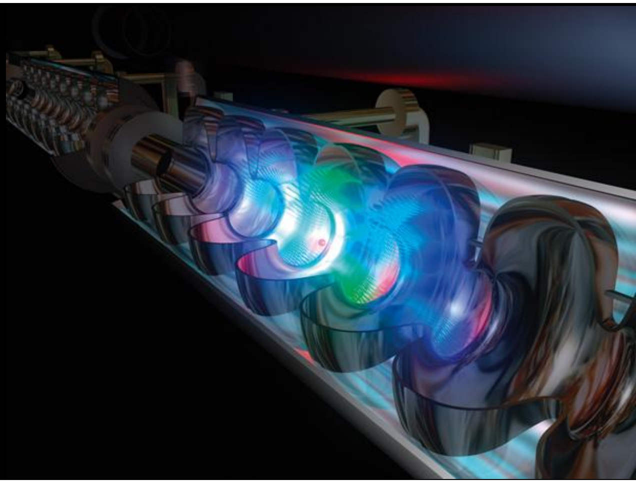
R-parity violation at LHC & ILC

Ongoing LHC searches and impact on ILC



Benedikt Vormwald, Jenny List,
Gudrid Moortgat-Pick
Linear Collider Forum
DESY Hamburg, 07.-09.02.2012

Outline

- R-parity violation
- Ongoing RPV searches at LHC and impact on ILC studies
- Status of ILC RPV analysis
- 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 (⇔SM)
- *B* and *L* violation never observed

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

$$\boxed{P_R = (-1)^{3B+L+2S}}$$

⟶ SM particles: $P_R = +1$

⟶ SUSY partners: $P_R = -1$

DESY

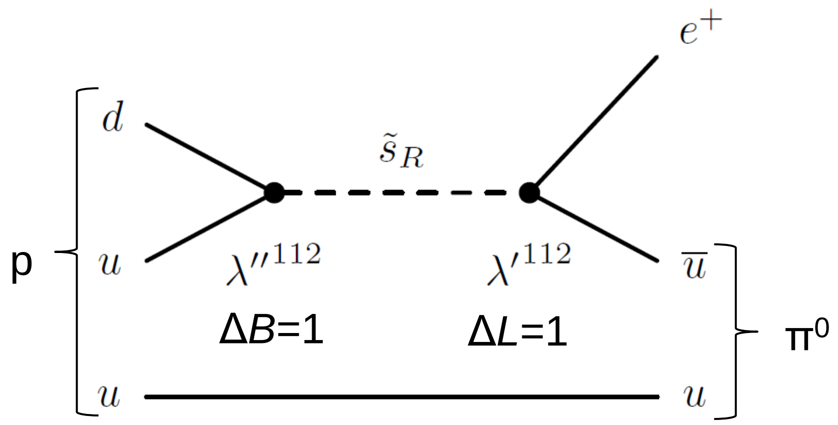
R-parity violation

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 λ“·λ‘
- 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

R-parity violation

W. Porod et. al.
arXiv:hep-ph/0011248

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 Δm_{ij}^2

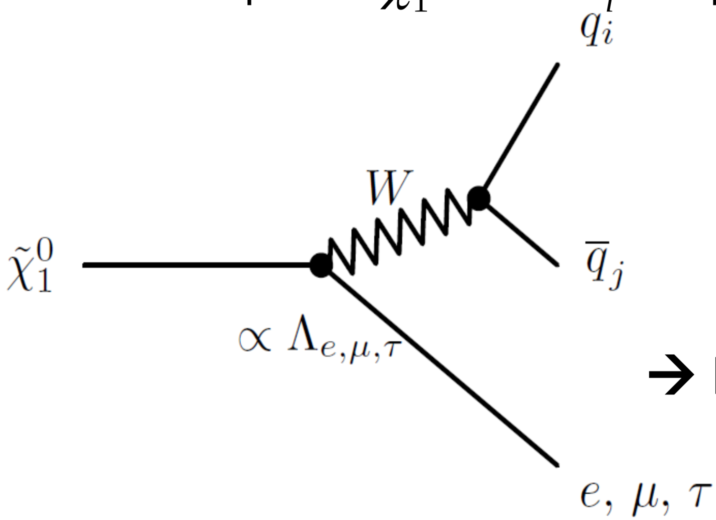
$$m_\upsilon = \frac{M_1 g^2 + M_2 g'^2}{4 \det M_{\chi^0}} \left|\vec{\Lambda}\right|^2$$

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

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

How is that connected to colliders?

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



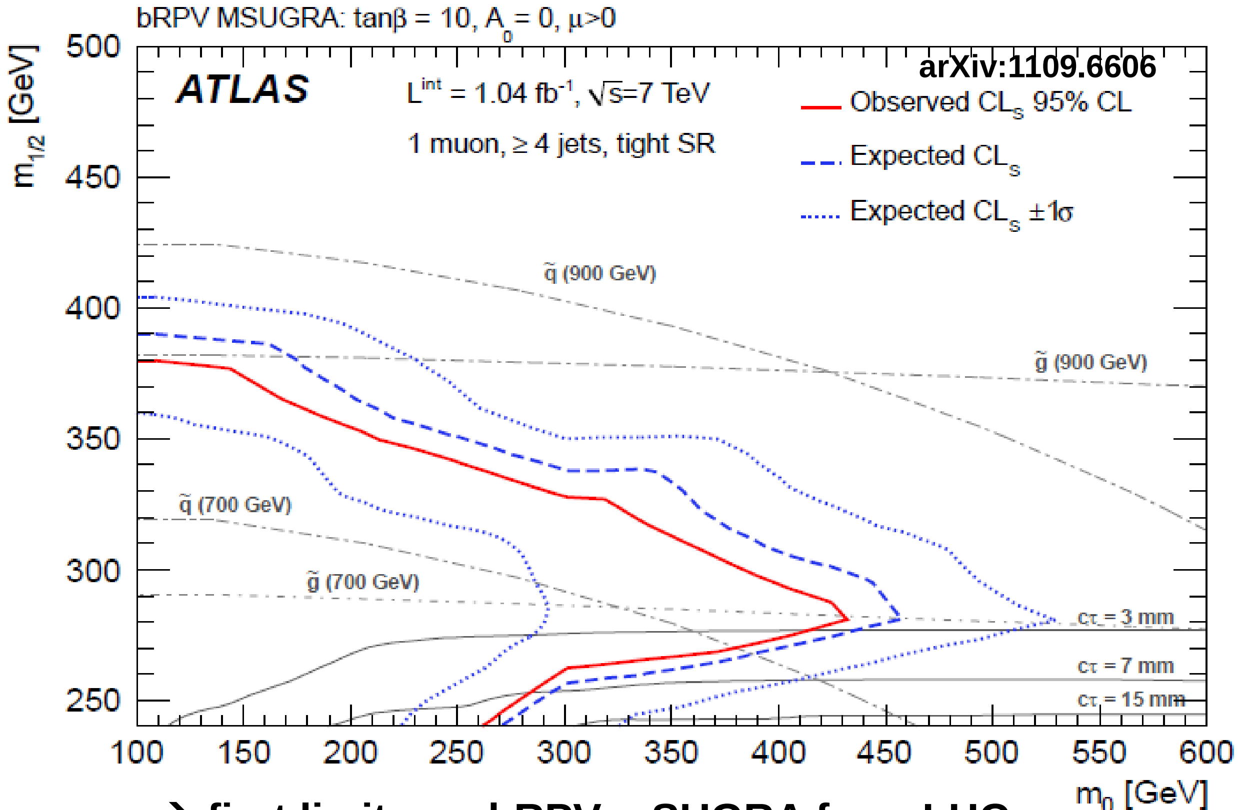
$$\tan^2\theta_{23} = \left|\frac{\Lambda_\mu}{\Lambda_\tau}\right|^2 \cong \frac{BR(\tilde{\chi}_1^0 \to \mu W)}{BR(\tilde{\chi}_1^0 \to \tau W)}$$

→ **Neutrino physics at collider experiments**

Searches for supersymmetry with respect to bRPV

- $\int L dt = 1\ fb^{-1}$
- 3 or **4 jets**
- **1 muon** or electron

for bRPV:
model tested for: cτ < 15 mm (→ $m_{1/2}$ > 240GeV)



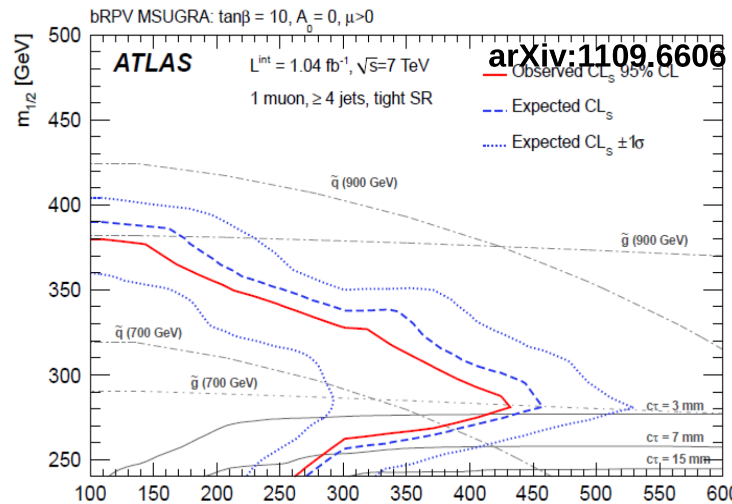
→ first limits on bRPV mSUGRA from LHC

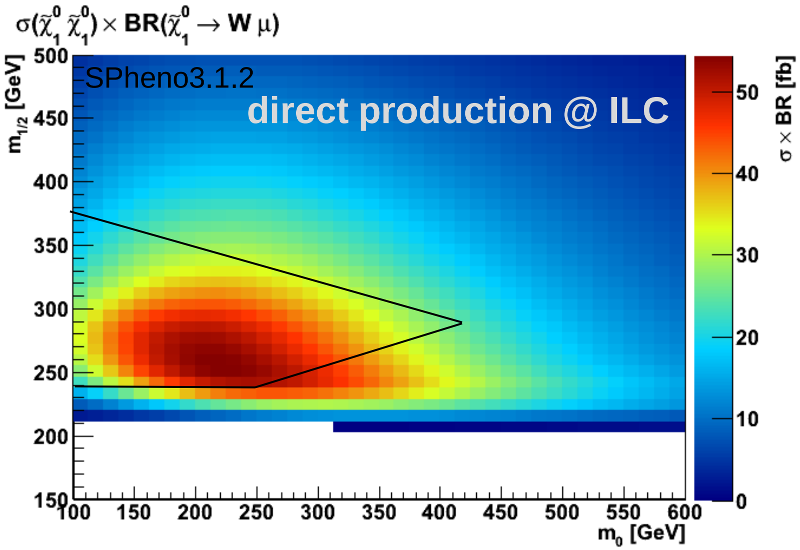
Impact on ILC

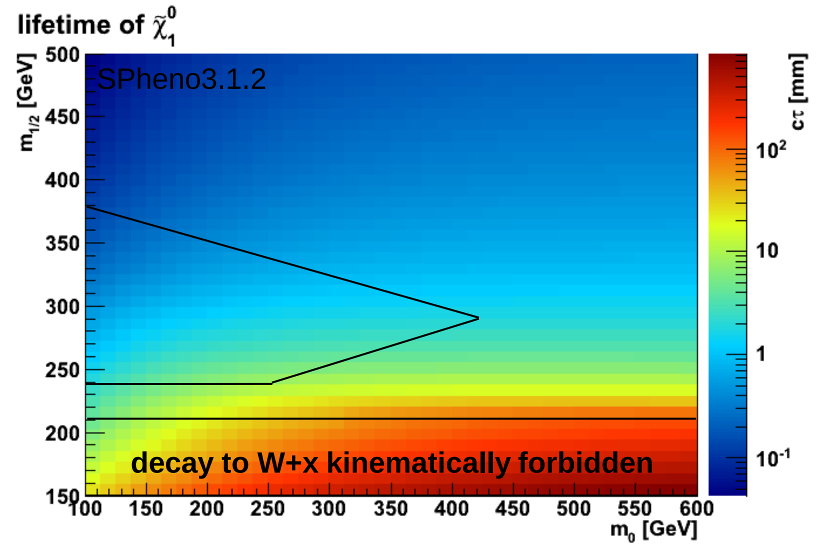
arXiv:1109.6606

Searches for supersymmetry with respect to bRPV

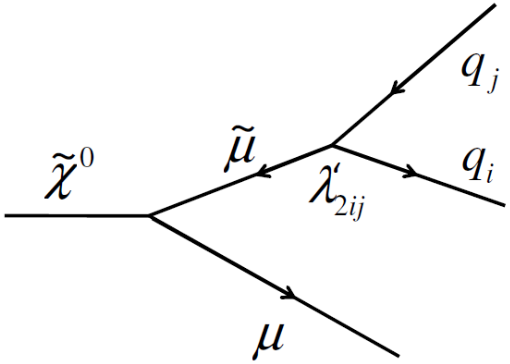
- LHC probes colored sector of theory "*...squark = gluino masses below 760 GeV are excluded*"
- increasing squark mass → drop of cross section
- exclusions for small $m_{1/2}$ much harder to achieve than for RPC SUSY model







Dedicated displaces vertex search

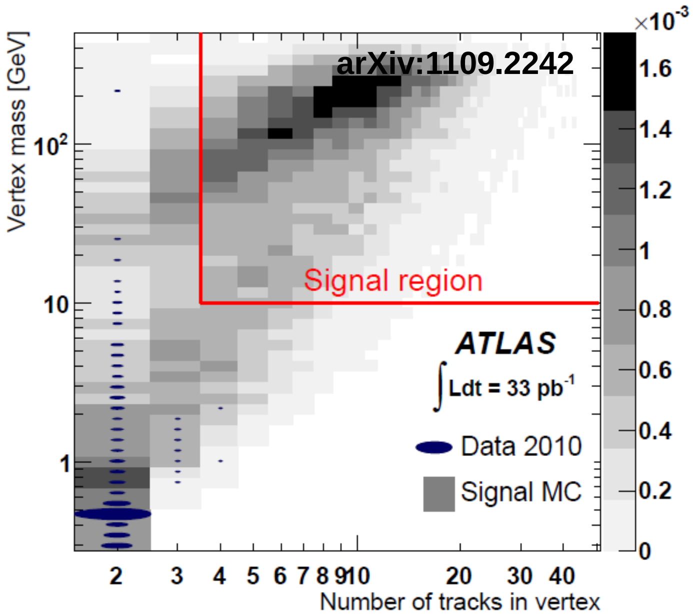


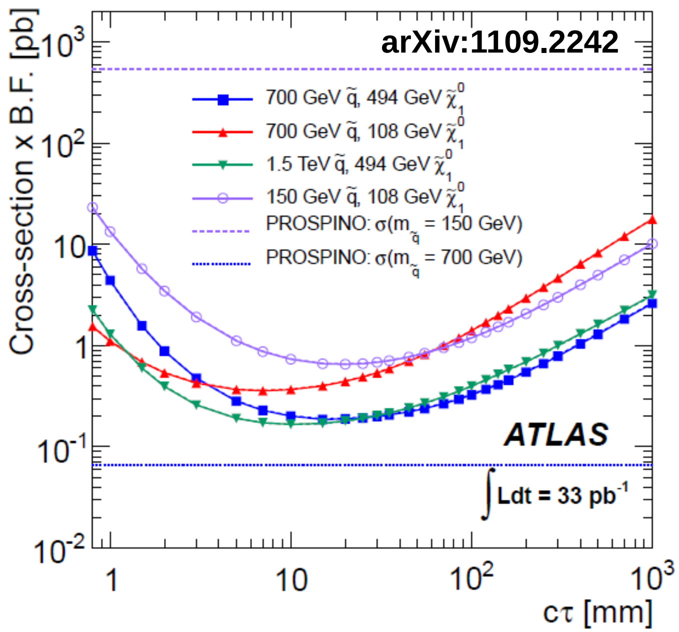
2010 data → $\int Ldt = 33\ pb^{-1}$

search for:

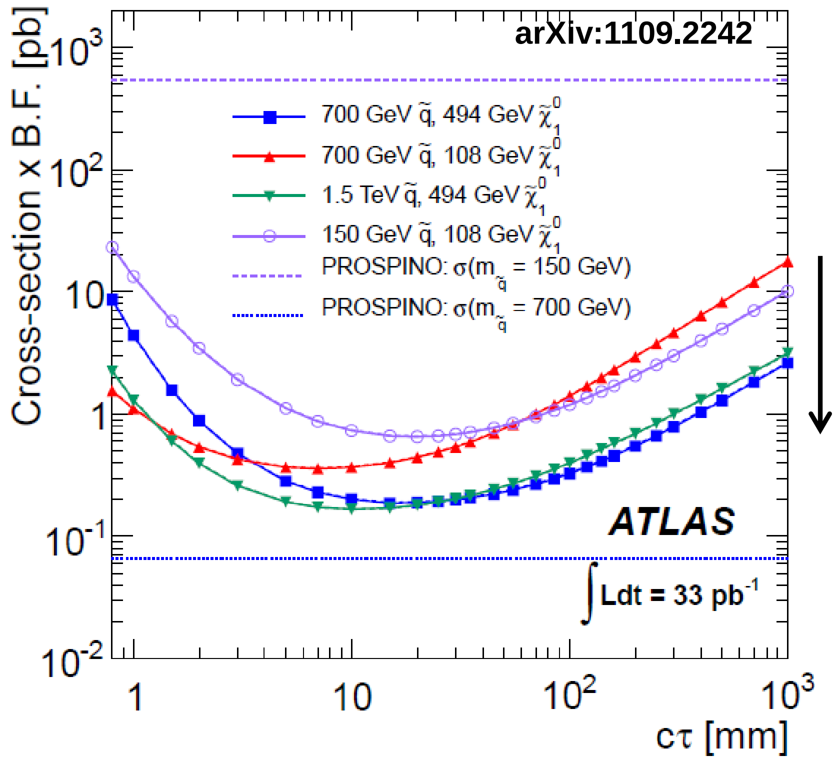
- $|z_{DV}| < 300mm$, $4mm < r_{DV} < 180mm$
- 1 high-p_t muon

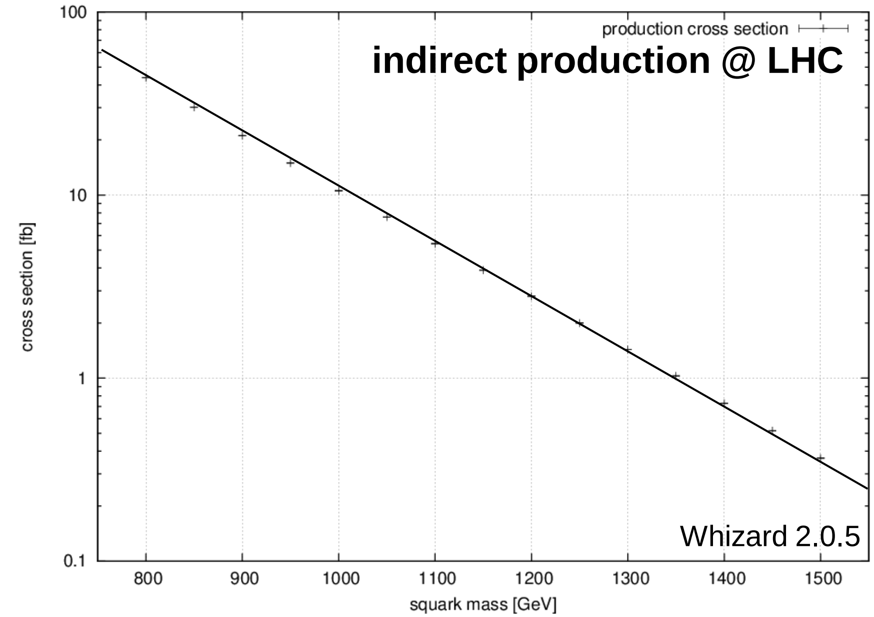
background free analysis ($N_{BG}<0.03$)





Dedicated displaces vertex search





extrapolation: $33pb^{-1}$ → $5fb^{-1}$
→ limits drop by a factor of ~√200 (=14)

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

Status of ILC RPV analysis

Direct production @ ILC

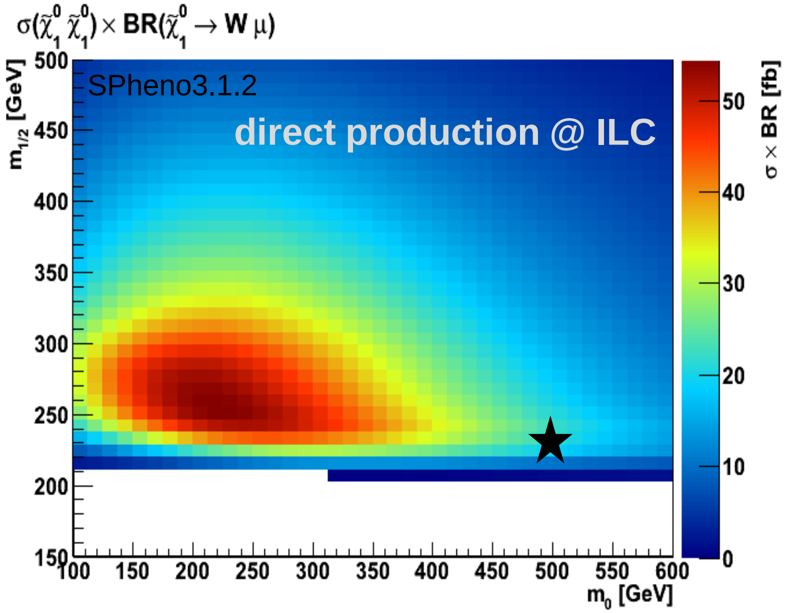
direct production cross section @ILC two orders of magnitudes higher than @LHC

example point: m_0 = 500 GeV, $m_{1/2}$ = 230 GeV, tan(β) = 10, sign(μ) = +, A_0 = 0 GeV

- m($\tilde{\chi}_1^0$) = 90 GeV
- cτ = 19.07mm
- BR($\tilde{\chi}_1^0$→ W μ) = 0.42
- BR($\tilde{\chi}_1^0$→ W τ) = 0.38

beam polarization √s = 500GeV:

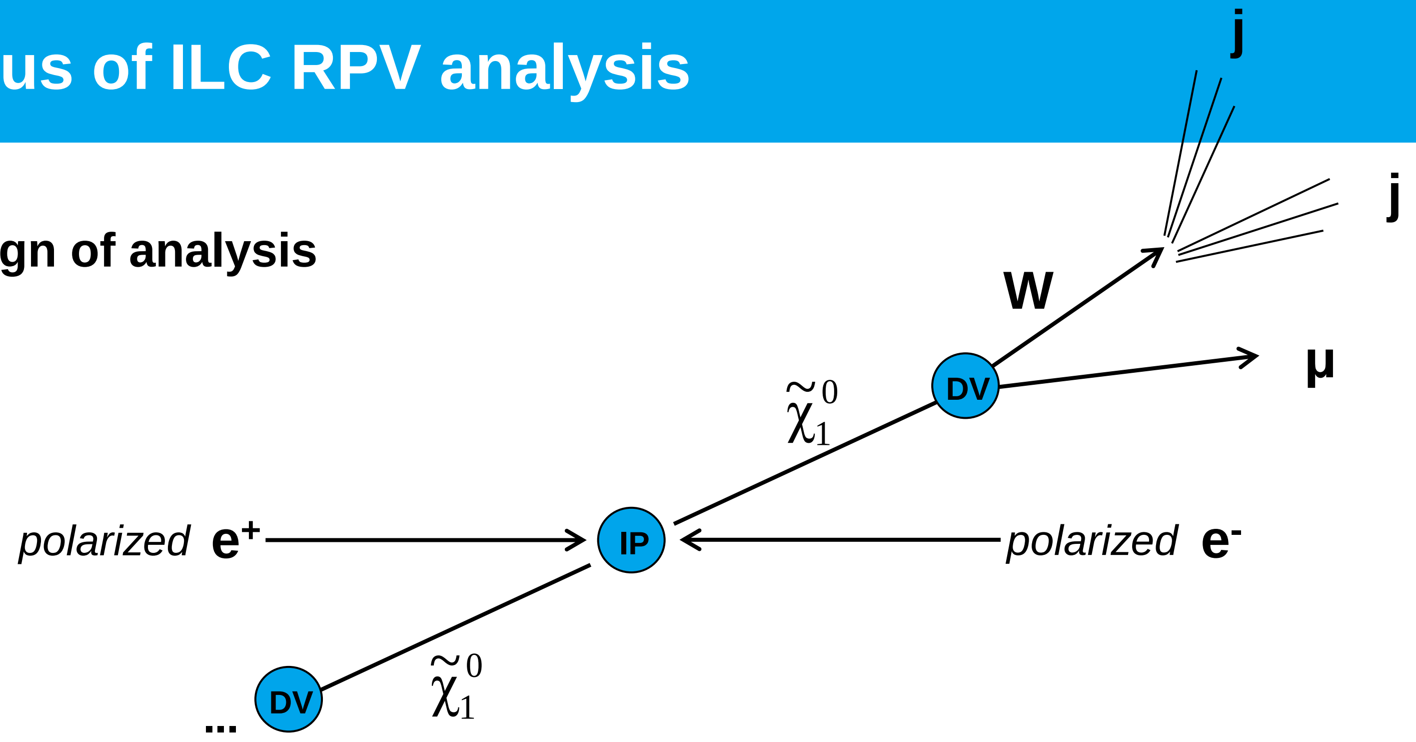
P(e+)	P(e-)	σ(ee→$\tilde{\chi}_1^0\tilde{\chi}_1^0$) [fb]
+0.3	-0.8	9
-0.3	-0.8	13
0	**0**	**44**
+0.3	+0.8	55
-0.3	**+0.8**	**101**



<u>expectations for ∫Ldt = 500 fb^{-1}</u>:
up to 12726 displaced (μ j j) - vertices
up to 11514 displaced (τ j j) - vertices

Status of ILC RPV analysis

Design of analysis



event selection:
- 2 displaced vertices
- reconstructed μ or τ from displaced vertex
- equal mass constraint of displaced vertices
- W mass constraint

→ **background free analysis**

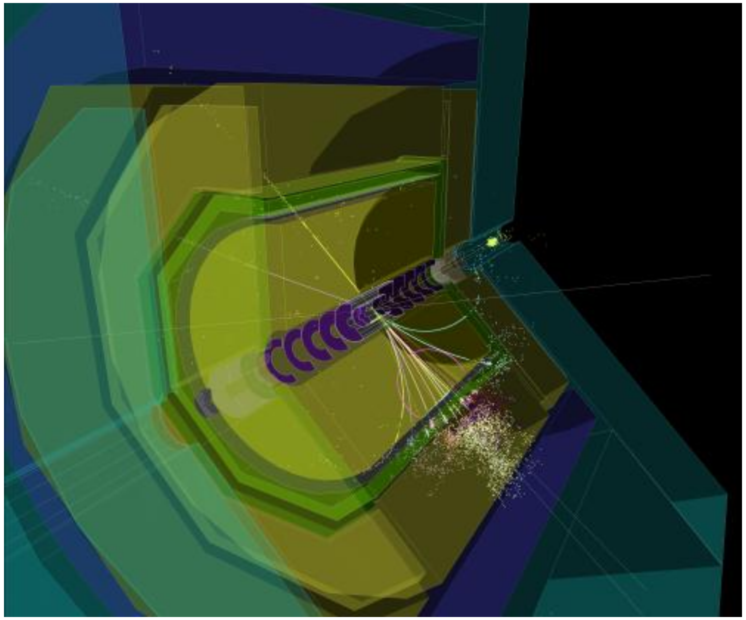
→ use hadronic decay channel of W: **full reconstruction of event possible**!

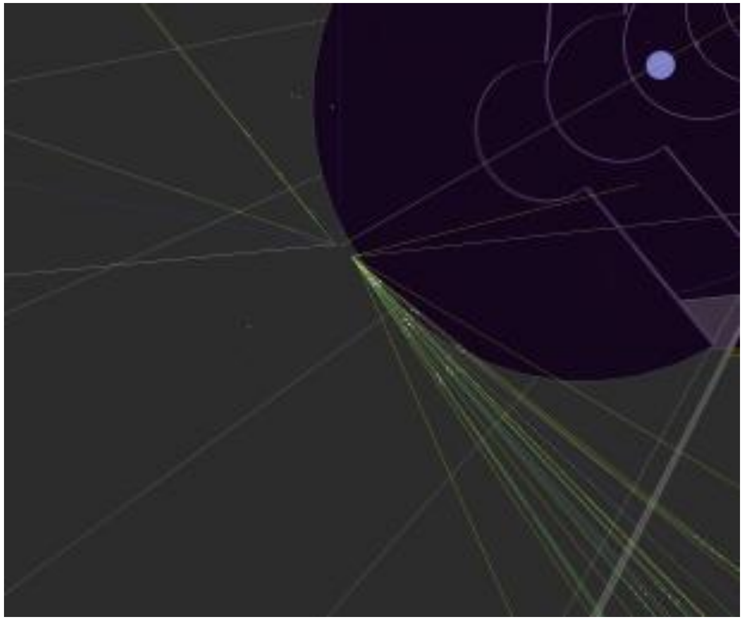
→ clean environment: good performance of tracking ***and*** vertex finding expected

Status of ILC RPV analysis

Status of bRPV displaced vertex search for ILC

- framework set up to generate events for almost any SUSY model (incl. bRPV)
  → Whizard & Sarah (see talk LC Forum Munich)
- found some problems in treatment of long-lived exotic particles in detector simulation
  → developed a new scheme for MOKKA to treat lifetime correctly





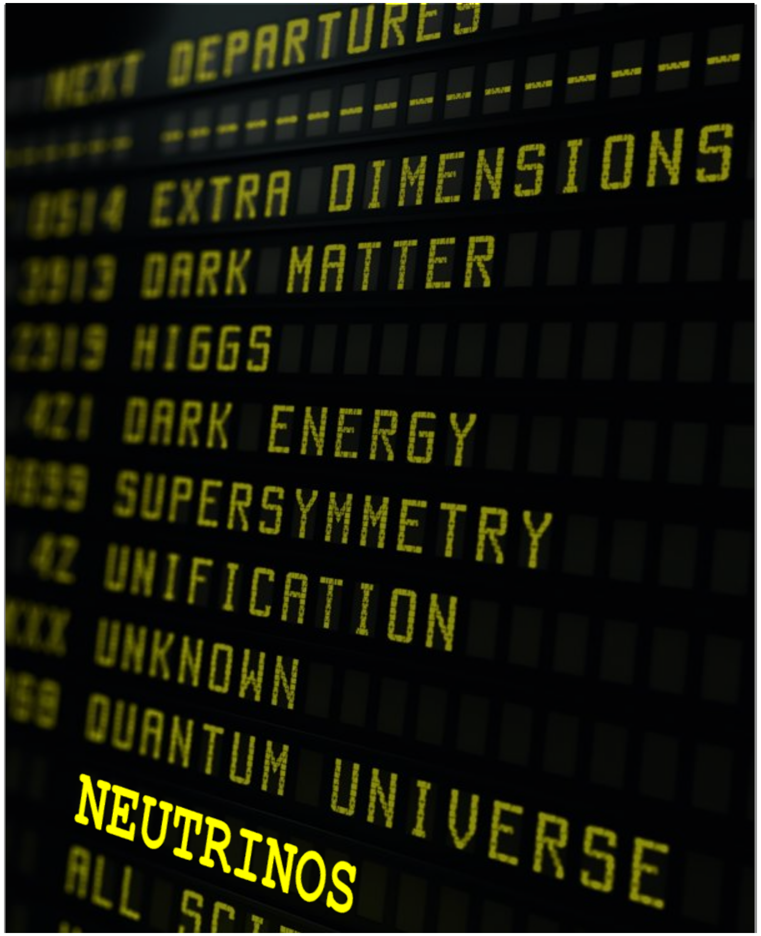
- waiting for fully reconstructed data (v13)

Conclusion

Conclusion

- R-parity violation is an interesting alternative to “normal” SUSY
- bRPV could explain neutrino parameters
- some RPV LHC searches ongoing
- especially for high squark masses: sensitivity of ILC expected to be better

- **ILC is the perfect machine to study new electroweak-coupling, long-lived particles**



Thank you for your attention.

Backup slides

Status of ILC RPV analysis

Direct production @ ILC

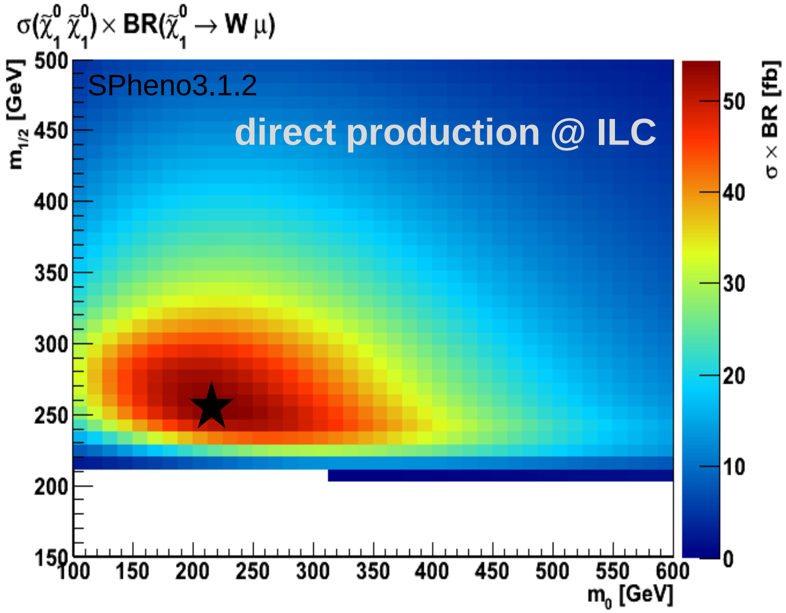
direct production cross section @ILC two orders of magnitudes higher than @LHC

example point: m_0 = 220 GeV, $m_{1/2}$ = 250 GeV, tan(β) = 10, sign(μ) = +, A_0 = 0 GeV

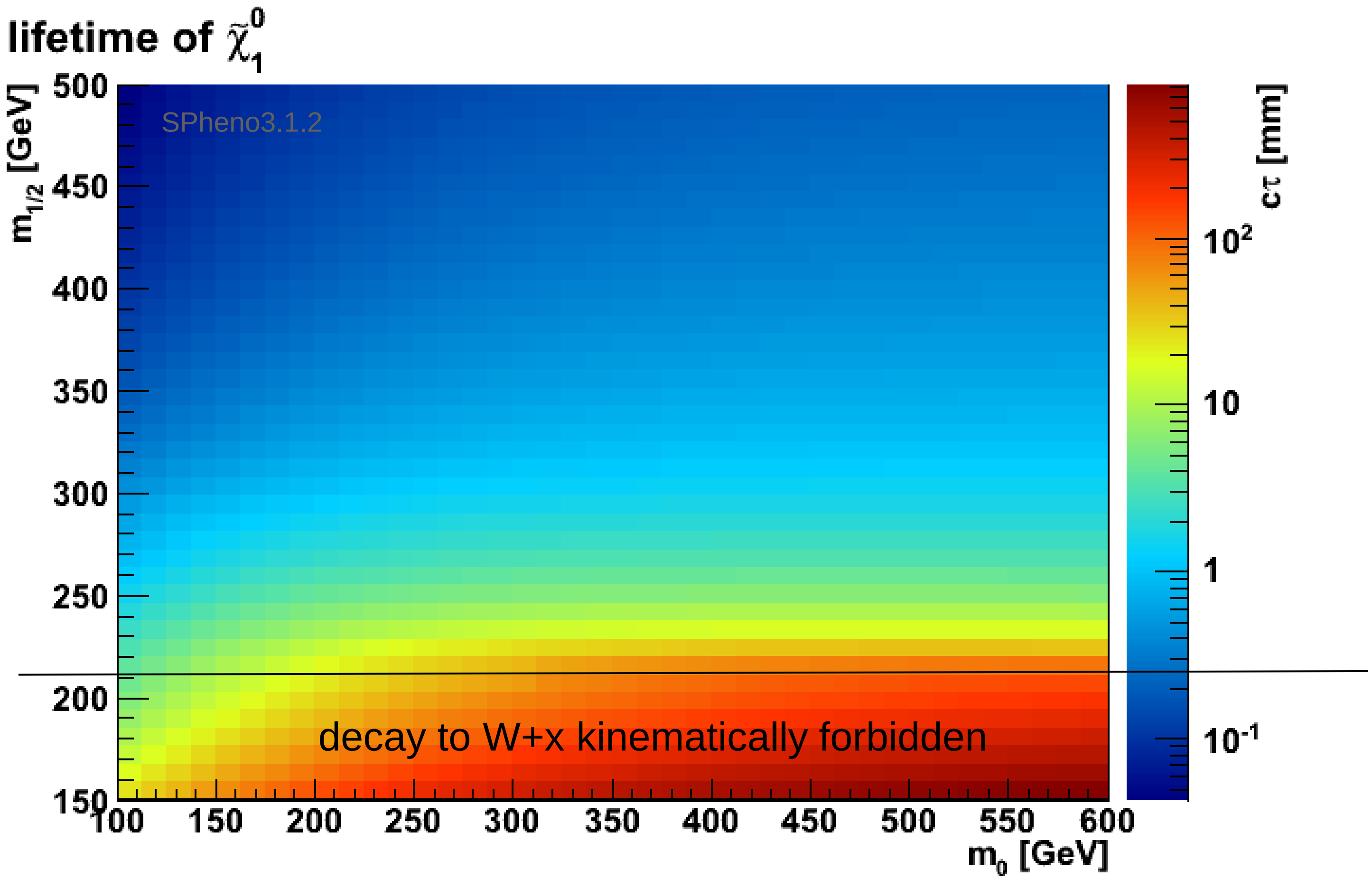
- m($\tilde{\chi}_1^0$) = 97 GeV
- cτ = 4.55mm
- BR($\tilde{\chi}_1^0$ → W μ) = 0.28
- BR($\tilde{\chi}_1^0$ → W τ) = 0.25

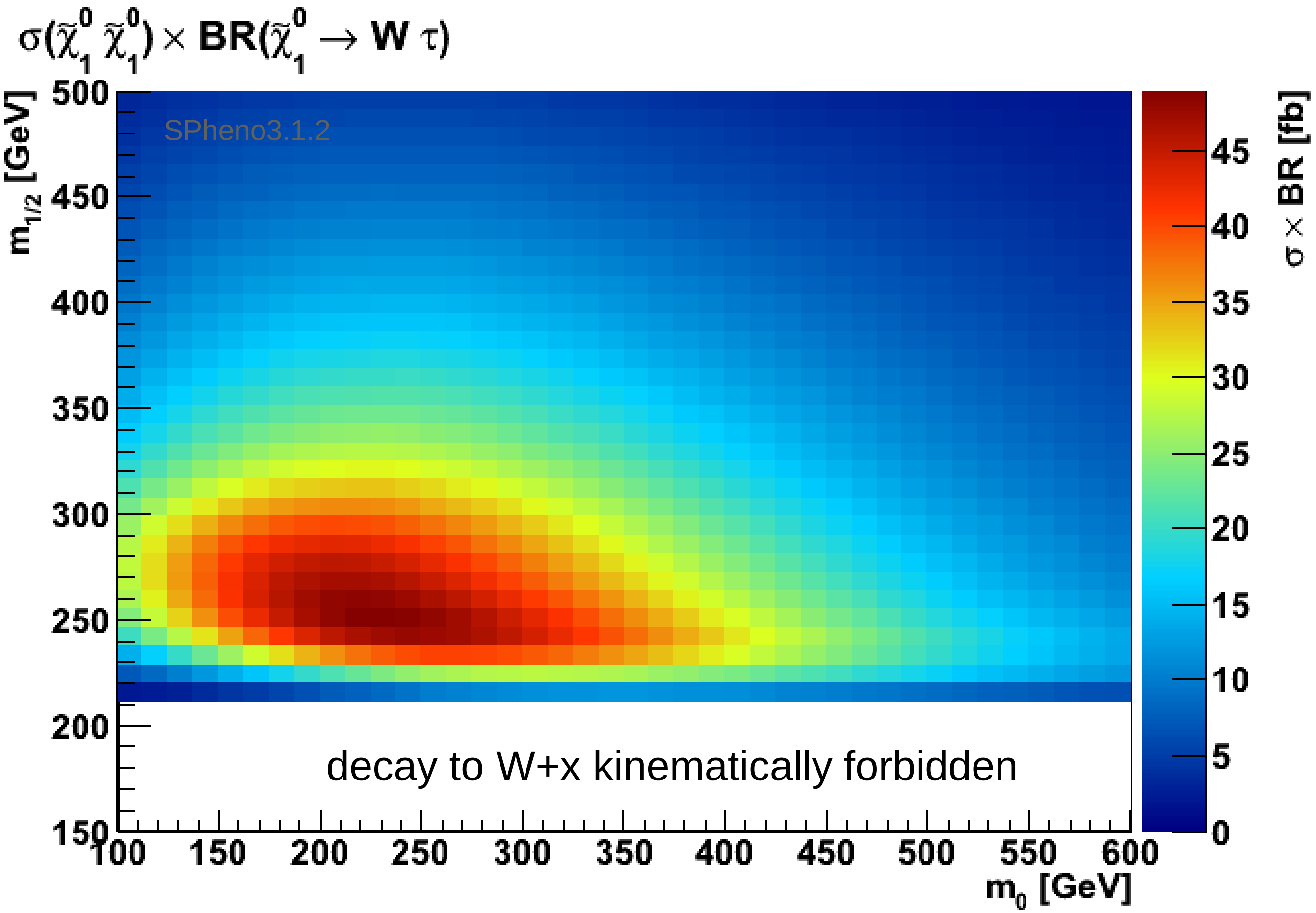
beam polarization √s = 500GeV:

P(e^+)	P(e^-)	σ(ee → $\tilde{\chi}_1^0 \tilde{\chi}_1^0$) [fb]
+0.3	-0.8	35
-0.3	-0.8	49
0	0	170
+0.3	+0.8	209
+0.3	-0.8	387

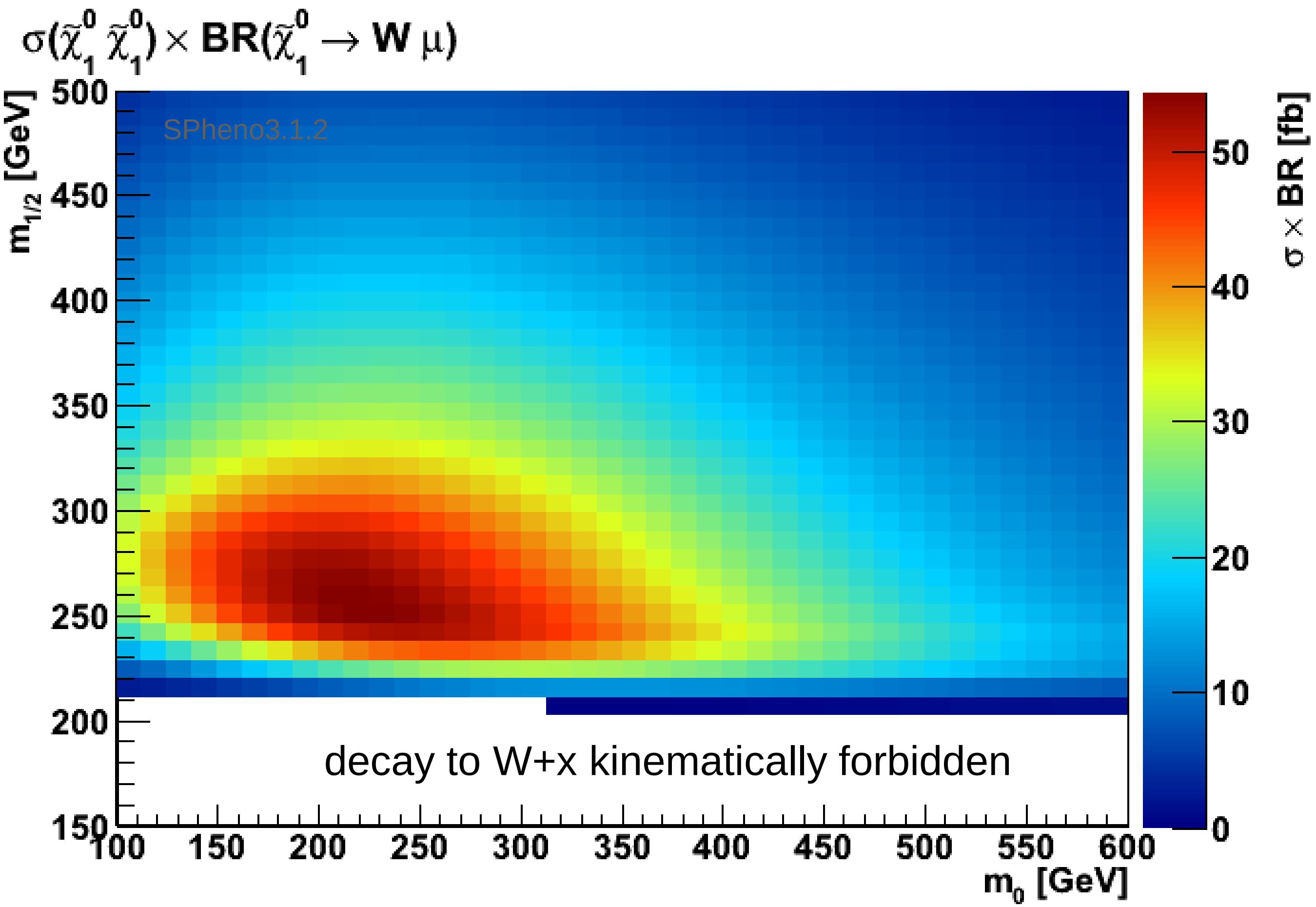


expectations for ∫Ldt = 500 fb^{-1}:
up to 32508 displaced (μ j j) - vertices
up to 29025 displaced (τ j j) - vertices

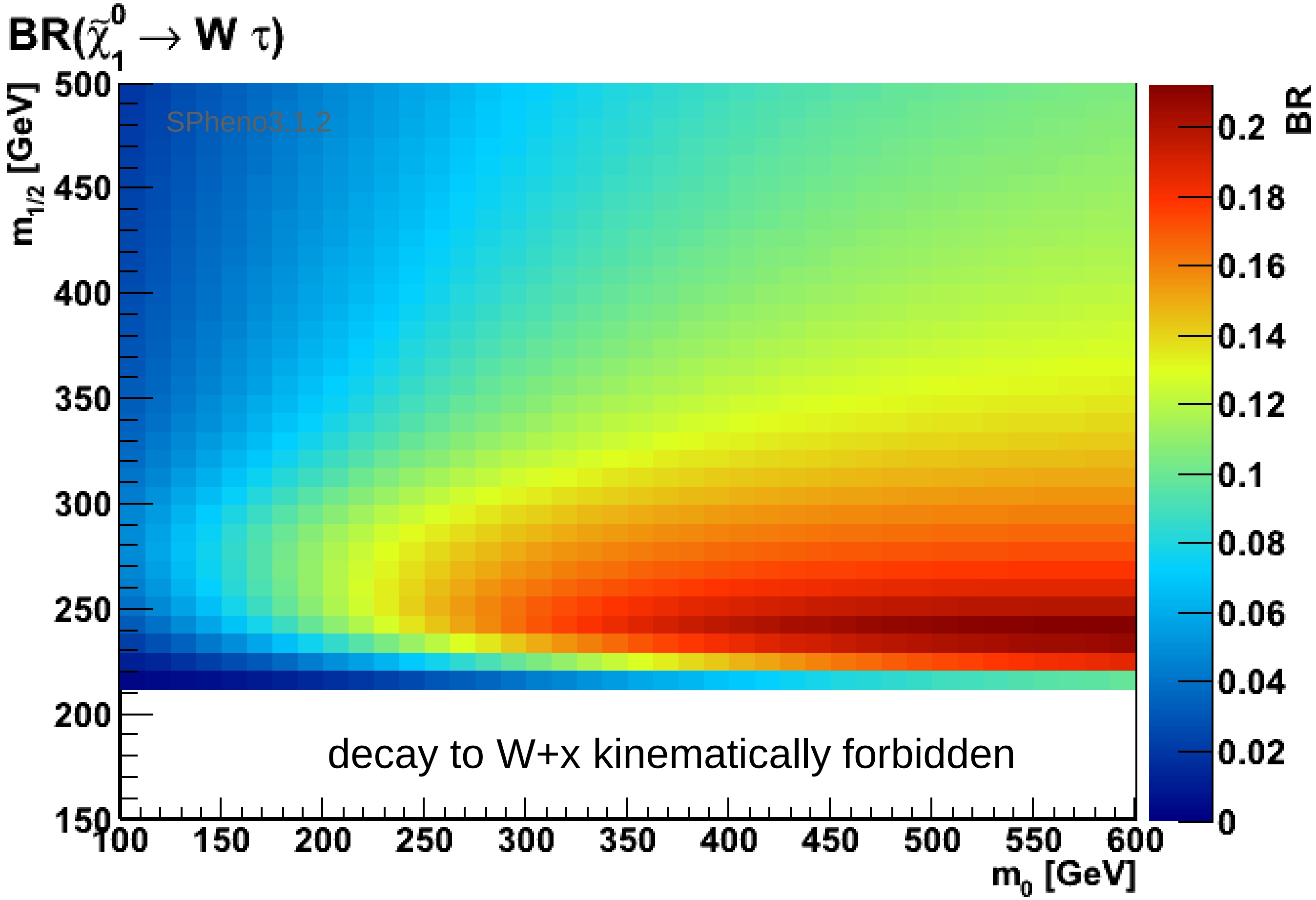

lifetime of $\tilde{\chi}_1^0$
SPheno3.1.2
$m_{1/2}$ [GeV]
500
450
400
350
300
250
200
150
100
150
200
250
300
350
400
450
500
550
600
m_0 [GeV]
$c\tau$ [mm]
10^2
10
1
10^{-1}
decay to W+x kinematically forbidden

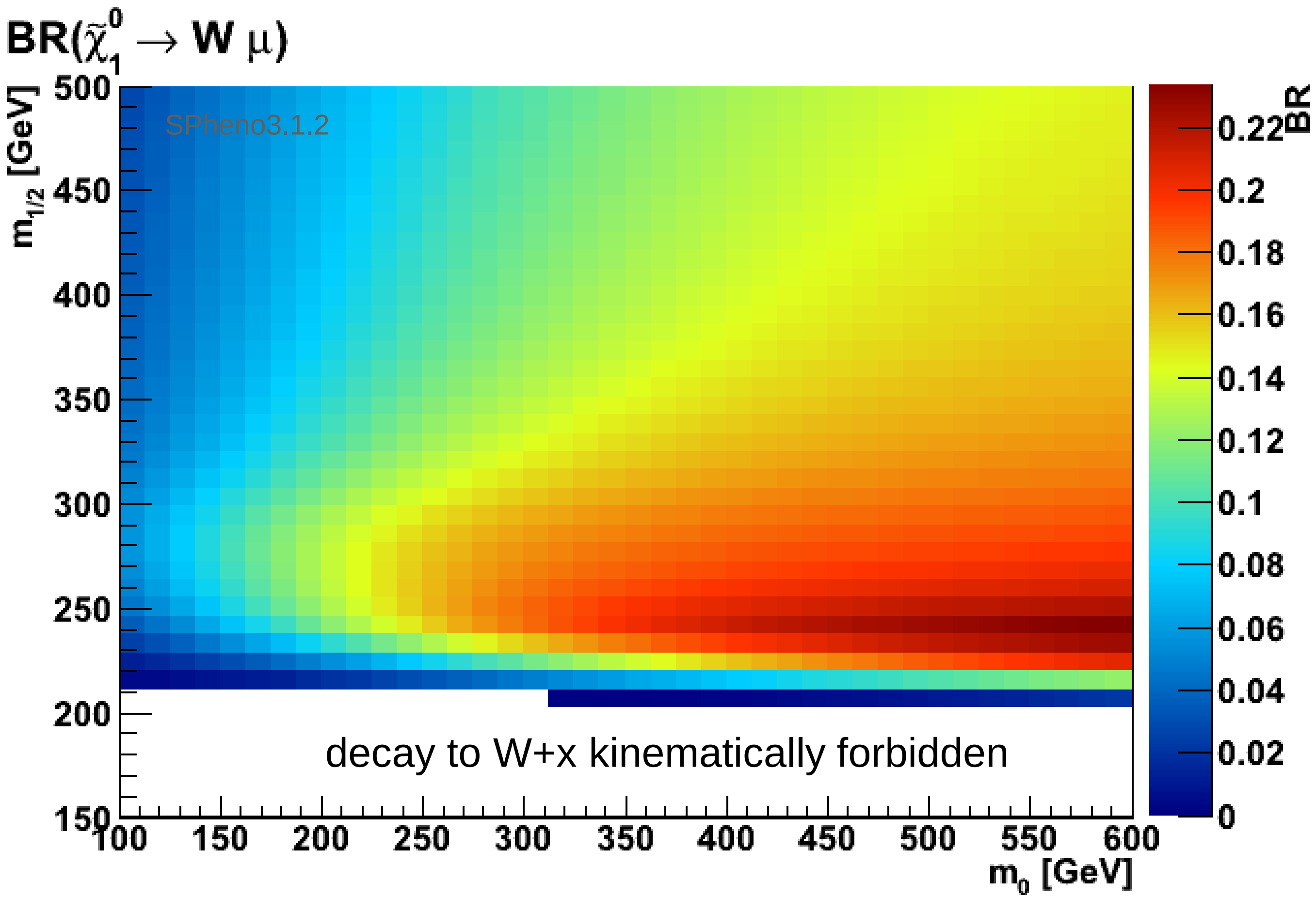


$\sigma(\tilde{\chi}_1^0\,\tilde{\chi}_1^0) \times BR(\tilde{\chi}_1^0 \rightarrow W\,\tau)$
SPheno3.1.2
decay to W+x kinematically forbidden
$m_{1/2}$ [GeV]
m_0 [GeV]
$\sigma \times BR$ [fb]
500
450
400
350
300
250
200
150
100
150
200
250
300
350
400
450
500
550
600
45
40
35
30
25
20
15
10
5
0

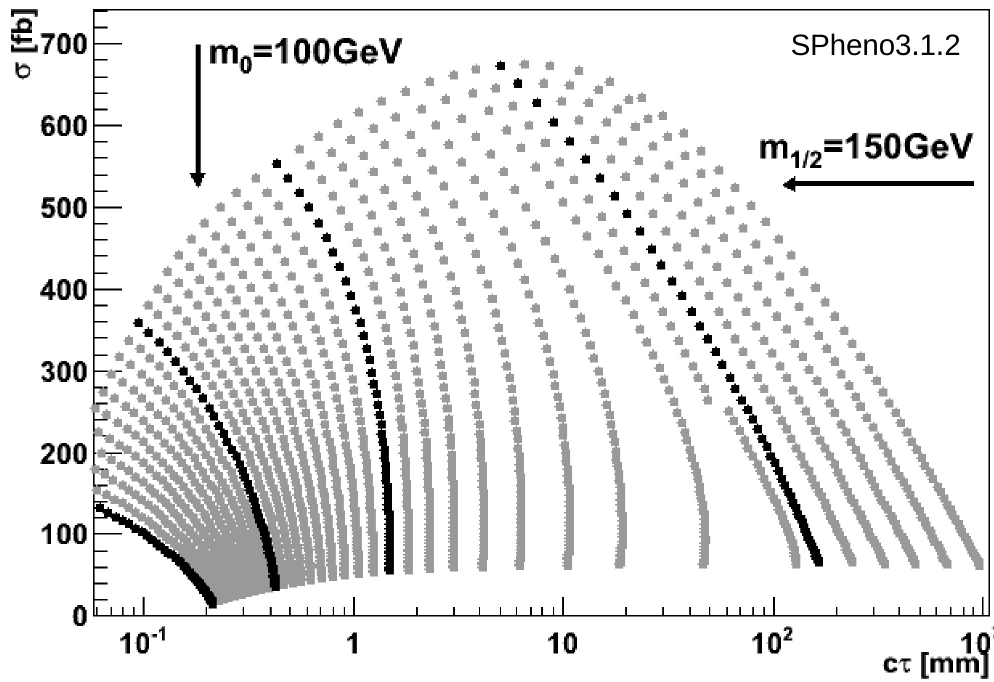


$\sigma(\tilde{\chi}_1^0 \tilde{\chi}_1^0) \times BR(\tilde{\chi}_1^0 \to W\mu)$
SPheno3.1.2
decay to W+x kinematically forbidden
$m_{1/2}$ [GeV]
m_0 [GeV]
$\sigma \times BR$ [fb]
500
450
400
350
300
250
200
150
100
150
200
250
300
350
400
450
500
550
600
50
40
30
20
10
0

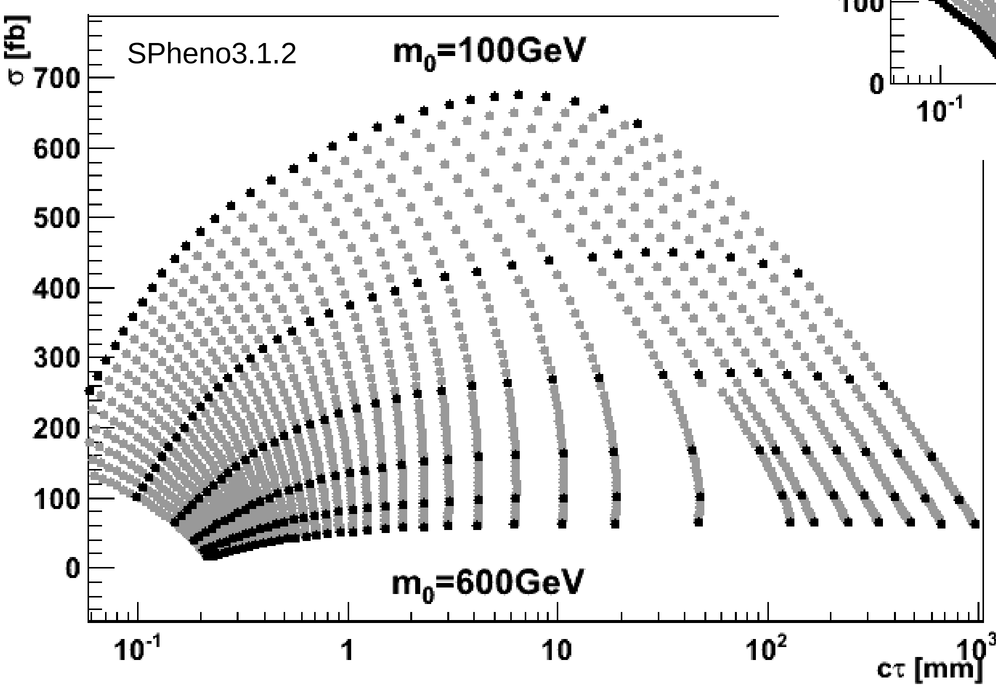

BR($\tilde{\chi}_1^0 \rightarrow$ W τ)
SPheno3.1.2
$m_{1/2}$ [GeV]
500
450
400
350
300
250
200
150
100
150
200
250
300
350
400
450
500
550
600
m_0 [GeV]
decay to W+x kinematically forbidden
BR
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0

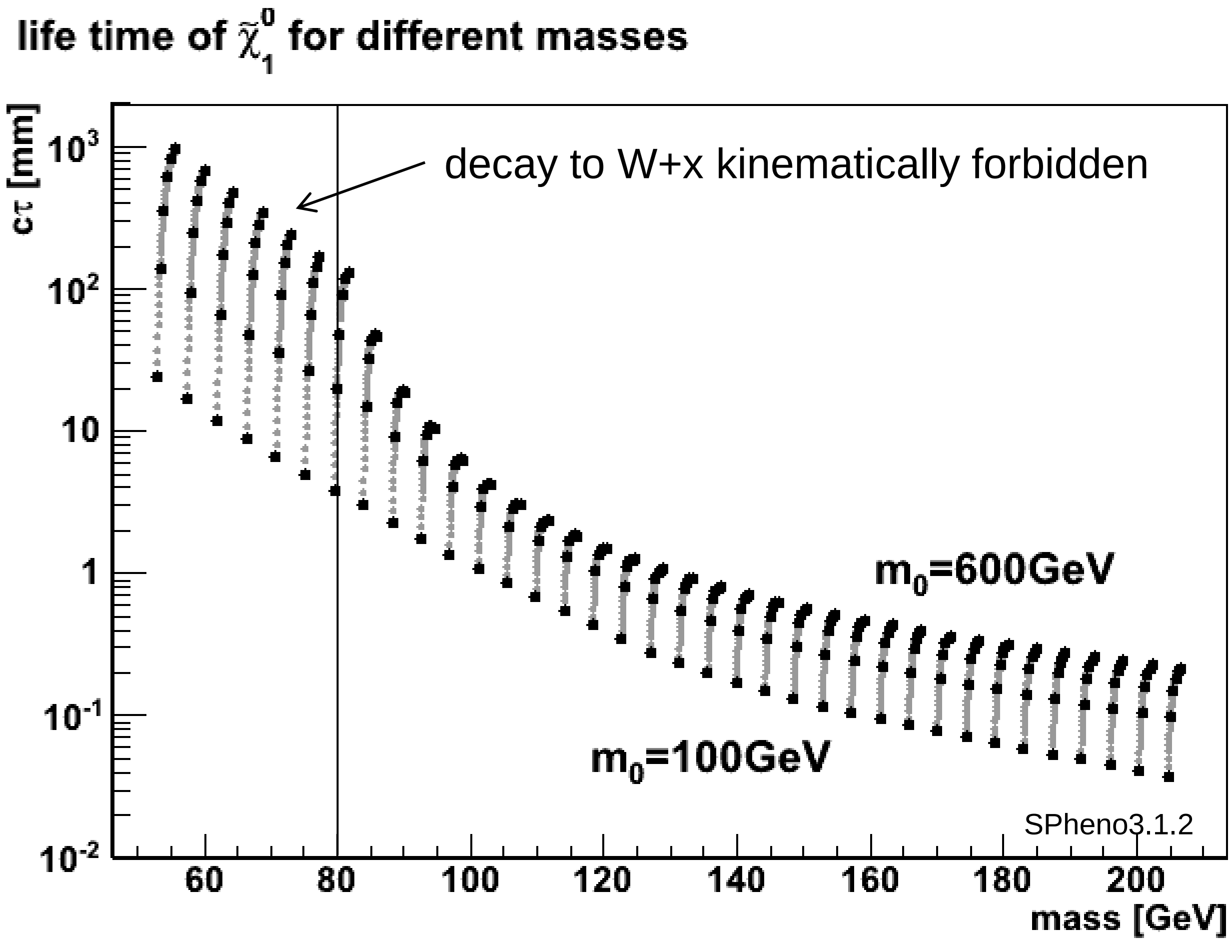

BR($\tilde{\chi}_1^0 \to W\,\mu$)
SPheno3.1.2
decay to W+x kinematically forbidden
$m_{1/2}$ [GeV]
m_0 [GeV]
BR
500
450
400
350
300
250
200
150
100
150
200
250
300
350
400
450
500
550
600
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0

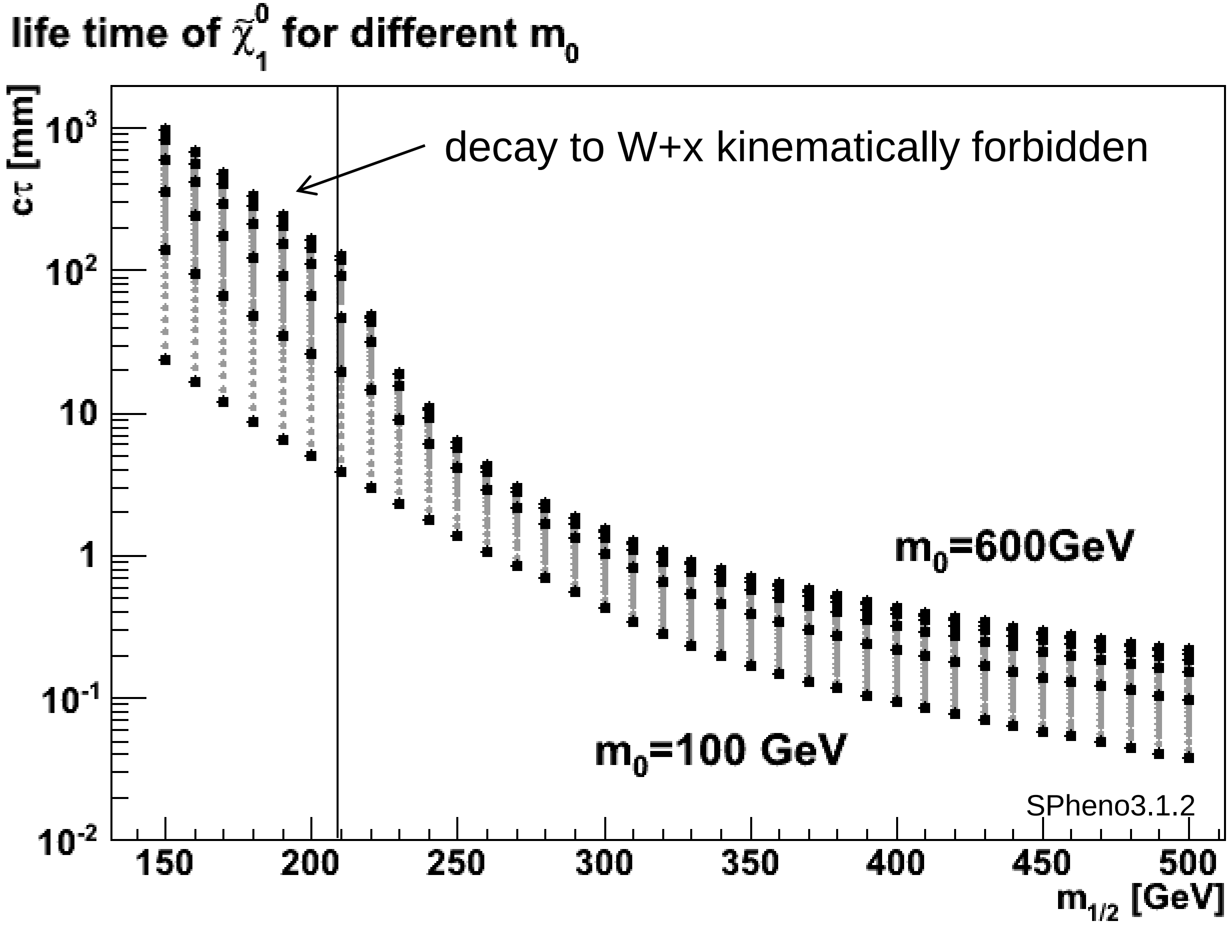
cross section vs. lifetime

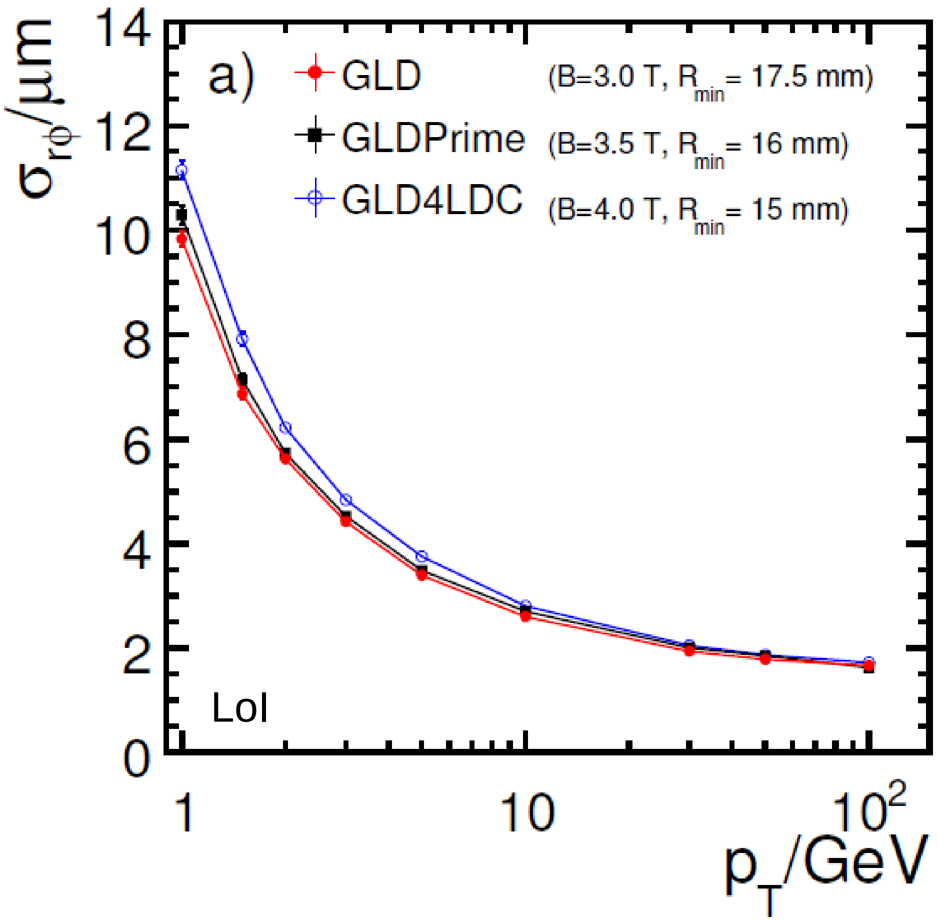


cross section vs. lifetime




life time of $\tilde{\chi}_1^0$ for different masses
cτ [mm]
10³
10²
10
1
10⁻¹
10⁻²
decay to W+x kinematically forbidden
m₀=600GeV
m₀=100GeV
SPheno3.1.2
60
80
100
120
140
160
180
200
mass [GeV]


life time of $\tilde{\chi}_1^0$ for different m_0
cτ [mm]
decay to W+x kinematically forbidden
m_0=600GeV
m_0=100 GeV
SPheno3.1.2
$m_{1/2}$ [GeV]
10^3
10^2
10
1
10^{-1}
10^{-2}
150
200
250
300
350
400
450
500


a)
GLD (B=3.0 T, R_min = 17.5 mm)
GLDPrime (B=3.5 T, R_min = 16 mm)
GLD4LDC (B=4.0 T, R_min = 15 mm)
LoI
σ_rφ/μm
p_T/GeV
0
2
4
6
8
10
12
14
1
10
10^2

R parity

W. Porod et. al.
arXiv:hep-ph/0011248

Superpotential

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

bRPV term $i = 1 \ldots 3$

→ Higgs/Slepton-mixing

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

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

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: $L_m = -\frac{1}{2}\left(\psi^0\right)^T \mathbf{M_N}\psi^0 + h.c.$

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

4x4 MSSM neutralino mixing matrix → M_{χ^0}

4x3 RPV matrix → m

R parity

W. Porod et. al.
arXiv:hep-ph/0011248

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: $\mathbf{M_N} = diag(M_{\chi^0}, m_{eff})$

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

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

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

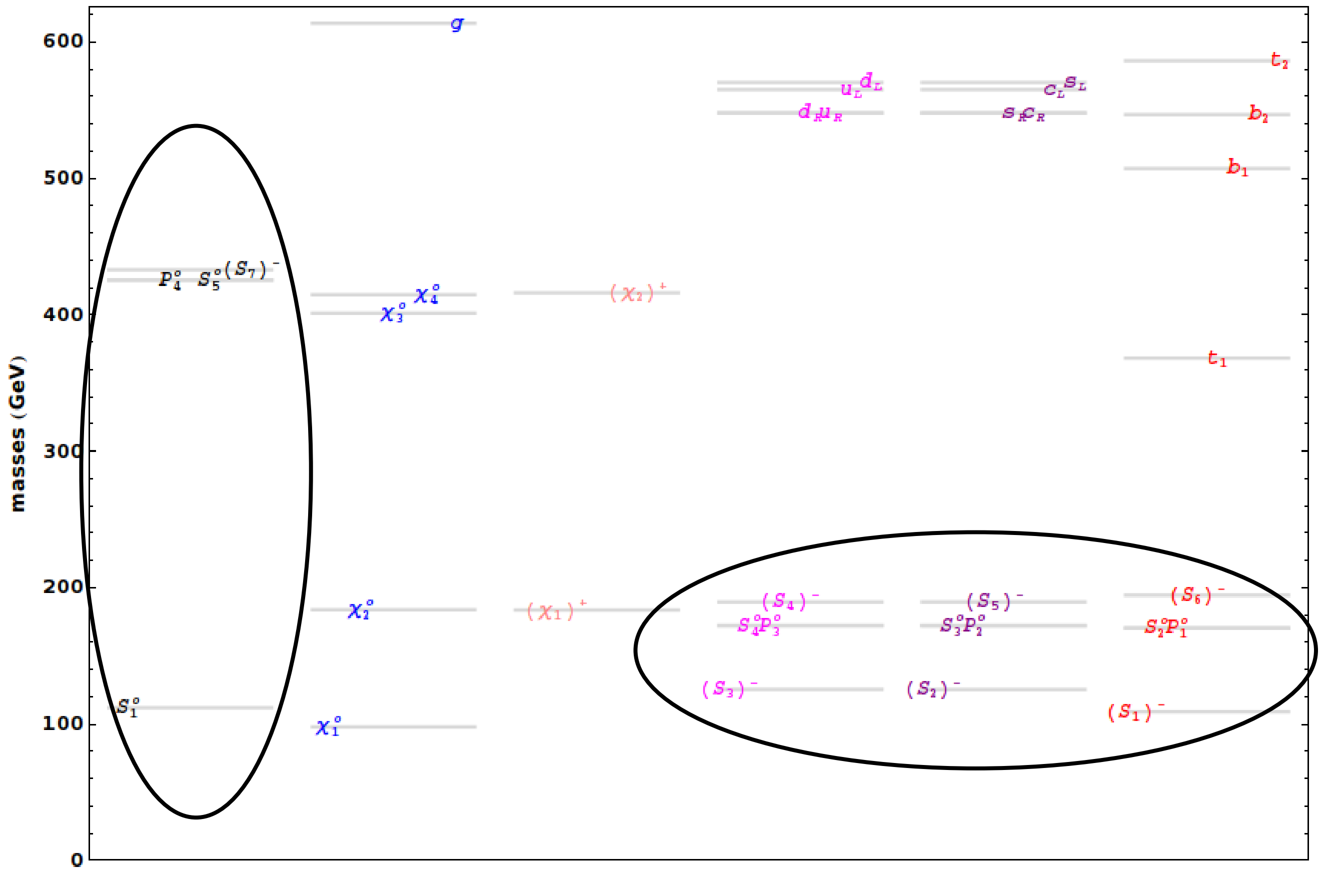
Benchmark scenario/ mass spectrum

MSSM – mSUGRA

SPS 1a‘
m_0 = 70 GeV
$m_{1/2}$ = 250 GeV
tan β = 10
sgn(μ) = 1
A_0 = -300 GeV

bRPV parameters
Fit to neutrino data

Spectrum generator
SPheno 3.0beta
(arXiv:hep-ph/0301101)



→ Higgs/Slepton mixing (new particle names S, P)

ILC potential

Systematical uncertainties (one example)

$\int L\,dt = 500\ fb^{-1}$ (4 years of ILC running)
$\sigma_{+-}(500GeV) = 2200$ fb
Detection efficiency = 0.5

→ $N_{W\mu} = 37500 \cdot 0.5 = 18750$ $\sigma_{rel}^{stat}=0.74\%$
→ $N_{W\tau} = 34100 \cdot 0.5 = 17050$ $\sigma_{rel}^{stat}=0.77\%$

$\boldsymbol{\sigma_{rel}^{stat}(Br(\chi\rightarrow W\mu)/\ Br(\chi\rightarrow W\tau)) \approx 1\%}$

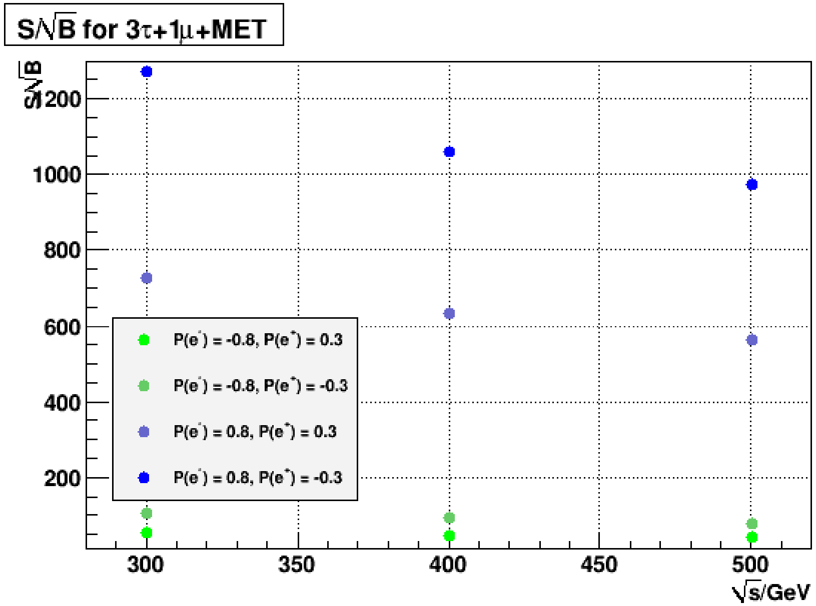
→ $\boldsymbol{\theta_{atm}=(46.36 \pm 0.15)^\circ}$

Signal/background estimation

- tree level cross sections for SM BG (Whizard 2.0; arXiv:0708.4233)
- just looking for similar final states

for example:

$$e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow (\nu\tau\tau)(\nu\tau\mu)$$
$$e^+e^- \rightarrow SM \rightarrow \tau\tau\tau\nu\mu\nu$$
$$= 3\tau + 1\mu + \mathrm{MET}$$



→ **Comparable results for almost all decay channels** (at least S/sqrt(B) > 10)