space (Grey points $m_{A_1} < 30$ GeV; green points $m_{A_1} \in [2m_\tau, 2m_b]$)

\[
(M^2_P)_{33} = \lambda A_\lambda \frac{v^2 \sin 2\beta}{2v_s} + \frac{\kappa v_s}{\sqrt{2}} \left( \frac{\sqrt{2}\lambda v^2 \sin 2\beta}{v_s} - 3A_\kappa \right)
\]

An important $A_1$ production rate can be achieved in the region where the spectrum is compressed.
Dark Matter constraints

Heavy dark matter region: $\chi\chi \rightarrow VV$

Higgs funnel region: $2m_\chi \sim m_H$

$Z$ boson funnel region: $2m_\chi \sim m_Z$

Point that have $\Omega h^2 < 0.131$ and $\Omega h^2 \in [0.107, 0.131]$ are shown in orange and blue.

Models in all three regions can survive dark matter direct detection.
Strategy of di-$\tau$ jet tagging

BDT with following variables:

- $N_{\text{track}}$: Number of tracks in the $\tau$(di-$\tau$) jet candidate.
- $f_{\text{cent}}$: Fraction of energy deposited in the $\Delta R < 0.1$ with respect to energy deposited in the $\Delta R < 0.2$ around the $\tau$(di-$\tau$) jet candidate.
- $f_{\text{track}}$: The transverse momentum of the highest-$p_T$ track in $\Delta R < 0.2$ around the $\tau$(di-$\tau$) jet candidate divided by the $p_T$ of the jet.
- $R_{\text{track}}$: $p_t$ weighted distance of all tracks to the $\tau$(di-$\tau$) jet candidate direction.
- $\Delta R_{\text{Max}}$: The maximum $\Delta R$ between a track in the $\Delta R < 0.2$ around the $\tau$(di-$\tau$) jet candidate and the jet direction.
- Track mass ($m_{\text{track}}$): Invariant mass calculated from the sum of the four-momentum of all tracks.
- $p_T/m$: Ratio between transverse momentum and mass of the $\tau$(di-$\tau$) jet candidate.
- $E_{\text{em}}/E_{\text{had}}$: The energy of the $\tau$(di-$\tau$) jet candidate deposit in electromagnetic calorimeter divided by that in hadronic calorimeter.
- $\tau_{21}$: The ratio between $\tau_2$ and $\tau_1$.

\[
\tau_N = \frac{\sum_k \min\{\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k}\}}{\sum_k p_{T,k} R_0}
\]
Strategy of di-$\tau$ jet tagging

$\tau$/di-$\tau$ jet has more centered energy distribution.

$f_{\text{cent}}$: Fraction of energy deposited in the $\Delta R < 0.1$ with respect to energy deposited in the $\Delta R < 0.2$ around the $\tau$(di-$\tau$) jet candidate.

![Graphs showing event fraction for different particles and energies.](image)
Strategy of di-$\tau$ jet tagging

$\tau$/di-$\tau$ jet contains sub-jets.

$$\tau_N = \frac{\sum_k \min\{\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k}\}}{\sum_k p_{T,k} R_0}, \quad \tau_{21} = \tau_2 / \tau_1$$
Di-$\tau$ tagging with BDT method

Jets issued from the fragmentation of light quarks are always harder to distinguish. The corresponding rejection power is increased when the jet energy is higher.
A benchmark point

\[
\tilde{\chi}_1^\pm (\rightarrow W^* \tilde{\chi}_1^0) \tilde{\chi}_{2,3}^0 (\rightarrow A_1 \tilde{\chi}_1^0)
\]

Preselection:

A). exactly one isolated lepton: \(p_T(l) > 10\) GeV, |\(\eta(l)\)| < 2.5; B). at least one jet: \(p_T(j) > 20\) GeV, |\(\eta(j)\)| < 2.5; C). no b-tagged jet.

| \(M_0\) | \(M_{1/2}\) | \(A_0\) | \(\lambda\) | \(\kappa\) | \(\tan \beta\) | \(\mu\) | \(A_\lambda\) | \(A_\kappa\) |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 1215.3 | 1872.8 | -4112.1 | 0.317 | 0.122 | 12.2  | 121.3 | 301.1 | 204.8 |
| \(m_{\tilde{\chi}_1^0}\) | \(m_{\tilde{\chi}_2^0}\) | \(m_{\tilde{\chi}_3^0}\) | \(m_{\tilde{\chi}_1^\pm}\) | \(m_{A_1}\) | \(m_{A_2}\) | \(m_{H_1}\) | \(m_{H_2}\) | \(m_{H_3}\) |
| 75.7  | -135.3 | 149.2  | 124.2  | 5.5   | 1538  | 93.8  | 125.9 | 1538  |
| \(\text{Br}_{\tilde{\chi}_1^0 \rightarrow A_1 \tilde{\chi}_1^0}\) | \(\text{Br}_{\tilde{\chi}_3^0 \rightarrow A_1 \tilde{\chi}_2^0}\) | \(\text{Br}_{\tilde{\chi}_3^0 \rightarrow A_1 \tilde{\chi}_2^0}\) | \(\text{Br}_{H_2 \rightarrow A_1 A_1}\) | \(\mu_{ggF}\) | \(\mu_{TBF}\) | \(\Omega h^2\) | \(\sigma_{SI}/\text{pb}\) |
| 98.9% | 12.9%  | 87.1%  | 93.6%  | 4.2%  | 1.06  | 1.02  | 0.107 | \(2.46 \times 10^{-10}\) |

\[ \tilde{\chi}_1^\pm (\rightarrow W^* \tilde{\chi}_1^0) \tilde{\chi}_{2,3}^0 (\rightarrow A_1 \tilde{\chi}_1^0) \]
Kinematic properties

For the benchmark point, $E(A_1) \gtrsim 50$ GeV is in general much larger than the $A_1$ mass, the pseudoscalar decay products (two tau leptons) turn out to be highly collimated.
Kinematic properties

The bulk of the signal events features at most two jets, while the leading jet is in general the boosted ditau object (in 70% of the cases for the benchmark point).
The BDT discrimination

- $n_j$: number of jets.
- $p_T(l)$: transverse momentum of the lepton.
- $p_T(j_1)$: transverse momenta of the leading jet.
- $p_T(j_2)$: transverse momenta of the second leading jet. softer for signal
- $m(j_1)$: invariant mass of the leading jet.
- $E_T$: missing transverse energy.
- $\Delta \phi(l, \vec{p}_T)$: azimuthal angle difference between the lepton and the missing momentum. correlated for $W$+jets
- $\Delta R(l, j_1)$: angular distance between the lepton and the leading jet.
- $m_T(l, \vec{p}_T)$: lepton-missing energy transverse mass. suppress $W$+jets
- $m_{T_2}(l, j_1)$: final state stranverse mass. reflecting $\mu - \chi_1$
The BDT discrimination

\[ \Delta \phi(l, p_T) : \]

\[ m_T(l, p_T) : \]
The BDT discrimination

Without di-τ tag:

With di-τ tag:
The BDT discrimination

An signal efficiency of about one percent can be obtained together with a background rejection rate of $10^4$ ($\gtrsim 10^5$) when the ditau tagging is ignored (included).

A $3\sigma$ hint for the class of NMSSM scenarios considered in this work could be observed at the early stage of the LHC Run–II, while a $5\sigma$ discovery could be expected with an integrated luminosity of at least $50$ fb$^{-1}$. 
In the parameter space with $m_{A_1} \in [2m_\tau, 2m_b]$, relatively small $\mu$ is favored by requiring sizeable $\text{Br}_{\tilde{\chi}_{2,3}^0 \rightarrow A_1 \tilde{\chi}_1^0}$ and small relic density $\Omega h^2 \lesssim 0.131$.

The light higgsinos can have large production rate at LHC, which in turn means large production rate of $A_1$.

The background rejection can be improved by more than one order of magnitude with the help of di-$\tau$ tagging.

$3\sigma$ hint for the signal is expected within the first 13 TeV data, and that a $5\sigma$ discovery could be envisaged for a luminosity of more than about 50 fb$^{-1}$. 