Supersymmetry and Other Scenarios of Physics beyond the Standard Model at a Linear Collider

An Experimental Perspective

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Linear Collider School,
Frauenchiemsee, August 2014

Ad Te ergo nunc mihi sermo dirigitur,

Search for New Physics has key role in the scientific justification of future colliders (including LHC upgrades);

It has also a great deal of uncertainty in absence of signals at LHC, most of current arguments (and all those given here) are speculative and/or probabilistic;

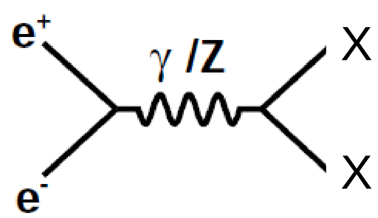
Here, the discussion will concentrate mostly on the techniques developed to reconstruct events from new physics processes and determine their properties;

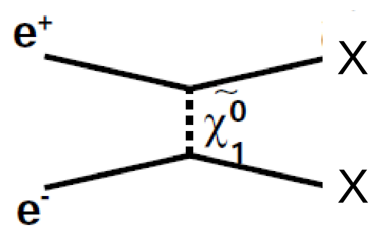
Plots, performance and results are taken from studies at LCs of different energies (from 0.3 to 3 TeV) and will not attempt to differentiate between different proposed designs in the following;

Signatures of Physics beyond the Standard Model at the LC

Main production process for new particles in e+e- collisions is pair production, in particular if NP has conserved quantum number (R-parity, KK-parity, …) to include DM candidate;

Production near threshold makes NP events more spherical than SM (ff, WW, ZZ) and escaping lightest new particle (if any) gives missing energy signature;





Pair production offers 2 x stat of particles with interesting reconstruction opportunities (tag one and look for second in unbiased way, correlations, …) but limits kinematic reach to $E_{cm}/2$;

Control of beam energy offers opportunity to perform threshold or resonance scans to determine mass & width, but also to choose energy to optimise S/B; profits of performant detector (Pflow, b-tagging, high granularity, excellent $\delta p/p$, ...);

Absence of trigger requirements ensures access to the “unexpected” (but only if existing and produced in collisions).

Supersymmetry

Possibly the best motivated model of BSM physics fully developed into a theory;

An opportunity to investigate the inter-connections between New Physics, the Higgs Sector and Cosmology;

More in general, a template of BSM scenarios with conserved quantum number and DM candidate;

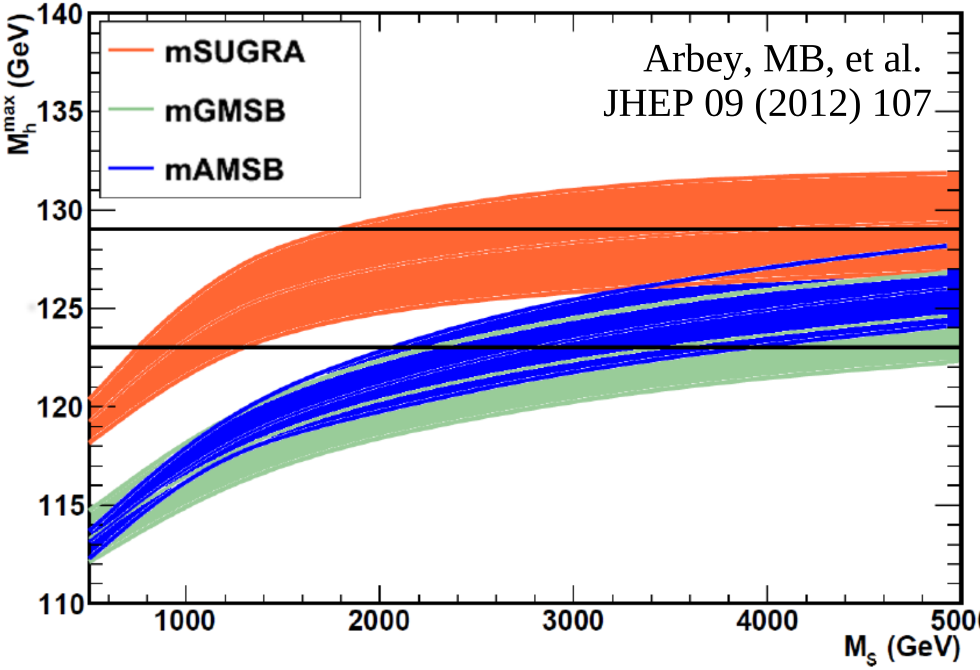
Highlights the potential complementarity between LHC and a LC.

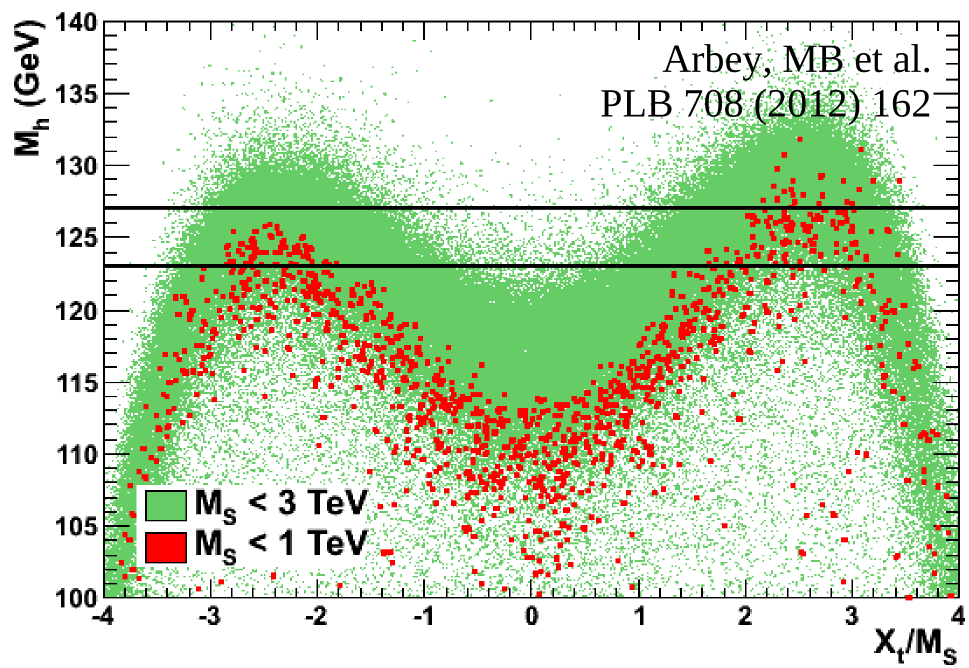
In primis, ...

Supersymmetry and the LC beams

Higgs Mass

Higgs mass of ~125 GeV requires relatively large M_{SUSY} value and stop trilinear coupling at or near maximal mixing scenario: $X_t = \sqrt{6} M_S$

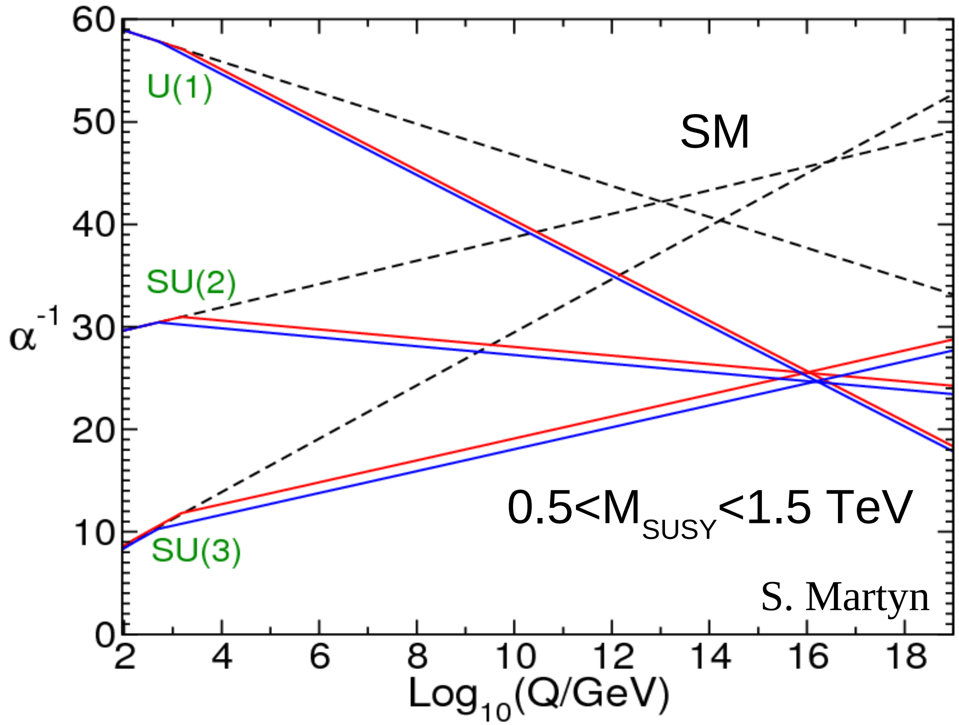




Gauge coupling unification

Low-energy SUSY at the TeV scale leads the running couplings for SU(3), SU(2) and U(1) to precisely meet at unification point (Amaldi et al PLB 260 (1991));

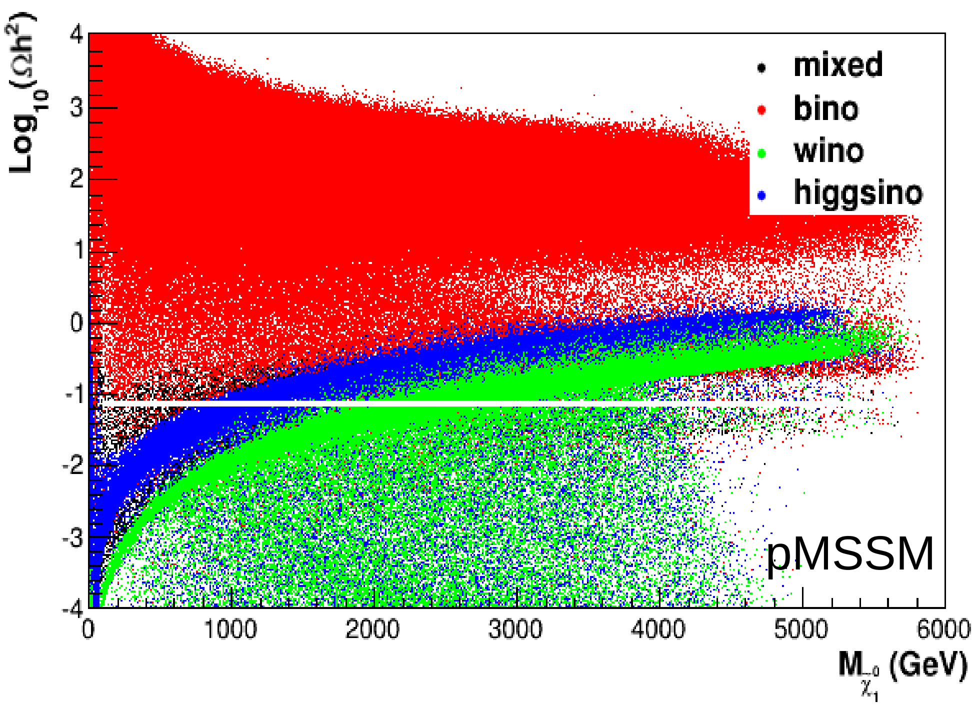
Condition fulfilled for broad range of M_{SUSY} values:



DM Relic Density

Low-energy SUSY with conserved R-parity leads to dark matter candidate (lightest neutralino χ^0_1= WIMP) with correct relic density for 100 GeV < M < few TeV (depending on neutralino nature) (WIMP miracle);

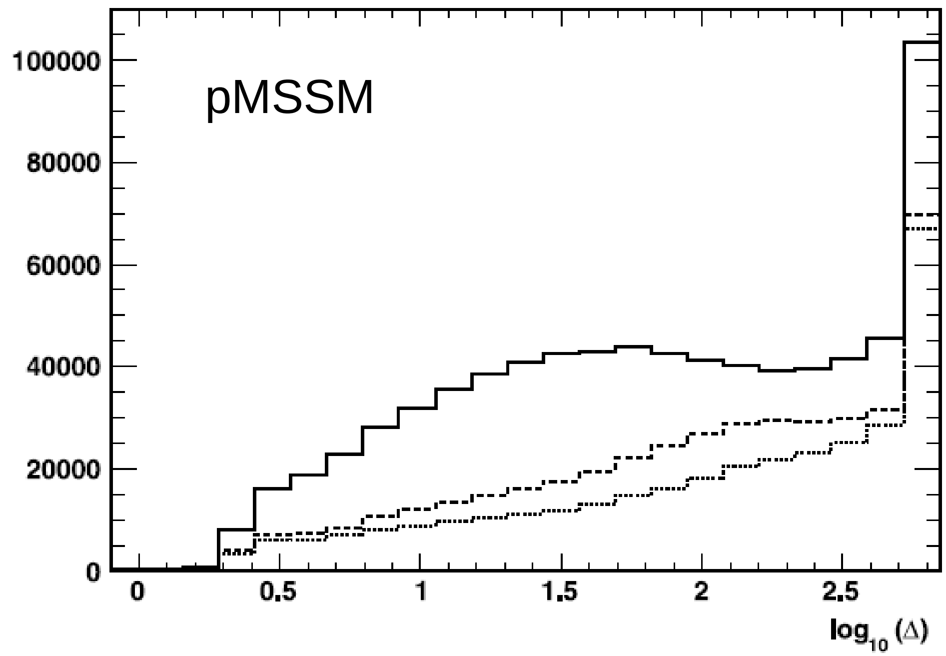
However neutralino LSP as heavy as 1-3 TeV "naturally" gives PLANCK relic density:



Fine Tuning and Naturalness

$$M_Z^2 = -M_{H_u}^2\left(1 - \frac{1}{\cos 2\beta}\right) - M_{H_d}^2\left(1 + \frac{1}{\cos 2\beta}\right) - 2|\mu|^2 \qquad \sin 2\beta = \frac{2b}{M_{H_u}^2 + M_{H_d}^2 + 2|\mu|^2}$$

$$\Delta = \left[\delta(\mu)^2 + \delta(b)^2 + \delta(M_{H_u}^2)^2 + \delta(M_{H_d}^2)^2\right]^{1/2}$$

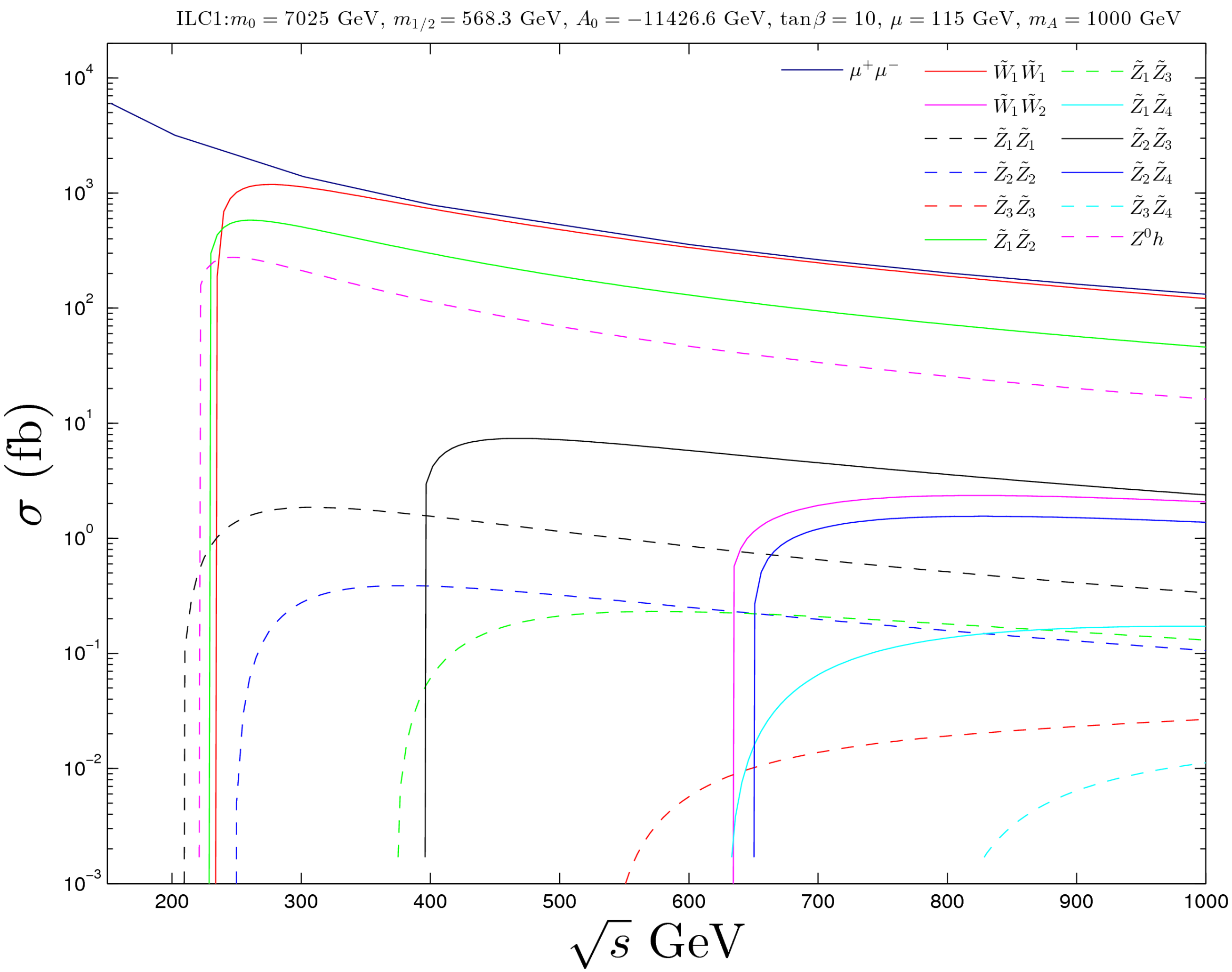


Small μ scenario

$\Delta_{EW} \sim \mu^2 / (M_Z^2/2)$

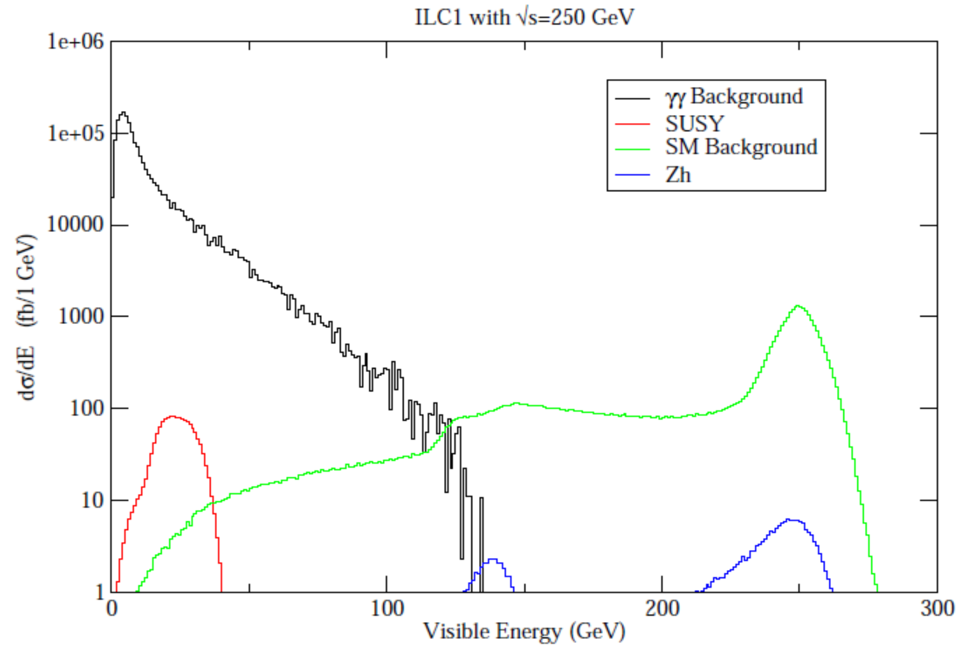
If the condition Δ_{EW} < 10-30 is imposed
→ 100 < |μ| < 300 GeV

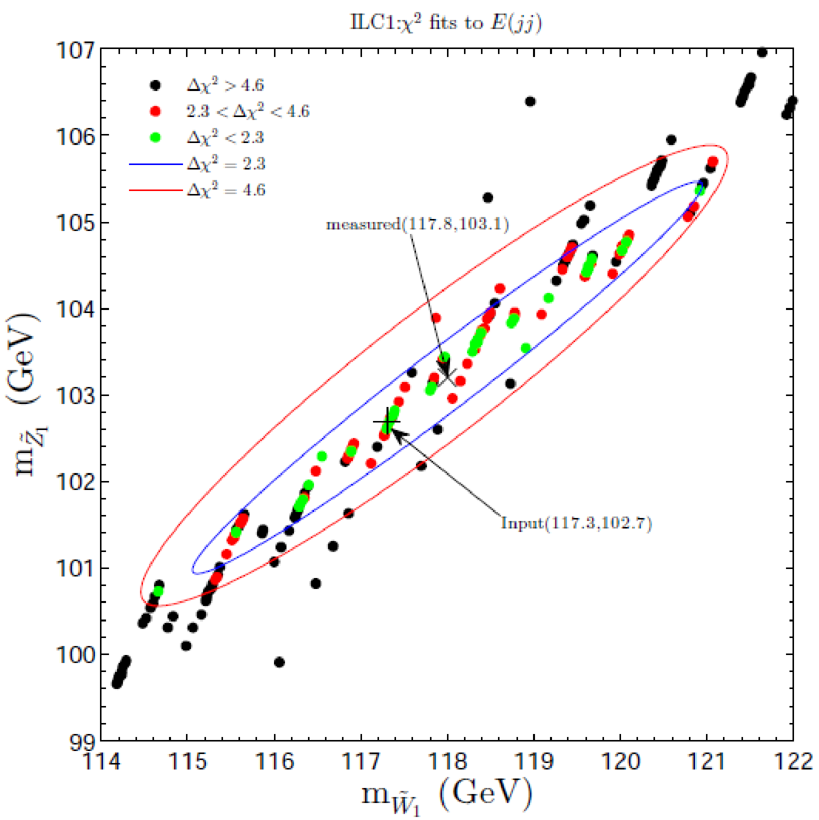
This can be fulfilled (among others) by NUHM2 models with light Higgsinos and stop + gluino in the few TeV mass range, providing the ILC with an abundant spectroscopy to study:

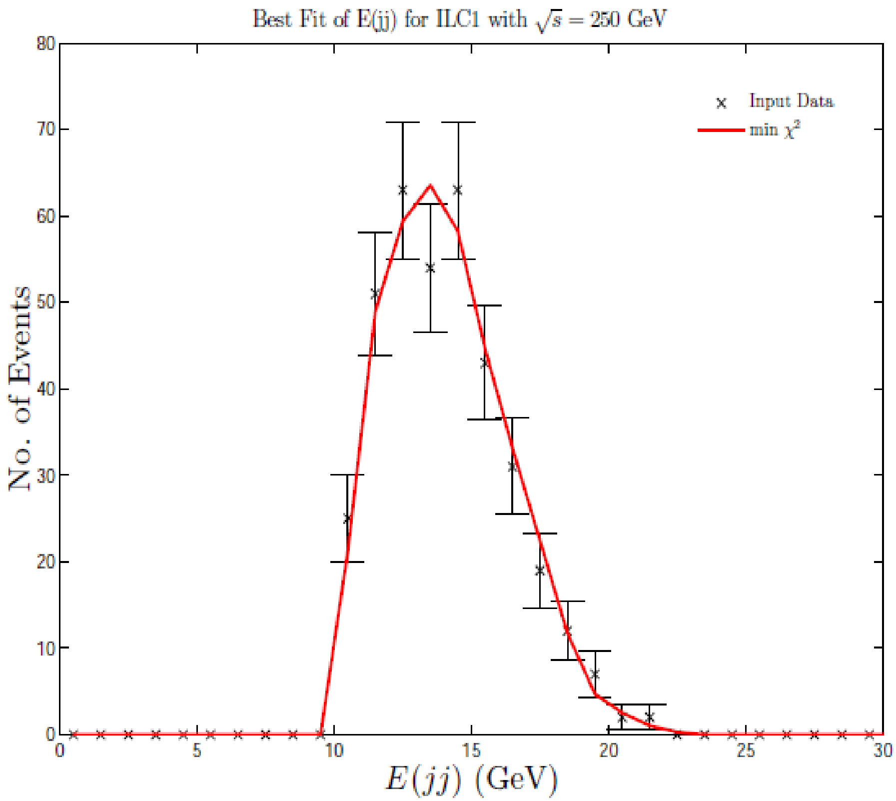


Baer et al., arXiv:1404.7510

Small μ scenario

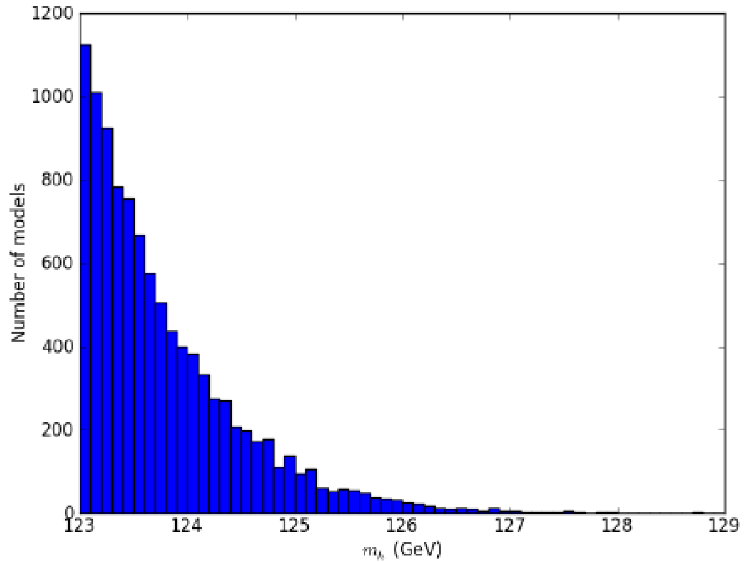




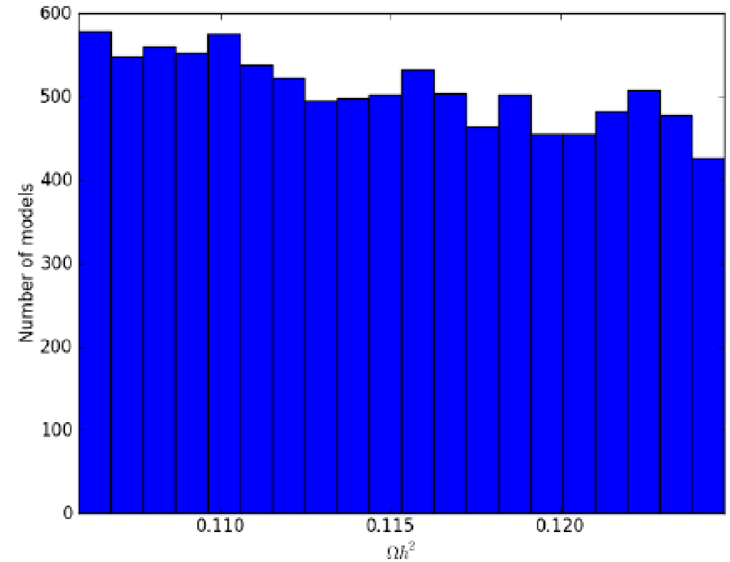


Baer et al., arXiv:1404.7510

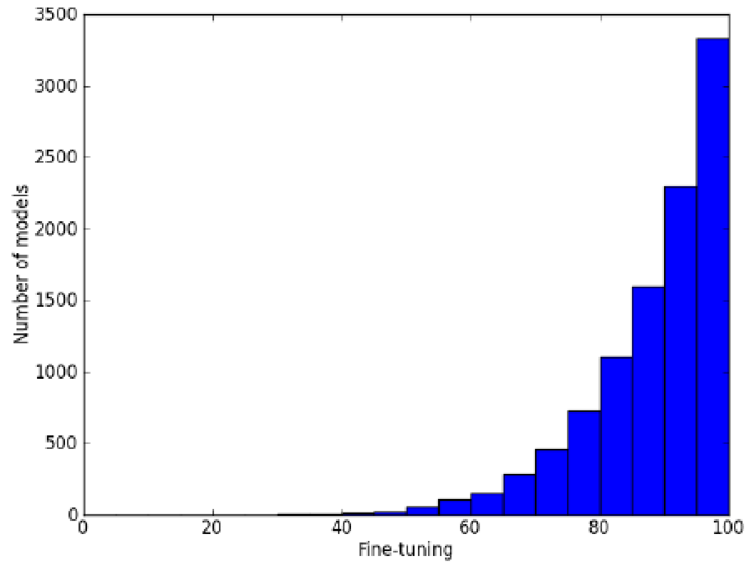
Fine Tuning and Naturalness in MSSM



M_h (GeV)

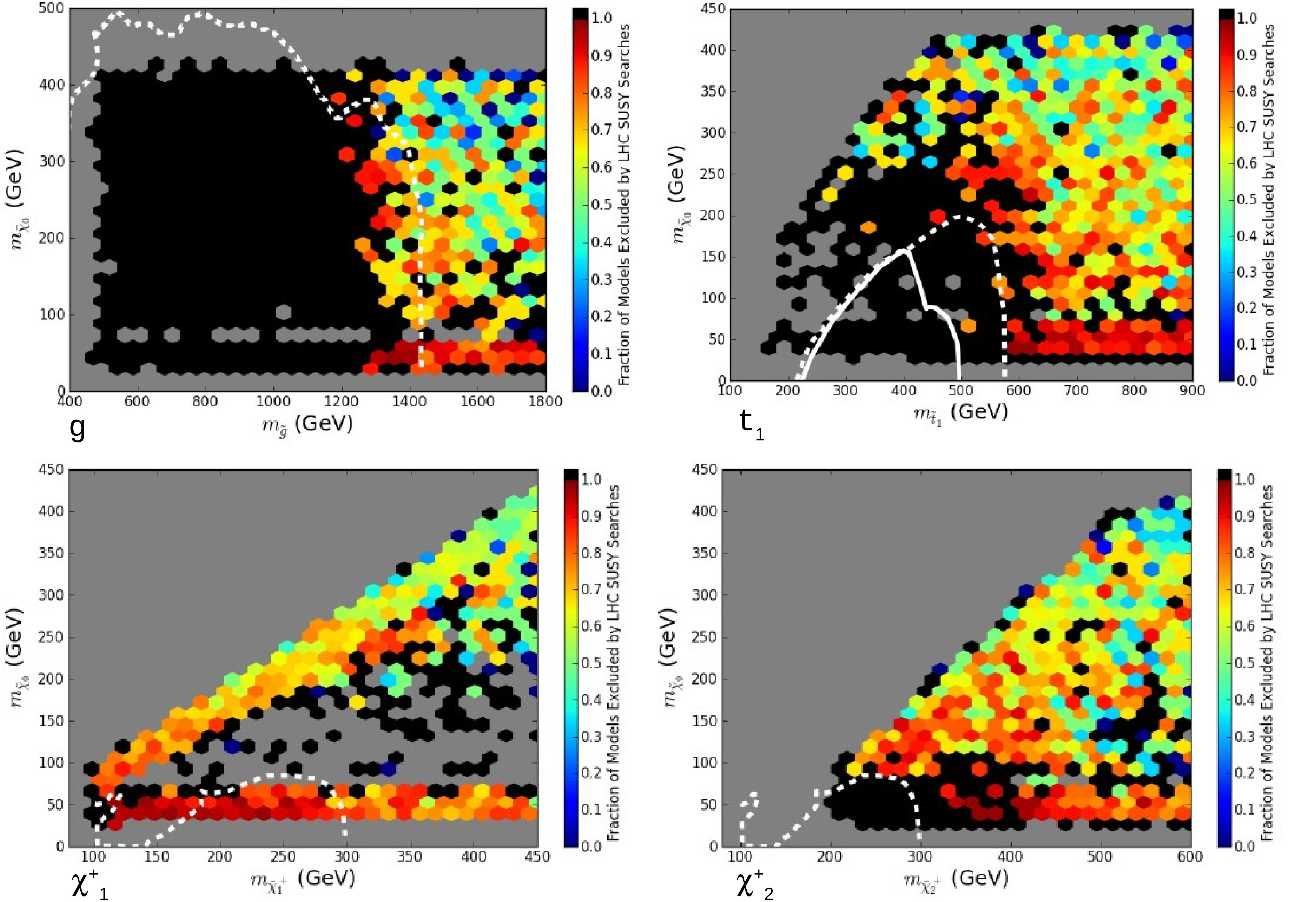


Ωh^2



Δ Fine Tuning

Cahill-Rowley et al, arXiv:1407.4130

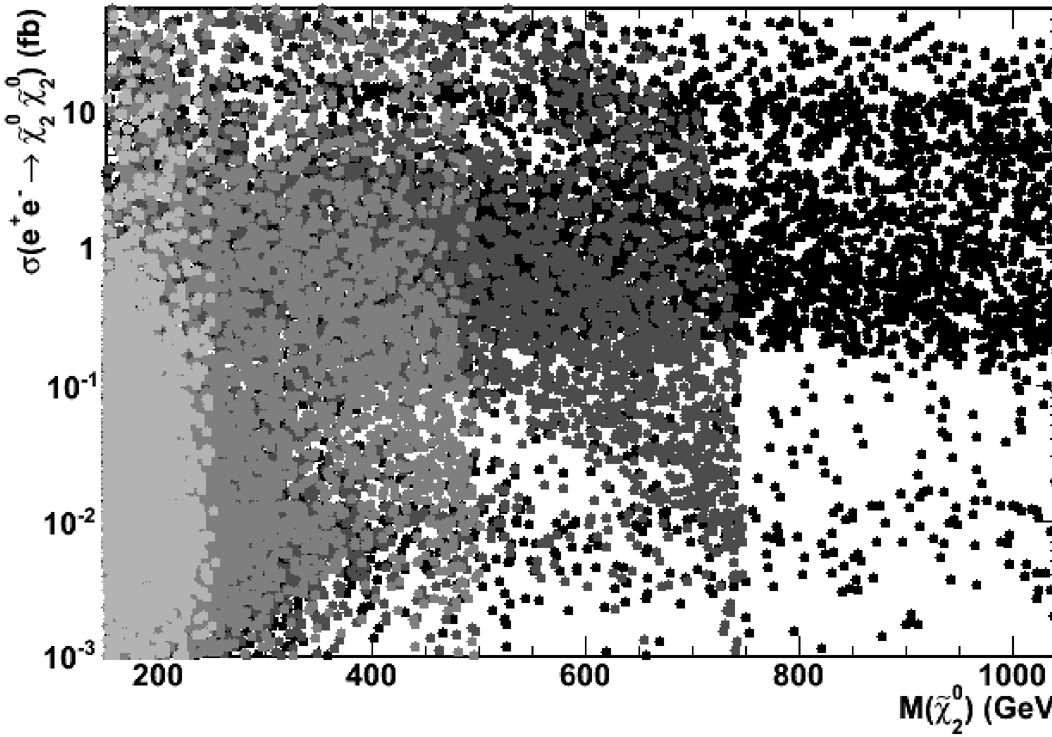


Cahill-Rowley et al, arXiv:1407.4130

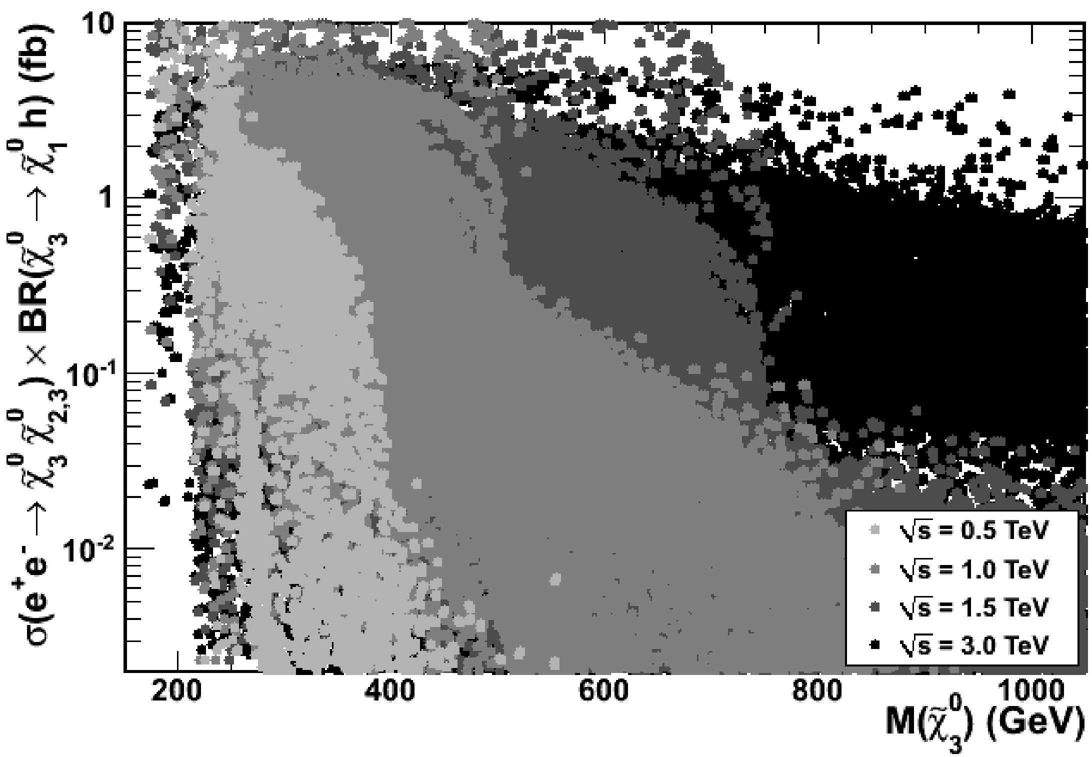
Cross sections at LC

Neutralino pair production cross sections at LC vs Ecm for points not excluded by flavour, lower energy and LHC data from flat pMSSM scan:

Values range from 0.1 (or less) up ~50 fb



$\chi^0_2\chi^0_2$

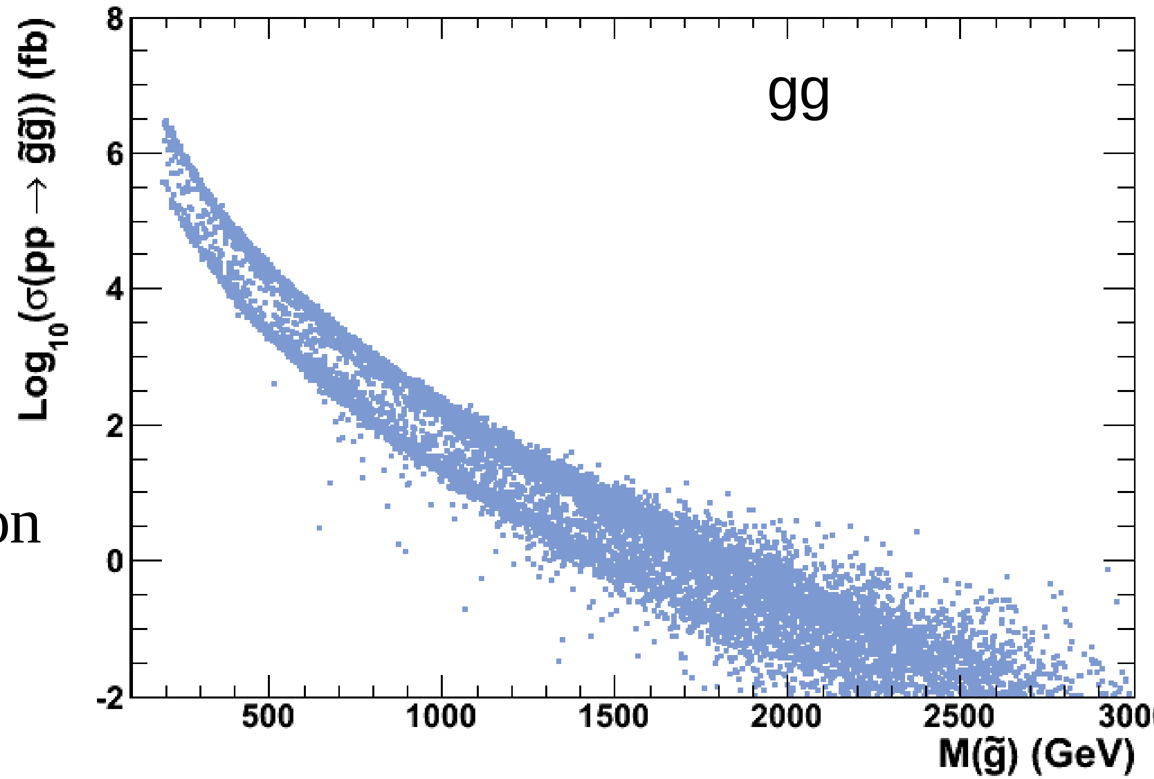


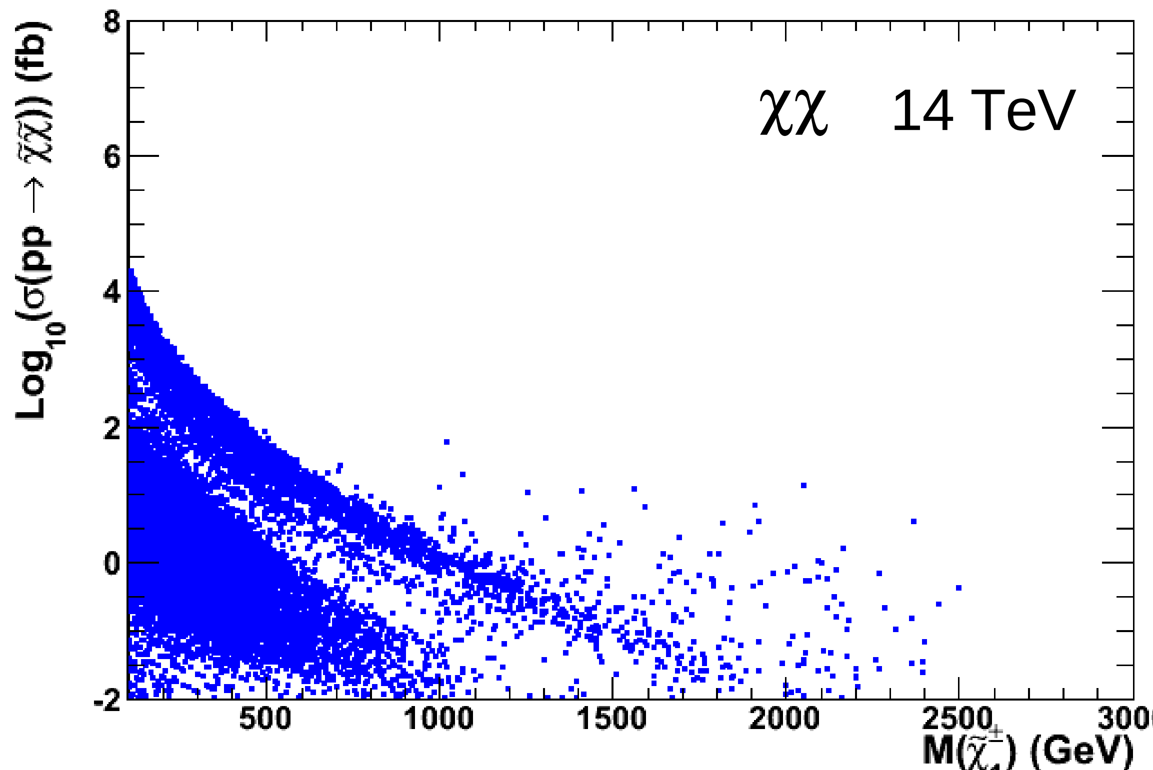
$\chi^0_2\chi^0_3$

Cross sections at LHC

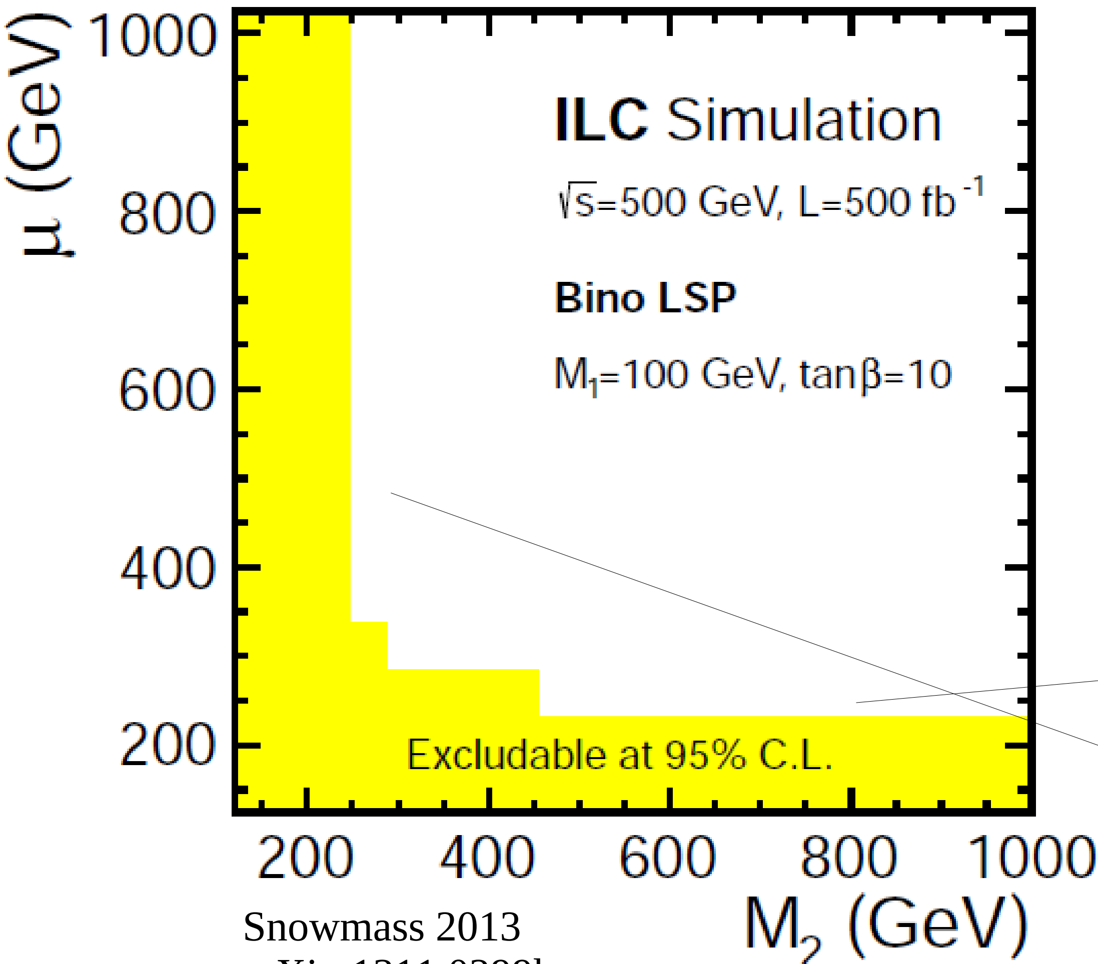
Inclusive (visible) χχ cross section compared to that for gg for the same pMSSM scan;

LHC trigger requires typically $\chi^-_1 \rightarrow W\,\chi^0_1 \rightarrow l\,\nu\,\chi^0_1$ with high pt lepton;

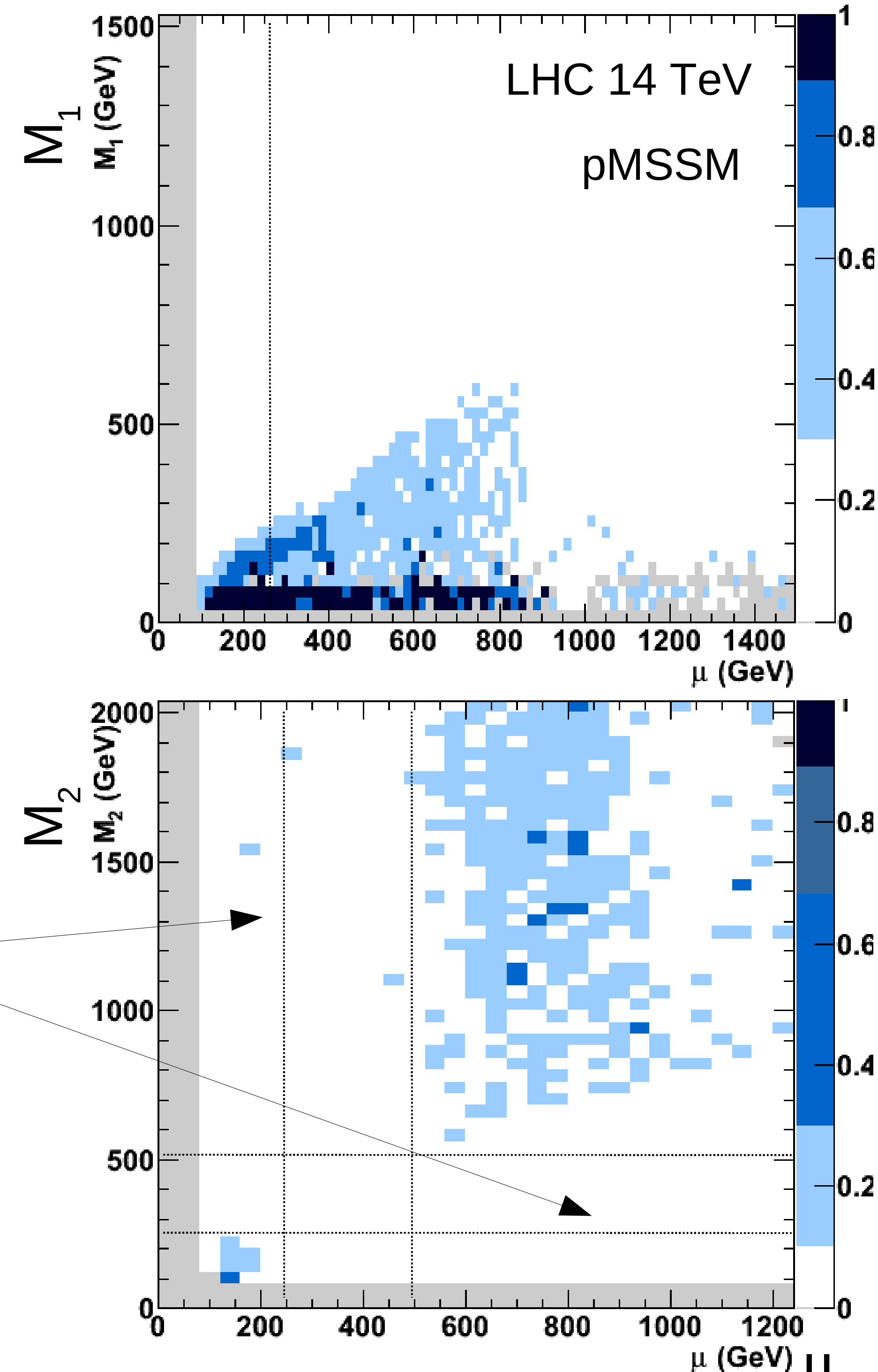




EWK-inos at LC and LHC



Snowmass 2013
arXiv:1311.0299h



Arbey, MB, Mahmoudi, (2014)

Deinde, ...

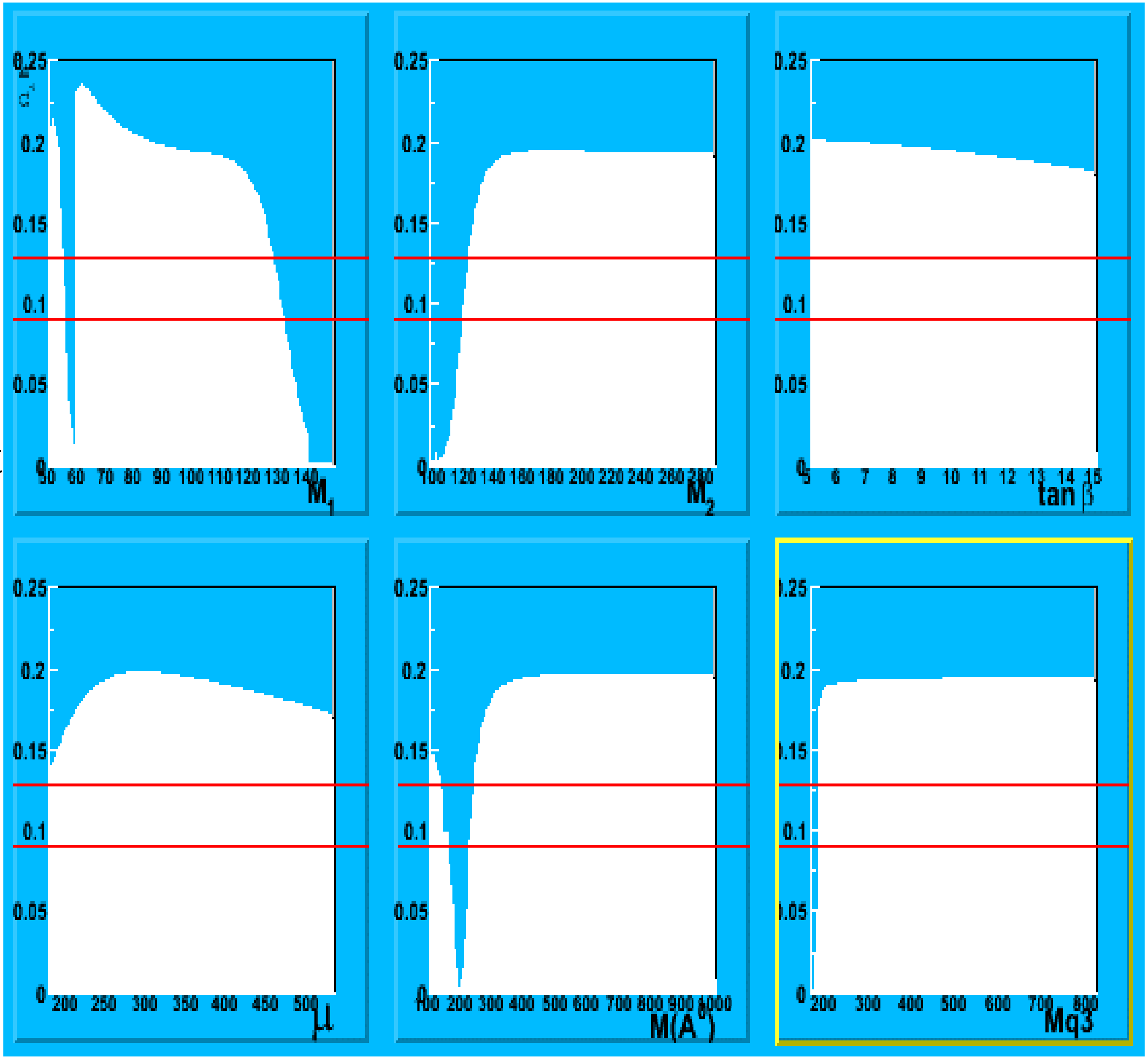
Mass Measurements at a LC

Why are SUSY masses so important ?

Reconstruct fundamental SUSY parameters;

Quantitatively test agreement of calculated neutralino relic density and scattering cross section to CMB and DM direct searches →

Test SUSY effects in flavour and Higgs physics with high accuracy.



Mass Measurements at a LC: Kinematical Endpoints

$$\mathrm{E}_{\mathrm{BH,BL}} = \gamma \left(E_B^* \pm \beta E_B^* \right)$$

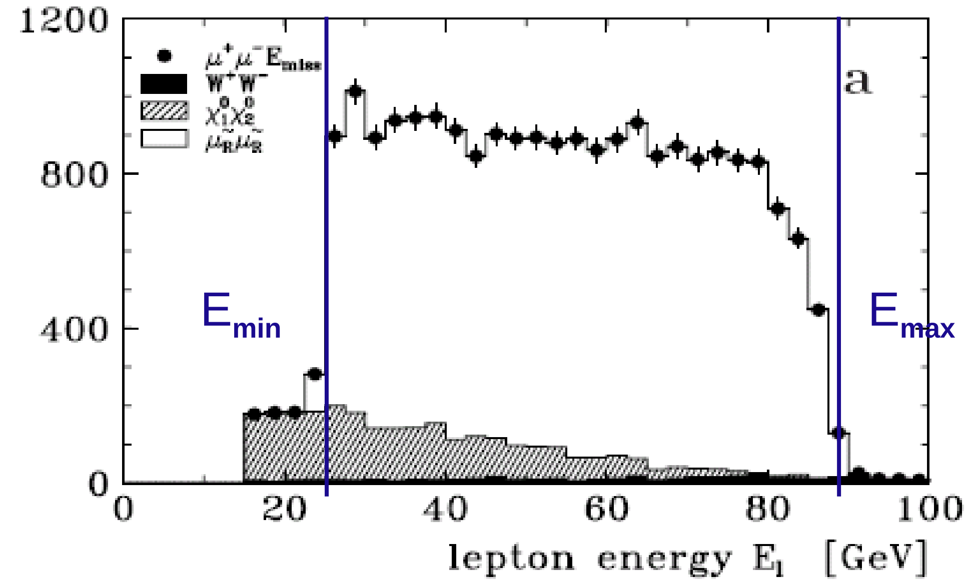
$$\tilde{A} \to B\tilde{C} \qquad E_B^* = \frac{M_A^2 + M_B^2 - M_C^2}{2M_A}$$

$$\gamma = \frac{\sqrt{s}}{2M_A} \qquad \beta = \sqrt{\frac{1 - 4M_A^2}{s}}$$

$$\tilde{A}' \to \tilde{A}B' \to B\tilde{C} \qquad \sqrt{s} - E_{B'H} < E_A < \sqrt{s} - E_{B'L}$$

Kinematical Endpoints with Muons

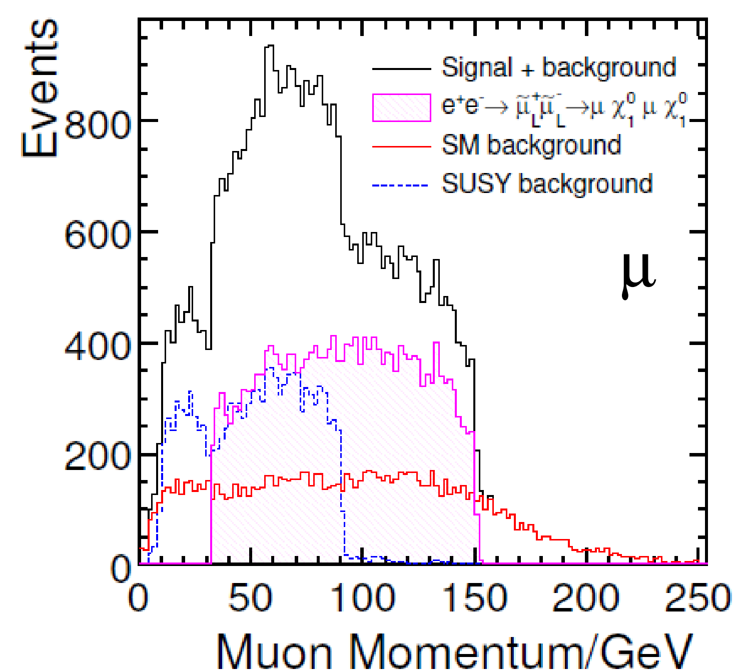
$$\tilde{\mu}_L \tilde{\mu}_L \rightarrow \mu\mu\tilde{\chi}_1^0\tilde{\chi}_1^0$$

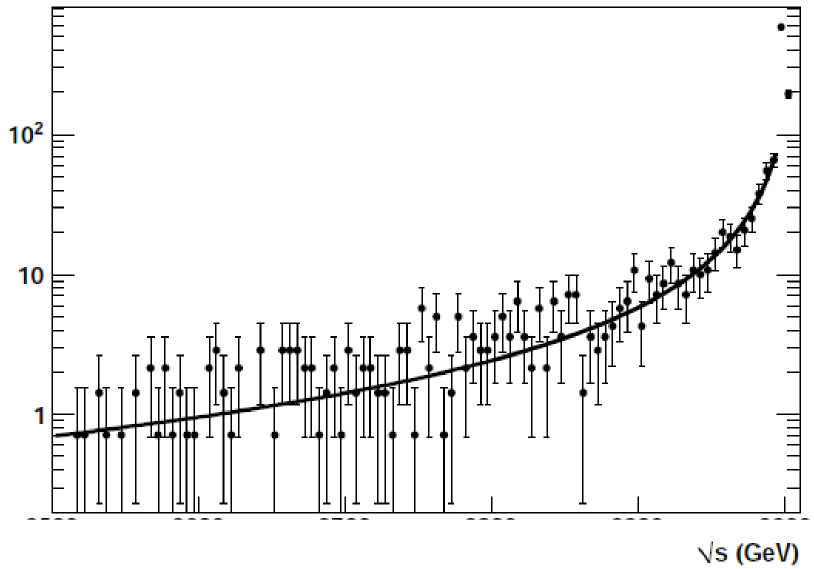


$$\tilde{\mu}_L \tilde{\mu}_L \rightarrow \mu\mu\tilde{\chi}_1^0\tilde{\chi}_1^0$$

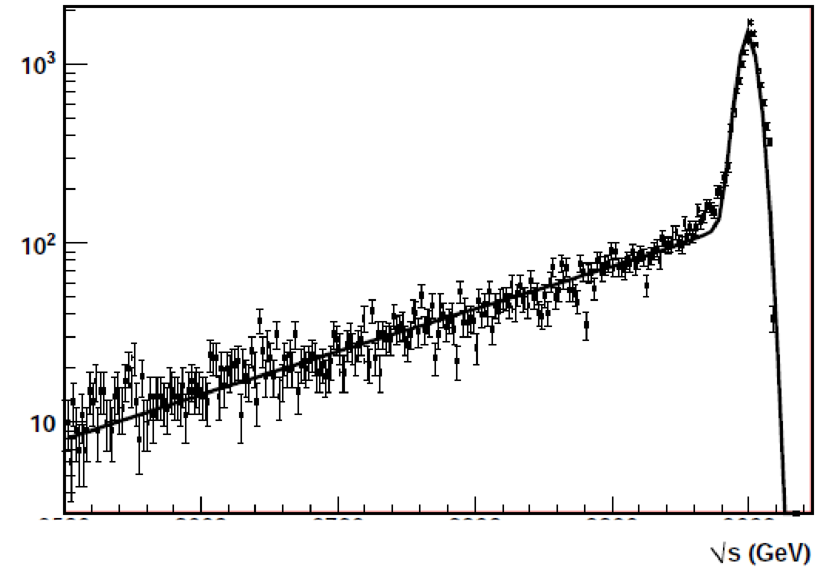
+

$$\tilde{\chi}_2^0\tilde{\chi}_1^0 \rightarrow \mu\mu\tilde{\chi}_1^0\tilde{\chi}_1^0$$



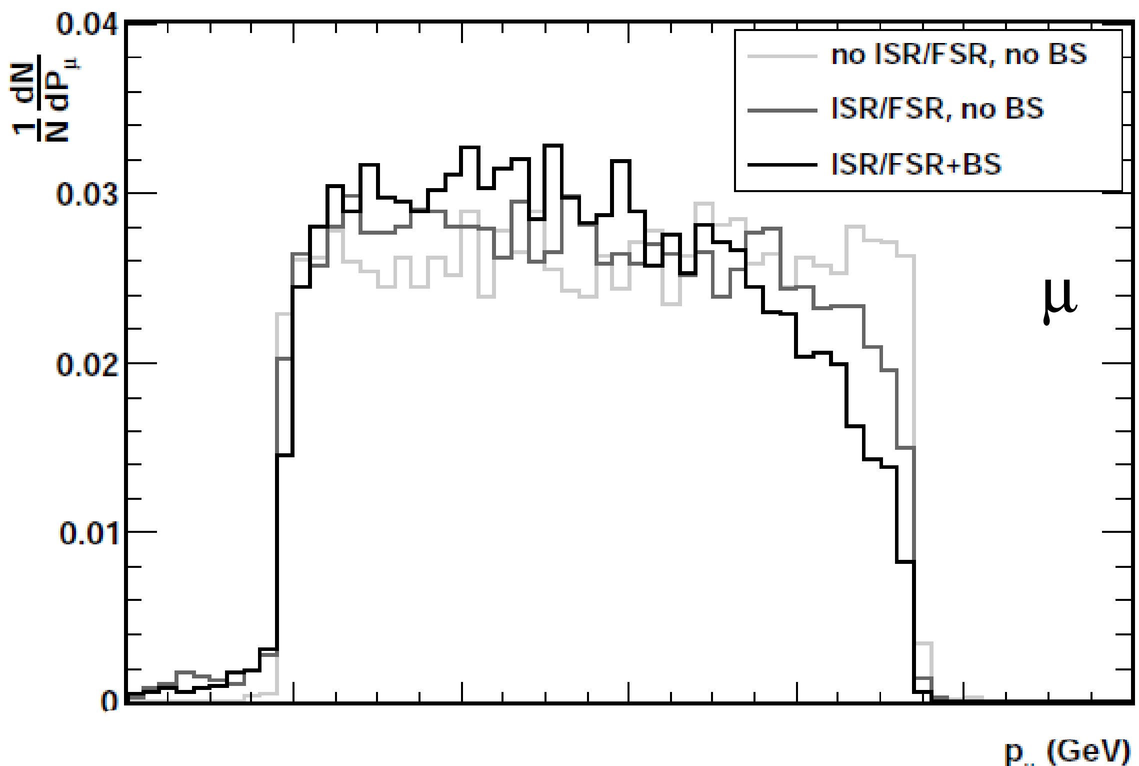


(a) ISR



(b) Beamstrahlung

$$\tilde{\mu}_L \tilde{\mu}_L \;\rightarrow\; \mu\mu\tilde{\chi}_1^0\tilde{\chi}_1^0$$

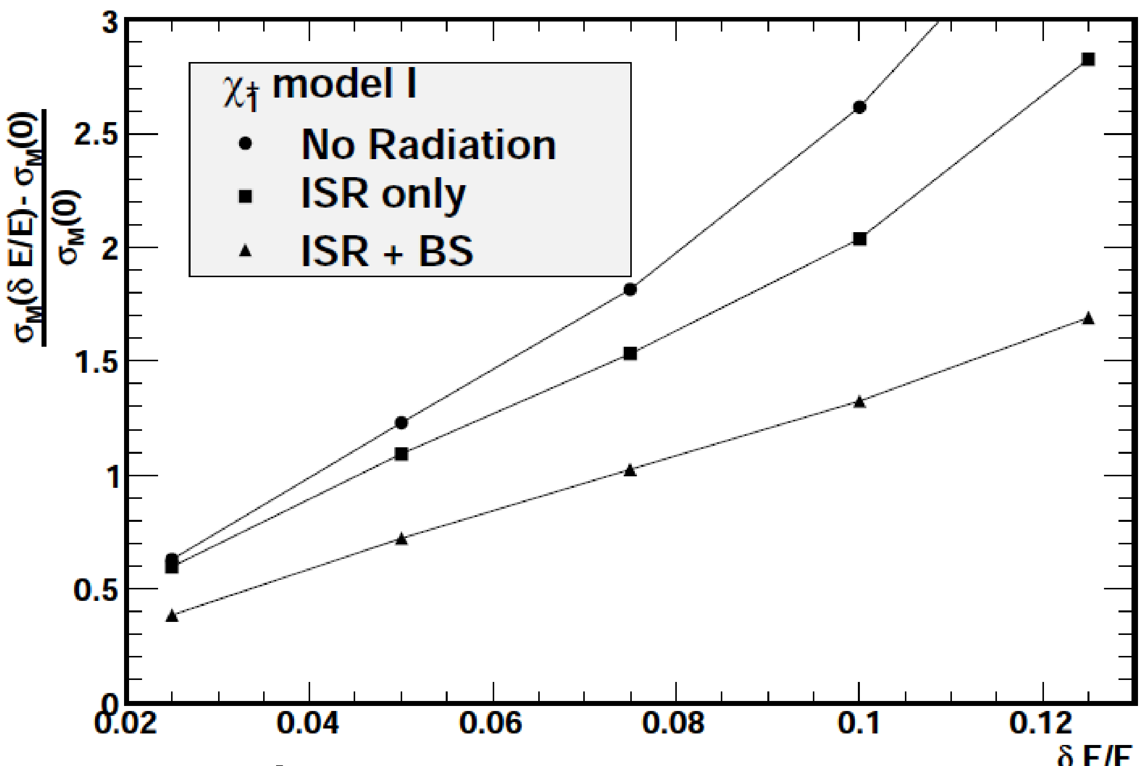


Accuracy typically limited by ISR+beamstrahlung, not δp/p (for LC det values).

Muons

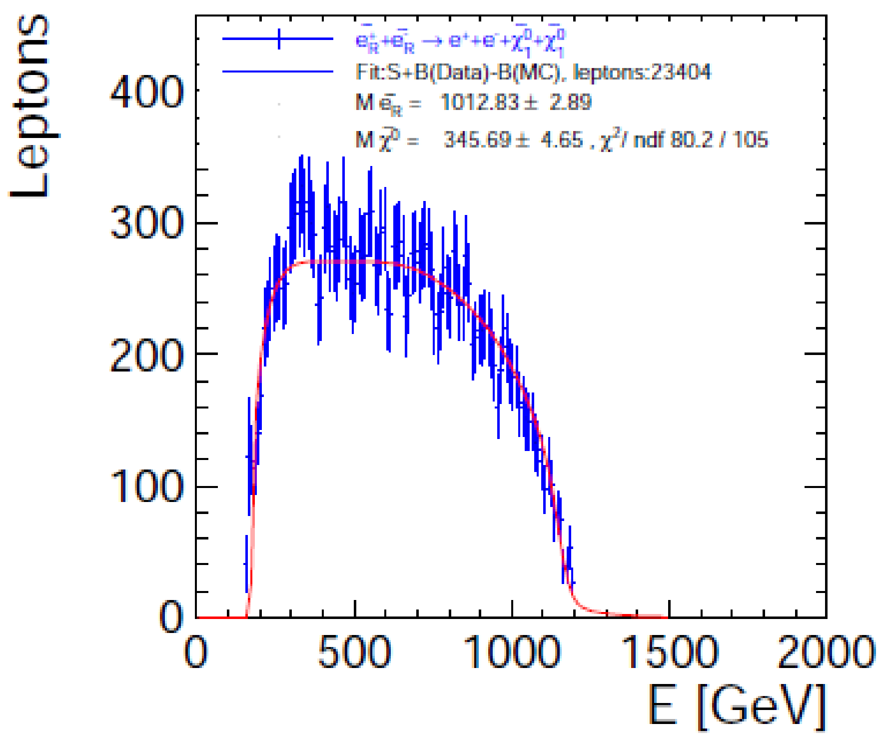
$\delta p_t/p_t^2$ ($\times 10^{-5}$ GeV^{-1})	$\sqrt{s}>$ (GeV)	Data Set	Pol (e^-/e^+)	BX	($M\pm\sigma_M$) (GeV) $\tilde{\mu}_R^\pm$	$\tilde{\chi}_1^0$
2.	2500	S	0/ 0	0	1104.6± 2.9	560.0 ± 1.7
2.	2500	S (G4+Reco)	0/ 0	0	1107.1± 2.8	560.1 ± 1.5
4.	2500	S	0/ 0	0	1102.8± 2.9	557.2 ± 2.8
6.	2500	S	0/ 0	0	1098.8± 3.1	559.1 ± 3.6
8.	2500	S	0/ 0	0	1101.0± 3.4	564.2 ± 4.0
20.	2500	S	0/ 0	0	1107.5± 4.2	575.7 ± 5.3

Bosons → jj

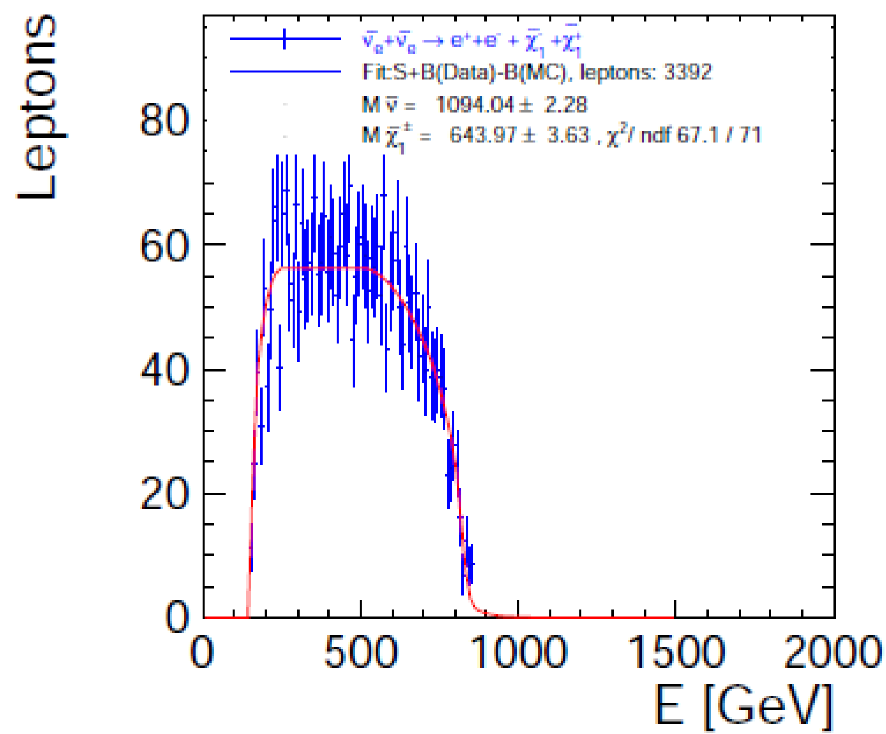


MB, N Alster, arXiv:1104.0523

Kinematical Endpoints with Electrons



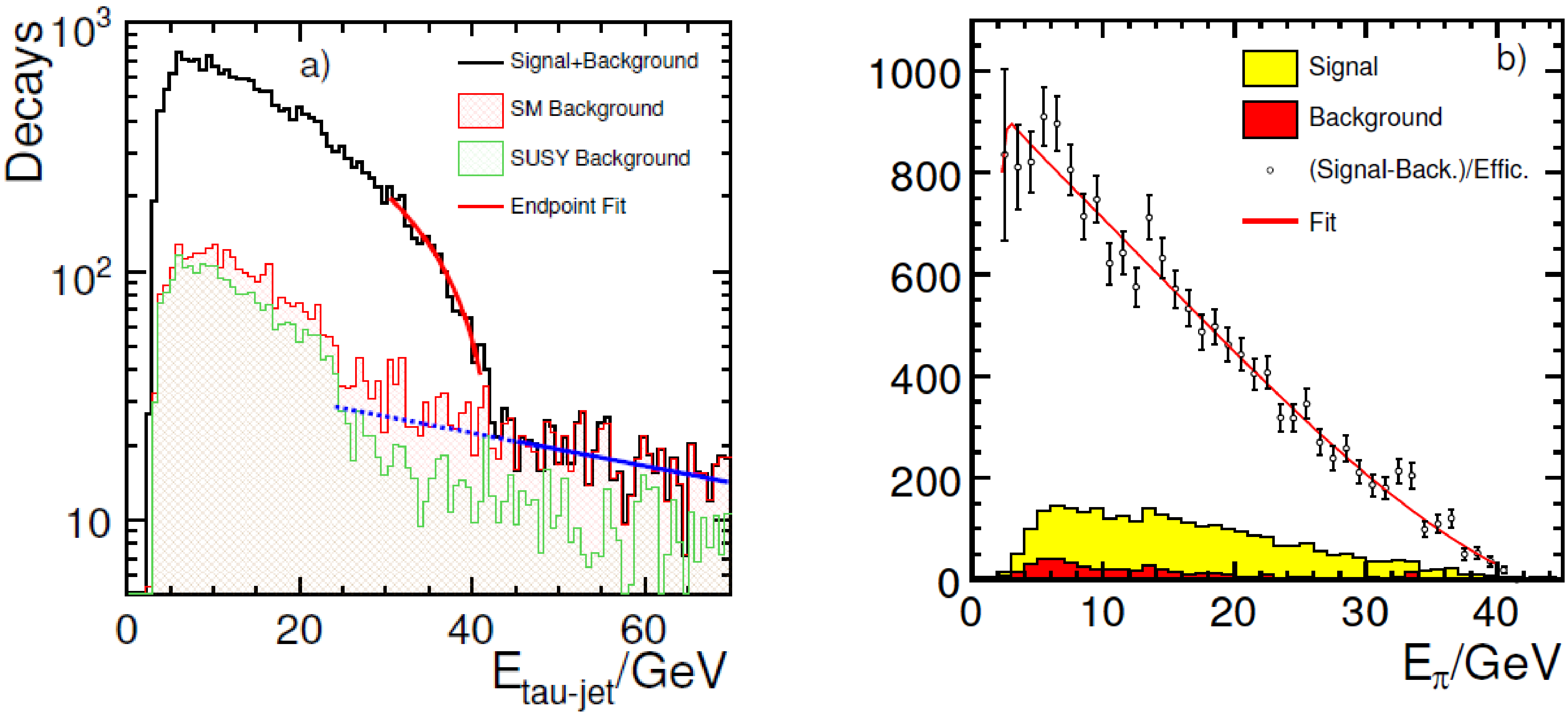
(a) $e^+e^- \to \tilde{e}_R^+\tilde{e}_R^- \; \sqrt{s} = 3$ TeV



(b) $e^+e^- \to \tilde{\nu}_e\tilde{\nu}_e \; \sqrt{s} = 3$ TeV

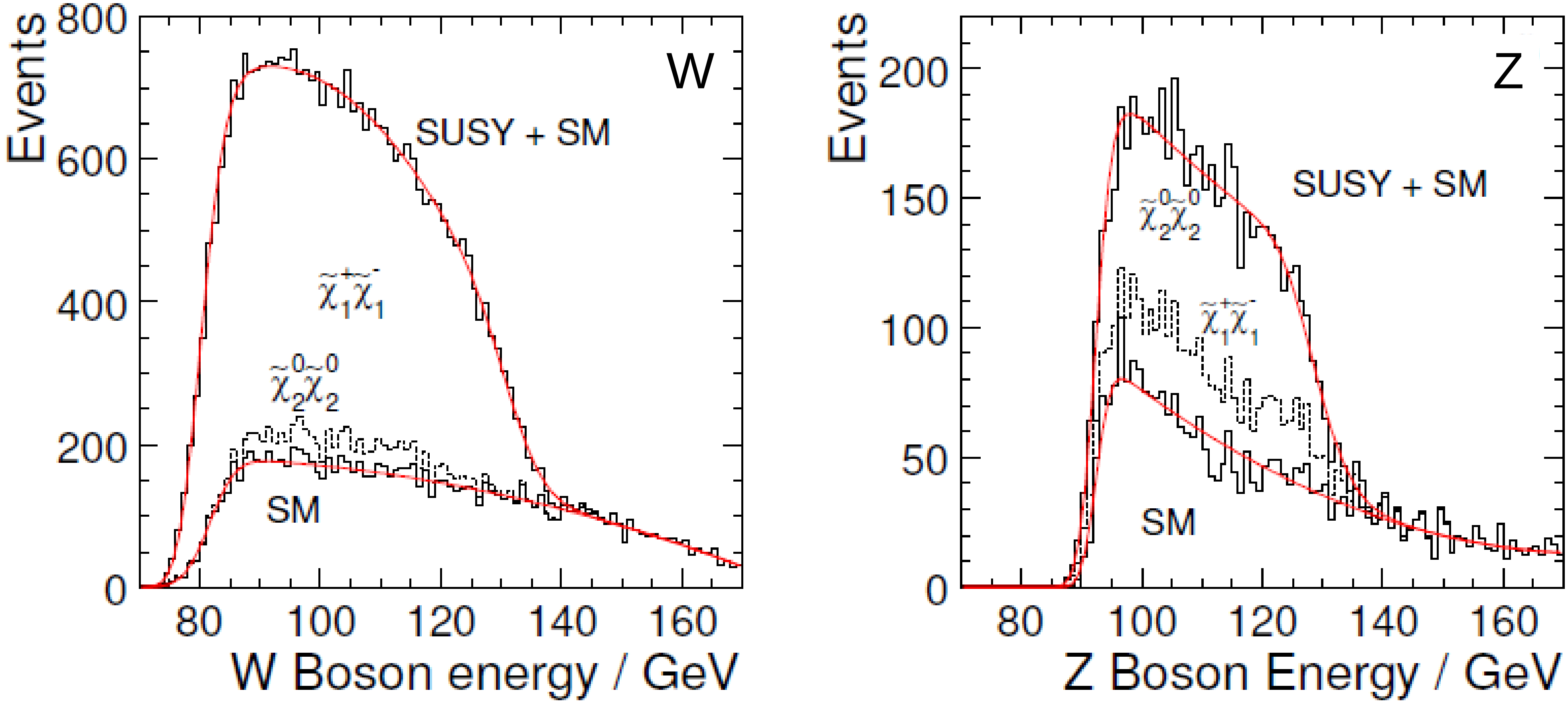
M.B. et al.,
JHEP 1309 (2013) 001

Kinematical Endpoints with Taus



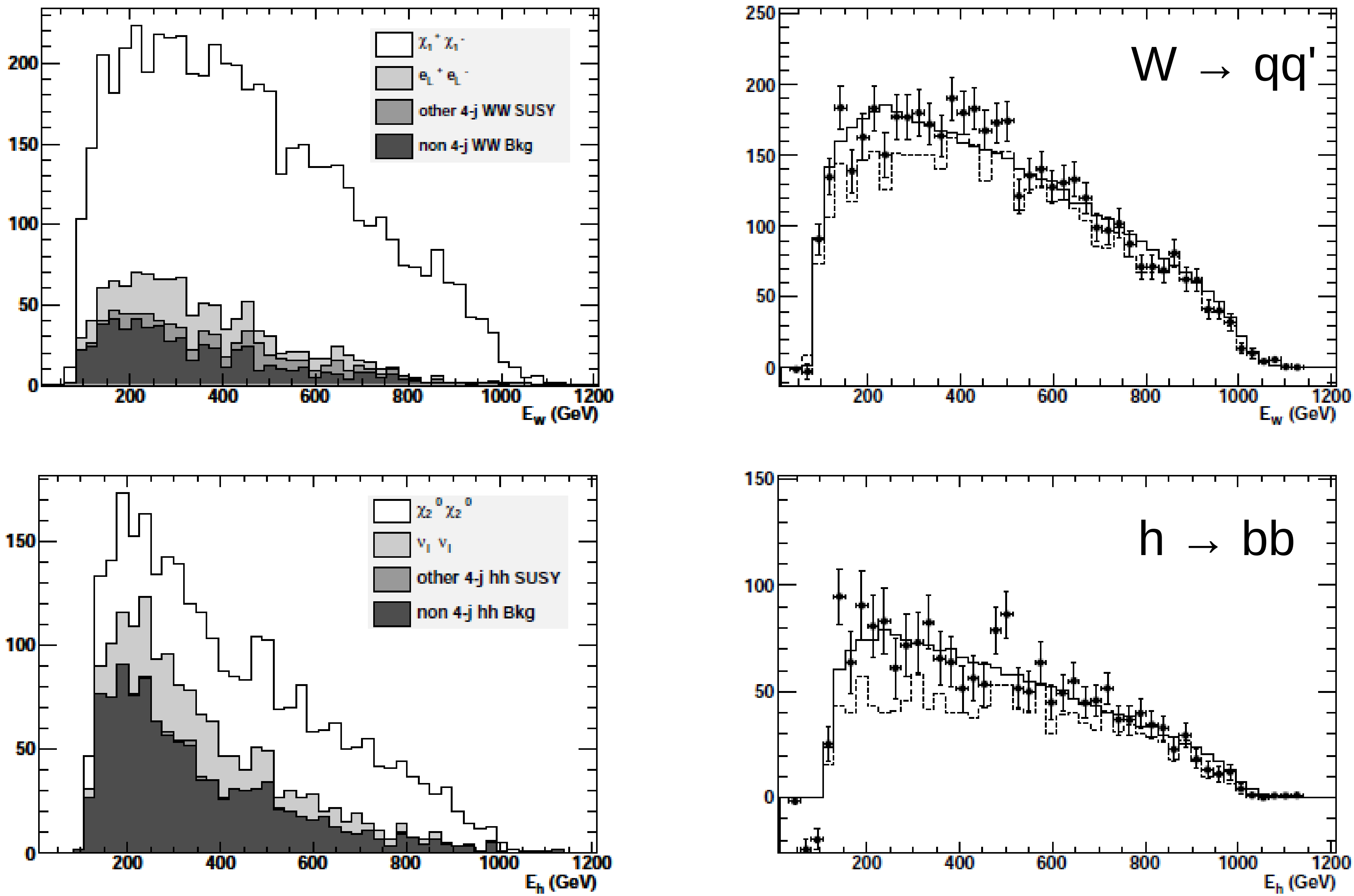
ILD LOI (2010)

Kinematical Endpoints
with W/Z/h → jj



ILD LOI (2010)

Kinematical Endpoints with W/Z/h → jj

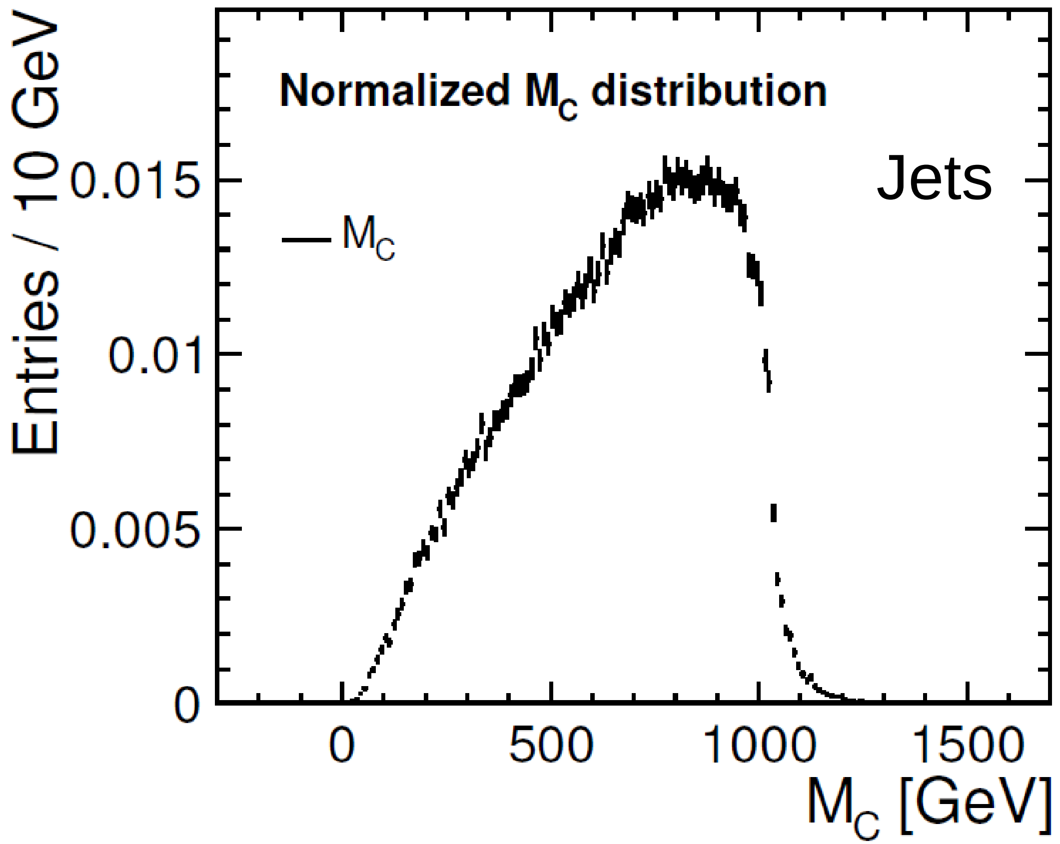


MB, N Alster, arXiv:1104.0523

Upper kinematical endpoint

If cm energy spread large and/or lower kinematic edge inaccessible due to bkg, cuts and/or resolution, can use upper edge of MC variable Which is constructed only with final state kinematics (LHC-like)

(Tovey, JHEP 0804 (2008), 034)



$$
\begin{aligned}
M_C &= \sqrt{(E_{q,1} + E_{q,2})^2 - (\vec{p}_{q,1} - \vec{p}_{q,2})^2} \\
&= \sqrt{2(E_1 E_2 + \vec{p}_1 \cdot \vec{p}_2)},
\end{aligned}
$$

$$
M_C^{max} = \frac{m_{\tilde{q}}^2 - m_{\chi}^2}{m_{\tilde{q}}}
$$

Simon, Weuste, arXiv:1202.3446

Mass Measurements at a LC: Threshold Scans

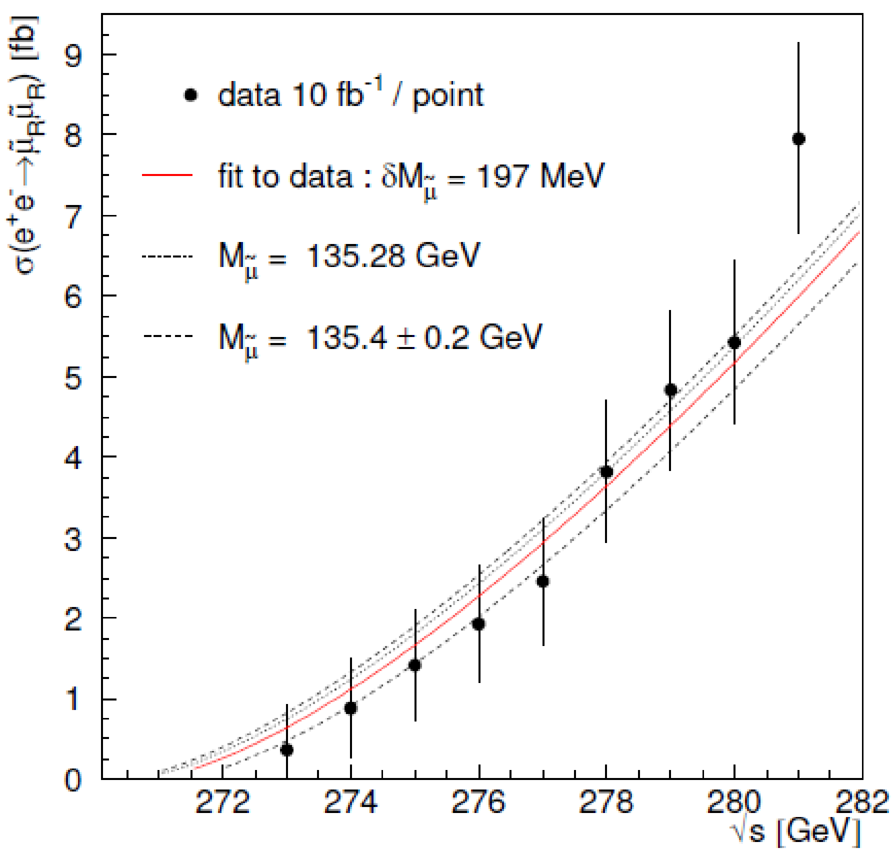
S-wave production ($\sigma \propto \beta$)

$$\delta m \simeq \Delta E \frac{1 + 0.36/\sqrt{N}}{\sqrt{18 N L \sigma}}$$

P-wave production ($\sigma \propto \beta^3$)

$$\delta m \simeq \Delta E \frac{1}{N^{1/4}} \frac{1 + 0.38/\sqrt{N}}{\sqrt{2.6 N L \sigma}}$$

Weak dependence of δm accuracy on nb. of scan points N, optimal scan with luminosity concentrated at 2 or 3 points



(G Blair, Snowmass 2001)

ILC DBD (2012)

Mass accuracies:
Low mass states

e^+e^-	m	δm_c	δm_{th}	Γ_{th}
R	143.0	0.2	0.2	<0.5
L	202.1		0.5	—
R	143.0	0.1	0.15	<0.4
L	202.1	0.8	0.3	<0.4
e	186.0	1.2	0.8	<0.7
1	133.2	0.3		
$\tilde{\chi}_1^\pm$	176.4	1.5	0.55	
$\tilde{\chi}_2^\pm$	378.2	3		
$\tilde{\chi}_1^0$	96.1	0.1		
$\tilde{\chi}_2^0$	176.8	2	1.2	
$\tilde{\chi}_3^0$	358.8	3–5		
$\tilde{\chi}_4^0$	377.8	3–5		

e^-e^-	m	δm_{th}	Γ_{th}
R	143.0	0.05	0.21 ± 0.05
L	202.1	0.25	0.25 ± 0.04

Mass accuracies:
High mass states

Particle	Mass (GeV)	Born	ISR	ISR+BS	ISR+BS +Bkg	w/ Pol (+0.8/0)	w/ Pol (+0.8/-0.6)
Model I							
$\chi_1^\pm$	643.2	$\pm$ 0.6	$\pm$ 0.6	$\pm$ 0.7	$\pm$ 0.7	$\pm$ 0.5	$\pm$ 0.4
χ_2^0	643.1	$\pm$ 4.3	$\pm$13.8	$\pm$24.1	$\pm$25.6	$\pm$23.9	$\pm$18.1
$\chi_2^\pm$	916.7	$\pm$ 0.8	$\pm$ 0.9	$\pm$ 1.3	$\pm$ 1.4	$\pm$ 1.1	$\pm$ 0.9

MB, N Alster, arXiv:1104.0523

Tertium, ...

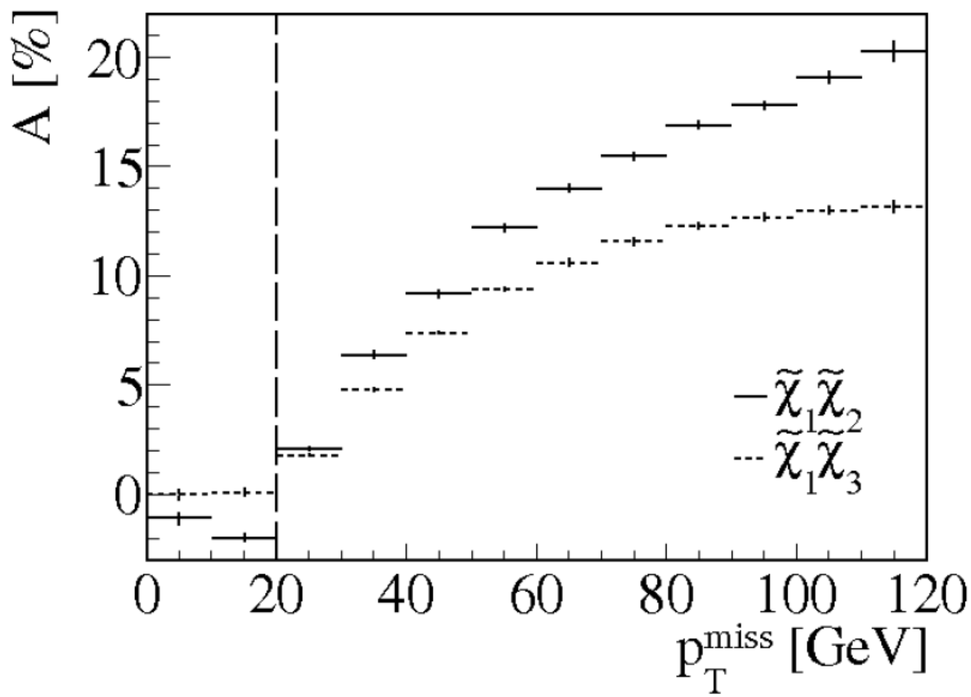
Branching Ratios, Spin & Angular Measurements

Decays of charginos and neutralinos into W/Z/h bosons well suited to e+e- features and detector response to separate boson masses through di-jet reconstruction;

Production cross sections of states accessible at 0.5 TeV can be determined to 0.5-2% accuracy;

Determination of tau polarisation offers sensitivity to mixing in the stau sector;

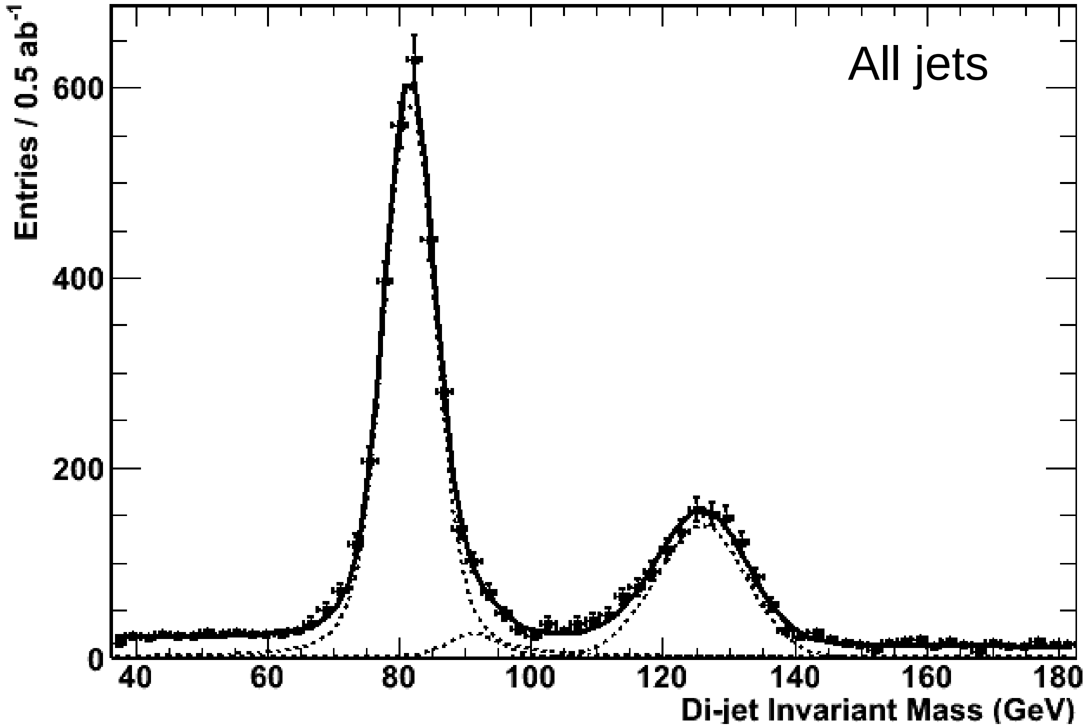
Processes such as $\tilde{\chi}_i^0 \to \tilde{\ell}_R \ell \to \ell\ell\tilde{\chi}_1^0$ are sensitive to CP asymmetries by using polarised beams →



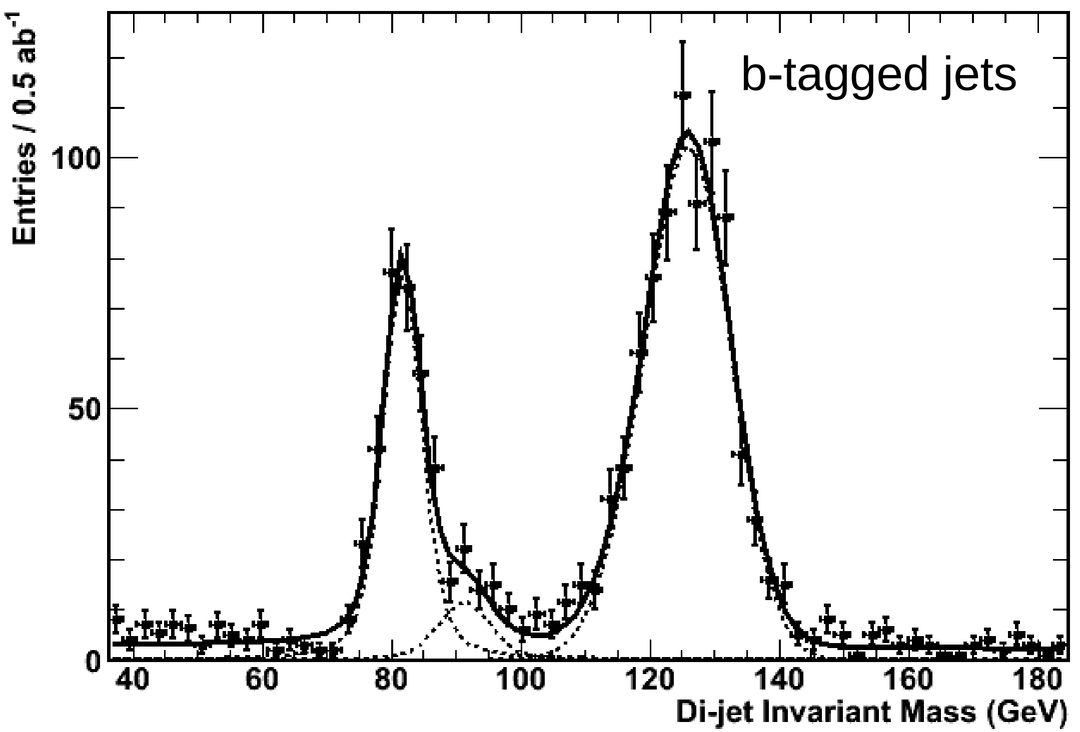
Kittel et al., EPJ C72 (2012) 1854

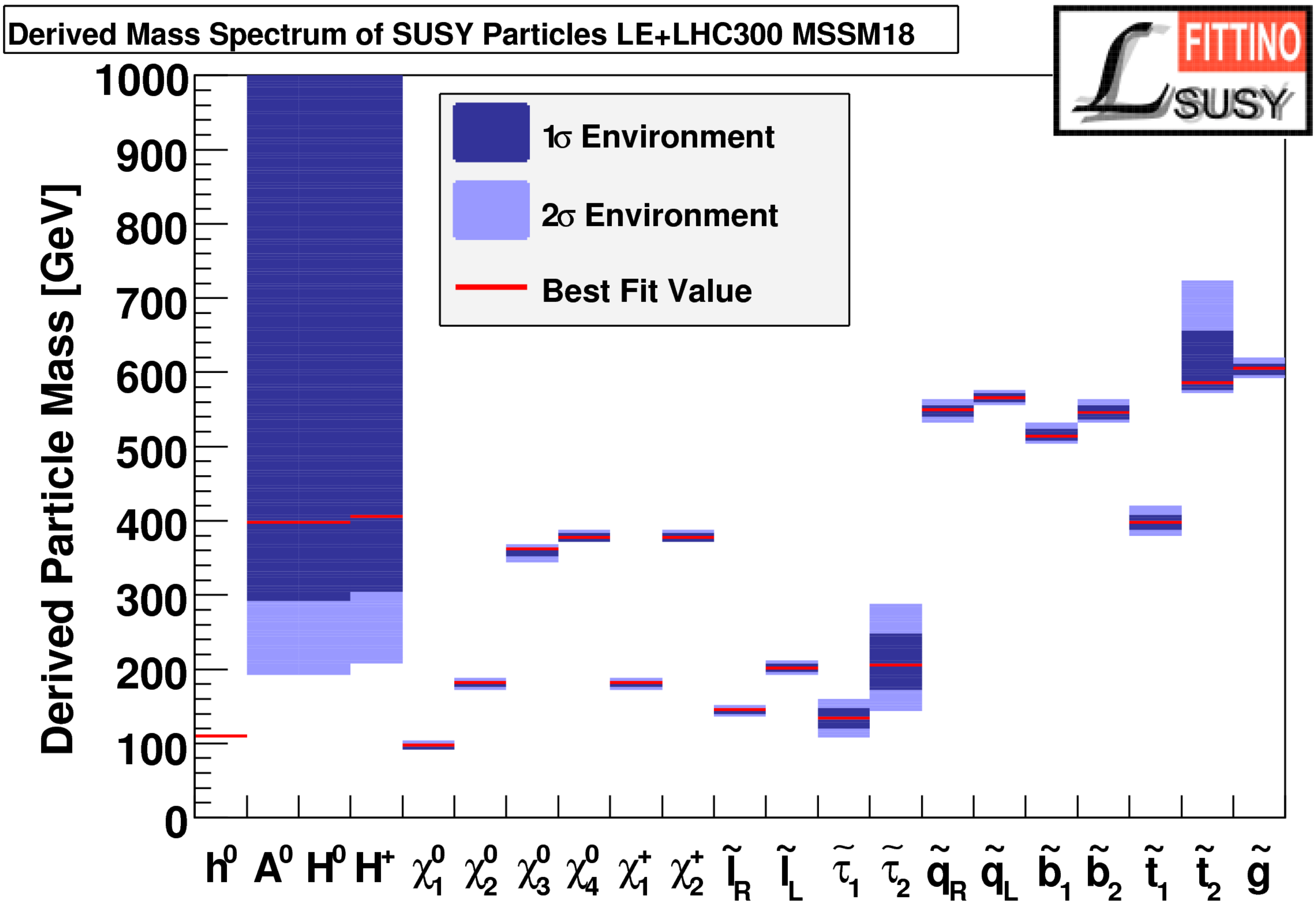
Inclusive SUSY analysis:

Determination of boson content of inclusive SUSY events in jjjj + Missing Energy final state:

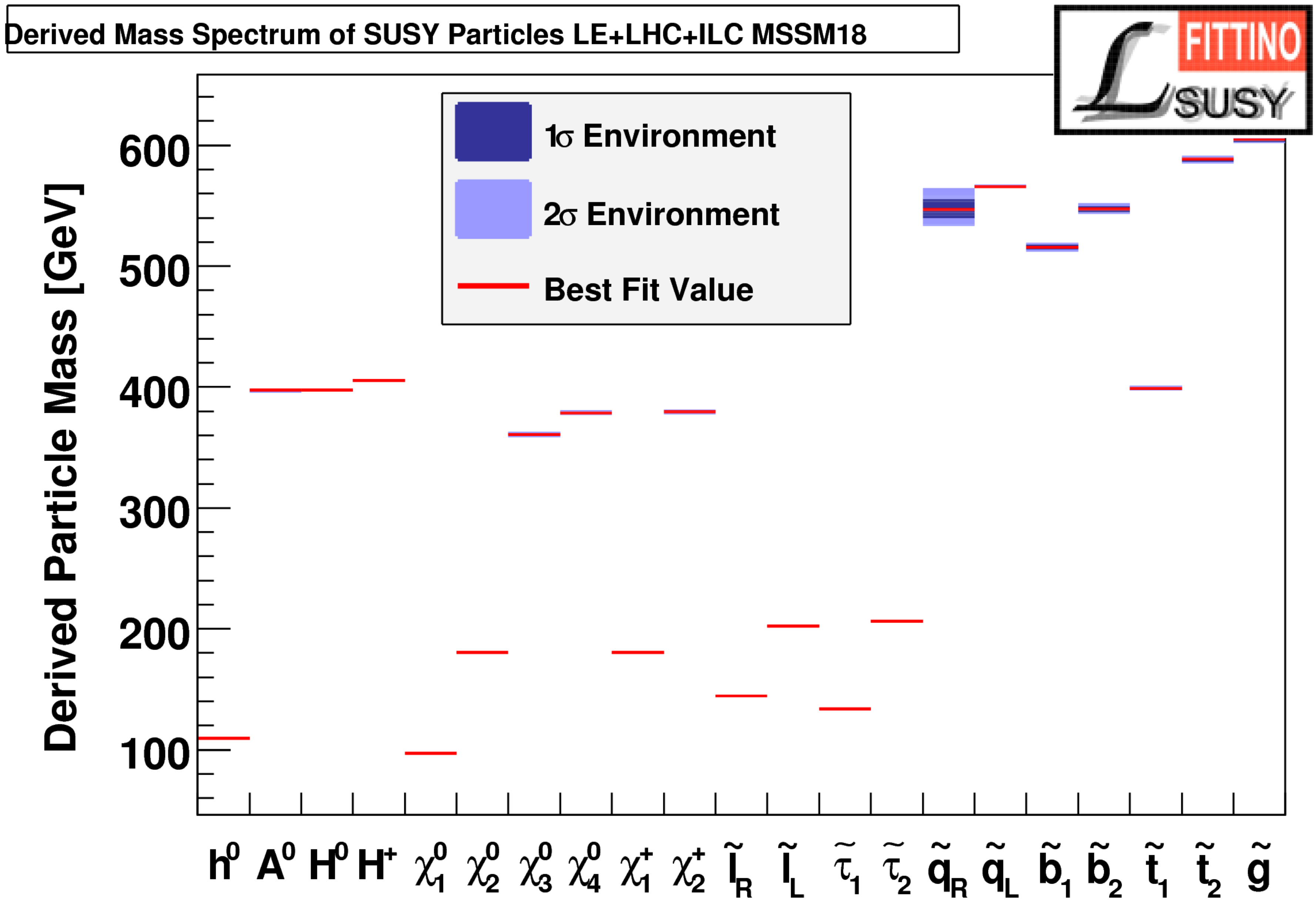


Boson	Fitted Fraction of Evts.	Simulated Fraction of Evts
$W^{\pm}$	0.650 ± 0.011	0.645 ± 0.005
Z^0	0.040 ± 0.009	0.020 ± 0.002
h^0	0.215 ± 0.010	0.243 ± 0.003



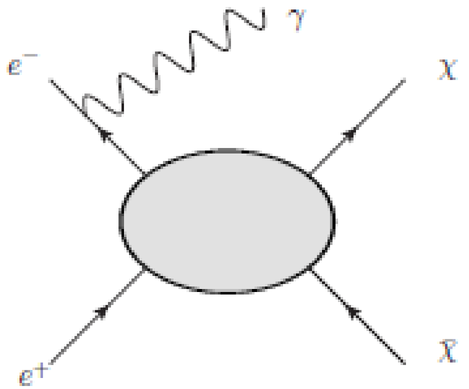


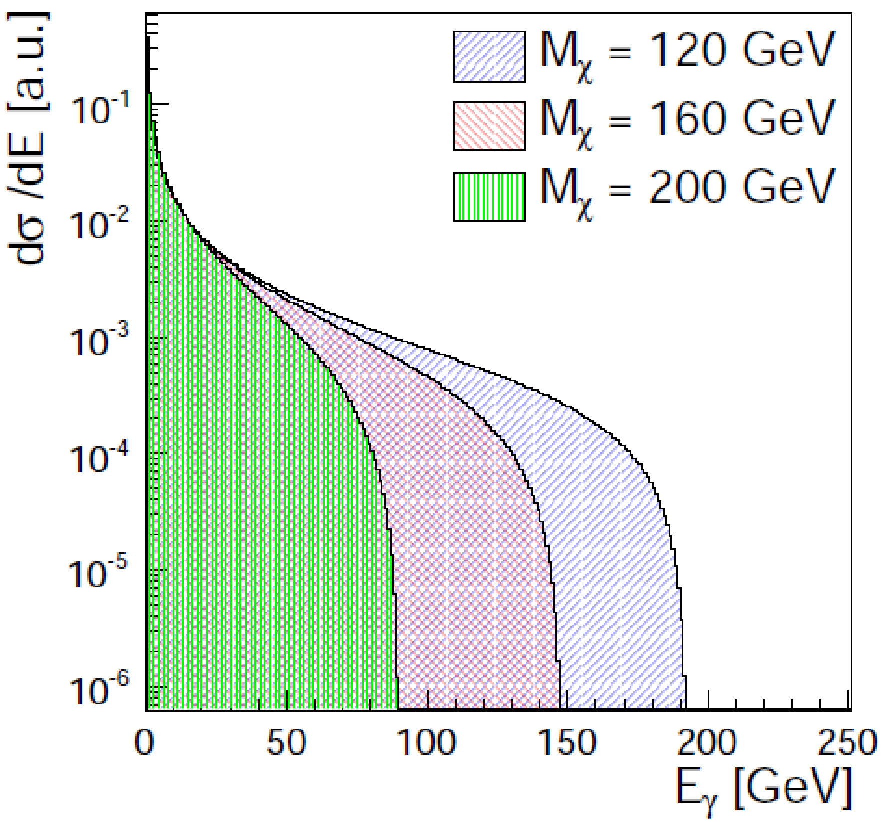
Derived Mass Spectrum of SUSY Particles LE+LHC300 MSSM18
FITTINO
SUSY
1σ Environment
2σ Environment
Best Fit Value
Derived Particle Mass [GeV]
0
100
200
300
400
500
600
700
800
900
1000
h^0 A^0 H^0 H^+ χ_1^0 χ_2^0 χ_3^0 χ_4^0 χ_1^+ χ_2^+ $\tilde{l}_R$ $\tilde{l}_L$ $\tilde{\tau}_1$ $\tilde{\tau}_2$ $\tilde{q}_R$ $\tilde{q}_L$ $\tilde{b}_1$ $\tilde{b}_2$ $\tilde{t}_1$ $\tilde{t}_2$ $\tilde{g}$


Derived Mass Spectrum of SUSY Particles LE+LHC+ILC MSSM18
FITTINO
SUSY
1σ Environment
2σ Environment
Best Fit Value
Derived Particle Mass [GeV]
600
500
400
300
200
100
h0 A0 H0 H+ χ01 χ02 χ03 χ04 χ+1 χ+2 l̃R l̃L τ̃1 τ̃2 q̃R q̃L b̃1 b̃2 t̃1 t̃2 g̃

Model-independent neutralino search
Single Photon at LC

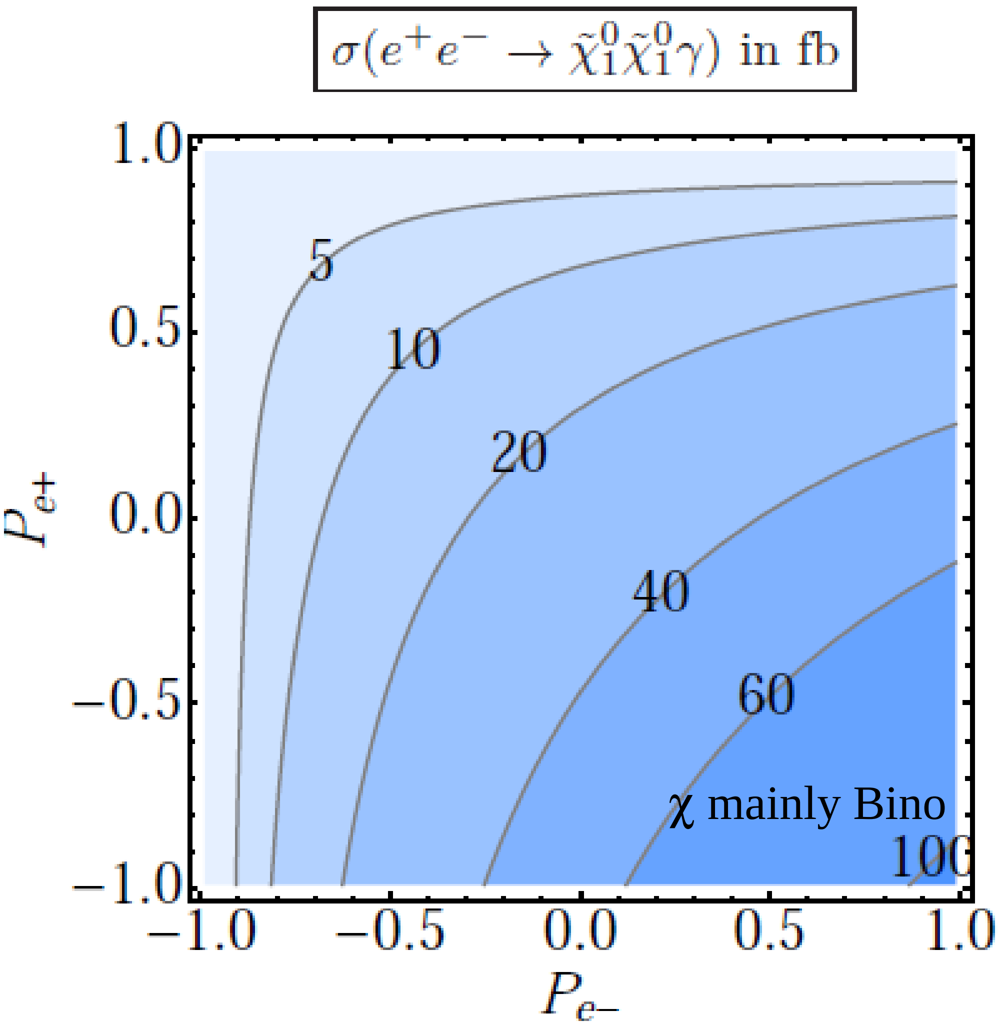
$$e^+ + e^- \to \tilde{\chi}_1^0 + \tilde{\chi}_1^0 + \gamma$$

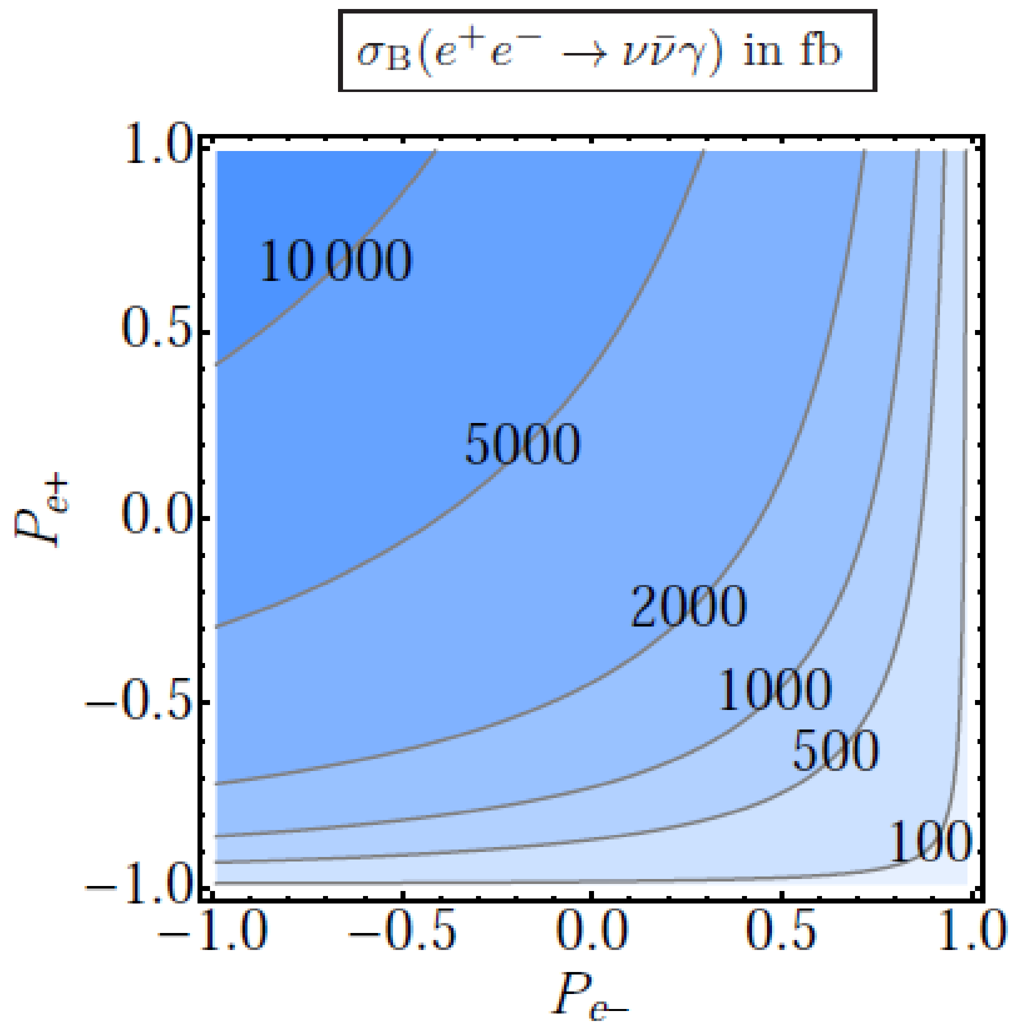




Bartels et al,
EPJ C72 (2012) 2213

Severe ννγ + radiative Bhaba (eeγ) background → no sensitivity at LEP;
Need high lumi + beam polarisation to enhance signal & suppress ννγ:





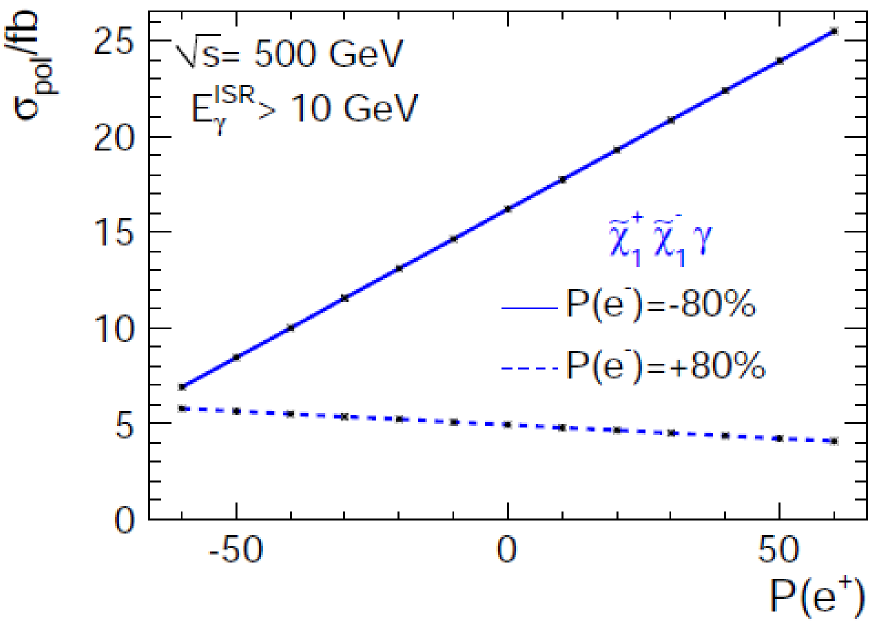
Bartels et al,
EPJ C72 (2012) 2213

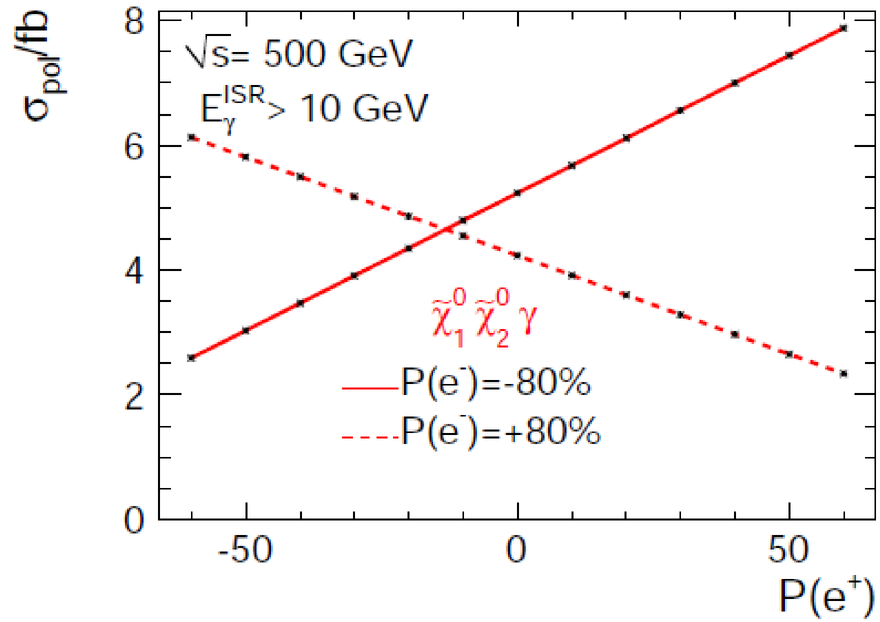
$$\sigma(P_{e^-}, P_{e^+}) = \frac{1}{4}\Big[(1+P_{e^-})(1+P_{e^+})\sigma_{RR} + (1-P_{e^-})(1-P_{e^+})\sigma_{LL} + (1+P_{e^-})(1-P_{e^+})\sigma_{RL} + (1-P_{e^-})(1+P_{e^+})\sigma_{LR}\Big].$$

$m_{\tilde{\chi}_1^0}$ [GeV]	$\pm$ stat. $\pm$ sys. ($\delta E \pm \delta\mathcal{L}$) (total) [GeV]	$(P_{e^-}; P_{e^+})$
97.7	$\pm$ 2.65 $\pm$ 0.09 $\pm$ 2.20 (3.44)	(0.8; 0.0)
97.7	$\pm$ 2.07 $\pm$ 0.09 $\pm$ 2.20 (3.02)	(0.8; −0.3)
97.7	$\pm$ 1.70 $\pm$ 0.09 $\pm$ 2.20 (2.79)	(0.8; −0.6)

Bartels et al,
EPJ C72 (2012) 2213

Low μ, small ΔM Higgsino scenarios using radiative events



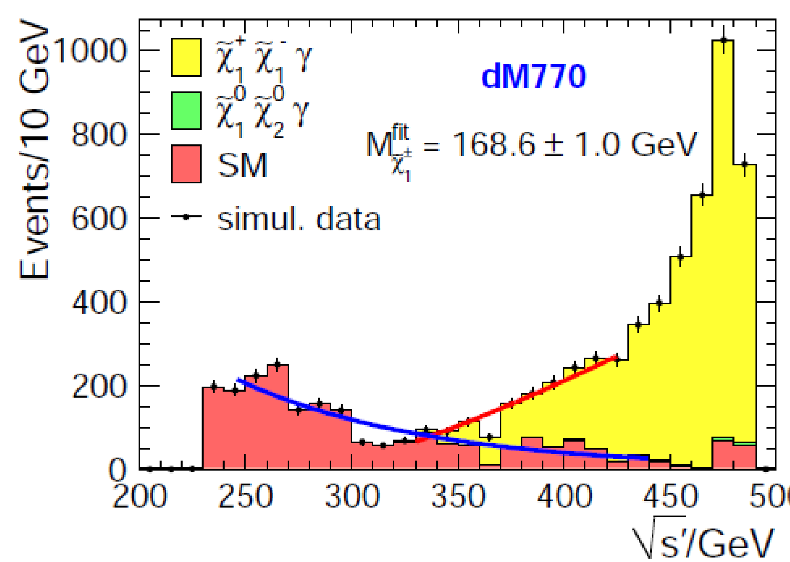


Study charginos and neutralinos with ΔM ~ 1 GeV at 0.5 TeV with polarised beams using ISR events and residual hadronic activity in detector:

$$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$$

$$e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0$$

$$s' = s - 2\sqrt{s}E_\gamma ;$$



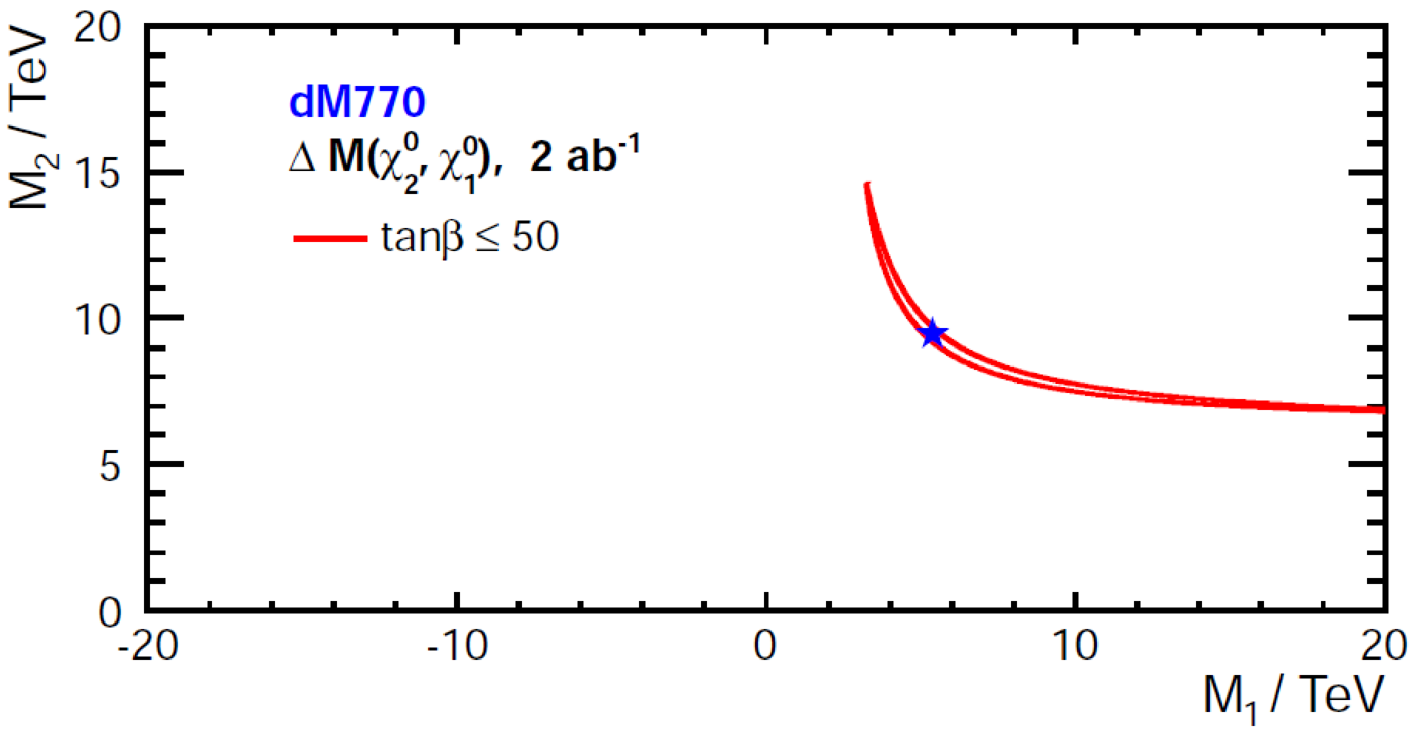
Berggren et al., EPJ C73 (2013) 2660

$$M^{\text{cal}}_{\tilde{\chi}^\pm_1} = 167.3 \pm 1.5\,\text{GeV} \quad (M^{\text{true}}_{\tilde{\chi}^\pm_1} = 167.4\,\text{GeV})$$

$$\Delta M^{\text{rec}}_{\tilde{\chi}^\pm_1 - \tilde{\chi}^0_1} = 810 \pm 40\,\text{MeV} \quad (\Delta M^{\text{true}}_{\tilde{\chi}^\pm_1 - \tilde{\chi}^0_1} = 770\,\text{MeV})$$

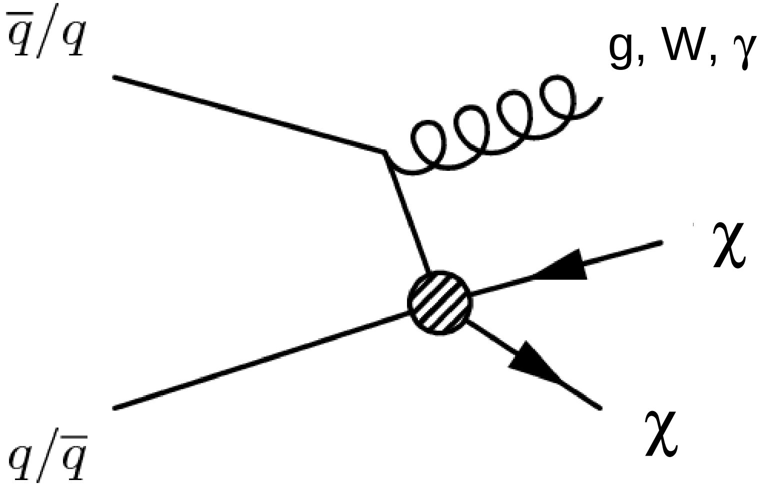
$$M^{\text{cal}}_{\tilde{\chi}^0_2} = 165.7 \pm 1.6\,\text{GeV} \quad (M^{\text{true}}_{\tilde{\chi}^0_2} = 167.6\,\text{GeV})$$

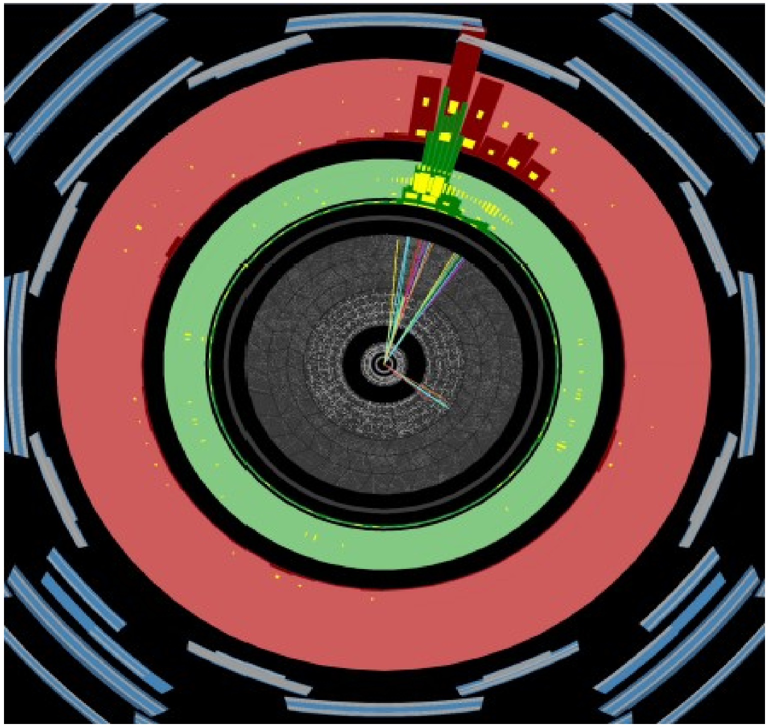
Extract model parameters from fit to measured masses and polarised cross sections:



Berggren et al., EPJ C73 (2013) 2660

Model-independent neutralino search
Mono-jet at LHC

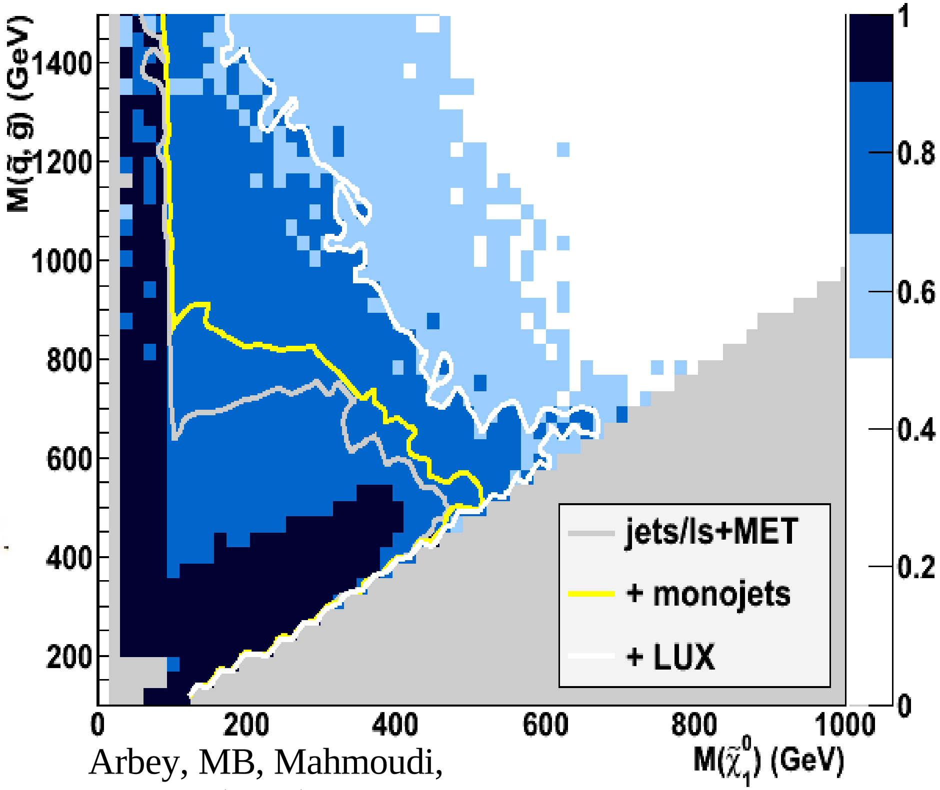




LHC collision can search for WIMP production through processes with large MET and one parton as "witness" of interaction;

"Model-independent" search, can be interpreted in MSSM in terms of $\chi^0{}_1$ sensitivity most performant for nearly degenerate sparticles;

Results interpreted as limits on $\Lambda \equiv M/\sqrt{g_\chi g_q}$ related to $\sigma_{\rm DD} \sim g_\chi^2\, g_q^2\, \frac{\mu^2}{M^4}$ WIMP scattering xsec on nucleons for DM direct det. expts.



Arbey, MB, Mahmoudi,
PRD 89 (2014) 077701

Backgrounds: SM and BSM as backgrounds to BSM

SM irreducible backgrounds:

WW → llνν / lqqν;
ZZ → llνν, qqνν;
WWνν → llνννν, lqqννν, qqqqνν;
ZZνν → llllνν, llqqνν, qqqqνν;
WWZ → llνννν, lqqννν, qqqqνν, ...
tt → bWbW, blν bqq / blν blν;

SM small angle backgrounds:

e+e- → ll e+e-, qq e+e-;
e+e- → γ e+e-; …

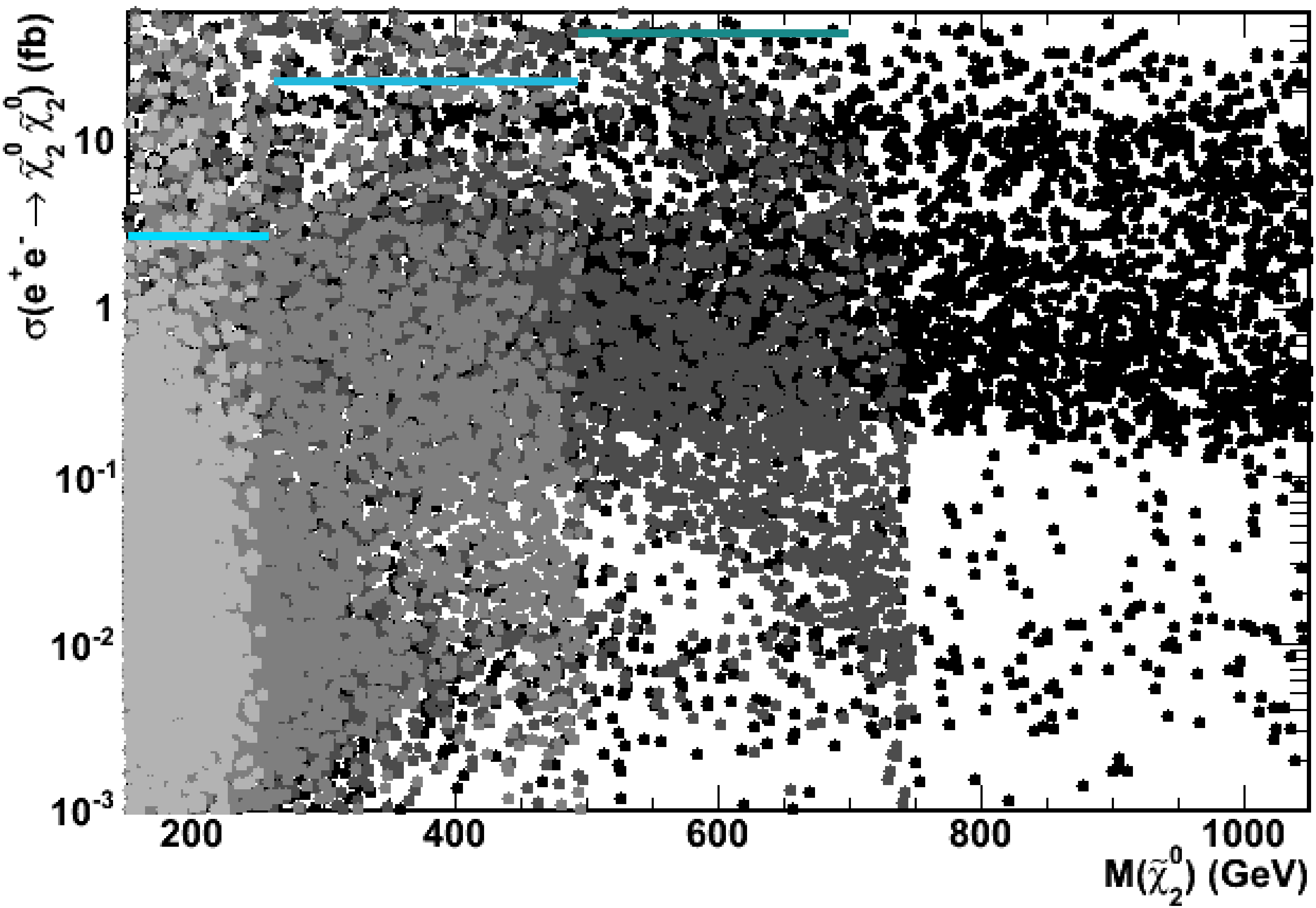
SUSY irreducible backgrounds:

Typical xsec of individual channels 0.25 – 0.05 of inclusive SUSY xsec;
Same final states may receive contributions from multiple channels (p.e.):

$e^+e^- \to \chi_1^+\chi_1^- \to W^+\chi_1^0 W^-\chi_1^0$ $\quad$ $\tilde{e}_L^\pm \to \chi^\pm \nu_e$

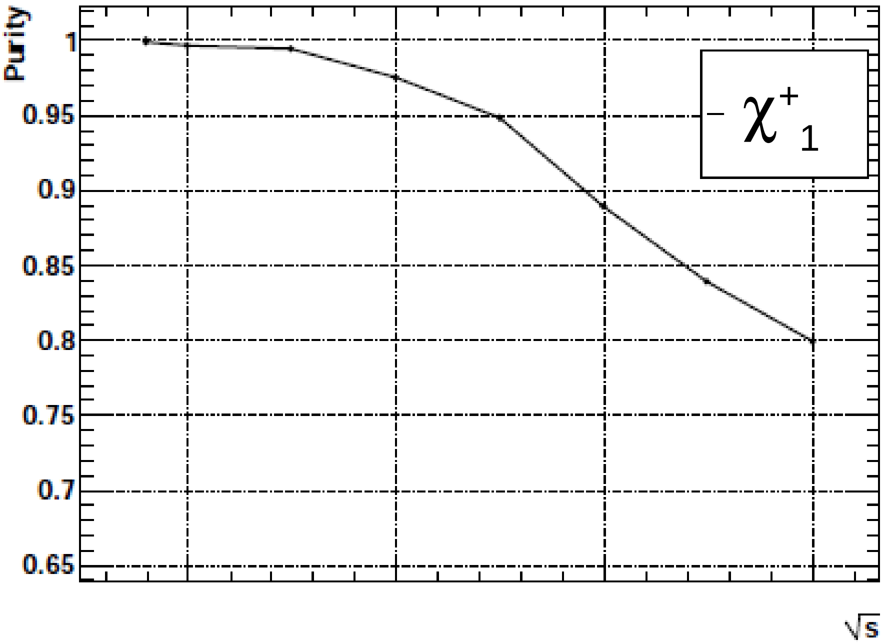
$e^+e^- \to \chi_2^0\chi_2^0$ $\quad$ $e^+e^- \to \tilde{\nu}_\ell\tilde{\nu}_\ell \to \chi_2^0 \nu_\ell \chi_2^0 \nu_\ell$

Backgrounds: SM as background to BSM

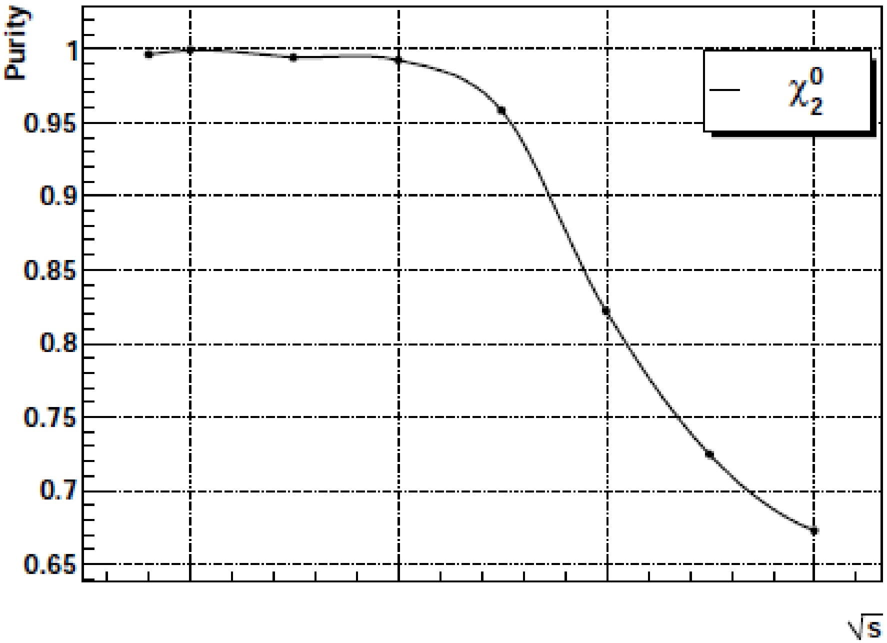


Backgrounds: BSM as background to BSM

Adjustable beam energy gives degree of freedom to adjust at best S/B

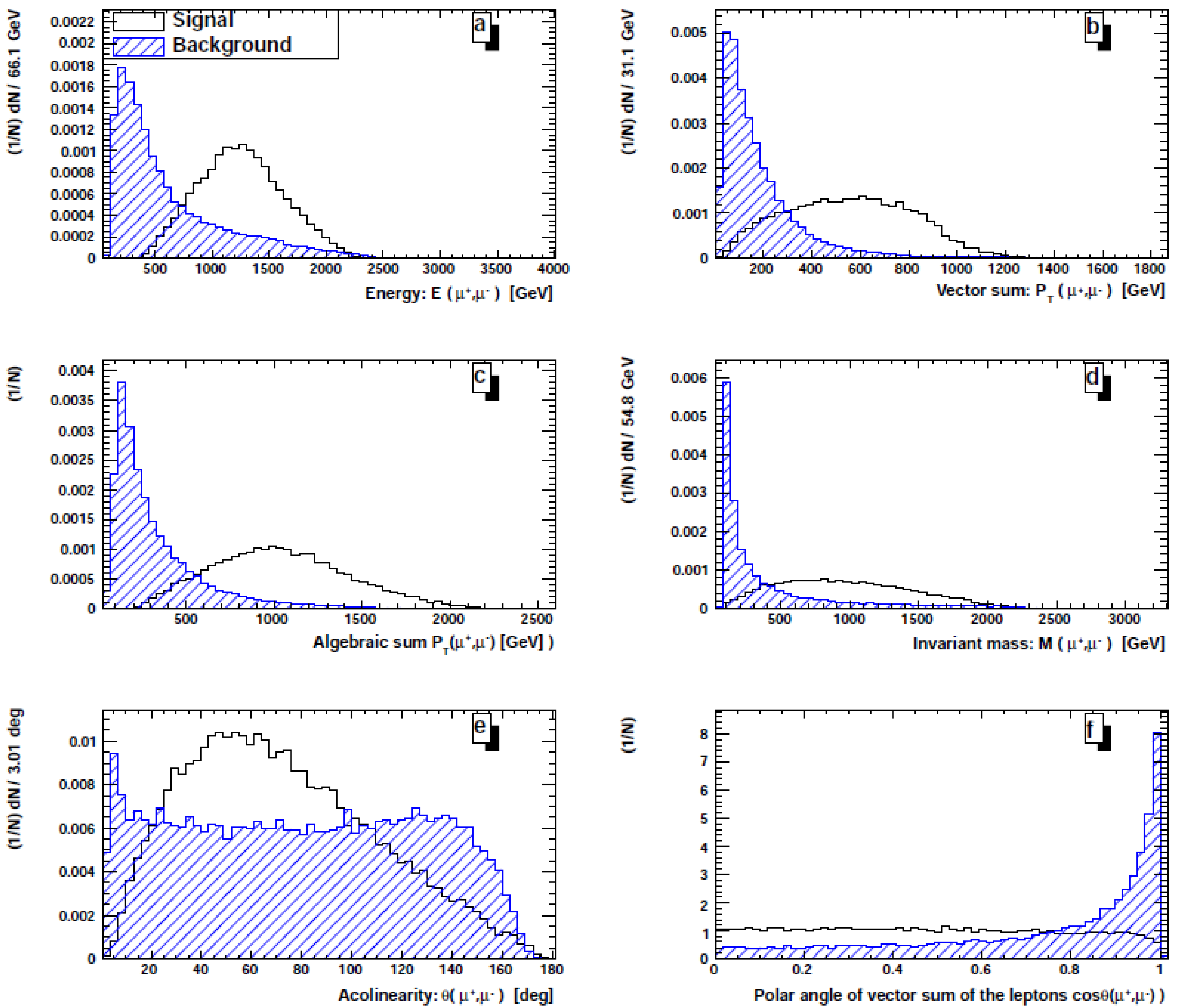


(a) $\chi_1^{\pm}$



(b) χ_2^0

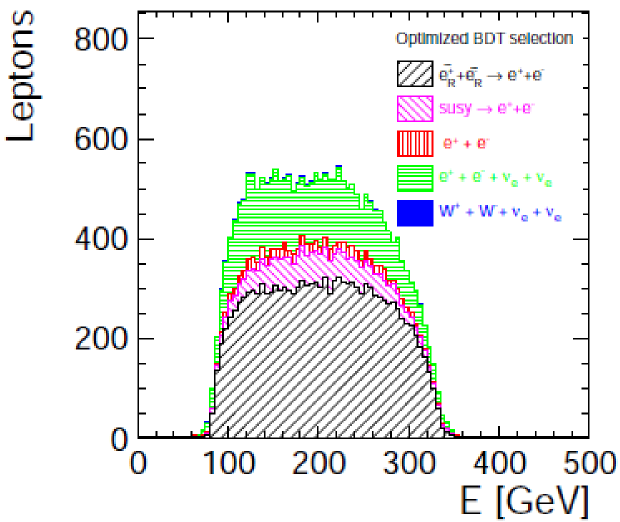
Backgrounds: SM (and BSM) as background(s) to BSM

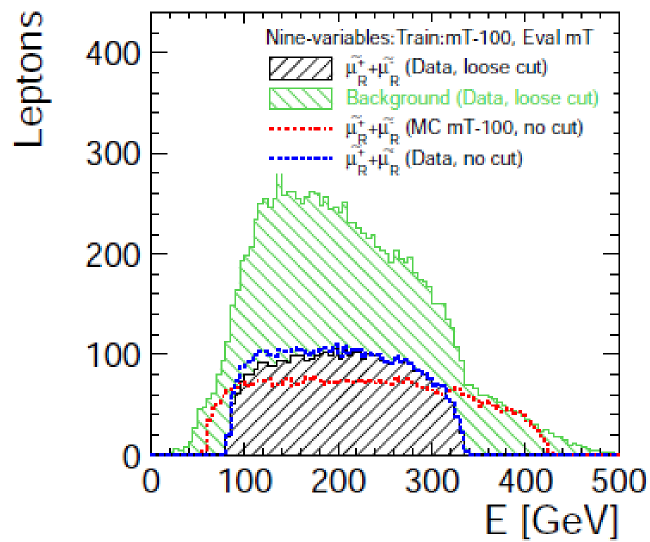


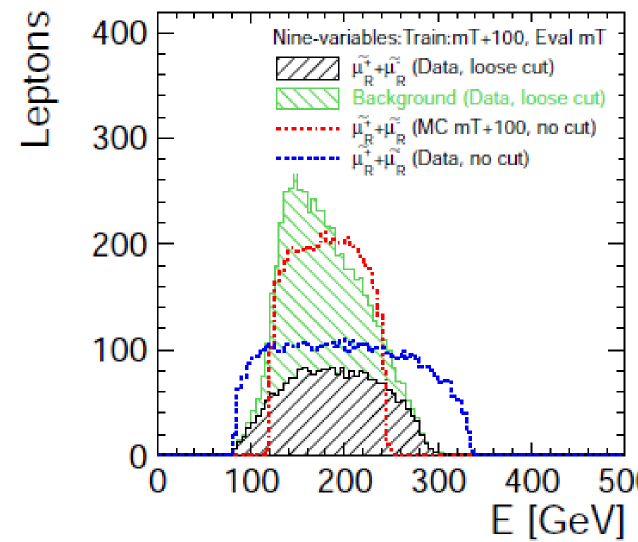
Backgrounds: SM (and BSM) as background(s) to BSM

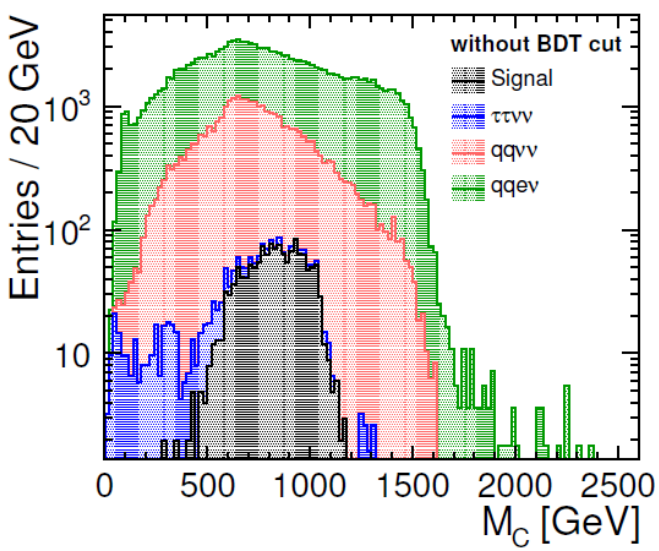
Widespread use of NN or BDT discriminant to suppress backgrounds in LC analyses;
While efficient these techniques raise concerns for:

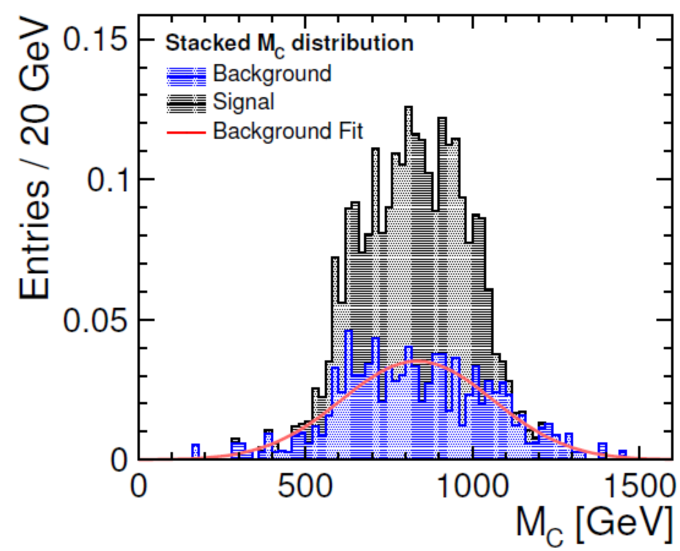
i) distortion of kinematical observables used for measurements;











Backgrounds: SM and BSM as backgrounds to BSM

ii) training of NN, BDT for BSM background which contains processes with unknown masses and/or branching fractions.

Cut based techniques appear in general preferable for unbiased signal selection.

Non-Supersymmetric Models of BSM Physics

Large corpus of non-SUSY BSM models addressing (at least some of) the same SM issues as SUSY;

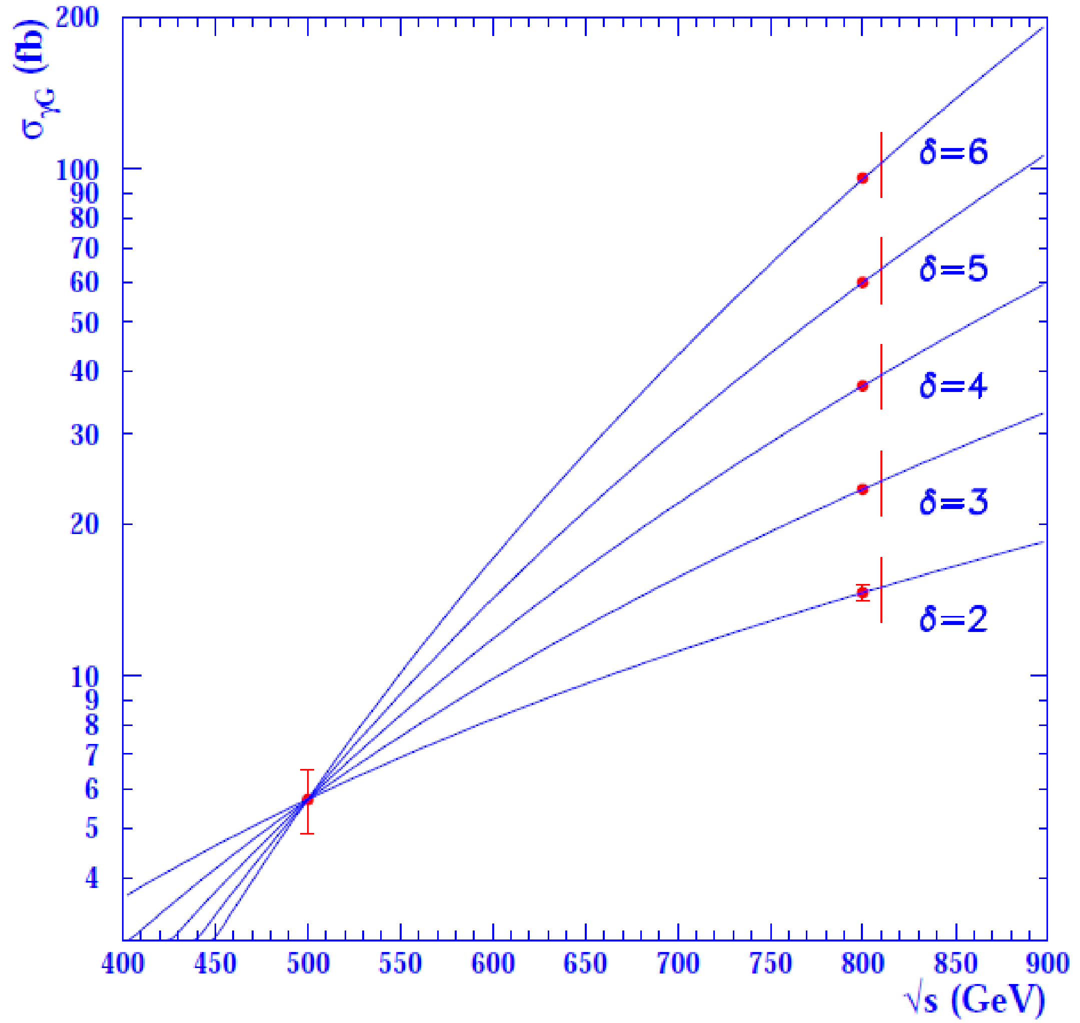
Extra spatial dimensions considered as solution to hierarchy problem and developed into paradigm to address several SM outstanding issues including DM and TeV-scale unification.

Collider phenomenology ranges from production of invisible gravitons (ADD large extra dimensions) to tower of resonance (KK excitations of graviton and SM particles in warped ED), to KK states decaying to SM particles + LKP (UED) thus mimicking R-parity conserving SUSY.

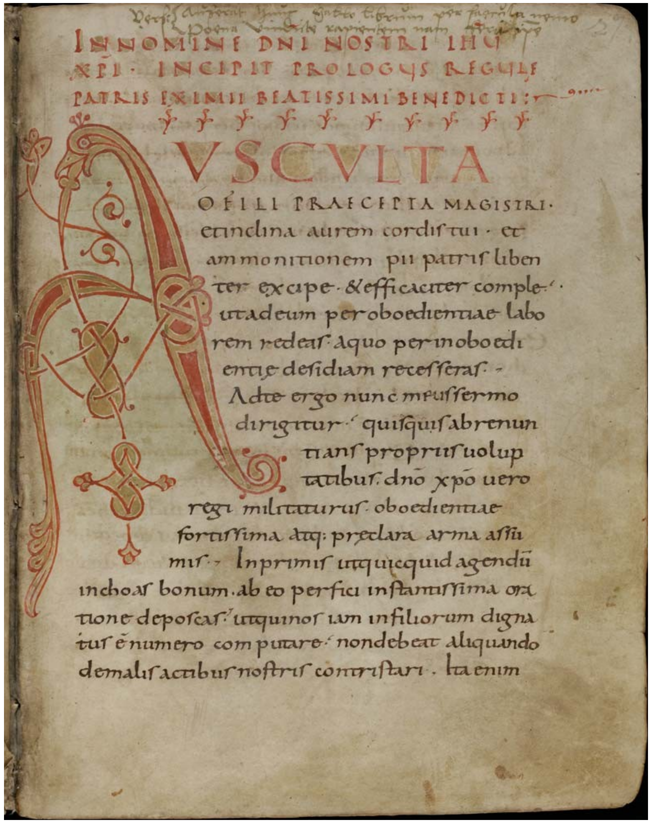
LHC constraints are already severe ...

Example: Single Photon from $e^+e^- \rightarrow \gamma G$

Emission of towers of KK gravitons (weakly interacting) $\rightarrow \sigma = \Sigma\, \sigma_{KKi}$



TESLA TDR (2001)



Et tunc demum ad maiora quae suprae commemoravimus doctrinae virtutumque culmina pervenies.

Linear collider of sufficient energy has important role for probing physics beyond the SM, in particular in its connections to the Higgs sector and Cosmology;

Mass measurements to percent or sub-percent accuracy, determination of quantum numbers and couplings, extraction of fundamental parameters are possible if new states are within kinematic reach;

Basic techniques for event reconstruction and measurement have been developed and perfected, ample room for improvements in inclusive studies of complex models, bkg (SM+BSM) rejection using non-biasing methods, global analysis of direct searches at LHC + LC and sensitivity from EW observables and Higgs couplings, … ;

As the history of Bl. Irmengard of Chiemsee OSB teaches us, understanding and recognition may take significant amount of time and repeated efforts but in the long term come, thanks to those who persisted.

Explicit