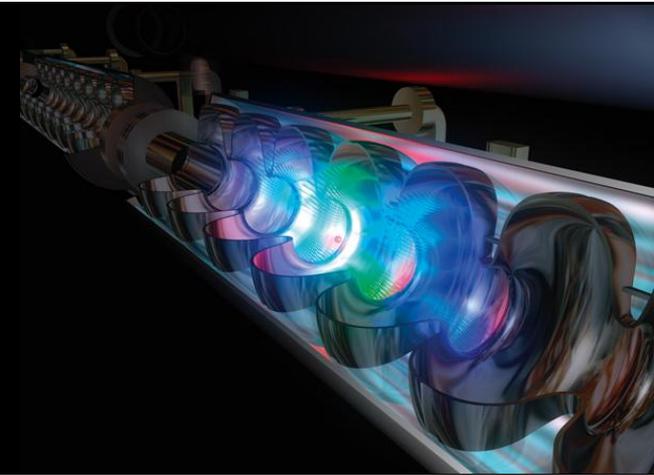


# R-parity violation at LHC & ILC

Ongoing LHC searches and impact on ILC



[Benedikt Vormwald](#), Jenny List

KILC 12

Daegu, Korea, 23.-27.04.2012

- R-parity violation
- Ongoing RPV searches at LHC
- Background study for bRPV search at ILC
- Conclusion



# R-parity violation

## MSSM Superpotential

$$W = h_U^{ij} \hat{Q}_i \cdot \hat{H}_u \hat{U}_j + h_D^{ij} \hat{Q}_i \cdot \hat{H}_d \hat{D}_j + h_E^{ij} \hat{L}_i \cdot \hat{H}_u \hat{R}_j - \mu \hat{H}_d \cdot \hat{H}_u$$

additional allowed terms:

$$W_{\Delta L=1} = \lambda^{ijk} \hat{L}_i \cdot \hat{L}_j \hat{R}_k + \lambda'^{ijk} \hat{L}_i \cdot \hat{Q}_j \hat{D}_k + \mu^i \hat{L}_i \cdot \hat{H}_u$$

$$W_{\Delta B=1} = \lambda''^{ijk} U_i \hat{D}_j \hat{D}_k$$

→ most general gauge-invariant and renormalizable superpotential

## What is R-parity?

- $B$  and  $L$  violating terms allowed in superpotential ( $\Leftrightarrow$  SM)
- $B$  and  $L$  violation never observed

→ introduce new symmetry which is a combination of  $B$ ,  $L$  (and  $S$ )

$$\boxed{P_R = (-1)^{3B+L+2S}} \quad \begin{array}{l} \longrightarrow \text{SM particles: } P_R = +1 \\ \longrightarrow \text{SUSY partners: } P_R = -1 \end{array}$$



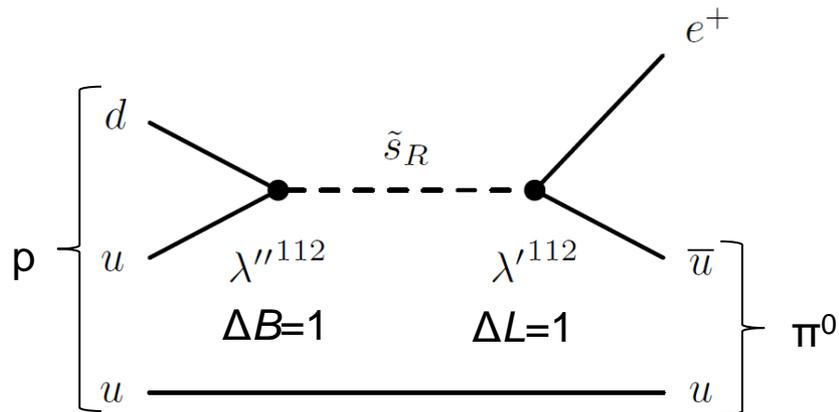
# R-parity violation

## Consequences of conservation

- $\Delta B \neq 0$  and  $\Delta L \neq 0$  prohibited
- sparticles can only be produced in pairs
- SUSY decay products contain odd number of LSPs
- LSP absolutely stable

**BUT** claim for conservation arbitrary from theoretical point of view

## How to break R-parity?



experimental bounds: e.g. proton decay

- strong bounds on  $\lambda'' \cdot \lambda'$
- in good approximation:  
→ only break either *B* or *L*

- **strong** R-parity violation: decay topology of SUSY particles completely changes
- **weak** R-parity violation: only decay of (long-lived) LSP to SM particles



## Some facts of bilinear R-parity violation

- largest neutrino mass at tree level
- 2 mixing angles at tree level
- remaining masses/angles at 1-loop-level
- correct scales of mass differences  $\Delta m_{ij}^2$

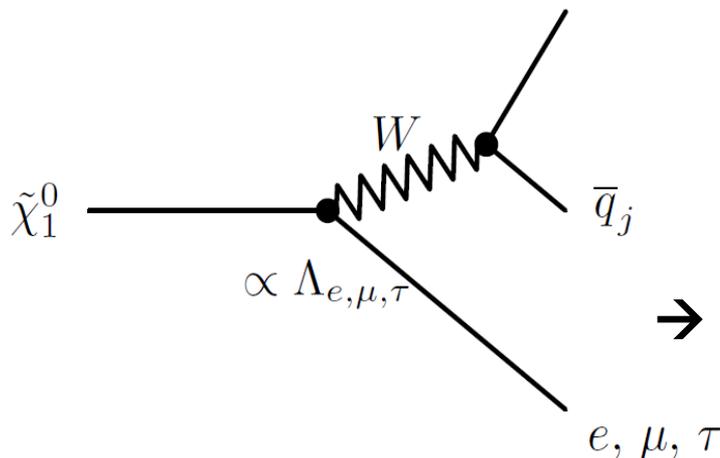
$$m_\nu = \frac{M_1 g^2 + M_2 g'^2}{4 \det M_{\chi^0}} |\vec{\Lambda}|^2$$

$$\tan \theta_{23} = \frac{\Lambda_\mu}{\Lambda_\tau}$$

$$\tan \theta_{13} = -\frac{\Lambda_e}{\sqrt{\Lambda_\mu^2 + \Lambda_\tau^2}}$$

## How is that connected to colliders?

dominant part of  $\tilde{\chi}_1^0 - W - l_i$  coupling:  $O_i^L = \Lambda_i \cdot f(M_1, M_2, \mu, \tan \beta, v_d, v_u) \propto \Lambda_i$



$$\tan^2 \theta_{23} = \left| \frac{\Lambda_\mu}{\Lambda_\tau} \right|^2 \cong \frac{BR(\tilde{\chi}_1^0 \rightarrow \mu W)}{BR(\tilde{\chi}_1^0 \rightarrow \tau W)}$$

→ Neutrino physics at collider experiments

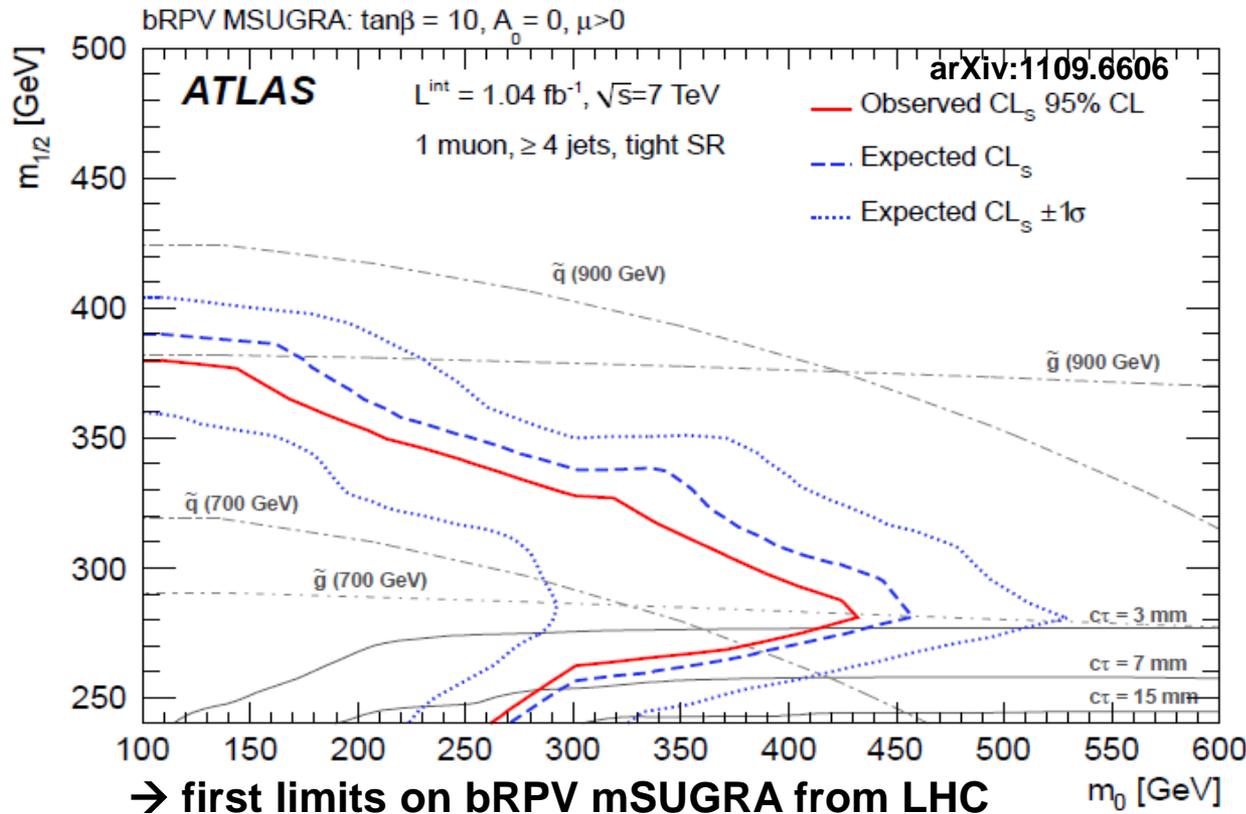
## Searches for bRPV supersymmetry in context of mSUGRA ( $\int L dt = 1 \text{ fb}^{-1}$ )

search for:

- 3 or 4 jets
- 1 muon or electron

for bRPV:

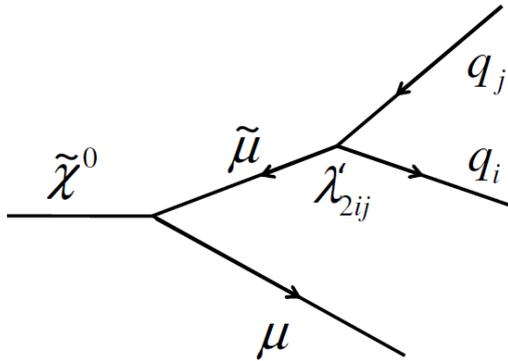
model tested for:  $c\tau < 15 \text{ mm}$  ( $\rightarrow m_{1/2} > 240 \text{ GeV}$ )



- exclusions for small  $m_{1/2}$  much harder to achieve than for RPC SUSY model
- LHC probes colored sector of theory  
*"...squark = gluino masses below 760 GeV are excluded"*
- increasing squark mass  $\rightarrow$  drop of cross section



## Dedicated displaced vertex search ( $\int Ldt = 33 \text{ pb}^{-1}$ )



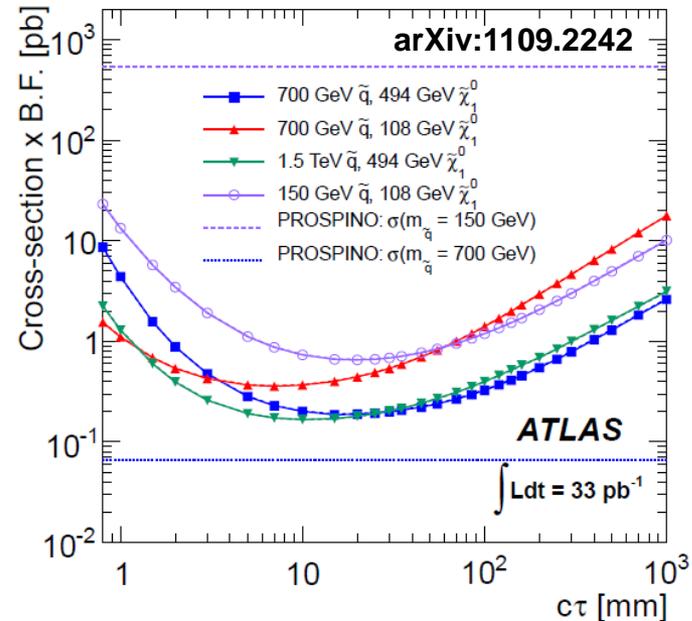
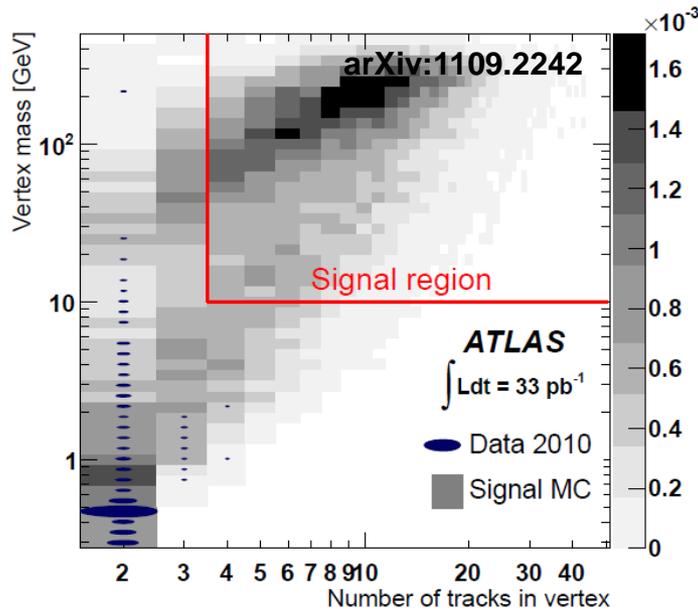
search for:

- $|z_{DV}| < 300\text{mm}$ ,  $4\text{mm} < r_{DV} < 180\text{mm}$
- 1 high- $p_t$  muon

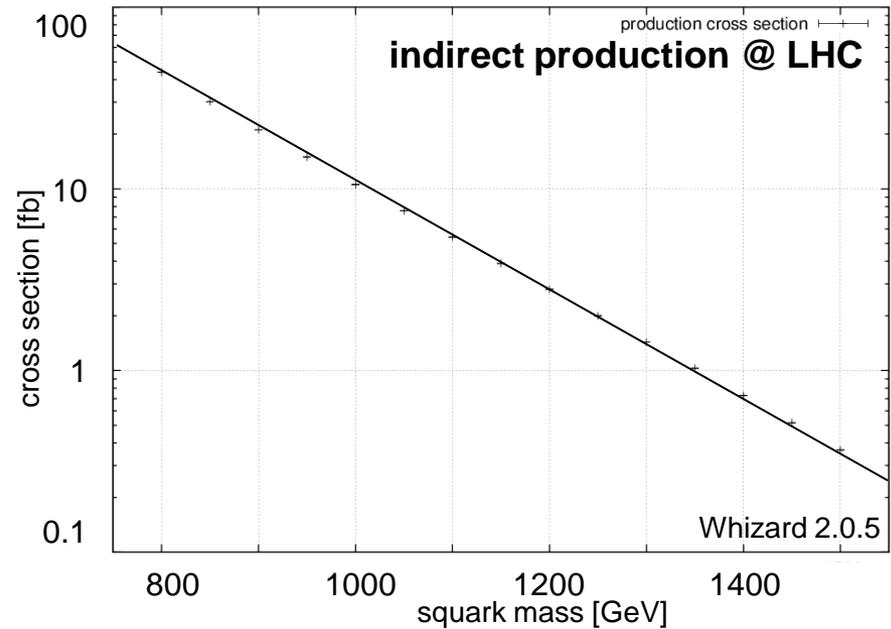
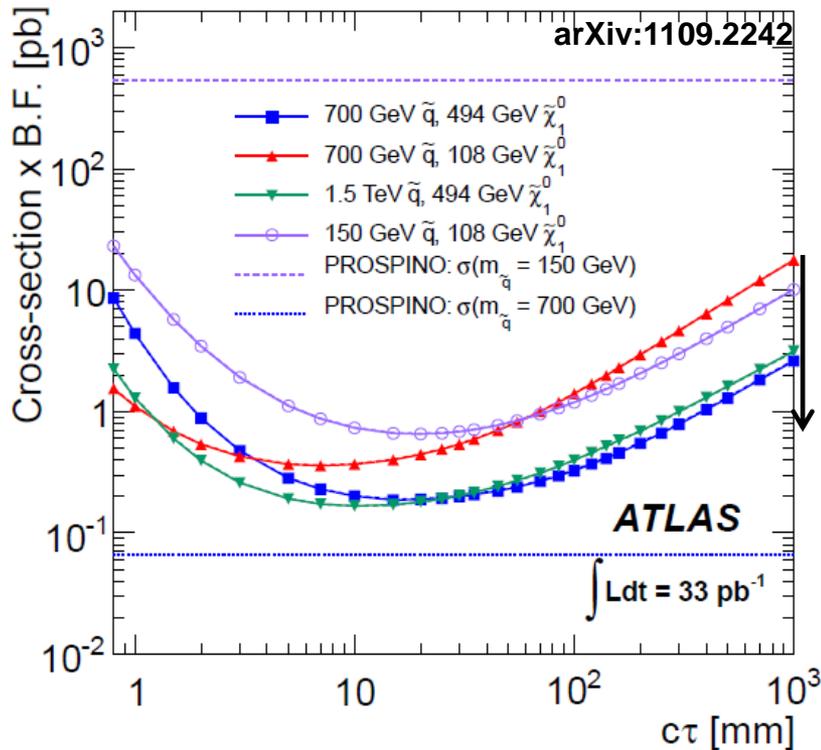
background free analysis ( $N_{BG} < 0.03$ )

assumption:

di-squark production  $\rightarrow$  direct decay to LSP



## Dedicated displaced vertex search



extrapolation:  $33\text{pb}^{-1} \rightarrow 5\text{fb}^{-1}$   
 $\rightarrow$  limits drop by a factor of  $\sim\sqrt{200}$  (=14)

- consider ILC-friendly case  $\rightarrow$  light neutralino (red curve)
- even with higher statistics LHC sensitive to  $c\tau=[1\text{mm};12\text{mm}]$  for  $m_{\text{squark}}=700\text{GeV}$
- not sensitive in case of high squark masses and large  $c\tau$



# Prospects for bRPV searches at the ILC

## Direct production @ ILC

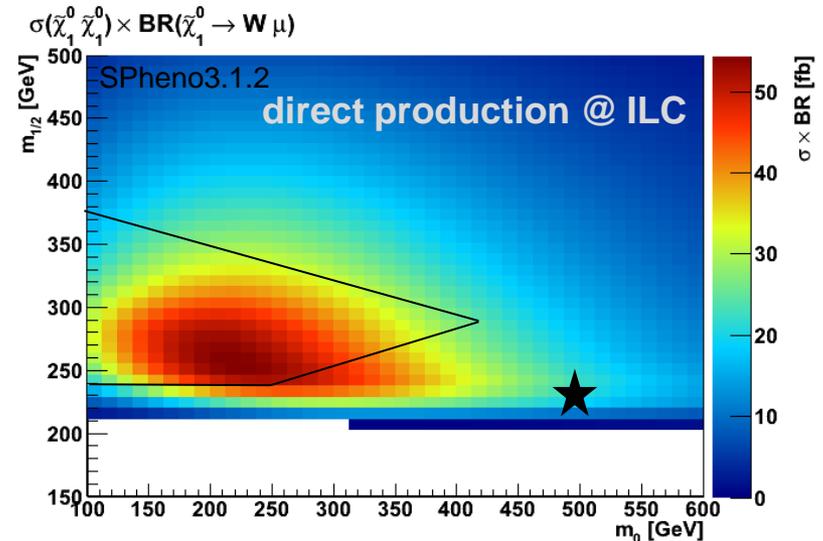
direct production cross section @ILC two orders of magnitudes higher than @LHC

**example point:** CMSSM:  $m_0 = 500$  GeV,  $m_{1/2} = 230$  GeV,  $\tan(\beta) = 10$ ,  $\text{sign}(\mu) = +$ ,  $A_0 = 0$  GeV

- $m(\tilde{\chi}_1^0) = 90$  GeV
- $ct = 19.07$ mm
- $\text{BR}(\tilde{\chi}_1^0 \rightarrow W \mu) = 0.42$
- $\text{BR}(\tilde{\chi}_1^0 \rightarrow W \tau) = 0.38$

beam polarization  $\sqrt{s} = 500$ GeV:

$P(e^+)$	$P(e^-)$	$\sigma(ee \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$ [fb]
+0.3	-0.8	9
-0.3	-0.8	13
<b>0</b>	<b>0</b>	<b>44</b>
+0.3	+0.8	55
<b>-0.3</b>	<b>+0.8</b>	<b>101</b>



expectations for  $\int L dt = 500 \text{ fb}^{-1}$ :

up to 12726 displaced ( $\mu j j$ ) - vertices

up to 11514 displaced ( $\tau j j$ ) - vertices



# Prospects for bRPV searches at the ILC

## Direct production @ ILC

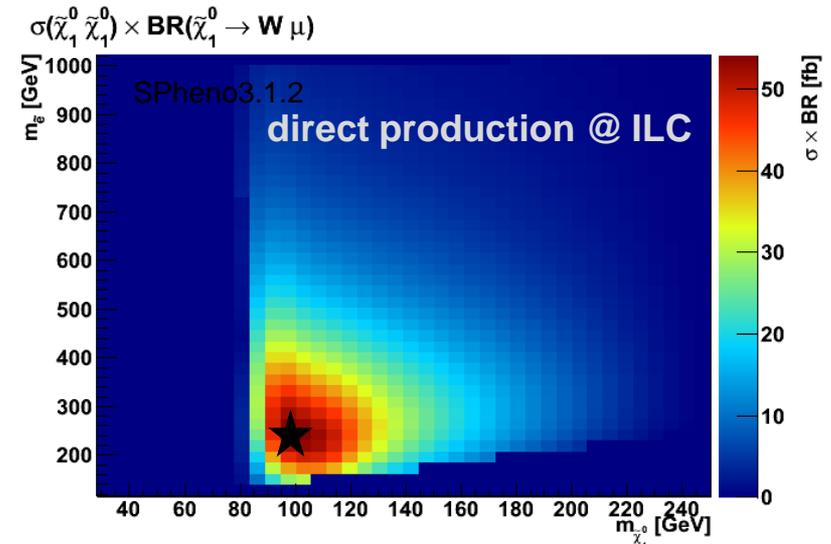
direct production cross section @ILC two orders of magnitudes higher than @LHC

**example point:** generic model

- $m(\tilde{\chi}_1^0) = 98.4 \text{ GeV}$
- $ct = 4.55 \text{ mm}$
- $\text{BR}(\tilde{\chi}_1^0 \rightarrow W \mu) = 0.28$
- $\text{BR}(\tilde{\chi}_1^0 \rightarrow W \tau) = 0.25$

beam polarization  $\sqrt{s} = 500 \text{ GeV}$ :

$P(e^+)$	$P(e^-)$	$\sigma(ee \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) \text{ [fb]}$
+0.3	-0.8	35
-0.3	-0.8	49
<b>0</b>	<b>0</b>	<b>170</b>
+0.3	+0.8	209
<b>-0.3</b>	<b>+0.8</b>	<b>387</b>



expectations for  $\int L dt = 500 \text{ fb}^{-1}$ :

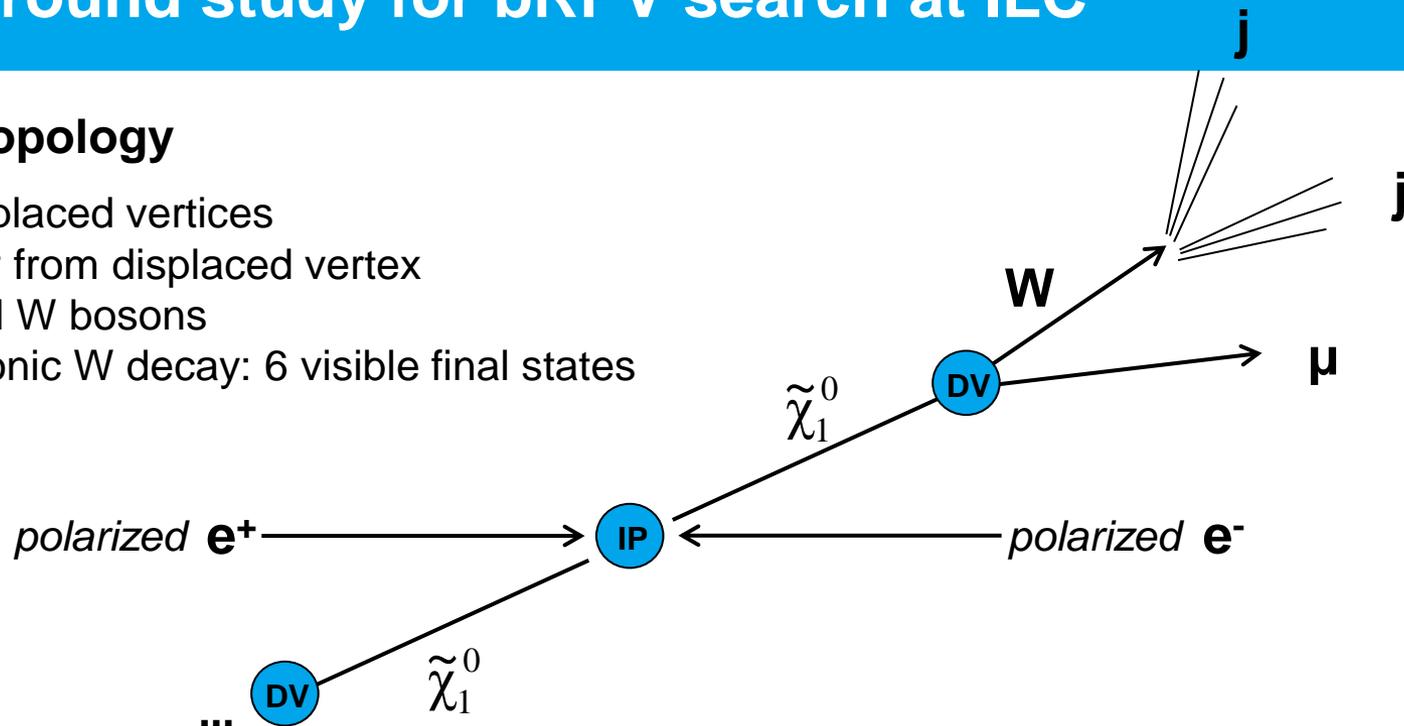
up to 32508 displaced ( $\mu jj$ ) - vertices

up to 29025 displaced ( $\tau jj$ ) - vertices

# Background study for bRPV search at ILC

## Event topology

- 2 displaced vertices
- $\mu$  or  $\tau$  from displaced vertex
- 2 real W bosons
- hadronic W decay: 6 visible final states



## Design of analysis

- force event into 6 jets
- 2 jets with least number of tracks and  $N < 4$  → "leptons"
- 4 jets with  $N \geq 4$  tracks → "quarks"
- find best combination of quark jets to form 2 W bosons
- add leptons to find best combination to form 2 equal mass objects

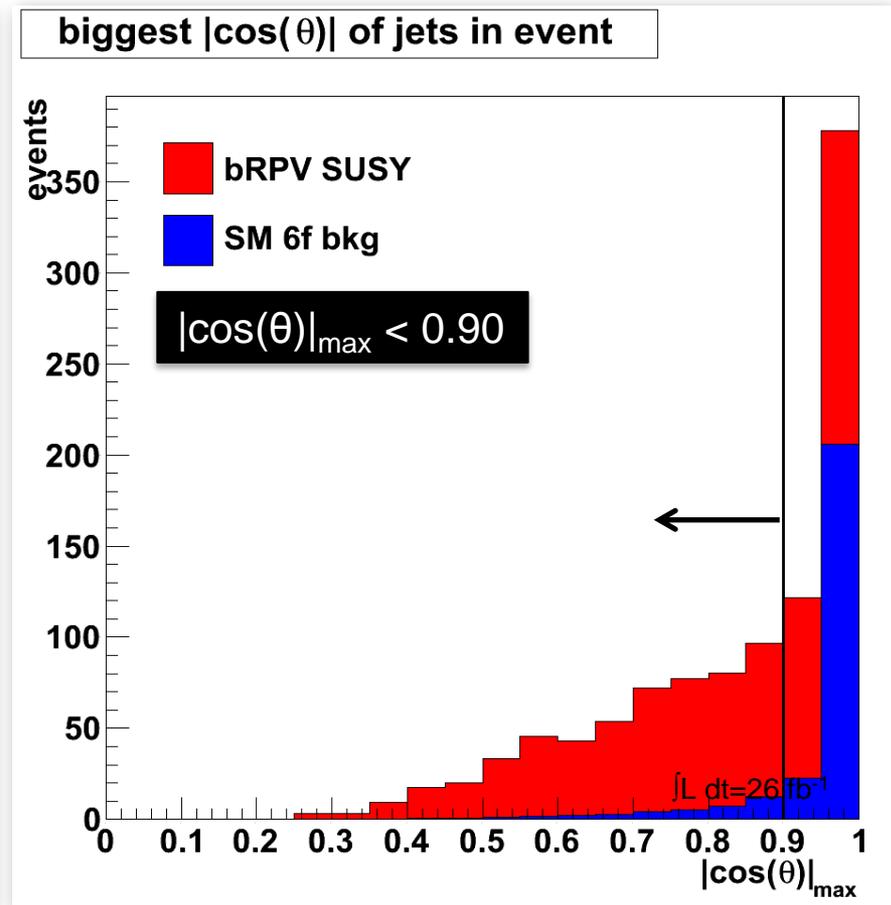
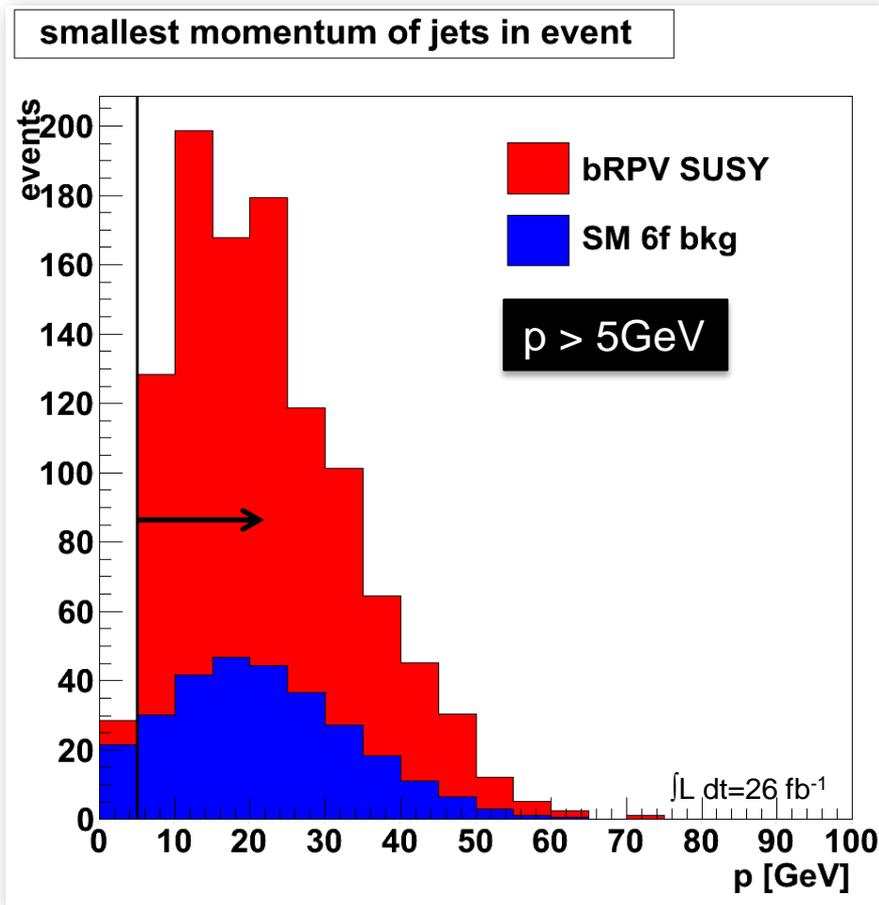
$$\chi^2 = \frac{(m_{ijk} - m_{lmn})^2}{(5 \text{ GeV})^2}$$

Analysis based on  $\int L dt = 26 \text{ fb}^{-1}$



# Background study for bRPV search at ILC

## Kinematic cuts

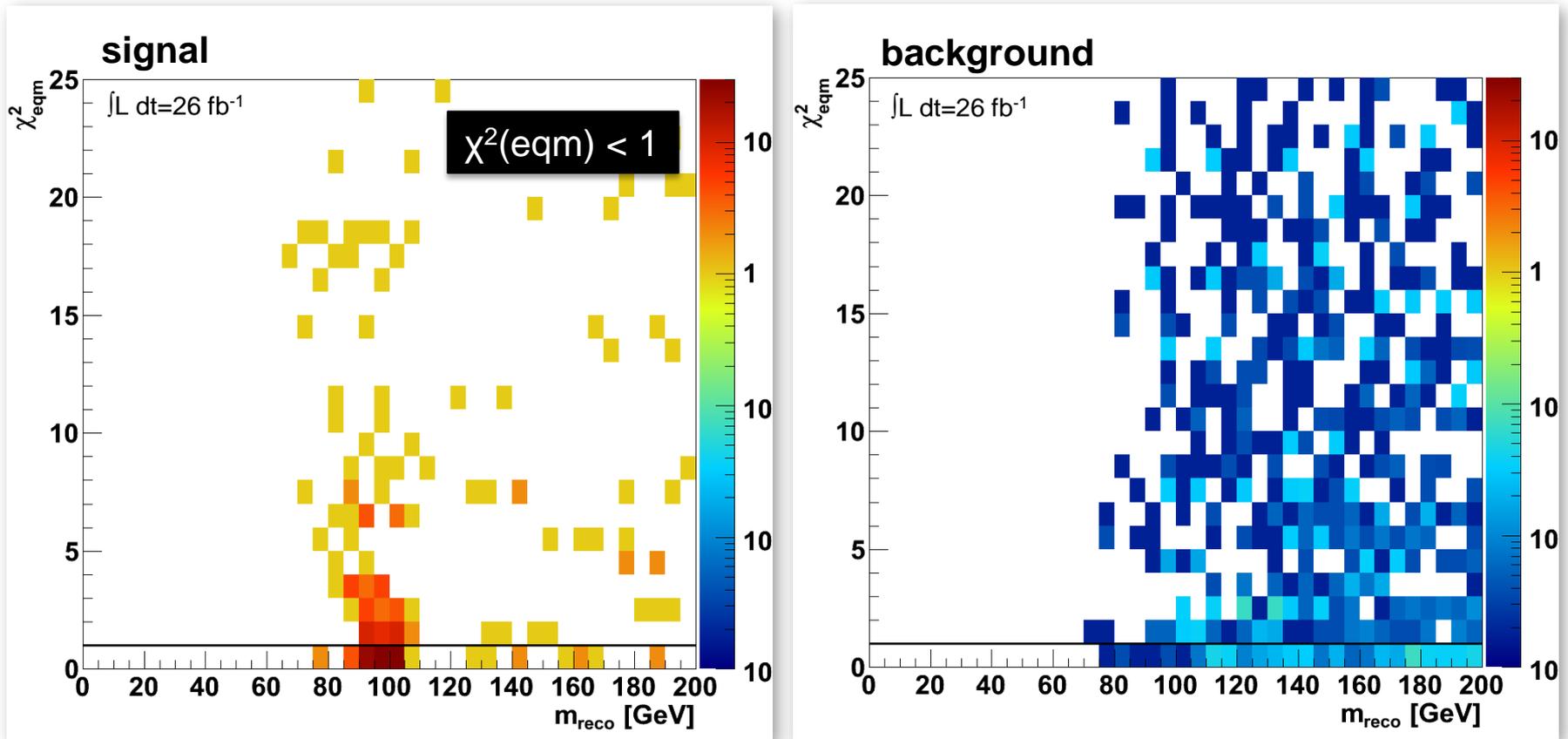


→  $\cos(\theta)$  very powerful to reduce background!



# Background study for bRPV search at ILC

## Chi2 of equal mass object reconstruction

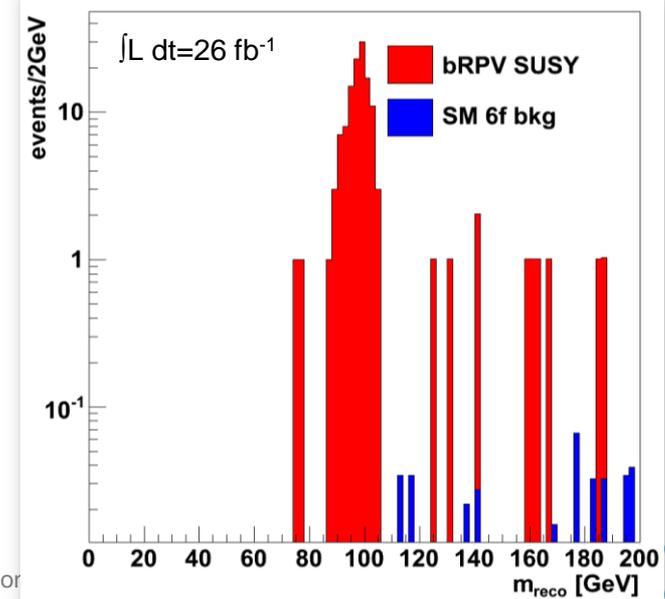
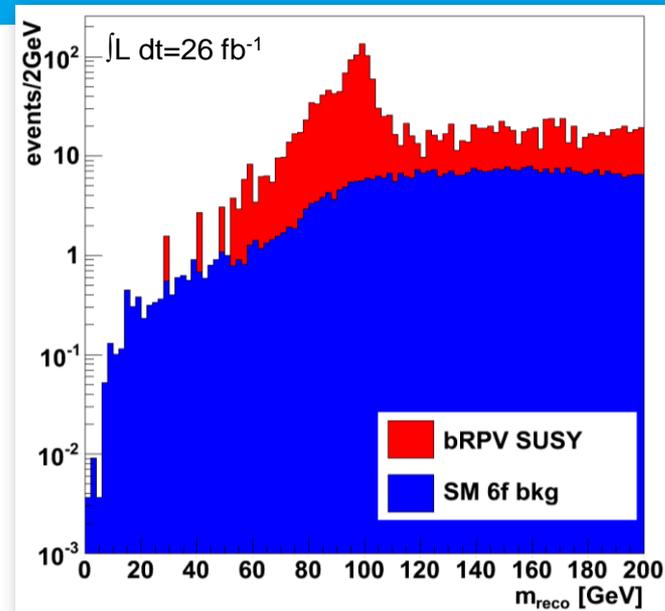


# Background study for bRPV search at ILC

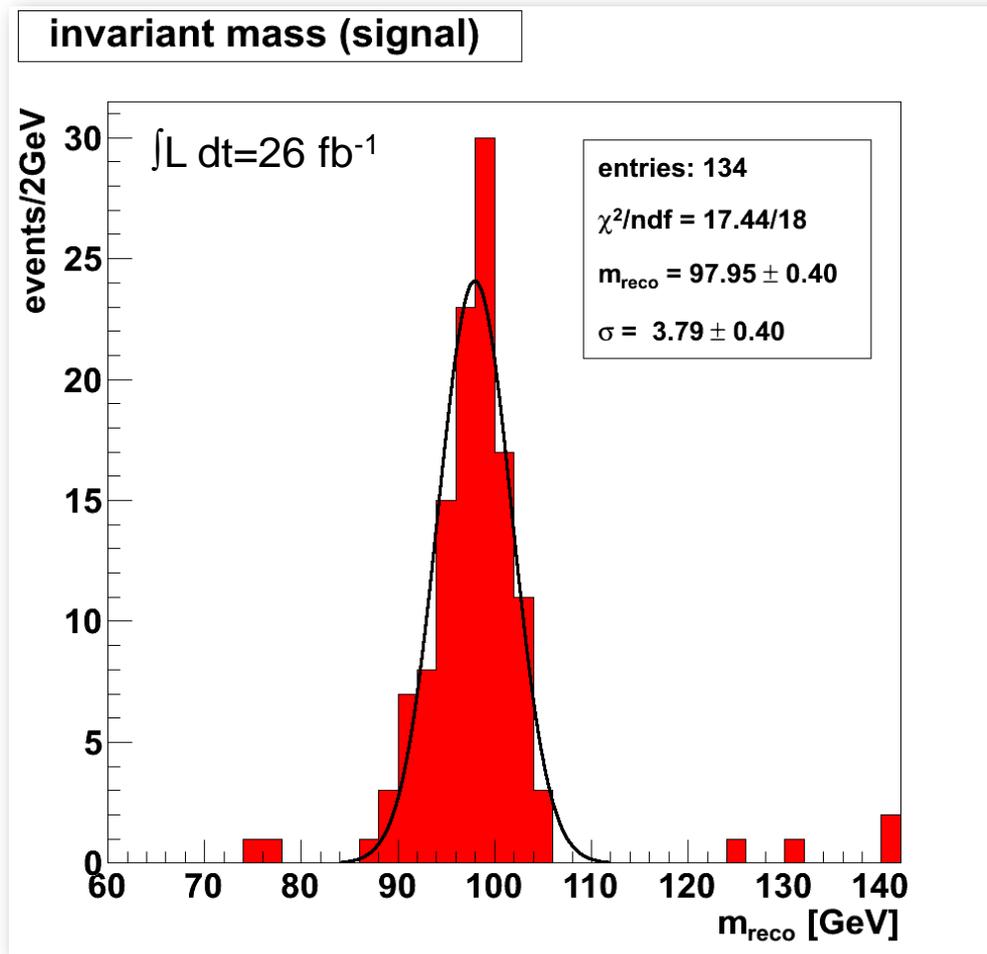
## Cut flow

cut flow	$\int L dt = 26 \text{ fb}^{-1}$	
	S	B
no cut	794	289.78
$p > 5 \text{ GeV}$	787	268.16
$ \cos(\theta) _{\max} < 0.9$	516	39.48
$N_{\min}(\text{q jets}) \geq 4$	446	33.71
$N_{\max}(\text{l jets}) < 4$	188	7.79
$\chi^2(\text{equal mass}) < 1$	67	0.41
<b>efficiency</b>	<b>0.084</b>	<b>0.001</b>

- even with this simple lepton identification  
~8% signal efficiency
- dedicated lepton finder will do much better
- **almost background free** (0.41 bg events)



## Neutralino mass reconstruction



theoretical value:

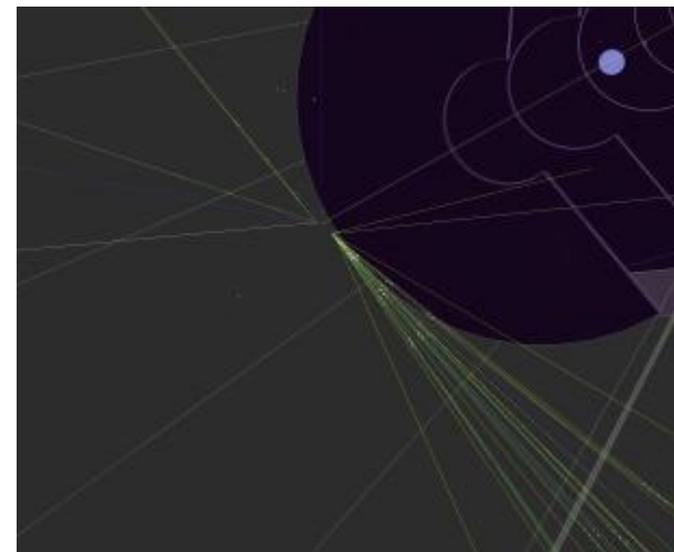
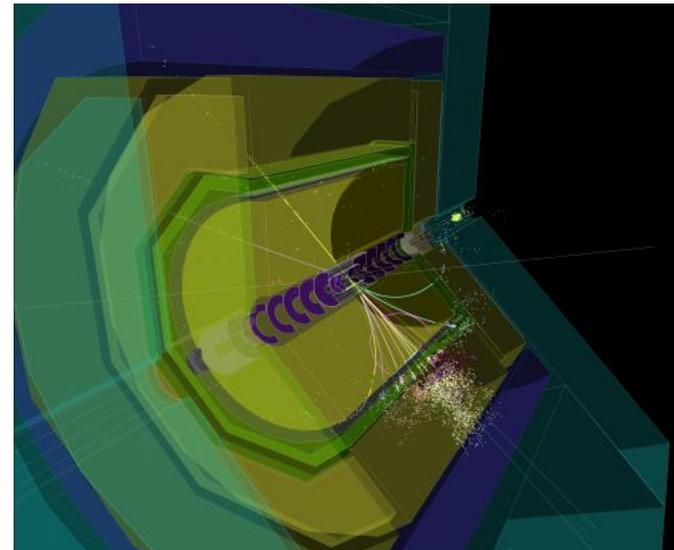
$$m(\tilde{\chi}_1^0) = 98.4 \text{ GeV}$$

# Conclusion

## Conclusion

- R-parity violation is an interesting alternative to R-parity conserving SUSY
- some RPV searches ongoing at LHC
- especially in the case of high squark masses: sensitivity of ILC expected to be better
- signature  $\chi \chi \rightarrow (W+I)+(W+I)$  almost background free
- interesting interpretation in terms of neutrino parameters
- other bRPV scenarios with similar experimental signature, that explain e.g. leptogenesis
- **ILC is the perfect machine to study this signatures**

**Thank you for your attention.**



# Backup slides



## Superpotential

$$W = \underbrace{\varepsilon_{ab} \left( h_U^{ij} \hat{Q}_i^a \hat{U}_j \hat{H}_u^b + h_D^{ij} \hat{Q}_i^b \hat{D}_j \hat{H}_d^a + h_E^{ij} \hat{L}_i^b \hat{R}_j \hat{H}_u^a - \mu \hat{H}_d^a \hat{H}_u^b \right)}_{\text{MSSM superpotential}} + \underbrace{\varepsilon_i \hat{L}_i^a \hat{H}_u^b}_{\text{bRPV term}}$$

→ Higgs/Slepton-mixing

→ Sneutrinos acquire VEV  $\langle \tilde{\nu}_i \rangle = v_i$

→ corresponding RPV soft SUSY breaking term  $L_{soft}^{BRpV} = -B_i \varepsilon_{ab} \varepsilon_i \tilde{L}_i^a H_u^b$

$i=1\dots3$

## masses and mixings of neutral fermions

Basis of neutral fermions:  $\psi^{0T} = (-i\lambda', -i\lambda^3, \tilde{H}_d^1, \tilde{H}_u^2, \nu_e, \nu_\mu, \nu_\tau)$

Mass terms in the Lagrangian are given by:  $L_m = -\frac{1}{2} (\psi^0)^T \mathbf{M}_N \psi^0 + h.c.$

$$\mathbf{M}_N = \begin{pmatrix} M_{\chi^0} & m^T \\ m & 0 \end{pmatrix}$$

4x4 MSSM neutralino mixing matrix → ← 4x3 RPV matrix



Approximate diagonalization of  $\mathbf{M}_N$

$$\mathbf{M}_N = \begin{pmatrix} M_{\chi^0} & m^T \\ m & 0 \end{pmatrix}$$

$\mathbf{M}_N$  can be block-diagonalized for small RPV parameters via the Seesaw-like diagonalization:

$$\mathbf{M}_N = \text{diag}(M_{\chi^0}, m_{\text{eff}})$$

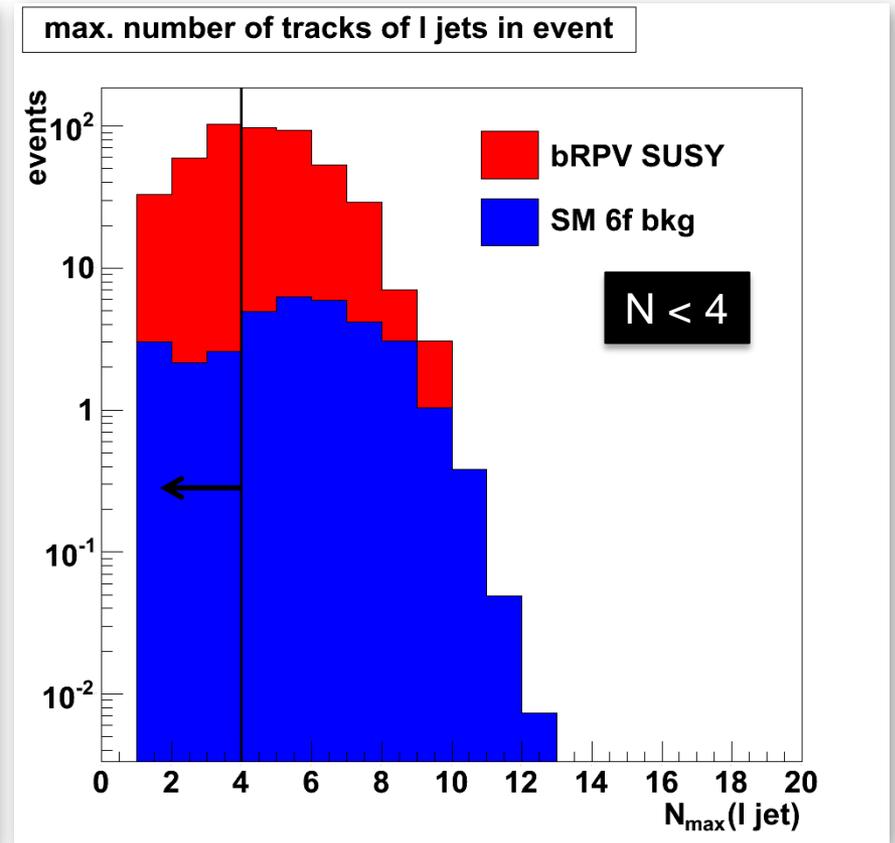
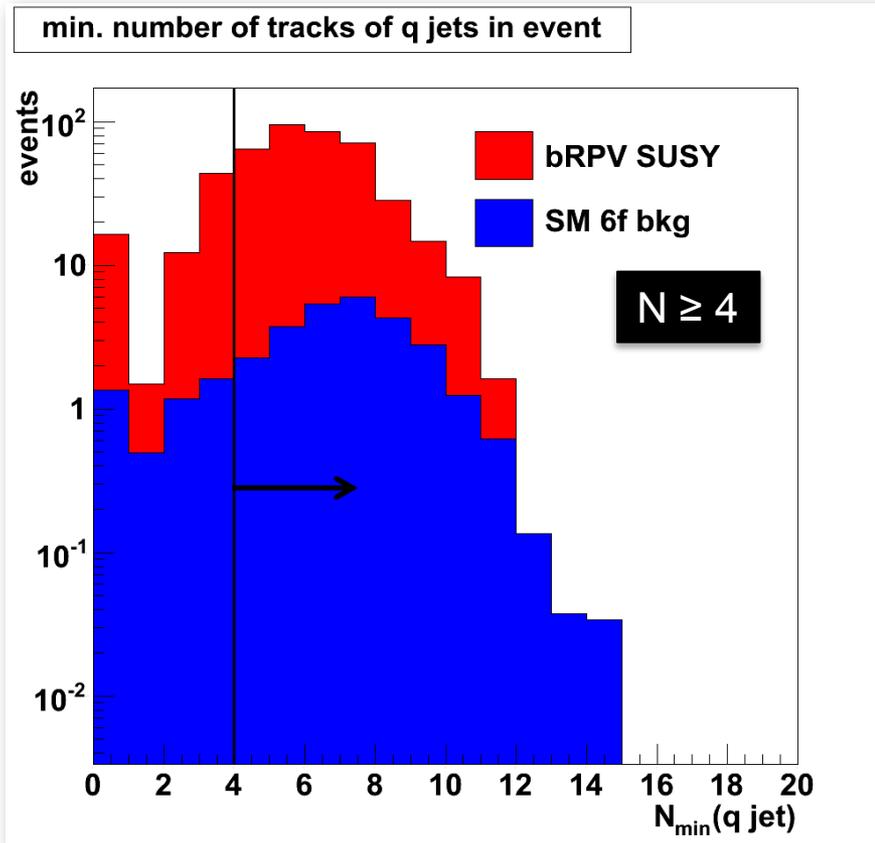
$$m_{\text{eff}} = -m M_{\chi^0} m^T = \frac{M_1 g^2 + M_2 g'^2}{4 \det M_{\chi^0}} \begin{pmatrix} \Lambda_e^2 & \Lambda_e \Lambda_\mu & \Lambda_e \Lambda_\tau \\ \Lambda_\mu \Lambda_e & \Lambda_\mu^2 & \Lambda_\mu \Lambda_\tau \\ \Lambda_\tau \Lambda_e & \Lambda_\tau \Lambda_\mu & \Lambda_\tau^2 \end{pmatrix}$$

where  $\Lambda_i = \varepsilon_i v_d + \mu v_i$  „alignment parameters“

A final diagonalization of  $M_{\chi^0}$  leads to the neutralino masses  $m_{\chi_i^0}$   
and a diagonalization of  $m_{\text{eff}}$  leads to one tree level neutrino mass.



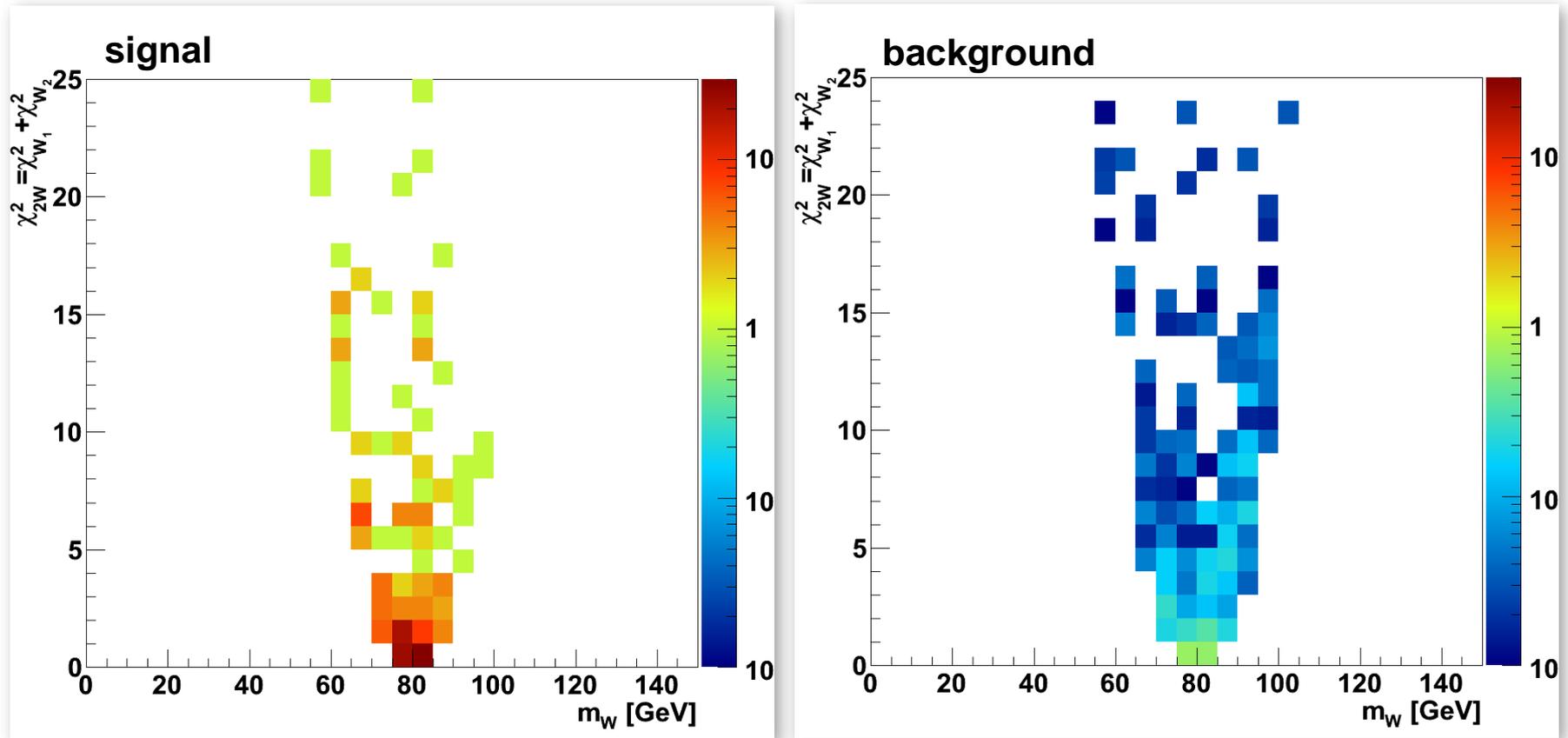
# Cut on number of tracks



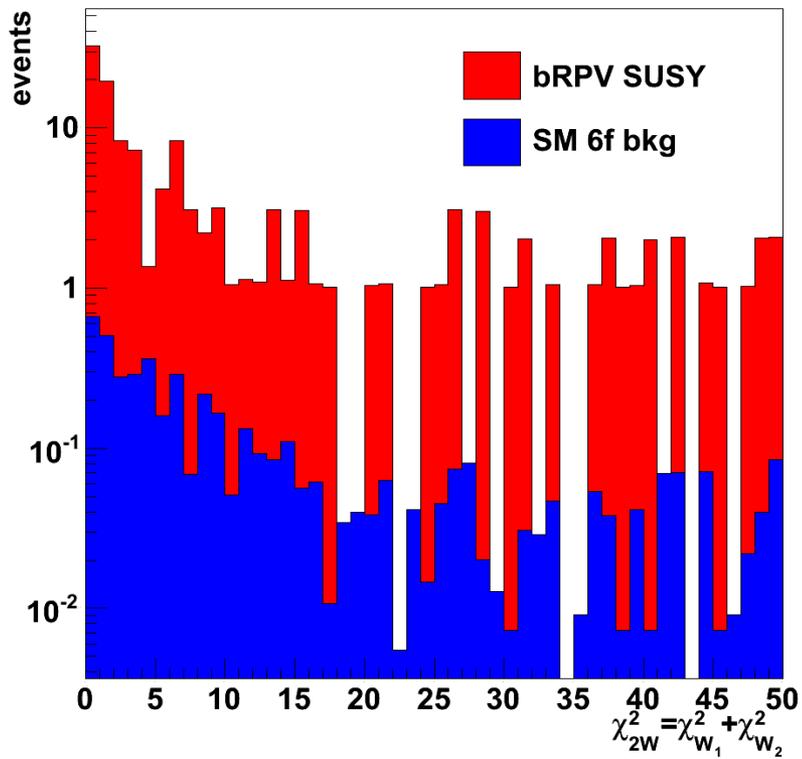
→ simple lepton finding has bad efficiency!



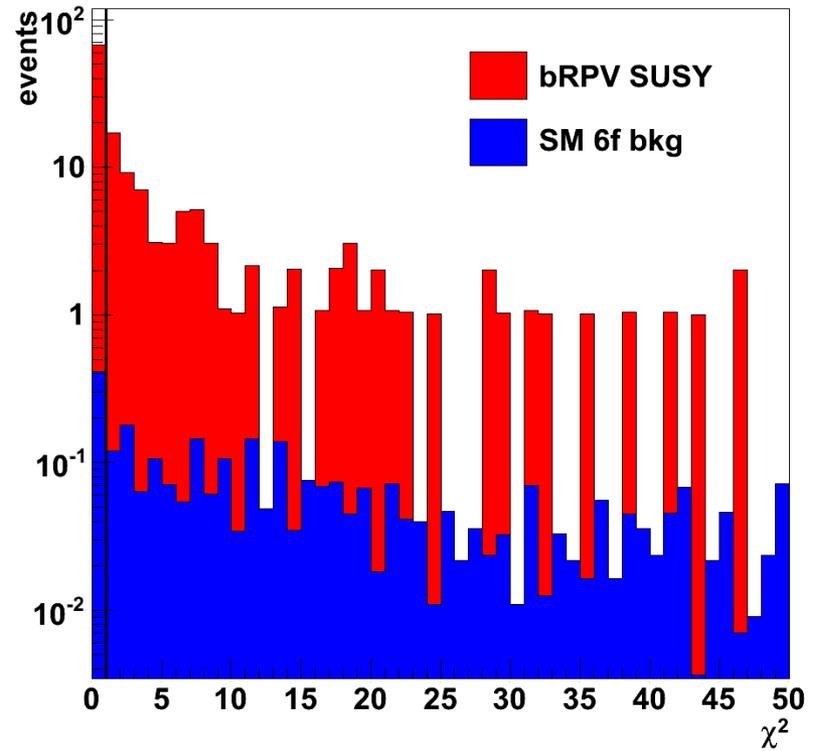
# Chi2 for W reconstruction

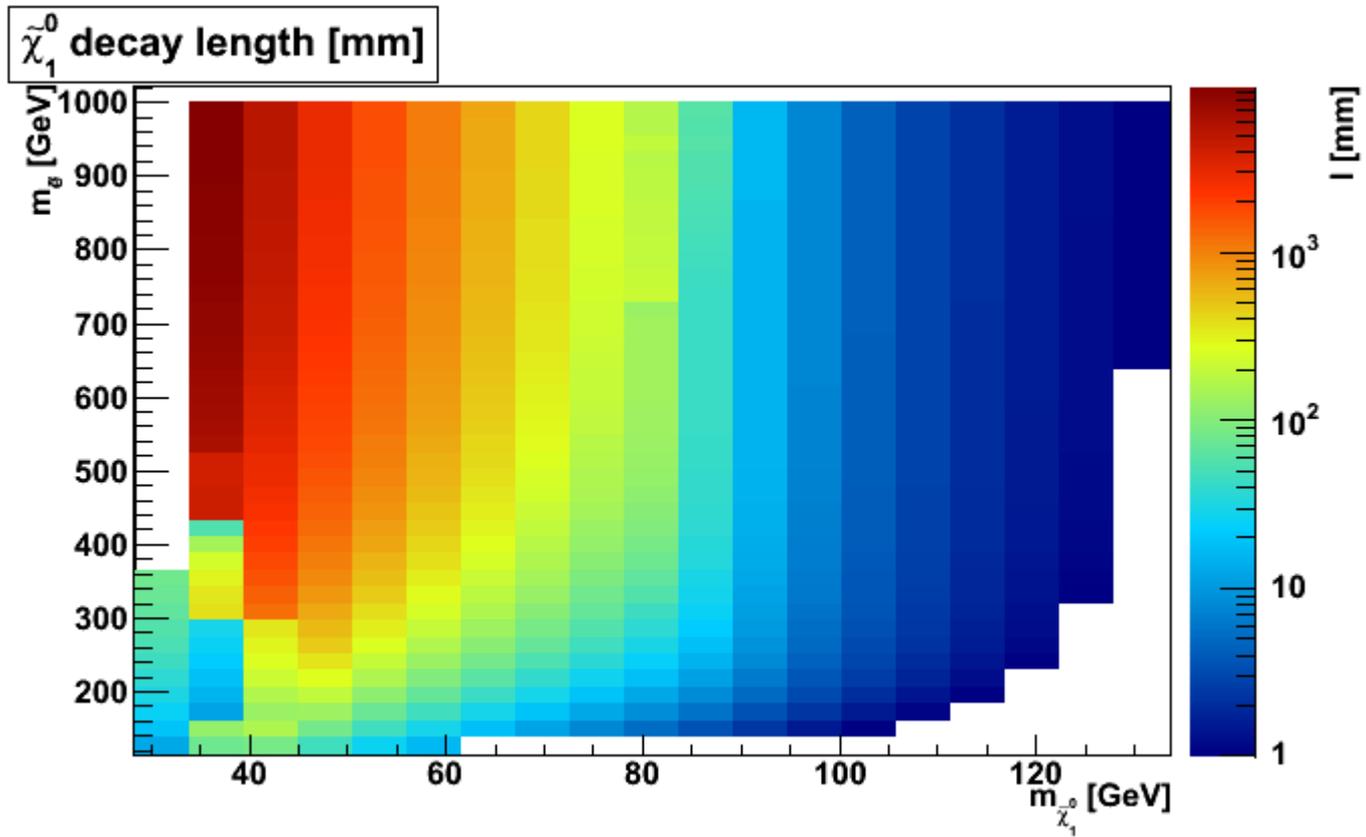


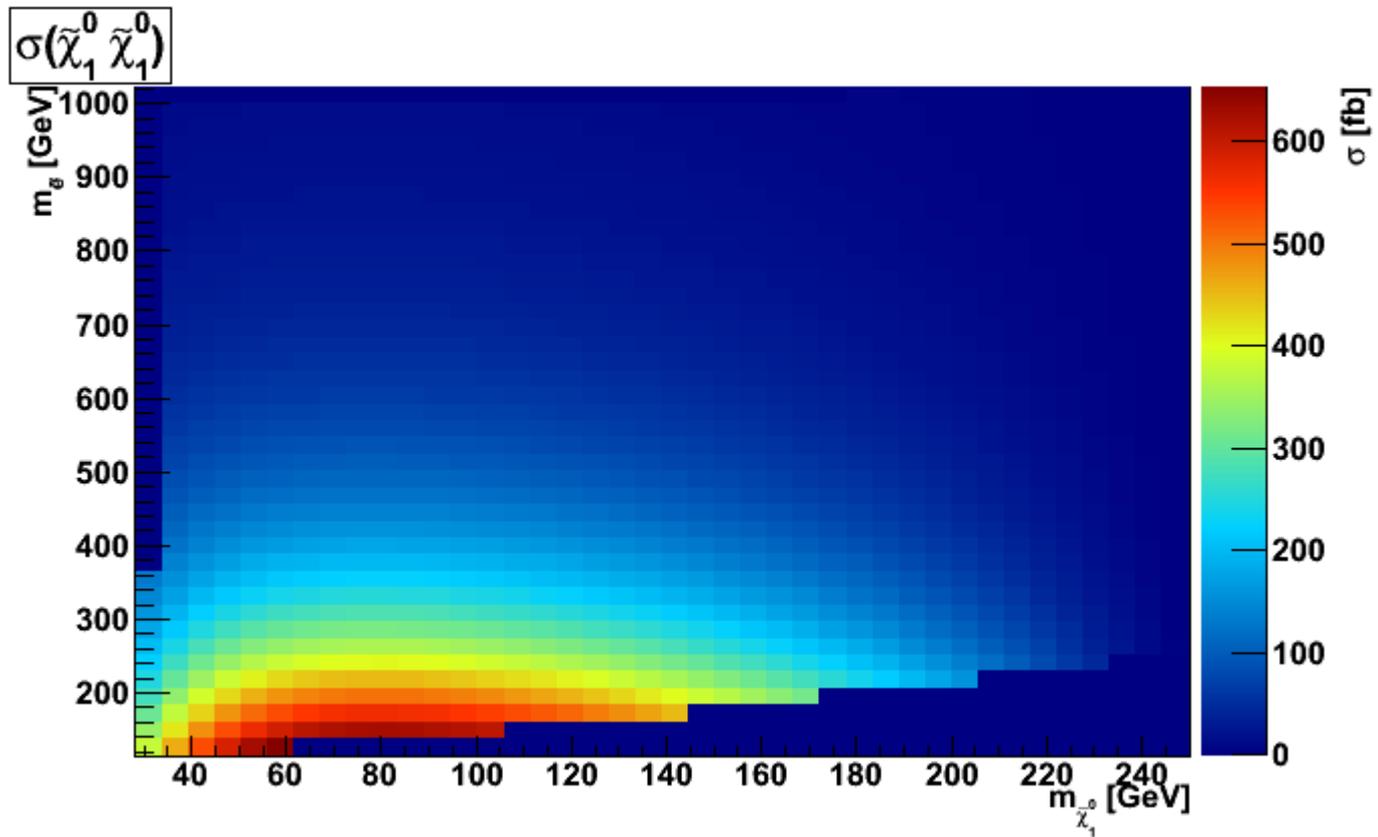
$\chi^2$  for reconstruction of 2 W

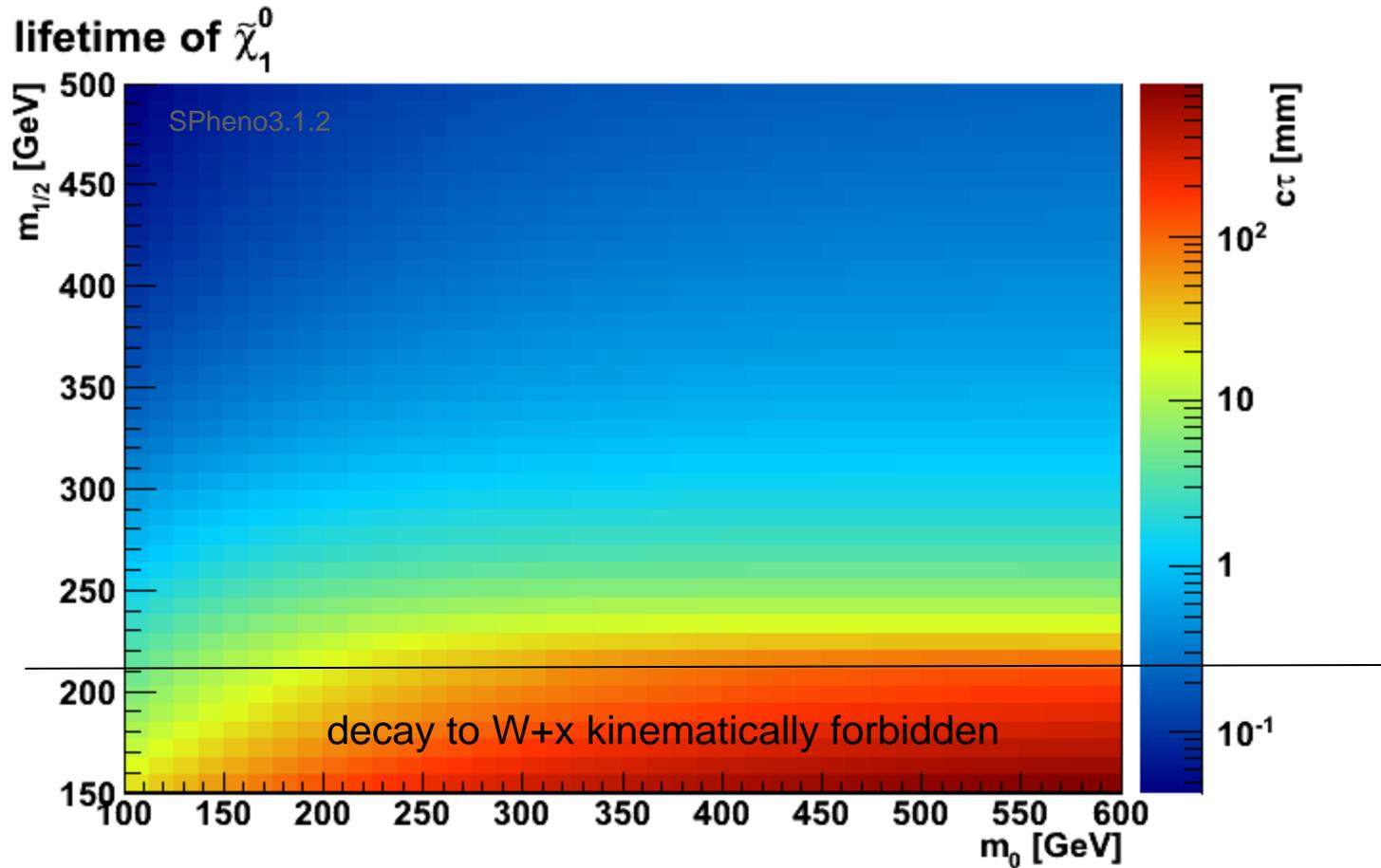


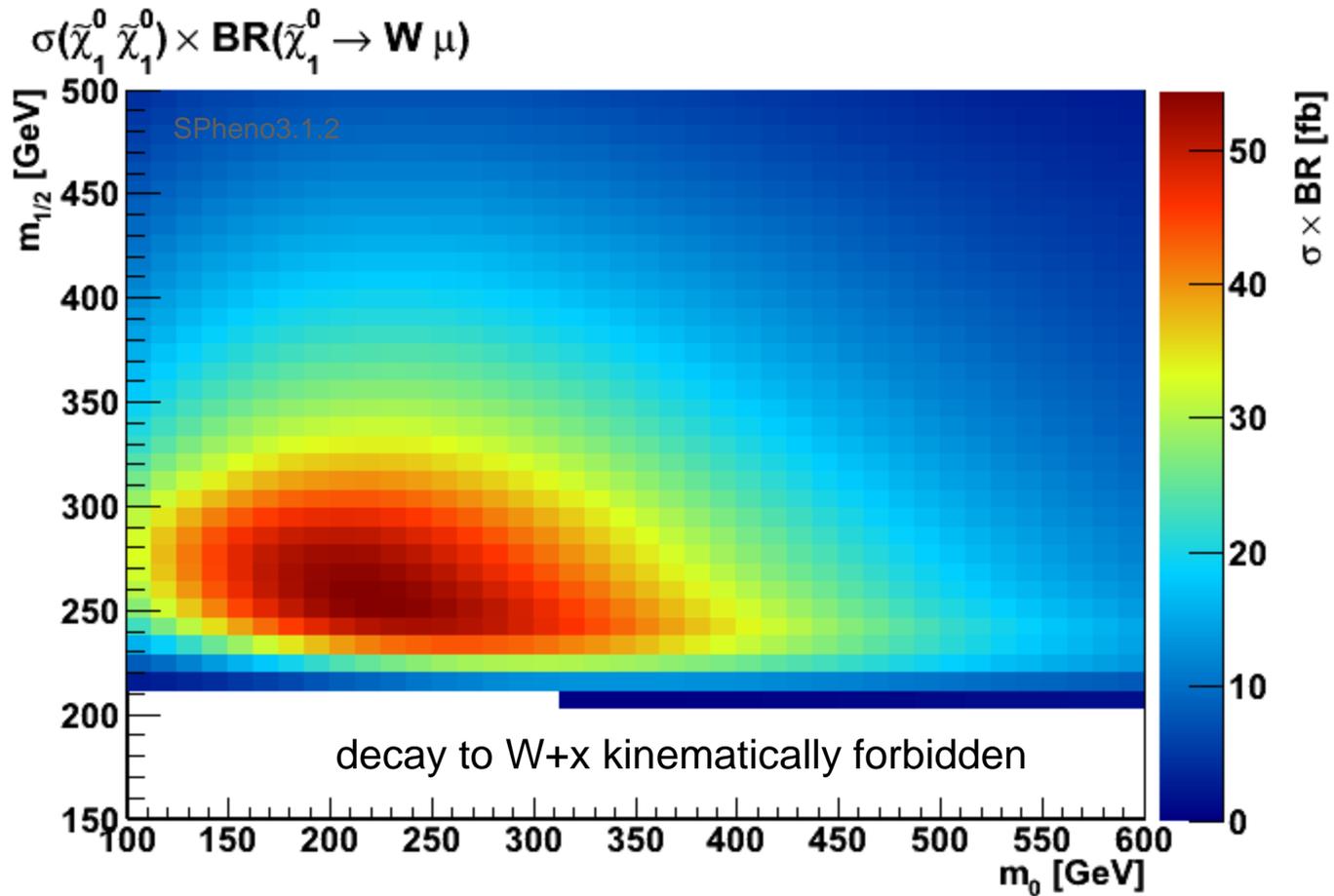
$\chi^2$  for reconstruction of equal mass objects

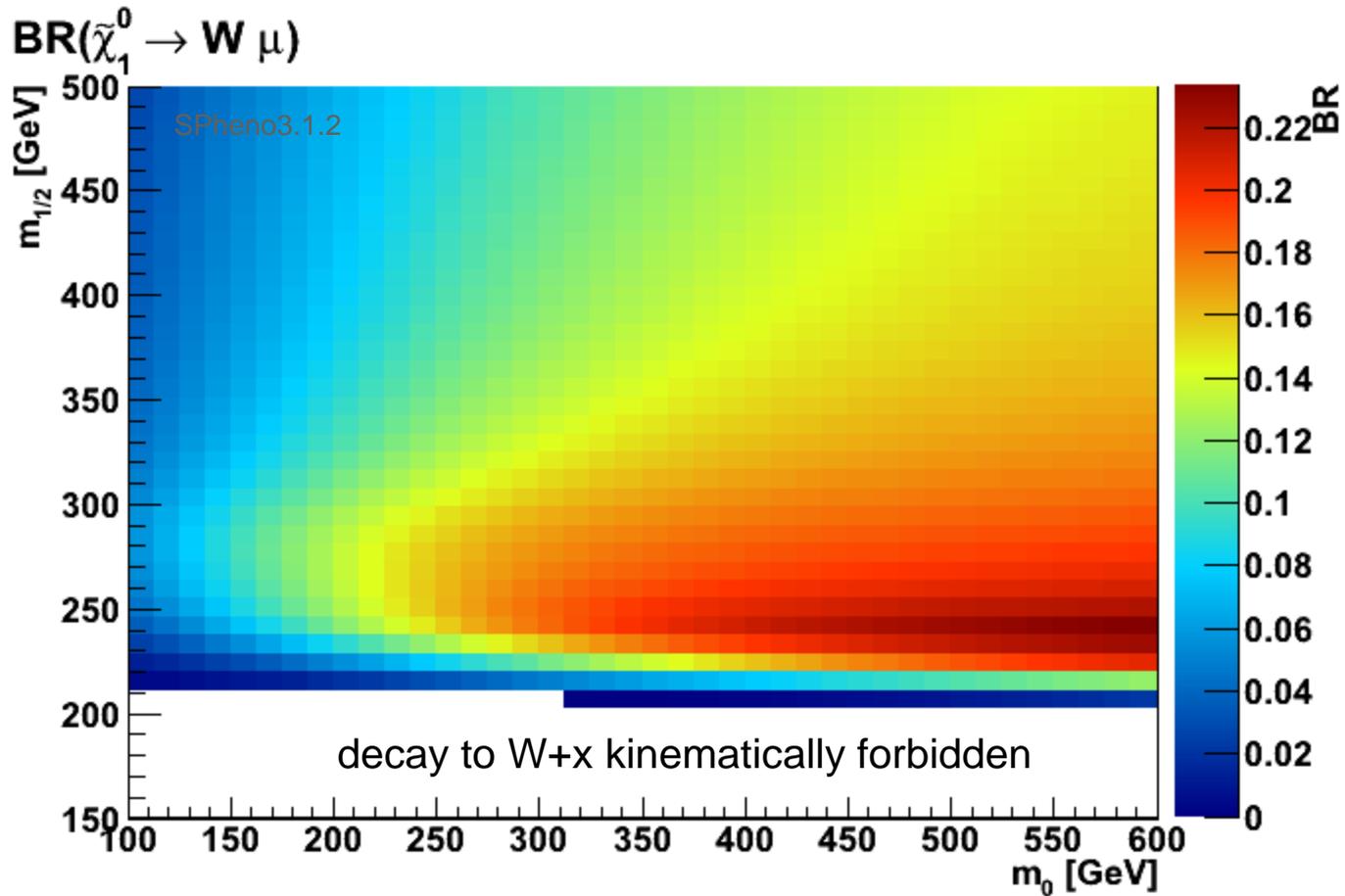




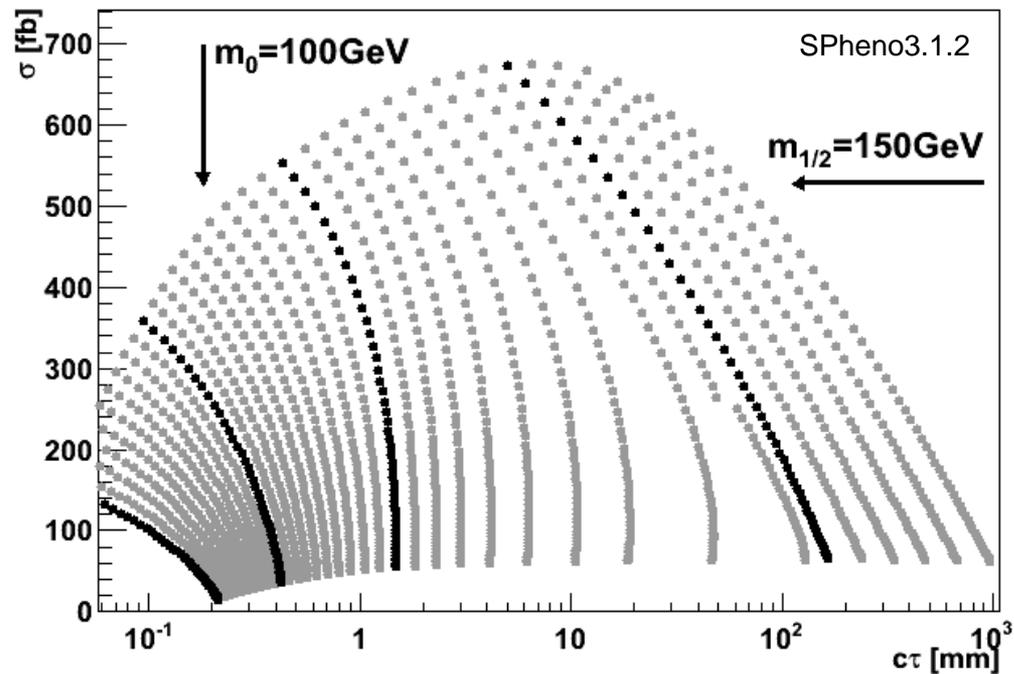








### cross section vs. lifetime



### cross section vs. lifetime

