

# Dark matter relic density from observations of supersymmetry at the ILC

Suvi-Leena Lehtinen

DESY

3.11.2015



PIER

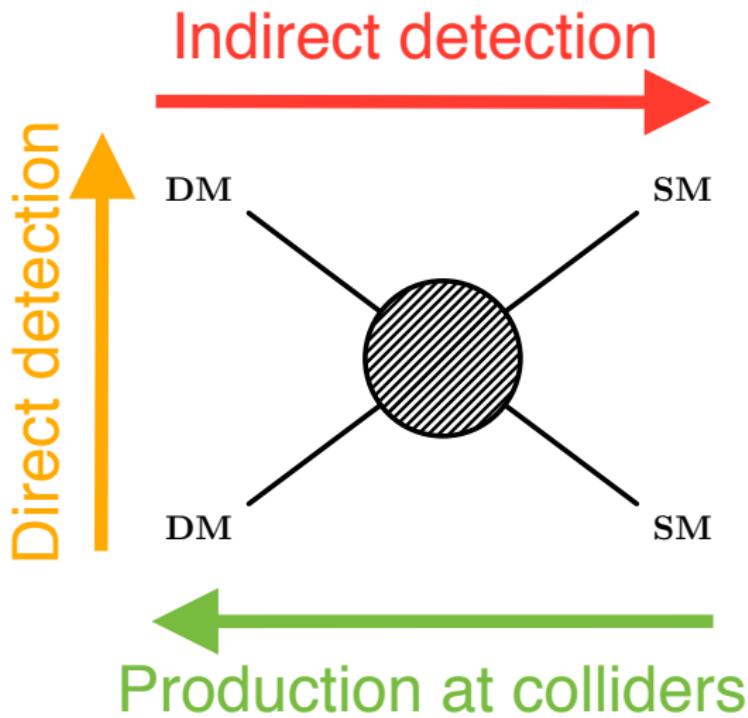
PIER  
Helmholtz  
Graduate  
School

A Graduate Education Program  
of Universität Hamburg  
in Cooperation with DESY

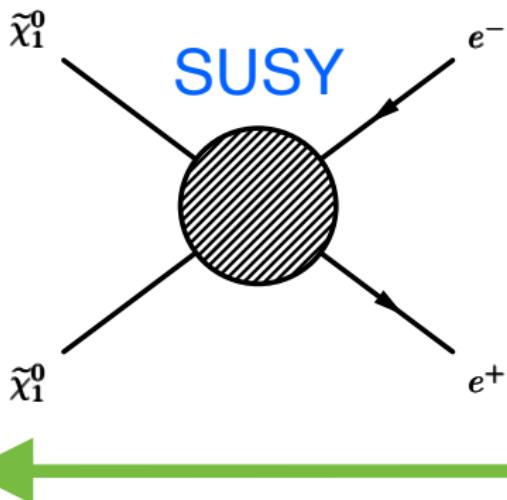


Universität Hamburg  
DER FORSCHUNG | DER LEHRE | DER BILDUNG

# Dark matter experiments



# Measurements at the ILC

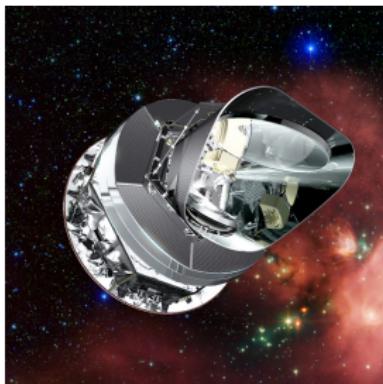


Production at the ILC

# Cosmological vs. collider precision

►  $\Omega_{CDM} h^2 = 0.1197 \pm 0.0022$

$$\implies \Delta = 2\%$$



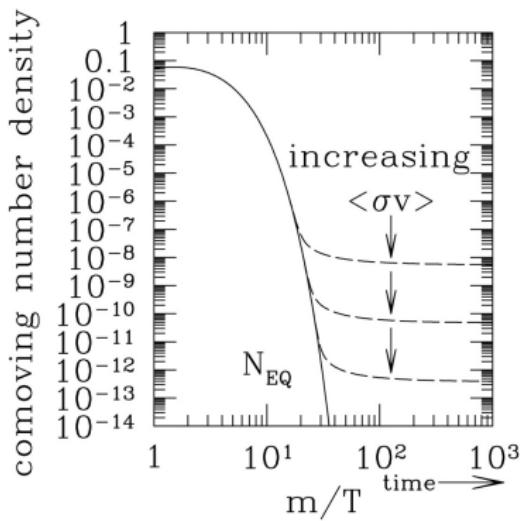
►  $\Omega_{CDM} h^2 = ? \pm ?$

$$\implies \Delta = ?\%$$



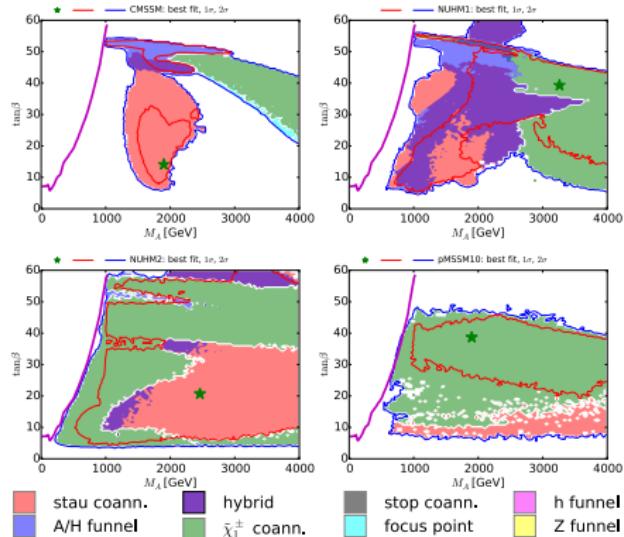
# How is DM relic density determined

- relic density  $\propto$  present day abundance  $Y(T_0)$
- $\frac{dY}{ds} \propto \langle\sigma v\rangle(Y^2 - Y_{eq}(T)^2)$
- Full model  $\implies$  prediction for relic density
- micrOMEGAs a code to calculate relic density  
arXiv:1305.0237



# Dark matter mechanisms in SUSY

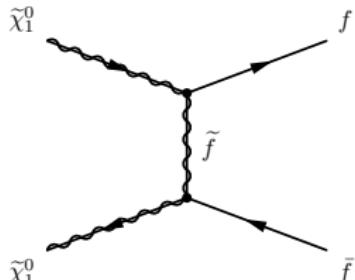
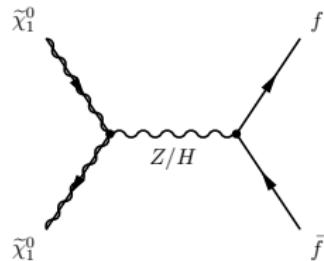
- Stau coannihilation is one of the preferred mechanisms to explain dark matter in SUSY



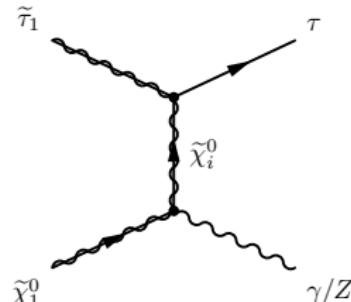
Mastercode arXiv:1508.01173v1

# Processes in stau coannihilation

- ▶ Pair annihilation depends on LSP mixing and sfermion mass



- ▶ Coannihilation depends strongly on the stau-LSP mass difference



# Variation of dark matter with masses

- Typical variations in a scenario with many light sparticles

Observable	$\pm$ variation	$\pm$ change in $\Omega$
$m_{\tilde{\chi}_1^0}$	1%	5%
$m_{\tilde{\tau}_1}$	1%	5%
$m_{\tilde{l}_R}$	1%	< 0.5%
$m_{\tilde{l}_L}$	1%	< 0.01%
$m_{\tilde{\nu}}$	10%	< 0.1%
$m_{H,A_0}$	10%	< 0.1%
$m_{\tilde{\chi}_i}$	10%	< 0.1%
$m_{\tilde{q}}$	10%	< 0.01%

- LSP and stau1 mass crucial, others much less important

# Variation of dark matter with mixings

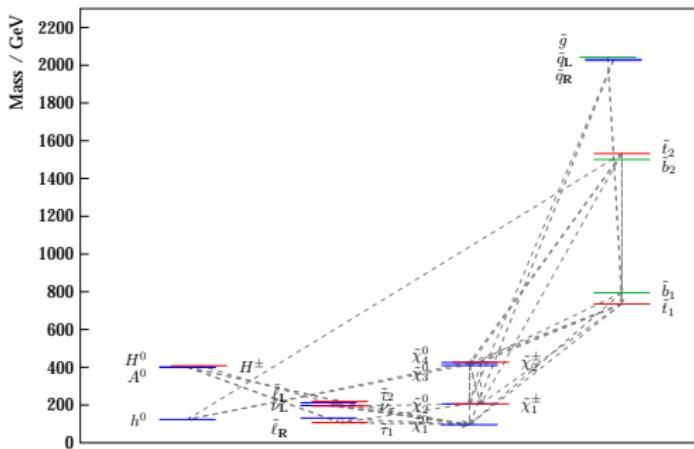
- ▶ Typical variations in a scenario with many light sparticles

"observable"	± variation	± change in $\Omega$
stau mixing angle $\theta_{\tau}$	1%	1%
binoness of LSP $N_{11}$	1%	3.5%
other neutralino mixings	100%	$\sim 1 - 4\%$
Higgs mixing	50%	2%
other mixings	50%	< 0.1%

- ▶ Stau and LSP mixing also crucial, Higgs and other neutralino mixings needed to  $\sim 10\%$
- ▶ What can the ILC give? Study a concrete example

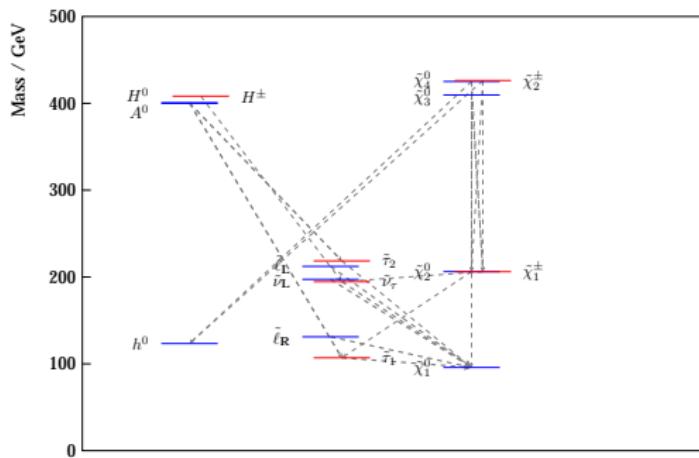
# Stau coannihilation observable at the ILC

- pMSSM point with 12 parameters "STC8" (arXiv:1307.0782)
- $m_{\tilde{\chi}_1^0} = 96$  GeV (bino),  $m_{\tilde{\tau}_1} = 107$  GeV (RH)
- True relic density value 0.113



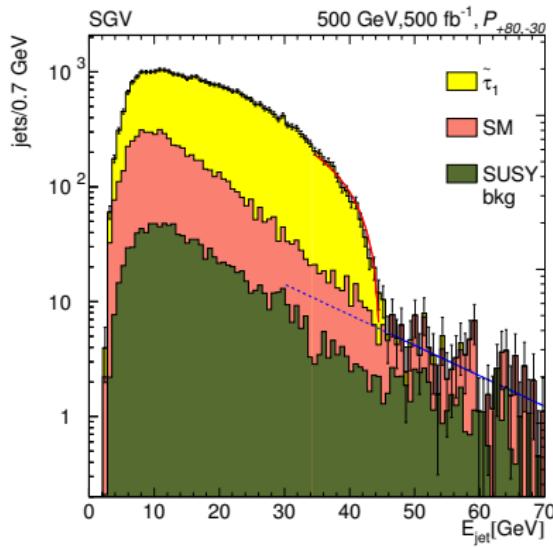
# Stau coannihilation observable at the ILC

- pMSSM point with 12 parameters "STC8" (arXiv:1307.0782)
- $m_{\tilde{\chi}_1^0} = 96$  GeV (bino),  $m_{\tilde{\tau}_1} = 107$  GeV (RH)
- True relic density value 0.113



# 500GeV measurements

- ▶ SGV analysis of STC8 done by Berggren (arXiv:1508.04383v1)
- ▶ More details tomorrow early afternoon BSM
- ▶  $\tilde{\tau}_1 \rightarrow \tilde{\chi}_1^0 \tau$  endpoint  $\implies \Delta m_{\tilde{\tau}_1} = 0.15\%$



# 500GeV measurements

- Can discover of all sleptons, sneutrinos,  $\tilde{\chi}_1^0, \tilde{\chi}_2^0$  and  $\tilde{\chi}_1^\pm$
- Precisions on masses and mixings:

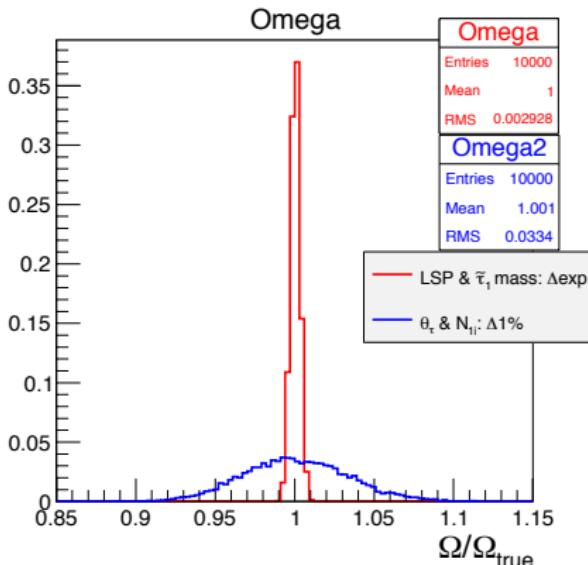
black=estimate, blue=analysis (arXiv:1508.04383v1)

$m_{\tilde{\chi}_1^0}$	0.15%	$m_{\tilde{\chi}_2^0}$	0.5%
$m_{\tilde{t}_1}$	0.16%	$m_{\tilde{t}_2}$	2.5%
$m_{\tilde{e}_R}$	0.17%	$m_{\tilde{\mu}_R}$	0.40%
$m_{\tilde{e}_L}$	1%	$m_{\tilde{\mu}_L}$	1%
$m_{\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau}$	1%	$m_{\tilde{\chi}_1^\pm}$	1%
$\theta_\tau$	1%	$A_\tau$	20%
$N_{11,12,13,14}$	1% each	$Umix, Vmix$	20% each



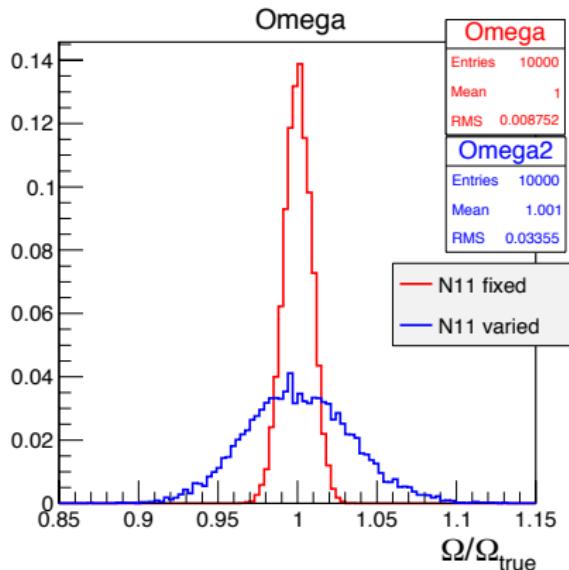
# Stau1 and LSP mass vs mixings

- Red: LSP mass and stau1 mass varied 0.15%
- Blue: LSP mixings and stau1 mixing varied 1%
- With these assumptions, mixings dominate uncertainty on relic density  $\Omega$



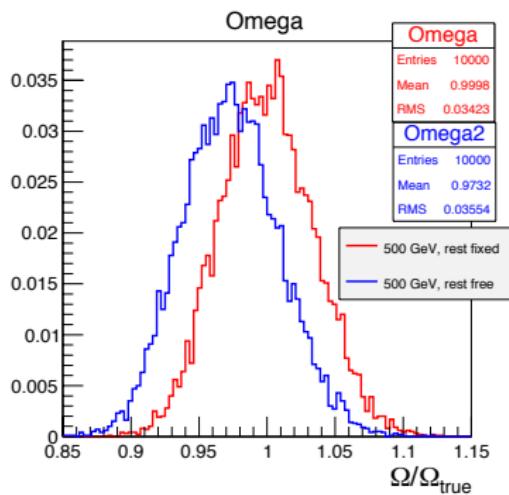
# Important to measure: binoness of LSP

- Blue: LSP and stau1 mass 0.15%, LSP, stau1 mixings 1%
- Red: same but N11 (binoness) fixed



# 500GeV measurements

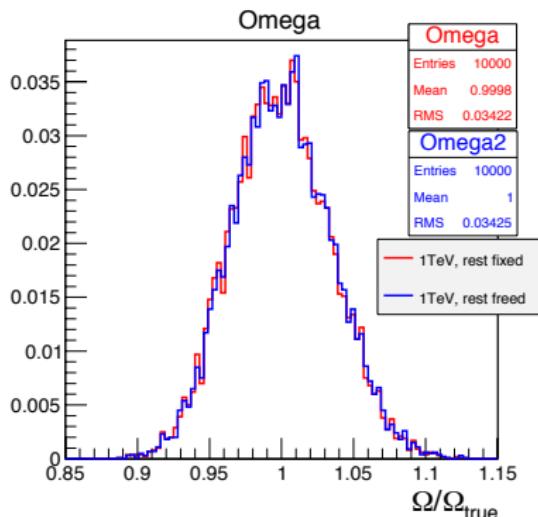
- Red: all sleptons, sneutrinos,  $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm$  varied, rest fixed.  
 $\Delta\Omega = 3.5\%$  (fix N11  $\implies \Delta\Omega = 2\%$ )
- Blue: same but squarks uniformly varied 1 - 50 TeV,  
higgses 0.4 - 2 TeV and  $\tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_2^\pm$  0.25 TeV - 2 TeV
- Unobserved sector causes  $\sim 1\sigma$  shift of the mean



# Assumptions for 1TeV measurements

- Assume no further improvement on light sparticle measurements (over-conservative)
- Extended Higgs masses:  $\Delta = 1\%$
- $\tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_2^\pm$ :  $\Delta = 1\%$

- Red: unobservables fixed
- Blue: unobservables free
- No shift from unobservables, width is similar



## Not considered

- ▶ MicrOMEGAs  $\implies$  tree-level SUSY cross-sections
- ▶ SUSY loop corrections can give  $\sim 10\%$   
(e.g. arXiv:0710.1821v3)
- ▶ This probably just a shift of the mean predicted  $\Omega$   
(for other coannihilation scenarios arXiv:1510.0629v1)



## Not considered

- MicrOMEGAs  $\implies$  tree-level SUSY cross-sections
- SUSY loop corrections can give  $\sim 10\%$   
(e.g. arXiv:0710.1821v3)
- This probably just a shift of the mean predicted  $\Omega$   
(for other coannihilation scenarios arXiv:1510.0629v1)
- $h_0 - H_0$  mixing angle ignored
- Related to couplings of light Higgs

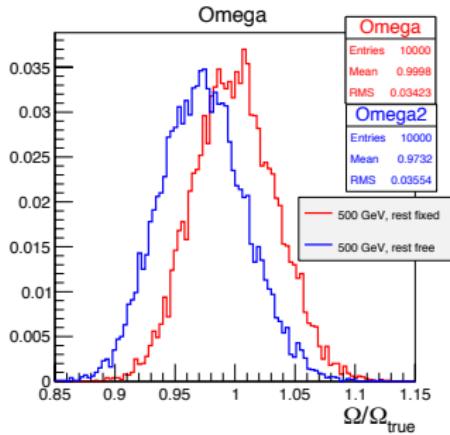


# Summary

- In stau-coannihilation: if sleptons, sneutrinos and light gauginos discovered and if mixings measured to 1%  
    ⇒ ILC precision on relic density  $\sim 2 \times$  Planck precision
- With current assumptions, uncertainties on mixing properties dominate over mass uncertainties
- Need a more reliable estimate of the ILC capabilities e.g. from tau polarisation and polarised cross sections
- With real discoveries would need to consider loop corrections



# Backup: 500 GeV assumptions



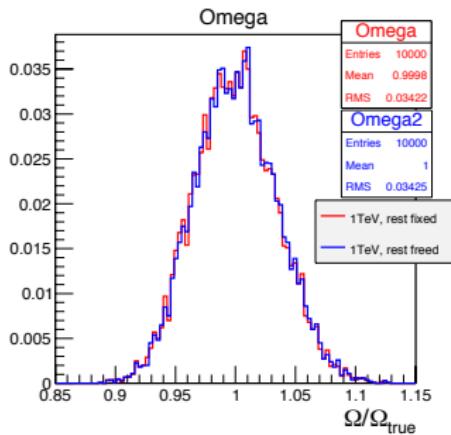
500GeV discoveries  
black=estimate, blue=analysis  
(arXiv:1508.04383v1)

$m_{\tilde{\chi}_1^0}$	0.15%	$m_{\tilde{\chi}_2^0}$	0.5%
$m_{\tilde{\tau}_1}$	0.16%	$m_{\tilde{\tau}_2}$	2.5%
$m_{\tilde{e}_R}$	0.17%	$m_{\tilde{\mu}_R}$	0.40%
$m_{\tilde{e}_L}$	1%	$m_{\tilde{\mu}_L}$	1%
$m_{\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau}$	1%	$m_{\tilde{\chi}_1^\pm}$	1%
$\theta_\tau$	1%	$A_\tau$	20%
$N_{11,12,13,14}$	1% each	$Umix, Vmix$	20% each

## Unobservables at 500GeV - uniform variations

$m_{\tilde{\chi}_3^0, \tilde{\chi}_4^0}$	0.25 – 2 TeV	$m_{\tilde{\chi}_2^\pm}$	0.25 – 2 TeV
$m_{H_0, A_0, H^\pm}$	0.4 – 2 TeV		
$m_{\tilde{d}_L, \tilde{u}_L, \tilde{s}_L, \tilde{c}_L}$ all equal	1 – 50 TeV	$m_{\tilde{d}_R, \tilde{u}_R, \tilde{s}_R, \tilde{c}_R} = m_{\tilde{d}_L} - 100$ GeV	
$m_{\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2}$ independent	0.6 – 50 TeV	$m_{\tilde{g}}$	1 – 50 TeV
$\theta_{t,b}$	$-\pi/2 \rightarrow \pi/2$	$A_{t,b}$	$-5000 \rightarrow 5000$

# Backup: 1 TeV assumptions



1 TeV observations			
$m_{\tilde{e}_R}$	0.17%	$m_{\tilde{\mu}_R}$	0.40%
$m_{\tilde{e}_L}$	1%	$m_{\tilde{\mu}_L}$	1%
$m_{\tilde{\tau}_1}$	0.16%	$m_{\tilde{\tau}_2}$	2.5%
$\theta_\tau$	1%	$A_\tau$	20%
$m_{\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau}$	1%	$m_{\tilde{\chi}_1^\pm}$	1%
$m_{\tilde{\chi}_1^0}$	0.15%	$m_{\tilde{\chi}_2^0}$	0.5%
$N_{12,13,14}$	1% each	$Umix, Vmix$	20% each
$m_{\tilde{\chi}_3^0, \tilde{\chi}_4^0}$	1%	$m_{\tilde{\chi}_2^\pm}$	1%
$m_{H_0, A_0, H^\pm}$	1%		

## Unobserved at 1 TeV

$m_{\tilde{d}_L, \tilde{u}_L, \tilde{s}_L, \tilde{c}_L}$	all equal	1 – 50 TeV	$m_{\tilde{d}_R, \tilde{u}_R, \tilde{s}_R, \tilde{c}_R} = m_{\tilde{d}_L} - 100$ GeV
$m_{\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2}$	independent	0.6 – 50 TeV	$m_{\tilde{g}}$ 1 – 50 TeV
$\theta_{t,b}$		$0 \rightarrow \pi/2$	$A_{t,b}$ 0 → –5000

