

Bilinear R-Parity Violation at the ILC.

Neutrino physics at a collider.



[Benedikt Vormwald, Jenny List](#)
LC Forum
Bonn, 29.-30.04.2014

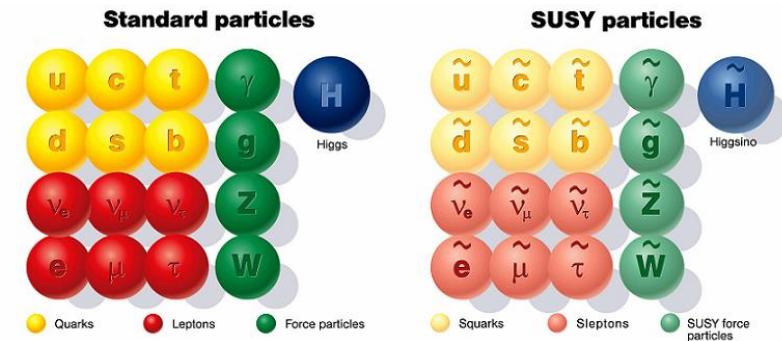
Outline

- Bilinear R Parity Violation
- Simplified bPRV SUSY Model at the ILC
- Event Reconstruction
- Measurement of Atmospheric Mixing Angle
- Discovery Potential
- Conclusions

Supersymmetric Extension of the Standard Model

What is SUSY?

- the only non-trivial extension of the Poincaré algebra
- fermionic d.o.f. \leftrightarrow bosonic d.o.f
- **broken** symmetry
- stabilises m_H , allows for gauge unification, offers in many cases a DM candidate, neutrino masses...



MSSM Superpotential

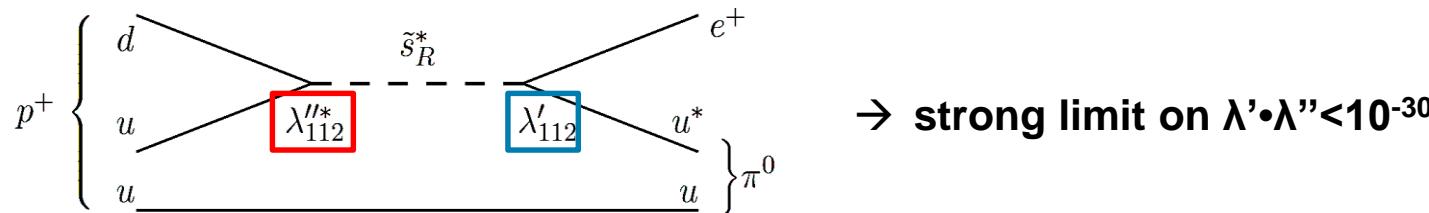
$$W = h_U^{ij} \hat{Q}_i \cdot \hat{H}_u \hat{U}_j + h_D^{ij} \hat{Q}_i \cdot \hat{H}_d \hat{D}_j + h_E^{ij} \hat{L}_i \cdot \hat{H}_u \hat{R}_j - \mu \hat{H}_d \cdot \hat{H}_u$$

additional gauge-invariant and renormalisable terms:

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

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

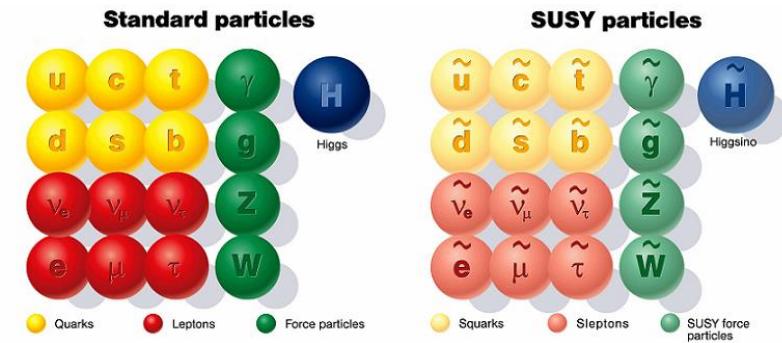
→ presence of $\Delta L=1$ and $\Delta B=1$ terms in Lagrangian would allow for rapid proton decay



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MSSM Superpotential

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

→ alternative: break R parity by allowing only $\Delta L=1$ or $\Delta B=1$ terms

- proton decay prohibited
- sparticles can only be produced in pairs
- SUSY decay products contain odd number of LSPs
- LSP **decays** to SM particles

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

MSSM with Bilinear R-Parity Violation

Some facts of bilinear R-parity violation

- neutrinos mix with neutralinos
- neutrinos acquire a mass
- correct scales of neutrino mass differences Δm_{ij}^2
- dynamic generation of neutrino mixing matrix

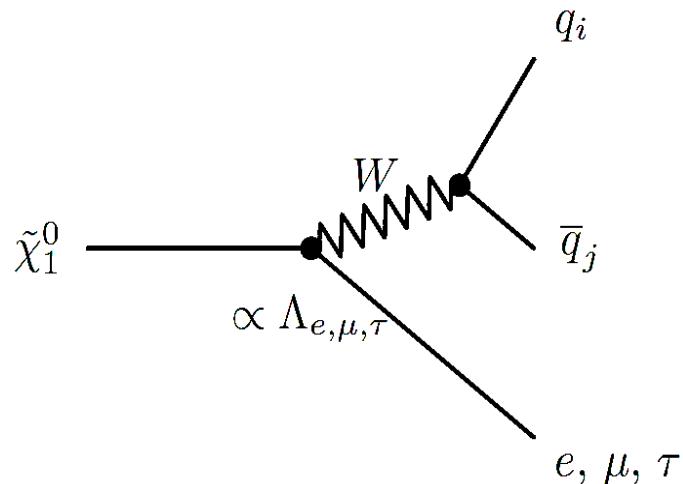
$$\tan \theta_{23} = \frac{\Lambda_\mu}{\Lambda_\tau}$$

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

Λ_l : “alignment parameter”

How is this connected to colliders?

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



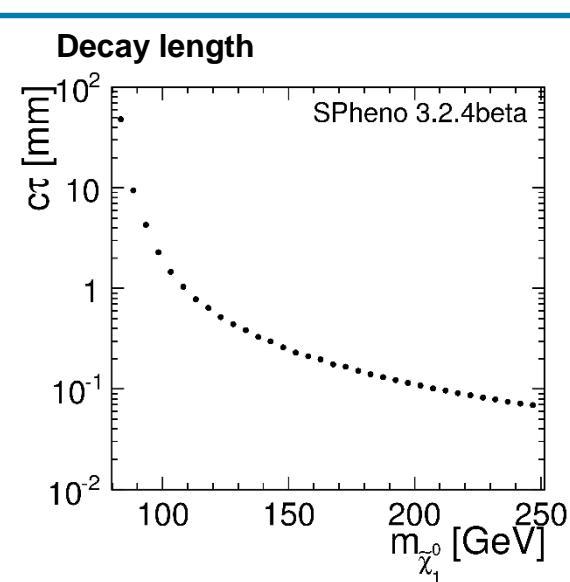
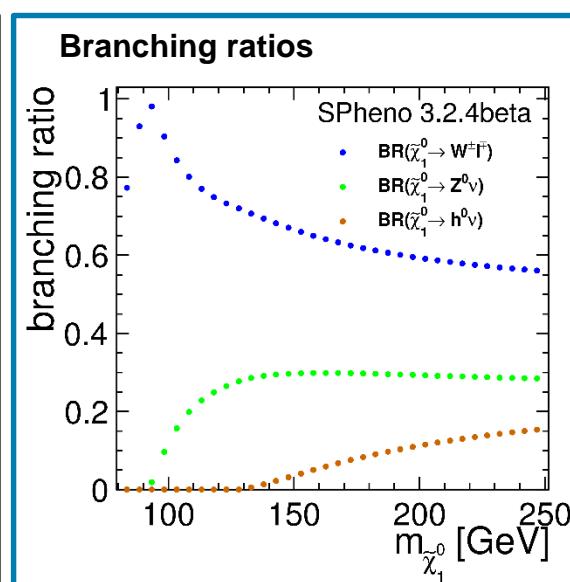
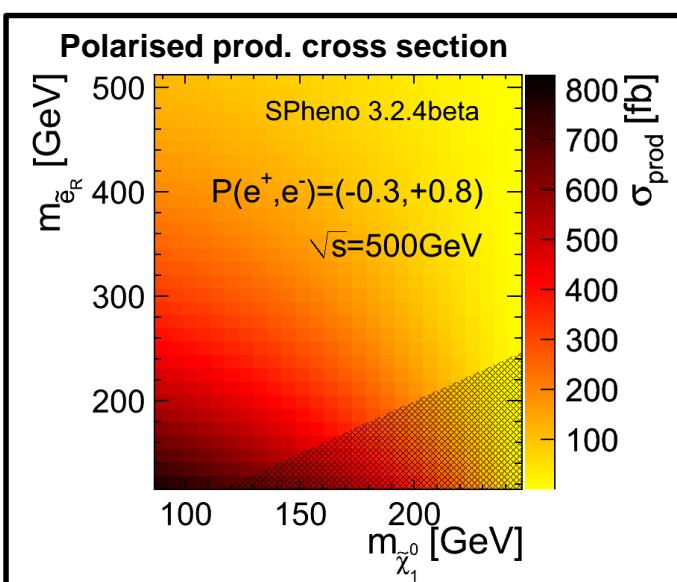
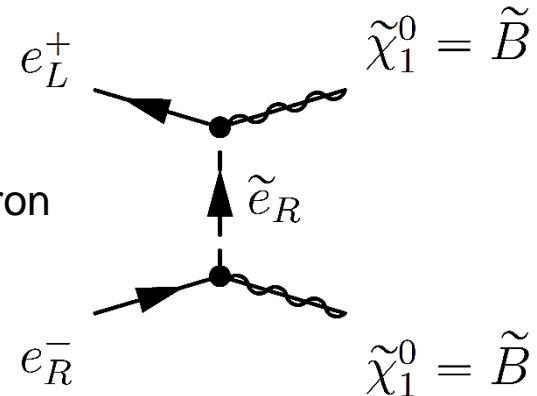
$$\tan^2 \theta_{23} = \left| \frac{\Lambda_\mu}{\Lambda_\tau} \right|^2 \cong \frac{BR(\tilde{\chi}_1^0 \rightarrow \mu W)}{BR(\tilde{\chi}_1^0 \rightarrow \tau W)}$$

→ Neutrino physics at the ILC

Simplified bRPV SUSY Model

Model definition

- bRPV parameters fit to neutrino data
- bino-like LSP → t-channel production
- heavy sparticles (\sim TeV), except for the LSP and right selectron
- relevant parameters for cross section:
 - right selectron mass
 - neutralino mass



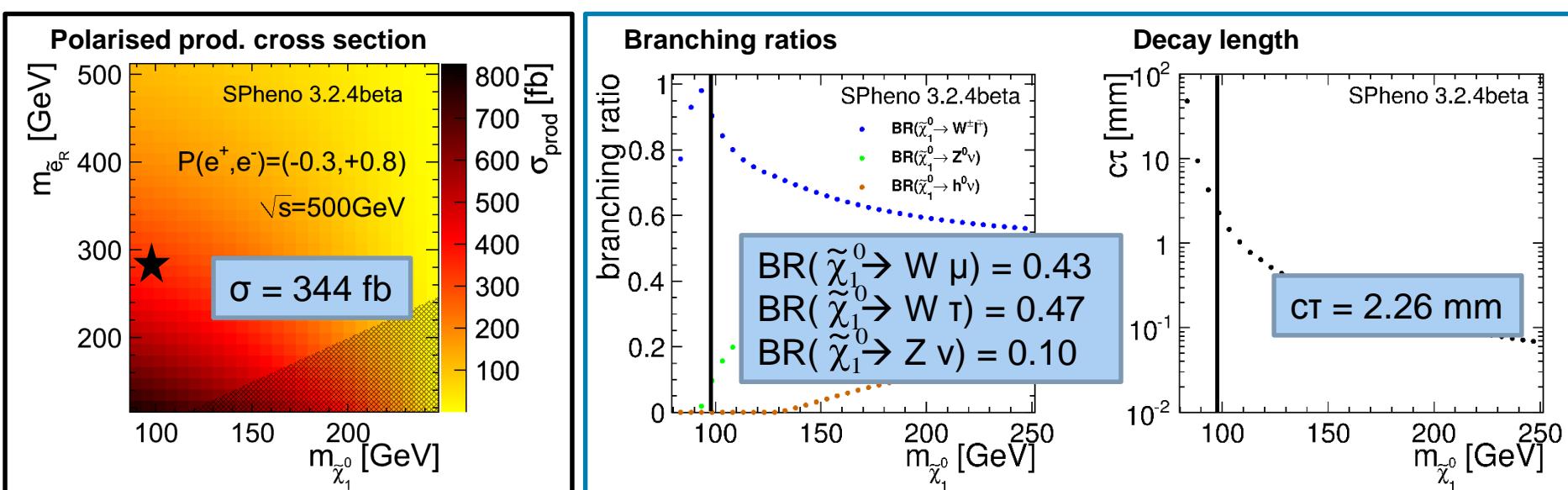
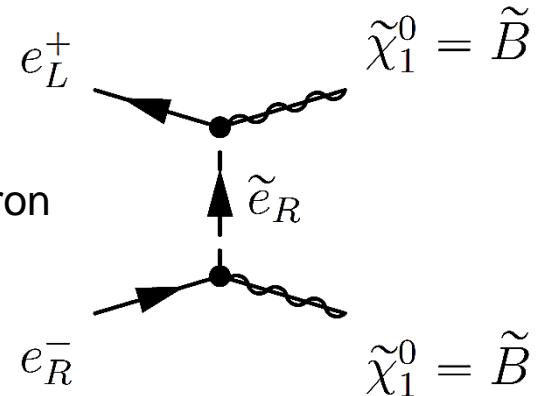
LSP production

LSP decay

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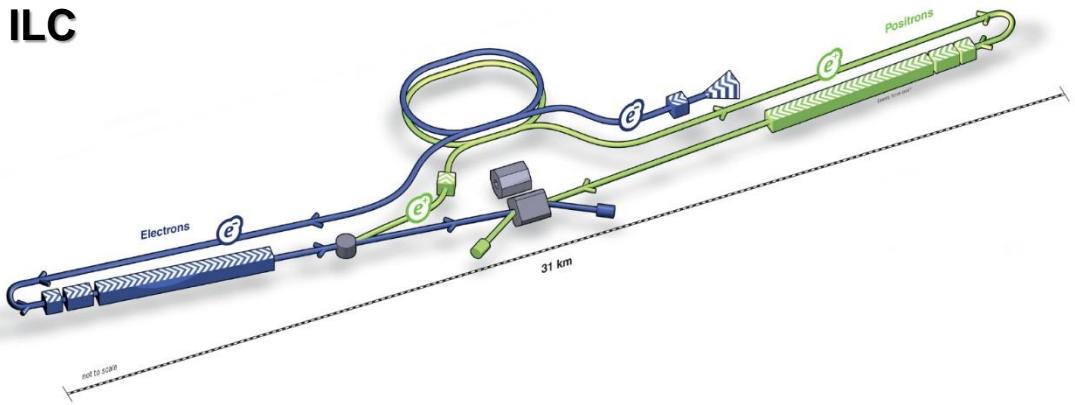


Studied example point:
 $m(\tilde{\chi}_1^0) = 98.5 \text{ GeV}$
 $m(\tilde{e}_R) = 280.0 \text{ GeV}$

→ conservative choice of LSP mass

Data Samples and Software

ILC



ILD



Datasets

- full SM background: DBD mass production (ILD_o1_v05, $\sqrt{s}=500\text{GeV}$)
- bRPV SUSY signal: private production ($\sqrt{s}=500\text{GeV}$, $\int L dt = 100\text{fb}^{-1}$)

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

ILC Whizard (v1.95)
including ILC beam spectrum

Event simulation/reconstruction

iLCsoft
standard DBD software
including $\gamma\gamma$ overlay

Event Topology

Goals

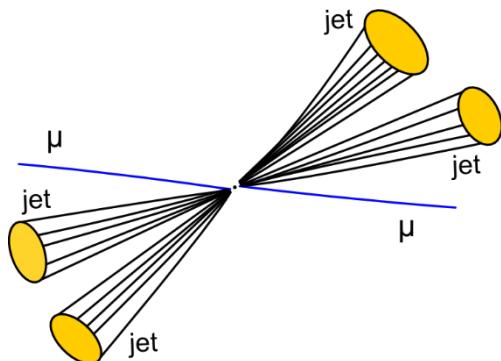
- select and distinguish LSP decays into μ and τ
- reconstruct neutralino mass
- measure the ratio of $BR(\tilde{\chi}_1^0 \rightarrow W \mu)$ and $BR(\tilde{\chi}_1^0 \rightarrow W \tau)$
- explore discovery potential of LSP decays in the simplified bRPV SUSY model

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

Event classes

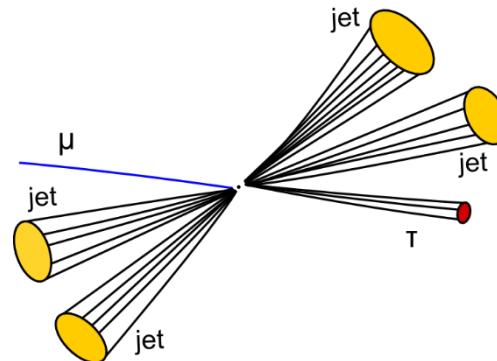
→ μ or τ from (displaced) vertices

→ 2 on-shell W bosons → **hadronic W-boson decay: 6 visible final state objects**



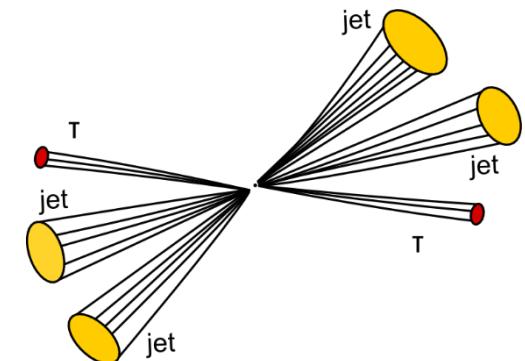
$\mu\mu$ channel

$\mu W \mu W \rightarrow 4$ jets



$\mu\tau$ channel

$\mu W \tau W \rightarrow 5$ jets

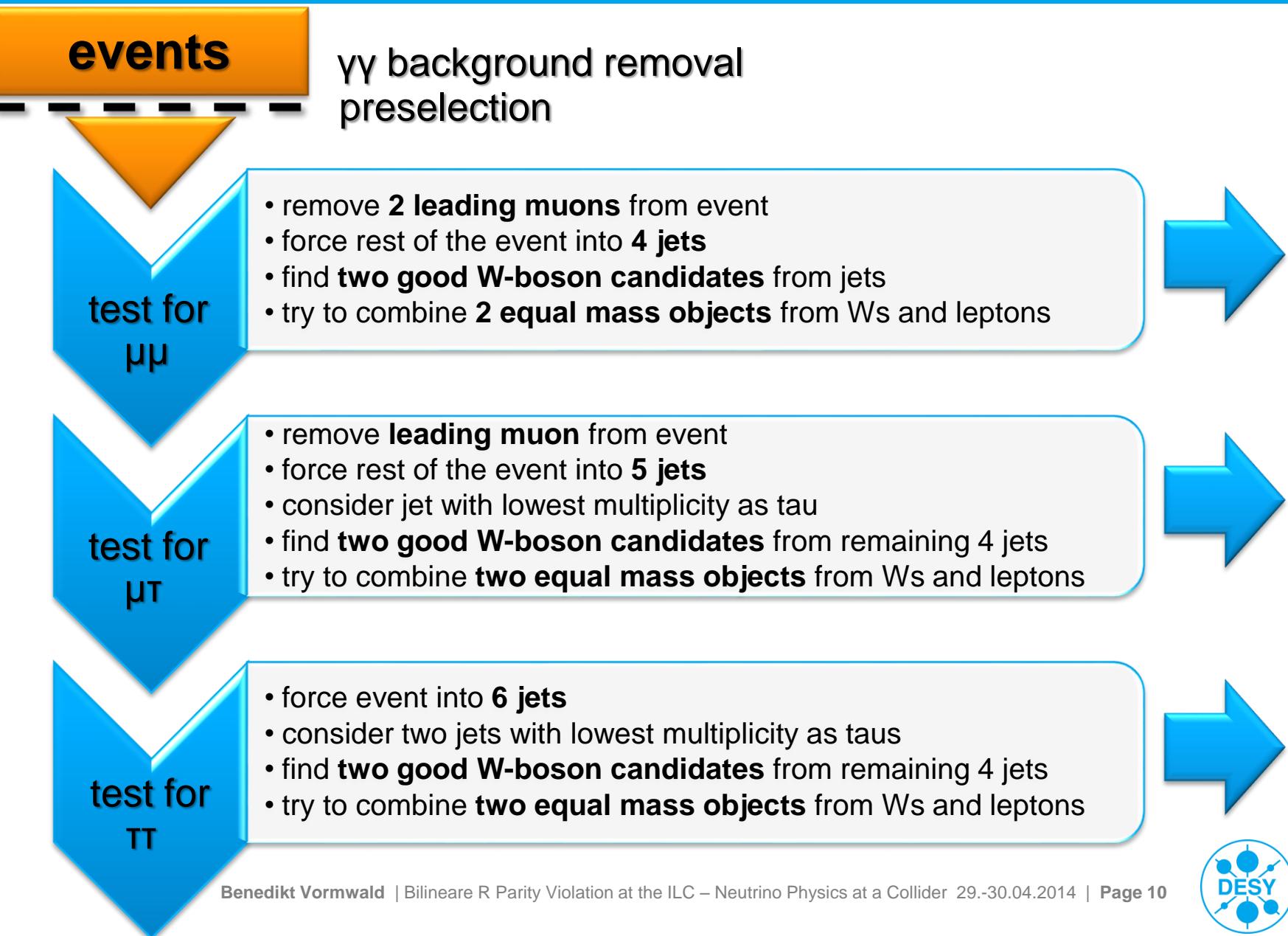


$\tau\tau$ channel

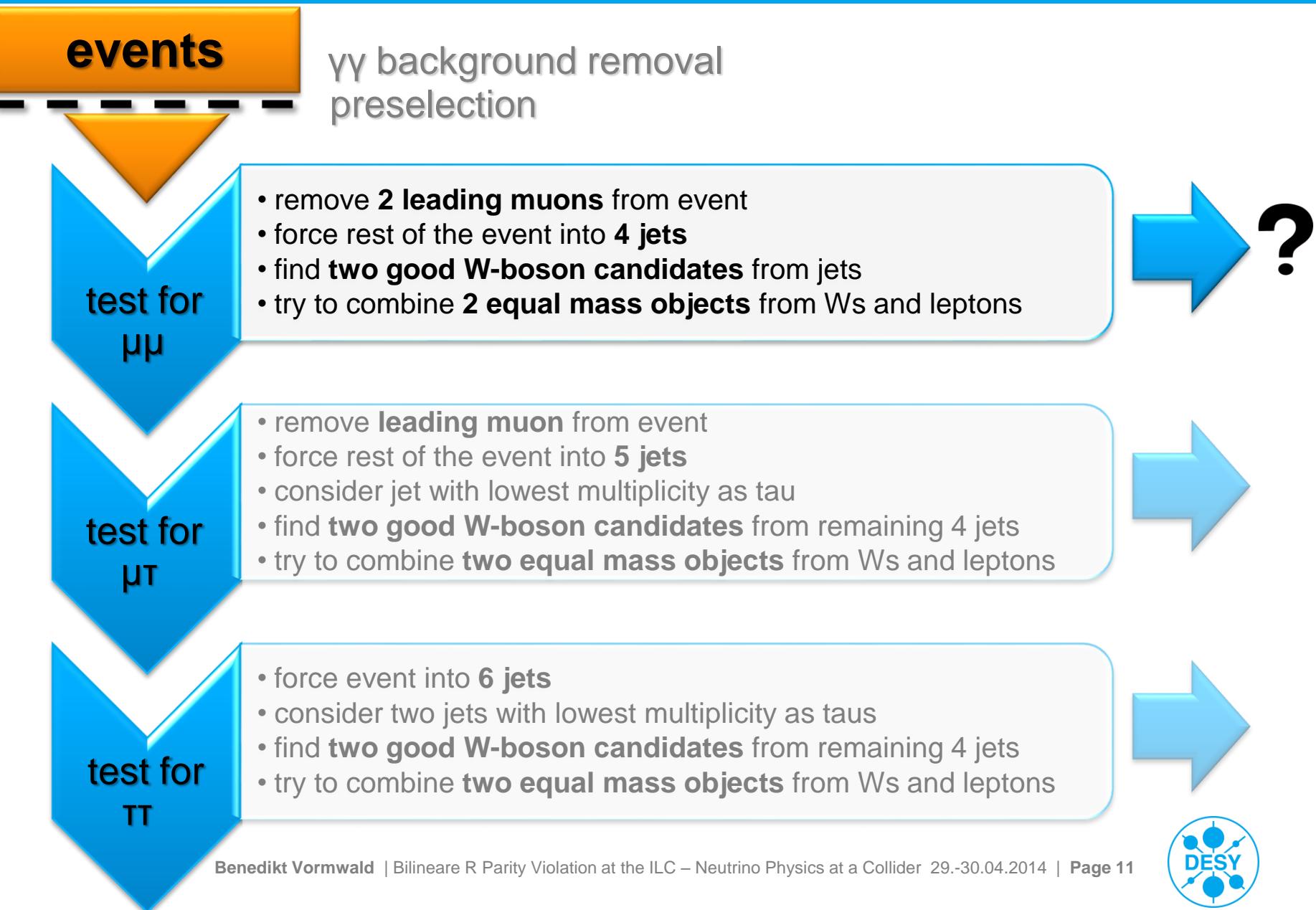
$\tau W \tau W \rightarrow 6$ jets

→ all other combinations of LSP decays considered as LSP background (LSP BG)

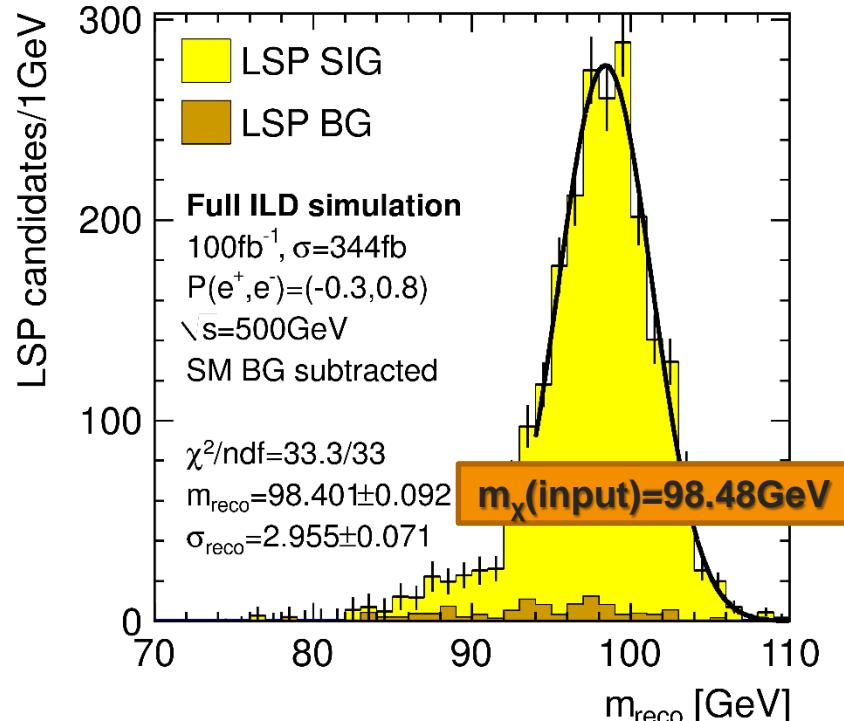
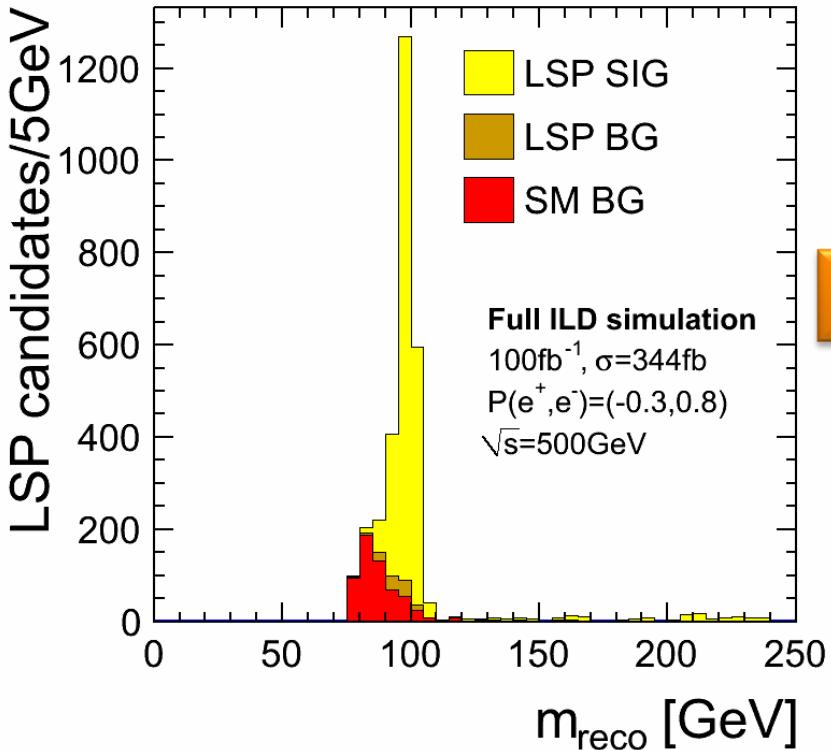
Reconstruction Strategy



Reconstruction Strategy



Full Event Reconstruction ($\mu\mu$ channel)

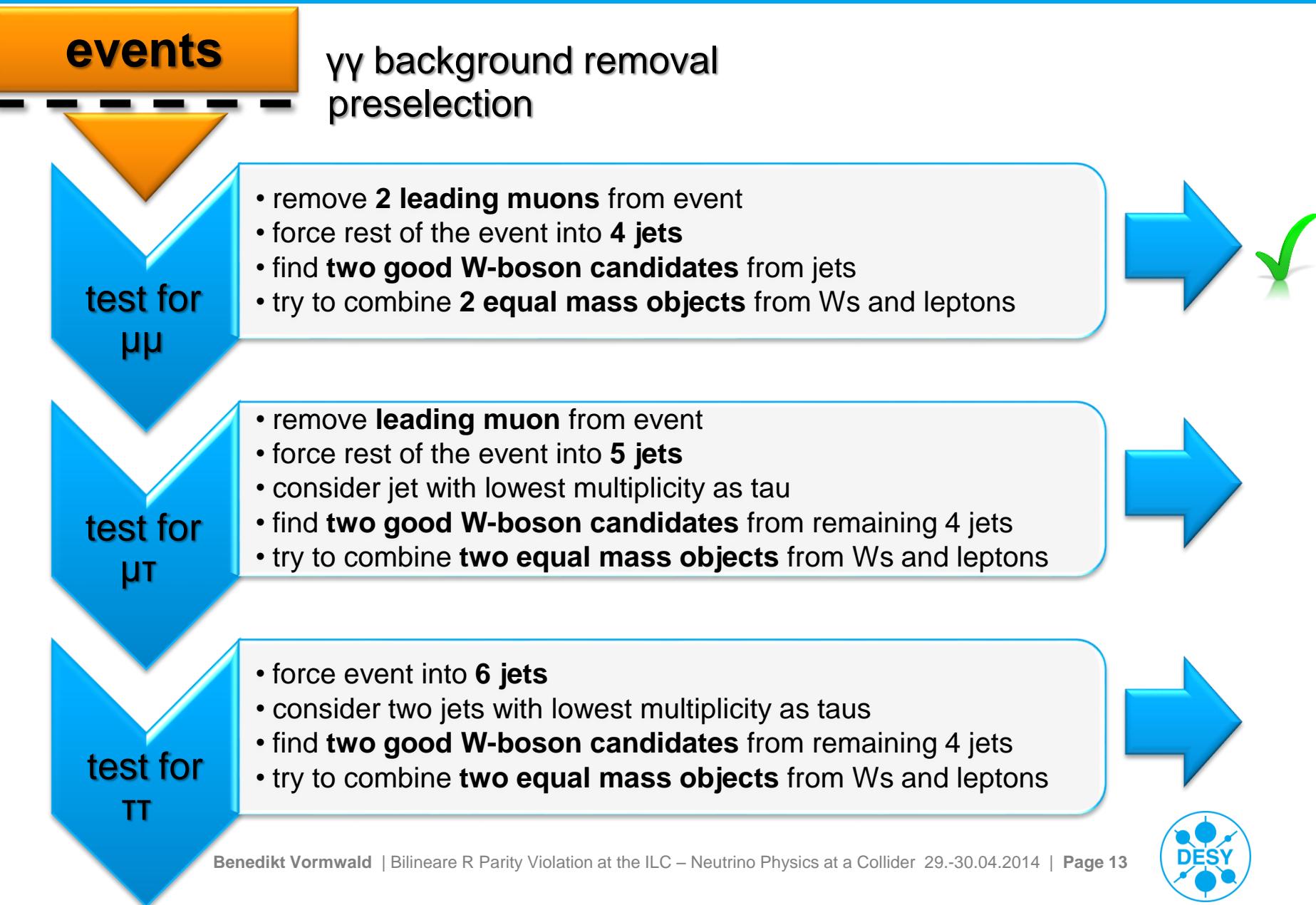


for $\int L dt = 500 \text{ fb}^{-1}$: **$\Delta m_x = 40(\text{stat.}) \pm 35(\text{syst.}) \text{ MeV}$**

sources of systematic errors:

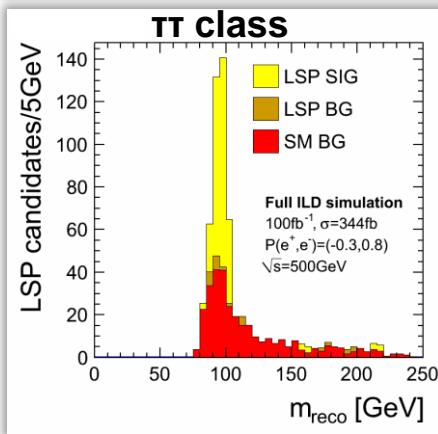
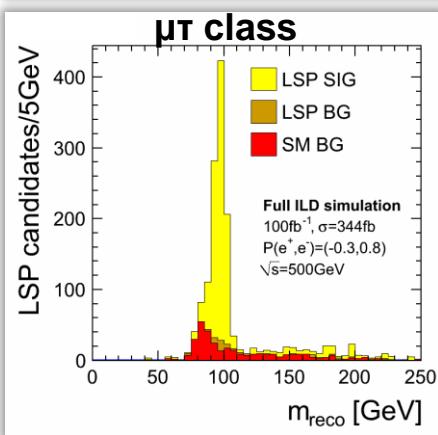
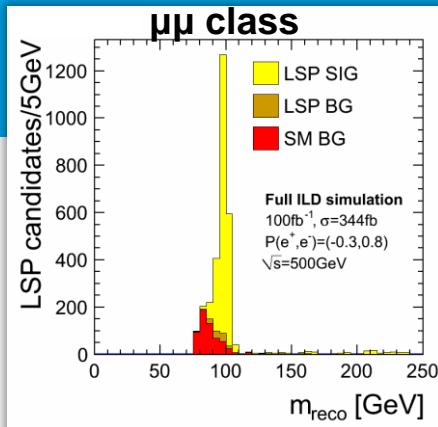
- MC background modelling
- jet energy scale
- muon momentum scale

Reconstruction Strategy



Efficiency Matrix

	true μW_{had}	μW_{had}	true τW_{had}	τW_{had}	LSP BG	SM
all events	2878	6238	3502	21516	3037266	
N($\mu\mu$ class)	913 0.317	204 0.033	37 0.011	59 0.003	298 $9.8 \cdot 10^{-5}$	
N($\mu\tau$ class)	16 0.006	451 0.072	87 0.025	29 0.001	175 $5.8 \cdot 10^{-5}$	
N($\tau\tau$ class)	0 0.000	2 >0.001	127 0.036	14 >0.001	160 $5.3 \cdot 10^{-5}$	



- main Standard Model background: W pairs, Z pairs
- Standard Model background suppression $10^{-4}\text{-}10^{-5}$
- τ-signature contribution in μ-selection class due to muonic τ decay

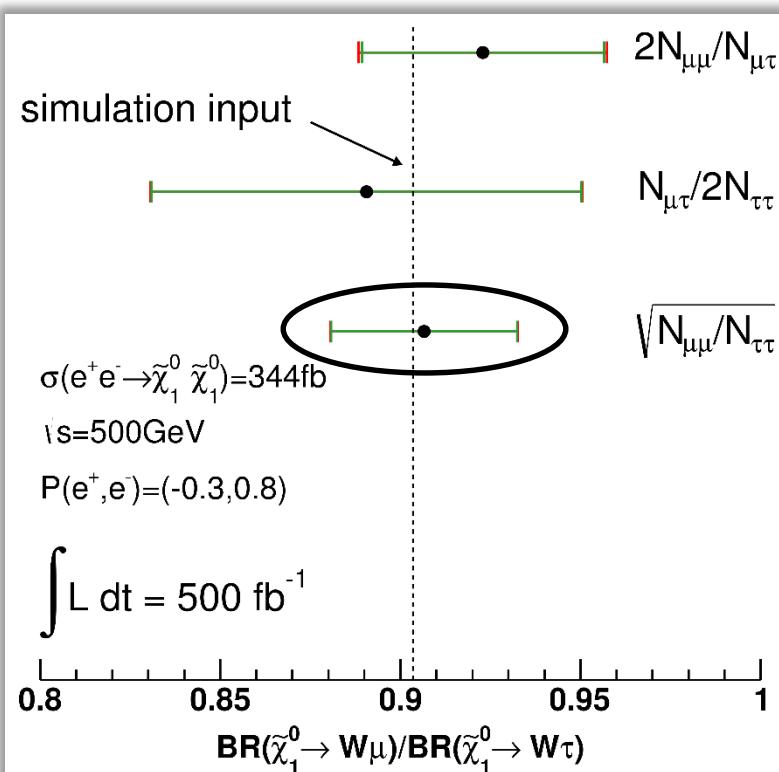
Precision Estimation of Double Ratio Measurement

Three ways of extracting ratio of BRs

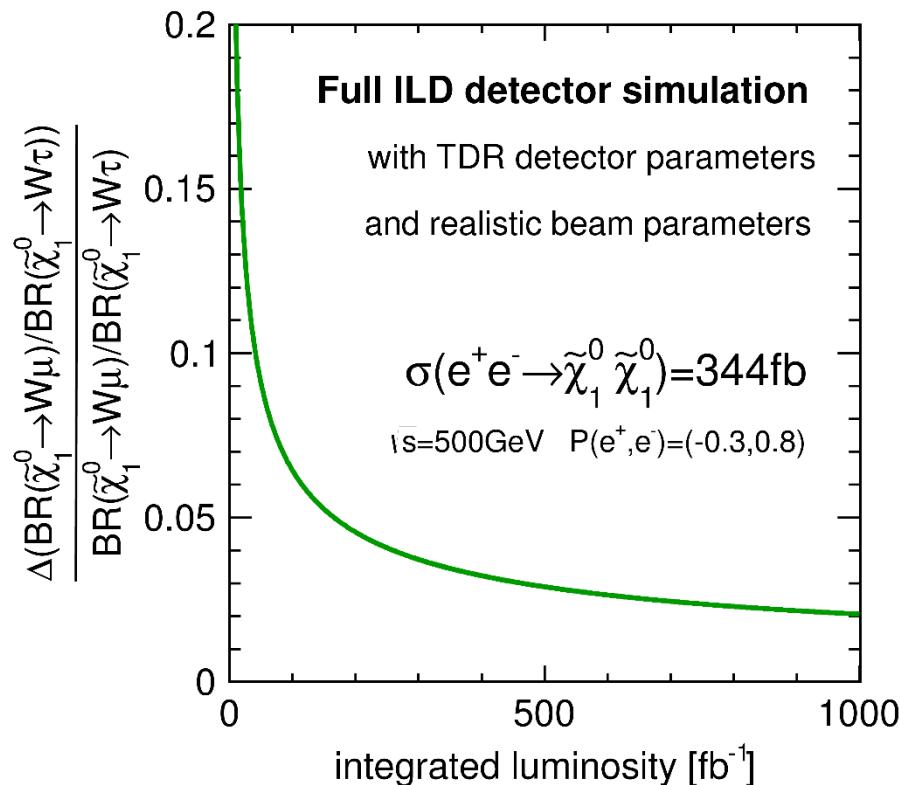
$$N_{\mu\mu} = N_{\tilde{\chi}_1^0 \tilde{\chi}_1^0} \cdot \text{BR}(\tilde{\chi}_1^0 \rightarrow W\mu)^2$$

$$N_{\mu\tau} = N_{\tilde{\chi}_1^0 \tilde{\chi}_1^0} \cdot 2 \text{BR}(\tilde{\chi}_1^0 \rightarrow W\mu) \text{BR}(\tilde{\chi}_1^0 \rightarrow W\tau)$$

$$N_{\tau\tau} = N_{\tilde{\chi}_1^0 \tilde{\chi}_1^0} \cdot \text{BR}(\tilde{\chi}_1^0 \rightarrow W\tau)^2$$

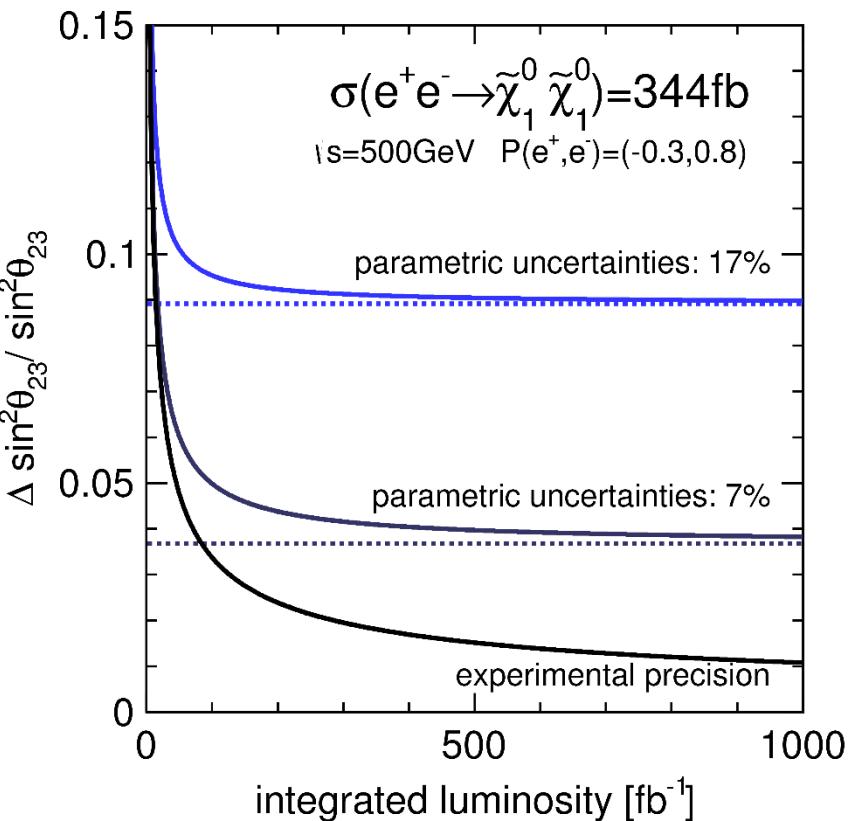
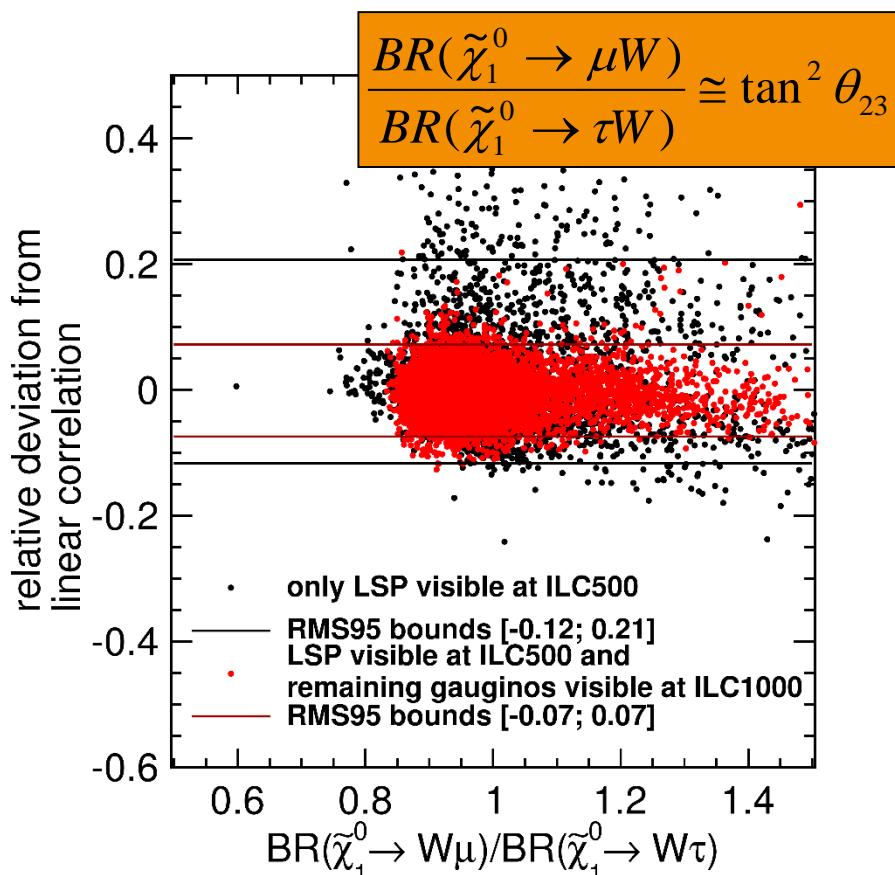


Relative error on ratio of BRs



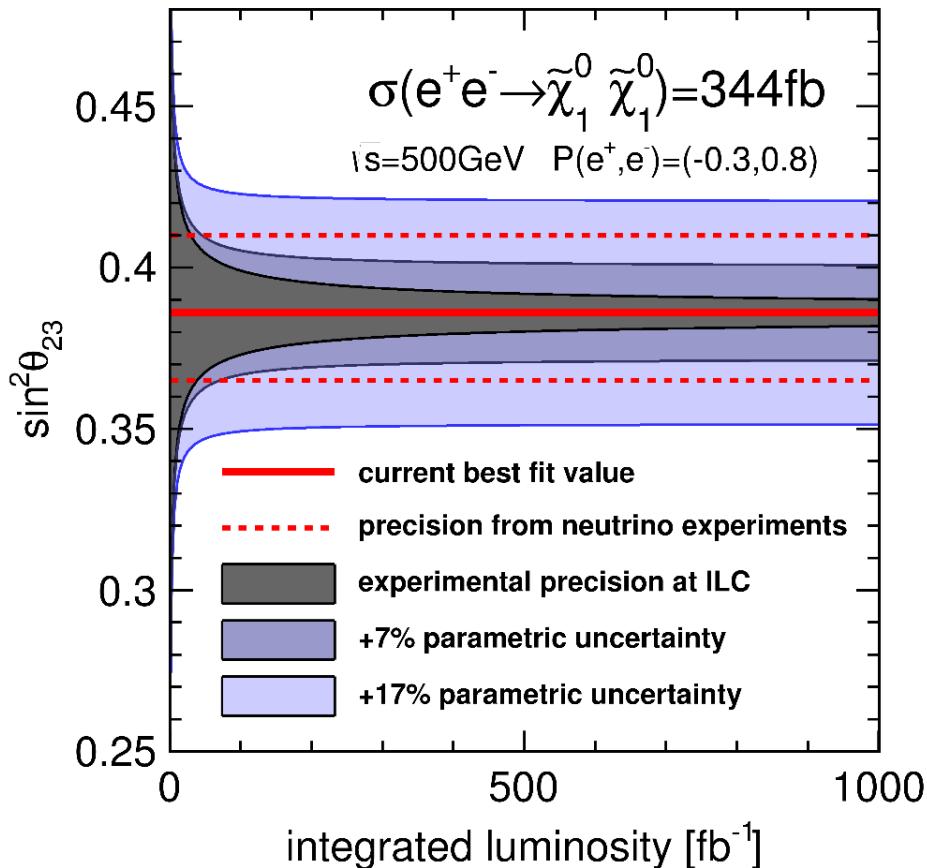
for $\int L dt = 500 \text{ fb}^{-1}$: **rel. uncertainty 2.9%**
 → uncertainty statistically limited

Parametric Uncertainties



- relation to atmospheric mixing angle only exact on tree level
- residual SUSY parameter dependencies enter via loops
- depending on knowledge of remaining particle spectrum

Determination of Atmospheric Neutrino Mixing Angle

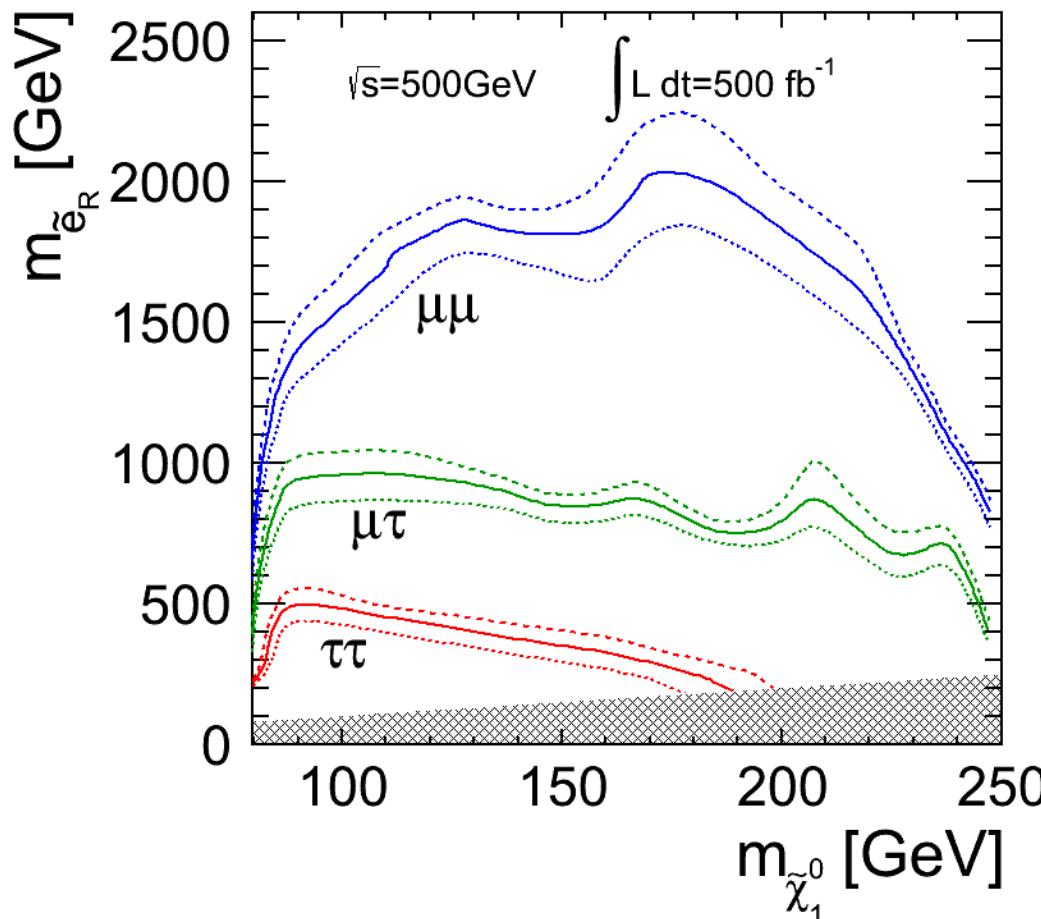


$$\frac{BR(\tilde{\chi}_1^0 \rightarrow \mu W)}{BR(\tilde{\chi}_1^0 \rightarrow \tau W)} \approx \tan^2 \theta_{23}$$

- measurement uncertainty in the order of precision of uncertainties from global neutrino oscillation data fits
- can help to resolve octant discrimination

→ ILC is capable to unveil whether bRPV SUSY is mechanism of neutrino masses and mixing

Discovery Reach in Parameter Plane

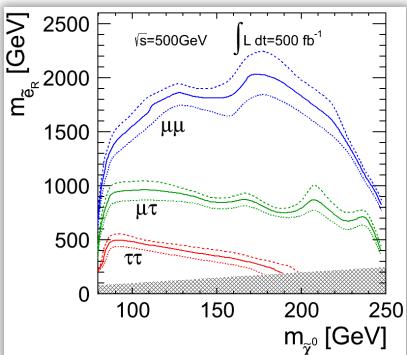
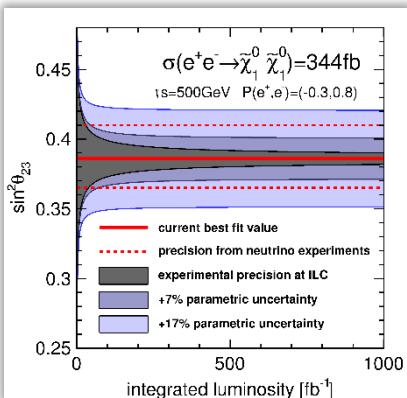
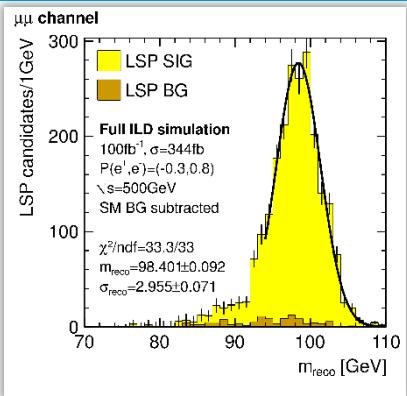


- conservative assumption: efficiency matrix unchanged for larger LSP masses
- $\mu\mu$ channel sensitive to selectron masses up to 2000 GeV
- positron polarisation increases sensitivity in selectron mass significantly

Conclusions

- > **bilinear R-parity violating SUSY** is a possible extension to the Standard Model explaining **neutrino phenomenology**
- > lightest **neutralino mass** can be reconstructed very precisely at the ILC:
 $\Delta m_x = 40(\text{stat.}) \pm 35(\text{syst.}) \text{ MeV} \text{ (500 fb}^{-1}\text{)}$
- > atmospheric neutrino mixing angle θ_{23} can be determined experimentally on percent level
- > probe large area of the parameter plane (selectron masses up to **1500 GeV** for almost the **whole accessible range of LSP masses**) (500 fb^{-1})

Eur.Phys.J. C74 (2014) 2720 (arxiv:1307.4074)



Backup slides

Bilinear R-parity violation

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

Superpotential

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

bRPV term
 $i = 1 \dots 3$

→ Higgs/Slepton-mixing

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

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

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 R-parity 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:

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

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

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

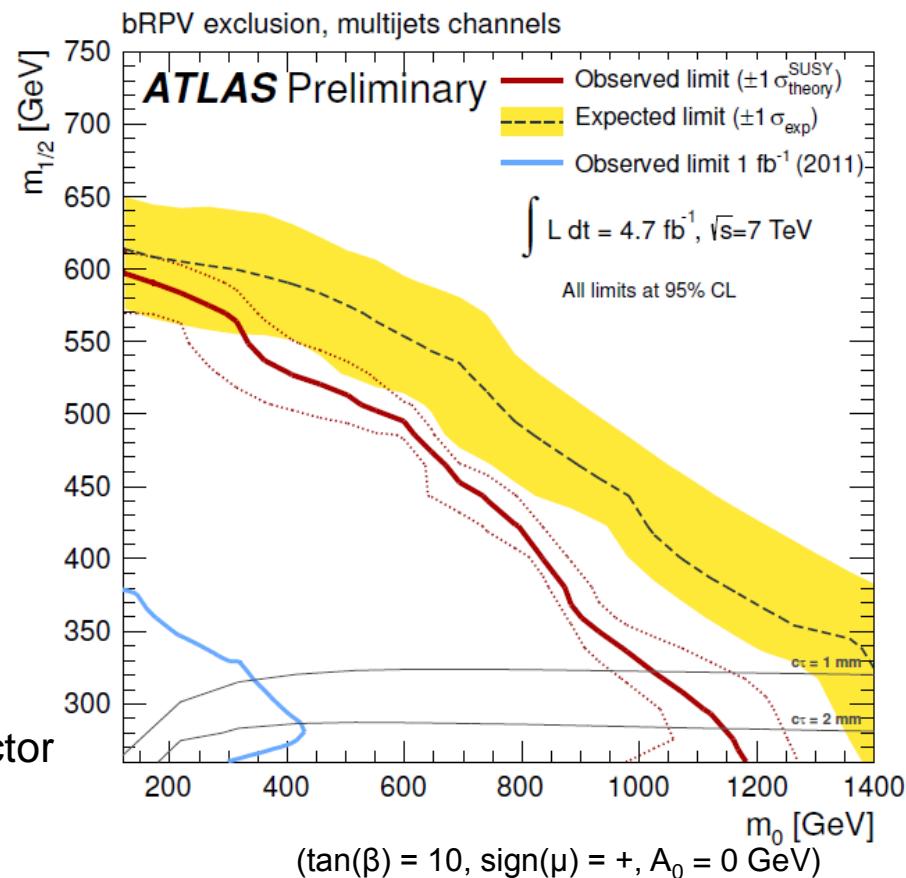
A final diagonalization of M_{χ^0} leads to the neutralino masses $m_{\chi_i^0}$ and a diagonalization of m_{eff} leads to one tree level neutrino mass.



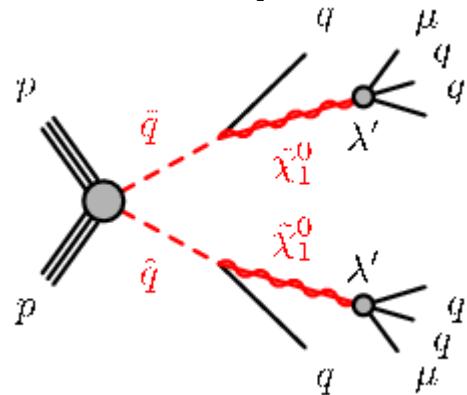
Explicit bRPV search

One dedicated bRPV mSUGRA search from ATLAS:

- large jet multiplicity
- 1 isolated lepton
- missing transverse momentum
- bRPV parameters fitted to neutrino data
- bRPV mSUGRA tested for $m_{1/2} > 240\text{GeV}$ ($\rightarrow c\tau < 15\text{ mm}$)
- analysis takes into account all possible production modes dominated by squark production and subsequent decays
- cMSSM couples EW sector and colored sector



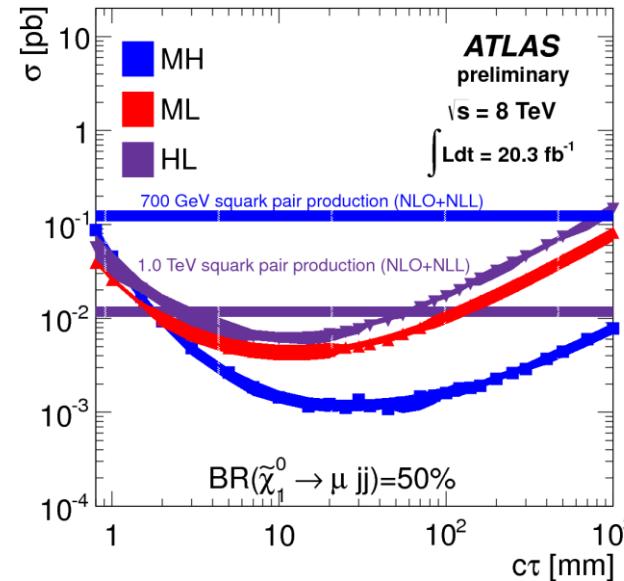
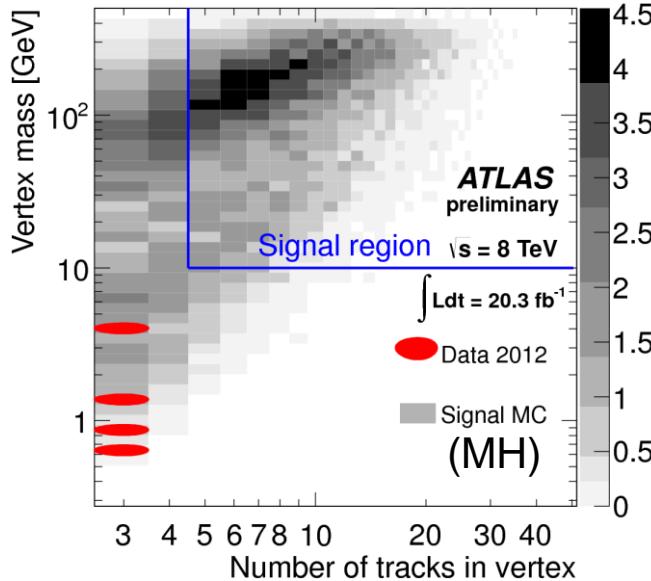
Dedicated displaced vertex search



search for:

- $|z_{\text{DV}}| < 300\text{mm}$, $r_{\text{DV}} < 180\text{mm}$
- 1 high- p_t muon ($> 55 \text{ GeV}$)

background free analysis ($N_{\text{BG}} < 0.02$)

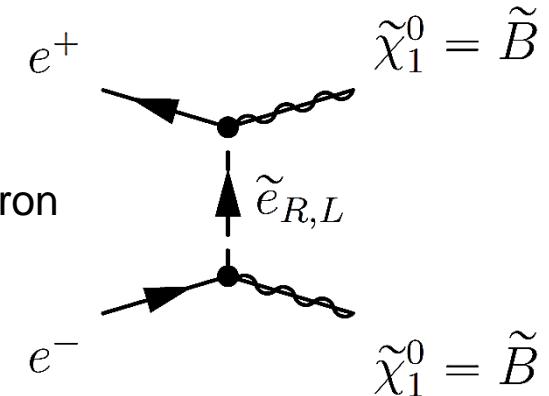


Sample	$m_{\tilde{q}}$ [GeV]	$m_{\tilde{\chi}_1^0}$ [GeV]
MH	700	494
ML	700	108
HL	1000	108

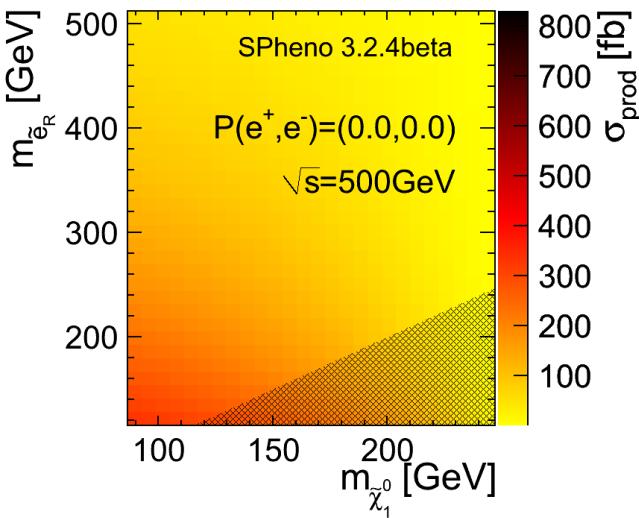
Simplified bRPV SUSY Model

Model definition

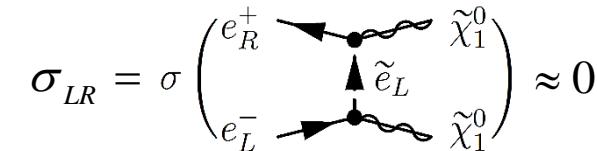
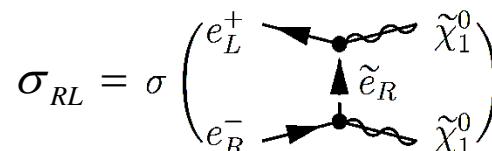
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Unpolarised prod. cross section



$$\sigma = \frac{1}{4} (1 + P_{e^-}) (1 - P_{e^+}) \sigma_{RL} + \frac{1}{4} (1 - P_{e^-}) (1 + P_{e^+}) \sigma_{LR}$$

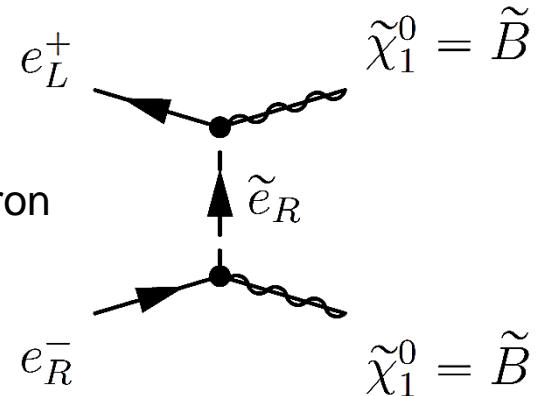


→ Beam polarisation can enhance the production mode

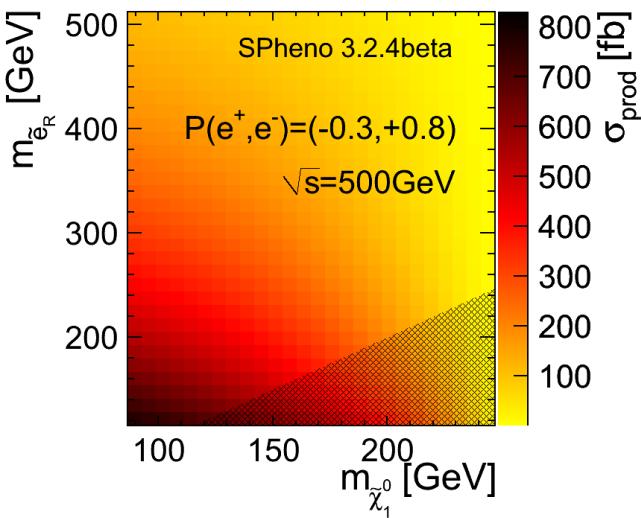
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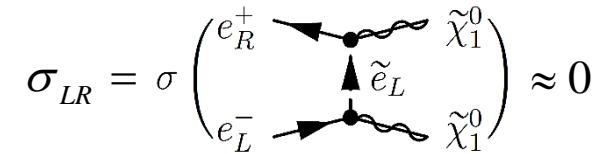
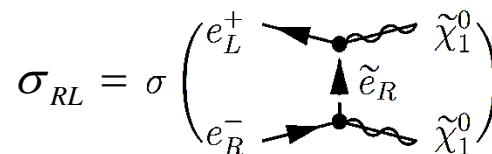
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Polarised prod. cross section



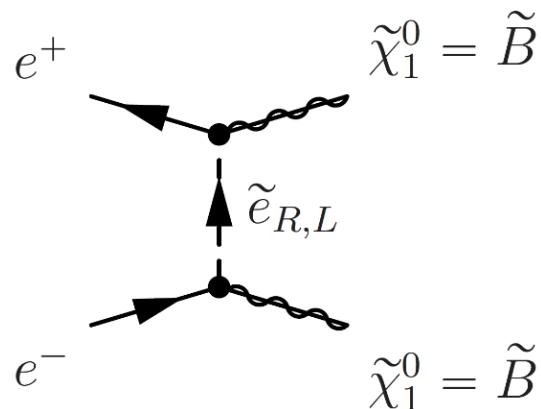
$$\sigma = \frac{1}{4} (1 + P_{e^-}) (1 - P_{e^+}) \sigma_{RL} + \frac{1}{4} (1 - P_{e^-}) (1 + P_{e^+}) \sigma_{LR}$$



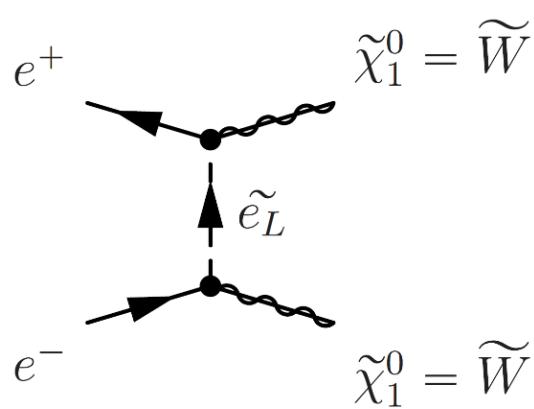
- Beam polarisation can enhance the production mode
- For the ILC baseline polarisation: **factor 2.34**

What, if the LSP is a...

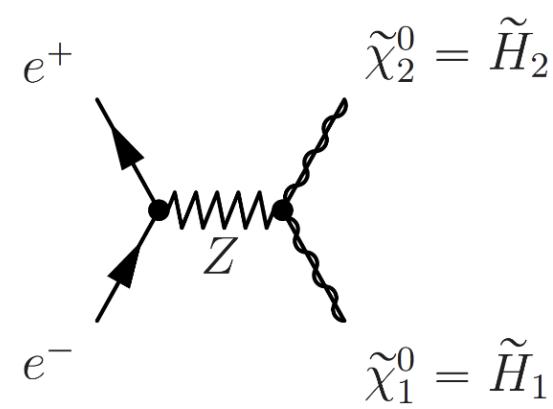
bino



wino



higgsino



left and right selectron
as exchange particle

only left selectron as
exchange particle

only associate
production possible

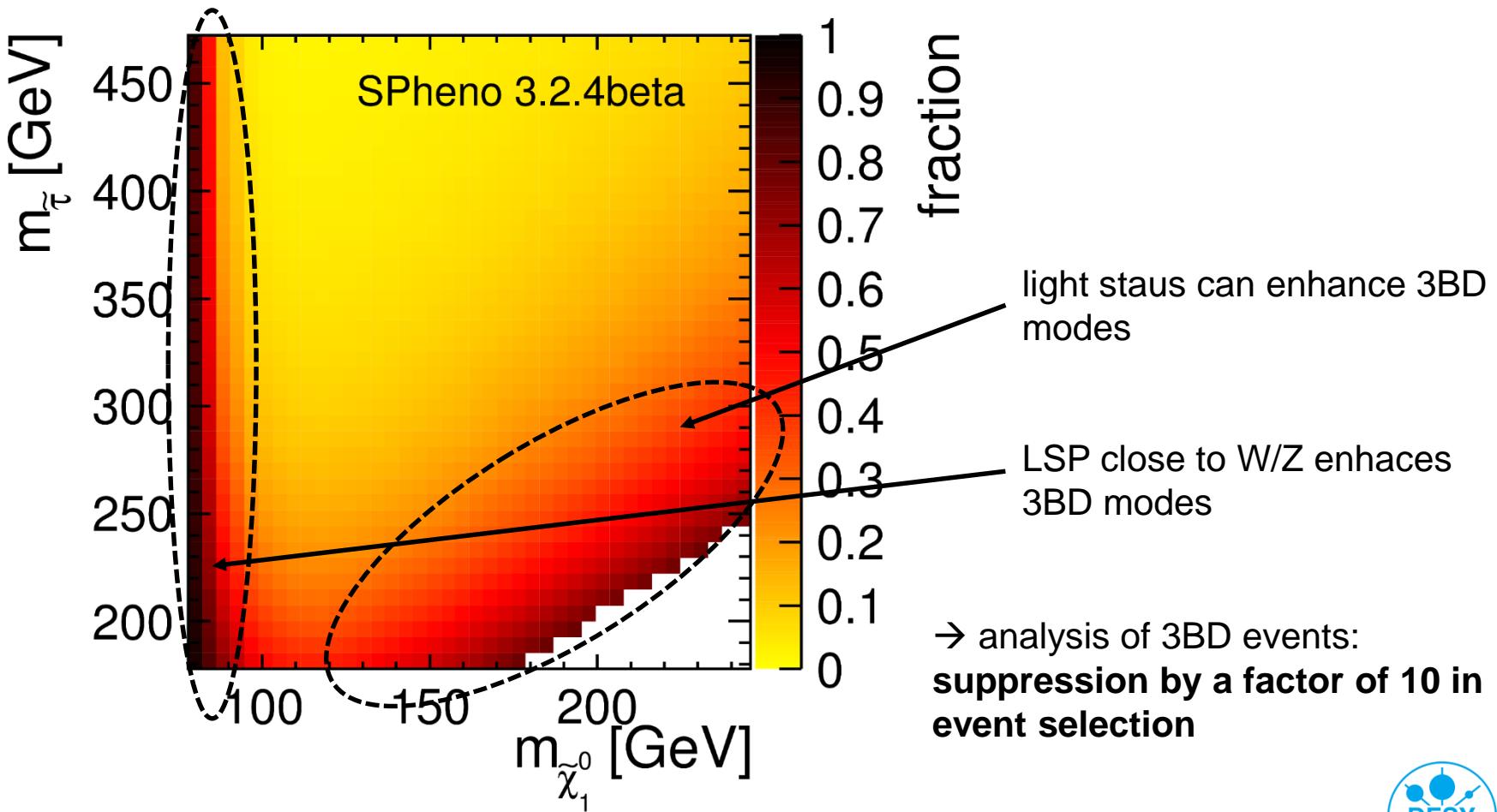
lightes and second-to-
lightes neutralino
usually close in mass
→ comparable to direct
pair production

What, if the remaining sparticles are lighter...

in general: the more SUSY particles in reach, the more LSP decays observable!

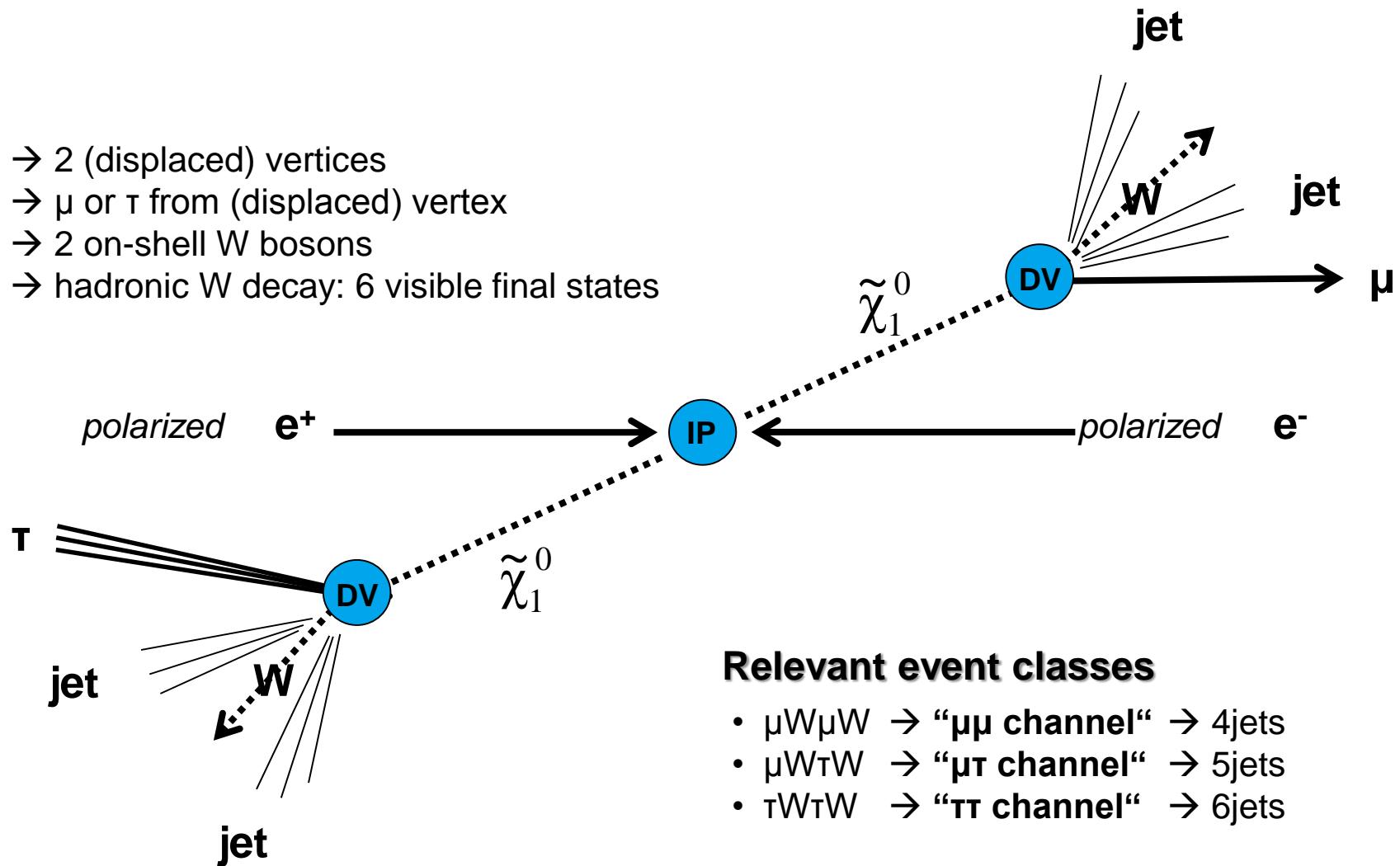
however: significant contribution from 3-body-decays possible

Fraction of 3-body decays



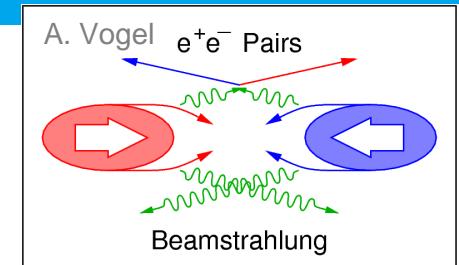
Event Topology

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

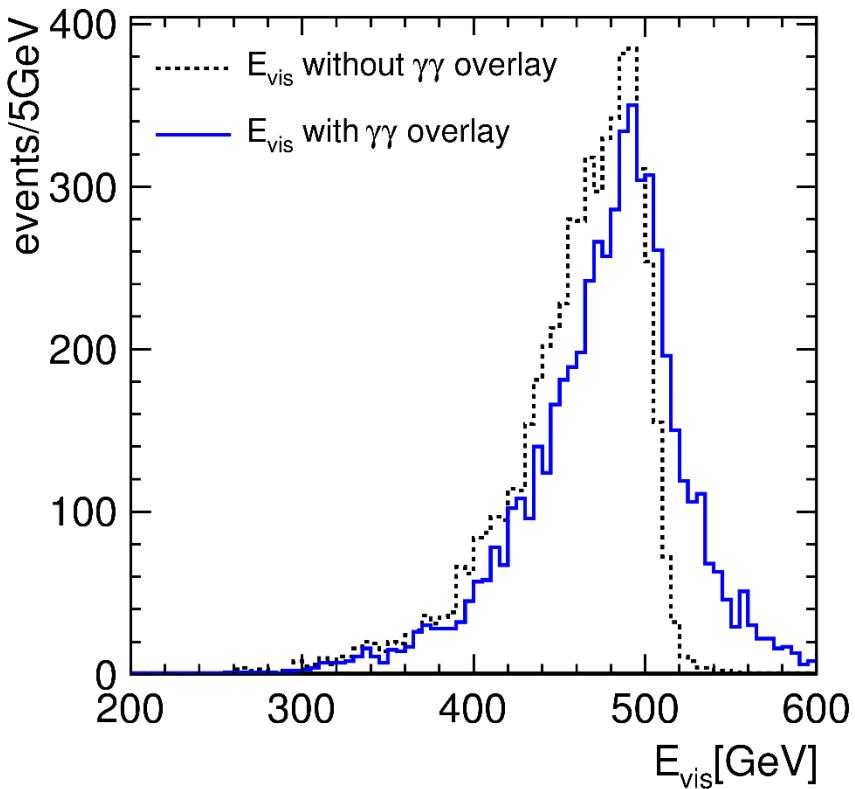


ILC Pileup – $\gamma\gamma \rightarrow$ hadrons Background Removal

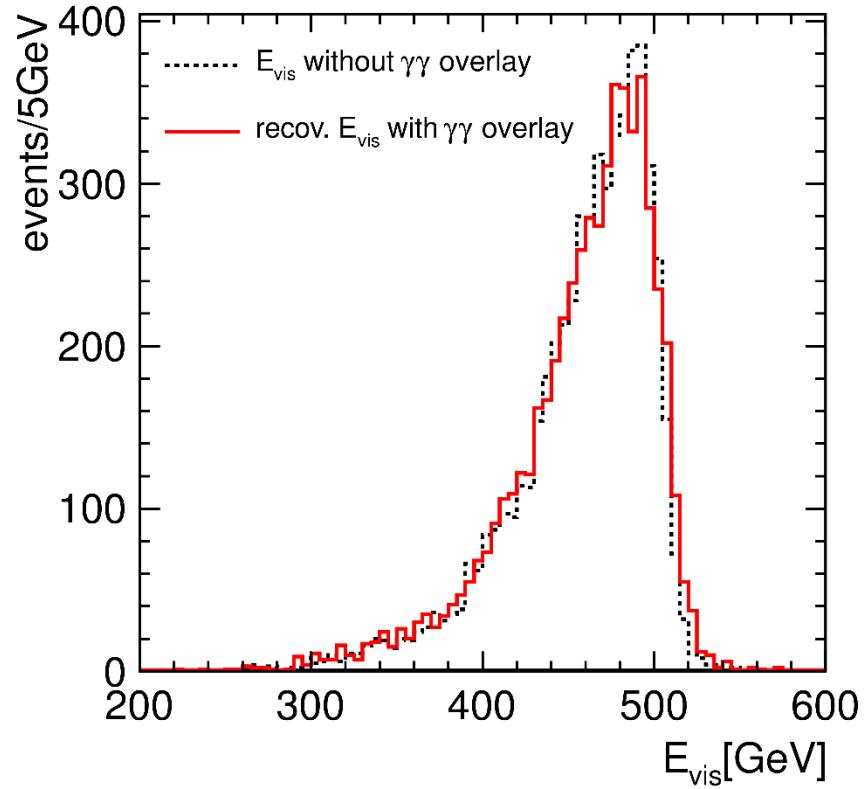
- overlaid $\gamma\gamma \rightarrow$ hadron events per interaction: $\langle N_{\gamma\gamma} \rangle = 1.7$
- exclusive jet clustering to remove beam background:
 k_T 1.3, ExclusiveNJets 6



Impact of $\gamma\gamma$ background

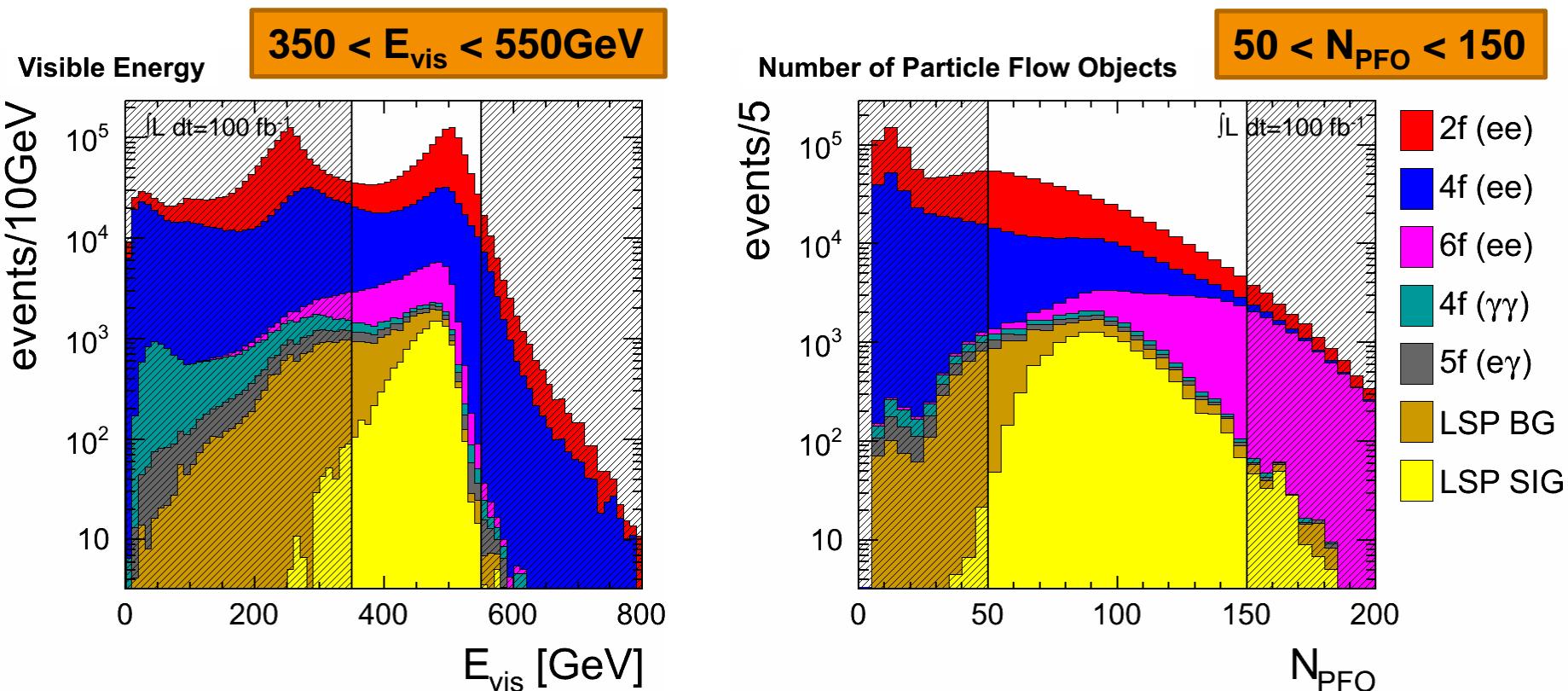


Effect of $\gamma\gamma$ background removal



→ all further analysis steps based on reconstructed particles in these 6 jets

Preselection

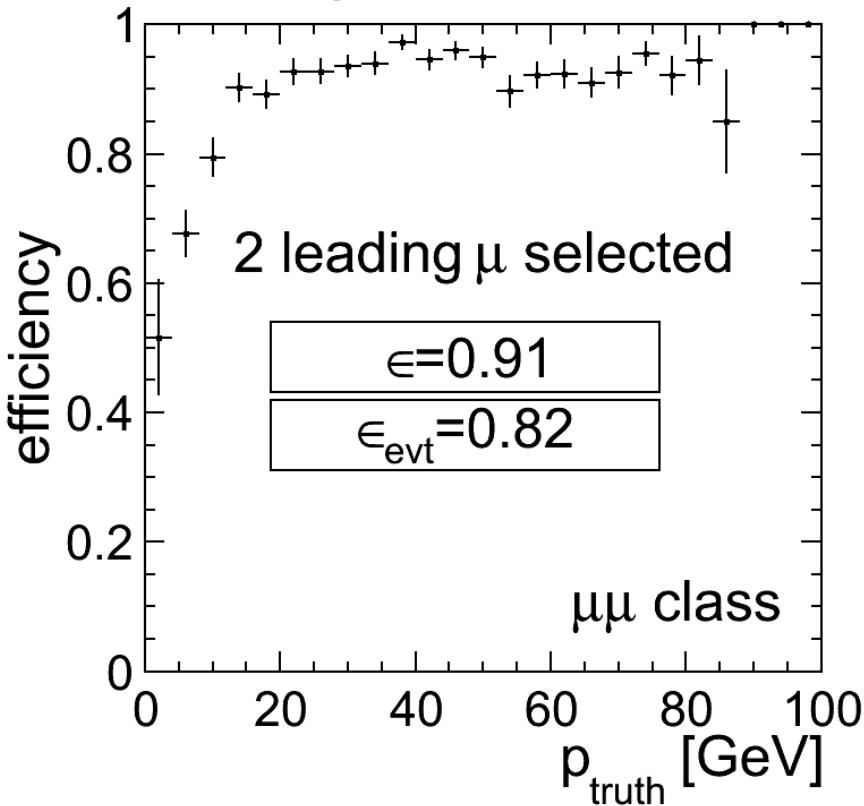


cut	SM	LSP BG	LSP SIG	$\mu\mu$ channel	$\mu\tau$ channel	$\tau\tau$ channel
no cut	3037266	21516	12618	2878	6238	3502
preselection	493467	7198	12026	2772	5946	3307
efficiency	0.162	0.335	0.953	0.963	0.953	0.944

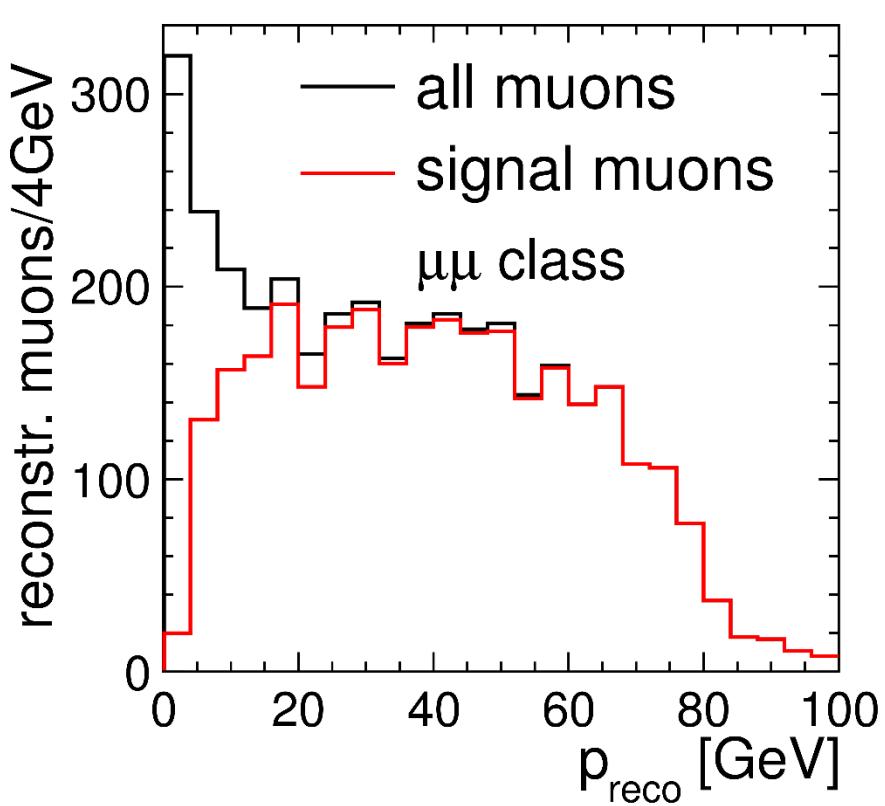
Signal Muon Selection ($\mu\mu$ channel)

- based on reconstructed muons (Pandora Particle Flow Object)
- no isolation required → depends on neutralino mass
- consider two most energetic muons as signal muons

Selection efficiency



Momentum distribution



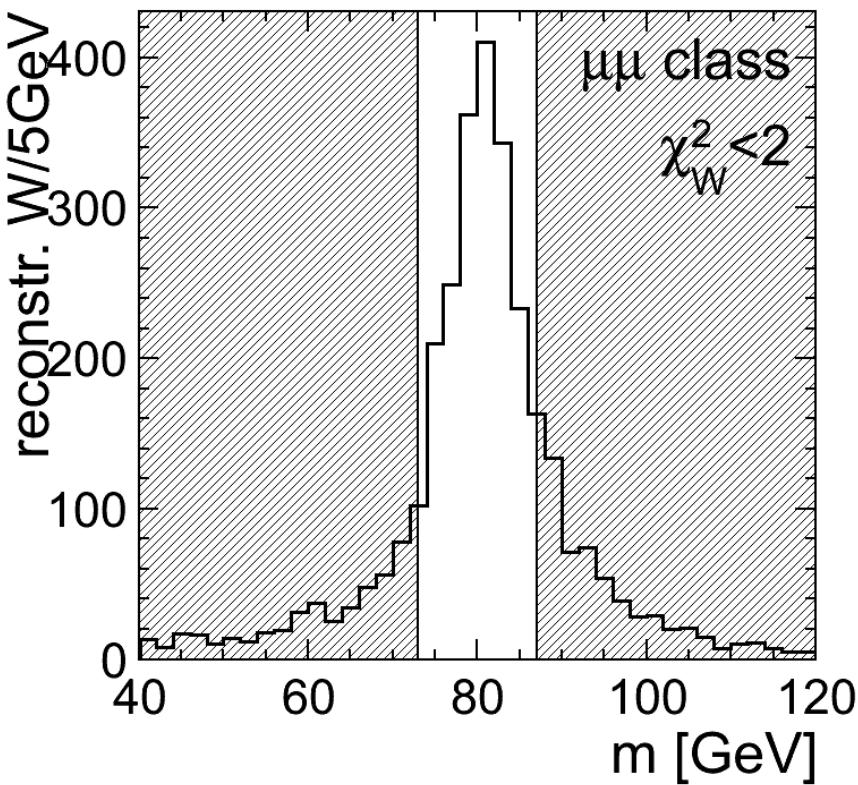
→ overall probability of selecting both signal muons correctly: 82%

W Boson Reconstruction ($\mu\mu$ channel)

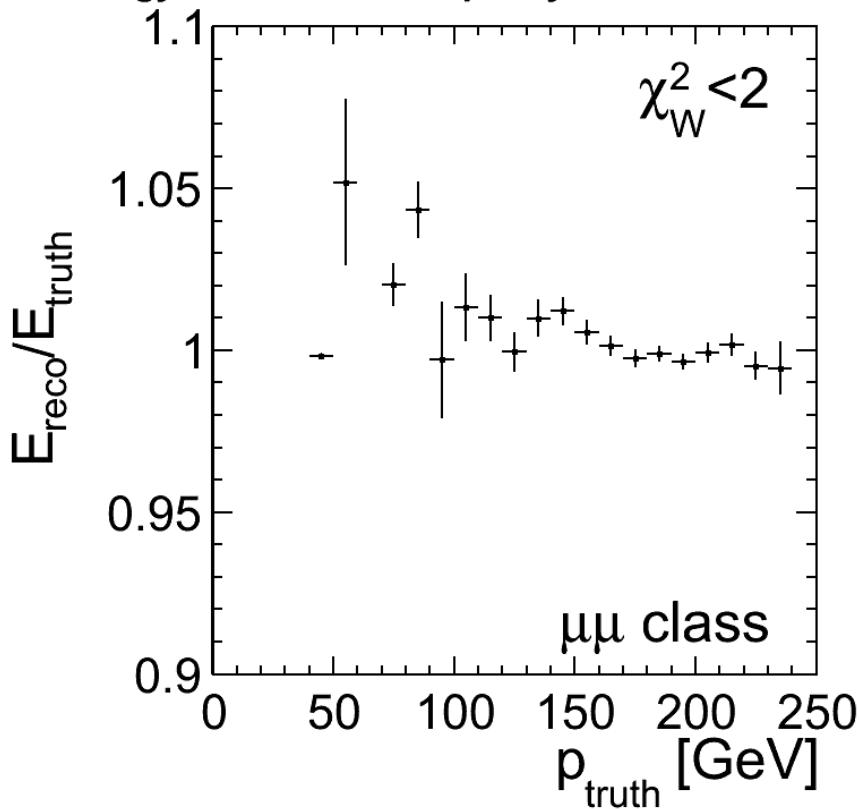
- remove leading muons from event
- force remaining objects into 4 jets (Durham)
- pair jets and test against W mass
- best jet combination is considered as W candidate

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

Reconstructed W mass



W energy reconstruction quality



→ very precise reconstruction of W boson decays from hadronic decays

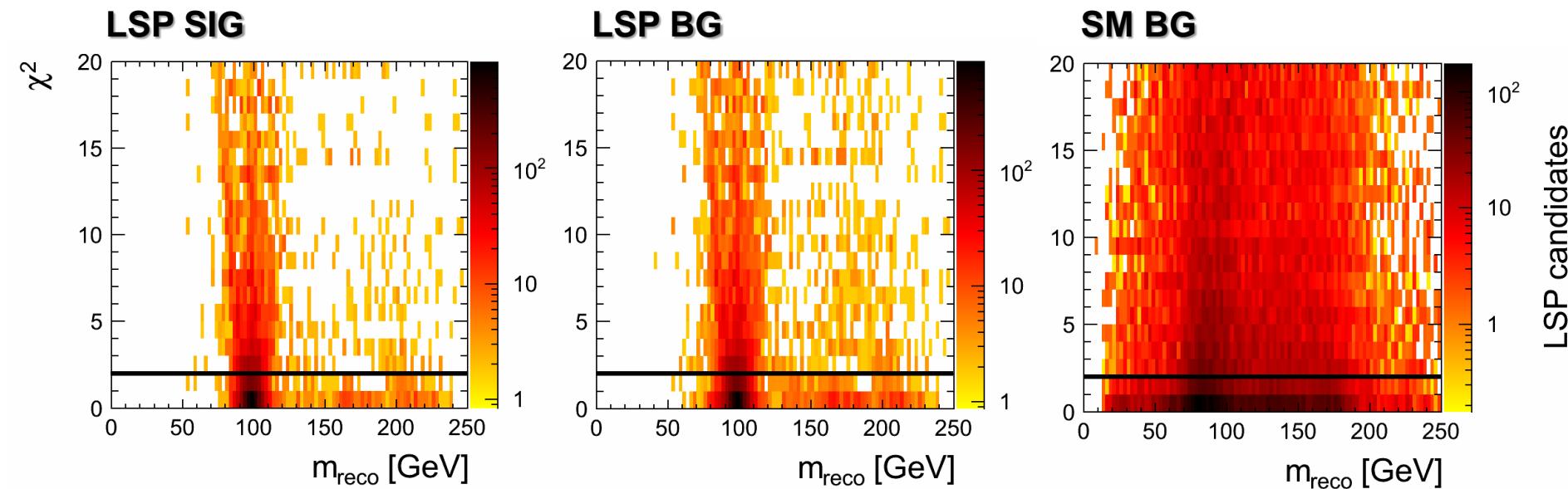
Full event reconstruction ($\mu\mu$ channel)

combine into two equal mass objects

2 μ

$$\chi^2_{\text{eqm}} = \frac{(m_{p1} - m_{p2})^2}{(5GeV)^2}$$

2 W

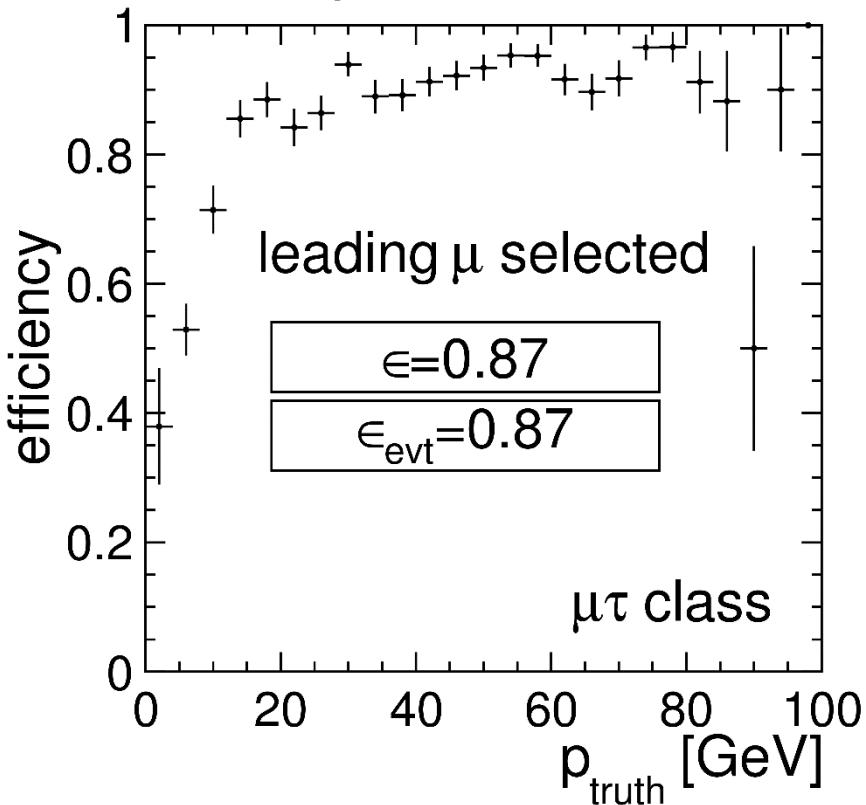


$$\rightarrow \chi^2_{\text{eqm}} < 2$$

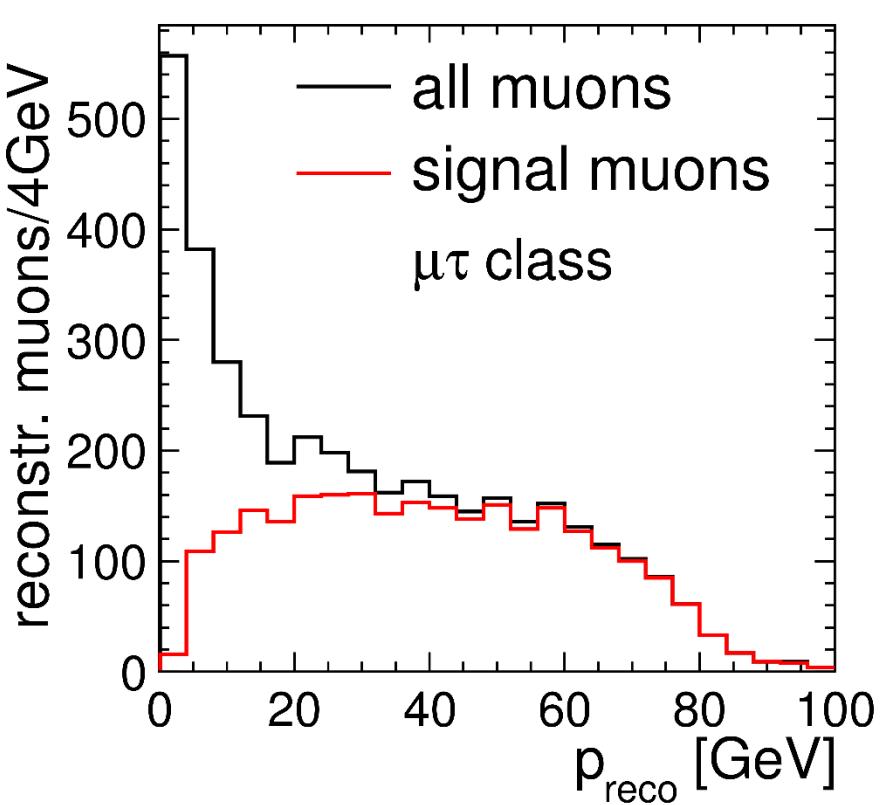
Signal Muon Selection ($\mu\tau$ channel)

- based on reconstructed muons (Pandora Particle Flow Object)
- no isolation required → depends on neutralino mass
- consider the most energetic muon as signal muon

Selection efficiency



Momentum distribution



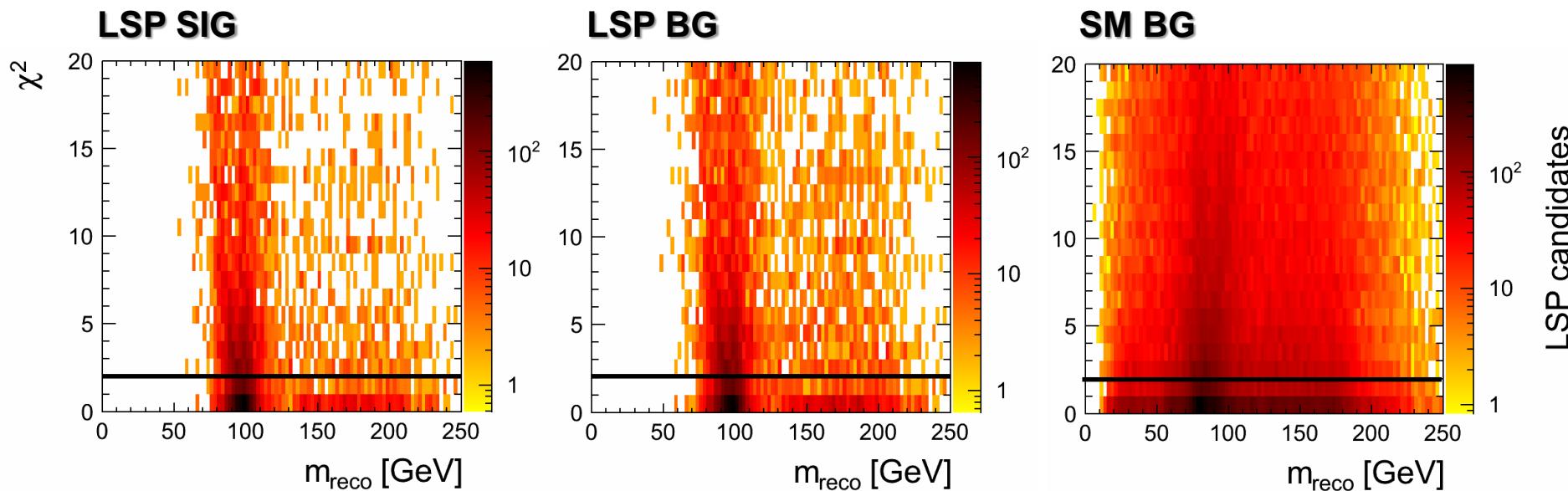
→ overall probability of selecting both signal muons correctly: 87%

Full event reconstruction ($\mu\tau$ channel)

combine into two equal mass objects



$$\chi^2_{\text{eqm}} = \frac{(m_{p1} - m_{p2})^2}{(5\text{GeV})^2}$$



$$\rightarrow \chi^2_{\text{eqm}} < 2$$

Full event reconstruction ($\mu\tau$ channel)

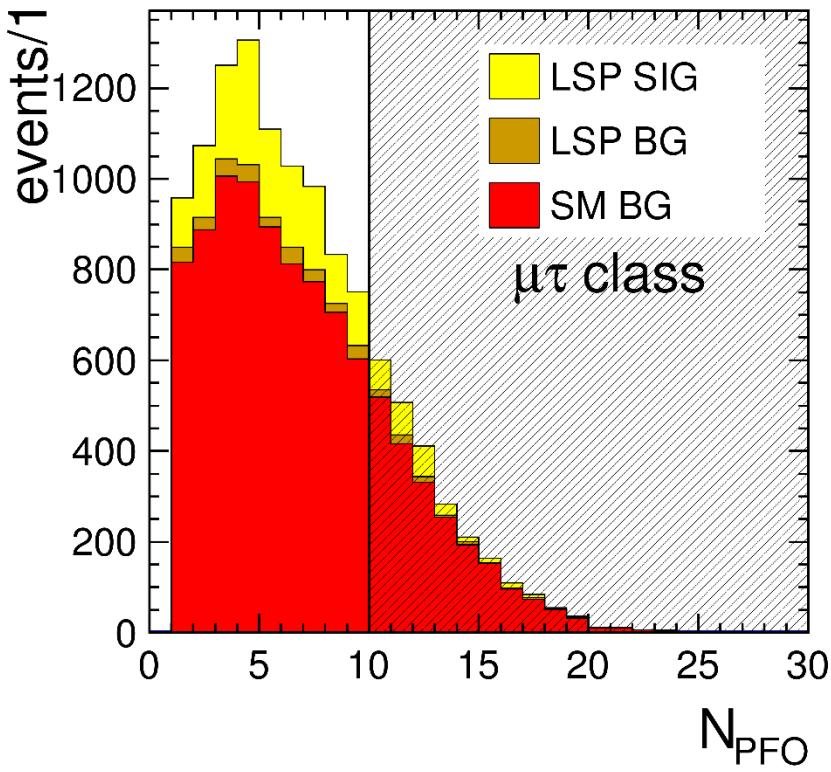
combine into two equal mass objects

$\mu + \tau$

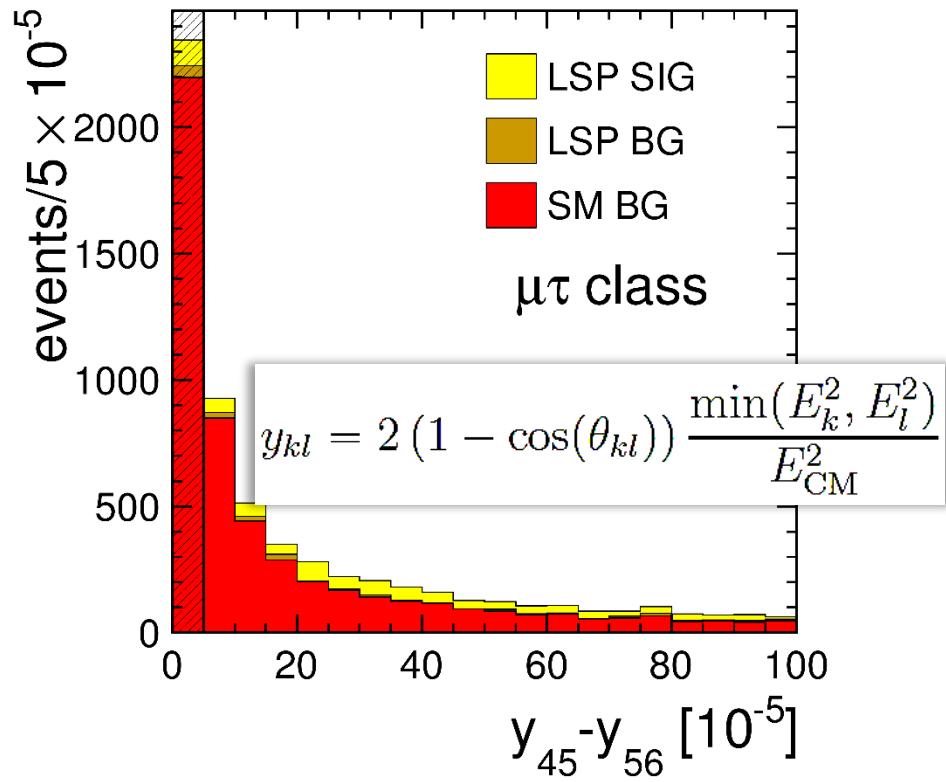
$$\chi^2_{\text{eqm}} = \frac{(m_{p1} - m_{p2})^2}{(5GeV)^2}$$

2 W

Number of PFOs in τ jet



Jet clustering parameter



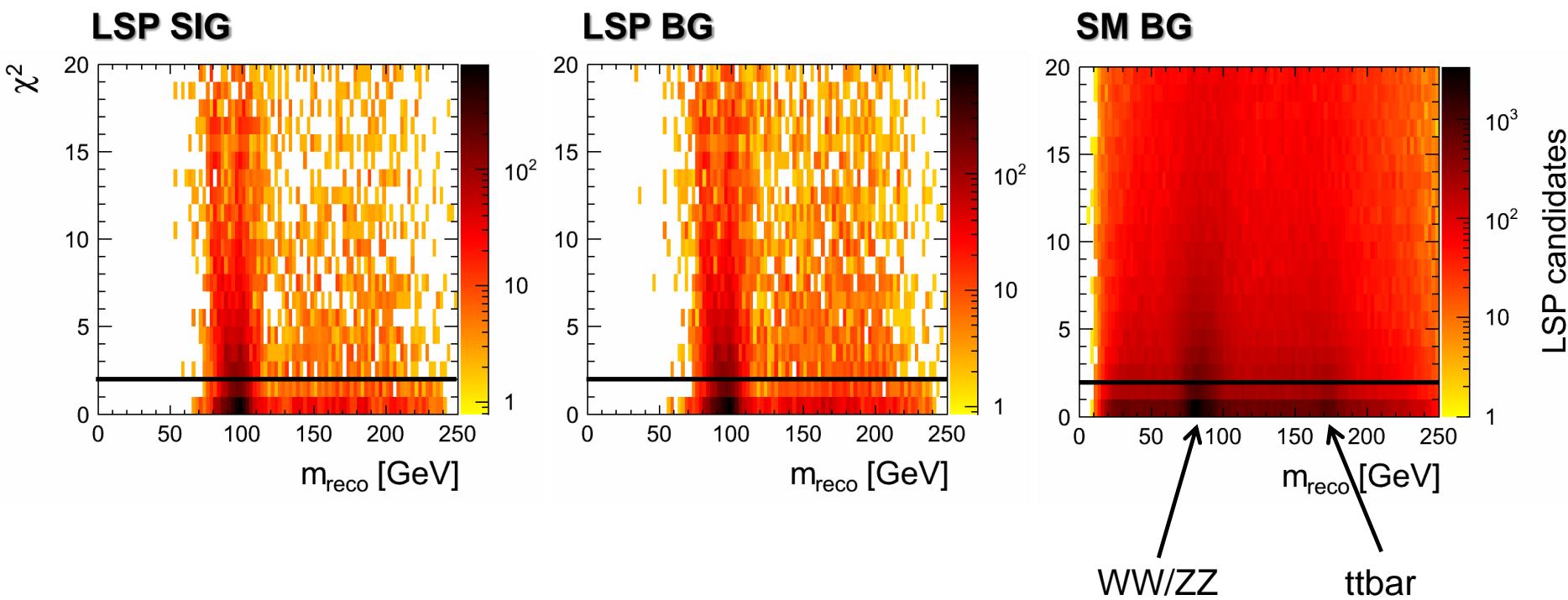
Full event reconstruction ($\tau\tau$ channel)

combine into two equal mass objects

2 T

$$\chi^2_{\text{eqm}} = \frac{(m_{p1} - m_{p2})^2}{(5\text{GeV})^2}$$

2 W



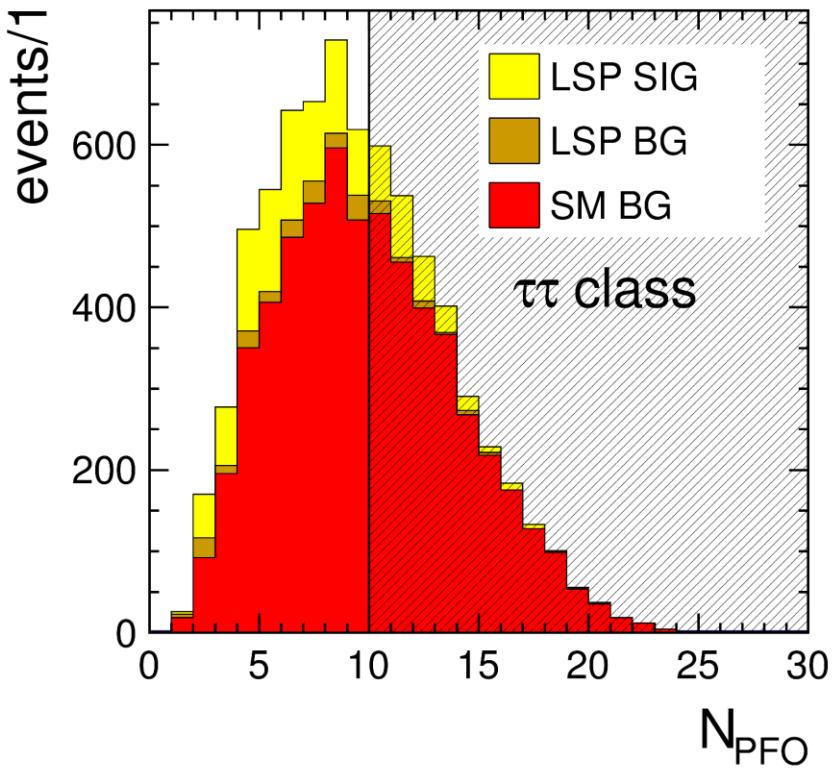
$$\rightarrow \chi^2_{\text{eqm}} < 2$$

Full event reconstruction ($\tau\tau$ channel)

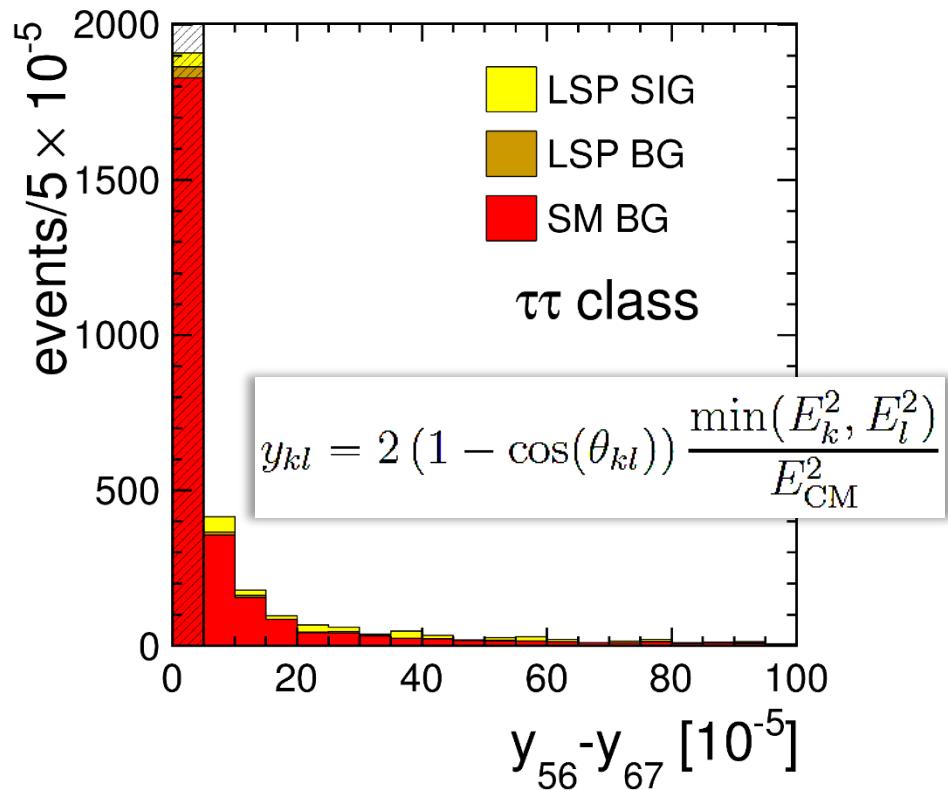
combine into two equal mass objects

$$2 \tau \rightarrow \chi^2_{\text{eqm}} = \frac{(m_{p1} - m_{p2})^2}{(5GeV)^2} \leftarrow 2 W$$

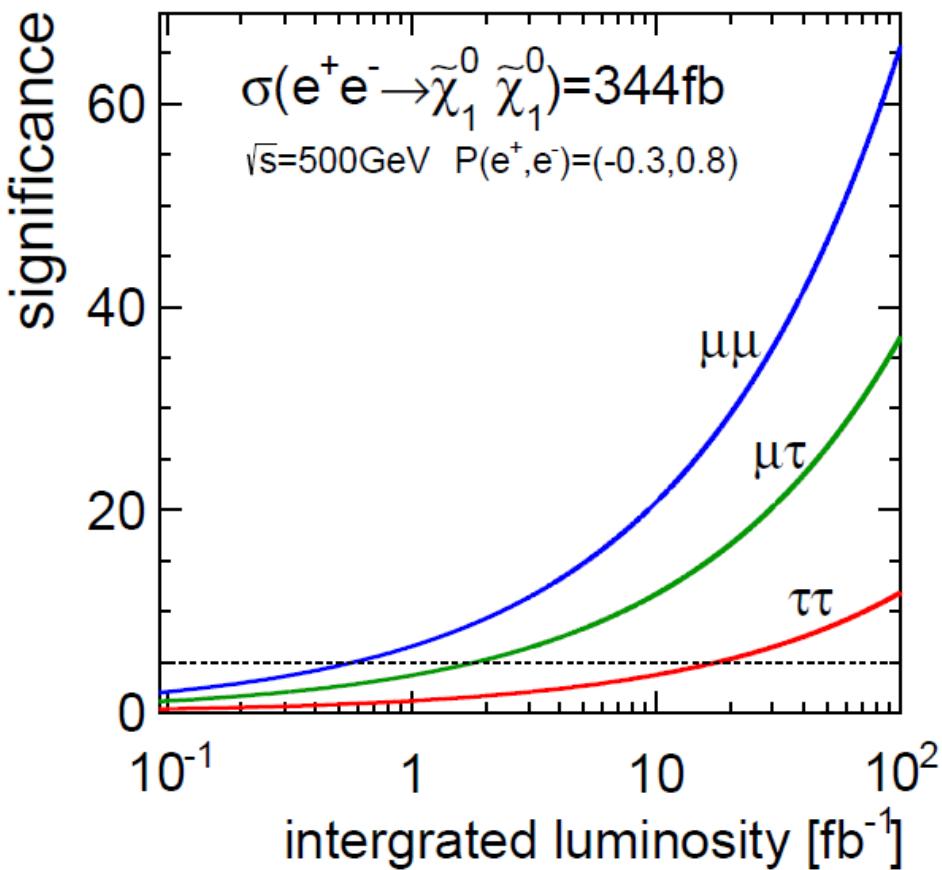
Number of PFOs in τ jet



Jet clustering parameter



Significance in Individual Channels



$$Q = \frac{P(n = N|S + B)}{P(n = N|B)} = \left(\frac{S}{B} + 1 \right)^N e^{-S}$$

$$m = \sqrt{2 \ln Q} = \sqrt{2N \ln \left(\frac{S}{B} + 1 \right) - 2S}$$

→ **5σ signal significance is reached from very early stage onwards in all channels**