

# Investigating light NMSSM pseudoscalar states with boosted ditau tagging

Jinmian Li

ARC Centre of Excellence for Particle Physics at the Terascale (CoEPP)  
University of Adelaide

*Based on*

*Eric Conte, Benjamin Fuks, Jun Guo, Jinmian Li, Anthony G. Williams, JHEP05(2016)100*

SUSY2016

Melbourne, 5th July, 2016

- 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

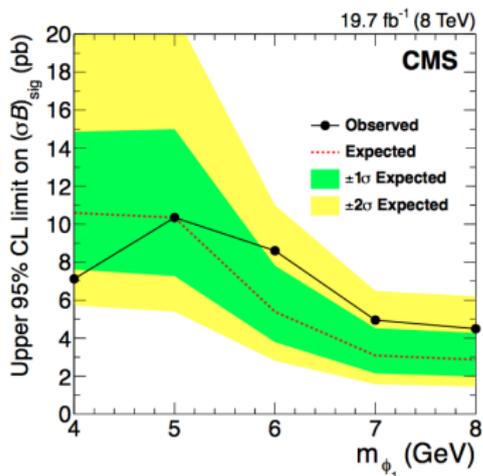
$$W \supset \lambda S H_u \cdot H_d + \frac{\kappa}{3} S^3$$

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

- 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.

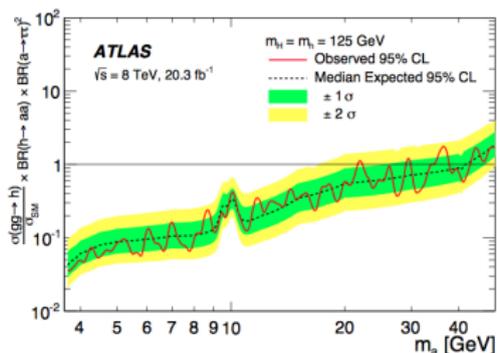
# LHC searches for light $A_1$

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



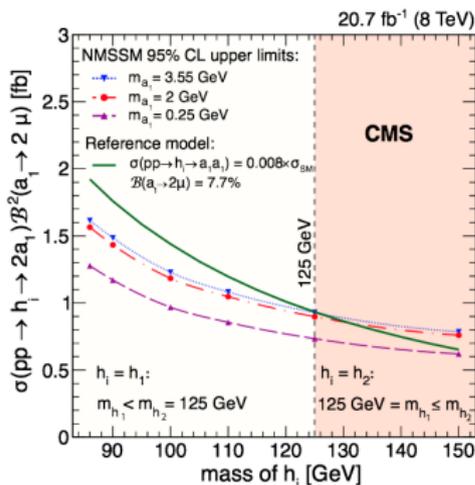
$$\frac{\Gamma(a \rightarrow \mu\mu)}{\Gamma(a \rightarrow \tau\tau)} = \frac{m_\mu^2}{m_\tau^2 \sqrt{1 - (2m_\tau/m_a)^2}} \sim 0.3\%$$

$$\text{Br}(a \rightarrow \mu\mu) + \text{Br}(a \rightarrow \tau\tau) = 1$$



LHC searches for light  $A_1$ 

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



- $\chi_i^0 \rightarrow A_1 \chi_j^0$

# NMSSM parameter space

Scanning the NMSSM parameter space in the following range:

$M_0/\text{GeV}$	$M_{1/2}/\text{GeV}$	$A_0/\text{GeV}$	$A_\lambda/\text{GeV}$	$A_\kappa/\text{GeV}$
[400,2000]	[1000,2000]	[-5000,-1000]	[-500,500]	[0,300]
$\lambda$	$\kappa$	$\tan\beta$	$\mu/\text{GeV}$	
[0.2,0.5]	[0.01,0.2]	[1.5,15]	[100,350]	

- $M_0, M_{1/2}, A_0, A_\lambda, A_\kappa$  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

$$(\mathcal{M}_S^2)_{33} = \lambda A_\lambda \frac{v^2 \sin 2\beta}{2v_s} + \frac{\kappa v_s}{\sqrt{2}} \left( A_\kappa + 2\sqrt{2}\kappa v_s \right)$$

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

- 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  $(\mathcal{M}_P^2)_{33}$ , the mass of the lightest singlet-like scalar state in the absence of a too large mixing will be smaller than 125 GeV.

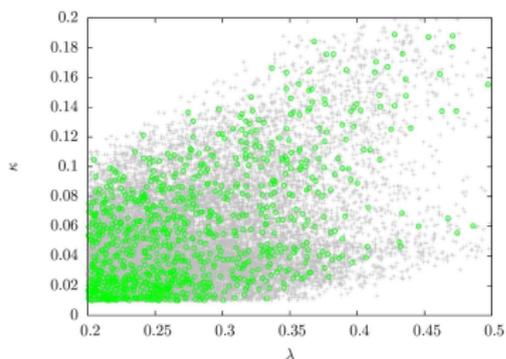
# NMSSM parameter space

(Grey points  $m_{A_1} < 30$  GeV; green points  $m_{A_1} \in [2m_\tau, 2m_b]$ )

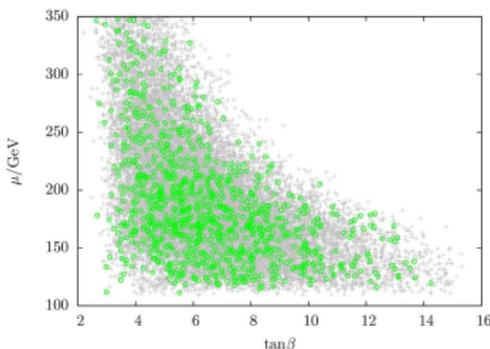
$$(\mathcal{M}_P^2)_{33} = \lambda A_\lambda \frac{v^2 \sin 2\beta}{2v_s} + \frac{\kappa v_s}{\sqrt{2}} \left( \frac{\sqrt{2}\lambda v^2 \sin 2\beta}{v_s} - 3A_\kappa \right)$$

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

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



$$A_\lambda \sim \frac{2\mu_{\text{eff}}}{\sin 2\beta} - \frac{2\kappa\mu_{\text{eff}}}{\lambda} \quad \& \sin 2\beta \ll \lambda/\kappa$$

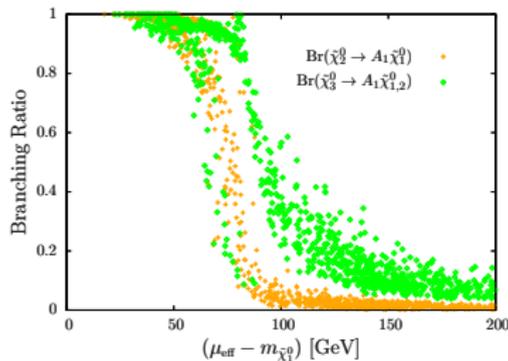
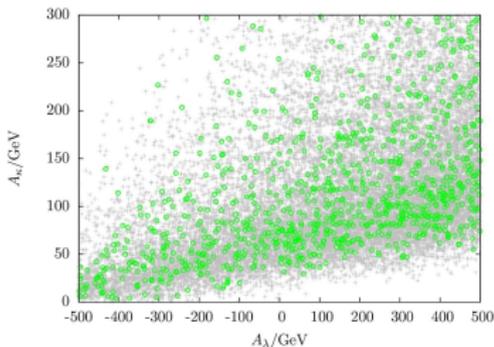


# NMSSM parameter space

(Grey points  $m_{A_1} < 30$  GeV; green points  $m_{A_1} \in [2m_\tau, 2m_b]$ )

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

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

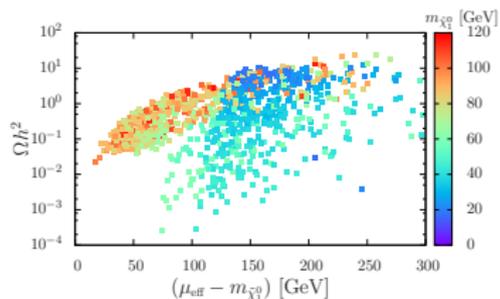


# Dark Matter constraints

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

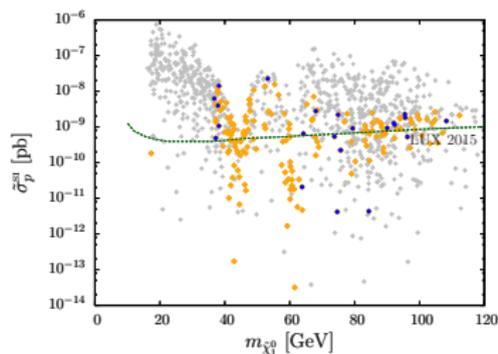
Higgs funnel region:  $2m_\chi \sim m_H$

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:

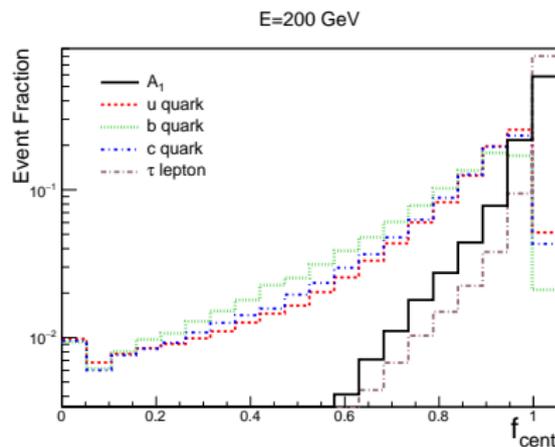
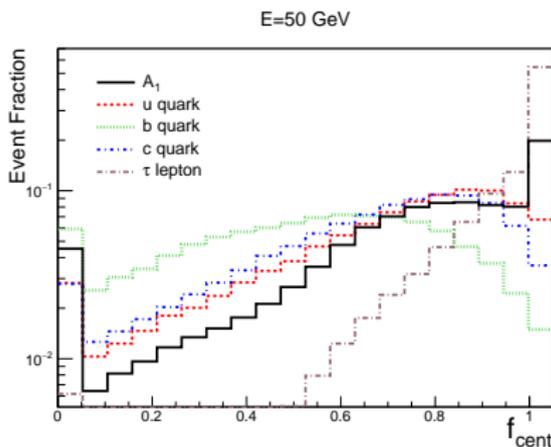
- $N_{\text{track}}$ : Number of tracks in the  $\tau(\text{di-}\tau)$  jet candidate.
- $f_{\text{cent}}$ : Fraction of energy deposited in the  $\Delta R < 0.1$  with respect to energy deposited in the  $\Delta R < 0.2$  around the  $\tau(\text{di-}\tau)$  jet candidate.
- $f_{\text{track}}$ : The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

$$\tau_N = \frac{\sum_k \min\{\Delta R_{1,k}, \Delta R_{2,k}, \dots, \Delta R_{N,k}\}}{\sum_k p_{T,k} R_0}$$

# Strategy of di- $\tau$ jet tagging

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

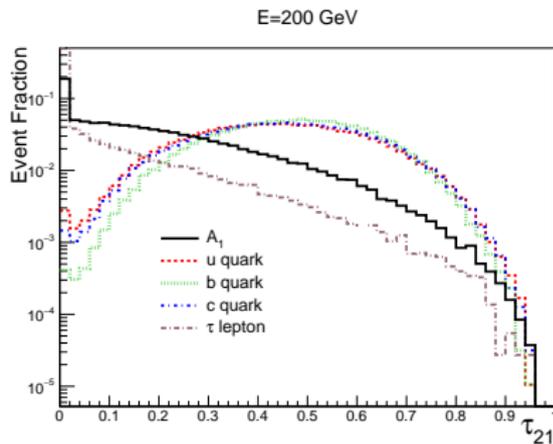
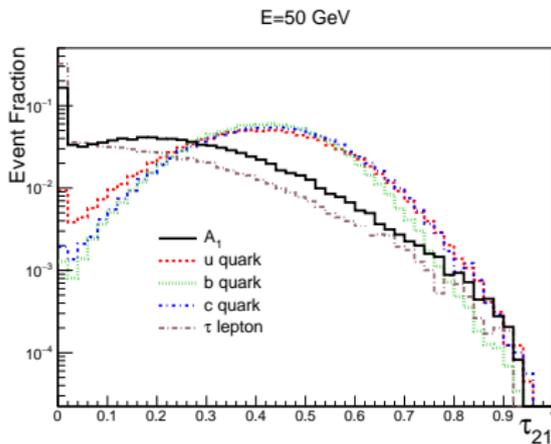
$f_{\text{cent}}$ : Fraction of energy deposited in the  $\Delta R < 0.1$  with respect to energy deposited in the  $\Delta R < 0.2$  around the  $\tau$ (di- $\tau$ ) jet candidate.



# Strategy of di- $\tau$ jet tagging

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

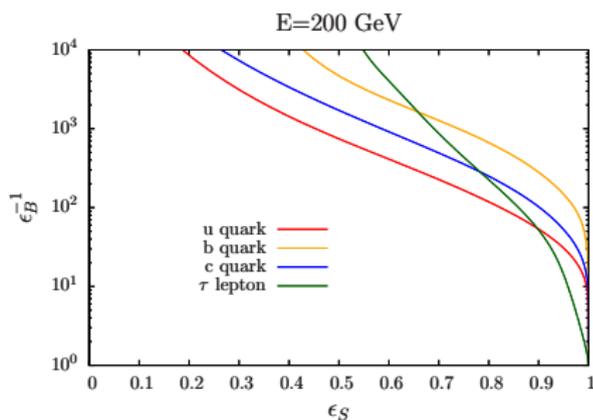
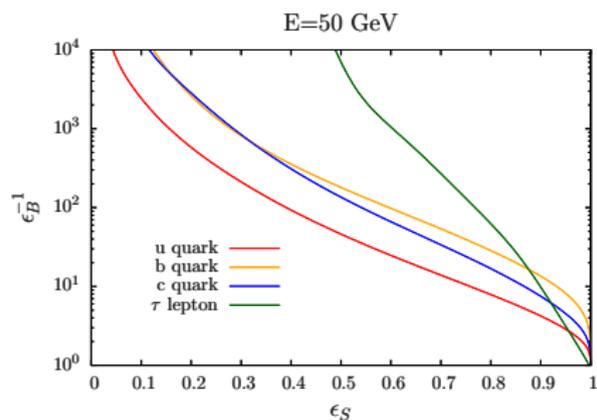
$$\tau_N = \frac{\sum_k \min\{\Delta R_{1,k}, \Delta R_{2,k}, \dots, \Delta R_{N,k}\}}{\sum_k p_{T,k} R_0}, \quad \tau_{21} = \tau_2/\tau_1$$



# 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

$M_0$	$M_{1/2}$	$A_0$	$\lambda$	$\kappa$	$\tan\beta$	$\mu$	$A_\lambda$	$A_\kappa$
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
$\text{Br}_{\tilde{\chi}_2^0 \rightarrow A_1 \tilde{\chi}_1^0}$	$\text{Br}_{\tilde{\chi}_3^0 \rightarrow A_1 \tilde{\chi}_1^0}$	$\text{Br}_{\tilde{\chi}_3^0 \rightarrow A_1 \tilde{\chi}_2^0}$	$\text{Br}_{A_1 \rightarrow \tau\tau}$	$\text{Br}_{H_2 \rightarrow A_1 A_1}$	$\mu_{\gamma\gamma}^{\text{ggF}}$	$\mu_{VV^*}^{\text{VBF}}$	$\Omega h^2$	$\sigma_p^{\text{SI}}/\text{pb}$
98.9%	12.9%	87.1%	93.6%	4.2%	1.06	1.02	0.107	$2.46 \times 10^{-10}$

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

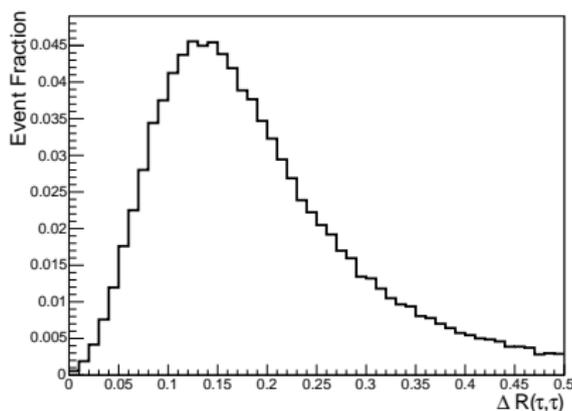
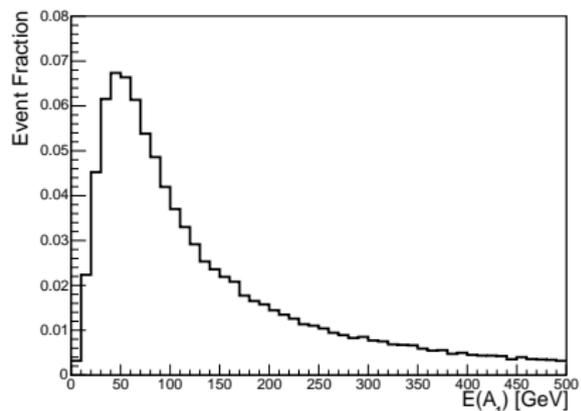
## Preselection:

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.

	$\tilde{\chi}^\pm \tilde{\chi}^0$ signal	$W_l$ plus jets	Top pair production	Diboson production
$\sigma^{13}$	3.38 pb	8452 pb	825 pb	159.3 pb
$\sigma^{\text{pre}}$	0.42 pb	4313 pb	62.9 pb	29.2 pb

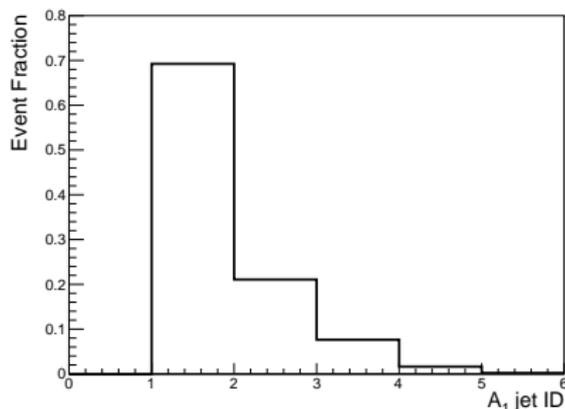
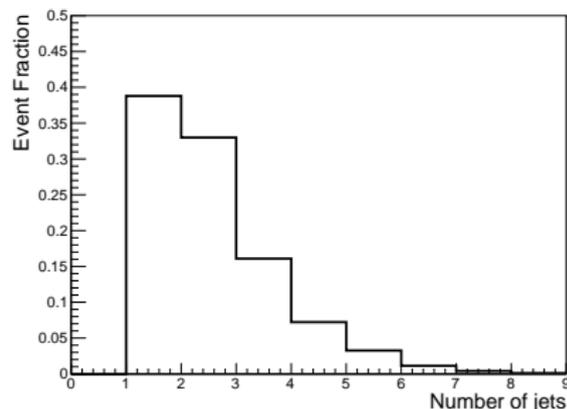
# Kinematic properties

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).

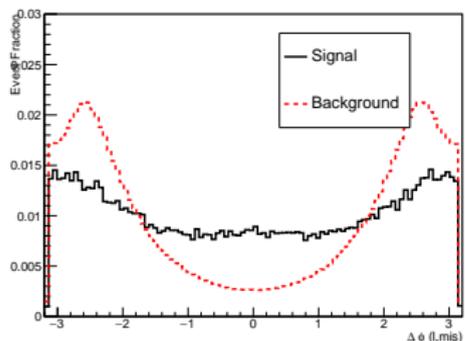


# The BDT discrimination

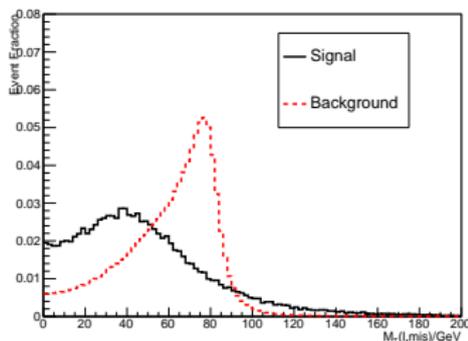
- $n_j$ : number of jets.
- $p_T(l)$ : transverse momentum of the lepton.
- $p_T(j_1)$ : transverse momenta of the leading jet.
- $p_T(j_2)$ : transverse momenta of the second leading jet. **softer for signal**
- $m(j_1)$ : invariant mass of the leading jet.
- $\cancel{E}_T$ : missing transverse energy.
- $\Delta\phi(l, \cancel{p}_T)$ : 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.
- $m_T(l, \cancel{p}_T)$ : lepton-missing energy transverse mass. **suppress  $W$ +jets**
- $m_{T_2}(l, j_1)$ : final state transverse mass. **reflecting  $\mu - \chi_1$**

# The BDT discrimination

$$\Delta\phi(l, \not{p}_T):$$

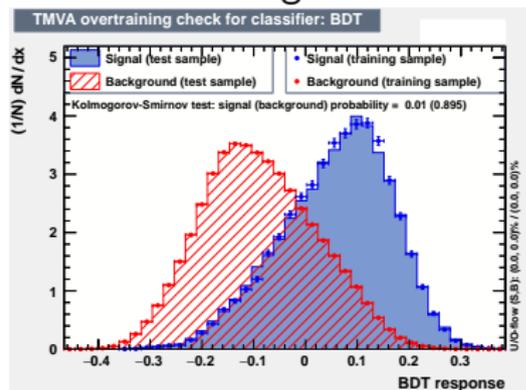


$$m_T(l, \not{p}_T):$$

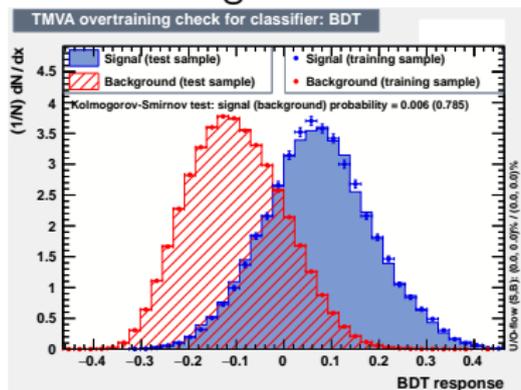


# The BDT discrimination

Without  $di\text{-}\tau$  tag:



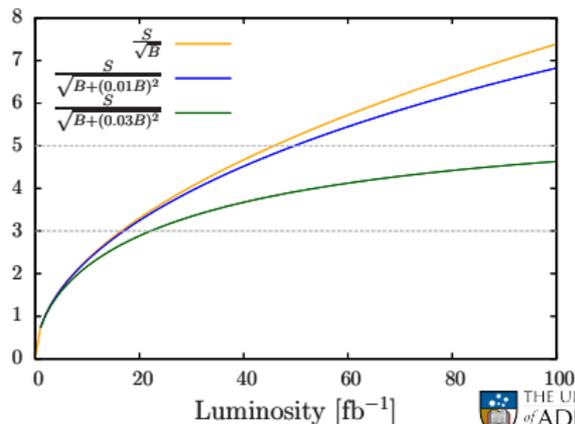
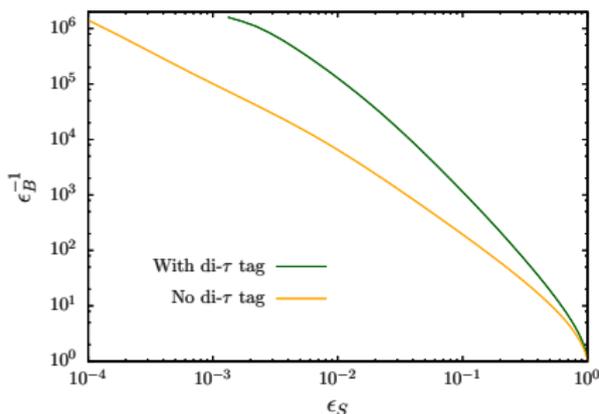
With  $di\text{-}\tau$  tag:



# 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  $50 \text{ fb}^{-1}$ .



# Conclusion

- 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  $50 \text{ fb}^{-1}$ .