Bilinear RPV at ATLAS and ILC

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ATLAS Experiment
Physics on the TeV-scale at the Large Hadron Collider

FSP 101 ATLAS

Bundesministerium für Bildung und Forschung

PHYSICS AT THE TERA SCALE Helmholtz Alliance

Overview

1. Bilinear R parity violation
2. ATLAS: LSP mass reconstruction using a pure leptonic LSP decay channel
3. ILC: polarized cross sections of e+/e- collider
4. Conclusion/Outlook

Overview

1. **Bilinear R parity violation**
2. ATLAS: LSP mass reconstruction using a pure leptonic LSP decay channel
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Bilinear P_R violation

What is R parity?

- *B* and *L* violating terms allowed in superpotential (⇎SM)
- *B* and *L* violation never observed (proton decay)

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

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

$\longrightarrow$ SM particles: $P_R = +1$

$\longrightarrow$ SUSY partners: $P_R = -1$

Consequences of conservation

- proton decay prohibited
- sparticles can only be produced in pairs
- SUSY decay products contain odd number of LSPs
- LSP absolutely stable

Bilinear P_R violation

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

⟶ SM particles: $P_R = +1$
⟶ SUSY partners: $P_R = -1$

Consequences of ~~conservation~~

BUT claim for conservation arbitrary from theoretical point of view

- proton decay prohibited → just break *L* **or** *B*
- sparticles can only be produced in pairs
- SUSY decay products contain odd number of LSPs

→ holds for **small RPV parameters**

- LSP absolutely stable → **LSP decays!**

Bilinear P_R violation

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

Superpotential

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

bRPV term
$i=1..3$

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

4x4 MSSM neutralino mixing matrix

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

4x3 RPV matrix

Bilinear P_R violation

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.

Bilinear P_R violation

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

Some results of this model

- **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

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

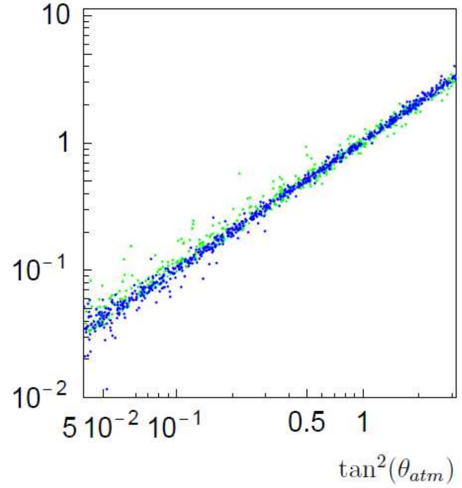
$$\tan\theta_{23} = \frac{\Lambda_\mu}{\Lambda_\tau}$$

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

How is that connected to colliders?

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

a) $\mathrm{Br}(\mu q q')/\mathrm{Br}(\tau q q')$



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

→ **Neutrino physics at collider experiments**

Overview

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2. **ATLAS: LSP mass reconstruction using a pure leptonic LSP decay channel**
3. ILC: polarized cross sections of e+/e- collider
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Phenomenology

(Semi-)leptonic LSP decay channels (@ATLAS benchmark point SU3)

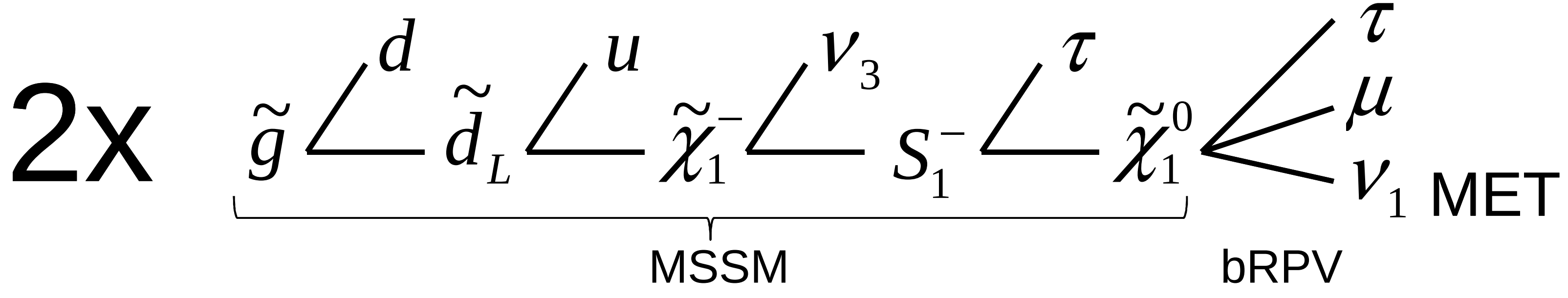
$\tilde{\chi}_1^0 \rightarrow \tau^{\pm} + e^{\mp} + \nu$	9 %
$\tilde{\chi}_1^0 \rightarrow \tau^{+} + \tau^{-} + \nu$	24 %
$\tilde{\chi}_1^0 \rightarrow \mu^{\pm} + \tau^{\mp} + \nu$	16 %
$\tilde{\chi}_0^1 \rightarrow W + l$	13 %

(data created with Spheno3.0beta36)

Why muon channel?
→ATLAS has a very good muon spectrometer!
→ Working group is interested in muons

Group in Valencia working on $\tilde{\chi}_1^0 \rightarrow W\mu$
(CERN-ATL-COM-PHYS-2009-543)

Typical bRPV SUSY decay chain



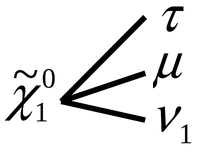
- bRPV (in that case) doesn‘t affect SUSY cascade
- two cascades with two neutralino decays in each event
- neutralino decays!

SM background reduction

Standard model backgrounds:

- ttbar
- single top
- W+jets
- Z+jets
- WW+WZ+ZZ
- QCD dijets

(officially produced Monte Carlo samples, CM=10TeV)



Reasonable Triggers

Signal final state signature:
mu, tau, missing E_T

mu10

tau20i

tau20i_mu10

Trigger	Signal eff.	BG eff.
mu10	0.58	$4.15\ 10^{-5}$
tau20i	0.65	$8.81\ 10^{-4}$
tau20i_mu10	0.38	$1.35\ 10^{-6}$

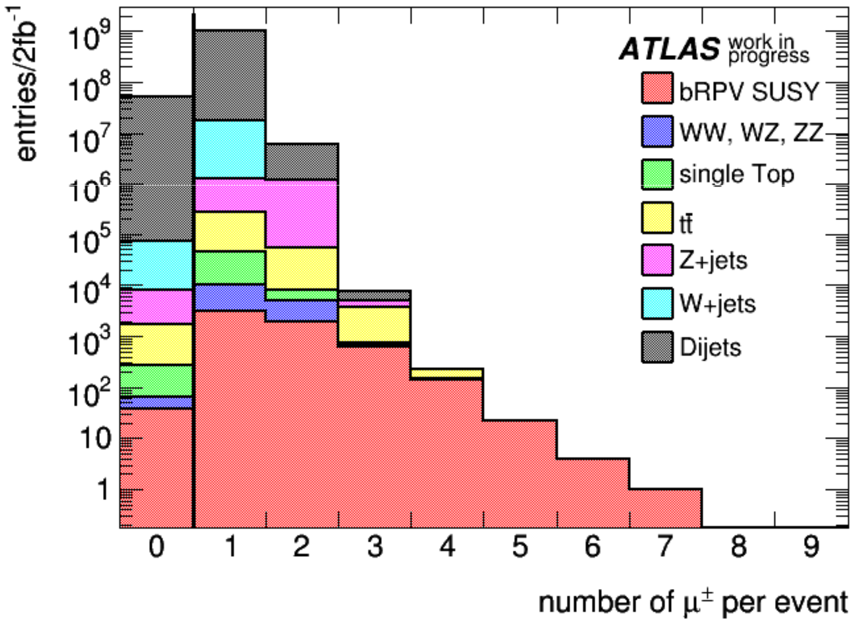
mu10	BG eff.
QCD dijets	$4.1\ 10^{-5}$
W+jets	0.29
Z+jets	0.43
ttbar	0.36
single top	0.30
WW+WZ+ZZ	0.39

→ trigger **mu10** chosen
→ available in L31 trigger menu
→ very good background reduction

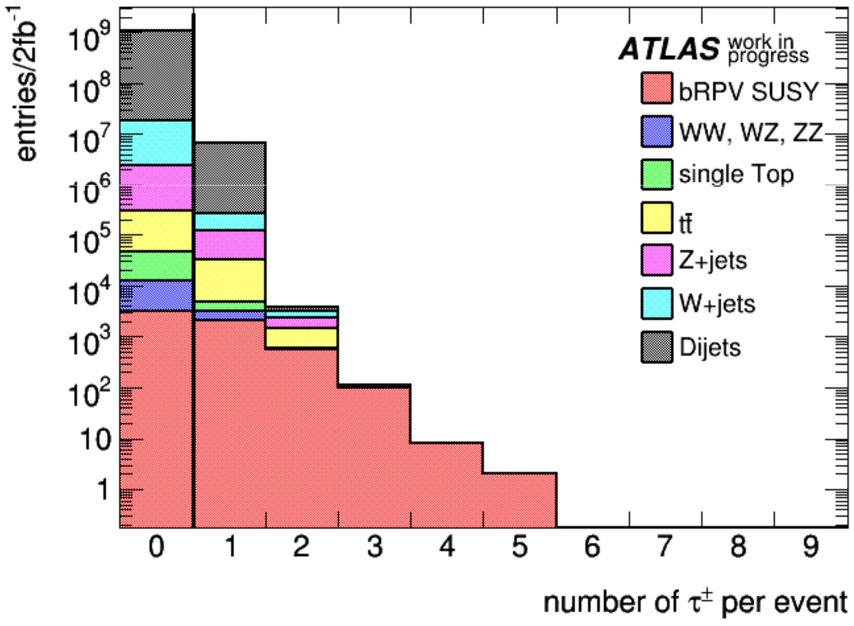
SM background reduction

Observables

Number of mu/tau



mu10 trigger, preselection cuts, CM=10TeV



mu10 trigger, preselection cuts, CM=10TeV

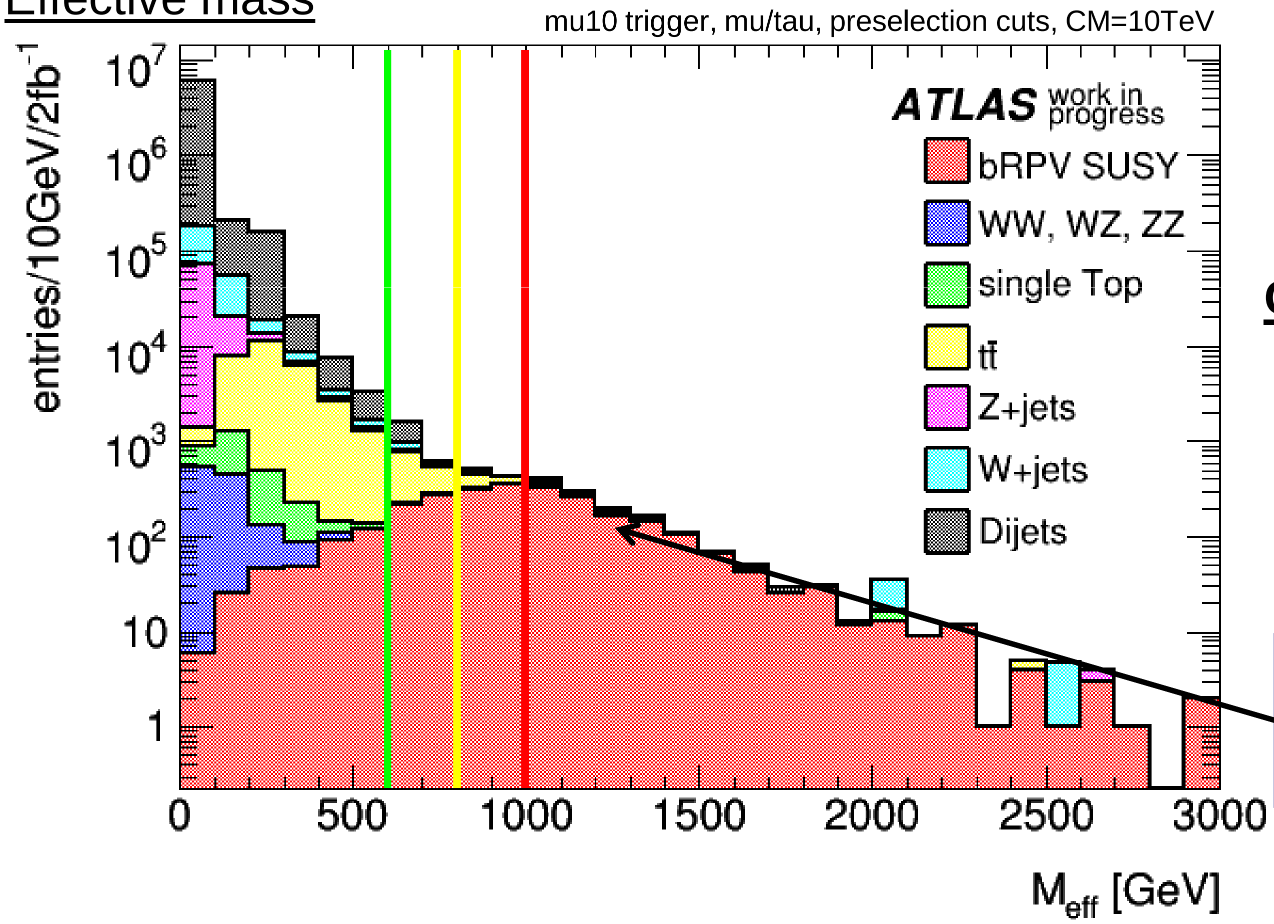
Asking for at least one muon and one tau in final state is very selective!

SM background reduction

Observables

$$M_{eff} = E_T^{miss} + \sum_{1...4} p_T^{jet} + \sum p_T^e + \sum p_T^\mu$$

Effective mass



Cuts:

loose: M_{eff}> 600 GeV

medium: M_{eff}> 800 GeV

tight: M_{eff}> 1000 GeV

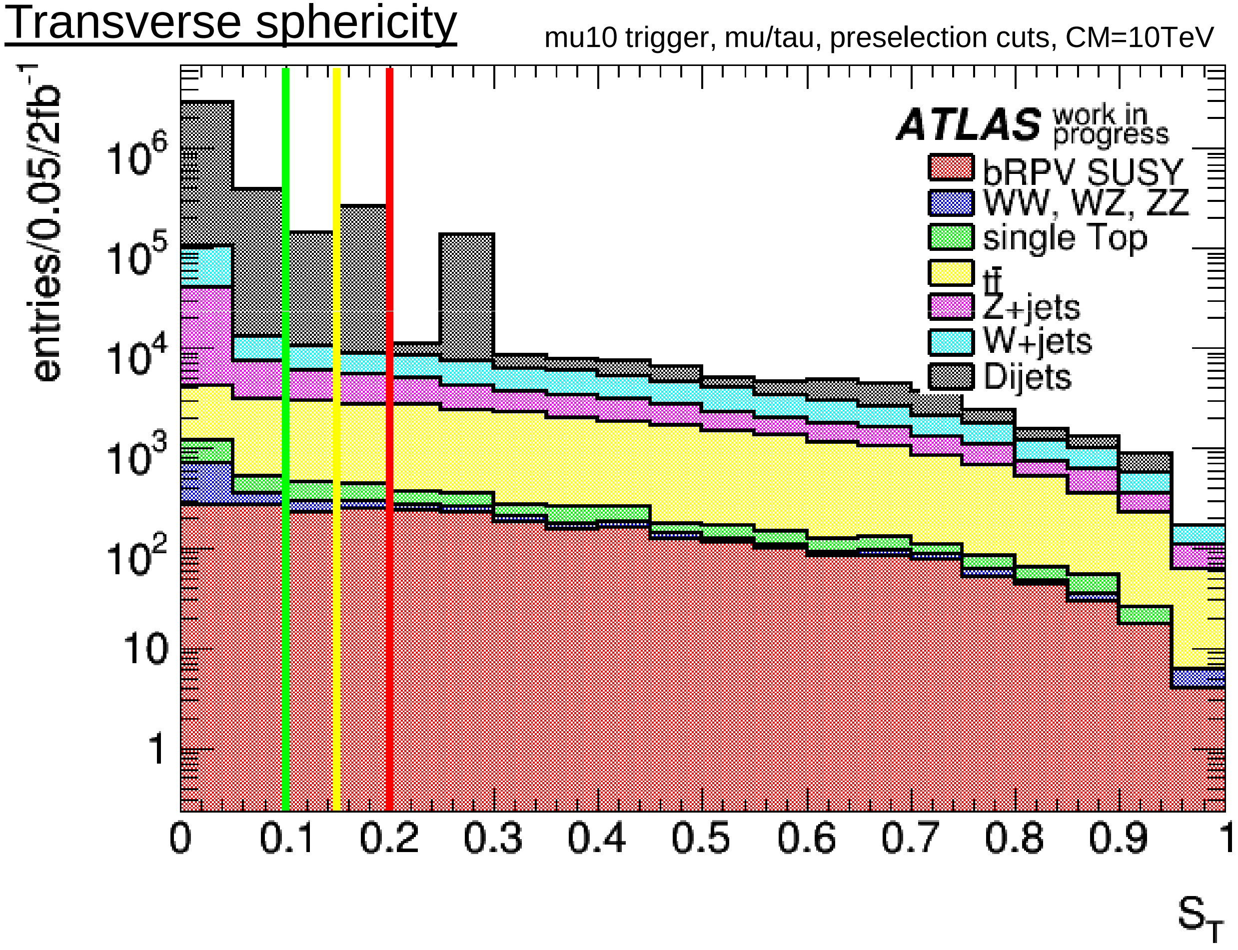
Maximum of (SUSY) signal M_{eff} at higher energy

SM background reduction

Observables

$$S_T = \frac{2\lambda_2}{\lambda_1 + \lambda_2} \quad \lambda_1, \lambda_2$$ eigenvalues of sphericity tensor

Transverse sphericity



Cuts:

loose : $S_T > 0.10$

medium : $S_T > 0.15$

tight : $S_T > 0.20$

Cut usefull for QCD background reduction

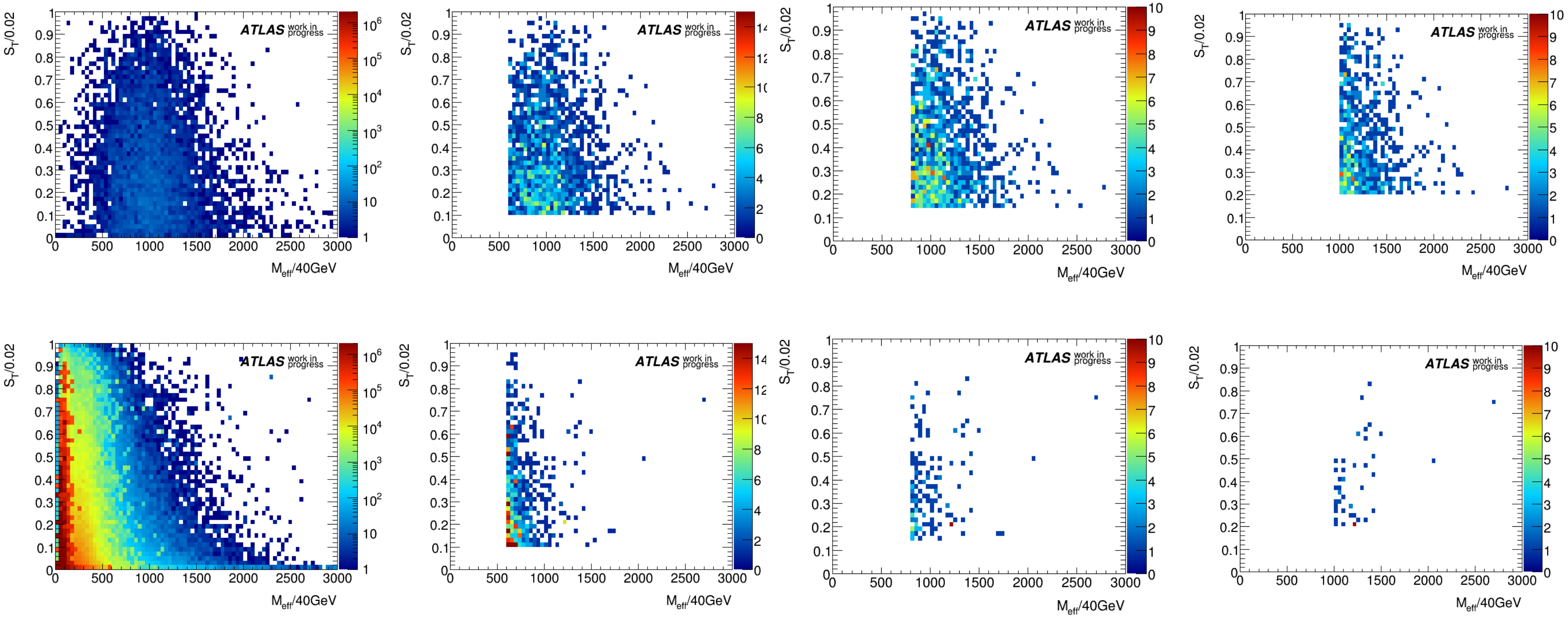
SM background reduction

Cuts - summary

triggered/preselected | mu/tau & loose | mu/tau & medium | mu/tau & tight

bRPV SUSY

background



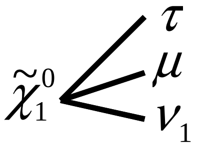
	loose	medium	tight
# events SUSY	1913	1339	727
# events BG	1493	160	54
S/B	1.3	8.4	13.4
S/√B	49.5	106.0	98.6

→ very good background reduction!

→ **medium** cuts are used

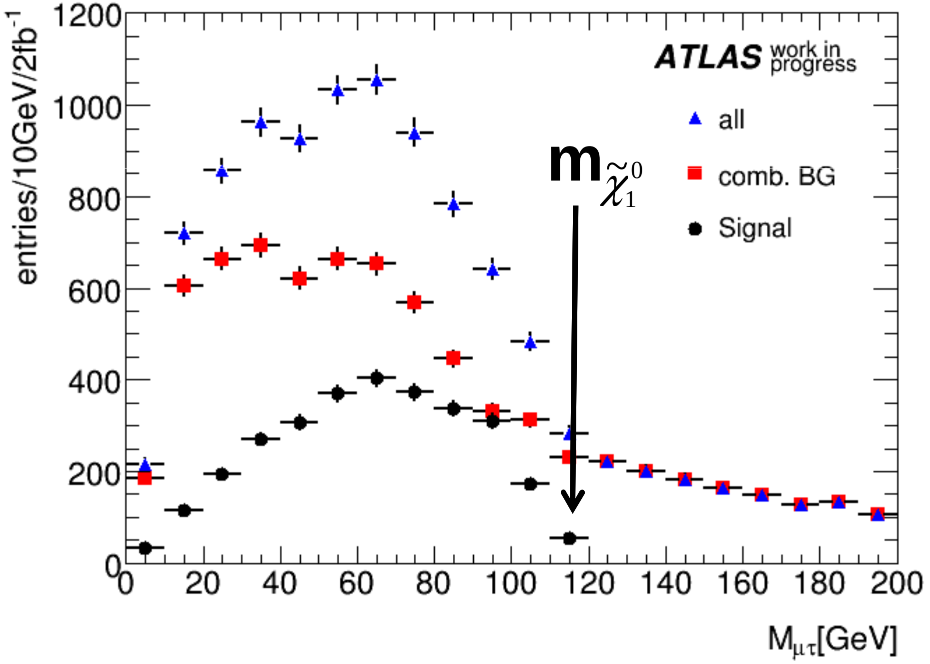
Mass reconstruction of LSP

Signal channel/ SUSY background



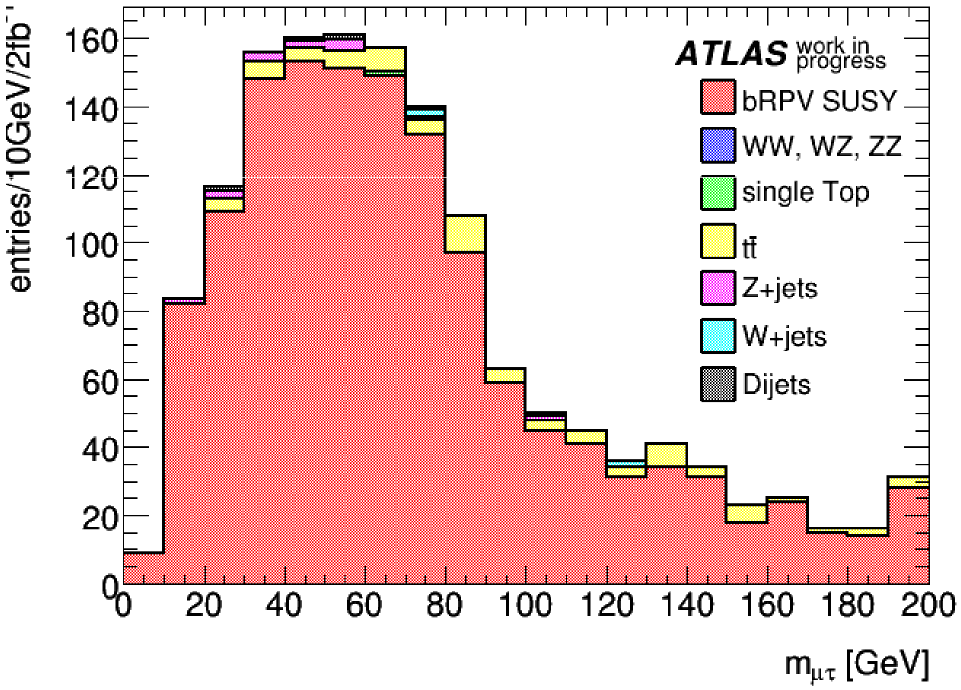
Calculation of invariant mass of μ and τ

Truth:



→ **dilepton edge (Three-body-decay)**

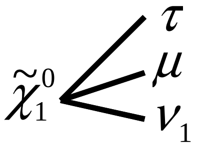
Reco:



→ **reduction of combinatorical BG necessary**

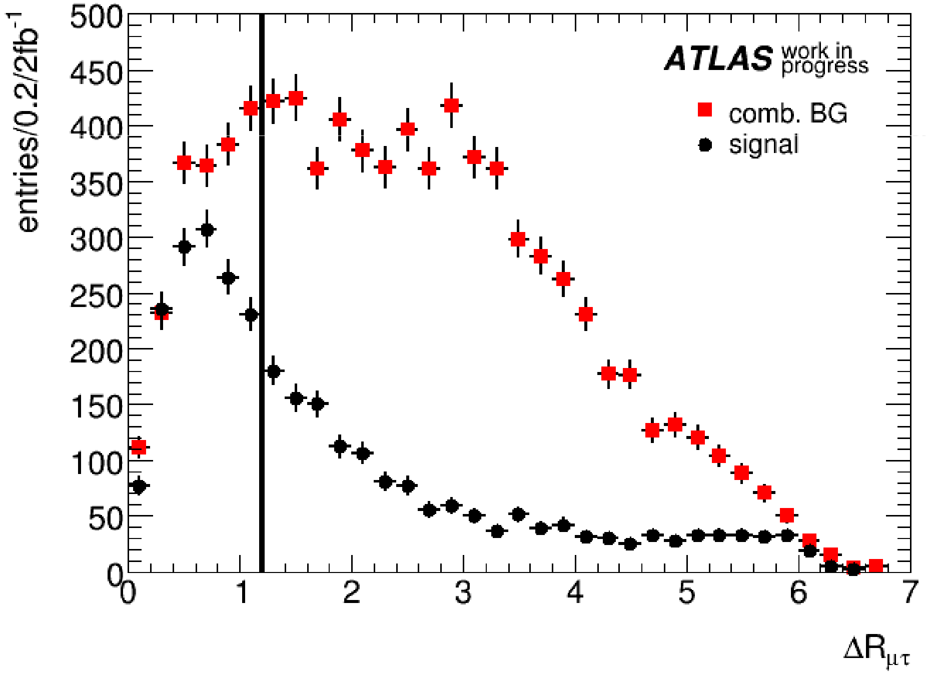
Mass reconstruction of LSP

Signal channel/ SUSY background

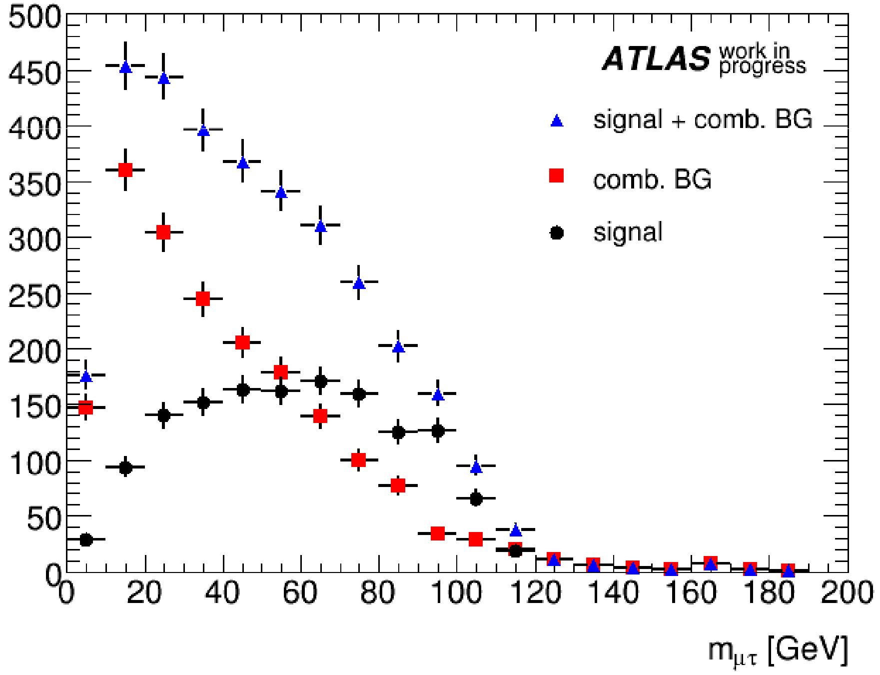


1. $\Delta R_{\mu\tau}$ cut for different μτ-pairs (truth)

$\Delta R_{\mu\tau}$ distribution of signal and BG pairs:



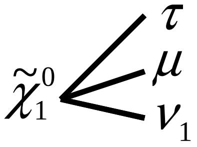
Resulting $m_{\mu\tau}$ distribution:



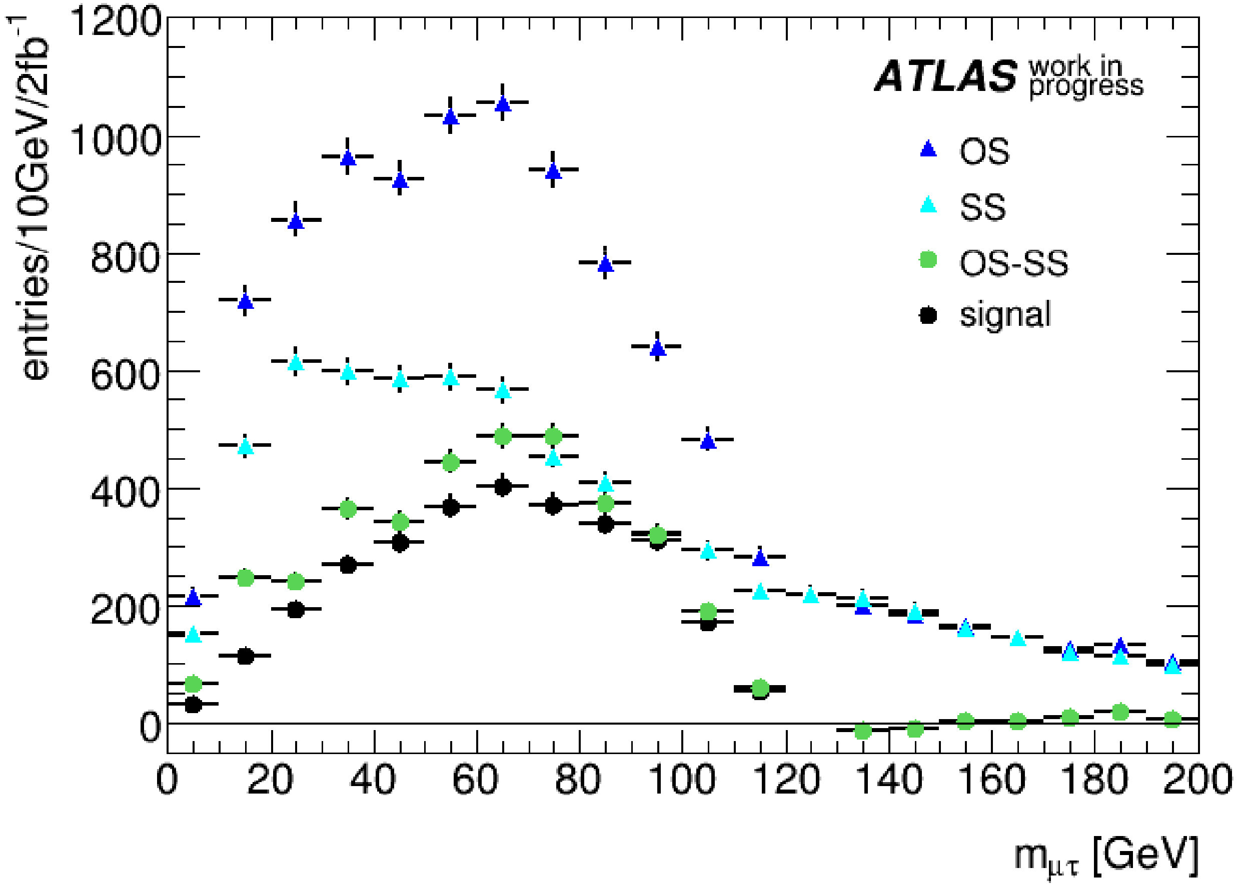
→ resonable cut: $\Delta R_{\mu\tau} < 1.2$ (χ decay products boosted)

Mass reconstruction of LSP

Signal channel/ SUSY background

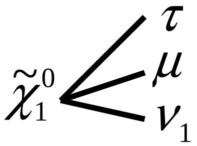


2. Opposite sign- same sign subtraction (truth)

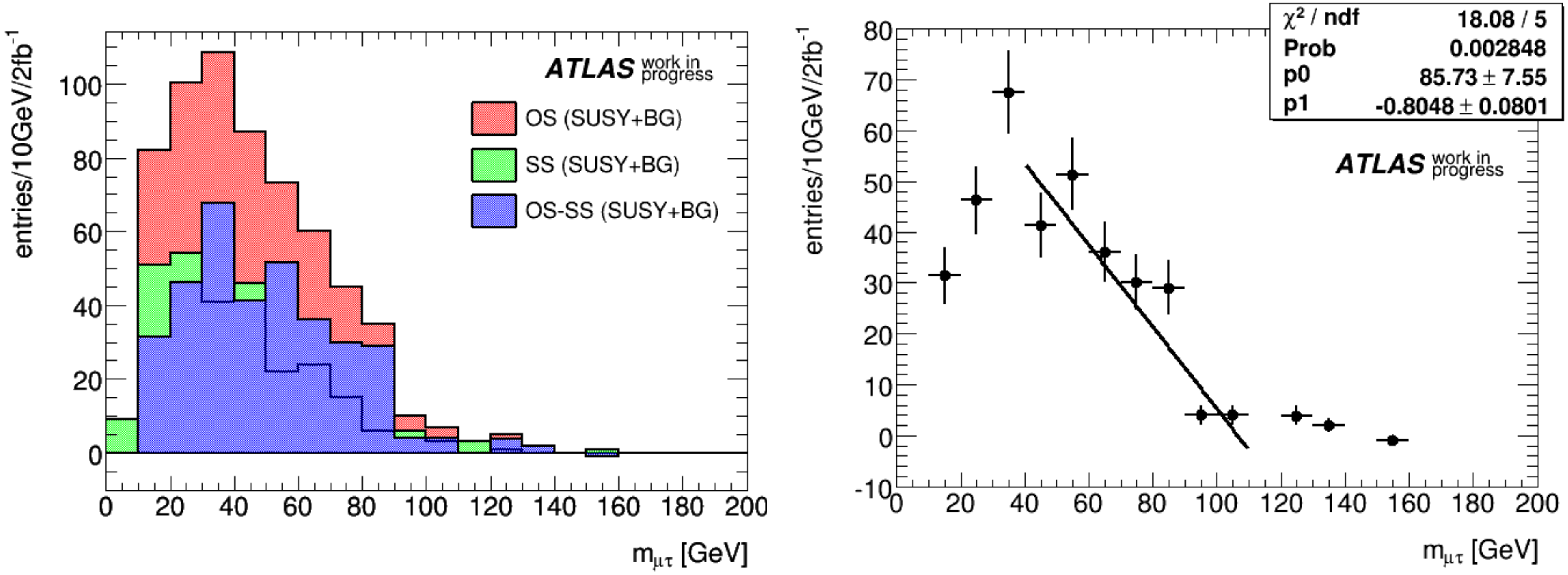


Mass reconstruction of LSP

Signal channel/ SUSY background



Invariant mass of μ and τ after $\Delta R_{\mu\tau}$ cut and OS-SS subtraction (reco)



Simple linear fit leads to mass-endpoint:

$$\boxed{m_{\chi}^{EP} = (107 \pm 14) GeV}$$

$$m_{\chi}^{theory} = 118 GeV$$

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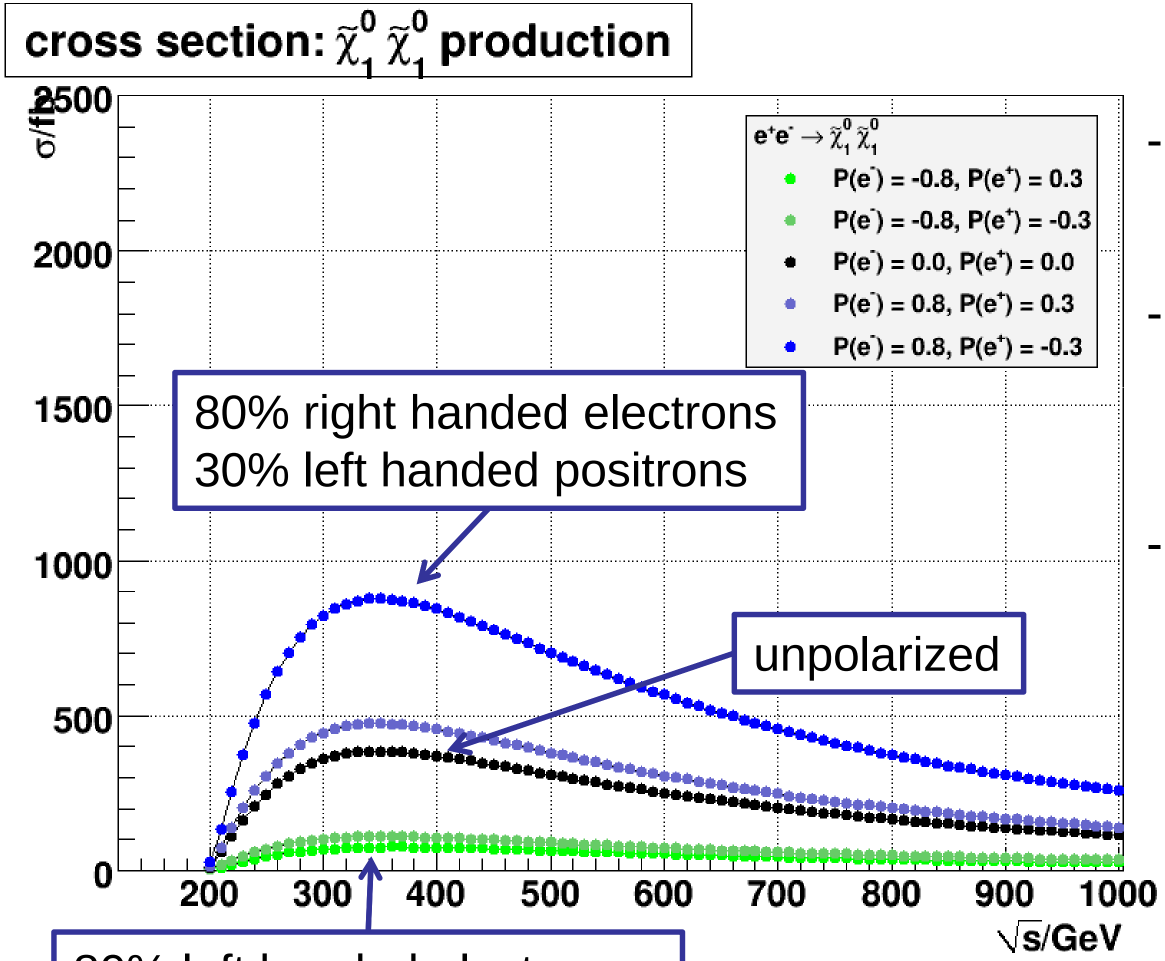
ILC potential

Production cross section

Attention: SPS1a‘



80% right handed electrons
30% left handed positrons

unpolarized

80% left handed electrons
30% right handed positrons

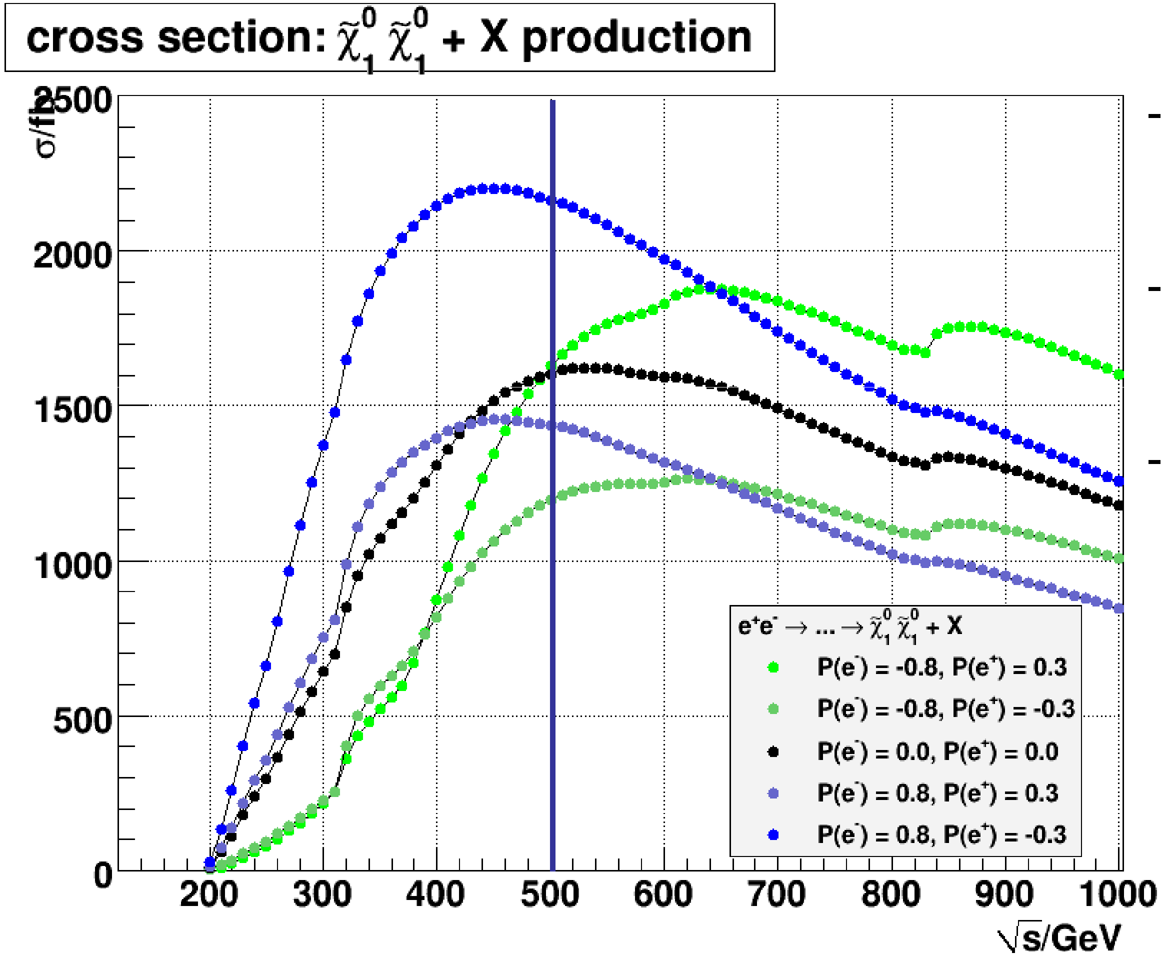
- ILC can collide polarized incomming particles (⇔LHC)

- ILC design parameters:
  - -0.3 (left) ≤ $P(e^+)$ ≤ 0.3 (right)
  - -0.8 (left) ≤ $P(e^-)$ ≤ 0.8 (right)

- production cross sections highly dependent on polarization

ILC potential

Production cross section



- small RPV parameters
  → LSP decays into SM

- typical SUSY cascades with LSP decay in the end

- almost all sparticle-production processes can be used to study LSP decays

→ ILC design energy: 500GeV

→ σ_{+-}(500GeV) = 2200 fb

ILC potential

Most important decay channels of LSP (@SPS1a')

LSP decay	Branching ratio
W μ	0.034
W τ	0.031
ν_2 b b	0.035
ν_1 τ e	0.159
ν_1 τ μ	0.279
ν_1 τ τ	0.453

Study neutrino parameters

neutrino mixing, …

Study LSP parameters

mass (endpoint), mixing character, ..

Decay width of LSP

$\overline{\Gamma} = 3.77\cdot10^{-13}$ GeV → $\overline{l} \approx 523\ \mu m$

Displaced vertices expected!

Analysis strategy

Looking for:
- LFV signal
- two displaced vertices per event (+cascade products from IP)
- high effective mass per event

ILC potential

Statistical uncertainties on θ_{atm}:

∫L dt = 500 fb^{-1} (4 years of ILC running)
σ_{+-}(500GeV) = 2200 fb
Detection efficiency = 0.5

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

σ_{rel}^{stat}(Br(χ→Wμ)/ Br(χ→Wτ)) ≈ 1%

→ θ_{atm}=(46.36+-0.15)°

Signal/background estimation

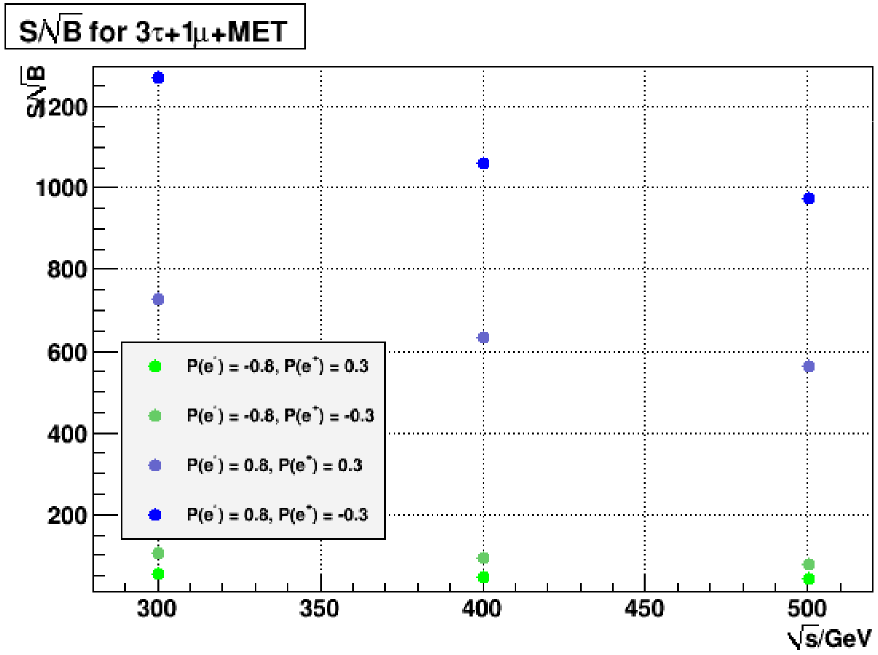
- tree level cross sections for SM BG (Whizard 2.0; arXiv:0708.4233)
- just looking for similar final states

for example:

$$e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow (\nu\tau\tau)(\nu\tau\mu)$$

$$e^+e^- \rightarrow SM \rightarrow \tau\tau\nu\mu\nu$$

$$= 3\tau + 1\mu + \mathrm{MET}$$



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

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Conclusion/Outlook

Conclusion

- bRPV enables access to **neutrino physics at the collider**
- ATLAS detector simulation:
    - **RPV signal should be observable**
    - dilepton edge can be used to **determine the mass of neutralino** (ATLAS)
    - Analysis should be redone at sqrt(s)=7 TeV (ATLAS)
- ILC case:
    - Polarisation is a very useful tool to increase signal over background (ILC)
    - ILC is highly capable to look at that kind of models

Outlook

- Implementation of bRPV in Whizard using FeynRules on the way
- Detailed ILC study in progress

Thank you for your attention!

References

Romao: *Testing Neutrino Parameters at Future Accelerators*.
arXiv:hep-ph/0211276v1

Hirsch, Díaz, Porod, Romae, Valle: *Neutrino Masses an Mixings from Supersymmetry with Bilinear R-Parity Violation: A Theory for Solar and Atmospheric Neutrino Oscillations*.
arXiv:hep-ph/0004115v2

Torro, Mitsou, Garcia: *Probing Bilinear R-Parity Violating Supersymmetry in the Muon plus Jets Channel.*
ATL-COM-PHYS-2009-543

ATLAS Collaboration: ATLAS CSC Note. Supersymmetry Searches with ATLAS

Backup Slides

Bilinear P_R violation

The model

Mass matrices

$$M_{\chi^0} = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g'v_d & \frac{1}{2}g'v_u \\ 0 & M_2 & \frac{1}{2}gv_d & -\frac{1}{2}gv_u \\ -\frac{1}{2}g'v_d & \frac{1}{2}g'v_u & 0 & -\mu \\ \frac{1}{2}gv_d & -\frac{1}{2}gv_u & -\mu & 0 \end{pmatrix}$$

$$m = \begin{pmatrix} -\frac{1}{2}g'v_1 & \frac{1}{2}gv_1 & 0 & \varepsilon_1 \\ -\frac{1}{2}g'v_2 & \frac{1}{2}gv_2 & 0 & \varepsilon_2 \\ -\frac{1}{2}g'v_3 & \frac{1}{2}gv_3 & 0 & \varepsilon_3 \end{pmatrix}$$

Phenomenology

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

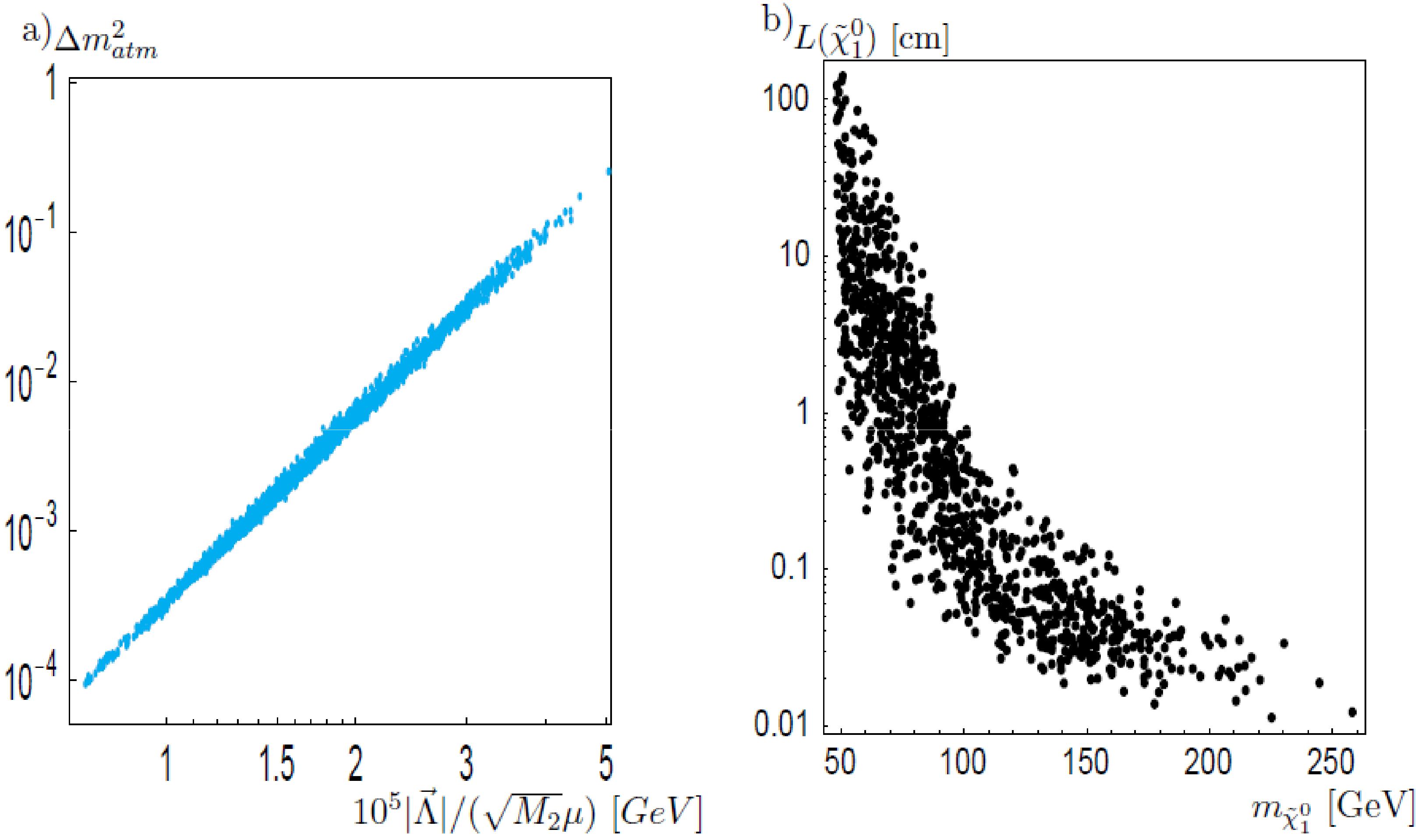


Figure 4: a) Δm^2_{atm} and b) neutralino decay length.

Benchmark scenarios

mSUGRA

SUSY has to be broken! **mSUGRA** (105 parameters → 5 parameters)

$$M_3 = M_2 = M_1 = m_{1/2}$$

$$\mathbf{m}^2_{\tilde{Q}} = \mathbf{m}^2_{\tilde{\bar{u}}} = \mathbf{m}^2_{\tilde{\bar{d}}} = \mathbf{m}^2_{\tilde{L}} = \mathbf{m}^2_{\tilde{\bar{e}}} = m_0 \mathbf{1} \quad m^2_{H_u} = m^2_{H_d} = m^2_0$$

$$\mathbf{a}_u = A_0 \mathbf{y}_u \quad \mathbf{a}_d = A_0 \mathbf{y}_d \quad \mathbf{a}_e = A_0 \mathbf{y}_e$$

$$\tan\beta$$

$$\mathrm{sgn}(\mu)$$

Planck scale

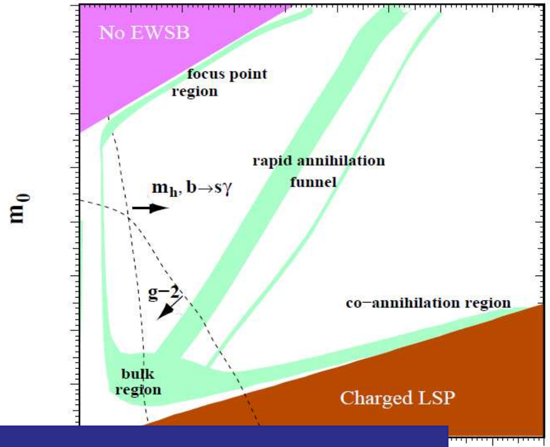
RGE

SPheno 3.0

SUSY spectrum & couplings **electroweak scale**

(W. Porod ,
arXiv:hep-ph/0301101)

Benchmark scenarios



SUSY benchmark points

Special benchmark points for ATLAS:

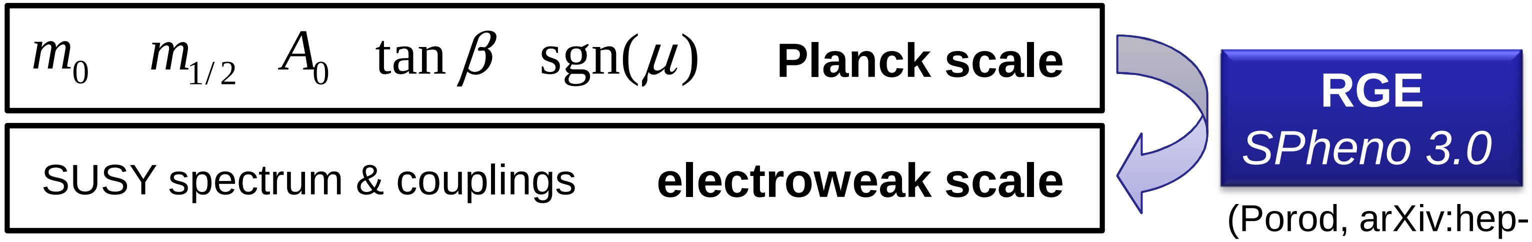
Name	m_0 [GeV]	$m_{1/2}$ [GeV]	A_0 [GeV]	tan β	sgn μ	Characteristics
SU1	70	350	0	10	+	Coanihilation region
SU2	3550	300	0	10	+	Focus point region
SU3	100	300	-300	6	+	Bulk region
SU4	200	160	-400	10	+	Low mass point
SU6	320	375	0	50	+	
SU8.1	210	360	0	40	+	Funnel region
SU9	300	425	20	20	+	

(ATLAS CSC Note)

Phenomenology

mSUGRA

SUSY has to be broken! **mSUGRA** (105 parameters → 5 parameters)



$m_0 \quad m_{1/2} \quad A_0 \quad \tan\beta \quad \mathrm{sgn}(\mu)$ **Planck scale**

SUSY spectrum & couplings **electroweak scale**

RGE
SPheno 3.0

(Porod, arXiv:hep-ph/0301101)

Comparison of SU benchmark points for LSP decay

SU benchmark points

→ ATLAS specific mSUGRA benchmark scenarios
→ SU3 chosen for analysis

Name	Characteristics	$m_{\chi 10}$ [GeV]	Decay length [µm]
SU1	Coanihilation region	139	124
SU2	Focus point region	120	2037
SU3	Bulk region	118	291
SU4	Low mass point	60	102 10^3
SU6		152	408
SU8.1	Funnel region	145	314
SU9		173	20

Phenomenology

Comparison of SU points for LSP decay

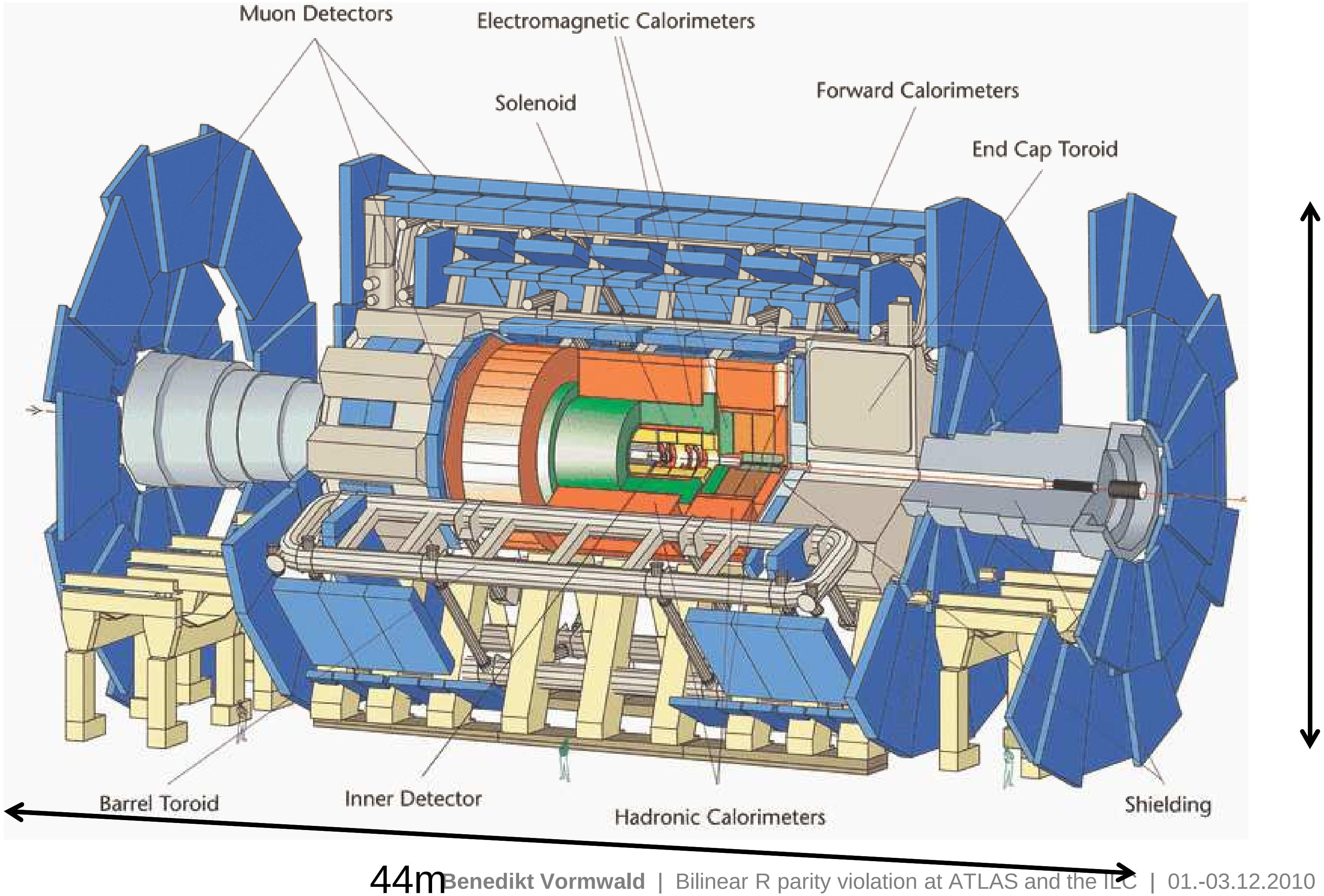
Chosen LSP-decay to investigate: $\tilde{\chi}_1^0 \rightarrow \mu^{\pm} + \tau^{\mp} + \nu$

Name	$m_{\chi 10}$	Decay length [m]	BR(2BD)	BR(3BD-non/semilept.)	BR(3BD-leptonic)	BR(χ^{10} -> τ τ ν)	BR(χ^{10} -> μ τ ν)
SU1	139	$1{,}2\ 10^{-4}$	0,32	0,02	0,66	0,33	0,10
SU2	120	$2{,}0\ 10^{-3}$	0,85	0,09	0,06	0,01	0,01
SU3	118	$2{,}9\ 10^{-4}$	0,46	0,05	0,49	0,25	0,08
SU4	60	0,1	~0	0,36	0,64	0,30	0,08
SU6	152	$4{,}1\ 10^{-4}$	0,73	0,01	0,26	0,14	0,03
SU8.1	145	$3{,}1\ 10^{-4}$	0,48	0,01	0,51	0,28	0,06
SU9	173	$2{,}0\ 10^{-5}$	0,88	0,01	0,11	0,06	0,01

(data created with Spheno 3beta36,
W. Porod , arXiv:hep-ph/0301101)

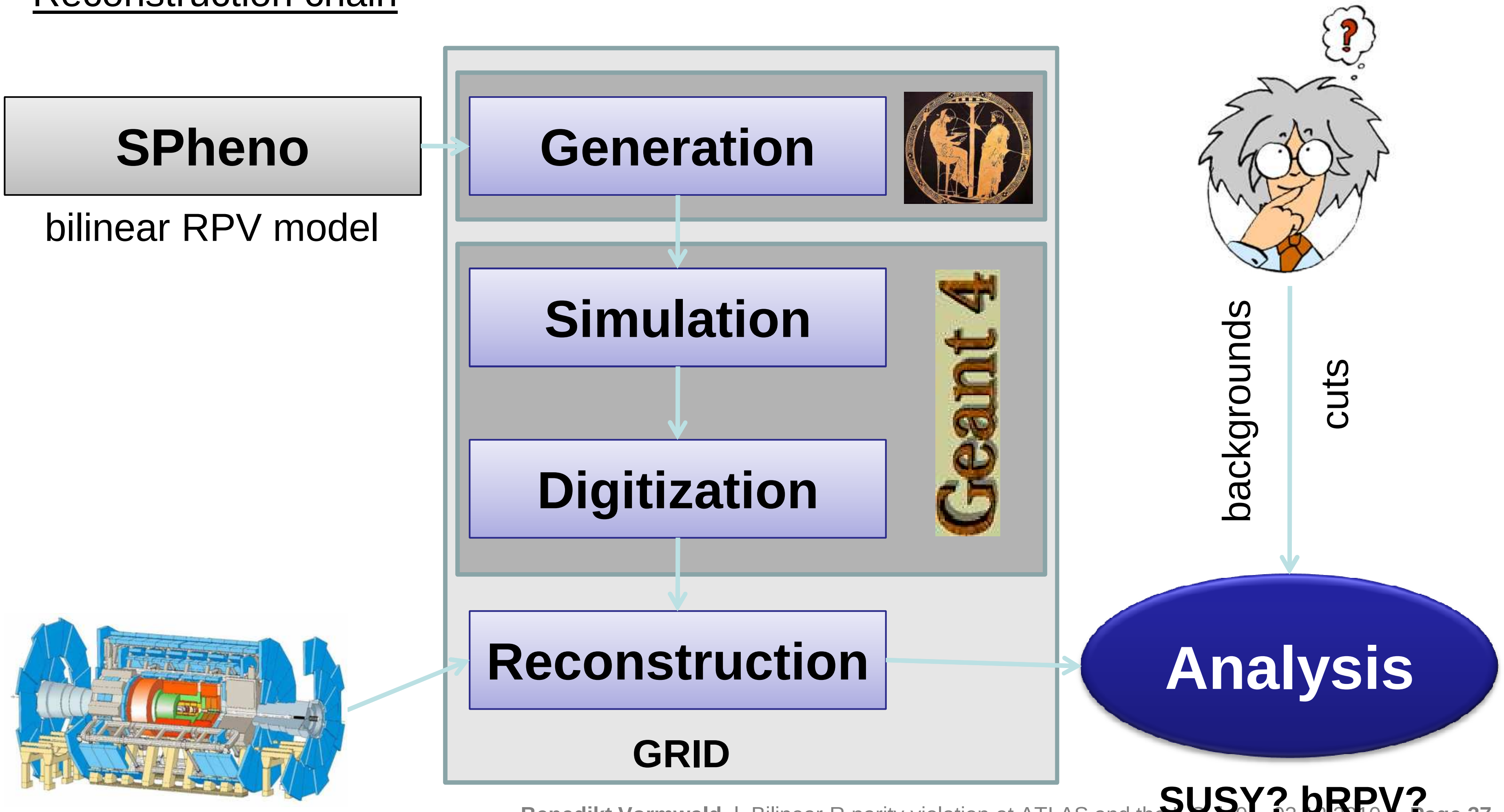
Experiment & Software

ATLAS detector



Software workflow

Reconstruction chain



SPheno

bilinear RPV model

Generation

Simulation

Digitization

Reconstruction

GRID

backgrounds

cuts

Analysis

SUSY? bRPV?

SPheno Parameters in bRPV

9 extra parameters for bRPV

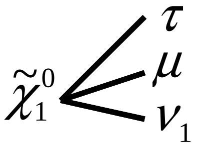
Define them explicitly

OR

Constraints:

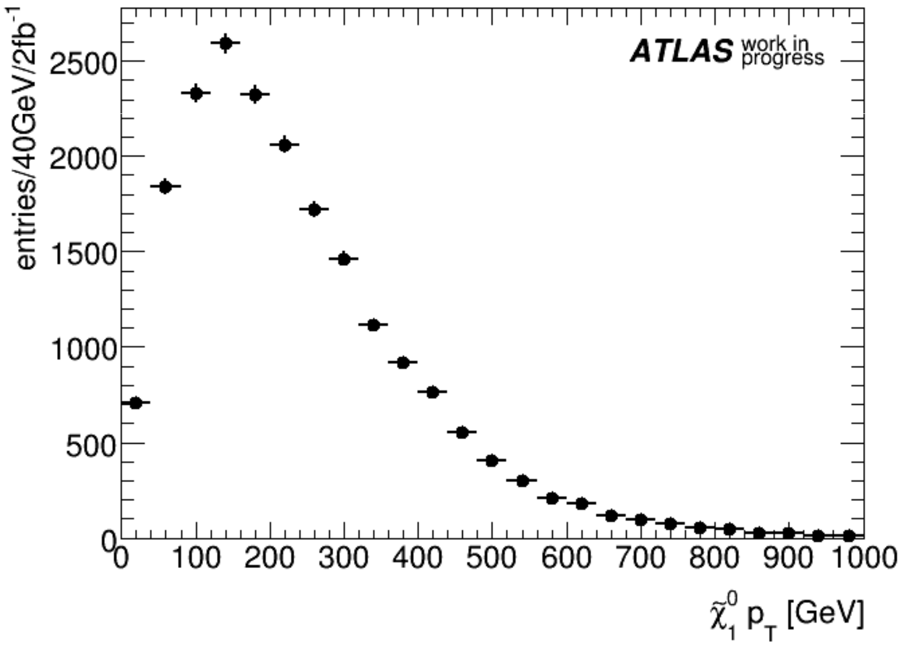
- Successful electroweak symmetry breaking corresponds to minimization of effective potential; technically: 3 extra tadpole equations linear in B_i
- Results from neutrino oscillation data (2 mass differences, 3 mixing angles) fix 5 bilinear parameters (ε_i,v_i)
- Remaining parameter should be of the same order as the others

Signal channel/ SUSY background



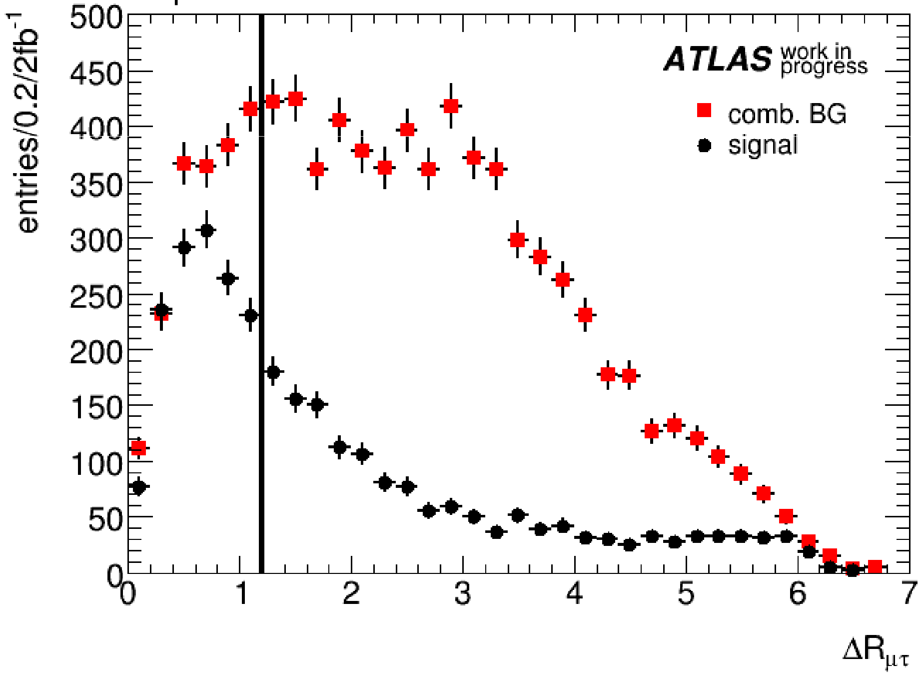
Calculation of invariant mass of μ and τ

p_t distribution of neutralinos:



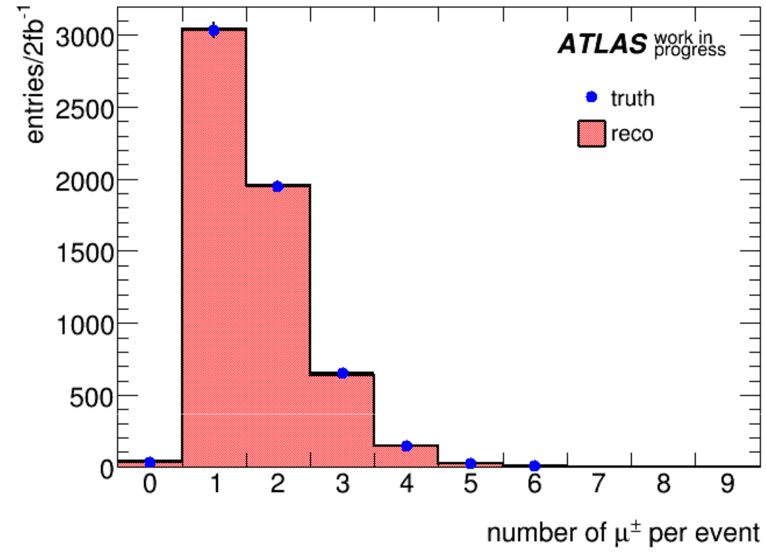
→ **Decay products should be boosted**

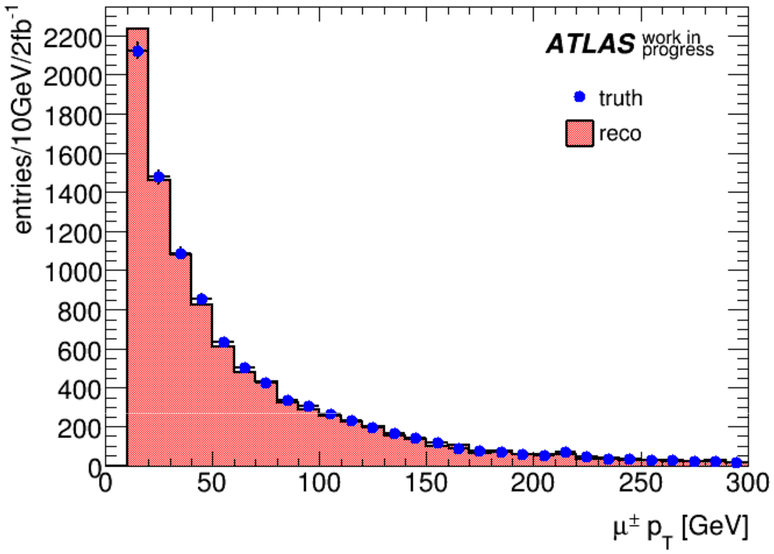
$\Delta R_{\mu\tau}$ distribution of signal and BG pairs:

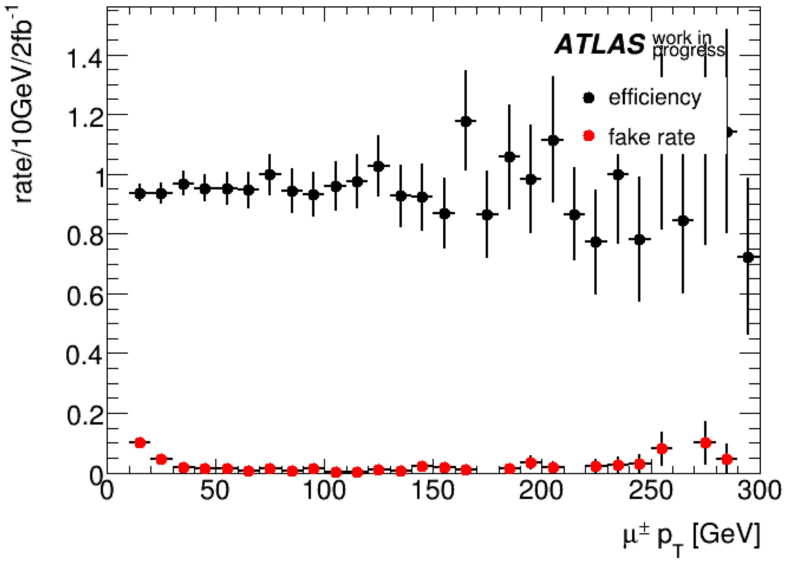


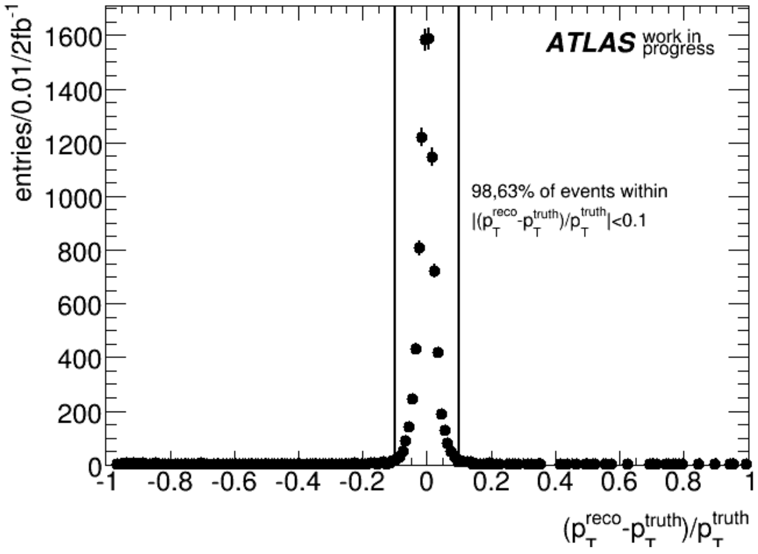
→ **Resonalble cut: $\Delta R_{\mu\tau} < 1.2$**

Reconstruction of muons









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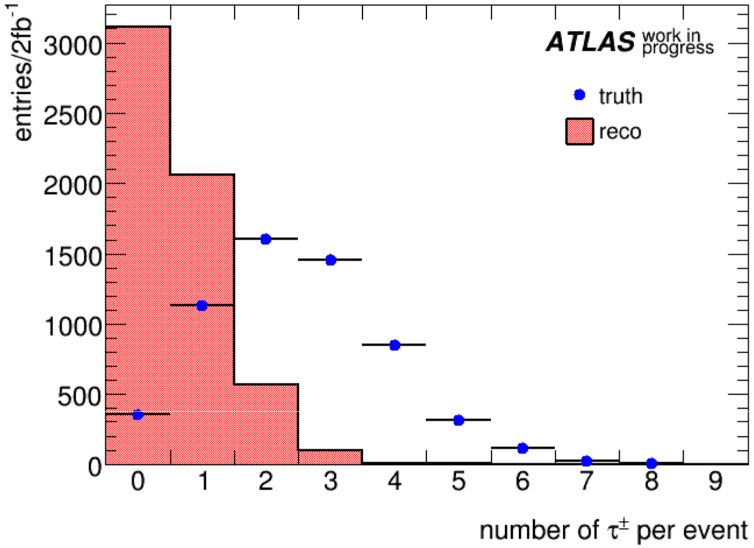
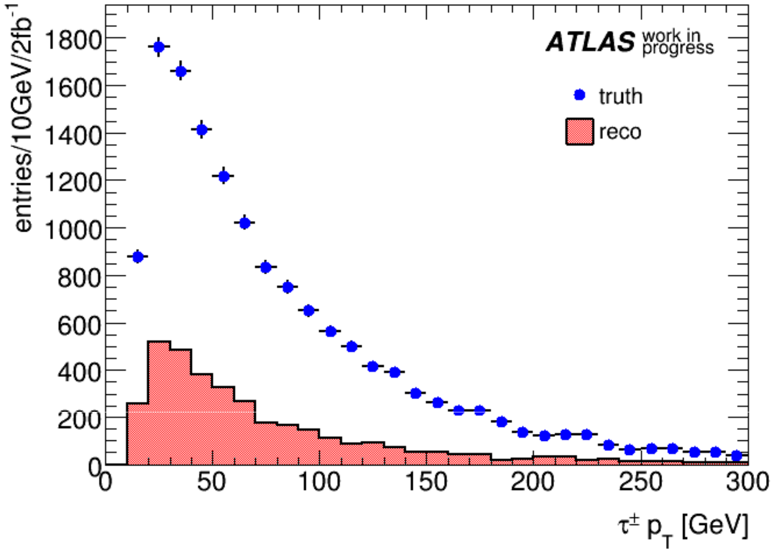
Analysis

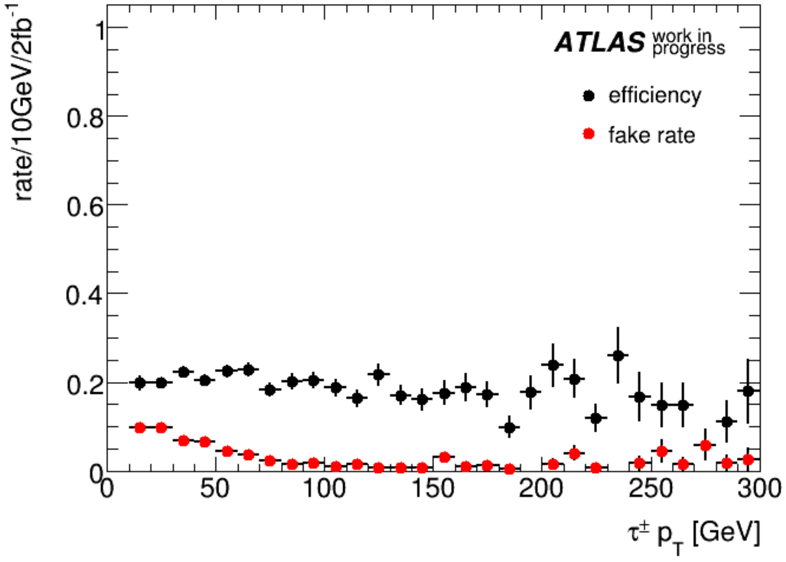
DESY

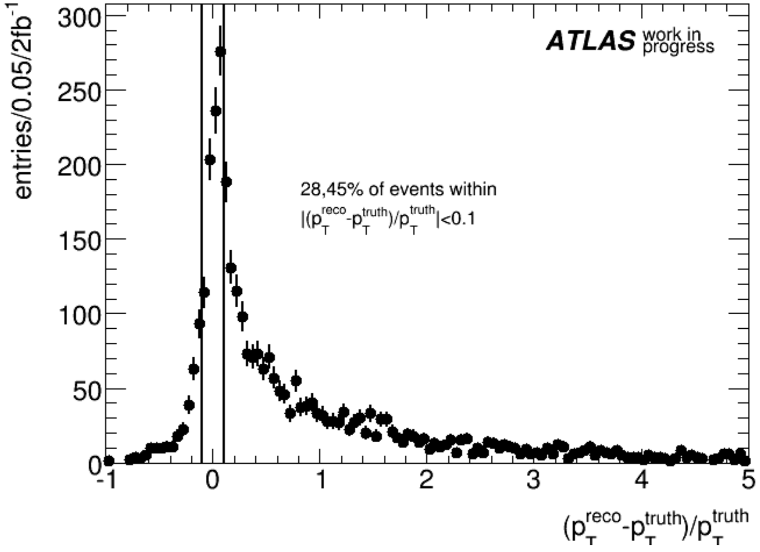
Reconstruction of taus

Truth including leptonic tau decays









Object Selection

Muons:

- combined muon
- pt > 10 GeV
- |η| < 2.7
- isolation cone 0.2/ 10 GeV

Electrons:

- isEm flag: „medium“
- pt > 10 GeV
- |η| < 2.5 and |η| ∉ [1.37,1.52]

Jets:

- pt > 20 GeV
- |η| < 2.5

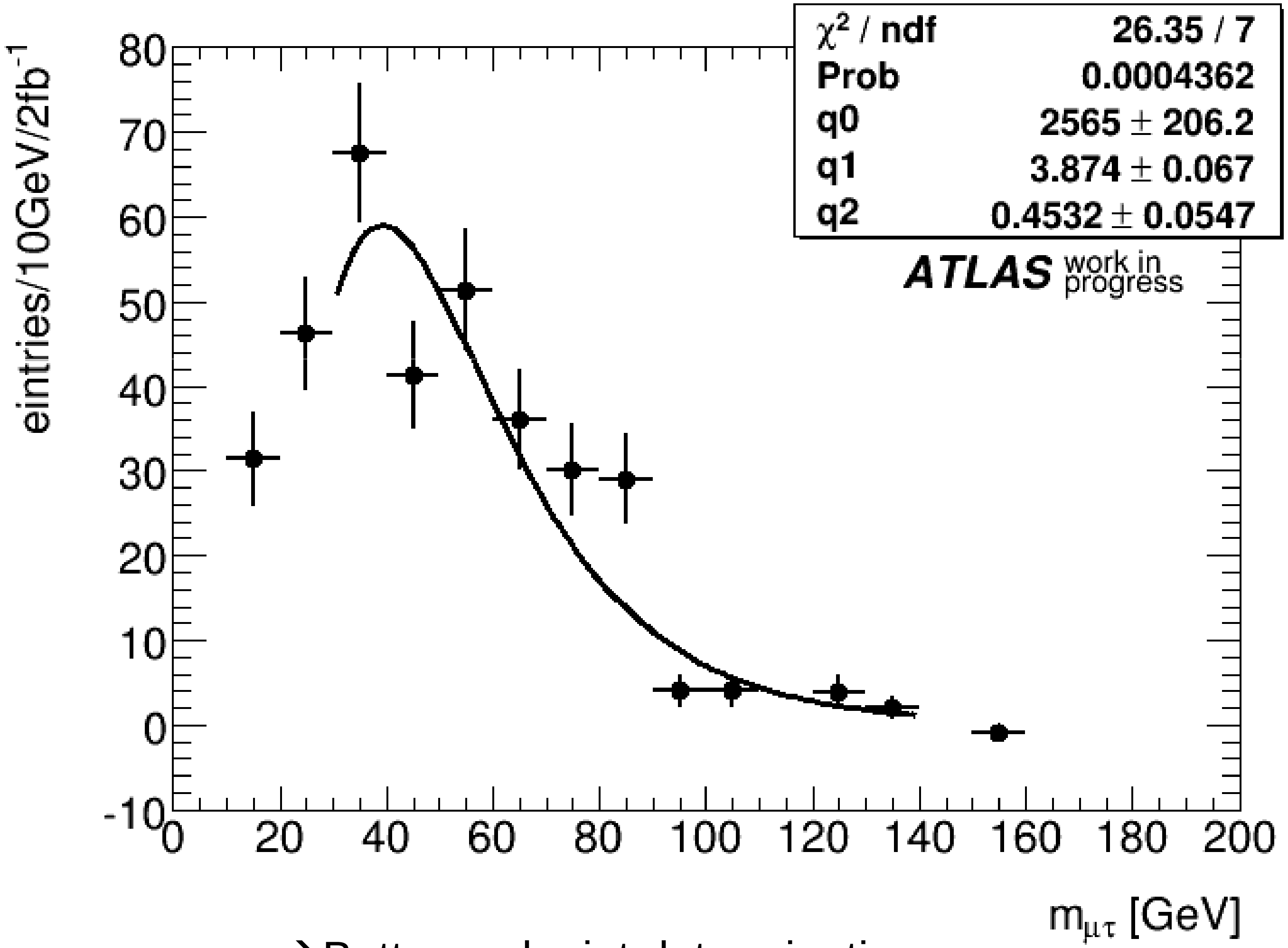
Taus:

- 1 / 3 tracks
- charge = ±1
- pt > 10 GeV
- |η| < 2.5 and |η| ∉ [1.37,1.52]
- Likelihood flag: „Loose“

Overlap removal:

- remove electrons within 0.2<ΔR<0.4 to a jet
- remove jets within ΔR<0.2 to an electron
- remove jets within ΔR<0.4 to another particle

Inflection point method

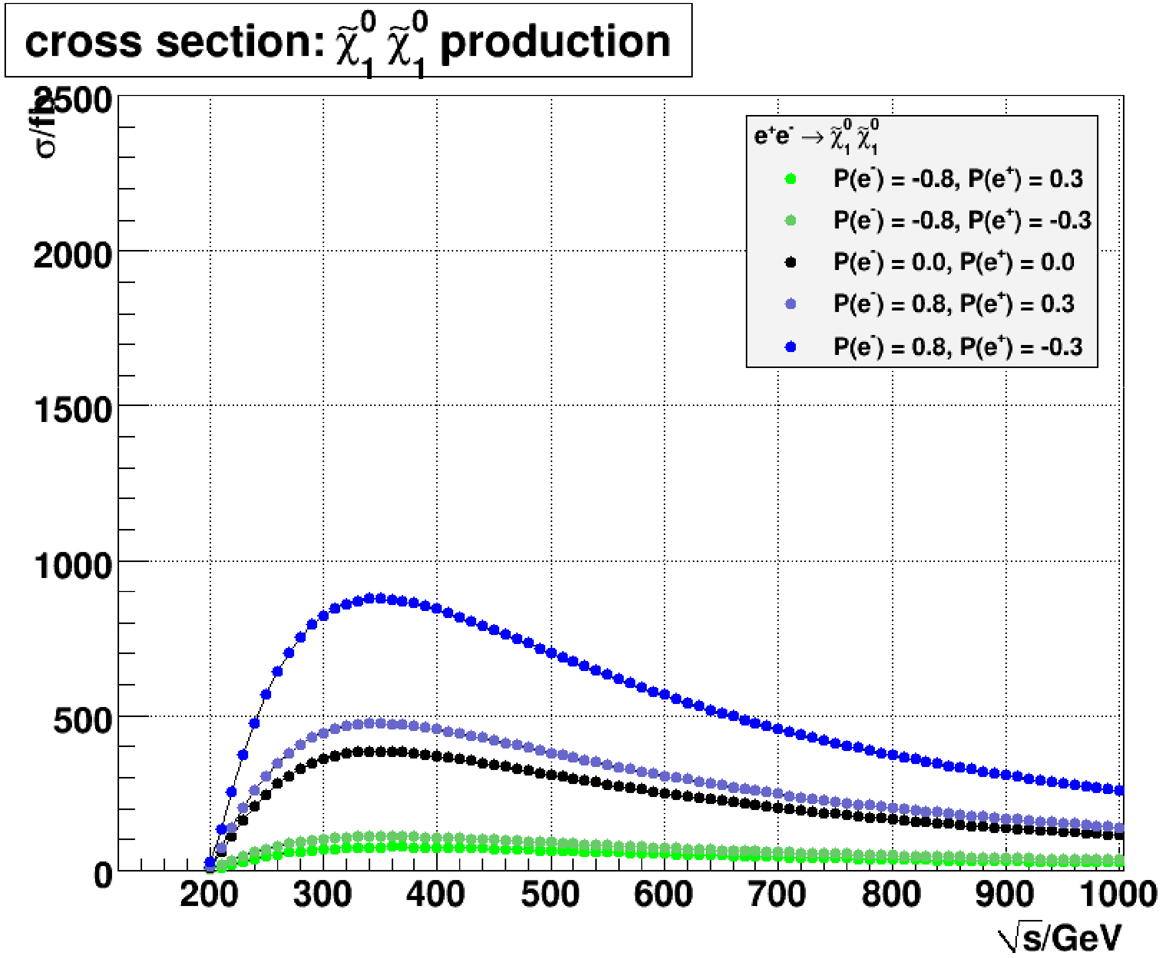


→Better endpoint determination

ILC potential

Attention: SPS1a‘

Production cross section



LSP mixing character:
83,9% Bino
4,0% u Higgsino
4,0% d Higgsino
8,1% Wino

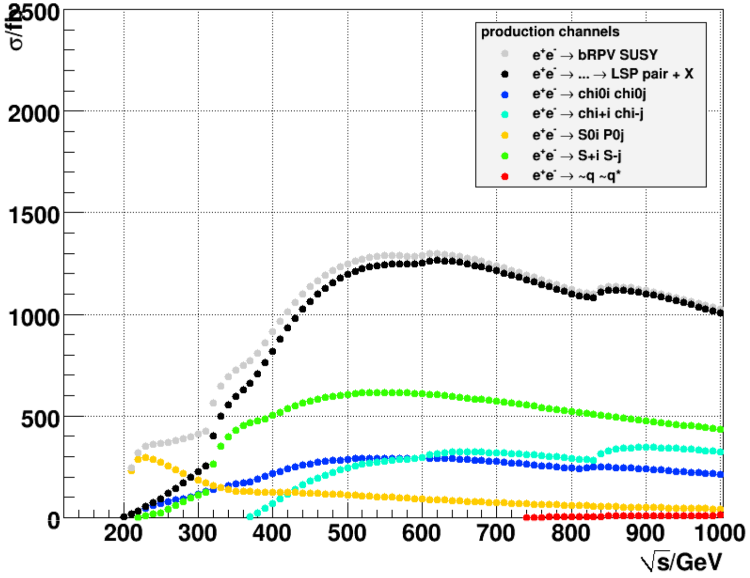
- main production processes:
  t-, u-channel

- „selectron“ exchange
  ($S^-_3 \approx \sim e^-_R$, $S^-_4 \approx \sim e^-_L$)

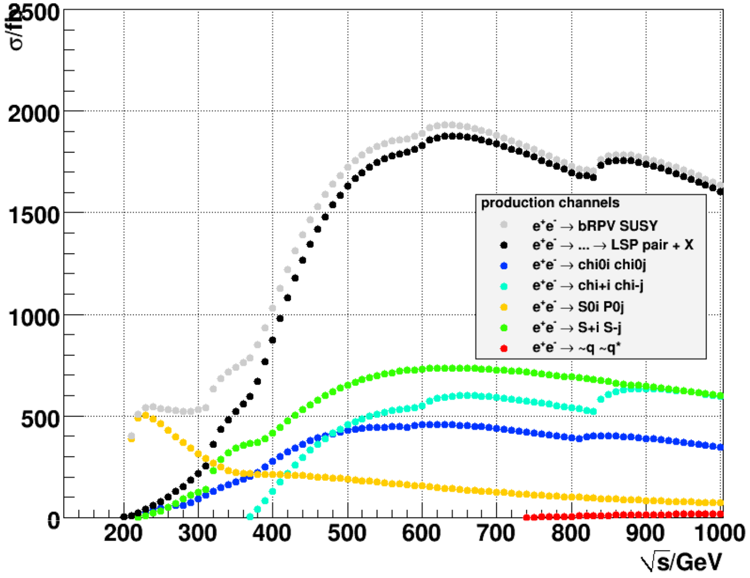
- $m(S^-_3) < m(S^-_4) \rightarrow \sigma_{+-} > \sigma_{-+}$

e$^+$/e$^-$ cross sections

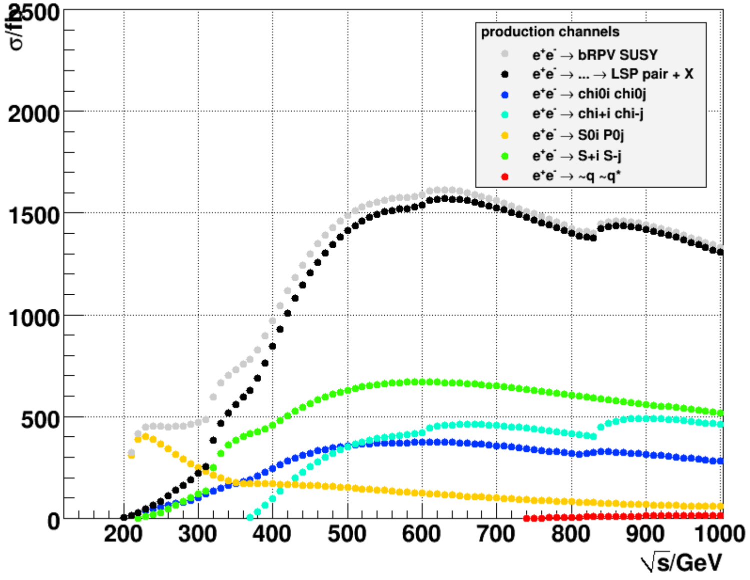
cross sections (P(e$^-$) = -0.8, P(e$^+$) = -0.3)



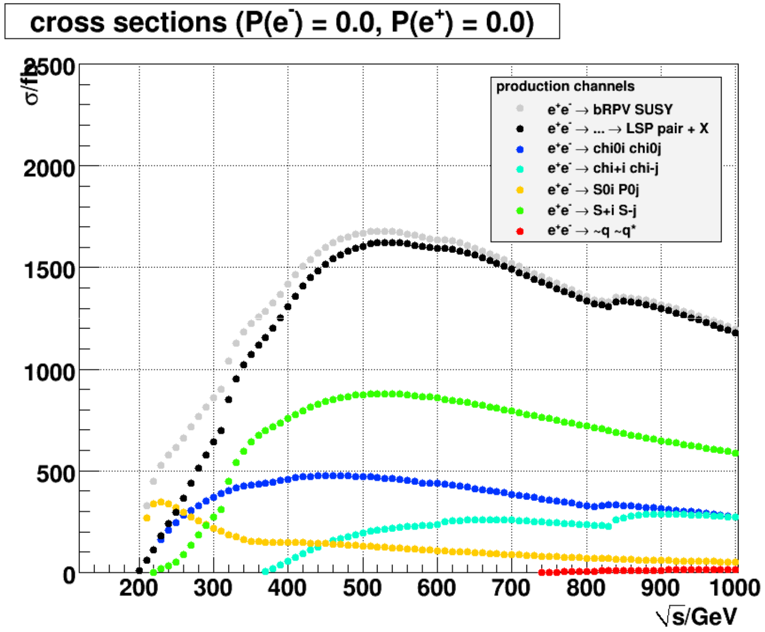
cross sections (P(e$^-$) = -0.8, P(e$^+$) = +0.3)



cross sections (P(e$^-$) = -0.8, P(e$^+$) = 0.0)

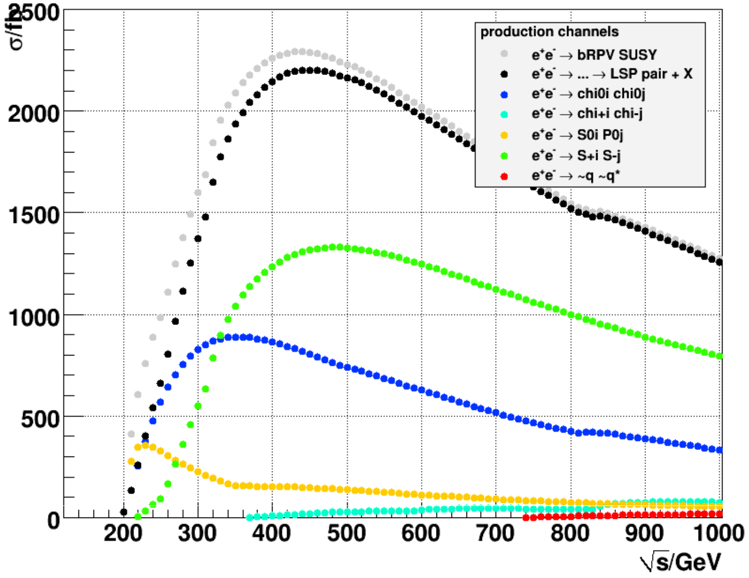


e^+/e^- cross sections

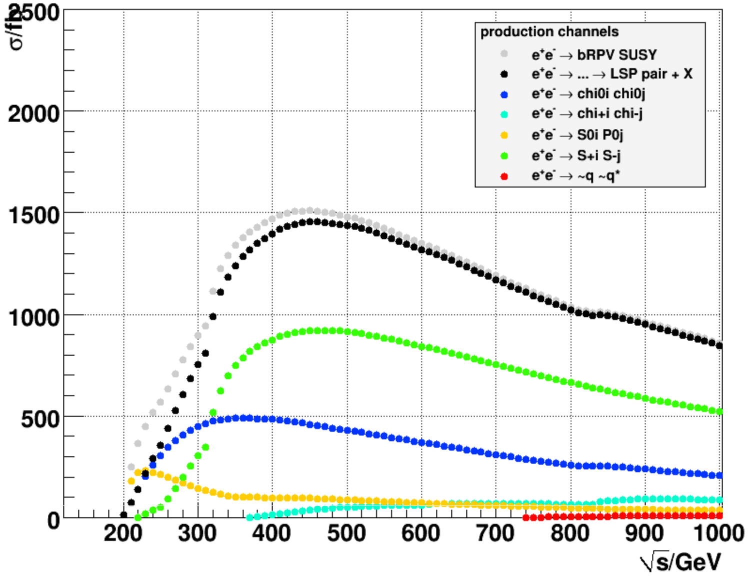


e^+/e^- cross sections

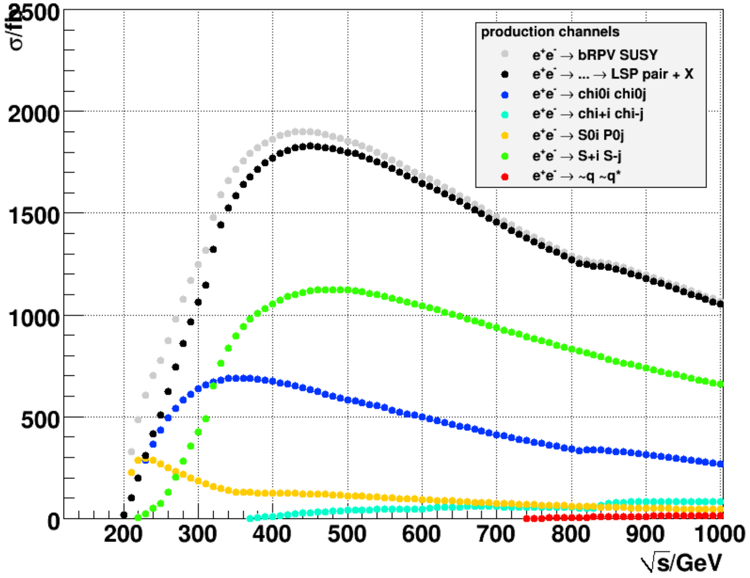
cross sections (P(e^-) = 0.8, P(e^+) = -0.3)



cross sections (P(e^-) = 0.8, P(e^+) = 0.3)

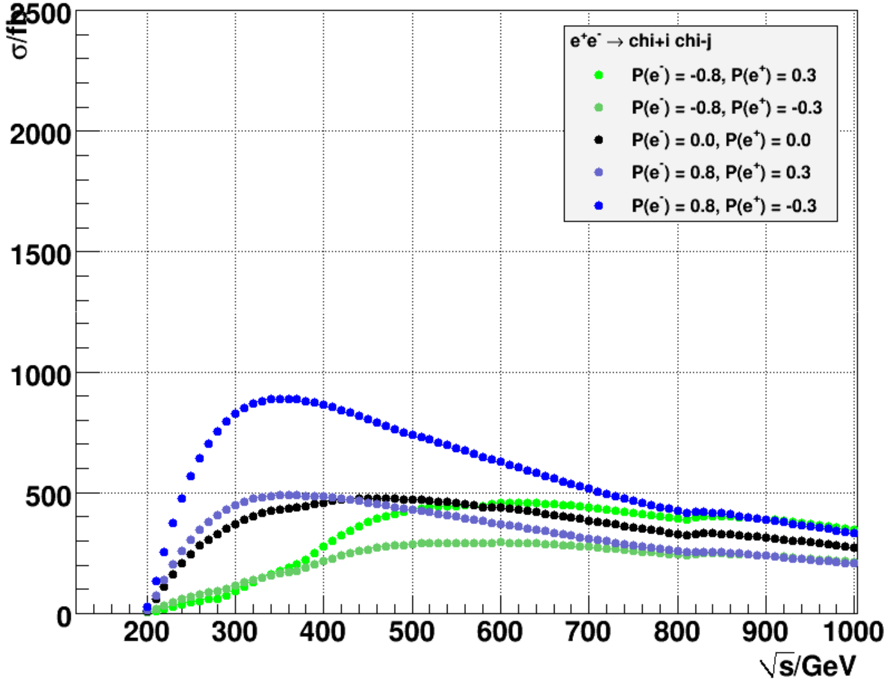


cross sections (P(e^-) = 0.8, P(e^+) = 0.0)

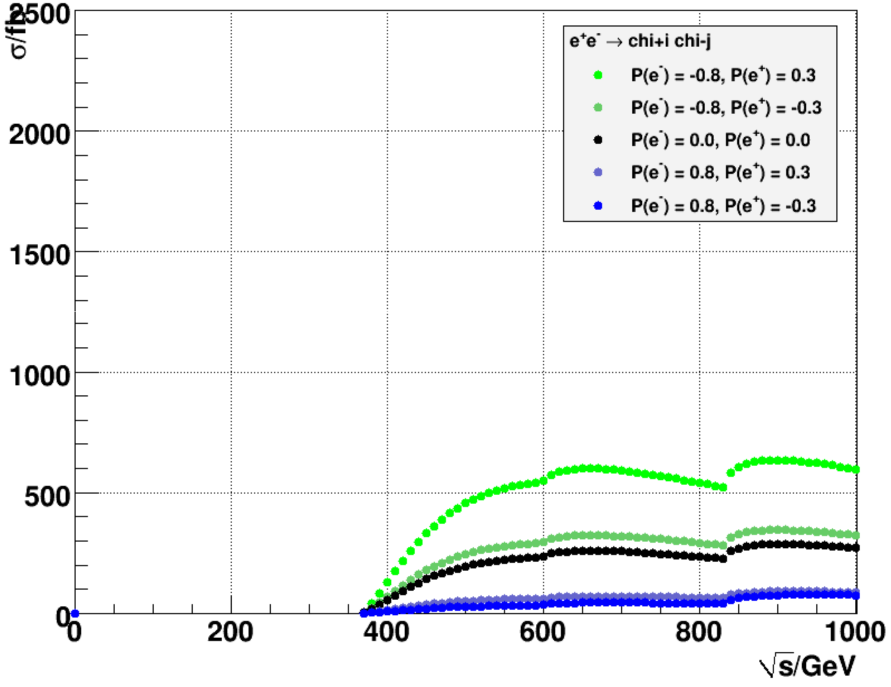


e^+/e^- cross sections

cross section: neutralino production

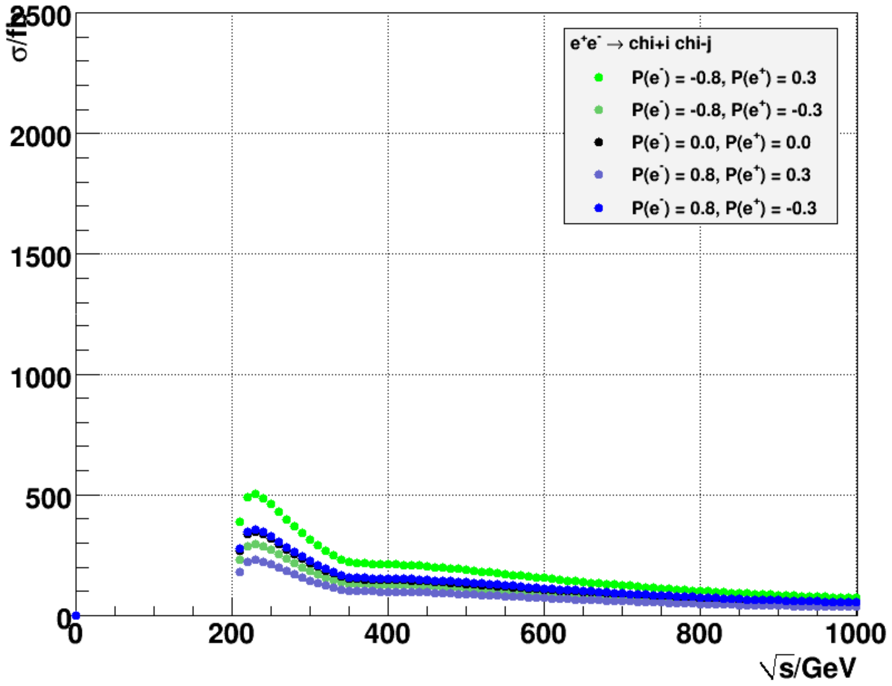


cross section: chargino production



e^+/e^- cross sections

cross section neutral scalar production



cross section charged scalar production