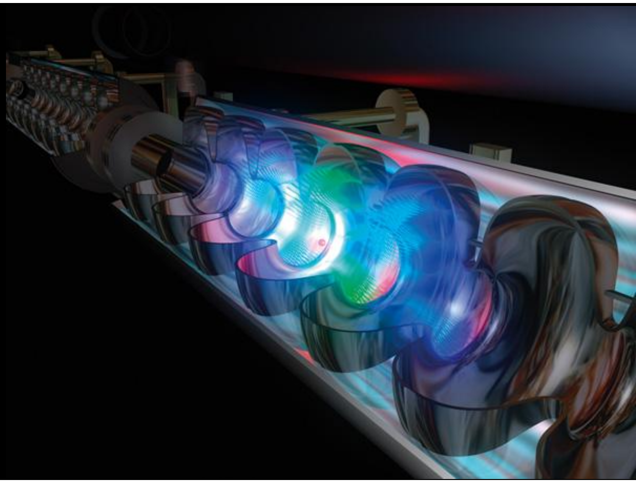
Bilinear R-Parity violation at the ILC.

Neutrino physics at colliders



Benedikt Vormwald, Jenny List
ECFA Workshop 2013
Hamburg, 27.05.-31.05.2013

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DESY

Outline

- Bilinear RPV – a motivation
- Analysis strategy
- Full Simulation
- Precision estimation for measuring the neutrino atmospheric mixing angle
- Conclusions

R-parity violation

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

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:

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

→ most general gauge-invariant and renormalizable superpotential

Some facts of bilinear R-parity violation

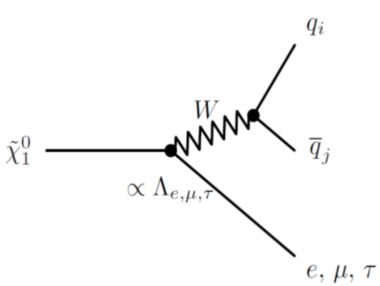
- **largest neutrino mass** at tree level
- **2 mixing angles** at tree level
- remaining masses/angles at 1-loop-level
- **correct scales** of mass differences Δm_{ij}^2

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

$$\tan\theta_{23} = \frac{\Lambda_\mu}{\Lambda_\tau} \qquad \tan\theta_{13} = -\frac{\Lambda_e}{\sqrt{\Lambda_\mu^2 + \Lambda_\tau^2}}$$

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

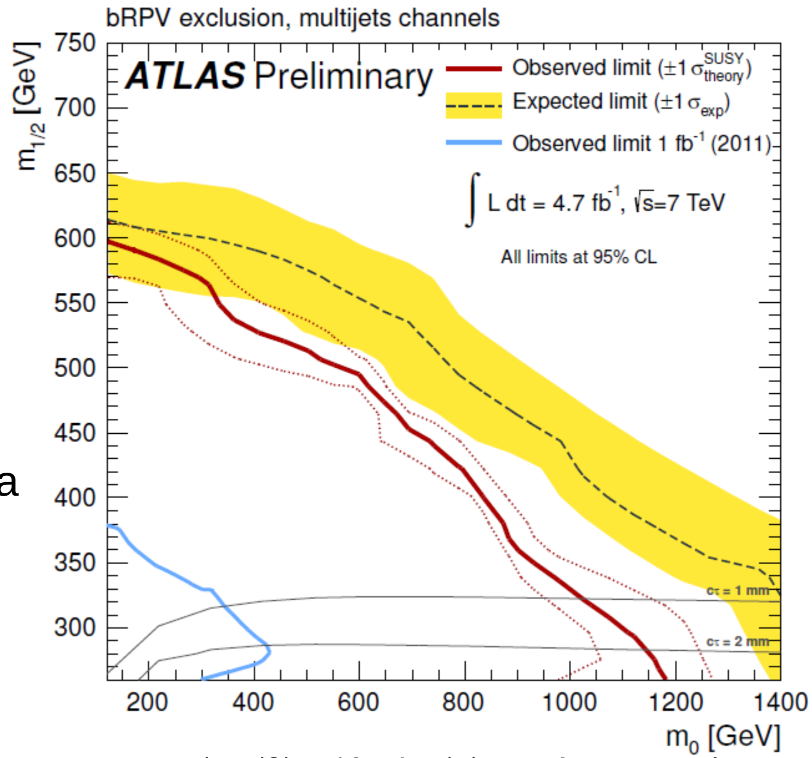
LHC searches

Situation at LHC

One dedicated bRPV mSUGRA search from ATLAS (**ATLAS-CONF-2012-140**):

- large jet multiplicity
- 1 isolated lepton
- missing transverse momentum

- bRPV parameters fitted to neutrino data
- bRPV mSUGRA tested for $m_{1/2}$ > 240GeV (→cτ < 15 mm)
- analysis probes colored sector of theory via squark production and subsequent decays
- coupling of EW sector and colored sector



($\tan(\beta) = 10$, sign(μ) = +, $A_0 = 0$ GeV)

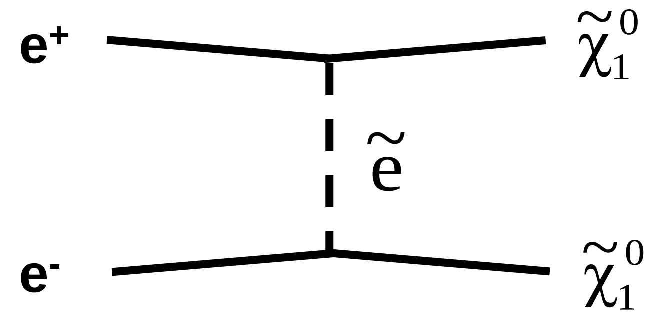
Situation at the ILC

- direct neutralino production → direct access to EW sector
- need better parametrization than mSUGRA to study phenomenology of this model, especially decouple EW sector from colored one → generic model

Generic SUSY model

Model definition

→ high squark masses (~1.5 TeV)
→ gaugino like LSP
→ most relevant parameters for cross section:
- selectron mass
- neutralino mass

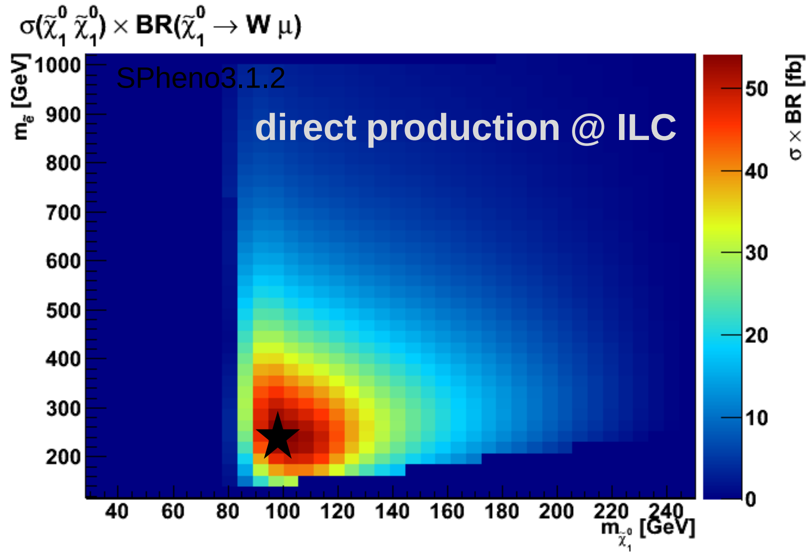


Example point

- $m(\tilde{\chi}_1^0)$ = 98.4 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**

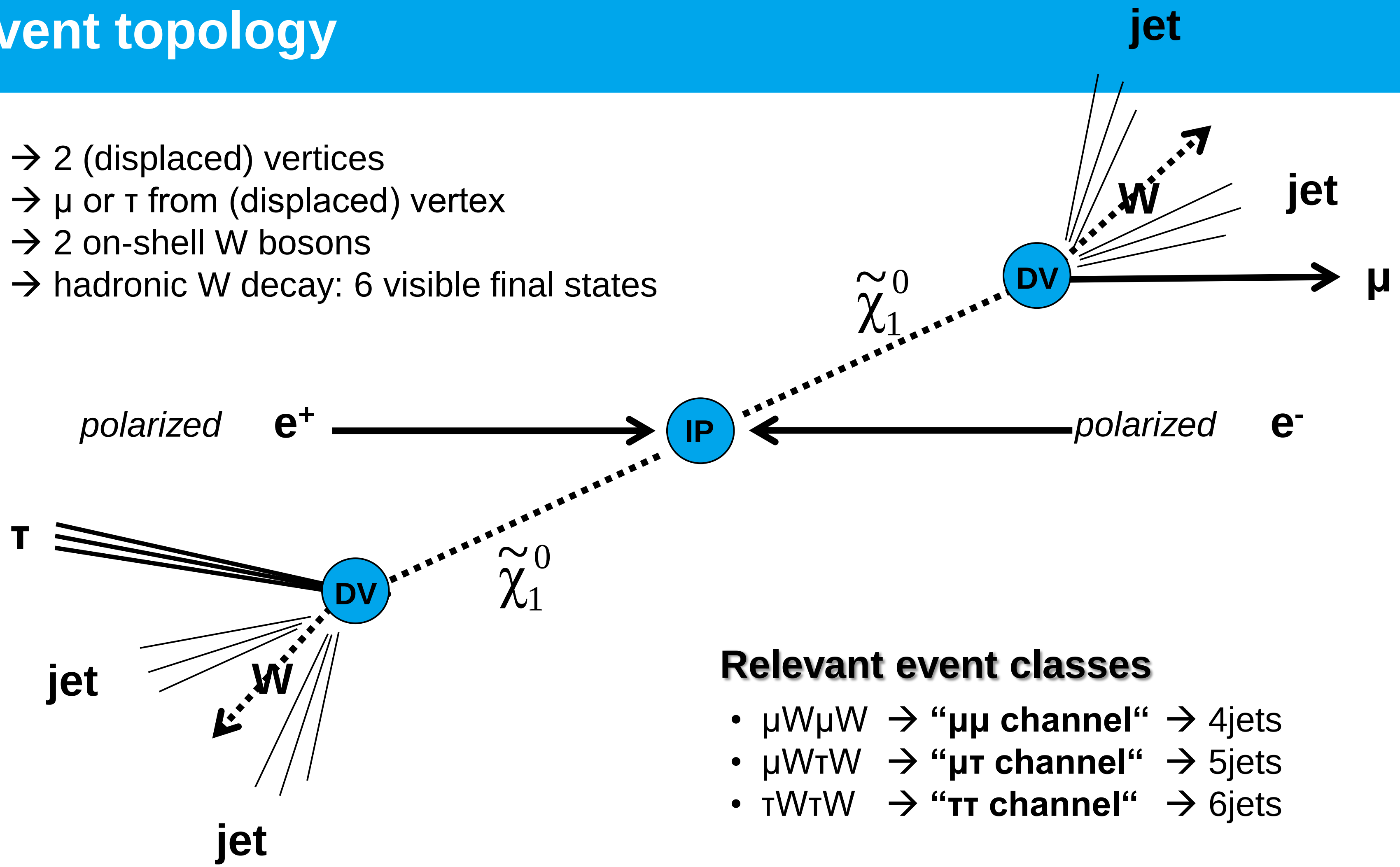


Expectations for ∫Ldt = 500 fb⁻¹

~193500 events:
- ~15170 (μW μW) events
- ~12093 (τW τW) events

Event topology

→ 2 (displaced) vertices
→ μ or τ from (displaced) vertex
→ 2 on-shell W bosons
→ hadronic W decay: 6 visible final states



Relevant event classes

- μWμW → **"μμ channel"** → 4jets
- μWτW → **"μτ channel"** → 5jets
- τWτW → **"ττ channel"** → 6jets

Goals

- reconstruct neutralino mass
- count event classes in order to measure ratio of BR(chi10→W μ) and BR(chi10→W τ)
- later step: measure decay length

Reconstruction strategy

events

γγ background removal
preselection

test for μμ

- remove **2 leading muons** from PFO objects
- force rest of the event into **4 jets**
- find **two good W** candidates from jets
- try to combine **2 equal mass objects** from Ws and leptons

test for μτ

- remove **leading muon** from PFO objects
- force rest of the event into **5 jets**
- consider jet with lowes multiplicity as tau
- find **two good W** candidates from remaining 4 jets
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test for ττ

- force event into **6 jets**
- consider two jets with lowes multiplicity as taus
- find **two good W** candidates from remaining 4 jets
- try to combine **two equal mass objects** from Ws and leptons

Datasets and used software

Datasets

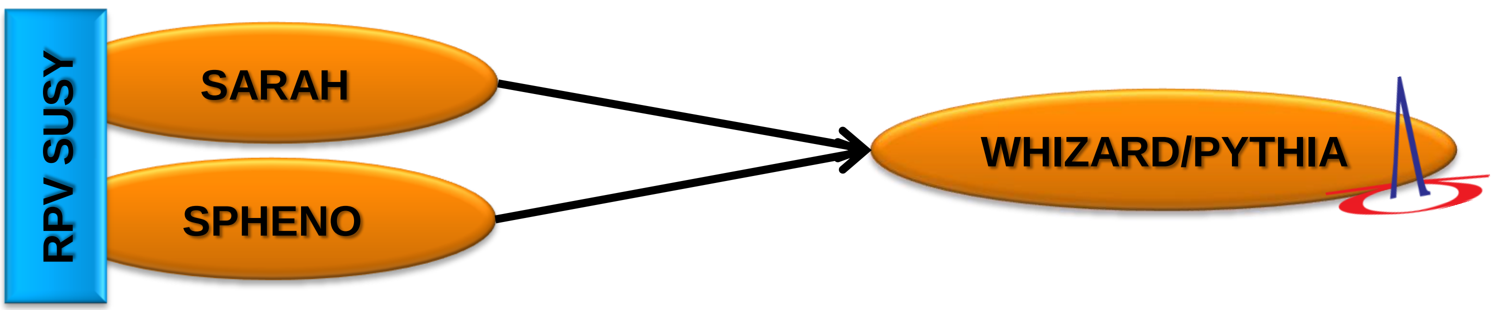
- 6f SM background: 500GeV DBD mass production (ILD_o1_v05)
- bRPV SUSY signal: private production with DBD software

Theory input

- *SARAH* for generating model files for event generator
- *SPheno* for SUSY parameter calculation and for fit of RPV parameters to neutrino data

Event generation

ILCWhizard (v1.95)
including ILC beam spectrum



Full Simulation

- simulated and reconstructed with ILCDIRAC system
- *reconstruction:* v01-16-p05_500
- *simulation:* v01-14-01-p00

data sample with:

100 fb^{-1}

500 GeV

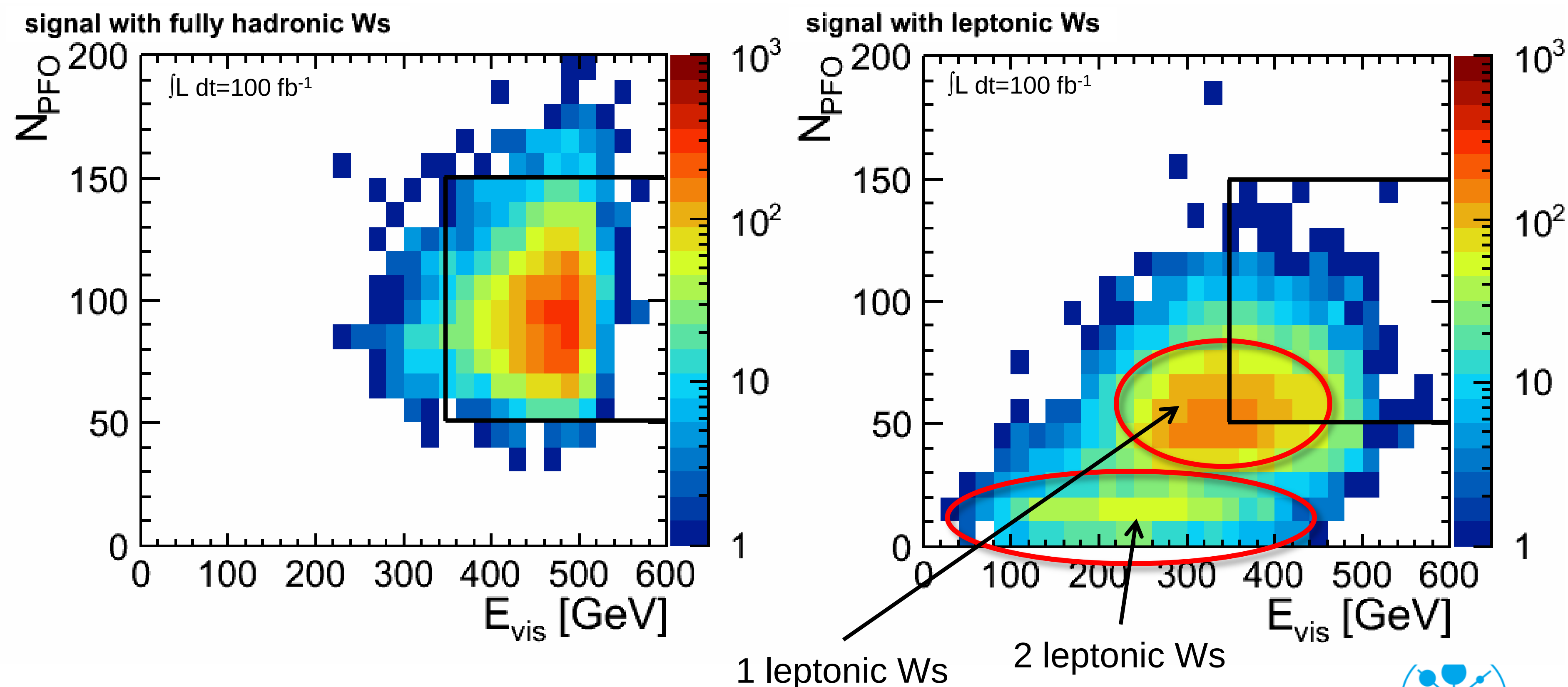
Preselection

select only events with high multiplicity and small missing energy:

- reduce SM 6f background
- reduce leptonic W decay contribution

→ E_{vis} > 350GeV
→ N_{PFO} > 50
→ N_{PFO} < 150

$lW_{had}lW_{had}$ | $lW_{had,lep}lW_{lep}$



Preselection – cut flow

cut	SUSY signal	SUSY non-signal	SM 6f background
no cut	5641	32564	49461
excl. k_T converged	5641	32299	49453
$E_{vis} > 350$ GeV	5483	11593	40224
$N_{PFO} > 50$	5468	8472	39927
$N_{PFO} < 150$	5390	8414	29825
efficiency	**0.96**	**0.26**	**0.60**

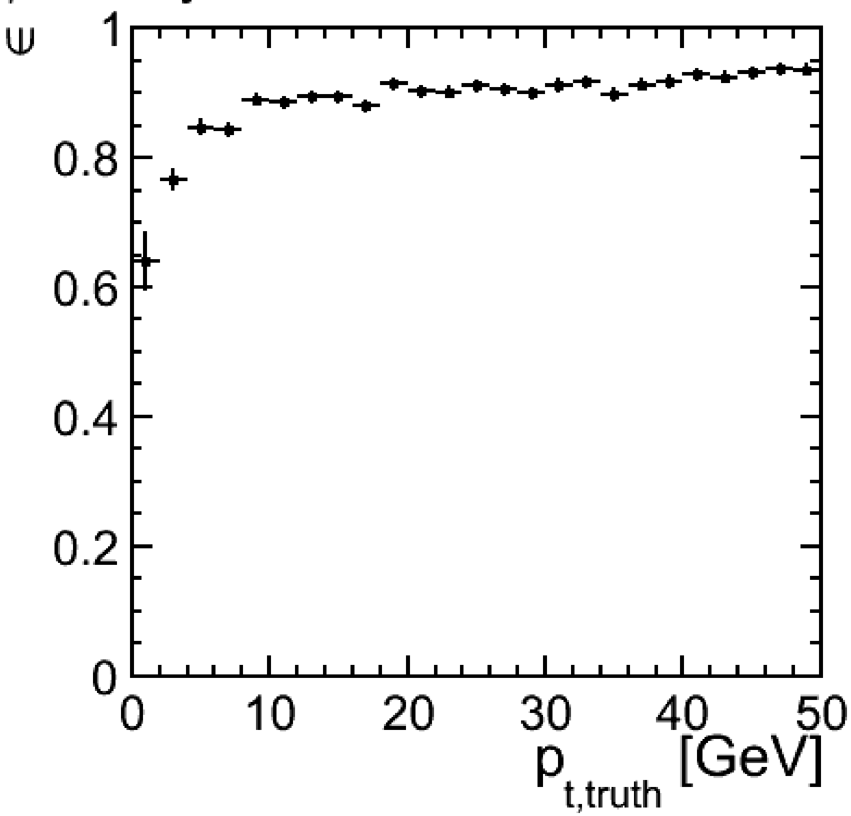
cut	μμ channel	μτ channel	ττ channel
no	1617	2783	1241
preselection	1561	2656	1173
efficiency	**0.965**	**0.954**	**0.945**

Muon reconstruction (μμ channel)

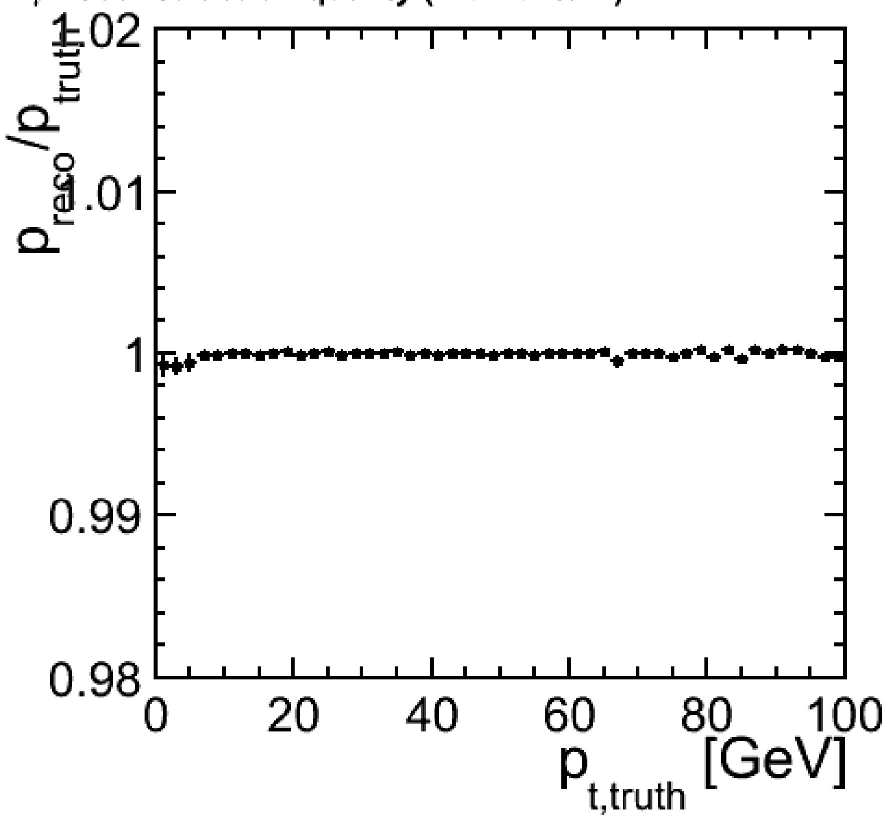
selection:

- Pandora PFO muons
- no isolation required → depends on neutralino mass
- keep two most energetic muons as signal muons

μ efficiency vs. momentum



μ reconstruction quality (momentum)



→ overall efficiency of signal muon: 91%

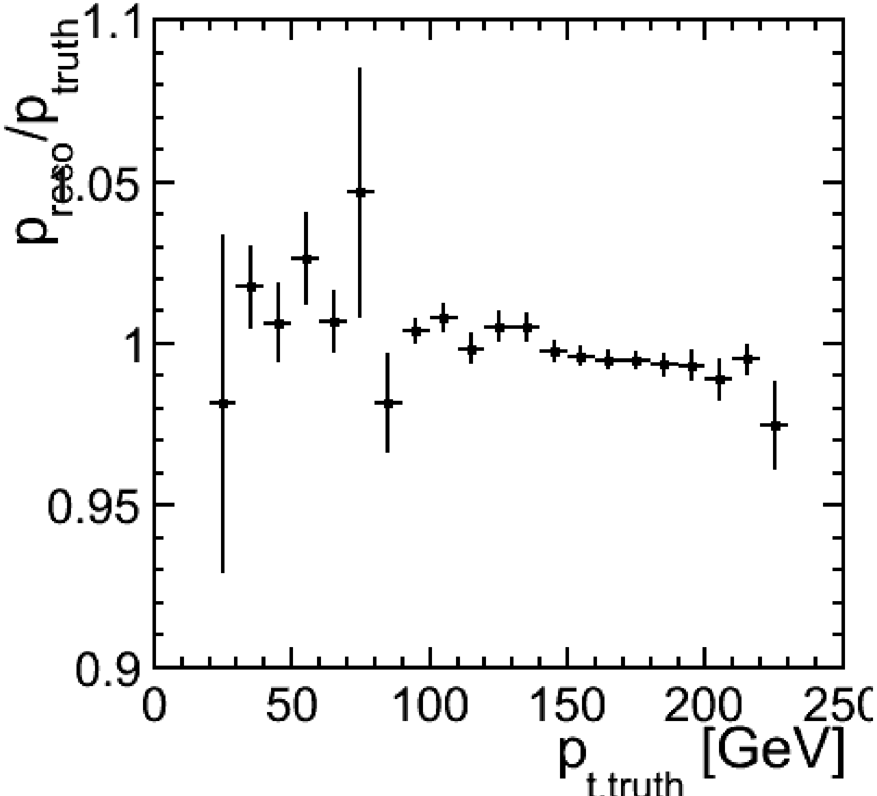
W reconstruction (μμ channel)

- remove leading muons from event
- force remaining objects into 4 jets (Durham)
- pair jets and test against W mass

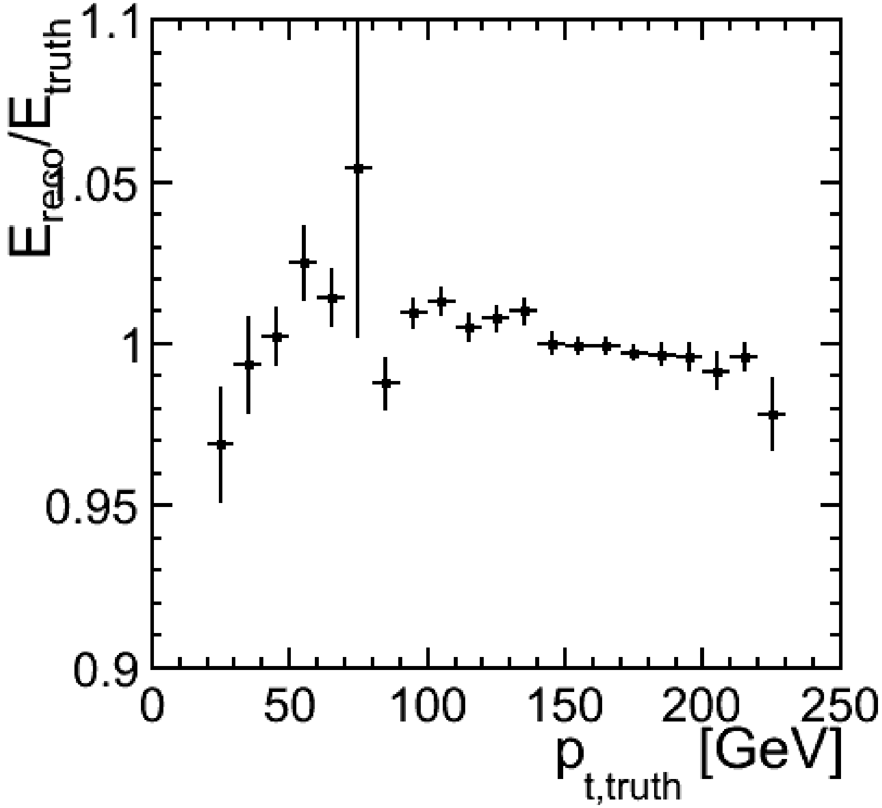
$$\chi_W^2 = \frac{(m_{reco} - m_W)^2}{(5GeV)^2}$$

best jet combination is considered as W

W reconstruction quality (momentum)



W reconstruction quality (energy)



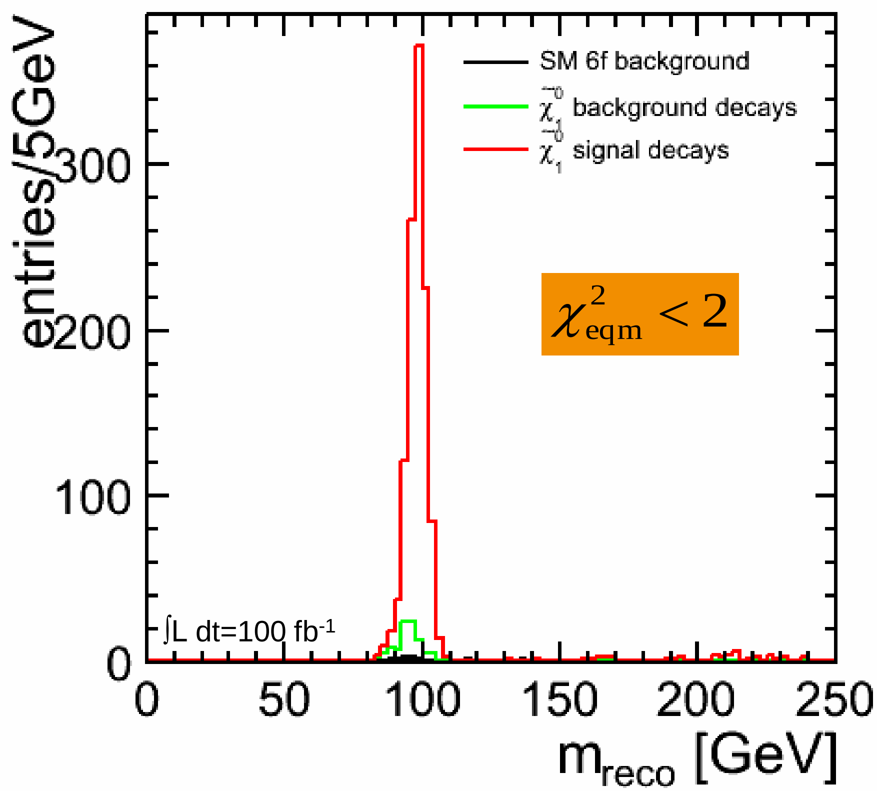
→ **W efficiency: 64% for ($\chi_W^2 < 2$) and can be further increased with kinematic fitting**

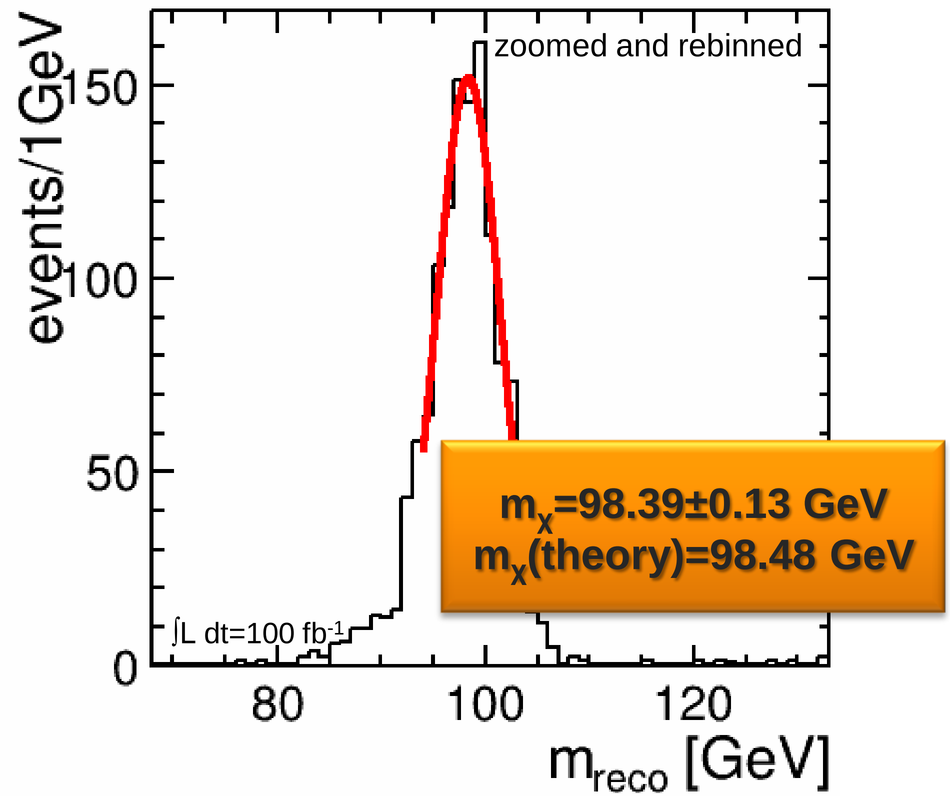
Full event reconstruction (μμ channel)

combine into two equal mass objects

2 μ → $$\chi^2_{\mathrm{eqm}} = \frac{(m_{\mathrm{p1}} - m_{\mathrm{p2}})^2}{(5GeV)^2}$$ ← 2 W

reconstructed mass in Wμ Wμ channel





→ **very clean reconstruction of neutralino mass**

→ **almost no 6f standard model background**

Full event reconstruction (other channels)

test for μτ

- remove **leading muon** from PFO objects
- force rest of the event into **5 jets**
- consider jet with lowes multiplicity as tau
- find **two good W** candidates from remaining 4 jets
- try to combine **two equal mass objects** from Ws and leptons

→ analog to μμ channel

test for ττ

- force event into **6 jets**
- consider two jets with lowes multiplicity as taus
- find **two good W** candidates from remaining 4 jets
- try to combine **two equal mass objects** from Ws and leptons

- number of events after preselection in ττ channel (μμ channel): 1173 (1561)
- W selection similar to selection in μμ channel :

$$\chi_W^2 < 2 \quad \text{using} \quad \chi_W^2 = \frac{(m_{\text{reco}} - m_W)^2}{(5GeV)^2}$$

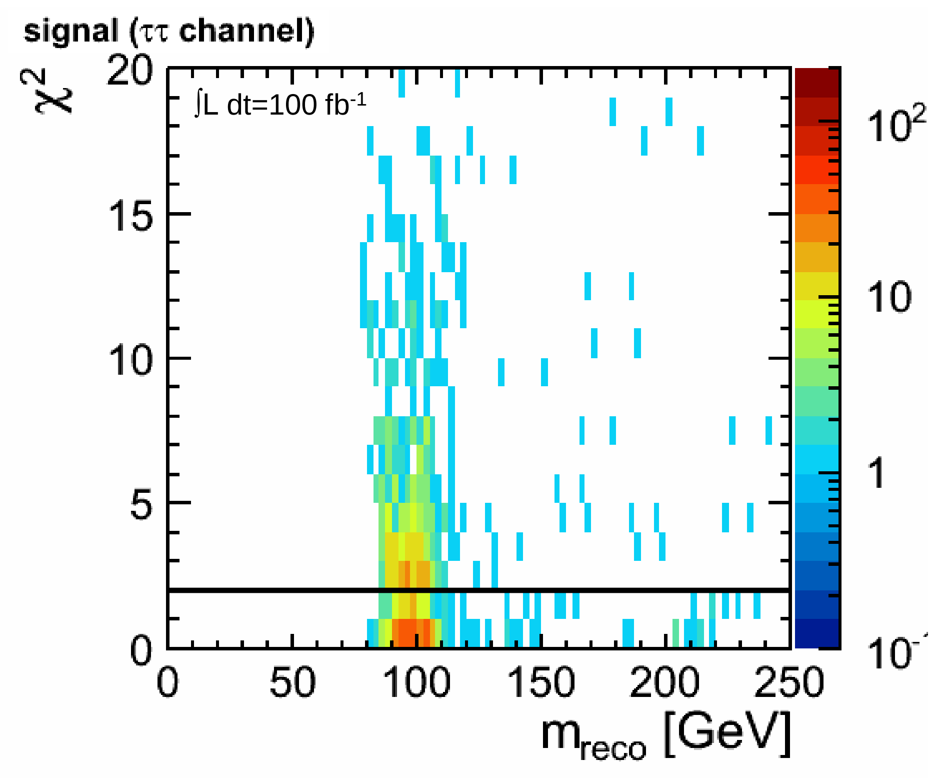
- efficiency for full event reconstruction including taus is expected to be much less than in muonic channel

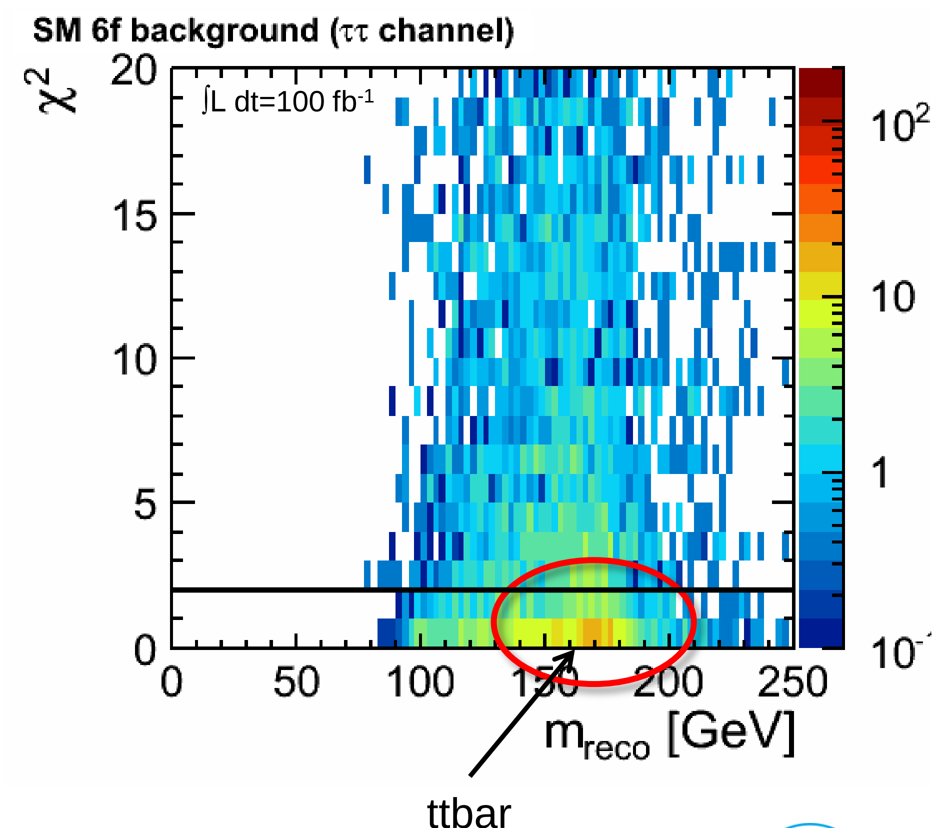
Full event reconstruction (ττ channel)

combine into two equal mass objects

2 τ → $$\chi^2_{\mathrm{eqm}} = \frac{(m_{\mathrm{p1}} - m_{\mathrm{p2}})^2}{(5GeV)^2}$$ ← **2 W**

aka “2 jet with least components“





DESY

Full event reconstruction (ττ channel)

combine into two equal mass objects

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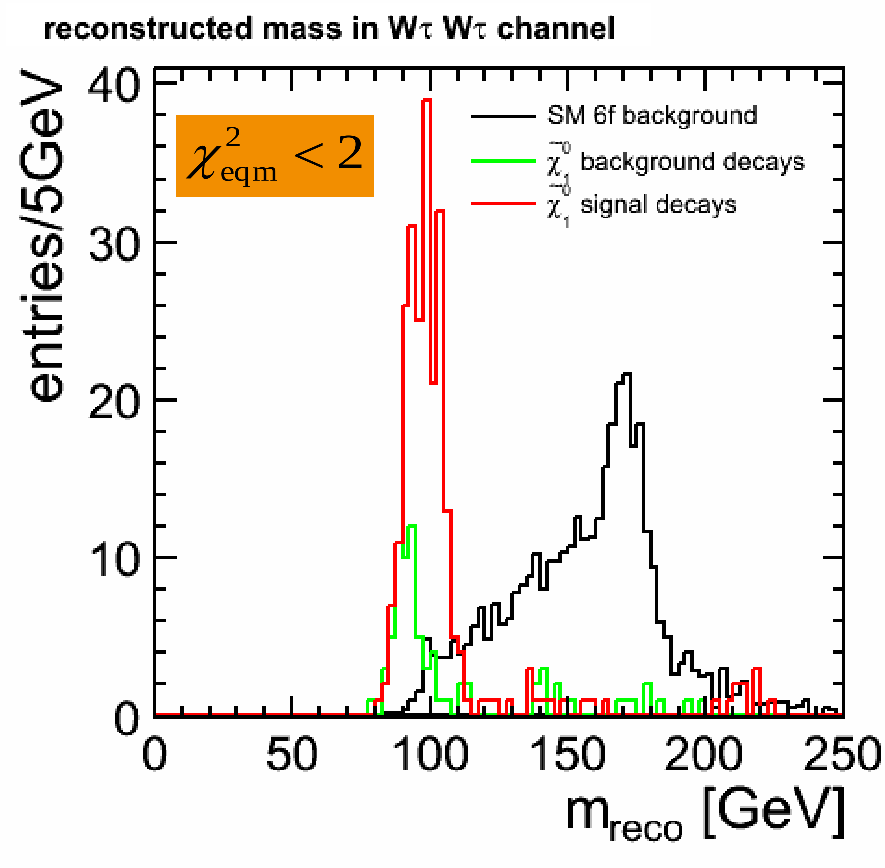

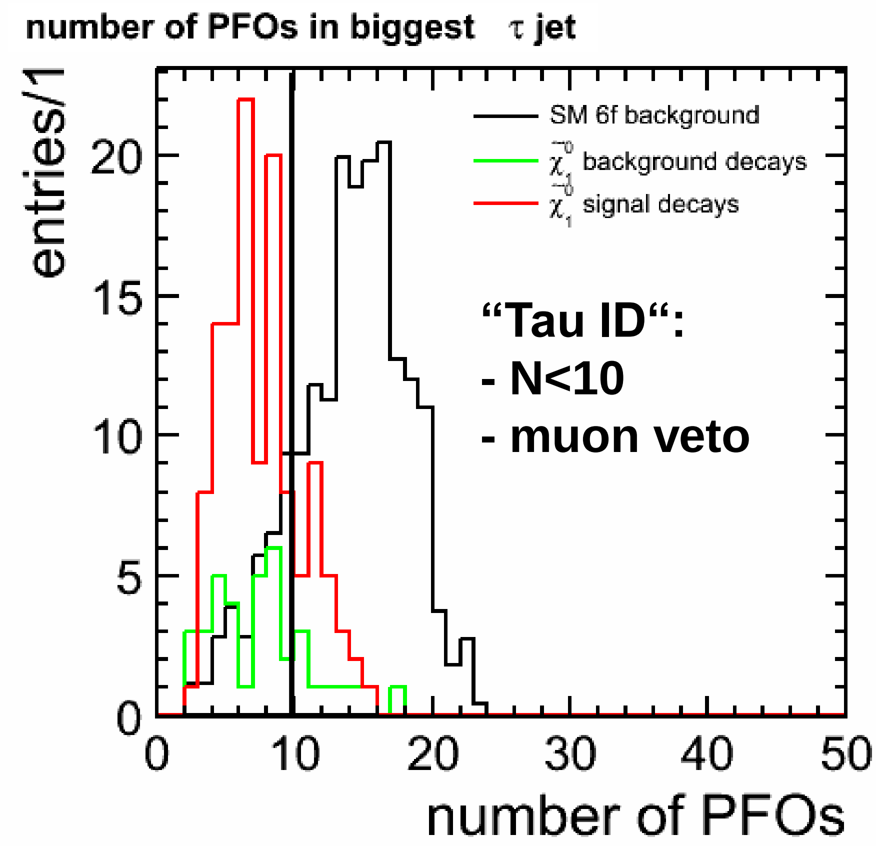

Full event reconstruction (ττ channel)

combine into two equal mass objects

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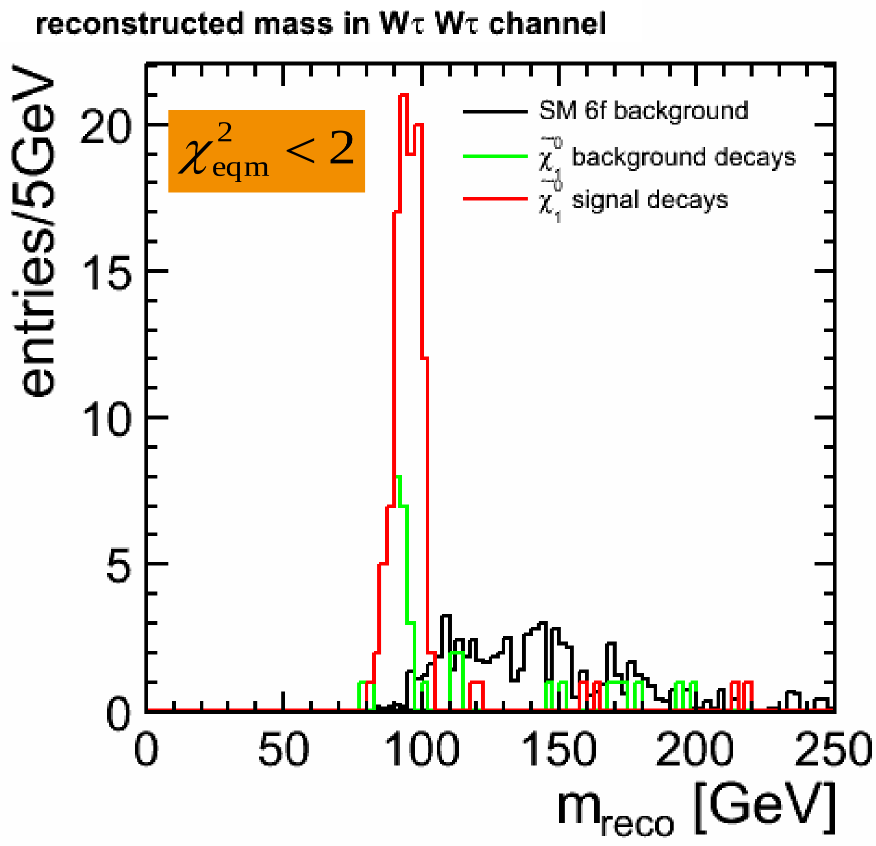
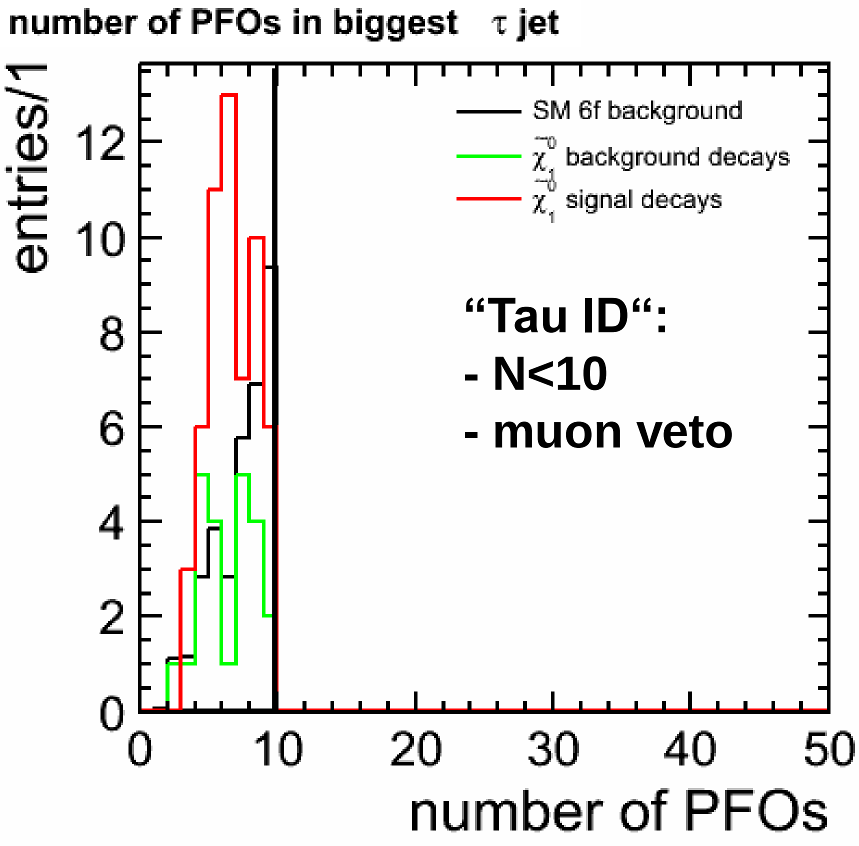


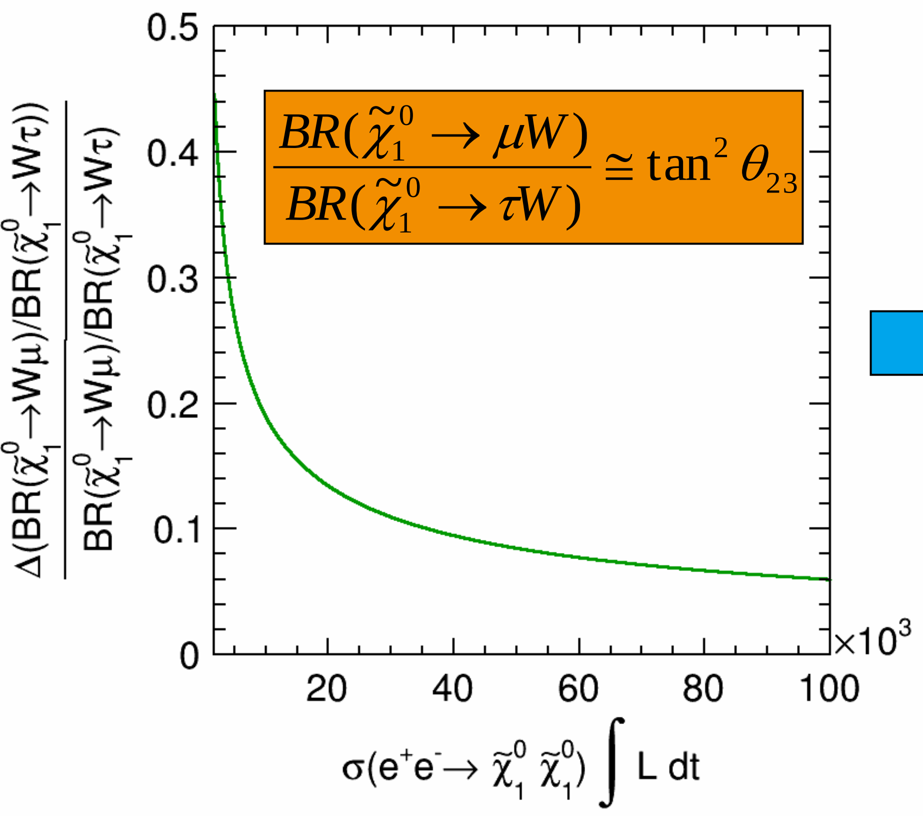


Efficiency matrix

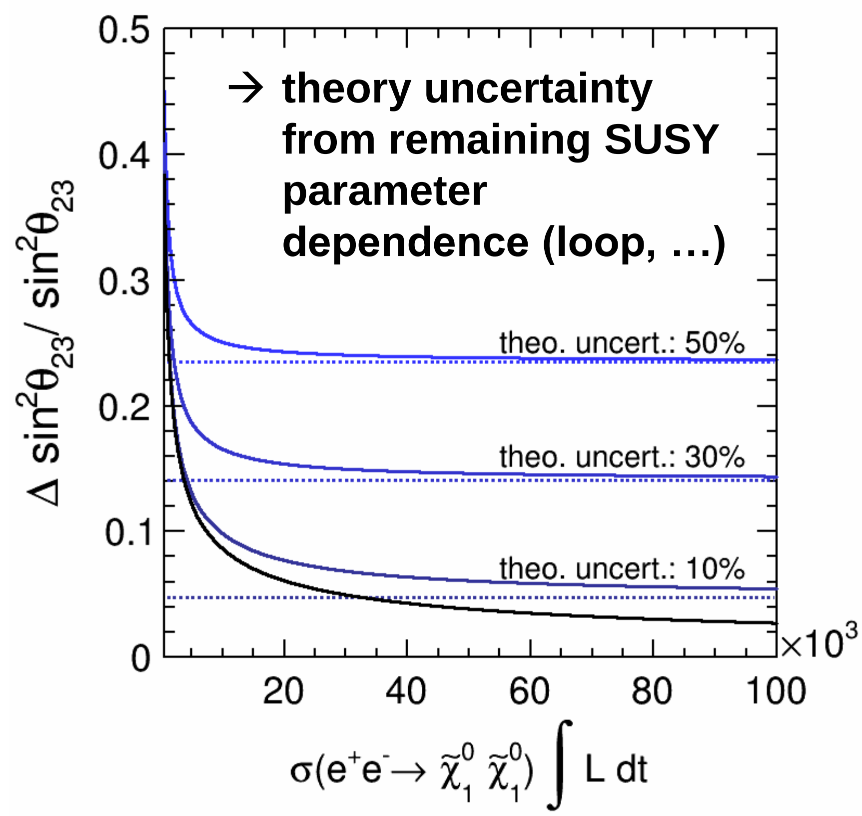
	true $\mu W_{had}\mu W_{had}$	true $\mu W_{had}\tau W_{had}$	true $\tau W_{had}\tau W_{had}$	SUSY non-signal	SM 6fBG
preselected	1561	2656	1173	8414	29825
N(μμ channel)	**513** **0.329**	91 0.034	13 0.011	51 0.006	13 0.0004
N(μτ channel)	10 0.006	**216** **0.084**	33 0.028	33 0.004	25 0.0008
N(ττ channel)	0 0.000	2 0.009	**54** **0.046**	23 0.003	34 0.0011

→ SM 6f background controllable (especially in signal region)
→ entries in efficiency matrix reasonable
→ SUSY non-signal contribution dependent on SUSY parameters (mainly stau mass)

relative error on ratio of BRs



relative error on $\sin^2\theta_{23}$

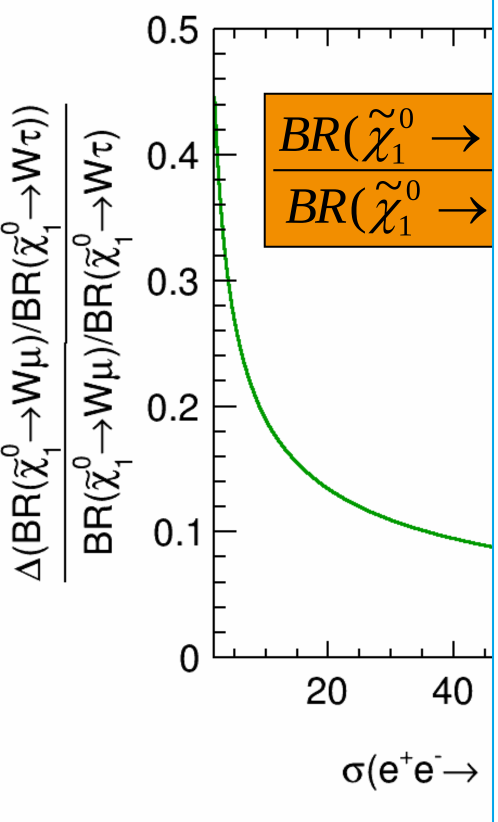


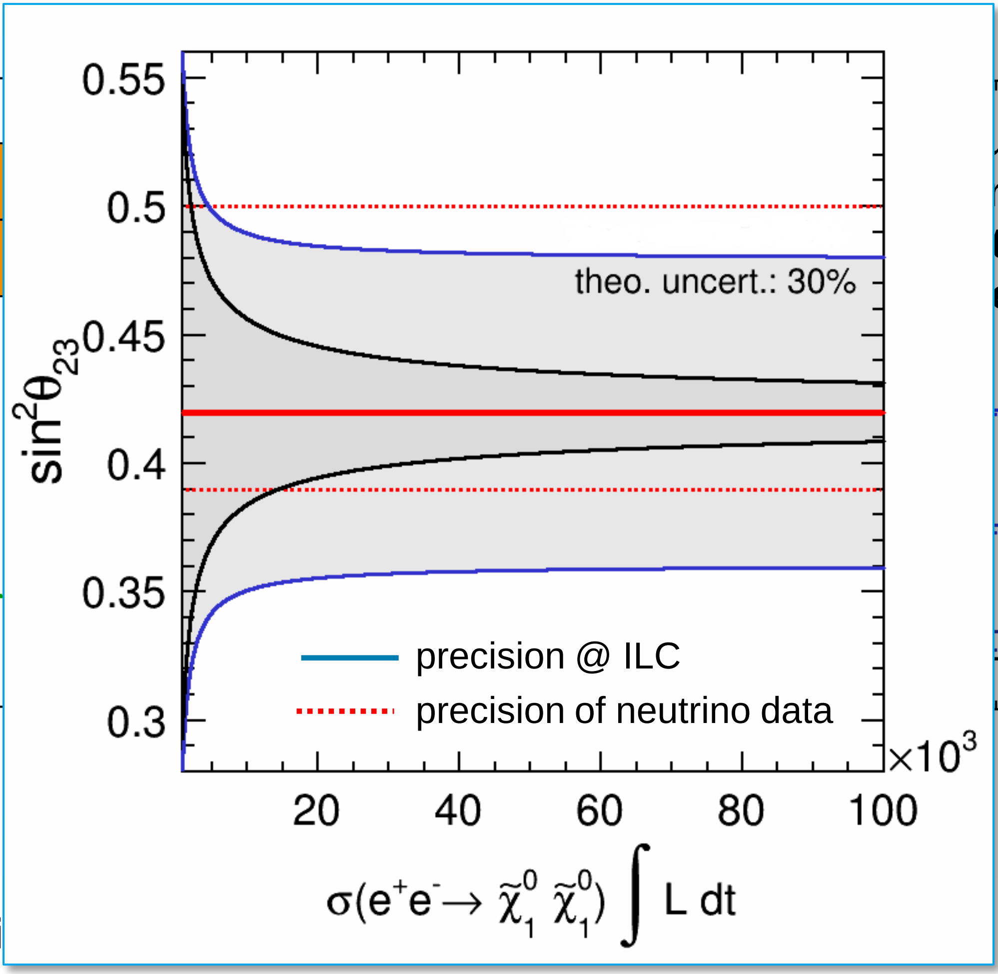
→ **~6% uncertainty after 100000 produced neutralino pairs**

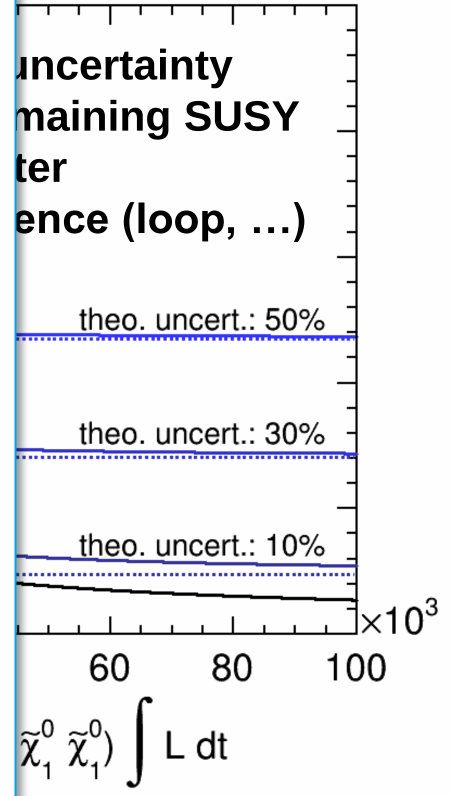
Precision estimation

relative error on ratio of BRs

relative error on $\sin^2\theta_{23}$:

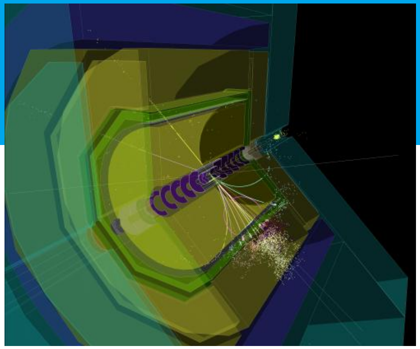




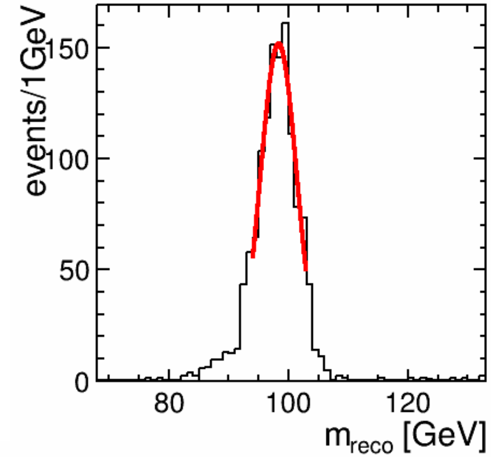


→ ~6% uncertai

Conclusions



- R-parity violation is an interesting alternative to R-parity conserving SUSY
- allows an interesting **interpretation** in terms of **neutrino parameters**
- **full ILD simulation** of a bRPV SUSY model performed
- very clean **event class selection** possible, almost no background
- precise chi10 mass reconstruction: **m_χ=98.39±0.13 GeV**
- **precision of atmospheric mixing angle measurement** in same ballpark as neutrino experiments



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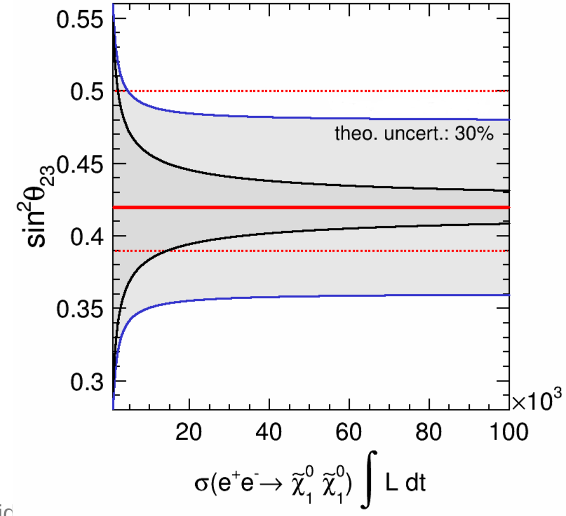

Backup slides

Bilinear R-parity violation

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

Superpotential

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

MSSM superpotential

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

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

4x4 MSSM neutralino mixing matrix

4x3 RPV matrix

Bilinear R-parity violation

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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.

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Situation at LHC

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- 1 isolated lepton
- missing transverse momentum

- bRPV parameters fitted to neutrino data
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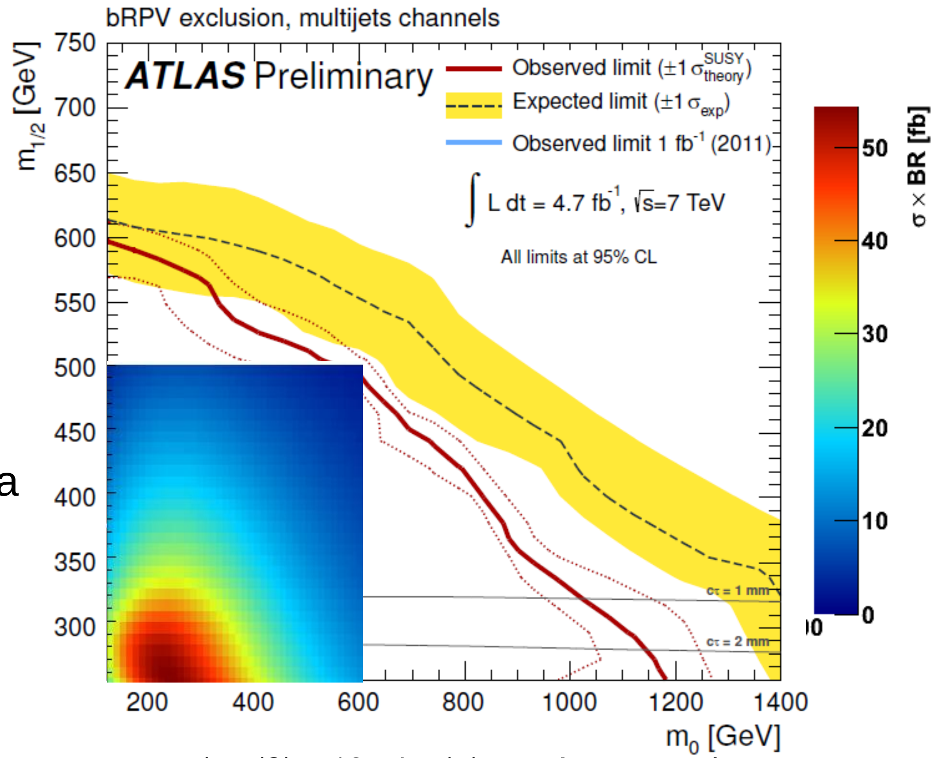

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Situation at the ILC

- direct neutralino production → direct access to EW sector
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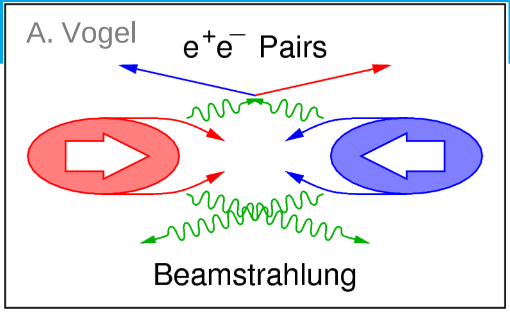
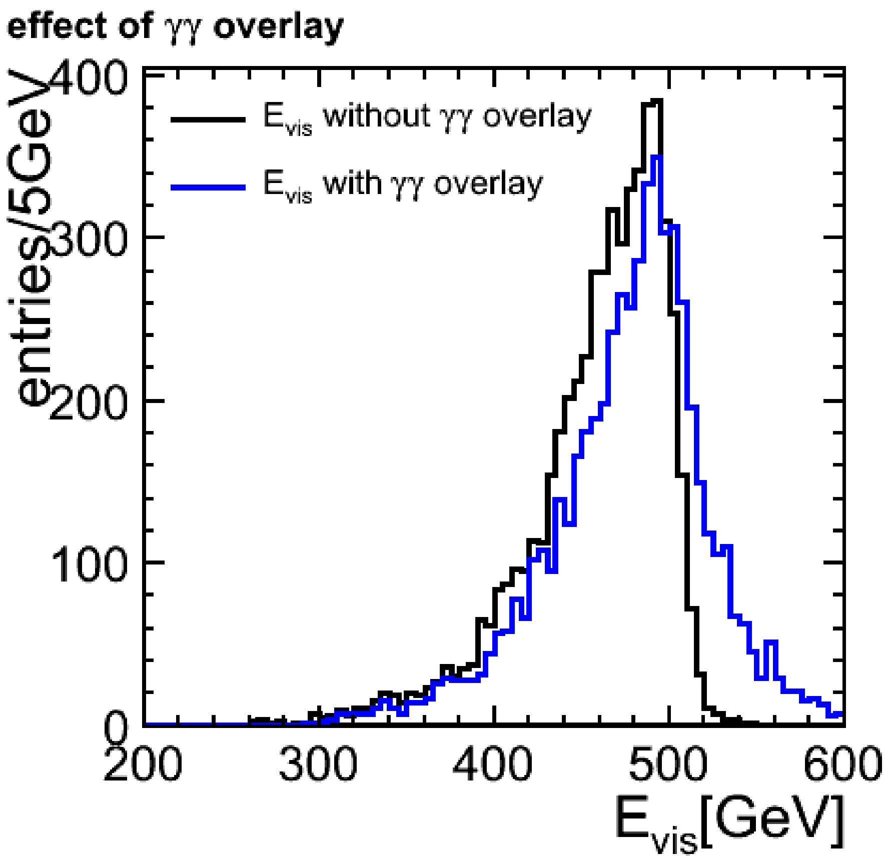
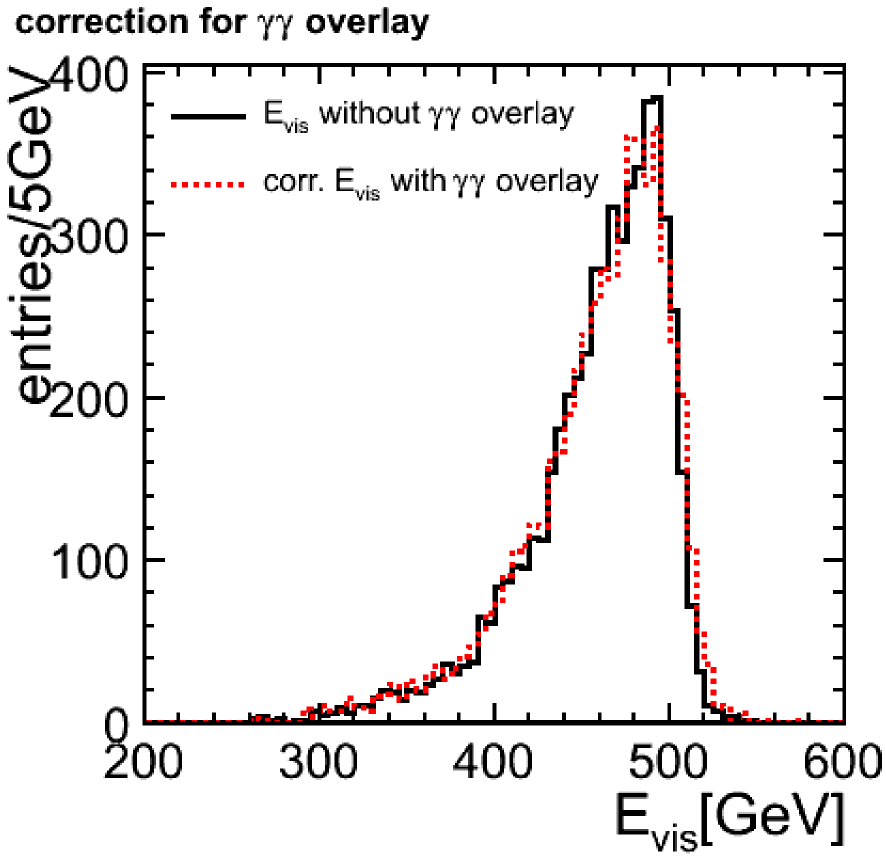
Beam background



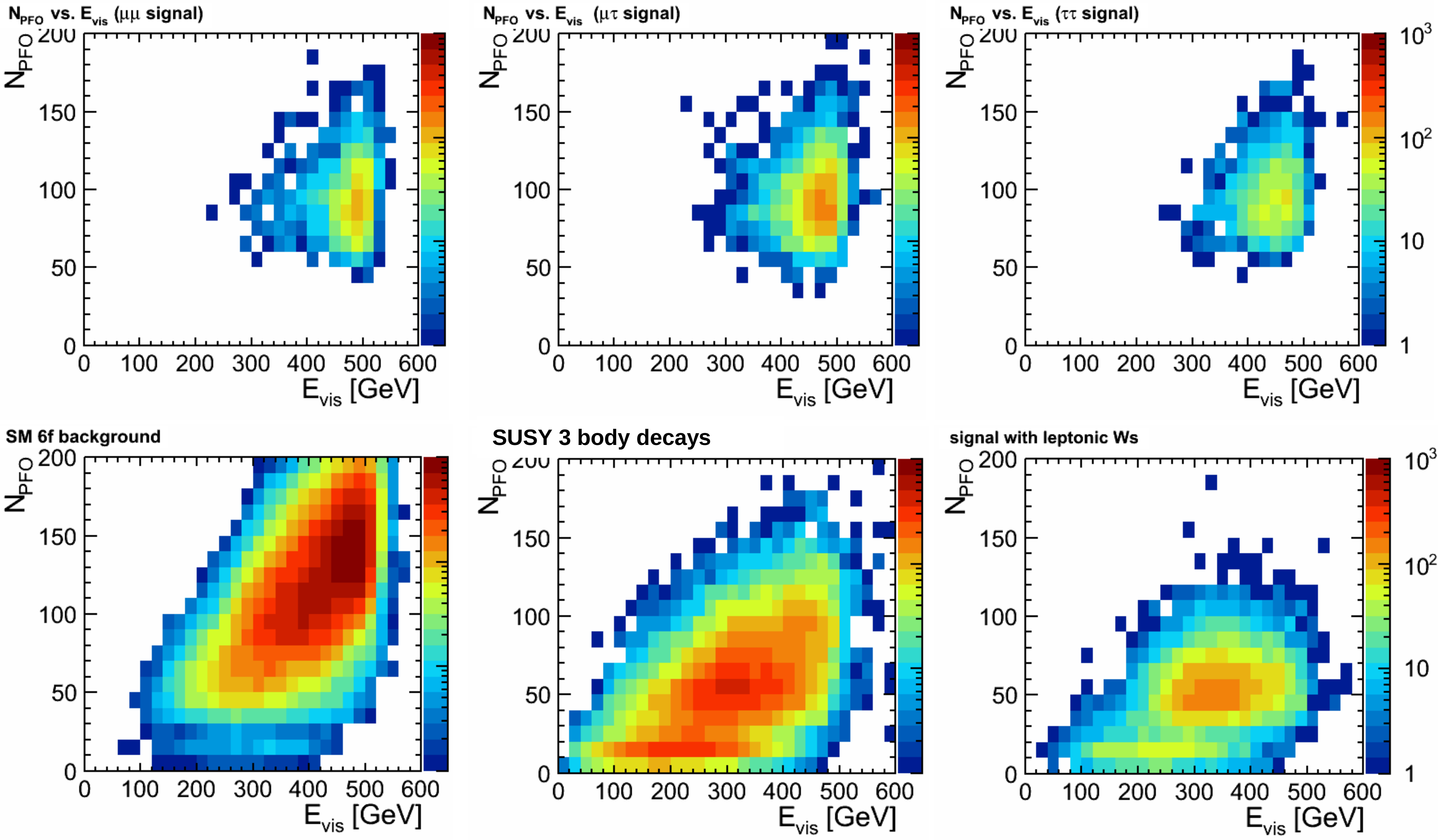
- overlaid γγ→hadron events per interaction: $\langle N_{\gamma\gamma} \rangle = 1.7$
- exclusive jet clustering to remove beam background:
  k_T 1.3, ExclusiveNJets 6





→ **all following steps based on reconstructed particles in these 6 jets**

Preselection (signal channels and background)



Preselection

select only events with high multiplicity and small missing energy:

- reduce leptonic W contribution
- reduce SM 6f background

→ E_{vis} > 350GeV
→ N_{PFO} > 50
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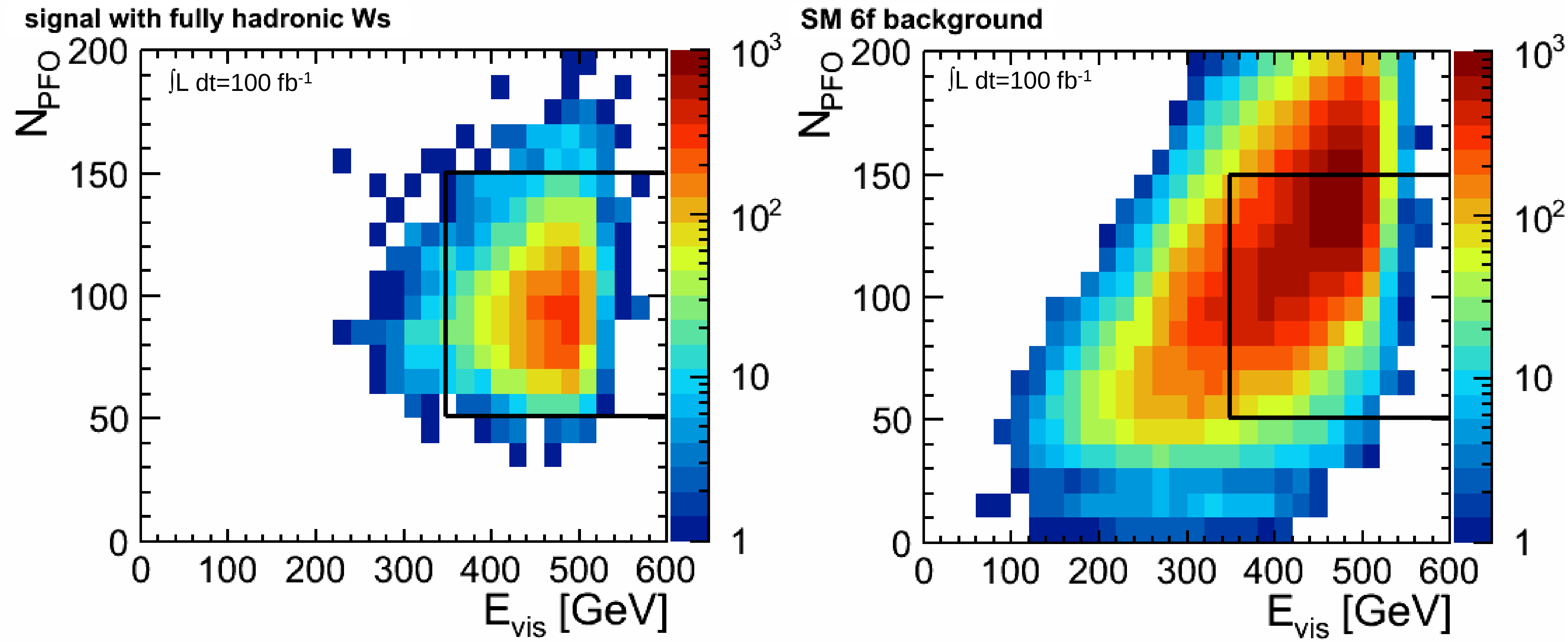
$lW_{had}lW_{had}$



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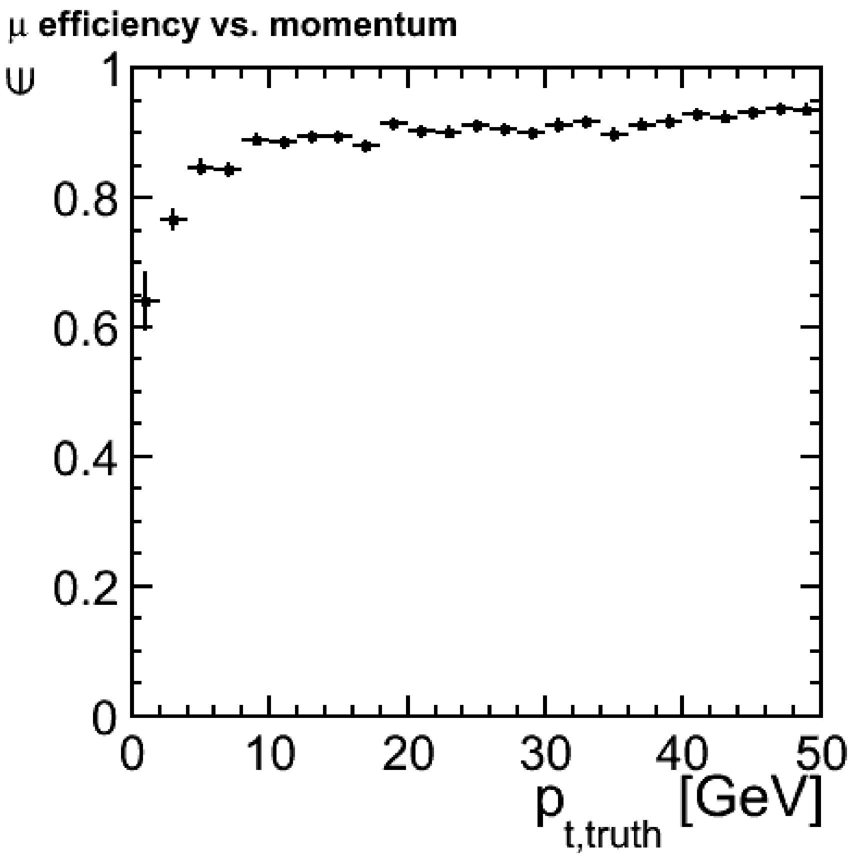
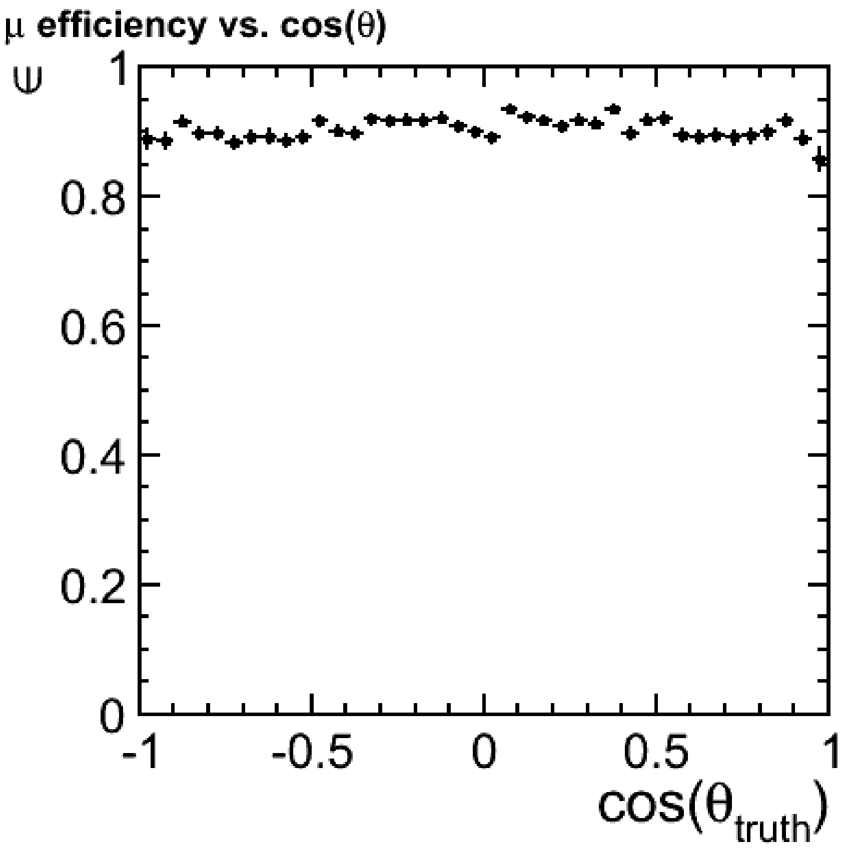
- keep two most energetic muons as signal muons

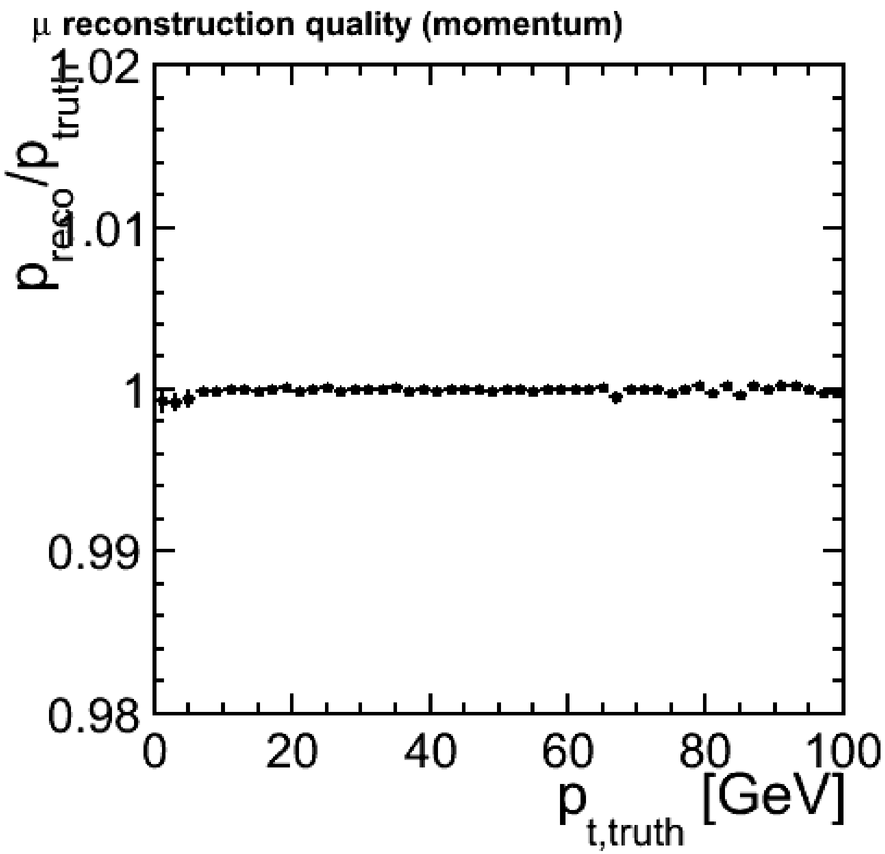


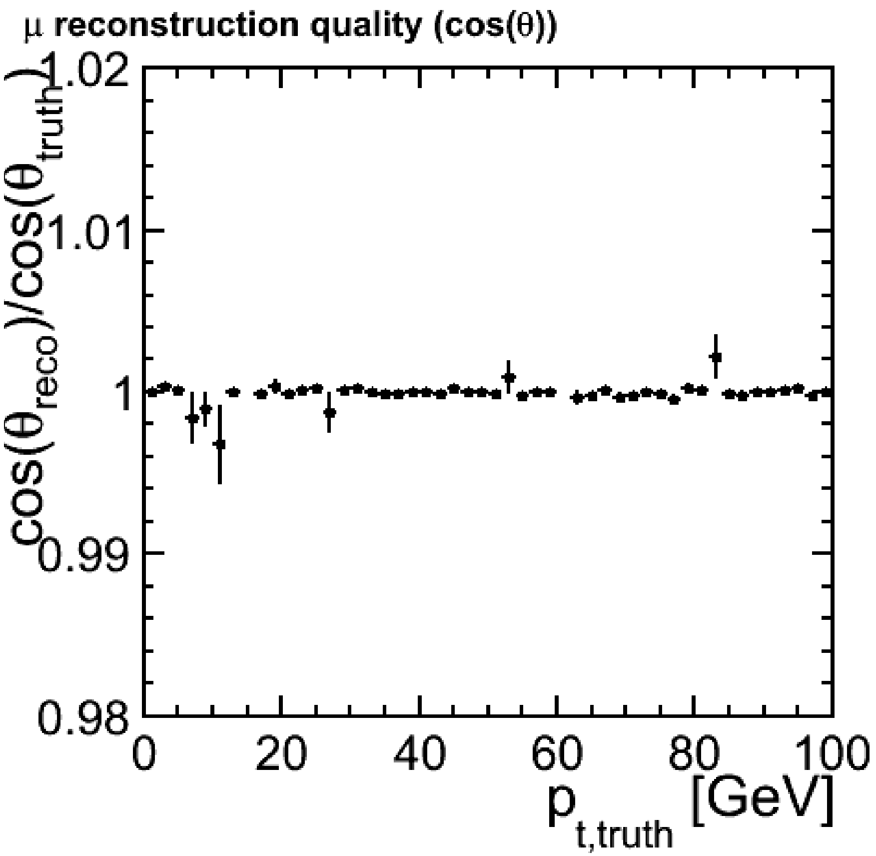


→ overall efficiency of signal muon: 91%

Muon reconstruction (μμ channel)

selection:
- Pandora PFO muons
- no isolation required → depends on neutralino mass
- keep two most energetic muons as signal muons





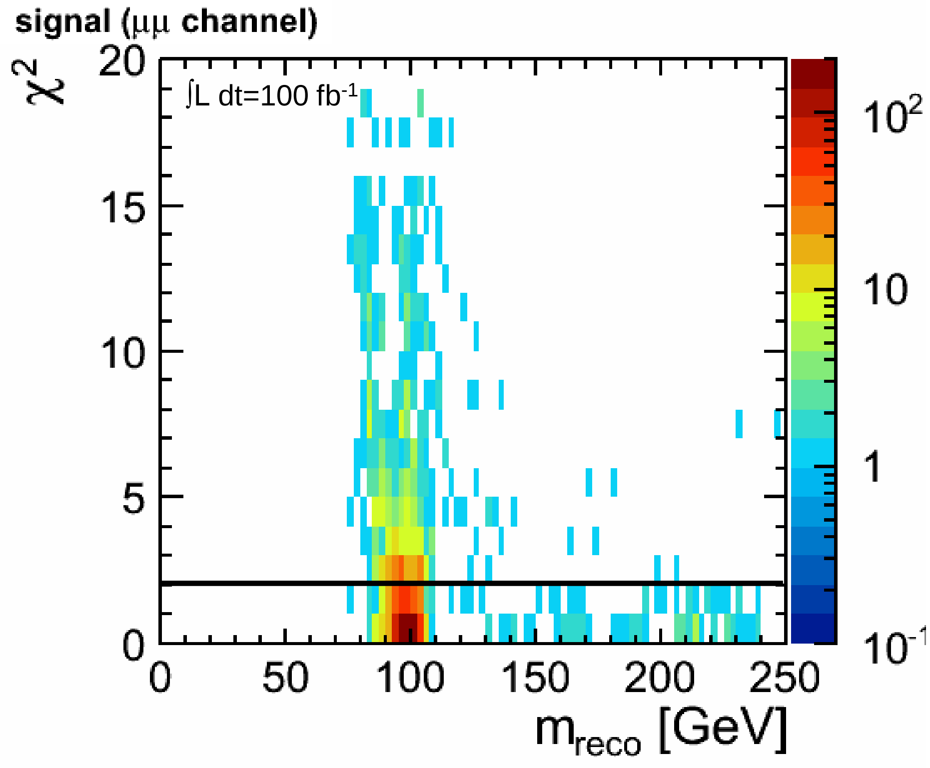
→ **almost perfect reconstruction of muons**

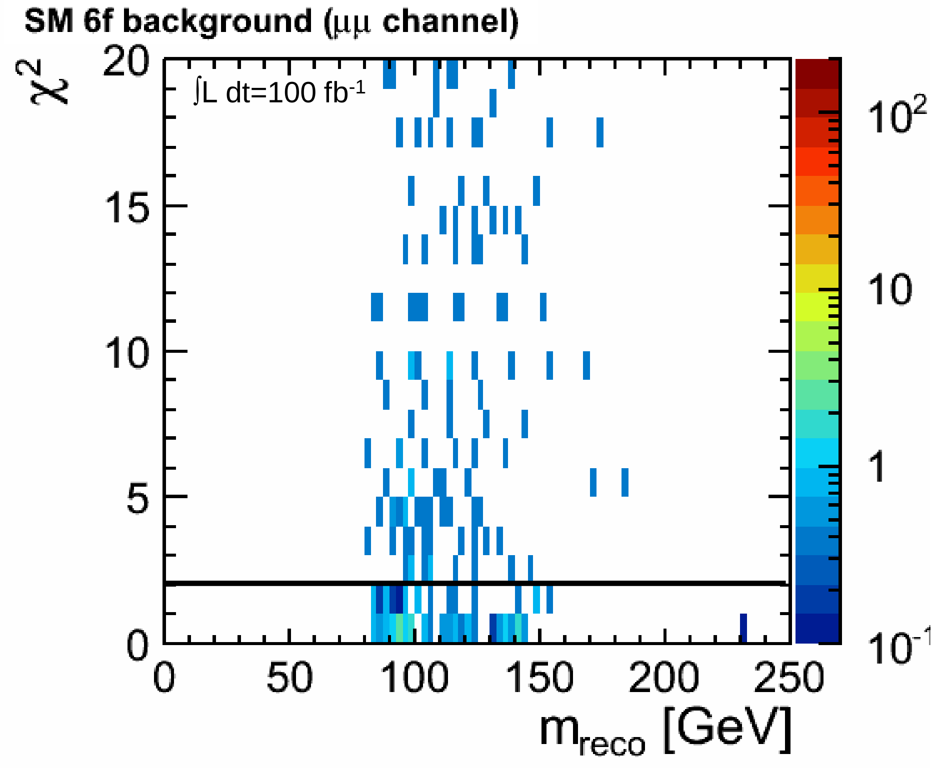
DESY

Full event reconstruction (μμ channel)

combine into two equal mass objects

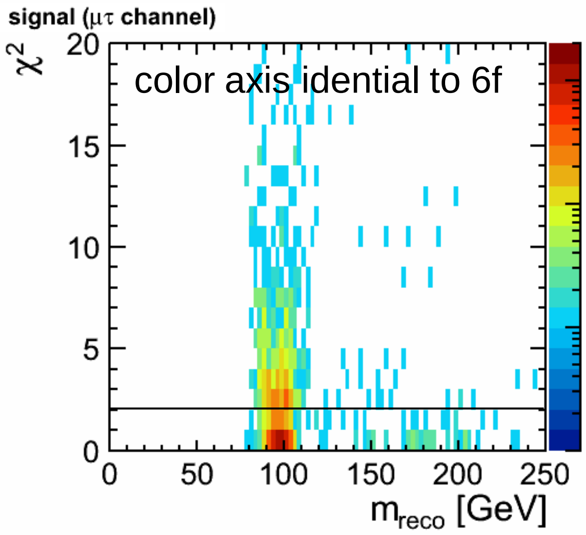
2 μ → $$\chi^2_{\mathrm{eqm}} = \frac{(m_{\mathrm{p1}} - m_{\mathrm{p2}})^2}{(5GeV)^2}$$ ← **2 W**

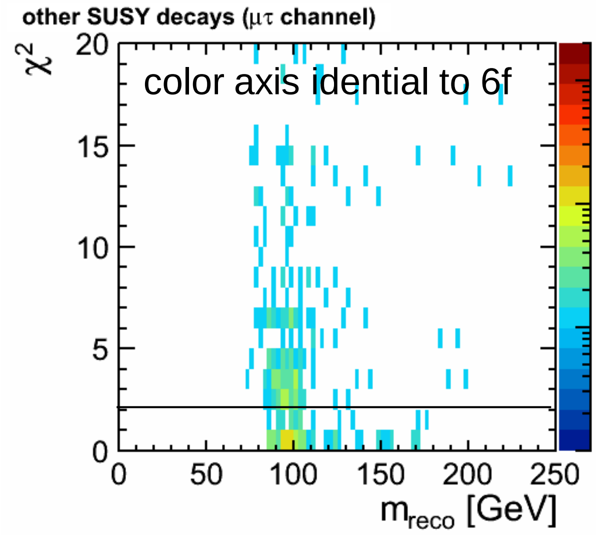


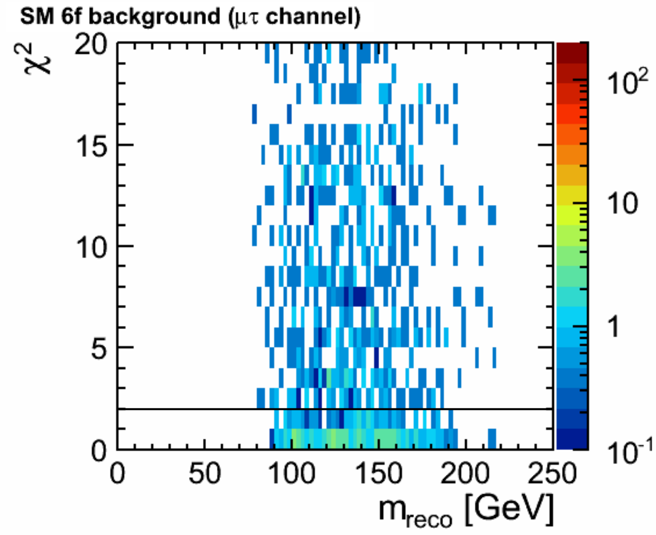


→ $\chi_{\mathrm{eqm}}^2 < 2$

Full event reconstruction (WμWτ channel)

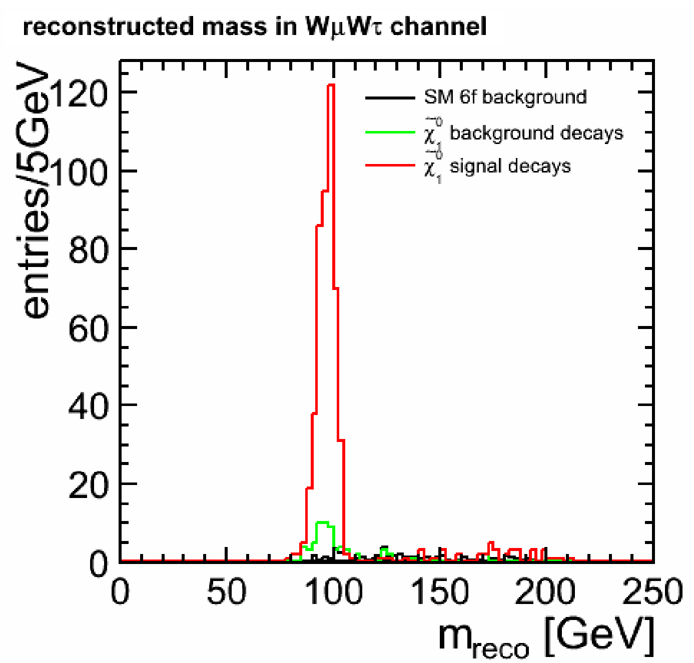






$$\chi_W^2 < 2$$

$$\chi_{eqm}^2 < 2$$



Precision estimation

$$A = BR_{\chi \to W\mu} \qquad B = BR_{\chi \to W\tau}$$

How many event would we expect to end up in each event class?

	true μWμW	true μWτW	true τWτW
N(μμ channel)	$A^2 \varepsilon_\mu^2$	$2AB\tau_\mu \varepsilon_\mu^2$	$B^2 \tau_\mu^2 \varepsilon_\mu^2$
N(μτ channel)	0	$2AB\tau_{had}\varepsilon_\mu \varepsilon_\tau$	$B^2 \tau_\mu \tau_{had} \varepsilon_\mu \varepsilon_\tau$
N(ττ channel)	0	0	$B^2 \tau_{had}^2 \varepsilon_\tau^2$

$$W_{had}^2 \varepsilon_W^2 \begin{pmatrix} A^2 \varepsilon_\mu^2 & 2AB\tau_\mu \varepsilon_\mu^2 & B^2 \tau_\mu^2 \varepsilon_\mu^2 \\ 0 & 2AB\tau_{had}\varepsilon_\mu \varepsilon_\tau & B^2 \tau_\mu \tau_{had} \varepsilon_\mu \varepsilon_\tau \\ 0 & 0 & B^2 \tau_{had}^2 \varepsilon_\tau^2 \end{pmatrix} \sigma \cdot \int L\,dt$$

assumptions for efficiencies and errors

use e.g. **N(μμ channel)** and **N(μτ channel)**
to estimate the statistical and systematical error on

$$\frac{A}{B} = \tan^2 \theta_{23}$$

Precision estimation

$$A = BR_{\chi\to W\mu} \qquad B = BR_{\chi\to W\tau}$$

How many event would we expect to end up in each event class?

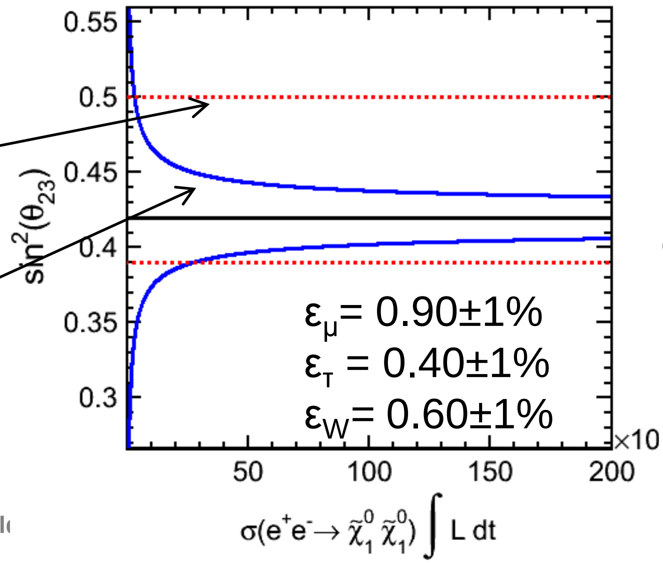
	true μWμW	true μWτW	true τWτW
N(μμ channel)	$A^2\varepsilon_\mu^2$	$2AB\tau_\mu\varepsilon_\mu^2$	$B^2\tau_\mu^2\varepsilon_\mu^2$
N(μτ channel)	0	$2AB\tau_{\text{had}}\varepsilon_\mu\varepsilon_\tau$	$B^2\tau_\mu\tau_{\text{had}}\varepsilon_\mu\varepsilon_\tau$
N(ττ channel)	0	0	$B^2\tau_{\text{had}}^2\varepsilon_\tau^2$

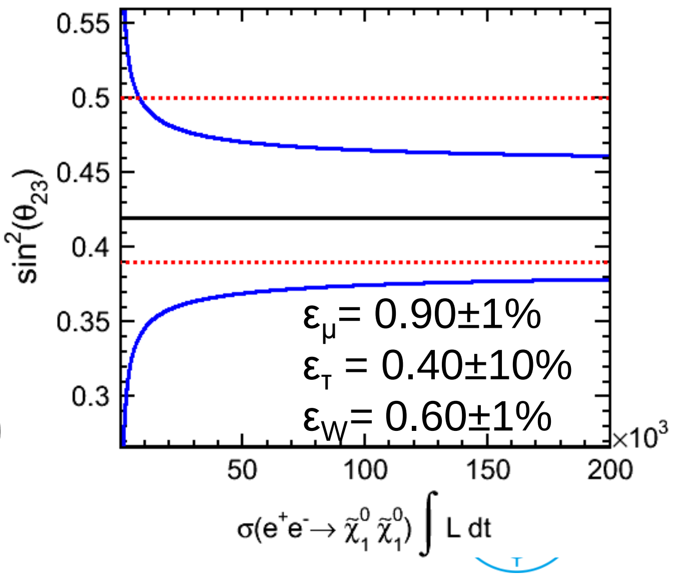
$$W_{\text{had}}^2\varepsilon_W^2 \begin{pmatrix} A^2\varepsilon_\mu^2 & 2AB\tau_\mu\varepsilon_\mu^2 & B^2\tau_\mu^2\varepsilon_\mu^2 \\ 0 & 2AB\tau_{\text{had}}\varepsilon_\mu\varepsilon_\tau & B^2\tau_\mu\tau_{\text{had}}\varepsilon_\mu\varepsilon_\tau \\ 0 & 0 & B^2\tau_{\text{had}}^2\varepsilon_\tau^2 \end{pmatrix} \sigma\cdot\int L\,dt$$

Translate into precision of neutrino mixing angle determination

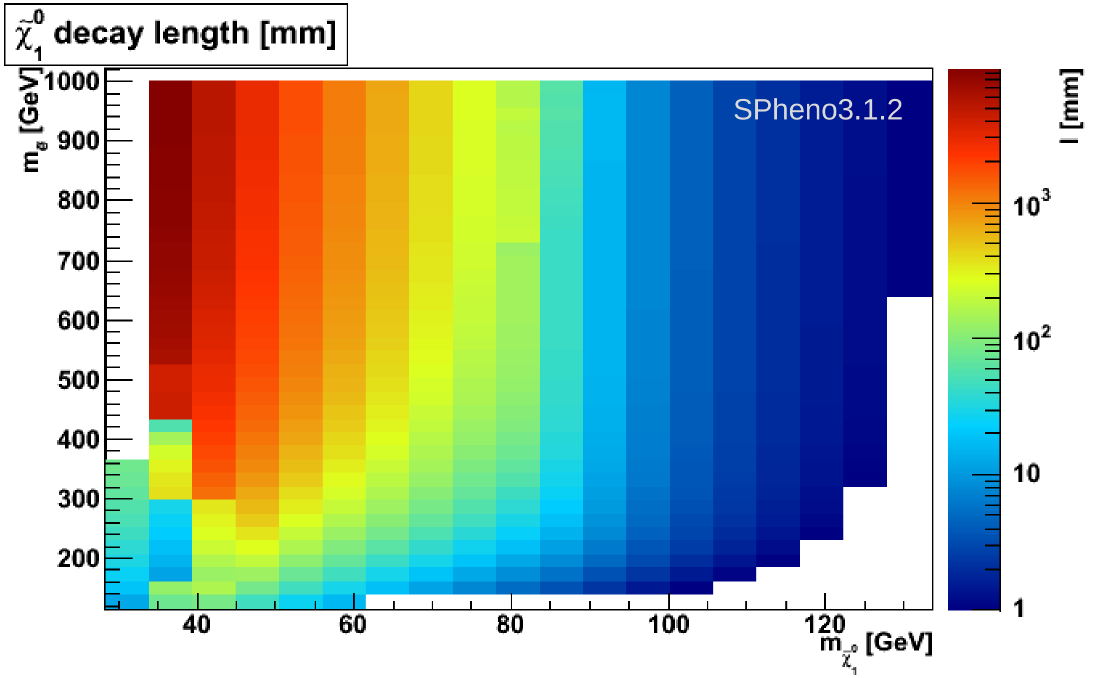
precision of neutrino data [PDG 2012]

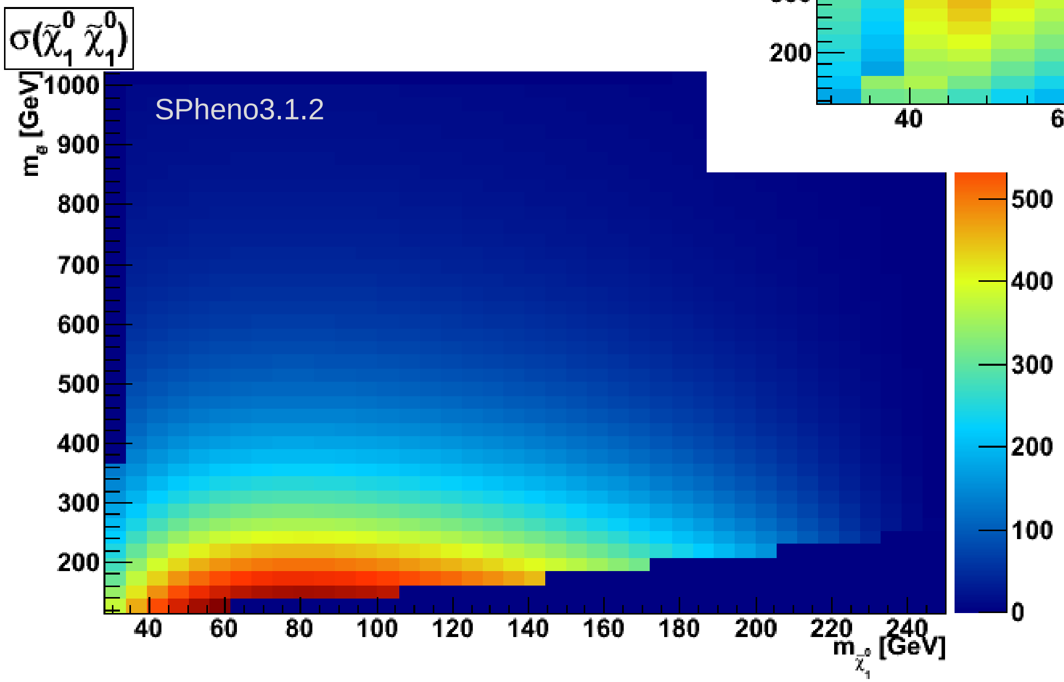
precision @ ILC





Bilinear R-parity violation





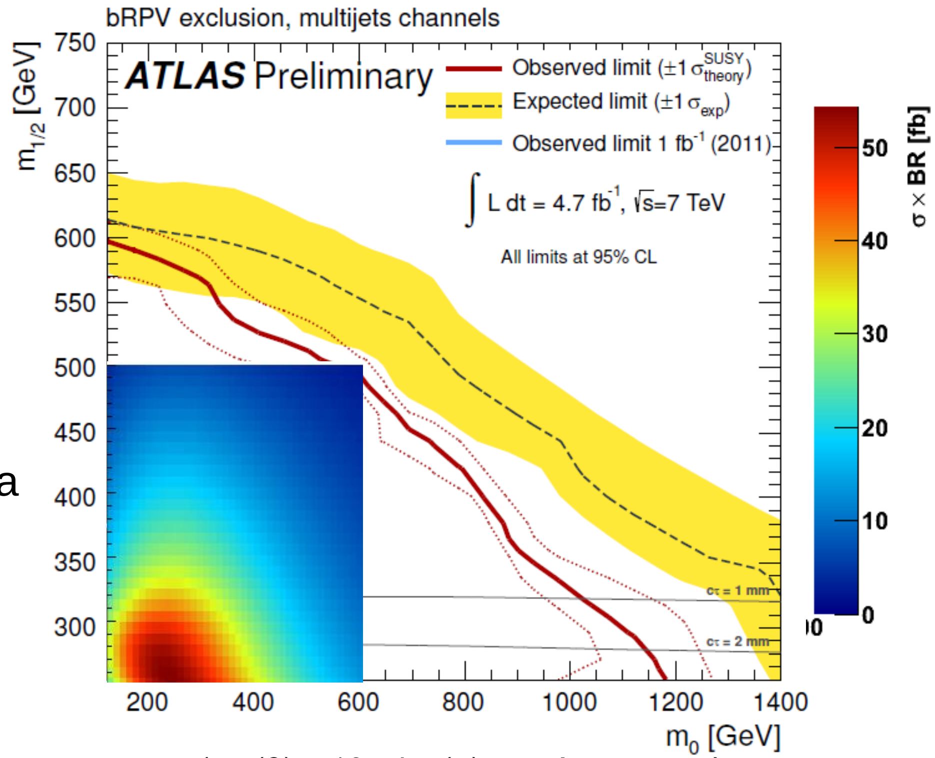
LHC searches

Situation at LHC

One dedicated bRPV mSUGRA search from ATLAS (**ATLAS-CONF-2012-140**):

- large jet multiplicity
- 1 isolated lepton
- missing transverse momentum

- bRPV parameters fitted to neutrino data
- bRPV mSUGRA tested for $m_{1/2}$ > 240GeV
- (→cτ < 15 mm)
- analysis probes colored sector of theory via squark production and subsequent decays
- coupling of EW sector and colored sector

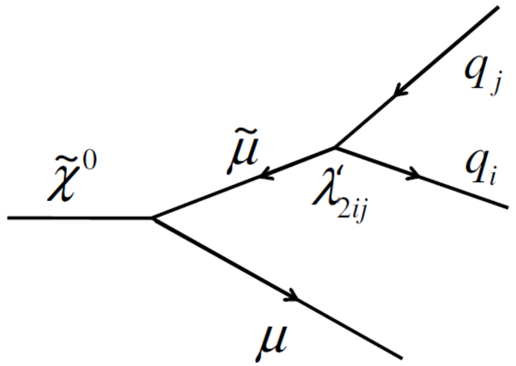


(tan(β) = 10, sign(μ) = +, A_0 = 0 GeV)

Situation at the ILC

- direct neutralino production → direct access to EW sector
- need better parametrization than mSUGRA to study phenomenology of this model, especially decouple EW sector from colored one → generic model

Dedicated displaced vertex search (∫Ldt = 33 pb-1)

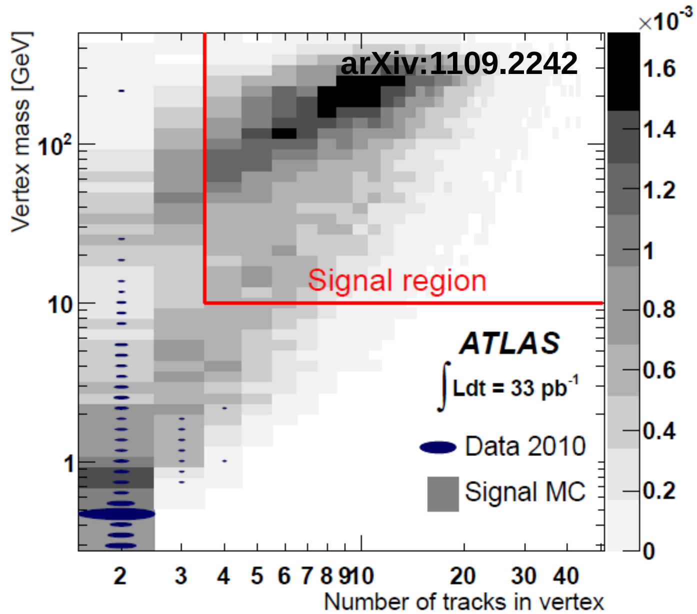


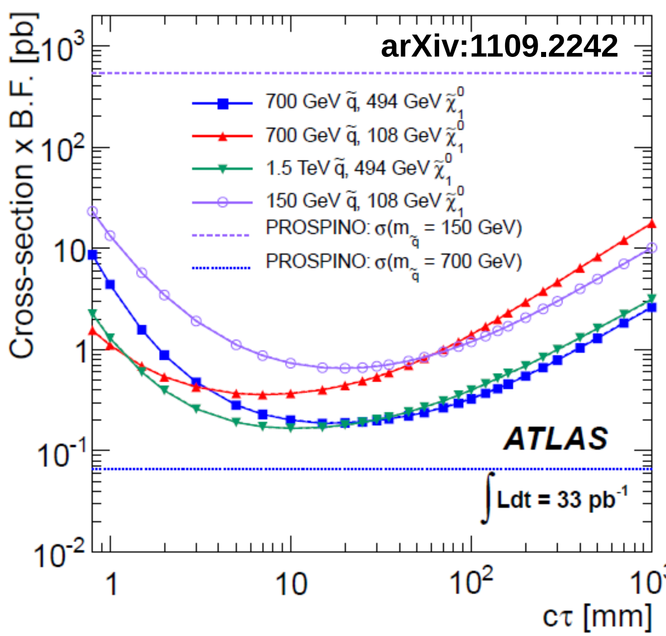
search for:

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

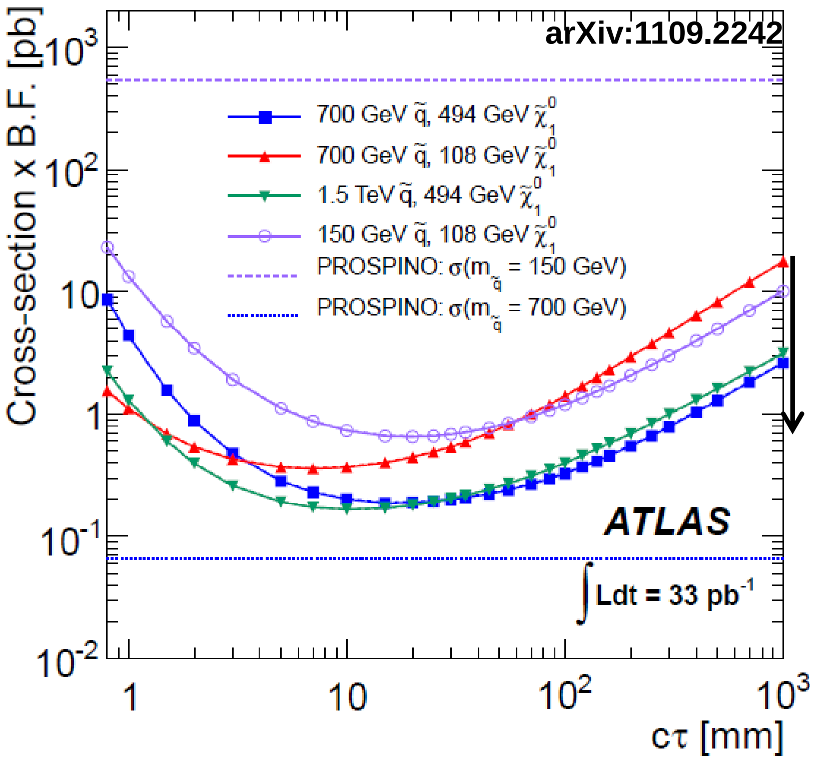
background free analysis (N_{BG}<0.03)

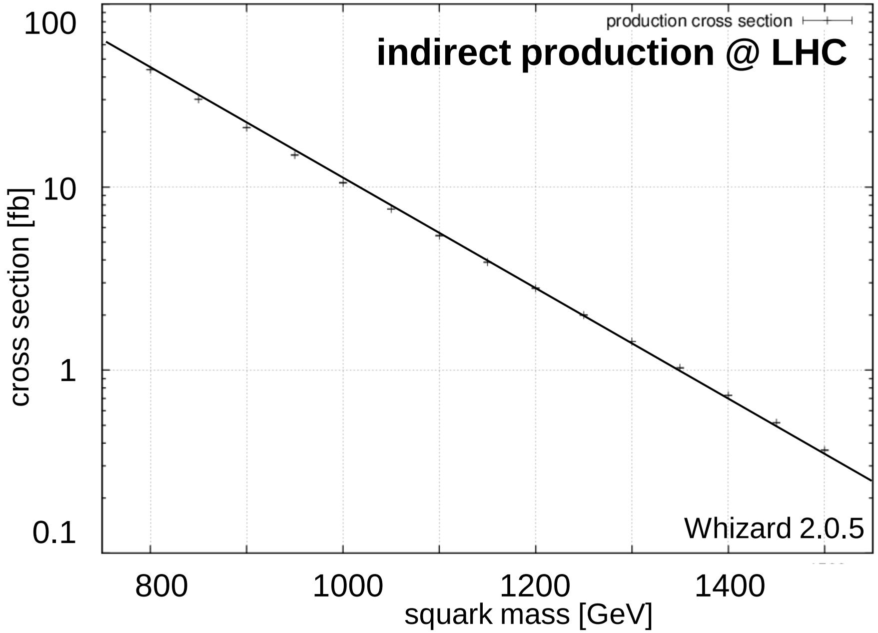
assumption:
di-squark production → direct decay to LSP





Dedicated displaced 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