Application of simplified model results to SUSY scenarios

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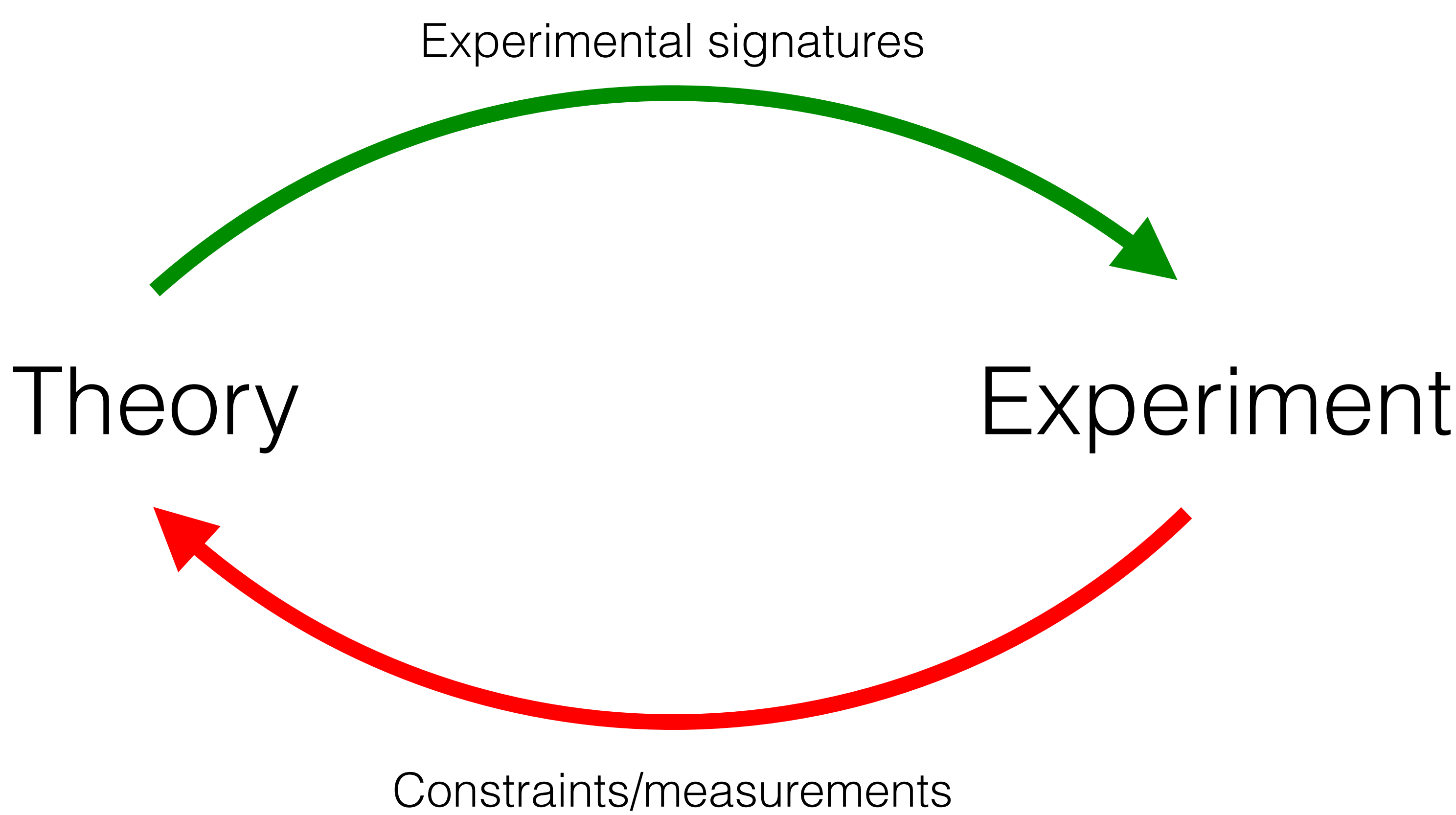
04/11/2015

Introduction



Question: How to most effectively exploit this interplay?

Focus purely on application of simplified model results for R-parity conserving SUSY

Additional constraints:

- Dark matter does not over close the Universe
- Dark matter direct direction constraints
- Higgs mass and branching ratio measurements
- Flavour physics constraints in particular $BR(B \to s\,\gamma)$ and $\mathrm{BR}(\mathrm{B_s} \to \mu\,\mu)$

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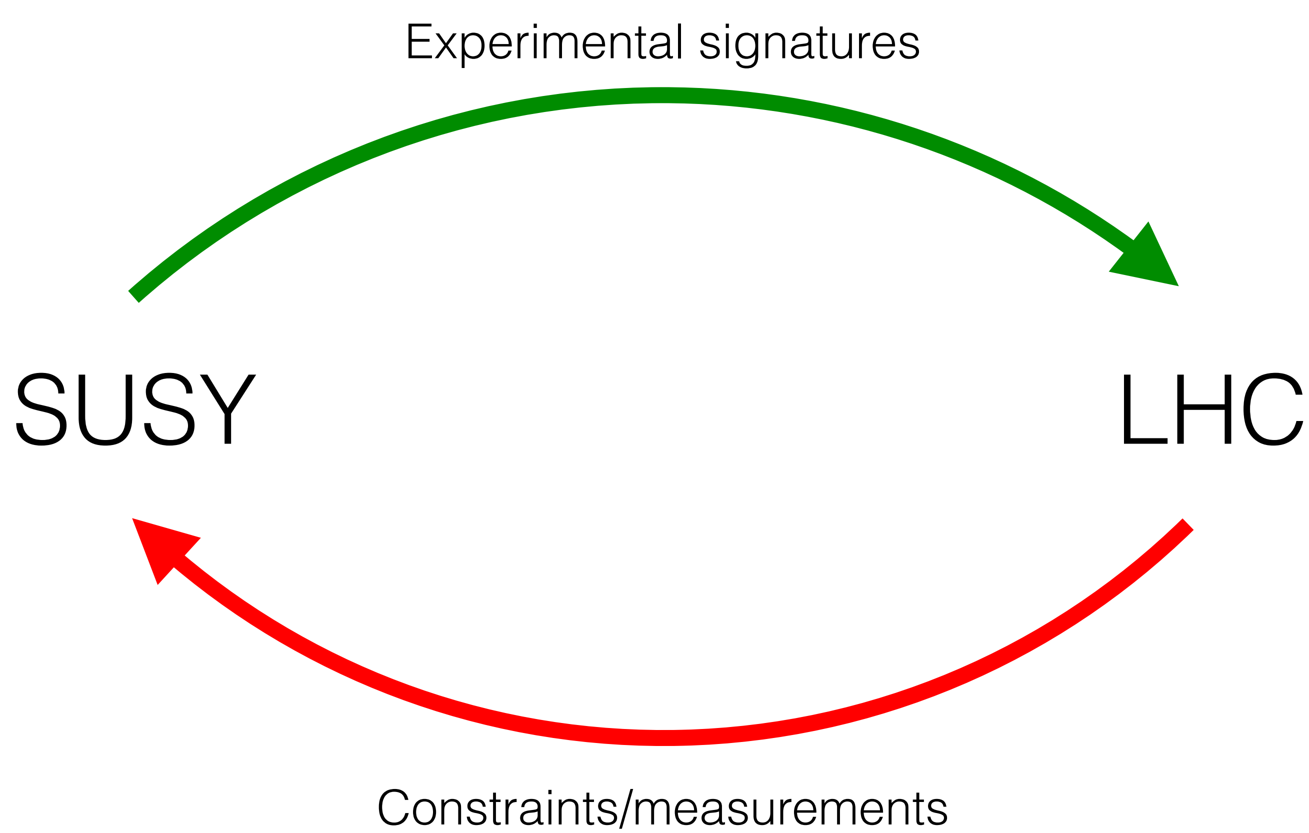

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LHC results

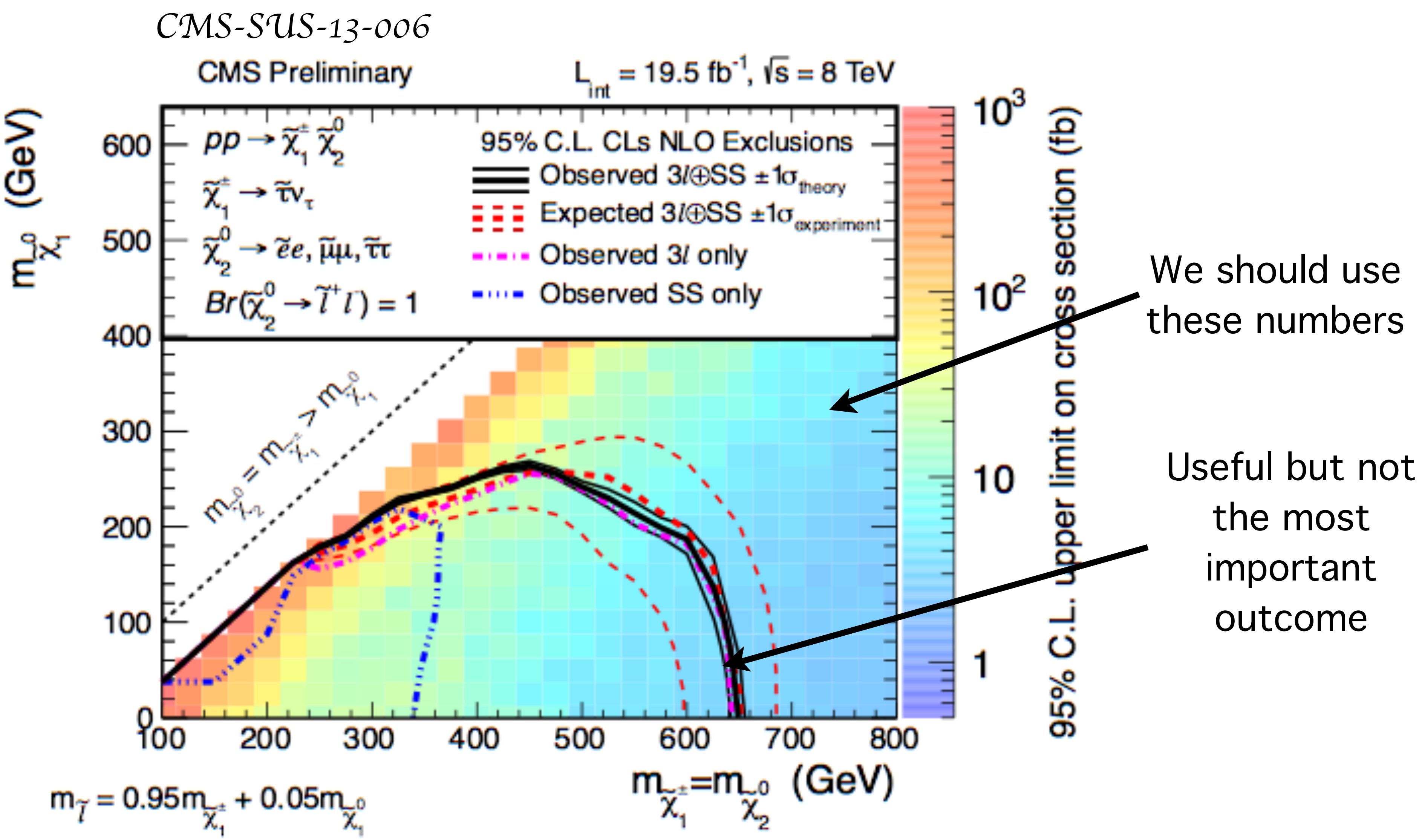
$$N_{evts} = \sum_i \mathcal{L} \times (\mathcal{A} \times \epsilon)_i \times (\sigma \times BR)_i$$

- *Generic reinterpretation*: Reconstruct the number of events by taking into account all possible decay chains
- *Simplified model reinterpretation(I)*: Obtain maximum allowed cross-section for a given decay chain
- *Simplified model reinterpretation(II)*: Reconstruct number of events by predefining efficiency maps

Generic reinterpretation	*Simplified model reinterpretation*
• Works for BSM model involving complex topologies/decays • Time consuming, demands computing power • Account for e.g. spin correlation of the process	• Assumes that BSM model contains only few light particles hence deals with simple topologies • Generic, simple and quick to use • Neglect e.g. spin correlation of the process

Simplified model reinterpretation - I

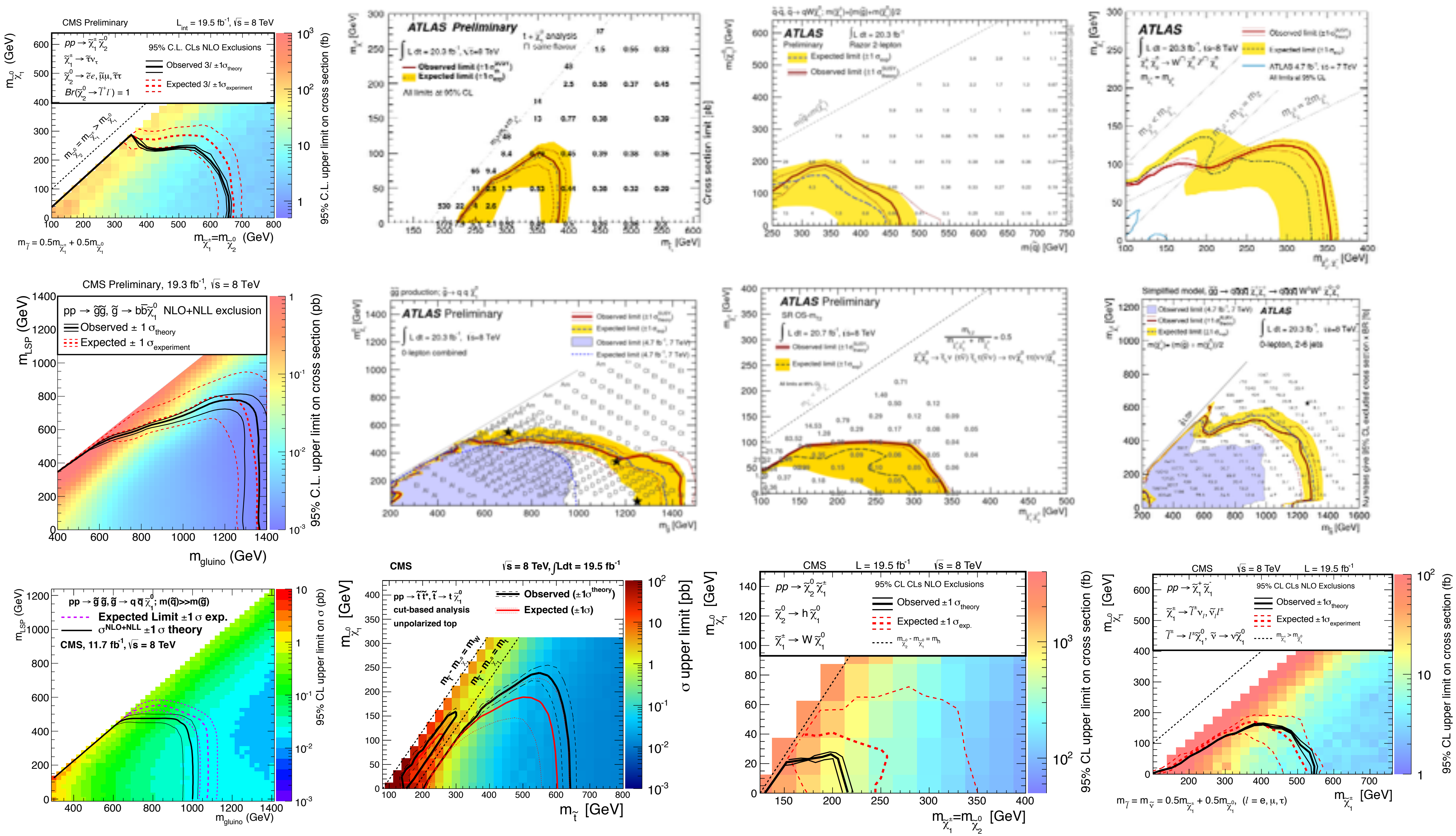
SMS result



- 95% CL UL is the maximum visible cross-section allowed for a specific decay chain and a mass combination

Is σ X BR (Mother mass, intermediate mass, LSP mass) of given model > the number on the plot? -- Yes, point excluded; No, point allowed

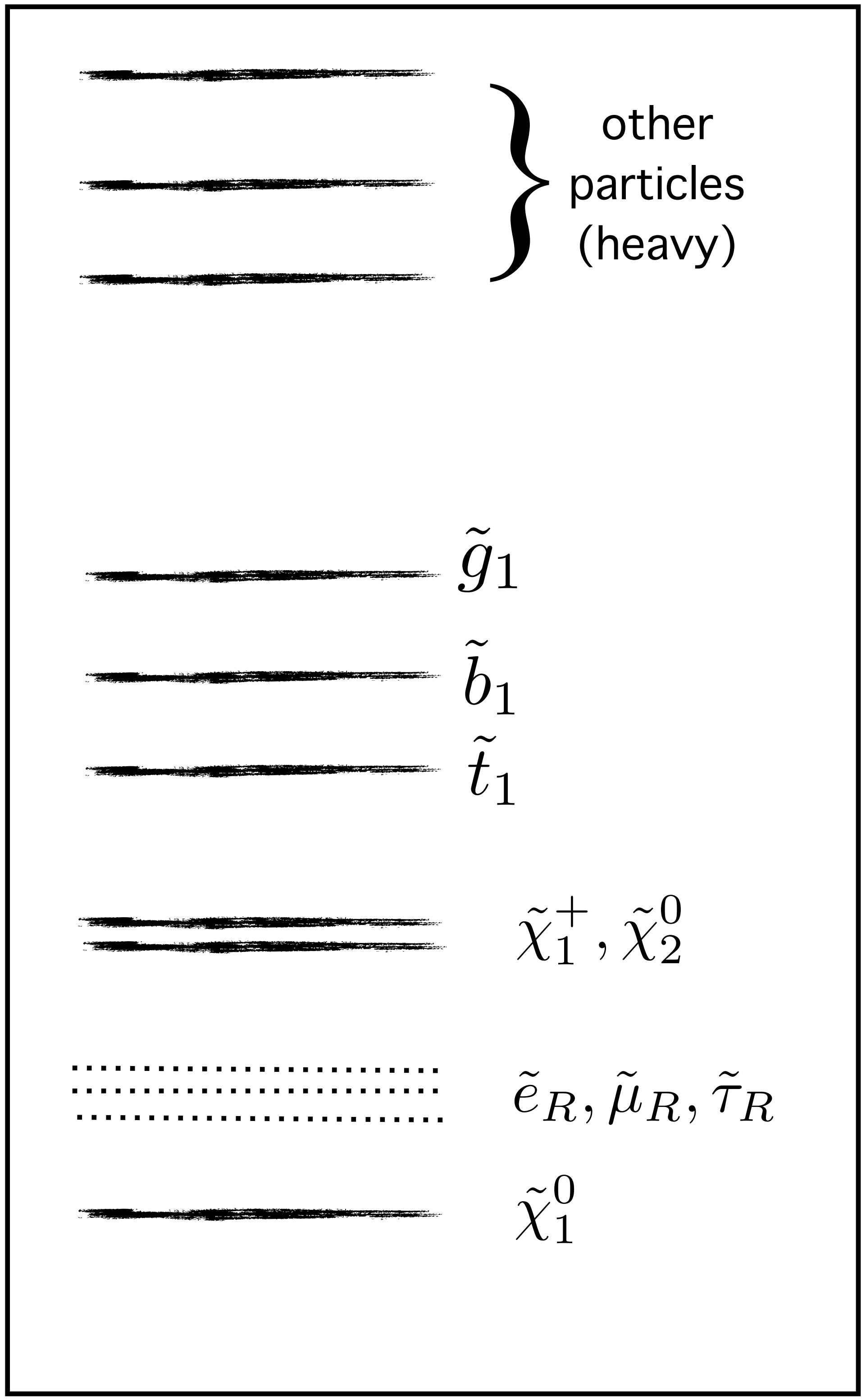
SMS result



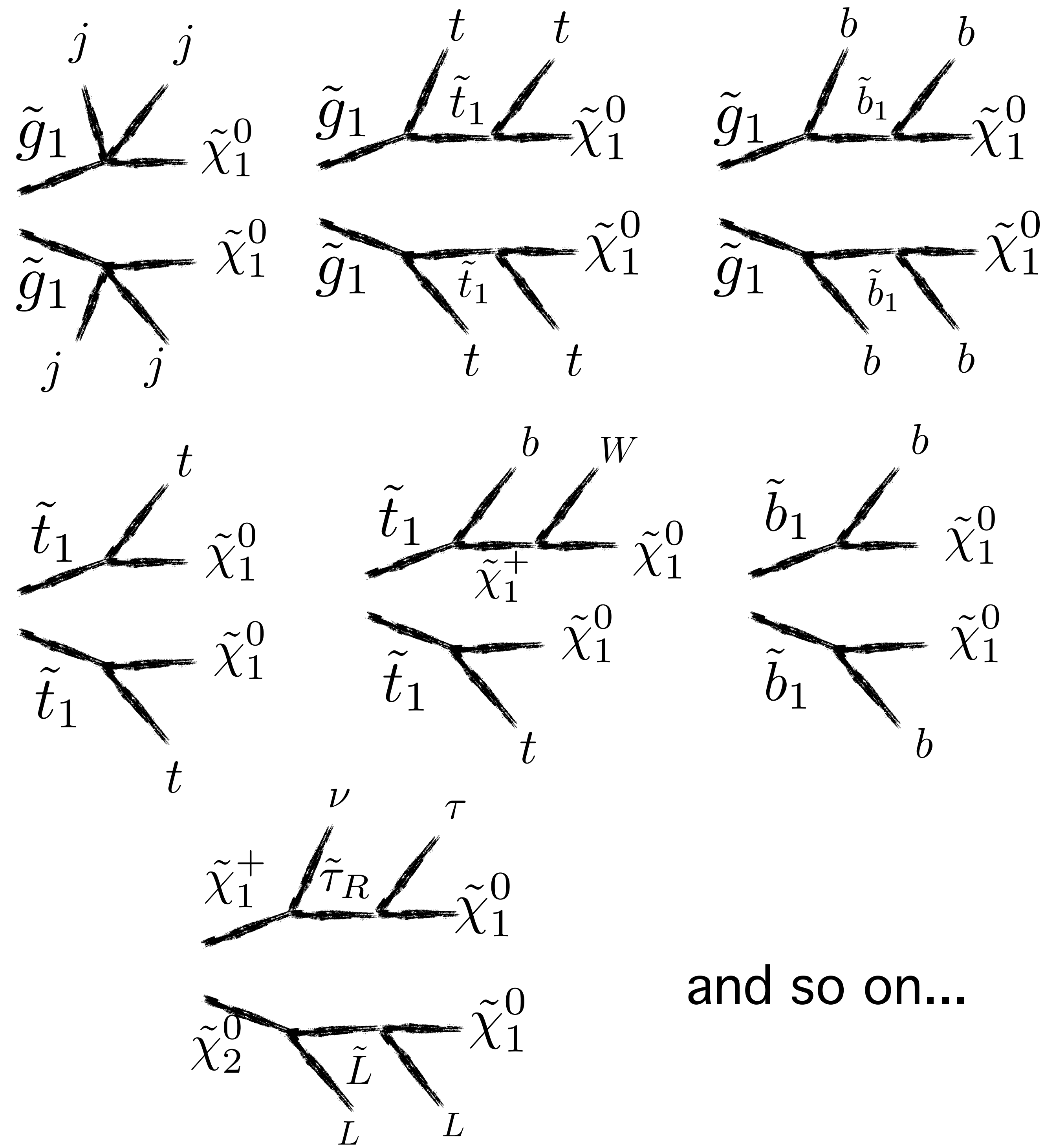
Many such results available for various decay chains

Generic MSSM spectra - I

Arbitrary MSSM spectrum



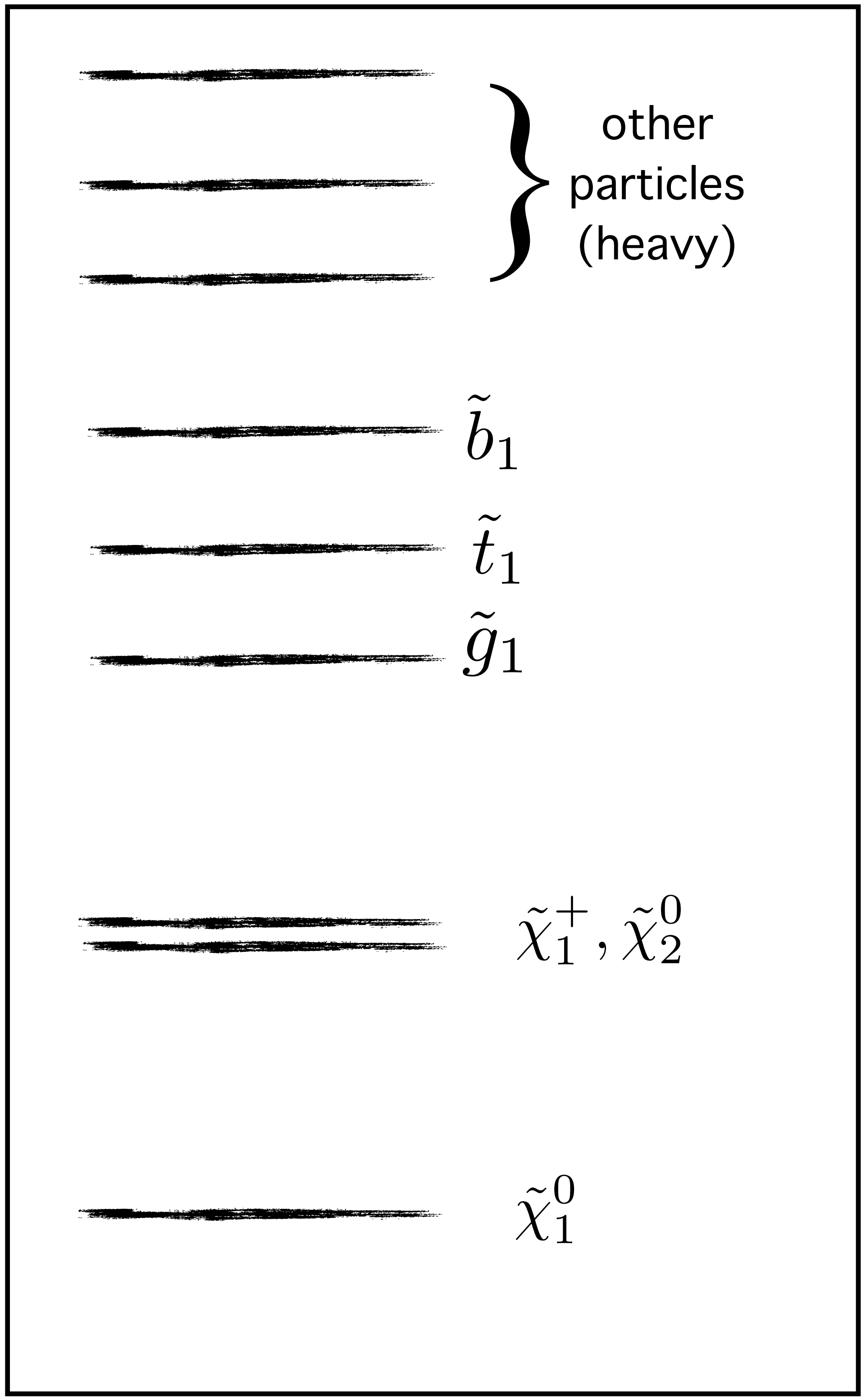
Contains many decays



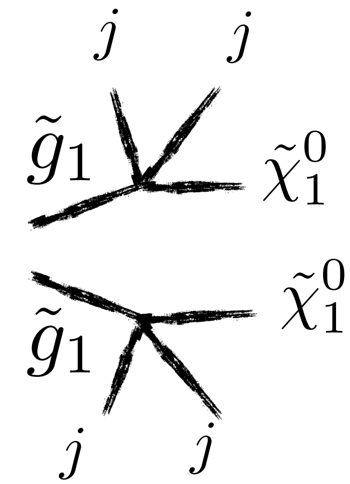
and so on...

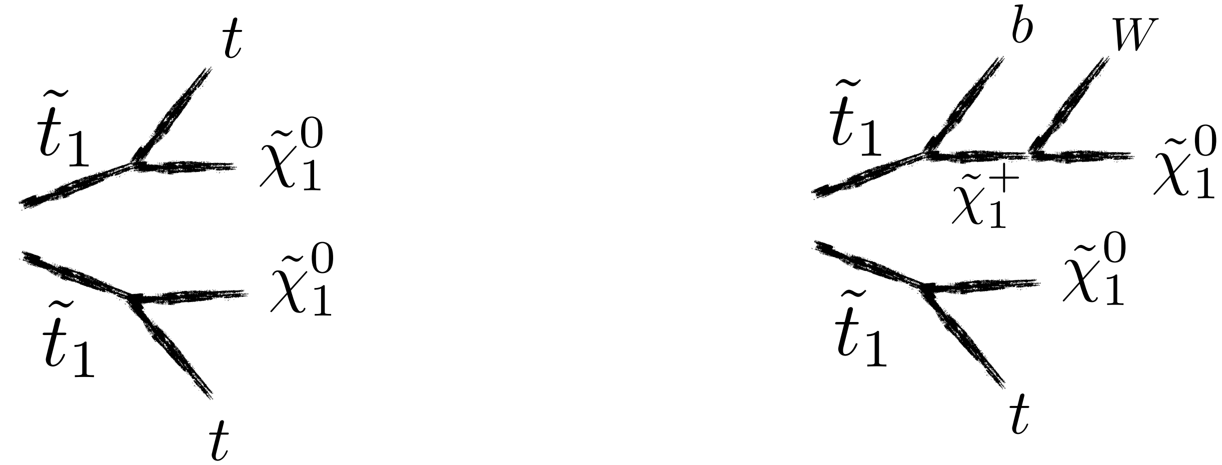
Generic MSSM spectra - II

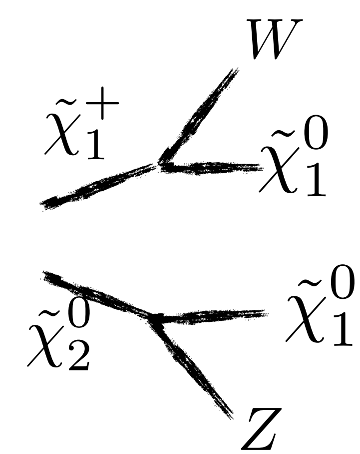
Arbitrary MSSM spectrum - II



Contains many decays





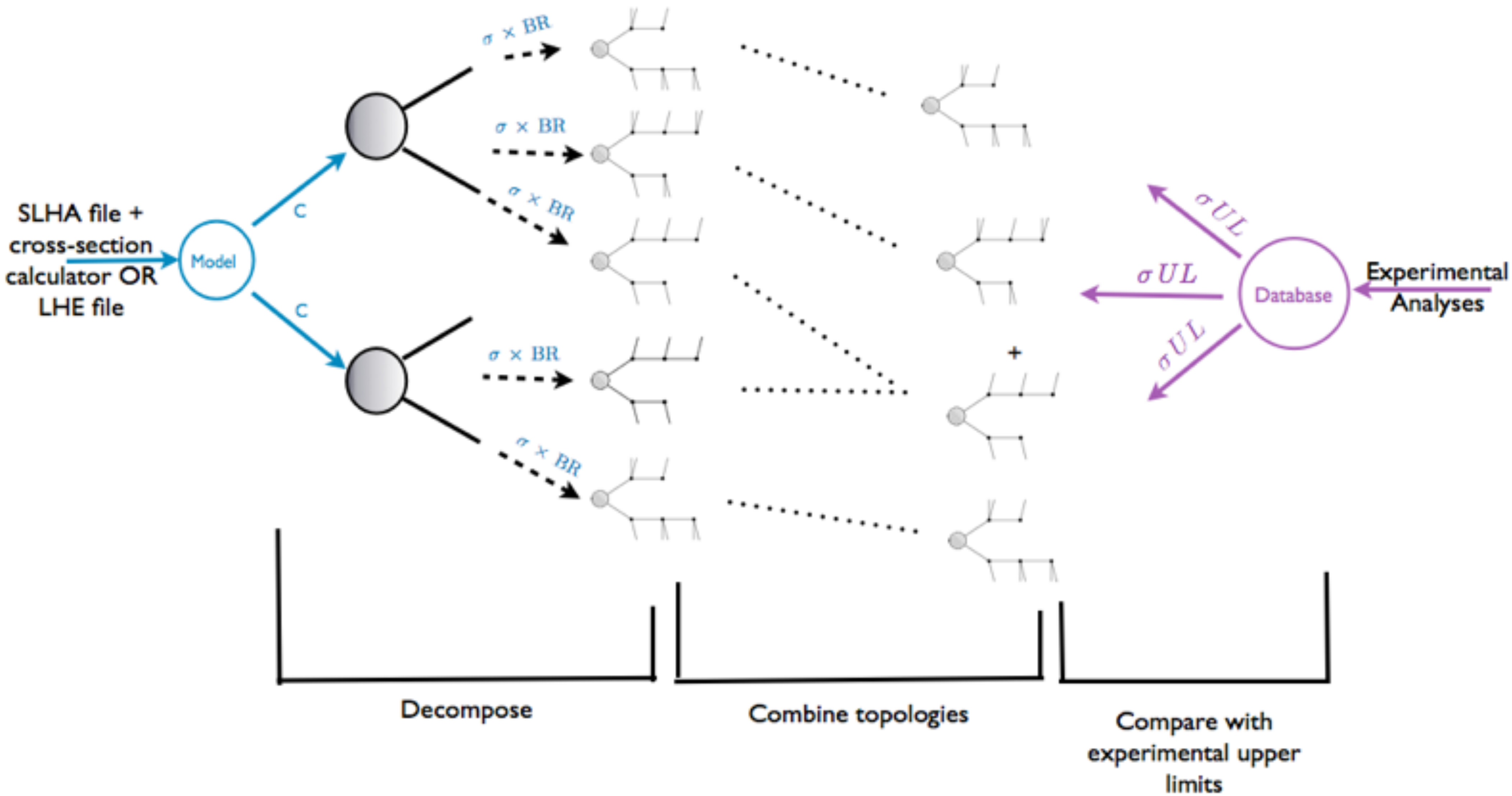


and so on...

SModelS framework

Kraml et al, arXiv:1412.1745
Eur.Phys.J. C74 (2014) 2868

- It assumes, for most experimental searches, the BSM model can be approximated by a sum over effective simplified models



- Current implementation assumes R-parity is conserved

Given
Spectra

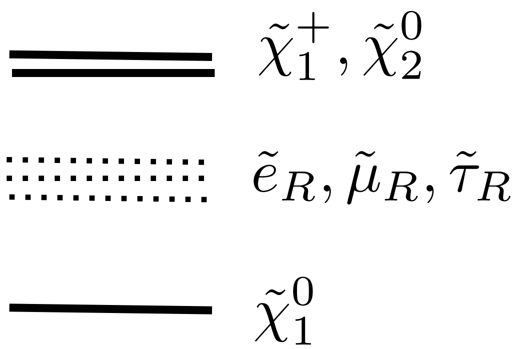
$\tilde{\chi}_1^+, \tilde{\chi}_2^0$

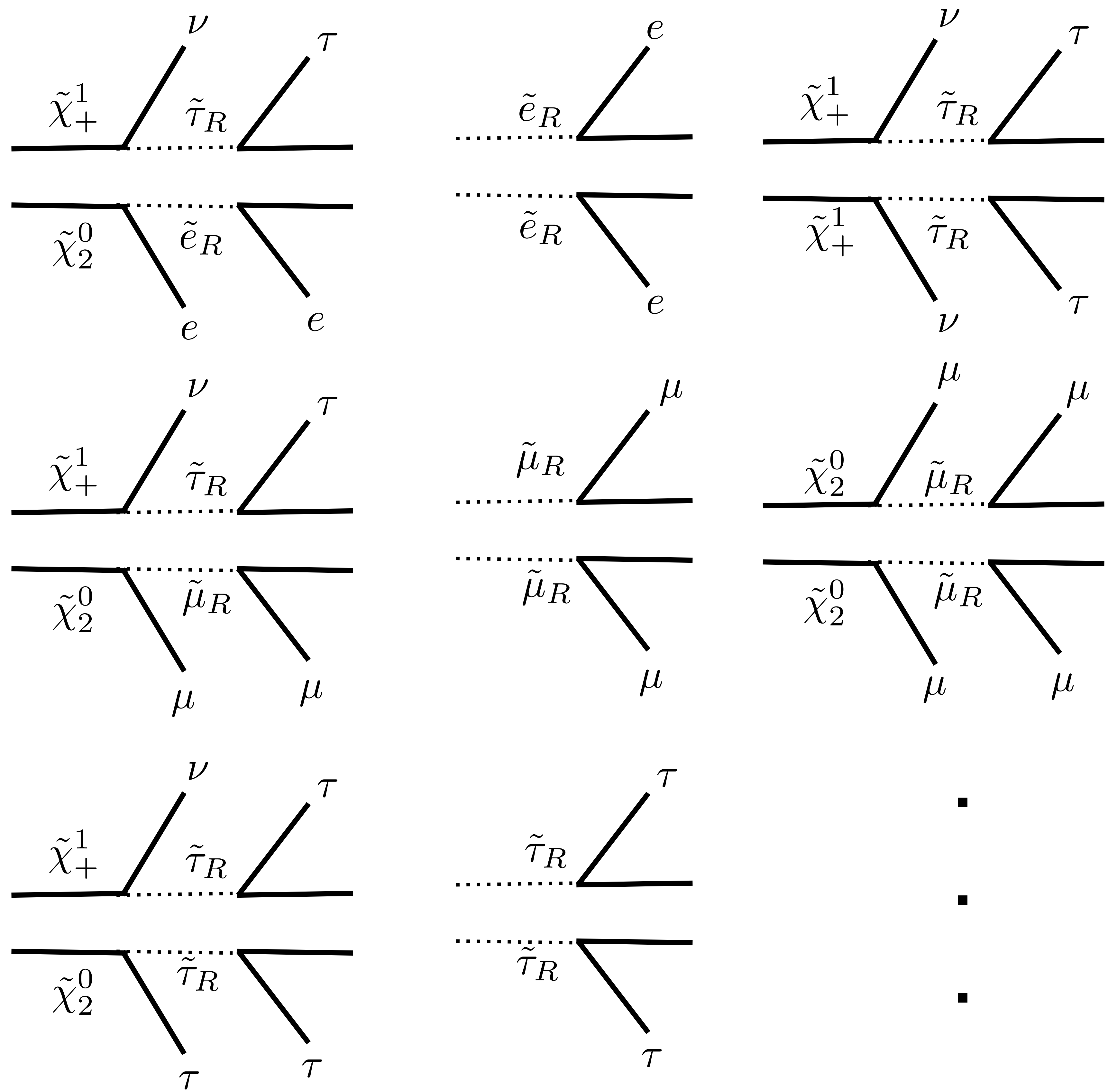
$\tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R$

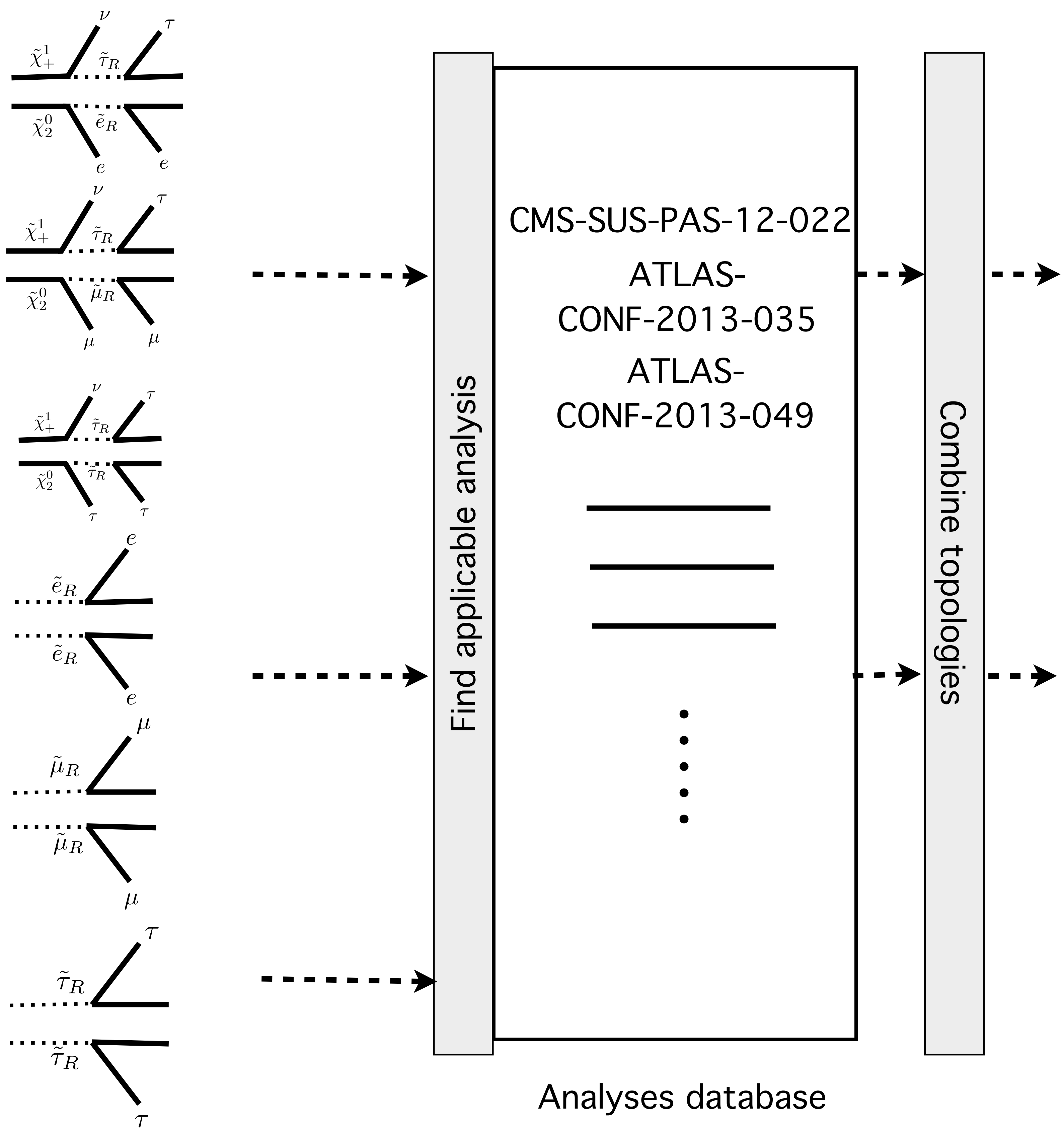
$\tilde{\chi}_1^0$

Decomposition

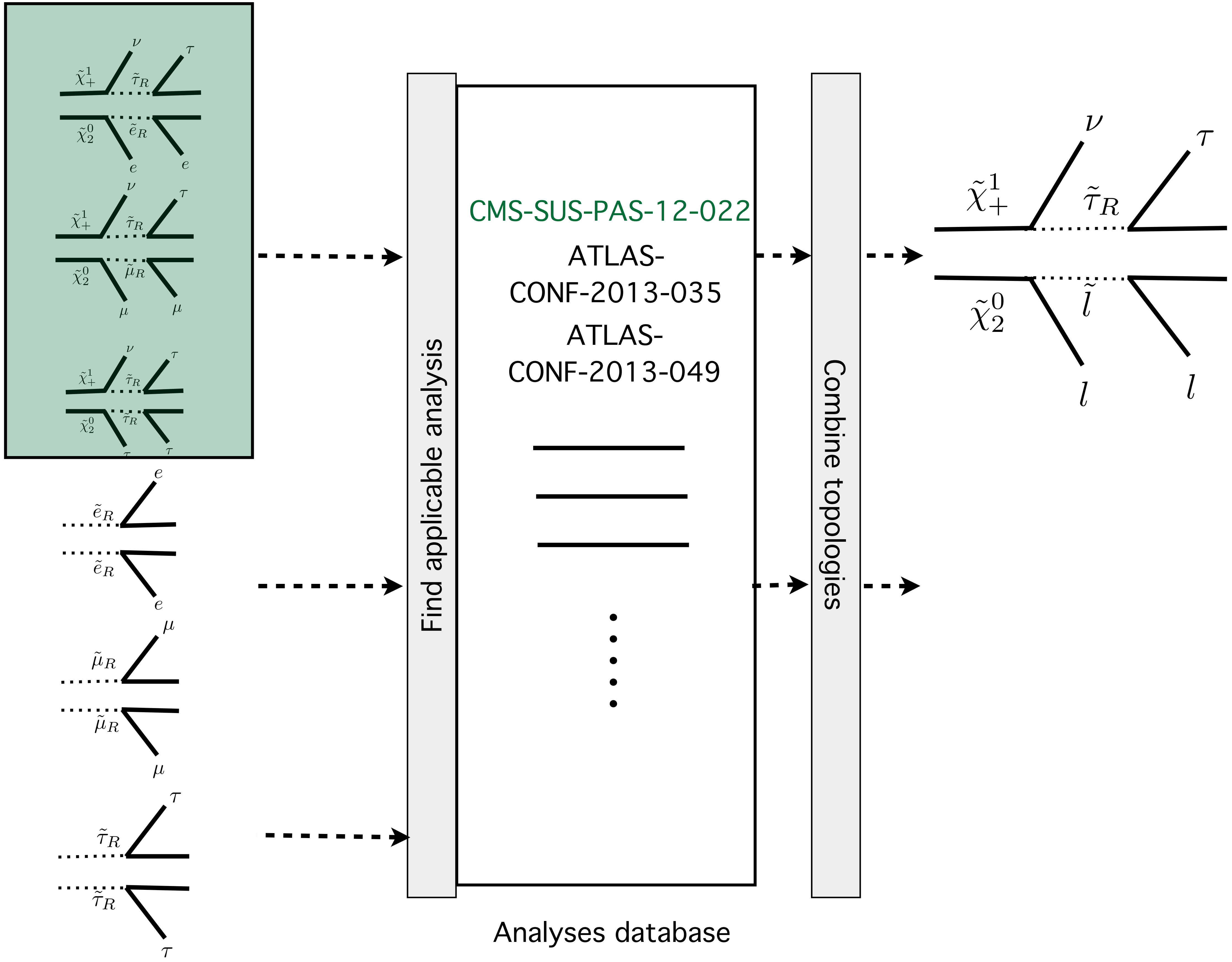
Given Spectra







CMS-SUS-PAS-12-022
ATLAS-CONF-2013-035
ATLAS-CONF-2013-049
Find applicable analysis
Combine topologies
Analyses database



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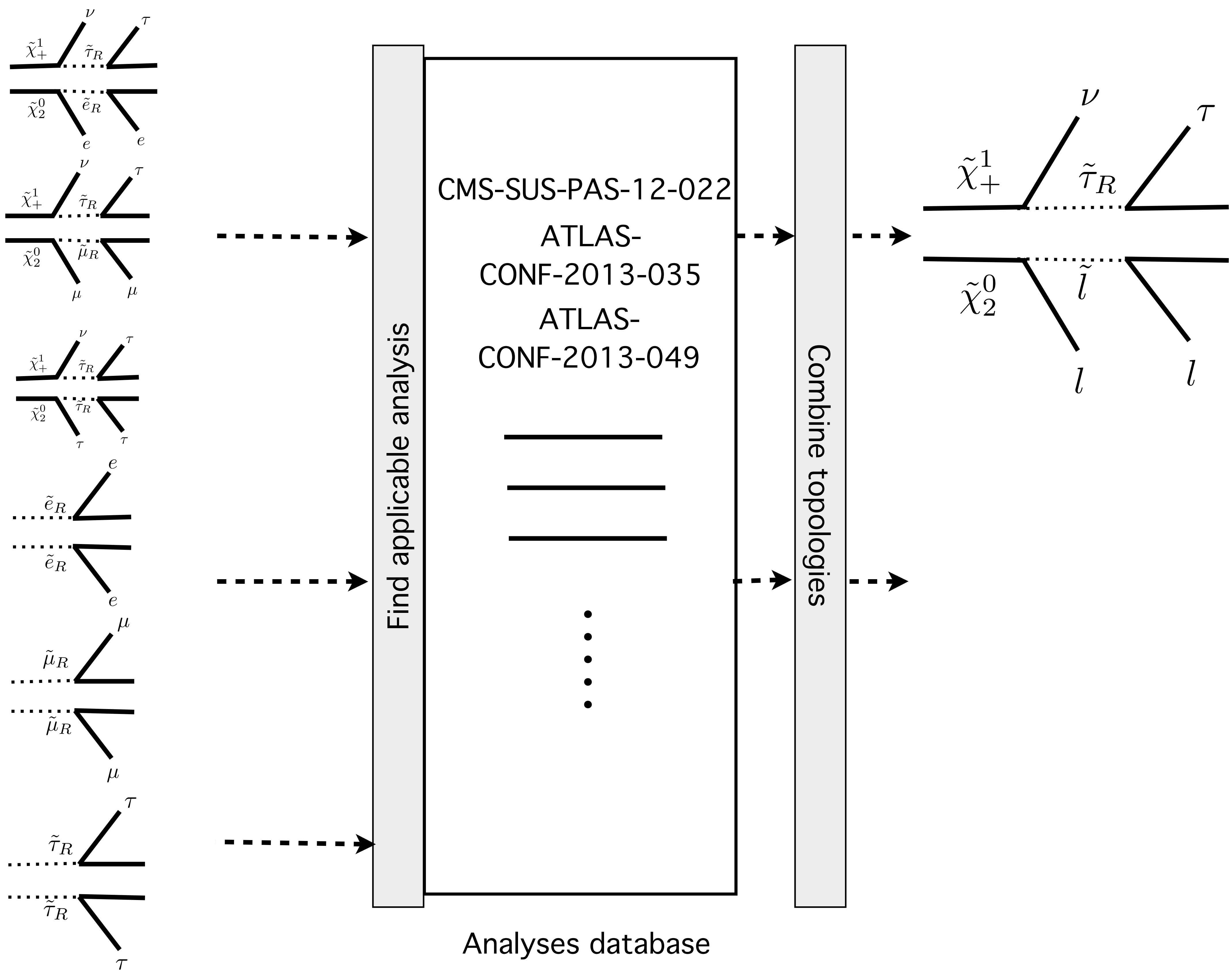
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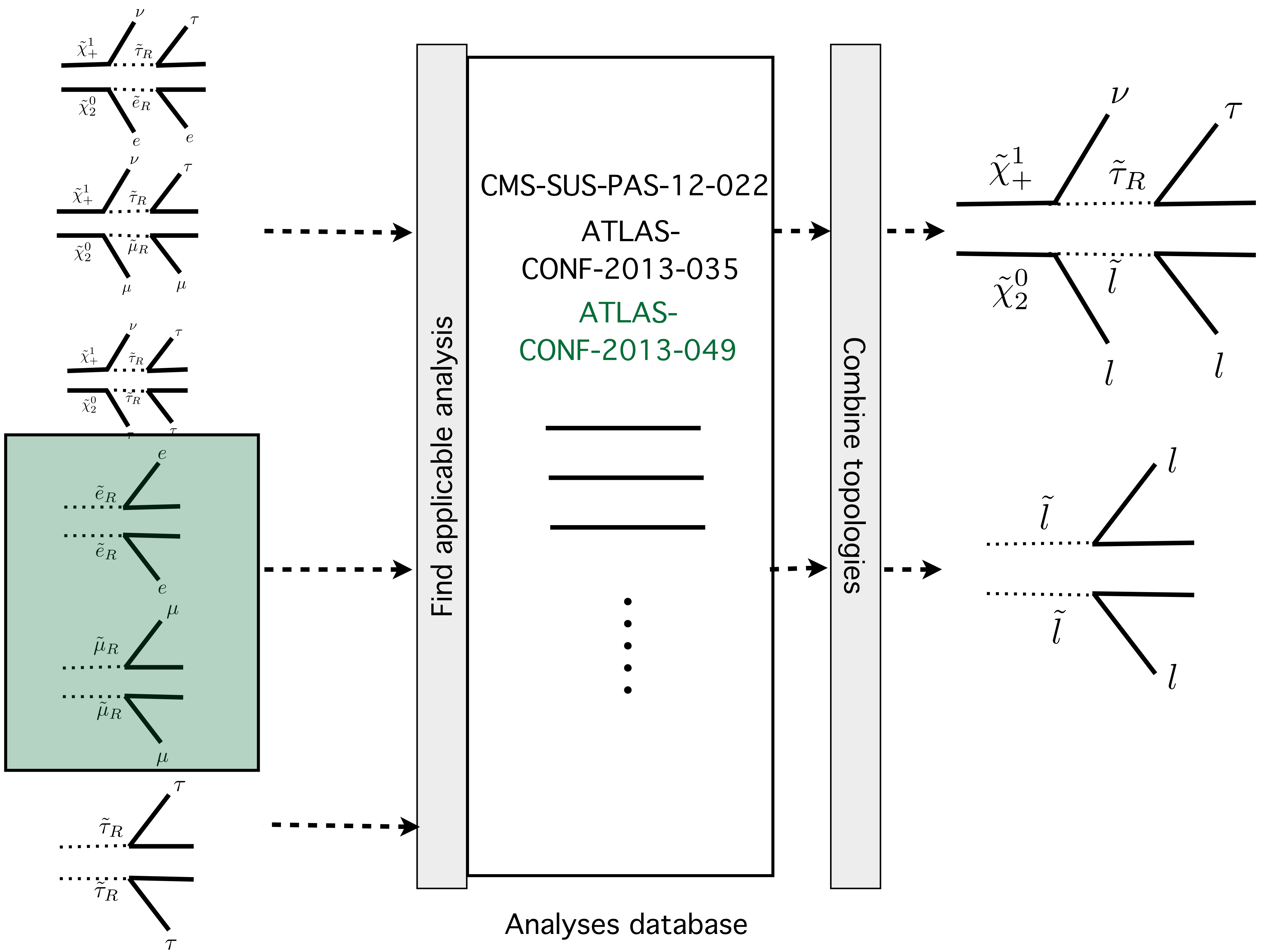
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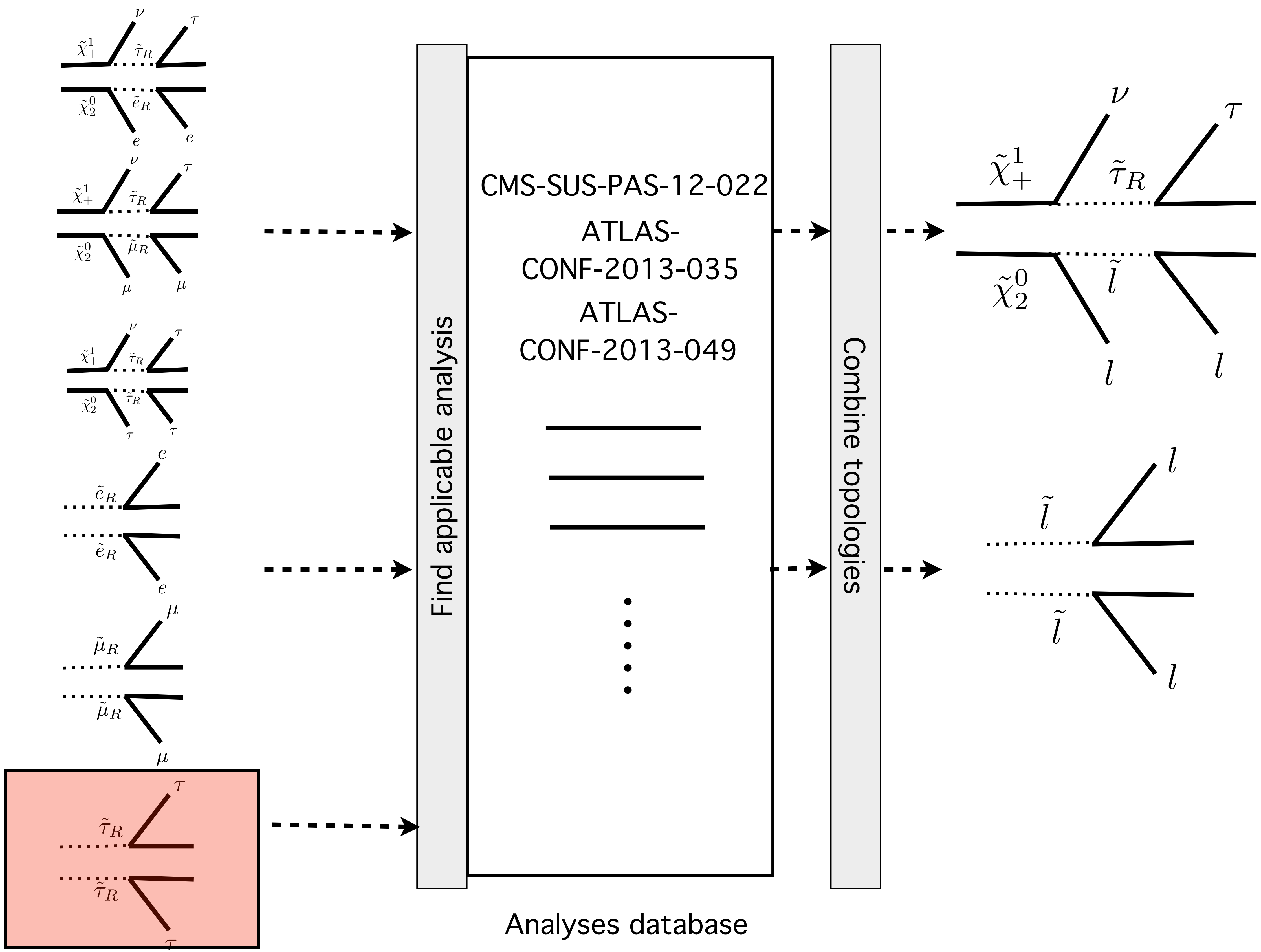

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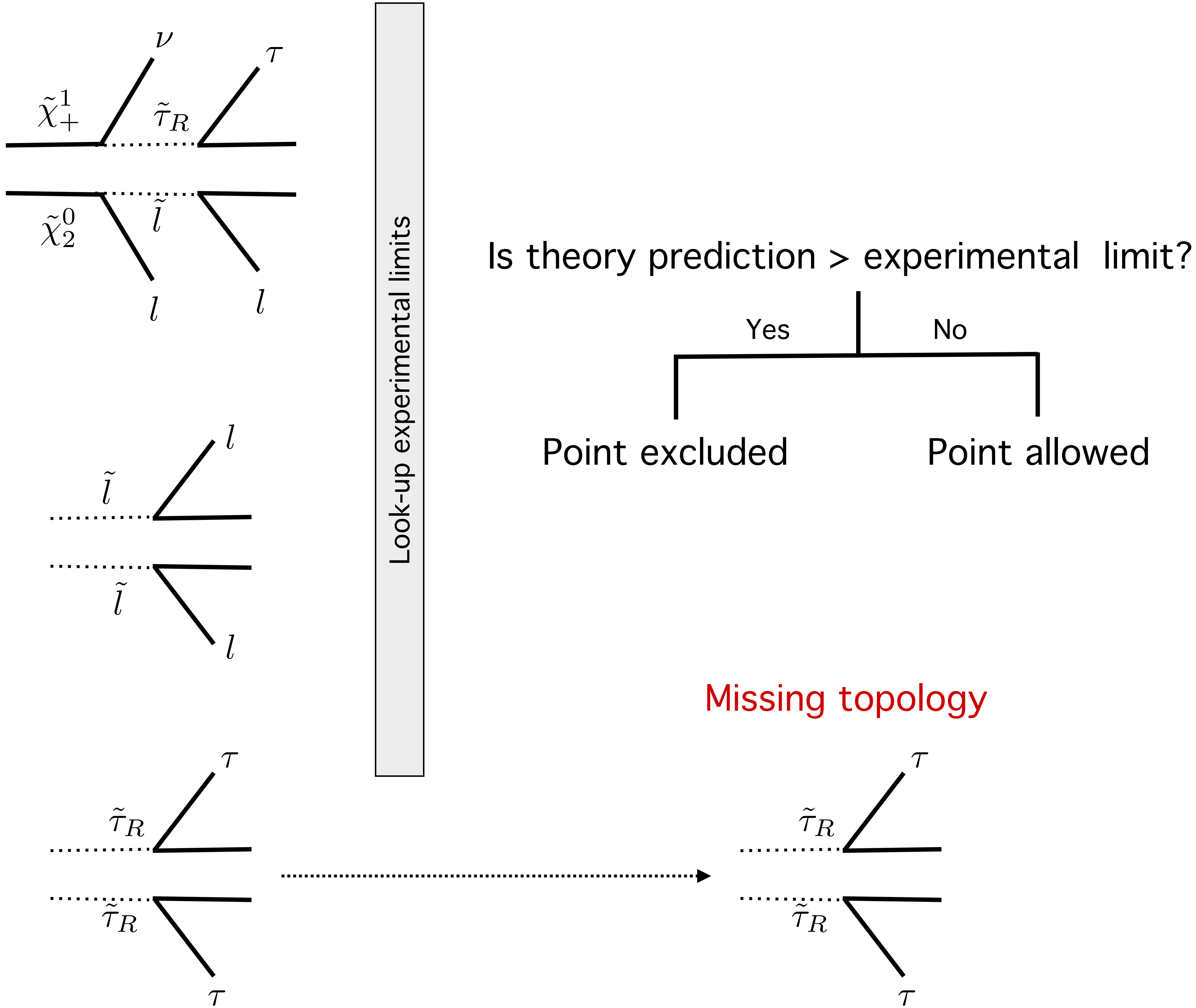

$\tilde{\chi}^1_+$
ν
$\tilde{\tau}_R$
τ
$\tilde{\chi}^0_2$
$\tilde{l}$
l
l
$\tilde{l}$
l
$\tilde{l}$
l
$\tilde{\tau}_R$
τ
$\tilde{\tau}_R$
τ
Look-up experimental limits
Is theory prediction > experimental limit?
Yes
No
Point excluded
Point allowed
Missing topology
$\tilde{\tau}_R$
τ
$\tilde{\tau}_R$
τ

SModelS framework

- Consider:

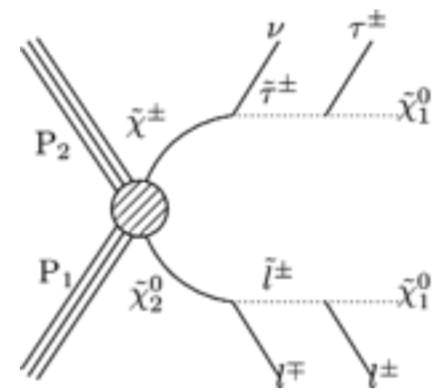
$\tilde{\chi}_1^+, \tilde{\chi}_2^0$

$\tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R$

$\tilde{\chi}_1^0$

Decompose

Element



description
masses
sigma X BR

Constraint

[[[nu],[tau]],[[L],[L]]]
[[300,200,100],[320,220,100]]
Sigma X BR

Look up upper limit if

Condition

[[[nu],[tau]],[[L],[L]]] >
3* [[[nu],[tau]],[[tau],[tau]]]

- The framework does not depend on characteristics of SUSY particles, can also be applied to decompose any BSM spectra of arbitrary complexity

SModelS language

(Why not) Use SMS results

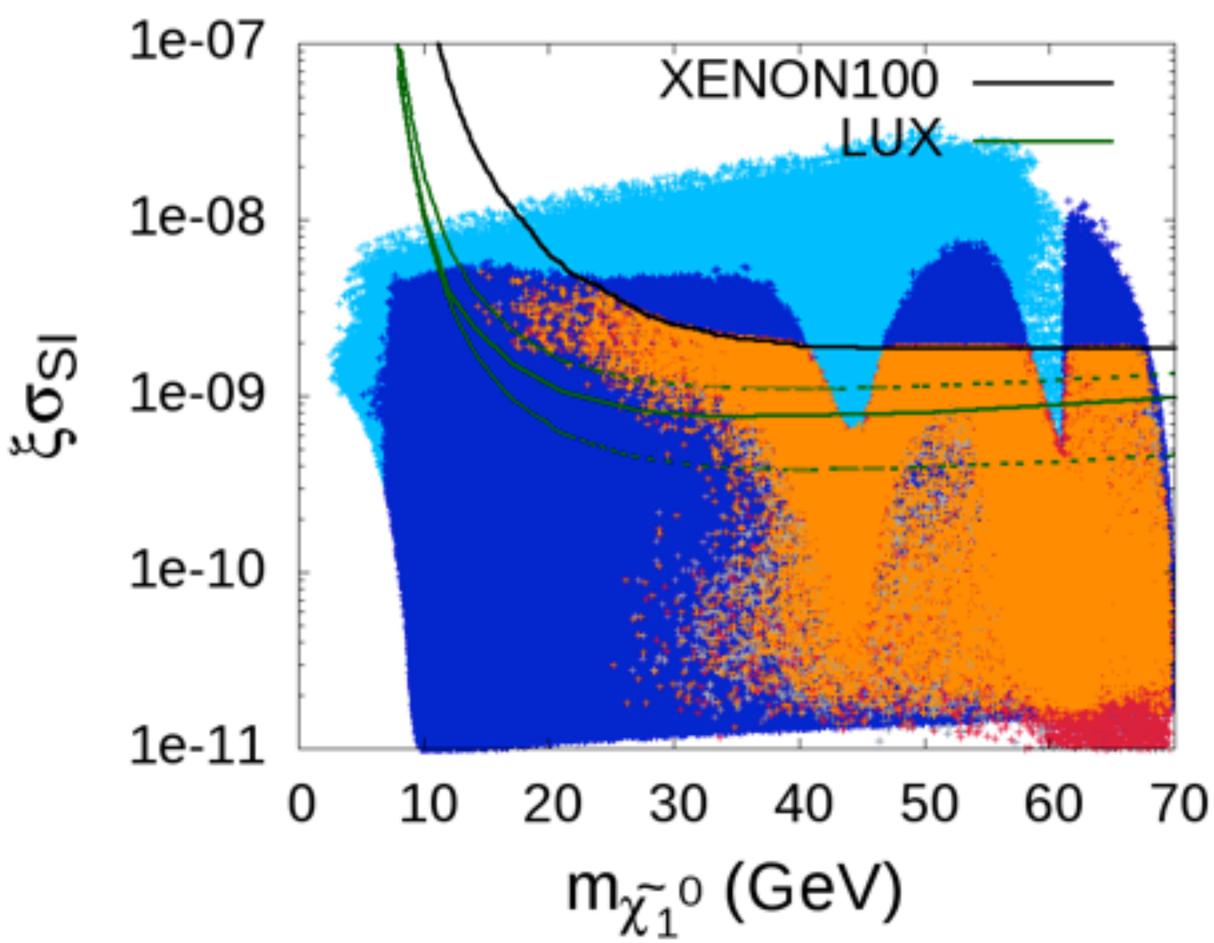
- Ignore kinematics of the process e.g. spin correlations
- Conclusions highly dependent on the availability of the results e.g. efficiency maps or upper limit maps
- Conservative limits, generic parameter space contains complicated decay chains
- SMS results almost always fail to constrain when there is no dominant decay channel (often the scenario)
- No statistical interpretation possible

Question

- Can the SMS interpretations which are directly available from the experimental collaborations be systematically used in order to draw conclusions about the viability of BSM parameter space?
- Can we have BSM search results which demonstrate the mightiness of LHC and are usable?

Neutralino LSP

G. Bélanger, G. Drieu La Rochelle, B. Dumont, R. Godbole, S. Kraml, S. Kulkarni PLB726 (2013) 773-780
see also: L. Calibbi, T. Ota, and Y. Takanishi, JHEP 1107 (2011) 013



- Flat random scan in pMSSM with 11 free parameters
- Relic generated with slepton co-annihilation
- Light neutralino respecting LHC searches can survive
- Constrain such scenarios by using Higgs signal strengths and invisible branching ratio constraints

- LUX disfavours the light neutralino DM region deemed viable in this study

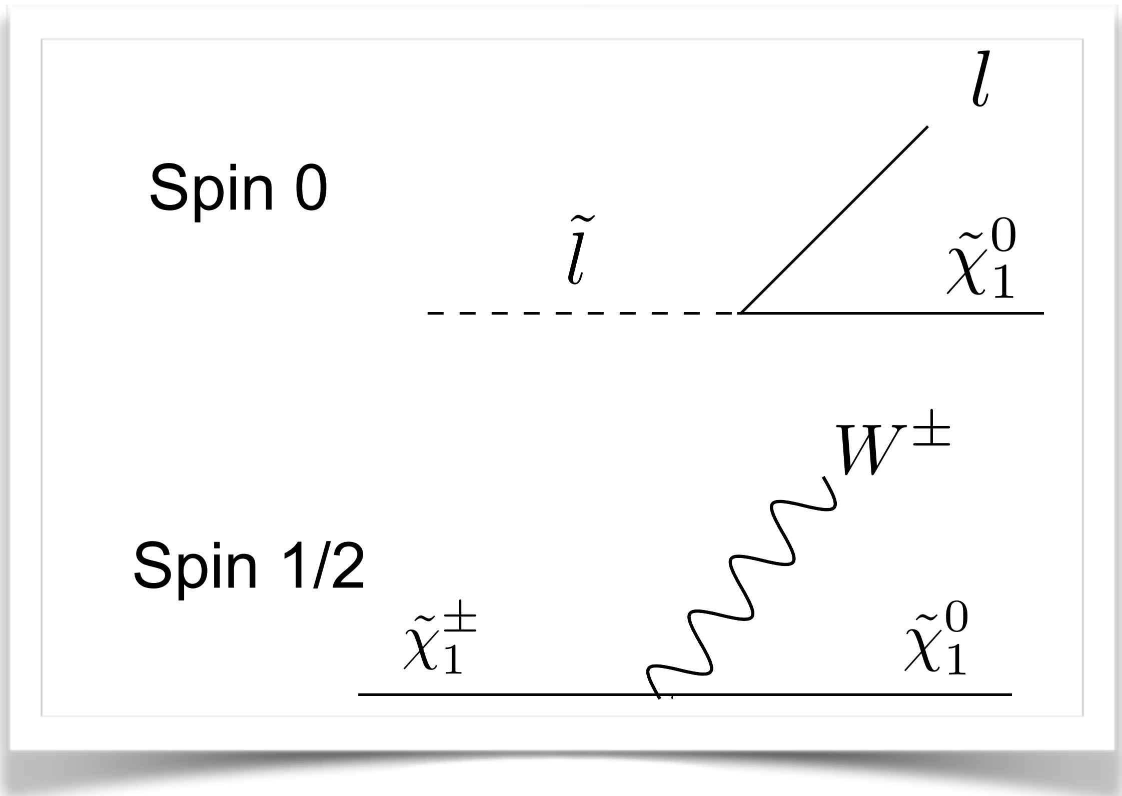
Basic constraints
Higgs couplings fits

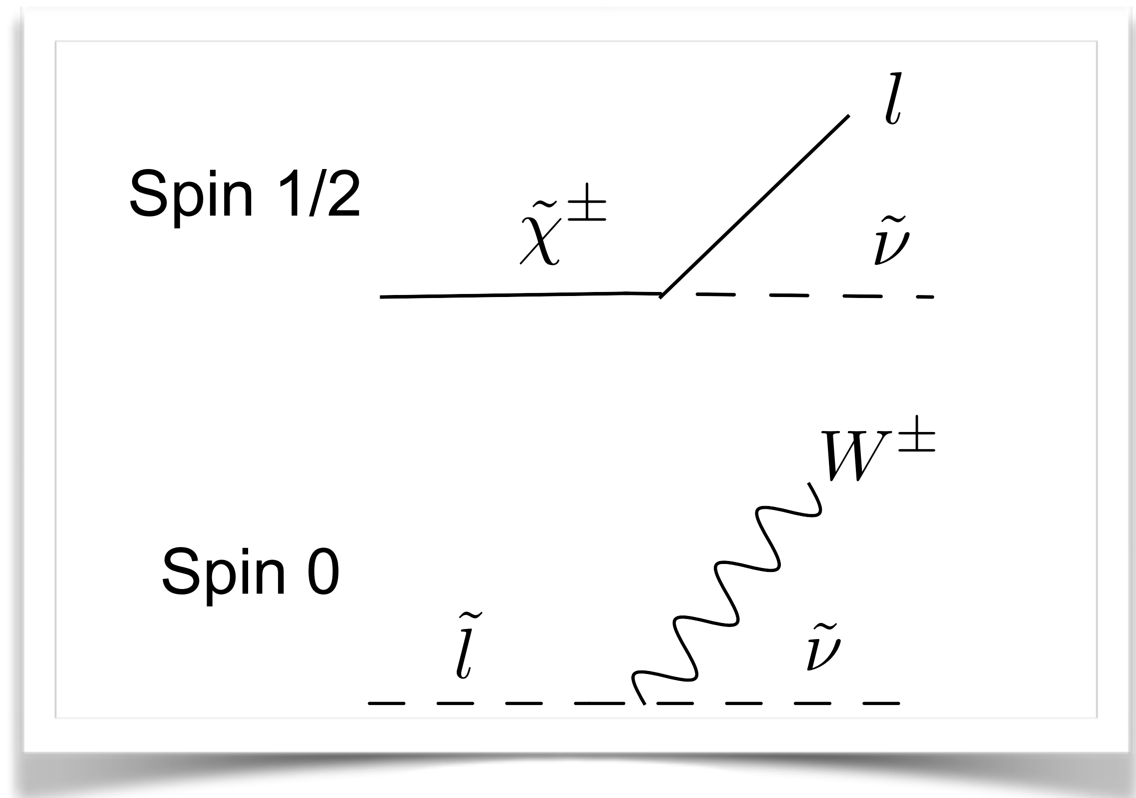
LHC results + upper limit of relic
LHC results + exact relic

Mixed Sneutrino LSP

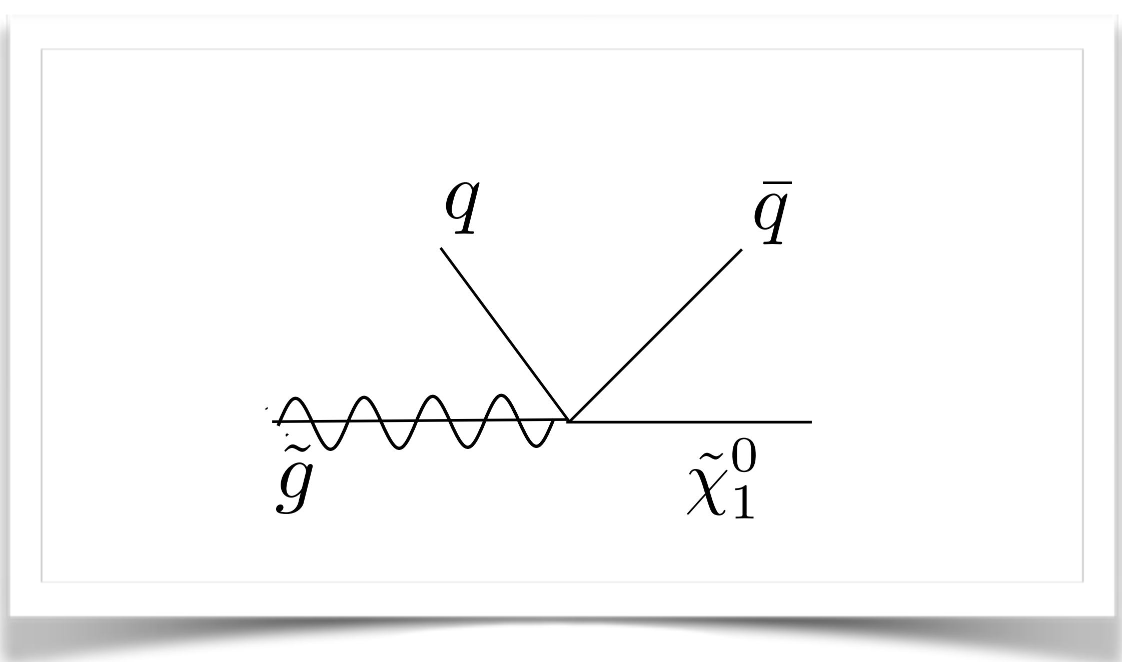
Neutralino LSP | Sneutrino LSP

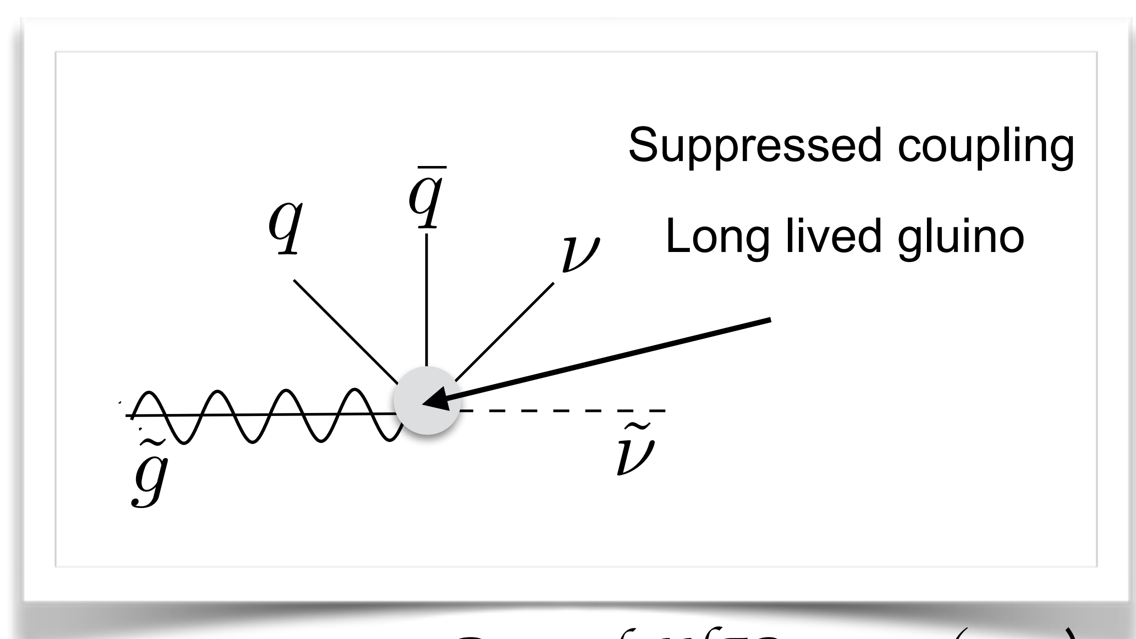
Can be the same





Can be very different



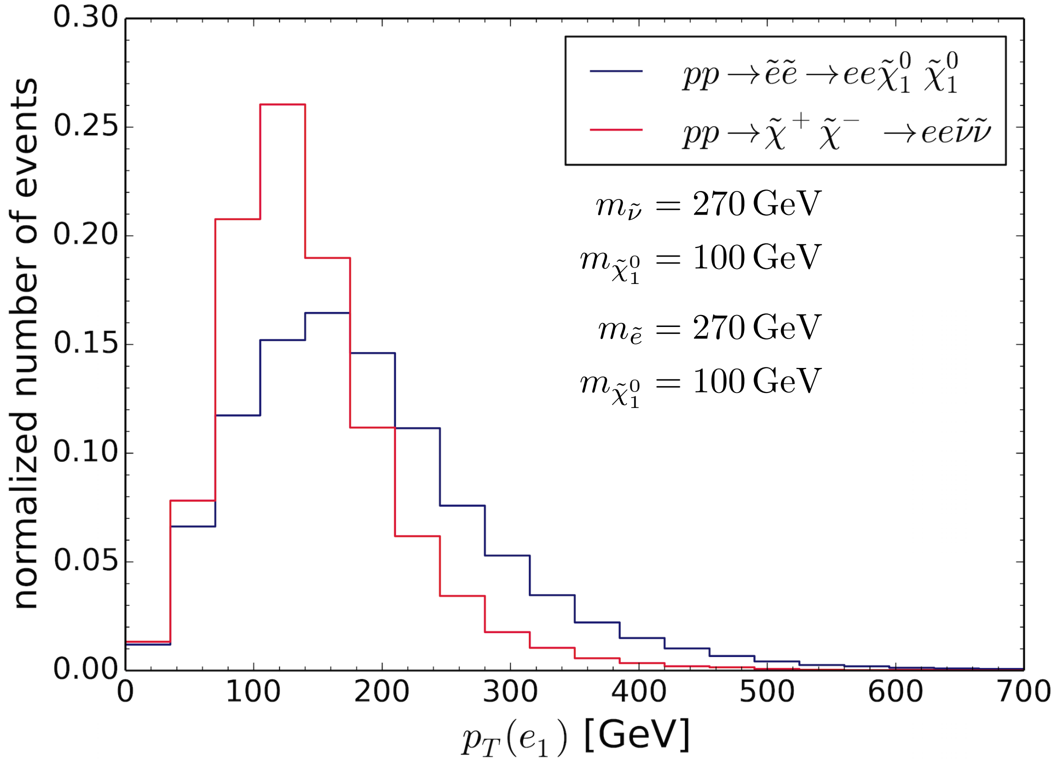


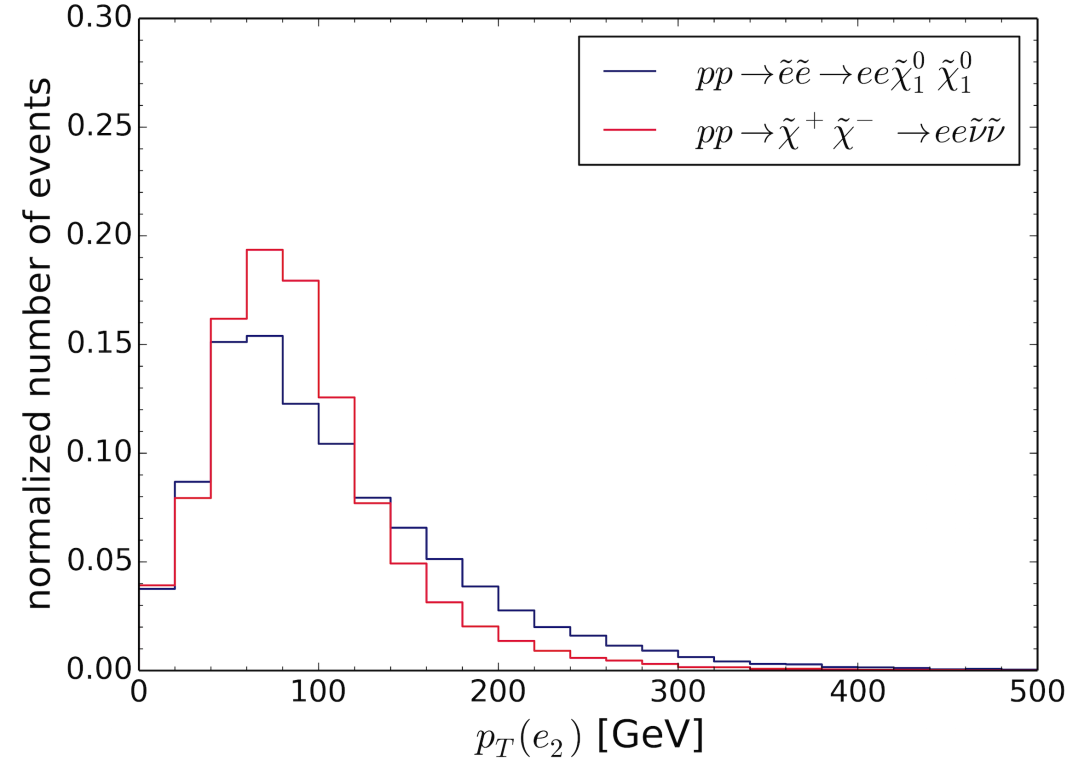
Dev et al, JHEP 09, 110 (2012)

Arina et al, JHEP04(2014)100

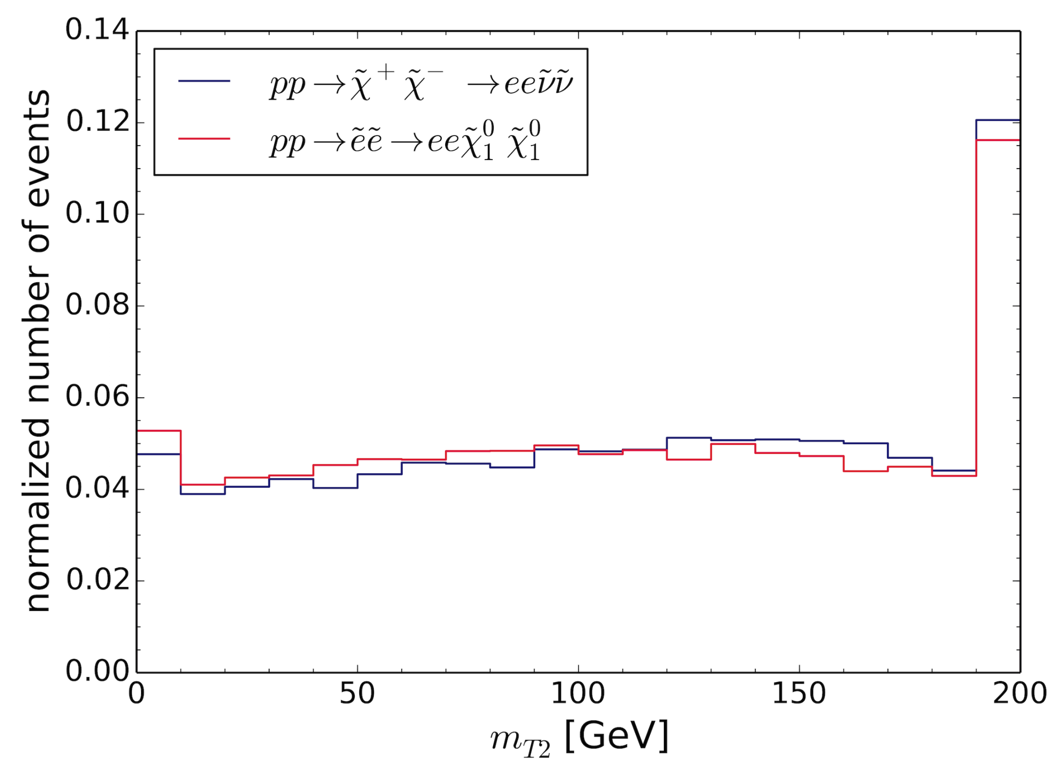
Validity of SMS results

ATLAS-SUSY-2013-11





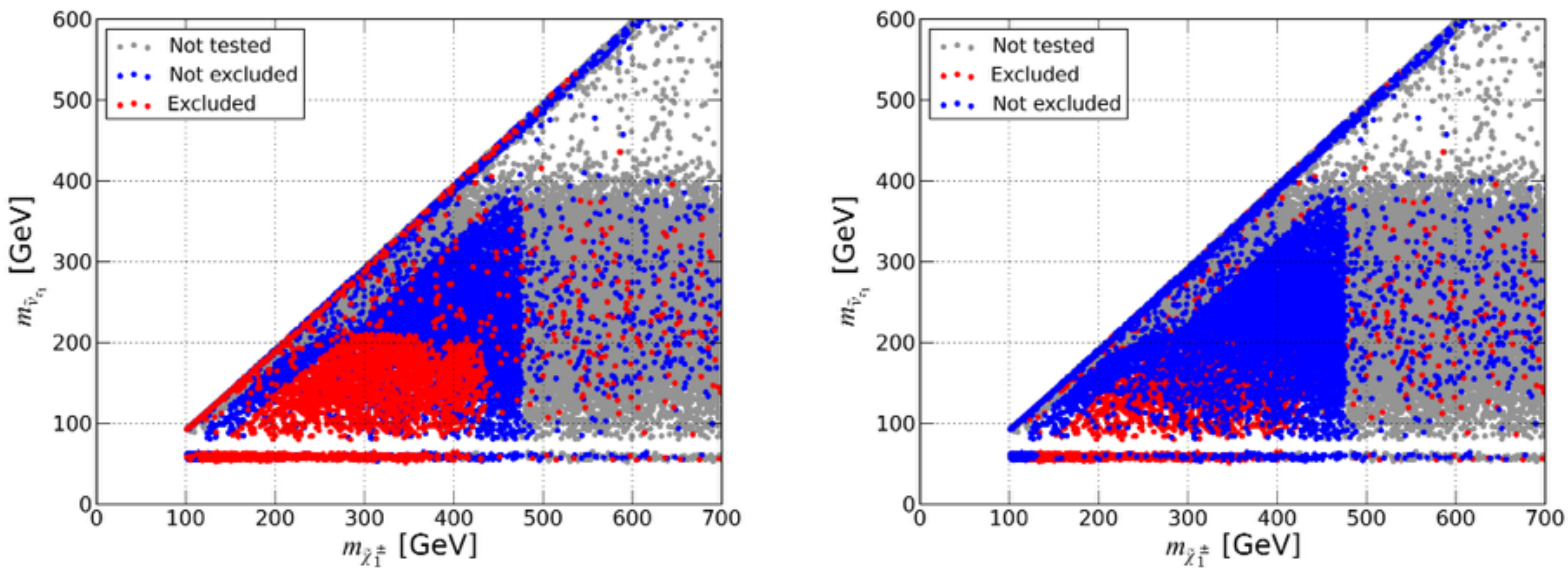
- Sample generation with MG5, decay with pythia6
- Slepton decays lead to harder leptons
- Explicit check of efficiencies by producing cutflows



LHC phenomenology

C. Arina M.E. Cabrera, S. Kraml, S. Kulkarni, U. Laa, JHEP 1505 (2015)

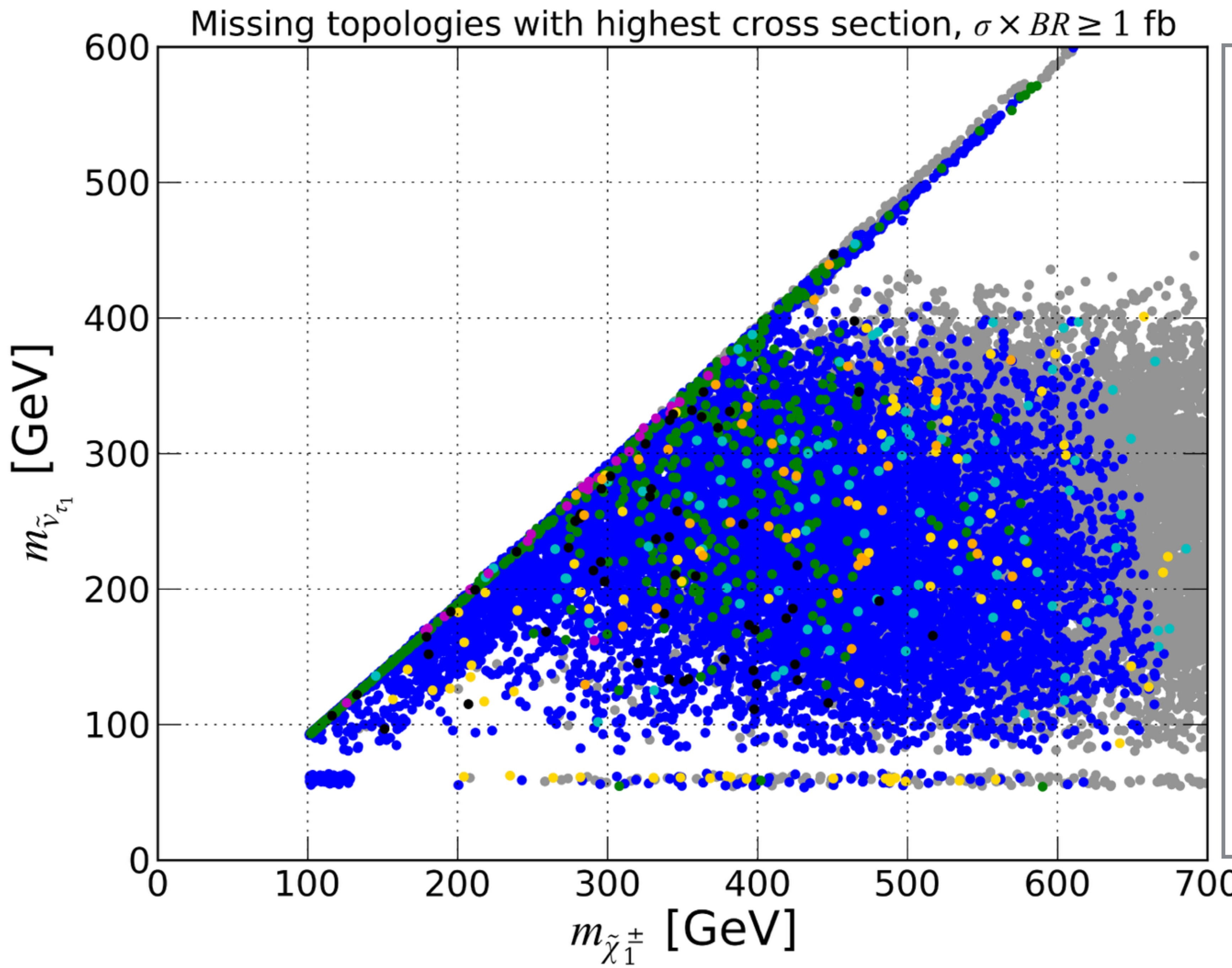
MCMC over 13 free parameters defined at the GUT scale

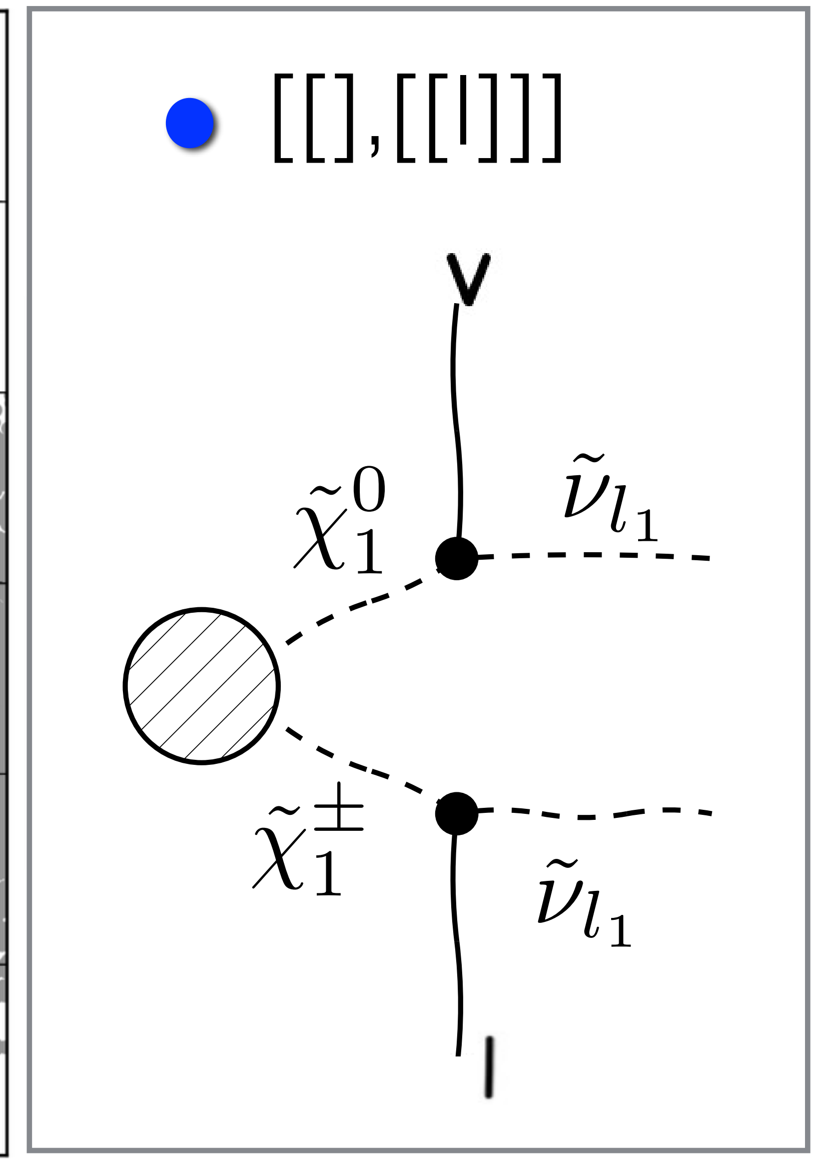


Many points can be excluded by using simplified model results however, many remain unchallenged

LHC phenomenology

Chiara Arina, M.E. Cabrera, S. Kraml, S. K., U. Laa, JHEP 1505 (2015)





Efforts ongoing to constrain this final state — new search strategy required

MSSM extensions

MSSM before the LHC Run-1

MSSM extensions

MSSM before the LHC Run-1

MSSM after the LHC Run-1

Ageing beauty of MSSM:

- Higgs branching ratio — Naturalness
- Dark matter experiments — LSP properties
- Direct searches at the LHC — Particle spectra and couplings, in particular gluino and squarks

Although, a lot of parameter is viable, extensions of MSSM are being considered seriously

MSSM extensions

UMSSM

- String inspired origin (E_6MSSM): MSSM with additional U(1)’ symmetry + right handed Dirac neutrino
- Two dark matter candidates: Neutralino, purely RH sneutrino
- N.B. model contains 6 neutralinos thanks to extra singlino and gauge boson
- Presence of additional Z’ gauge boson due to U(1)’ symmetry
- LHC constraints on Z’: model suffers from fine tuning

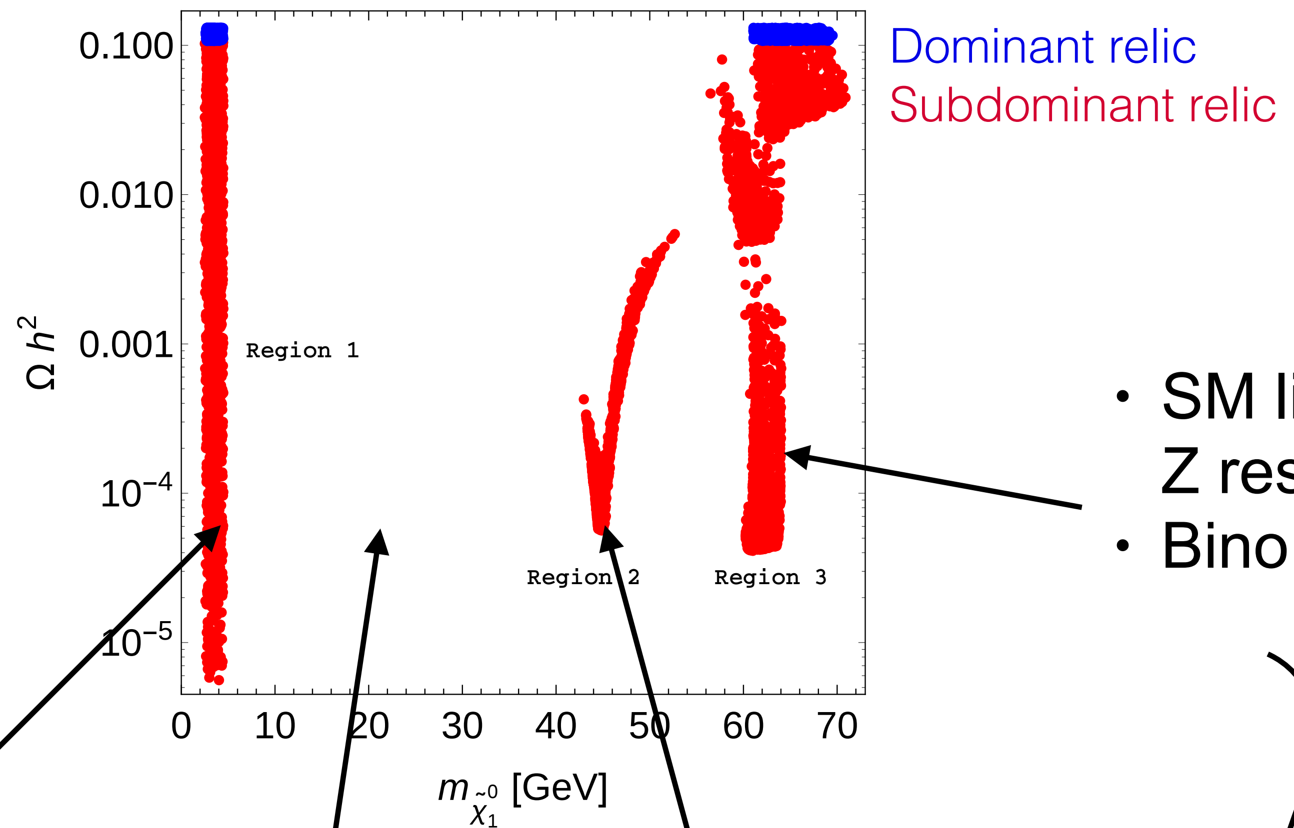
MNMSSM

- MSSM with additional singlet field
- Possess discrete R-symmetry which forbids cubic self interactions of the singlet filed
- No mass term for the pure singlino, only mixing with Higgsino raises singlino mass

NMSSM

D. Barducci, G. Bélanger, C. Hugonie, A. Pukhov, arXiv:1510.00246
See also: D. A. Vasquez, G. Belanger, C. Boehm, J. Da Silva, P. Richardson, PRD86 (2012) 035023

Feasibility study of a very light singlino DM ~< 5GeV
Semi universal MCMC scan over 9 parameters



- SM like h and Z resonance
- Bino LSP

h₁ SM like

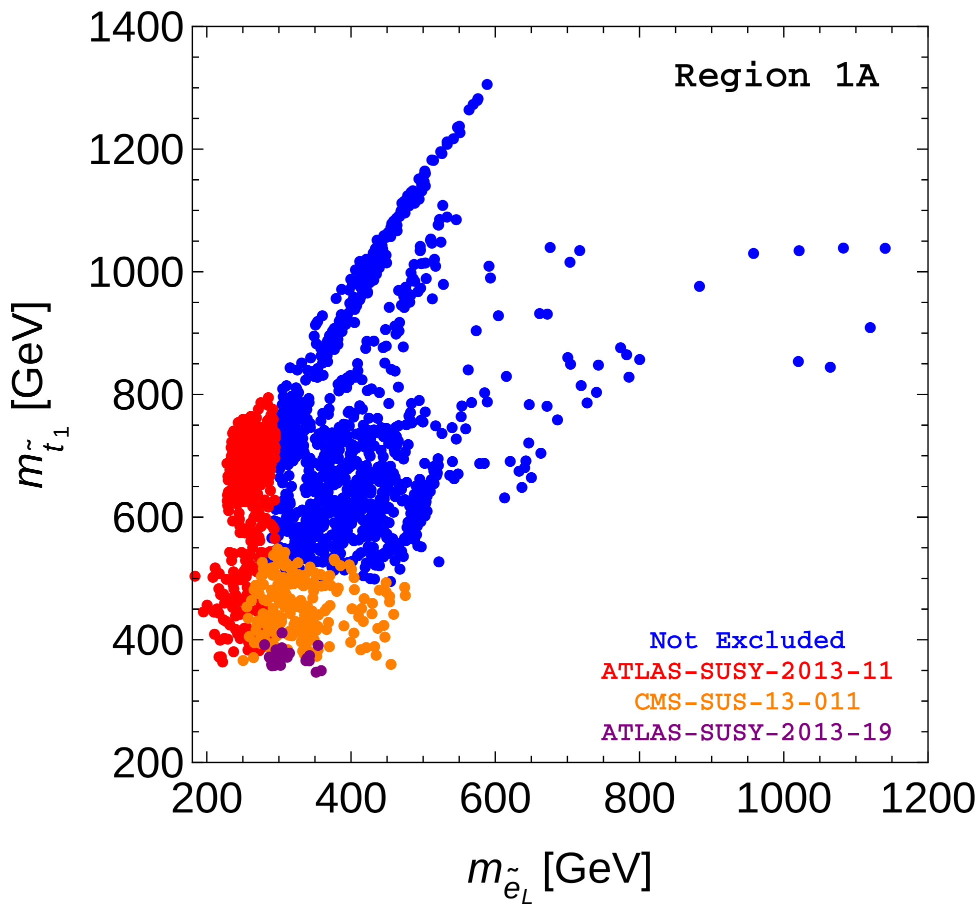
- Light pseudo scalar (singlet-like) Higgs resonance
- h_2 SM like
- Singlino LSP

- Gap due to Higgs invisible BR

- Z resonance
- Mixed singlino-higgsino LSP

h_1 SM like

NMSSM



- Region 1 containing light sleptons and stops completely constrained by SModelS
- Applying SMS results to light gluino is a generic problem
- Reinterpret LHC gluino searches for regions of parameter space containing light gluino (Generic reinterpretation)
- Only singlino LSP with mass ~5GeV can form entire dark matter, all other regions can only contribute to a subdominant component

Simplified model reinterpretation - II

See also:

M. Papucci, K. Sakurai, A. Weiler, L. Zeune, Eur.Phys.J. C74 (2014) 11, 3163

D. Barducci, A. Belyaev, M. Buchkremer, J. Marrouche,
S. Moretti, L. Panizzi, CPC 197 (2015) 263-275

Non-MET final states

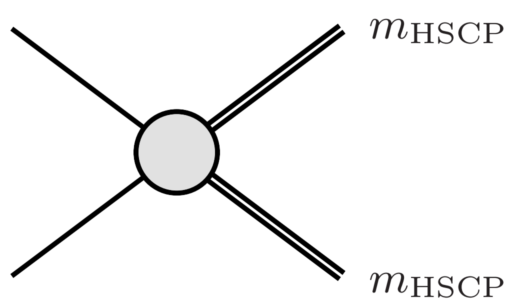
J. Heisig, A. Lessa, L. Quertenmont arXiv: 1509.00473

see also: G. Bélanger, J. Da Silva, U. Laa, A. Pukhov, JHEP 1509 (2015) 151

- Heavy stable charged particles: result of suppressed phase space
- A generic decomposition of the parameter space leads to:

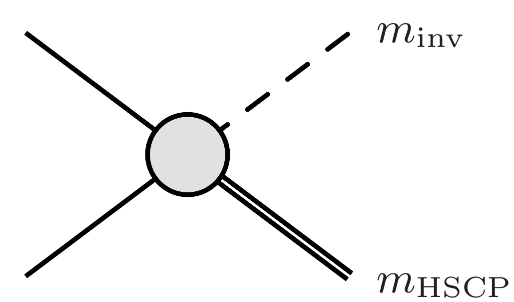
Purely HCSP final state

$$pp \to \widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^{\pm}$$

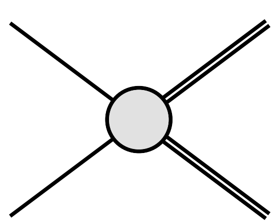


Mixed MET-HCSP final state

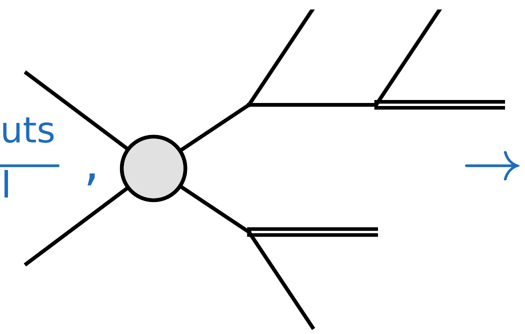
$$pp \to \widetilde{\chi}_1^{\pm}\widetilde{\chi}^{0}$$



- Precompute efficiencies for various decay chains



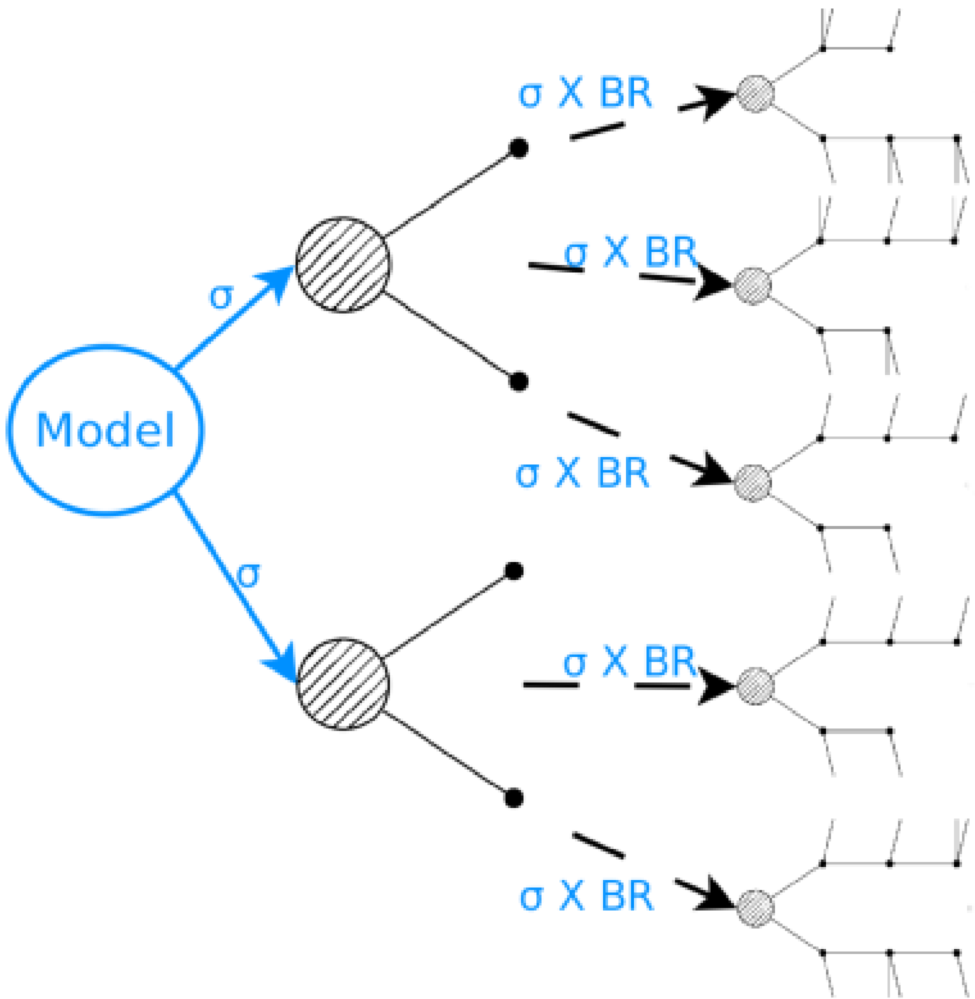
$$\to \epsilon_1(m_{\rm HSCP}) = \frac{\sigma^{\text{after cuts}}}{\sigma^{\text{total}}},$$



$$\to \epsilon_2\,(m_{\rm prod}, m_{\rm int}, m_{\rm HSCP}) \ldots$$

Non-MET final states

- Use precomputed efficiencies to constrain your model



$\longrightarrow (\sigma \times BR) \times \epsilon_1$

$\longrightarrow (\sigma \times BR) \times \epsilon_2$

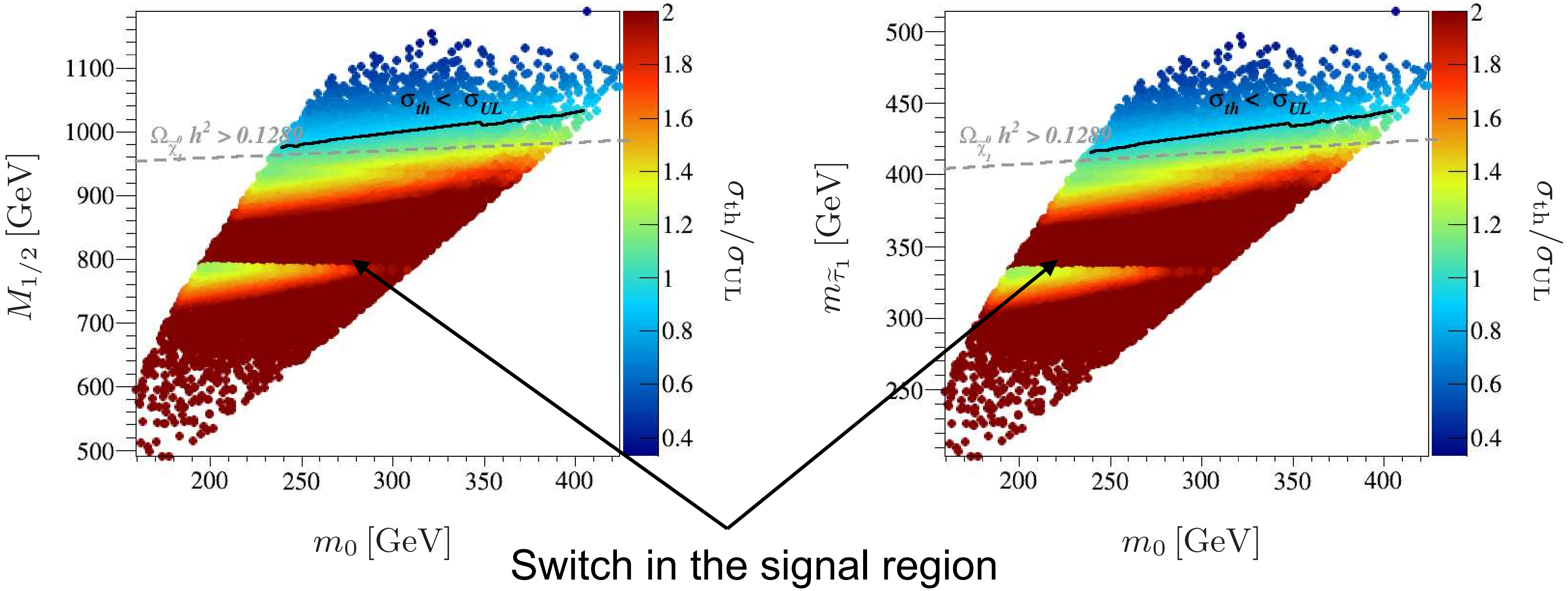
$\longrightarrow (\sigma \times BR) \times \epsilon_3 \quad \Rightarrow \sigma_{eff} = \sum_i (\sigma BR \epsilon_i)$

$\longrightarrow (\sigma \times BR) \times \epsilon_4$

$\longrightarrow (\sigma \times BR) \times \epsilon_5$

Charged particles

- Parameter space motivated by solution to cosmological ^{7}Li problem
- Parameter space consists of long lived staus — dark matter neutralino



- Non-MET searches dominate the exclusion
- Entire parameter space compatible with relic density constraints is excluded by LHC results

SMS wish list

Currently, SModelS group is implementing all efficiency maps from all 8 TeV results, so far only work on ATLAS is near completion

Out of 15 analysis 6 can not be used

1. Give efficiency maps for all signal regions, information on only best SR does not help
2. For topologies containing more than two masses, give at least three mass planes which can be interpolated between (for both efficiency maps and upper limit maps)
3. For such maps, give consistent results, we have cases when we can not complete closure test
4. For cross section upper limit maps provide maps which can be interpolated, too coarse a binning can not be used

Conclusions

1. SMS results come with their pros and cons, a big pro is simplicity and speed of usage, and a big con is conservative limits
2. However, they can effectively constrain parameter space
3. They provide an important feedback e.g. missing topologies, to the experimentalists and put the hard work they have done to a practical use
4. Usage of efficiency maps over upper limits map will be very beneficial in many cases (does not mean upper limits should be discarded)
5. An important opportunity for the experimentalists and theorists to contribute and collaborate
6. Finally, it is possible to extend simplified model analysis to non-MET searches and such inclusions will only improve the situation further

Backup

Mixed Sneutrino LSP

Inclusion of neutrino mass terms modify scalar sector as well:

$$W = \epsilon_{ij}(\mu \hat{H}_i^u \hat{H}_j^d - Y_l \hat{H}_i^d \hat{L}_j \hat{R} + Y_\nu \hat{H}_i^u \hat{L}_j \hat{N})$$

$$V_{\text{soft}} = M_L^2\, \tilde{L}_i^* \tilde{L}_i + M_N^2\, \tilde{N}^* \tilde{N} - [\epsilon_{ij}(\Lambda_l H_i^d \tilde{L}_j \tilde{R} + \Lambda_\nu H_i^u \tilde{L}_j \tilde{N}) + \text{h.c.}]$$

Borzumati & Nomura, hep-ph/0007018

Arkani-Hamed et al., hep-ph/0006312

Dirac masses for neutrinos: $m_D = v_u Y_\nu$

Sneutrino left and right components mix:

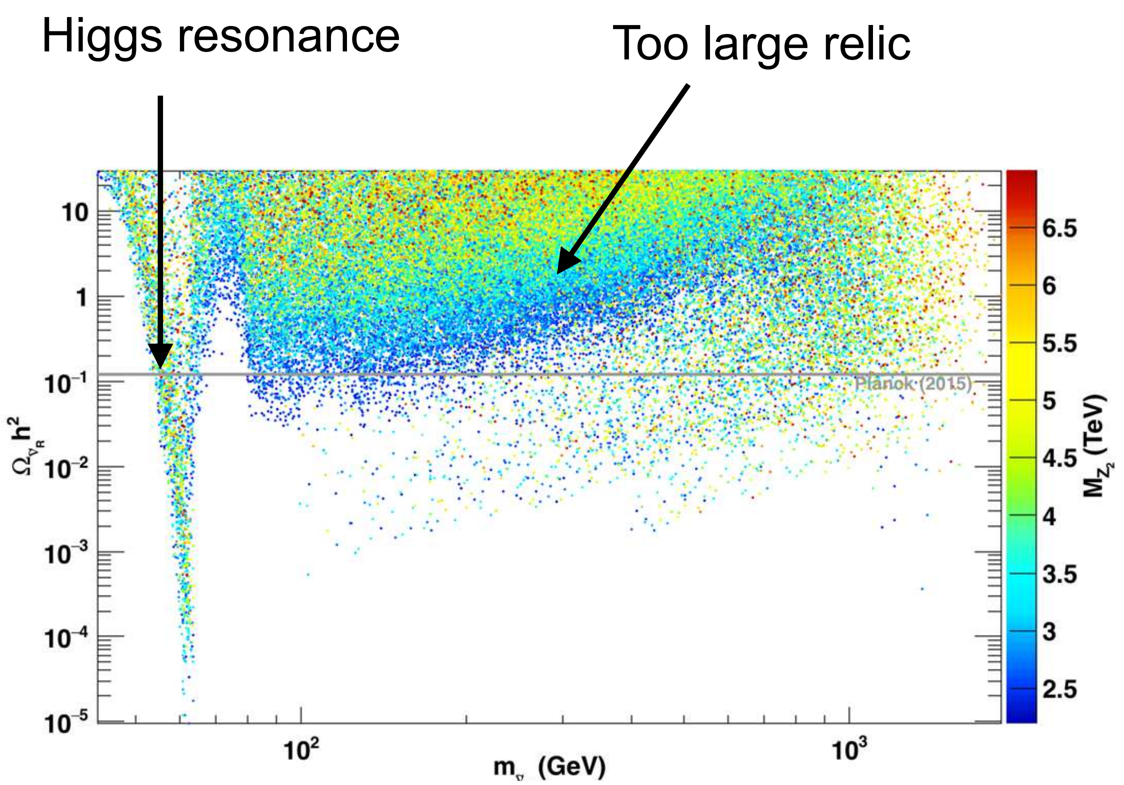
$$\begin{cases} \tilde{\nu}_{\tau_1} = -\sin\theta_{\tilde{\nu}}\ \tilde{\nu}_L + \cos\theta_{\tilde{\nu}}\ \tilde{N} \\ \tilde{\nu}_{\tau_2} = +\cos\theta_{\tilde{\nu}}\ \tilde{\nu}_L + \sin\theta_{\tilde{\nu}}\ \tilde{N} \end{cases}$$

$$\mathcal{M}_{LR}^2 = \begin{pmatrix} m_L^2 + \frac{1}{2} m_Z^2 \cos(2\beta) + m_D^2 & \frac{v}{\sqrt{2}} A_{\tilde{\nu}} \sin\beta - \mu m_D \text{cotg}\beta \\ \frac{v}{\sqrt{2}} A_{\tilde{\nu}} \sin\beta - \mu m_D \text{cotg}\beta & m_N^2 + m_D^2 \end{pmatrix}$$

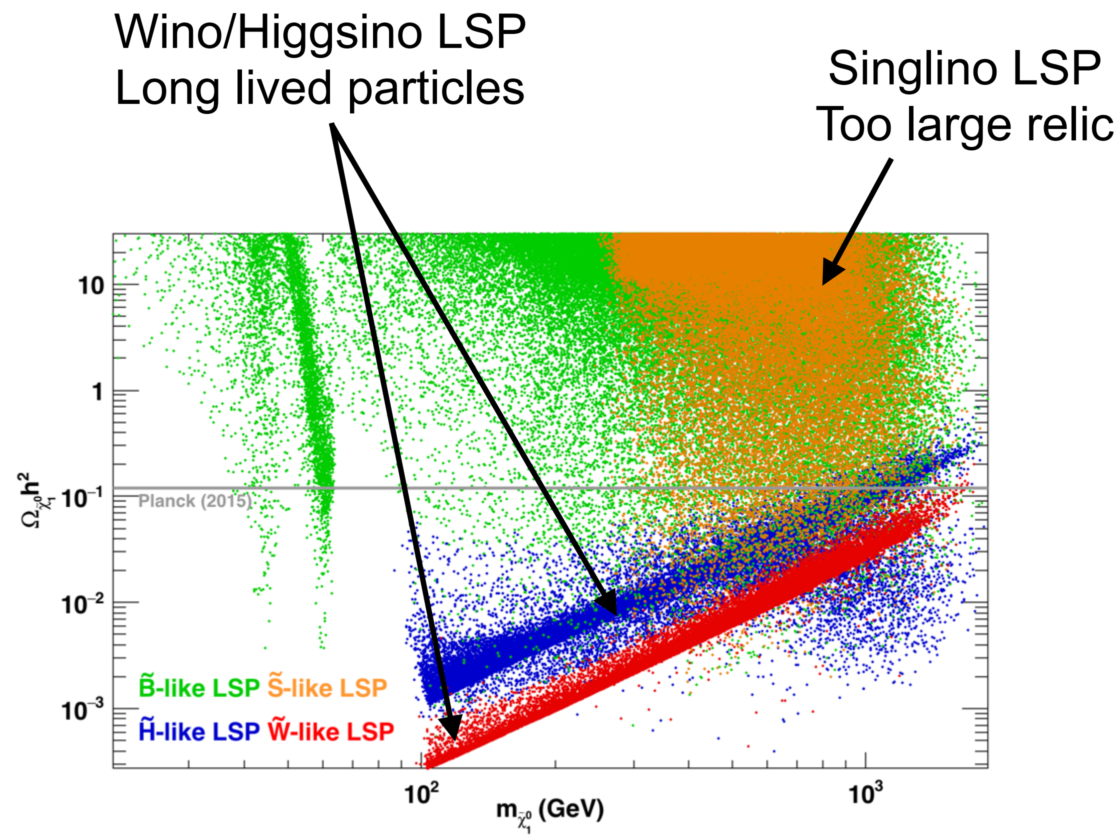
Sneutrino LSP models address two issues at once: DM and neutrino masses

UMSSM

Sneutrino LSP

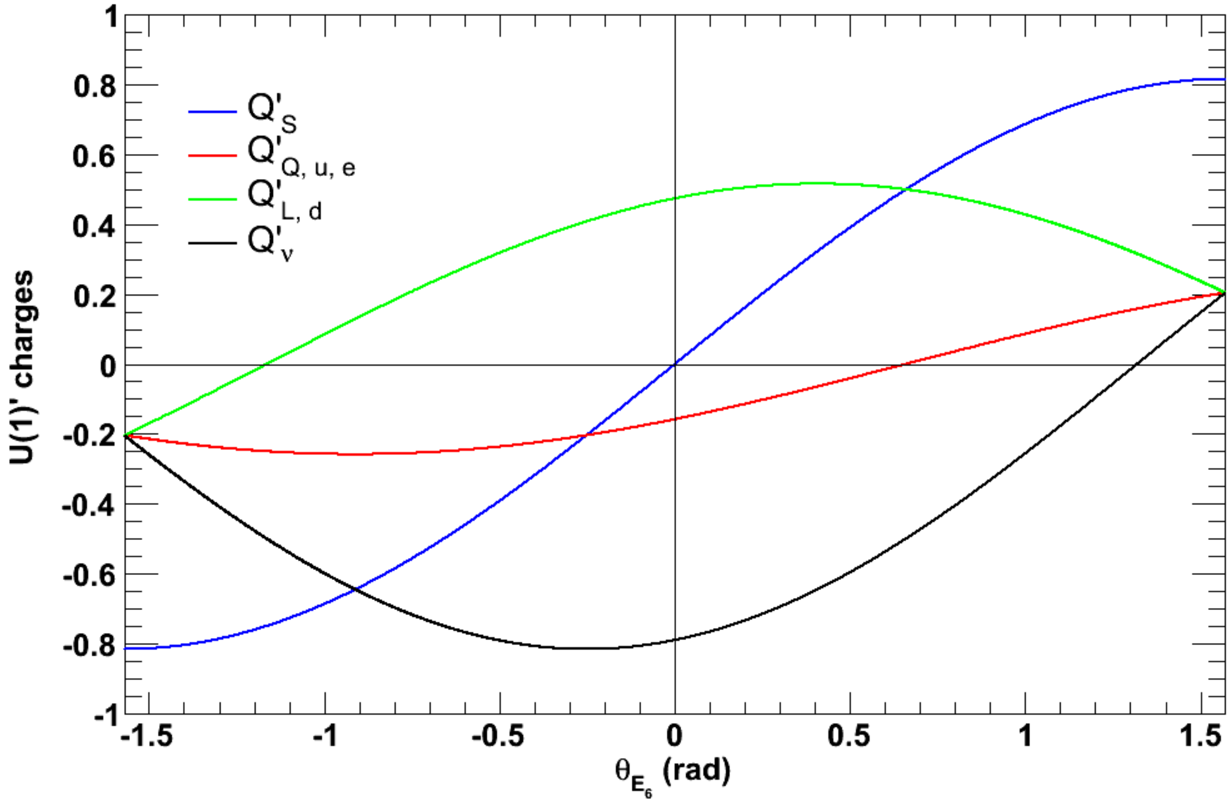


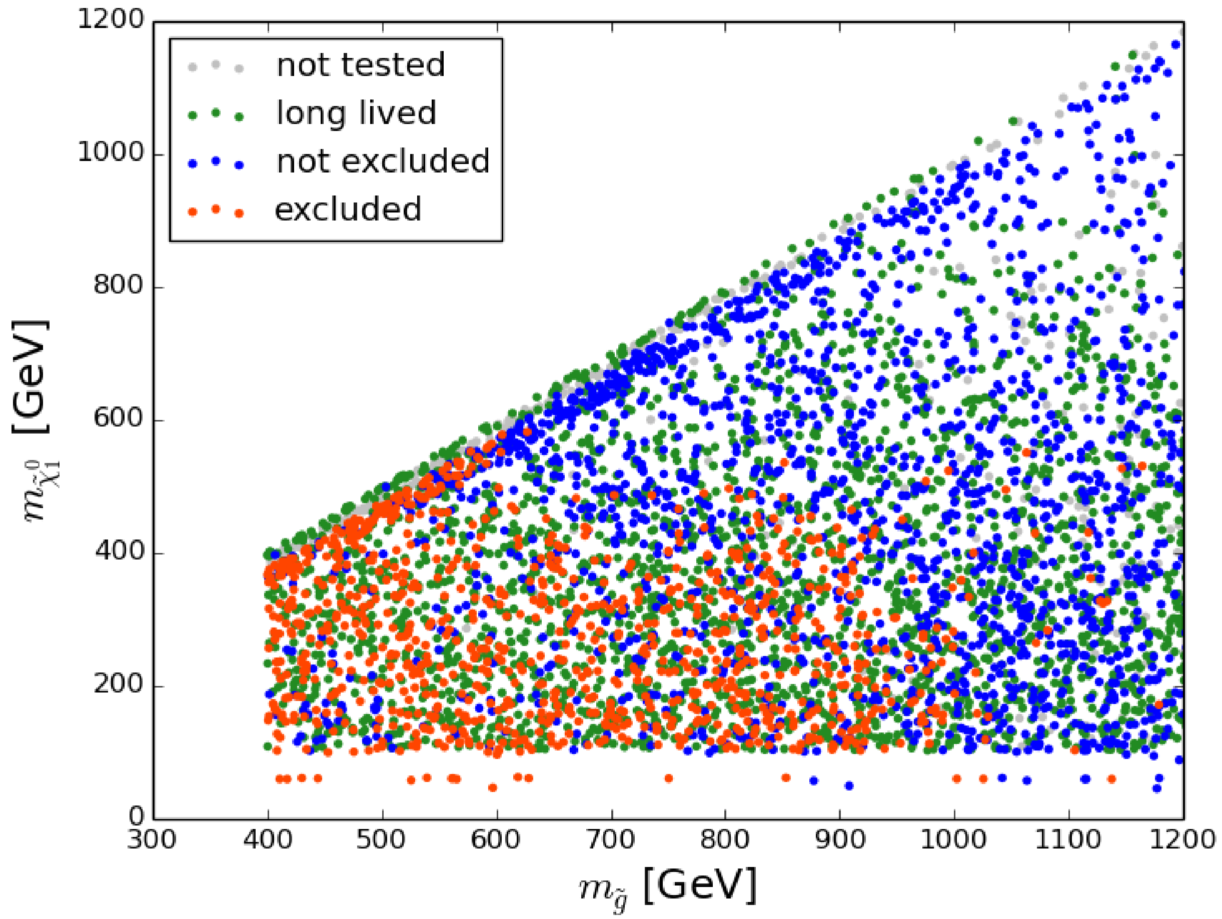
Neutralino LSP



UMSSM

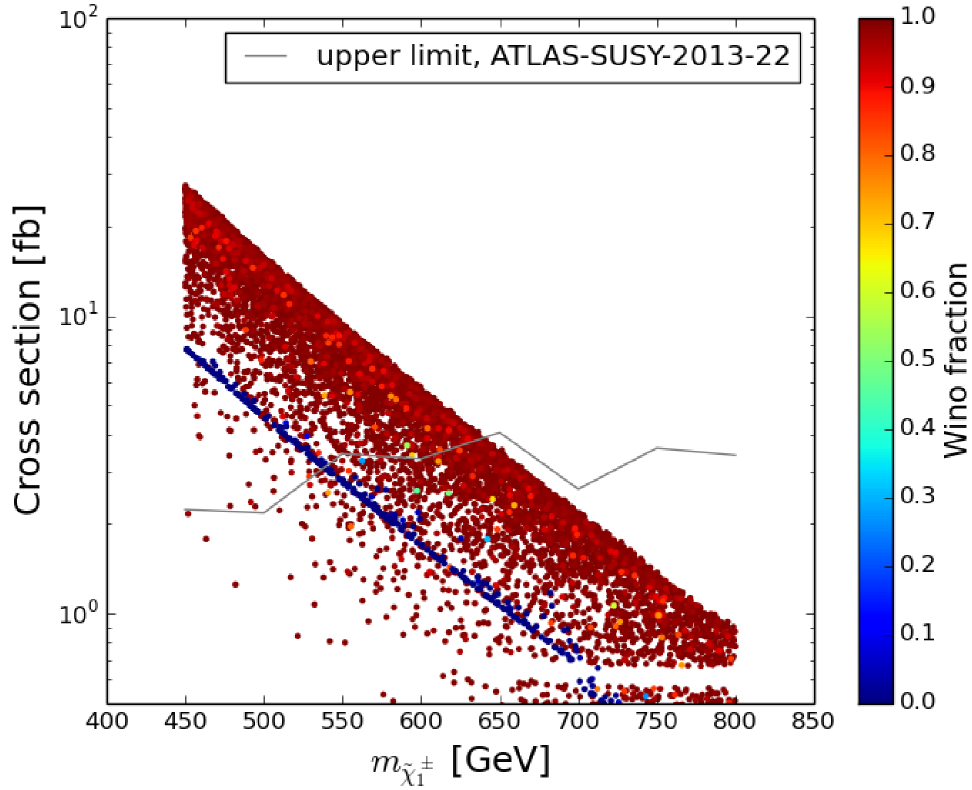
G. Bélanger, J. Da Silva, U. Laa, A. Pukhov, JHEP 1509 (2015) 151





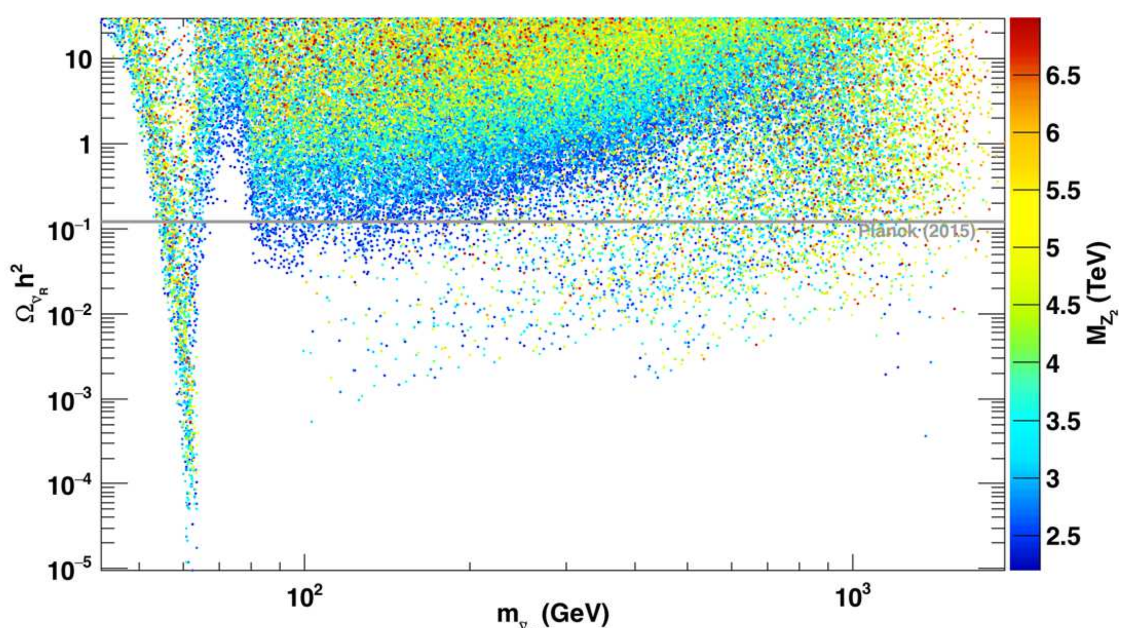
- Non-degenerate squark masses as a consequence of additional D-term contributions due to new U(1)' couplings
- Light squarks evade SMS constraints which assume degenerate squark masses
- Light gluinos decay via light squarks hence evade SMS constraints

UMSSM

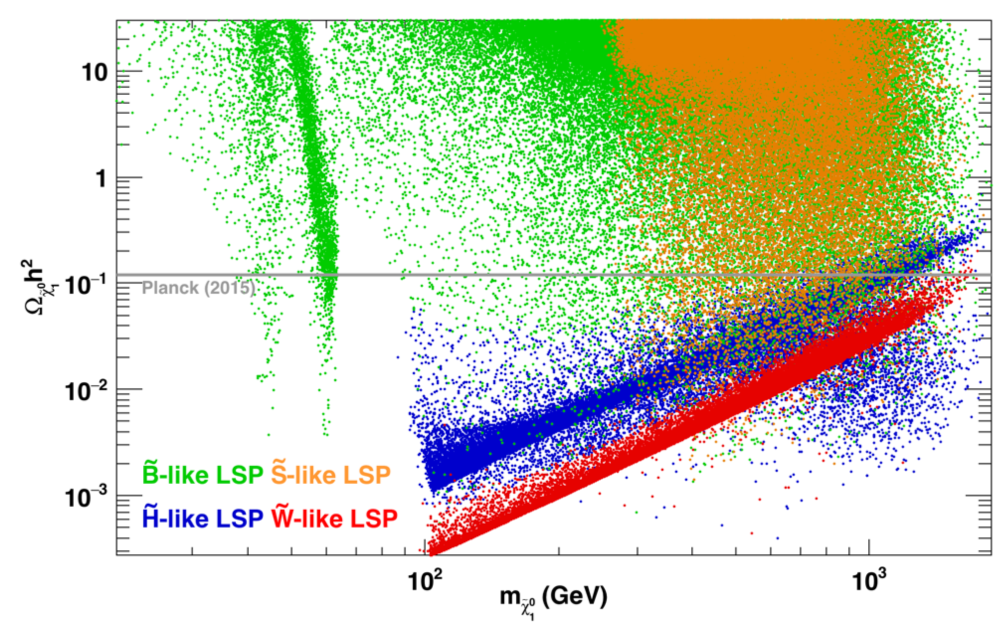


- Winolike chargino leads to long lived charged final states
- Simple minded application of the D0 and ATLAS searches for long lived particles
- A lot of parameter space is already constrained using SMS however use of general reinterpretation will help even further

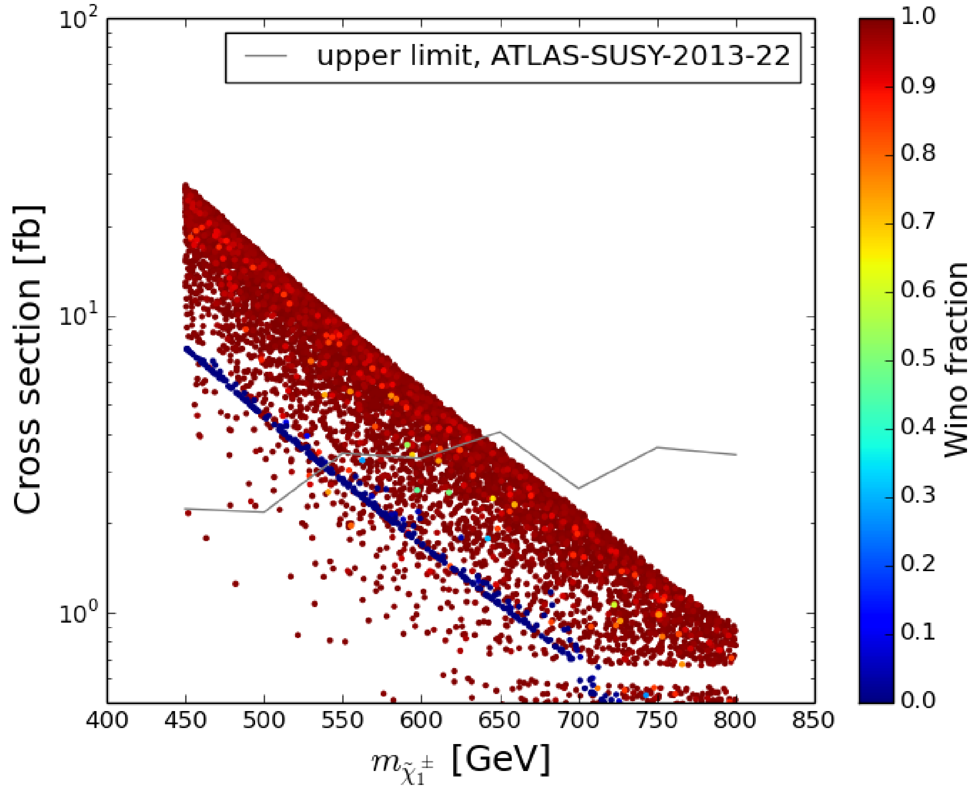
Sneutrino LSP



Neutralino LSP



UMSSM



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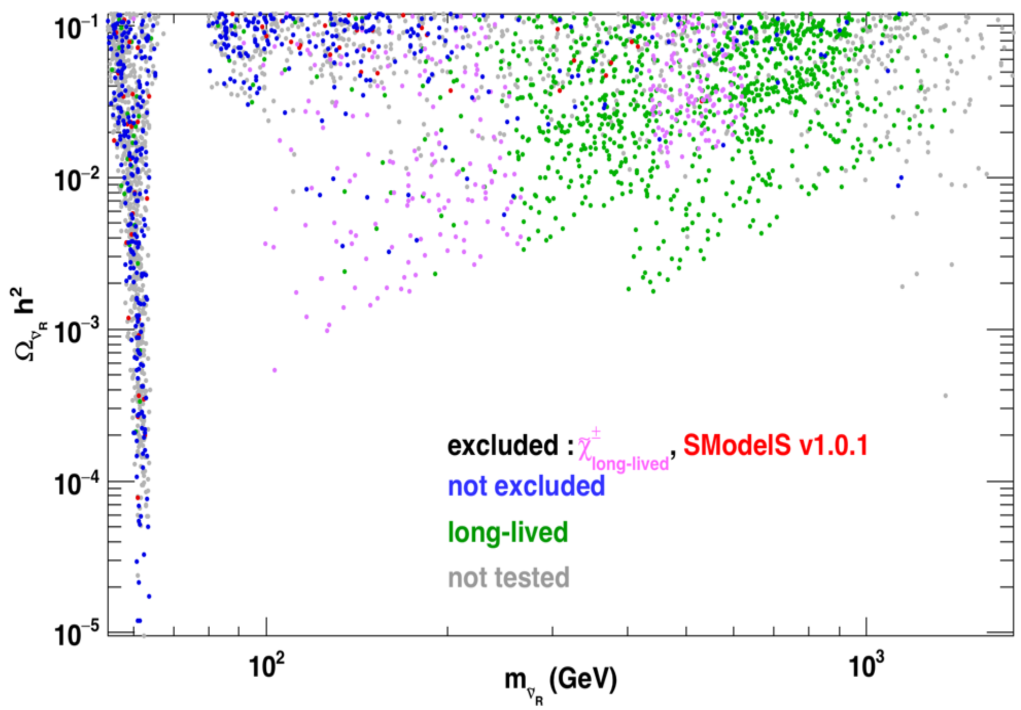

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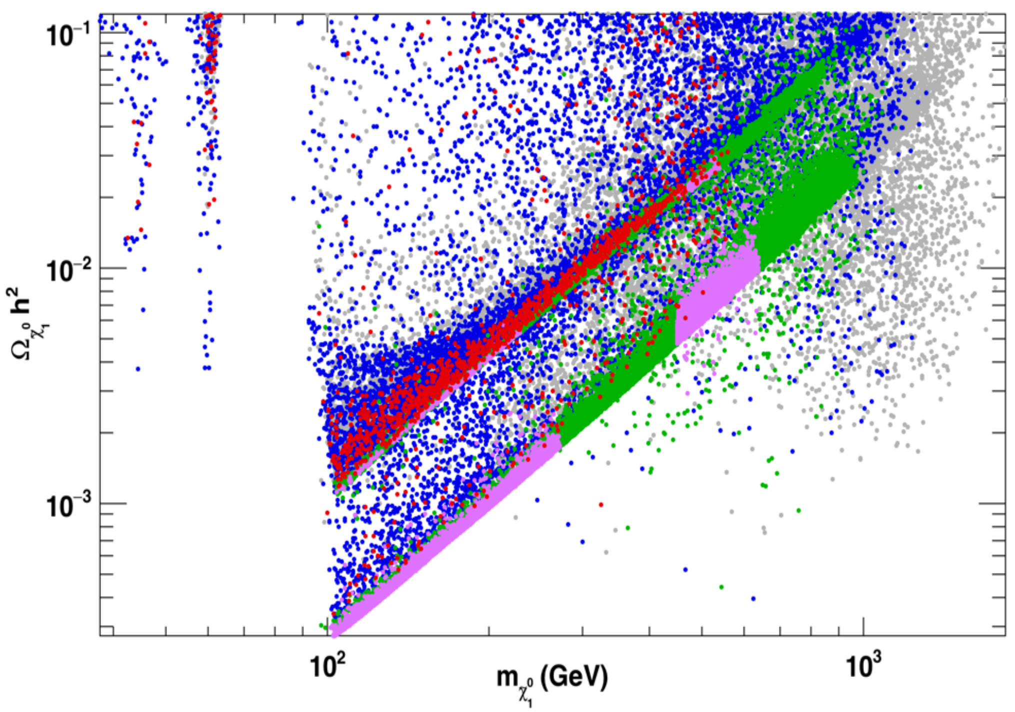
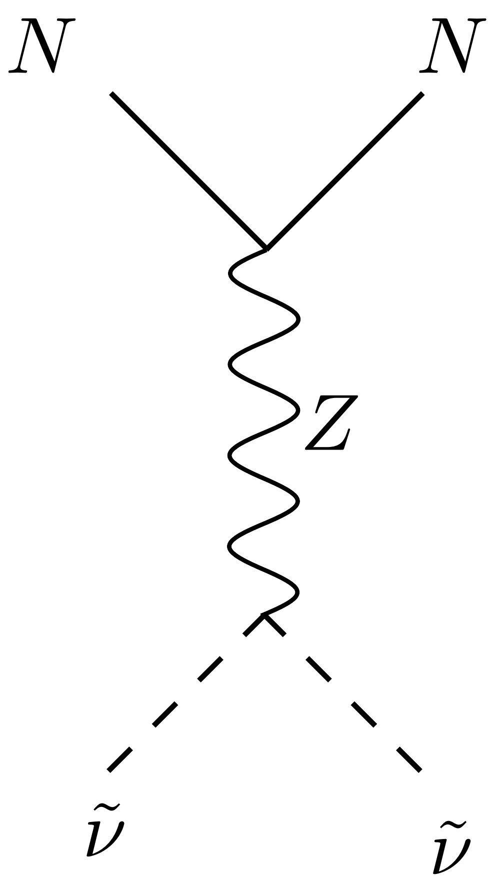
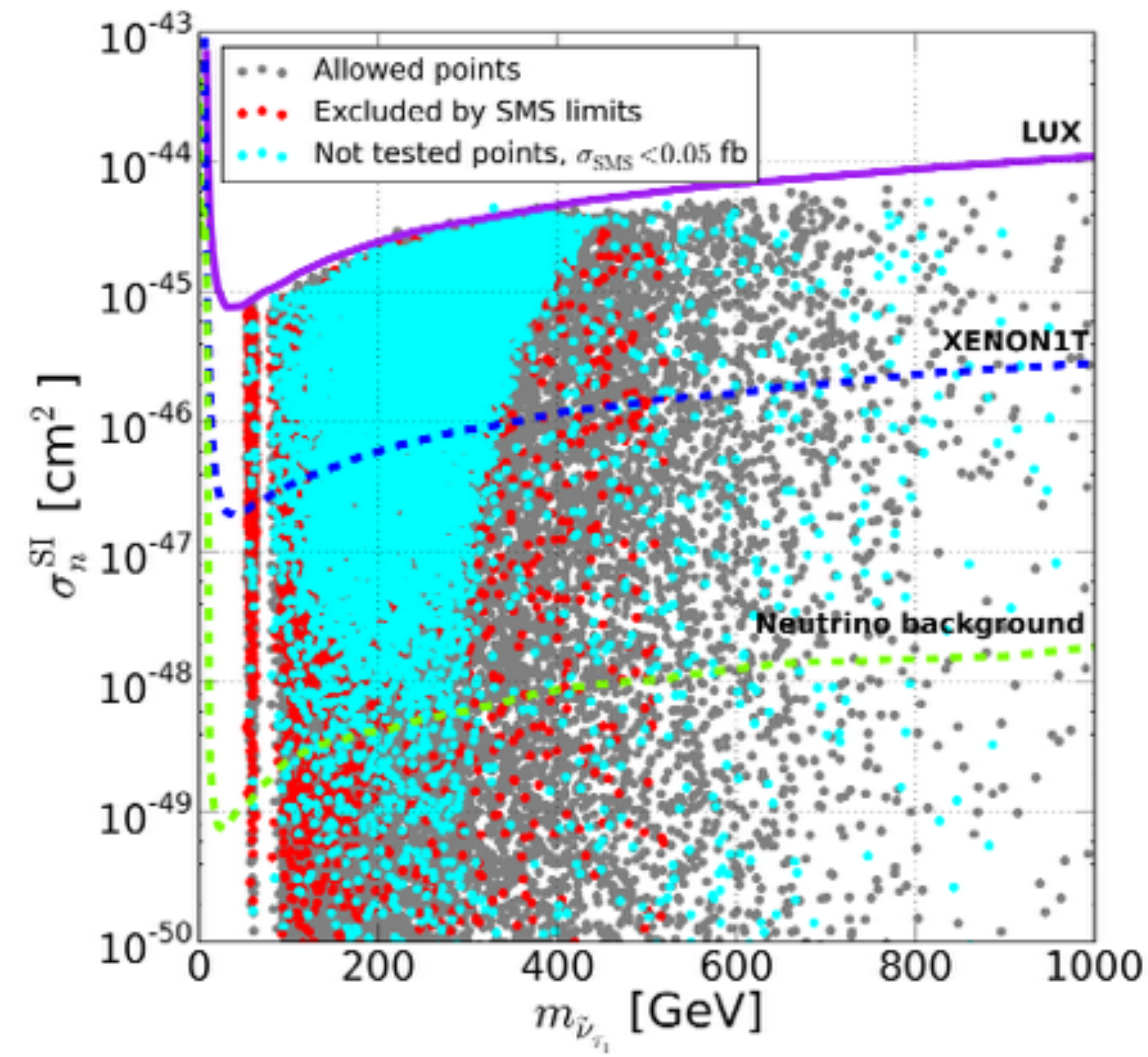


Direct detection

Chiara Arina, M.E. Cabrera, S. Kraml, S. K., U. Laa, JHEP 1505 (2015)
See also Dumont et al, JCAP09(2012)013



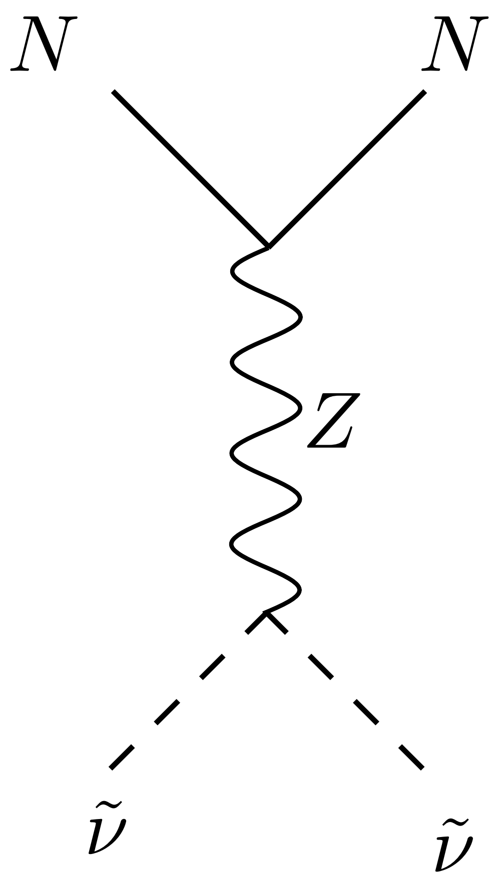


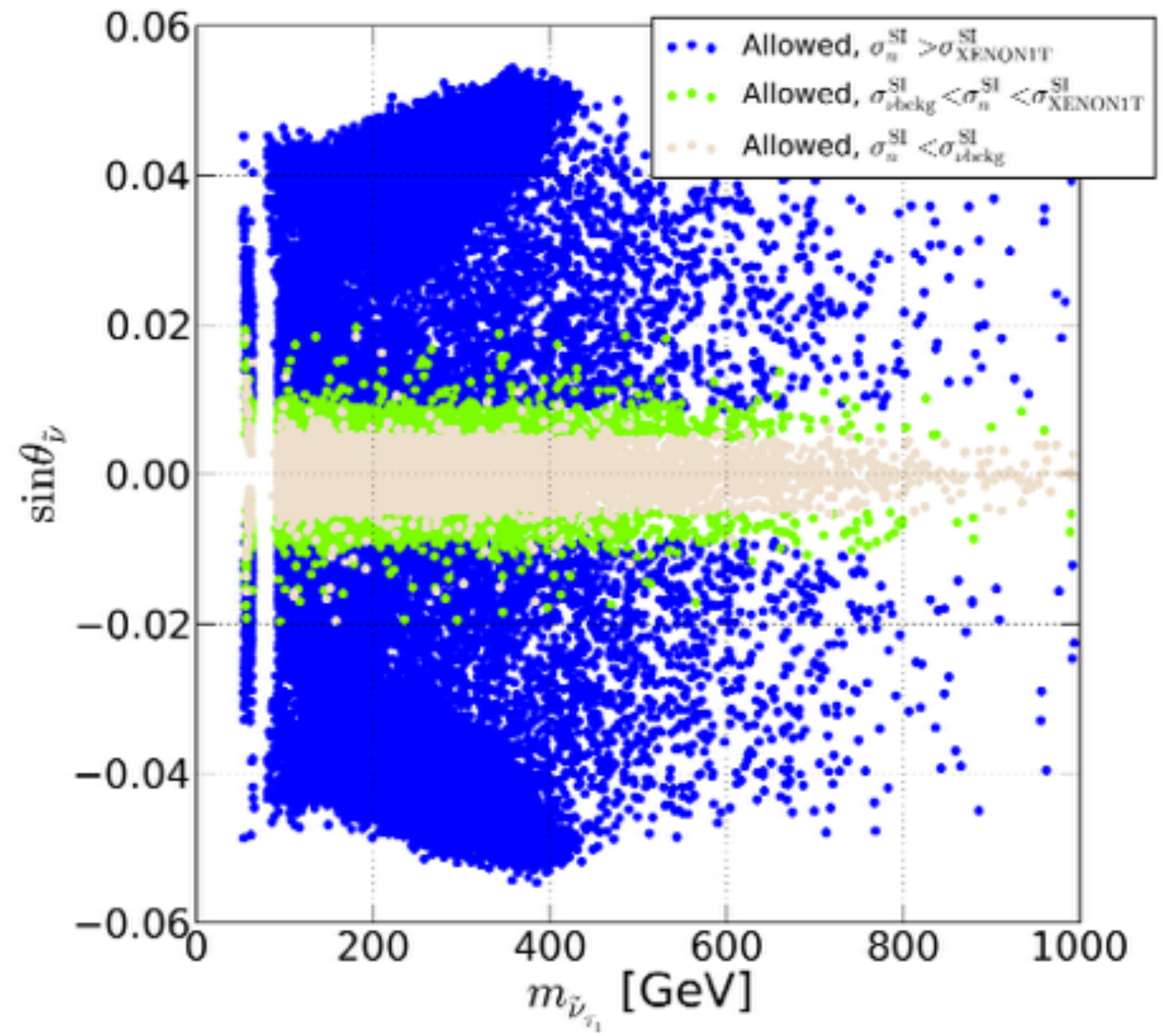
Direct detection detects how much LH part of sneutrino can survive (Z coupling)

Strong exclusion from LUX experiment

Direct detection

Chiara Arina, M.E. Cabrera, S. Kraml, S. K., U. Laa, JHEP 1505 (2015)





Direct detection detects how much LH part of sneutrino can survive (Z coupling)

Strong exclusion from LUX experiment

Parameter space

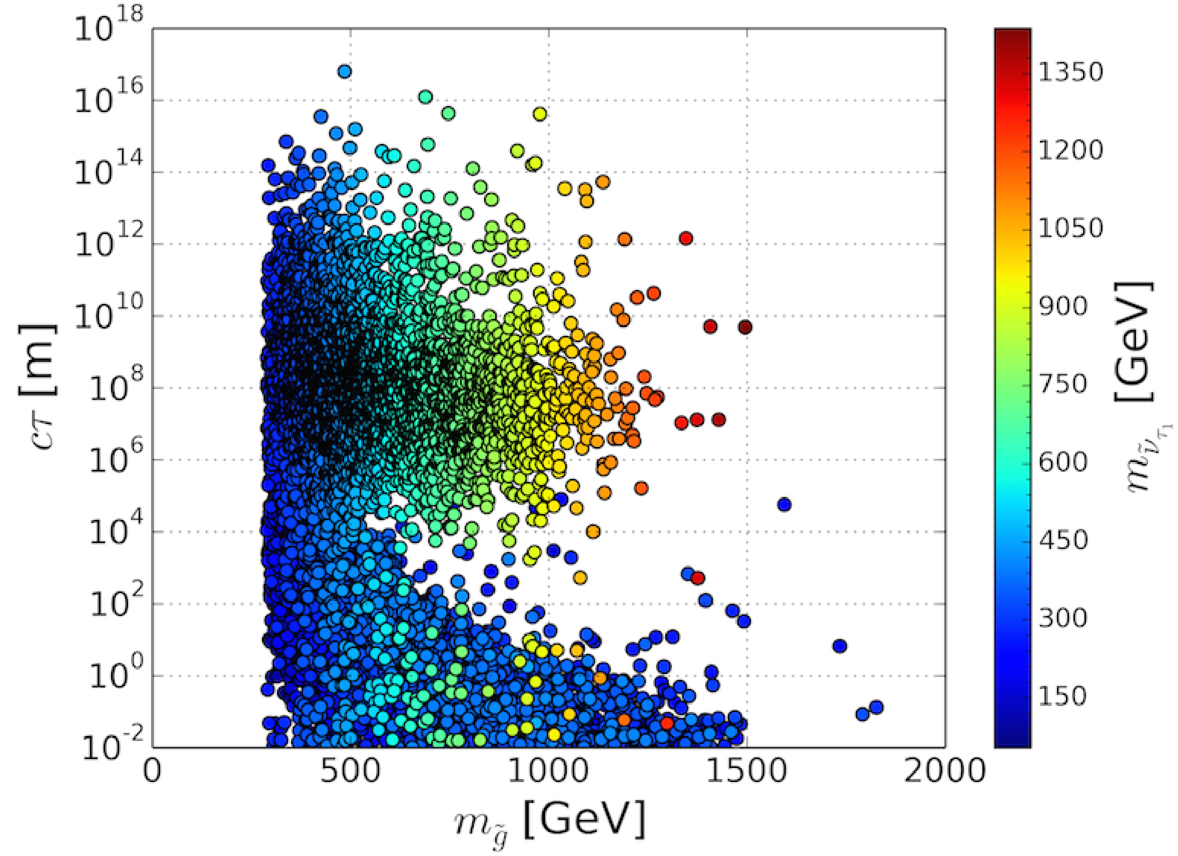
$$M_1, M_2, M_3, m_L, m_R, m_N, m_Q, m_H, A_l, A_{\tilde{\nu}}, A_q, \tan\beta, \mathrm{sgn}\mu$$

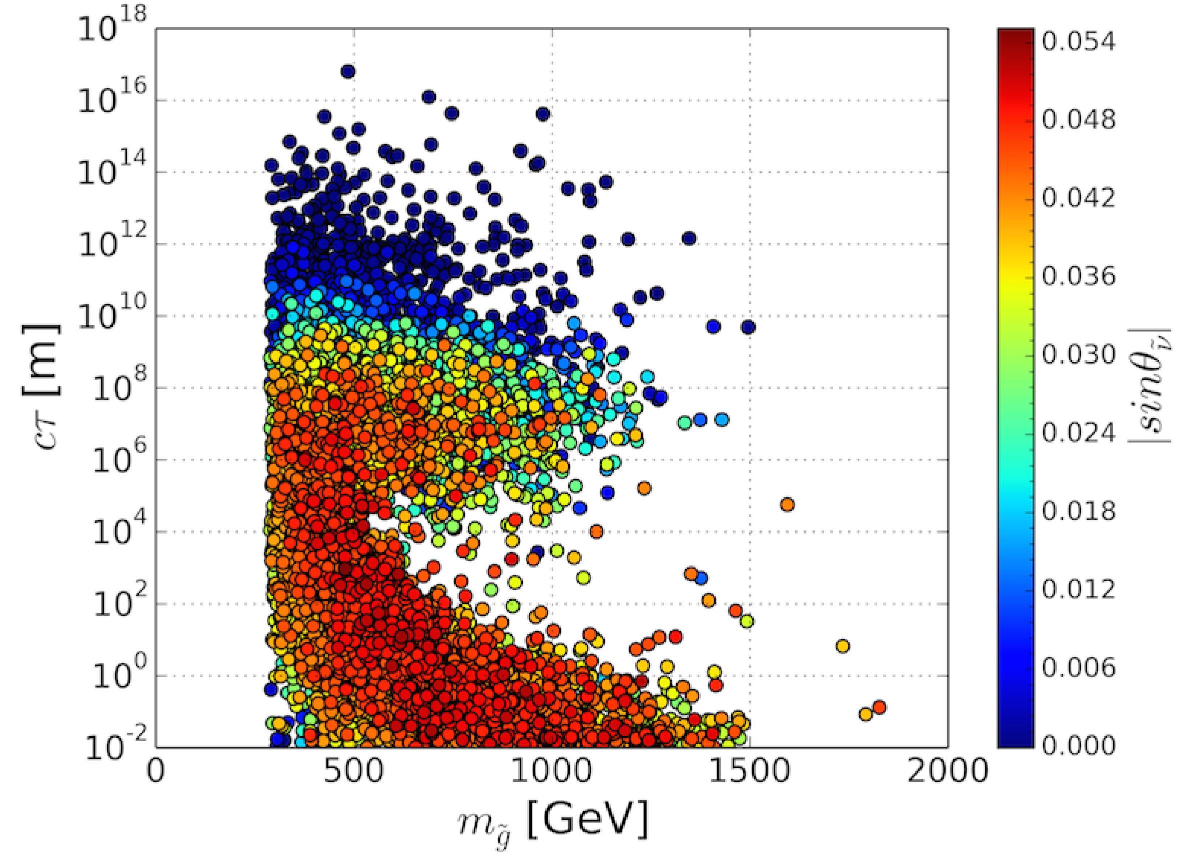
Nested sampling (several chains) with both log and flat priors on the free parameters

	Observable	Value/Constraint
Measurements	m_h	125.85 ± 0.4 GeV (exp) ± 4 GeV (theo)
(Gaussian likelihood	$\mathrm{BR}(B \to X_s\gamma) \times 10^4$	$3.55 \pm 0.24 \pm 0.09$ (exp)
function)	$\mathrm{BR}(B_s \to \mu^+\mu^-) \times 10^9$	$3.2^{+1.4}_{-1.2}$ (stat) $^{+0.5}_{-0.3}$ (sys)
Limits	$\Delta\Gamma_Z^{\mathrm{invisible}}$	< 2 MeV (95% CL)
	$\mathrm{BR}(h \to \mathrm{invisible})$	$< 20\%$ (95% CL)
(Step likelihood	$m_{\tilde{\tau}_1^-}$	> 85 GeV (95% CL)
function)	$m_{\tilde{\chi}_1^+}, m_{\tilde{e},\tilde{\mu}}$	> 101 GeV (95% CL)
	$m_{\tilde{g}}$	> 308 GeV (95% CL)

+ DM constraints

Long lived gluino

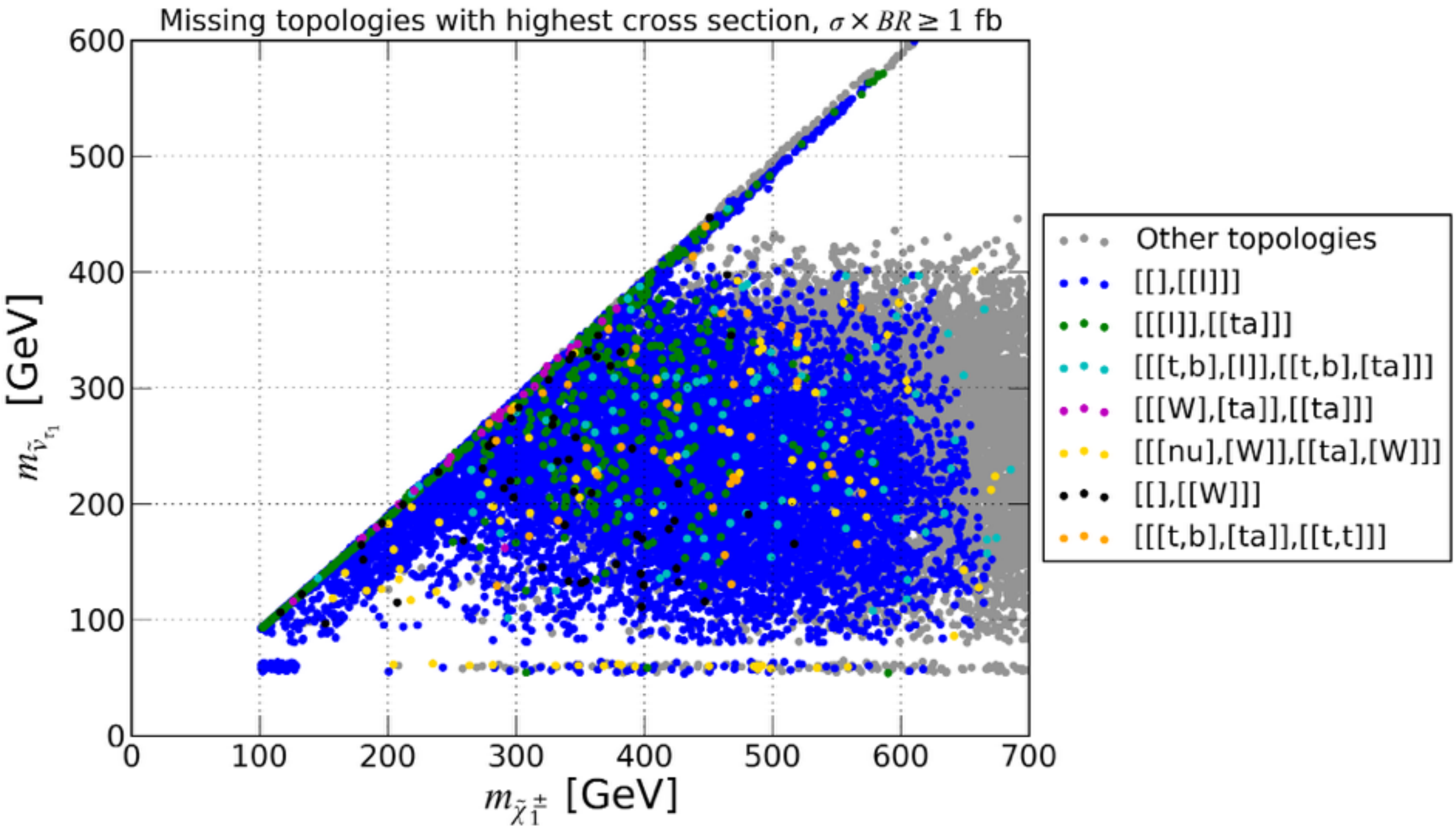




- Gluino four body decay (three body decay to LSP no longer possible
- Meta-stable gluino can occur even if squarks are not completely decoupled

Missing topologies

Chiara Arina, M.E. Cabrera, S. Kraml, S. K., U. Laa, JHEP 1505 (2015)



Cutflow comparison

Chiara Arina, M.E. Cabrera, S. Kraml, S. K., U. Laa, JHEP 1505 (2015)

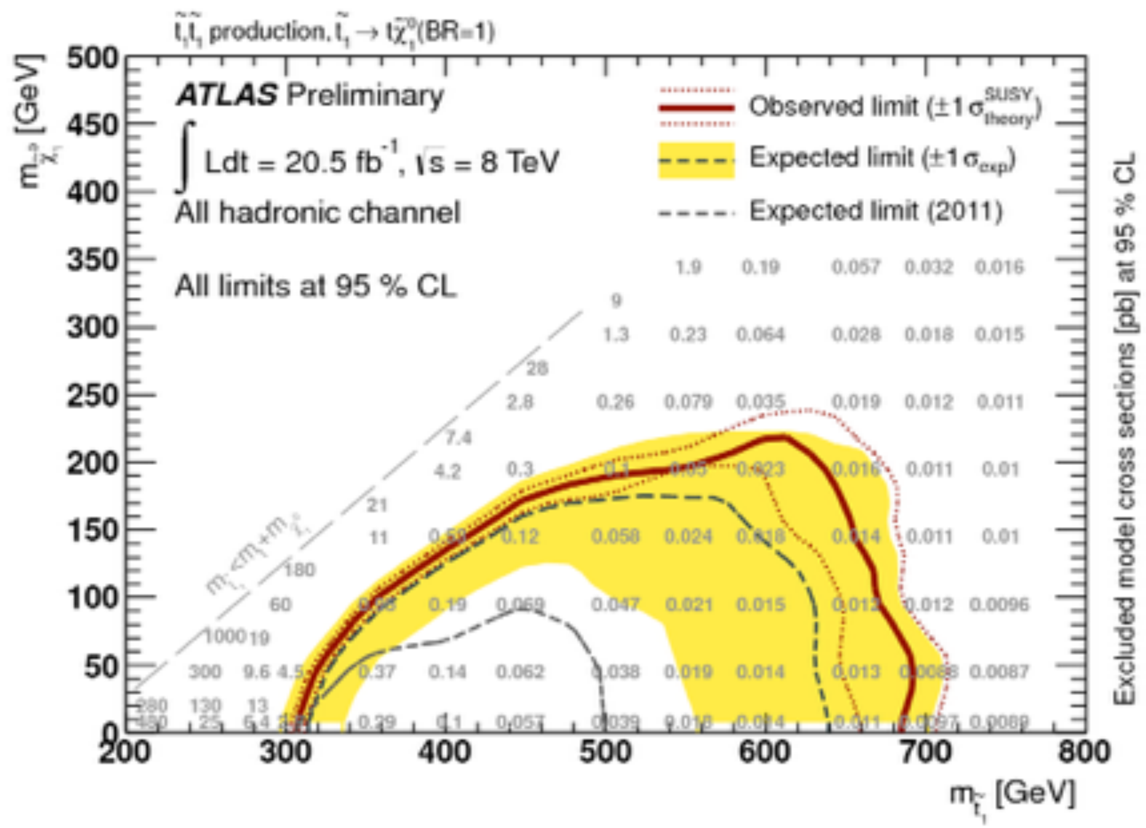
Cut	Slepton production	Chargino production
Common preselection		
Initial number of events	50000	50000
2 OS leptons	35133	33464
$m_{ll} > 20$ GeV	35038	33337
τ veto	35007	33318
ee leptons	35007	33318
jet veto	20176	19942
Z veto	19380	18984
Different m_{T2} regions		
$m_{T2} > 90$ GeV	11346	11594
$m_{T2} > 120$ GeV	8520	8828
$m_{T2} > 150$ GeV	5723	5926

Table 2: Comparison of the cut-flows for $pp \to \tilde{e}\tilde{e} \to e^+e^-\widetilde{\chi}_1^0\widetilde{\chi}_1^0$ and $pp \to \widetilde{\chi}_1^+\widetilde{\chi}_1^- \to e^+e^-\tilde{\nu}_1\tilde{\nu}_1$ with $(m_{\tilde{l}^\pm},\ m_{\tilde{\chi}_1^0}) = (270,\ 100)$ GeV and $(m_{\tilde{\chi}_1^\pm},\ m_{\tilde{\nu}_1}) = (270,\ 100)$ GeV, respectively.

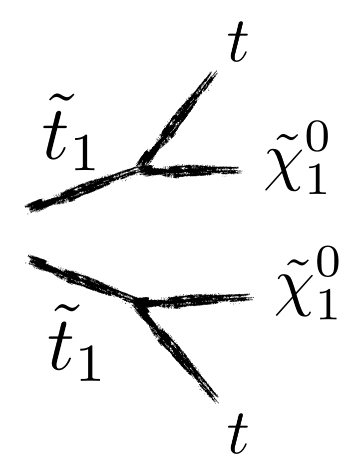
Simplified models

- Derive upper limits on sigma X BR for specific decay modes (Simplified models, fixed BR)

$$(\sigma \times BR)^{UL}_{expt}(m_{\tilde{t}_1}, m_{\tilde{\chi}^1_0}) \approx \frac{N^{evts}}{\mathcal{L} \times (\mathcal{A} \times \epsilon)}$$



ATLAS-CONF-2013-024



$\sigma^{U.L.}_{expt}(m_{\tilde{t}_1}, m_{\tilde{\chi}^0_1})$

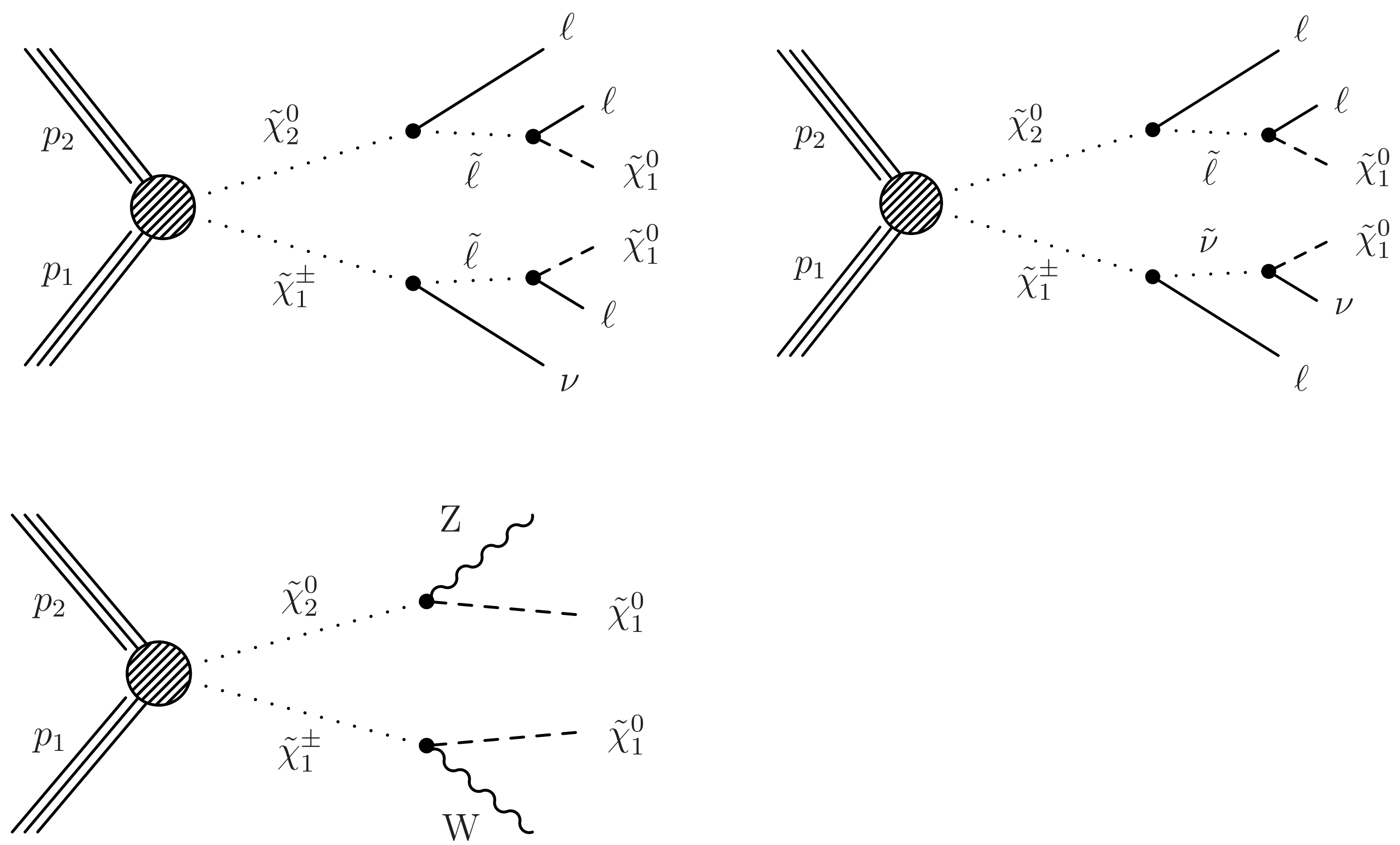
$\sigma_{th}(m_{\tilde{t}_1}, m_{\tilde{\chi}^0_1})$

Testing SUSY spectrum

- Final state with 3 leptons
- Possible topologies leading to this final state:

MadAnalysis5, CheckMate
Eur.Phys.J. C75 (2015) 2, 56
CPC 187 (2014) 227-265
ATOM (not public)

Electroweak -ino decays



- Analysis reimplementation can account for 3 lepton final state from all topologies

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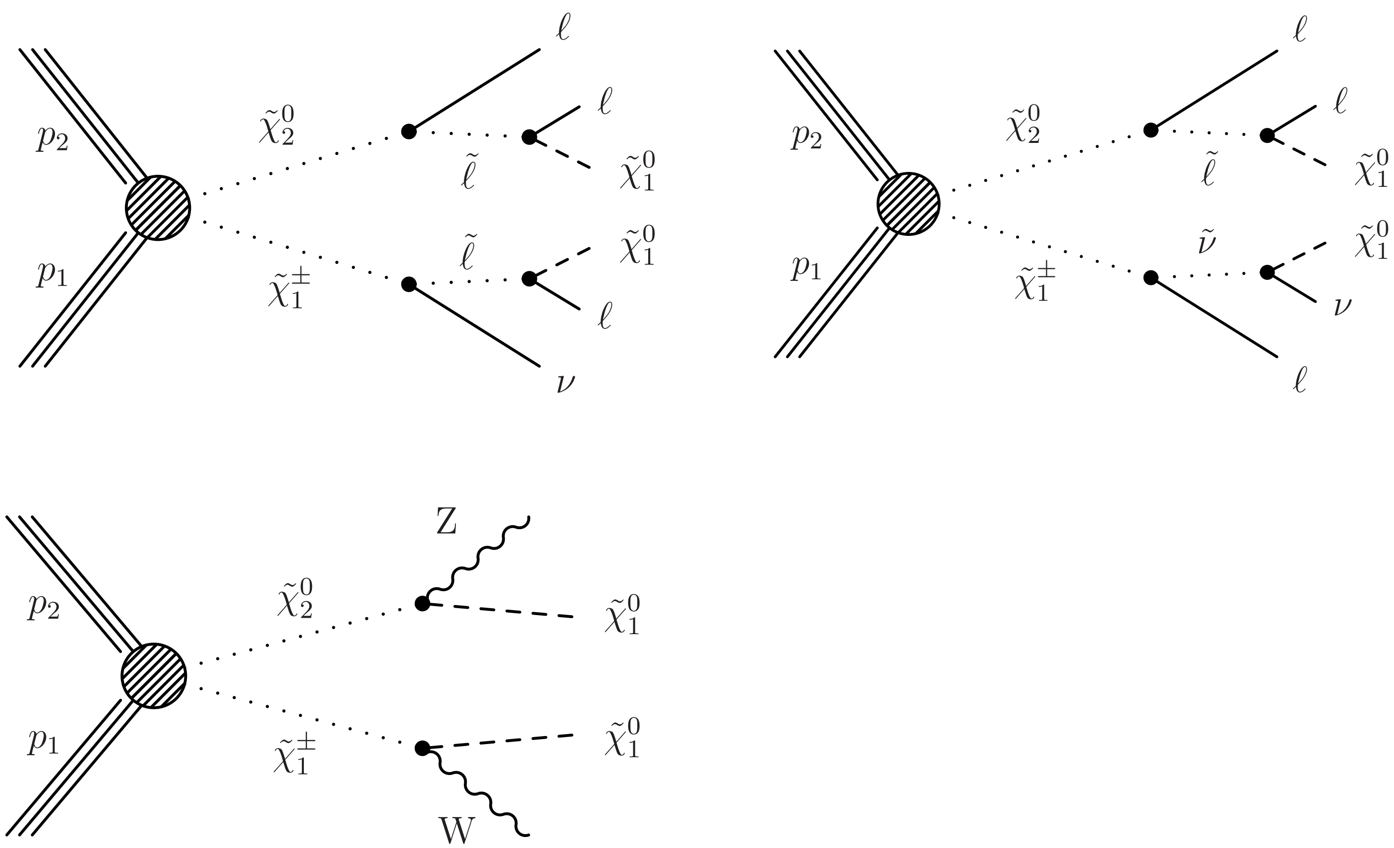
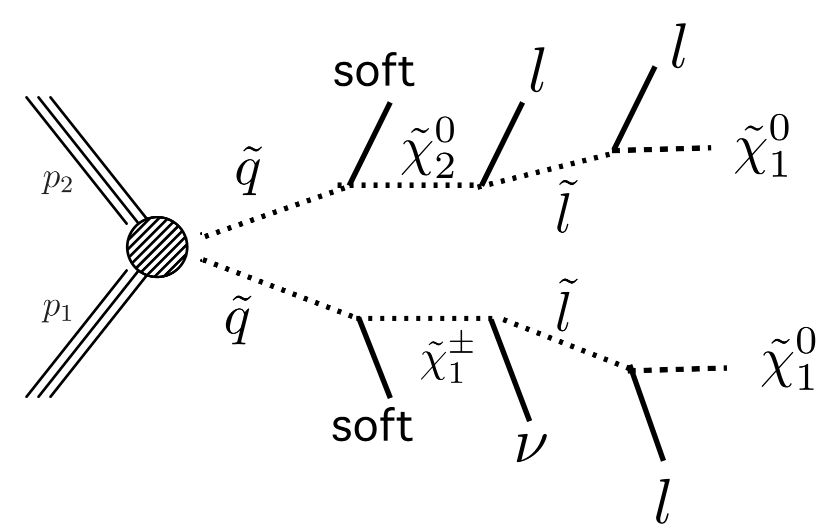


+ complicated cascade decays e.g.



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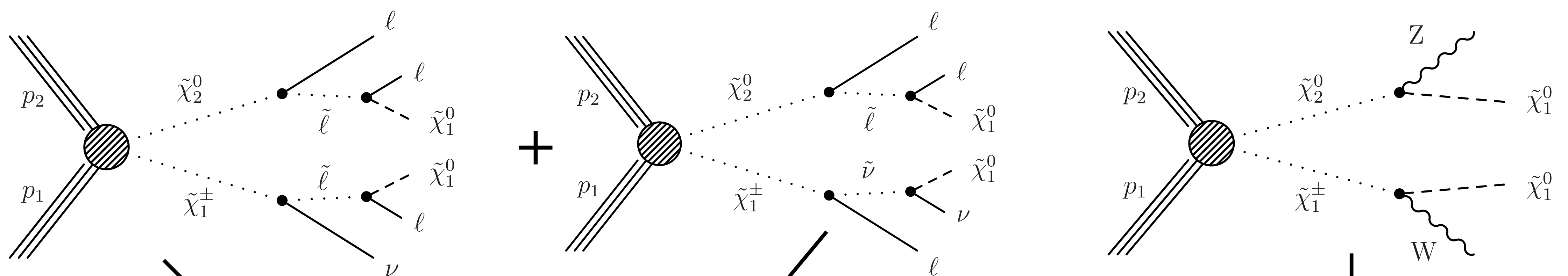
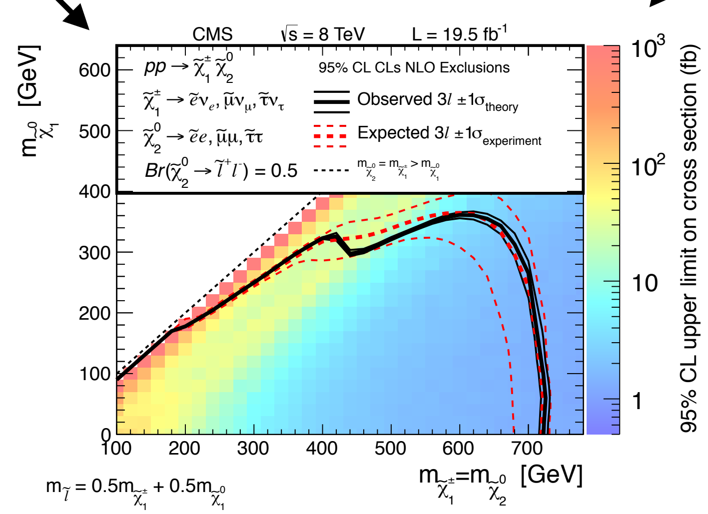
Testing SUSY spectrum

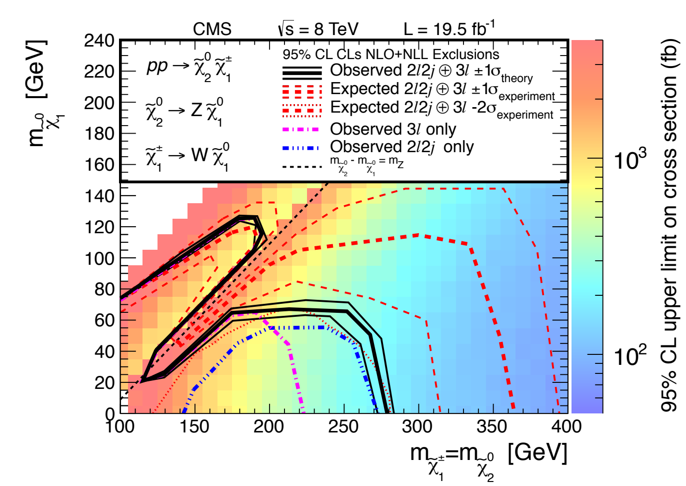
- Final state with 3 leptons

SModelS
EPJC 74:2868 (2014)

Upper limits on cross sections times branching ratio







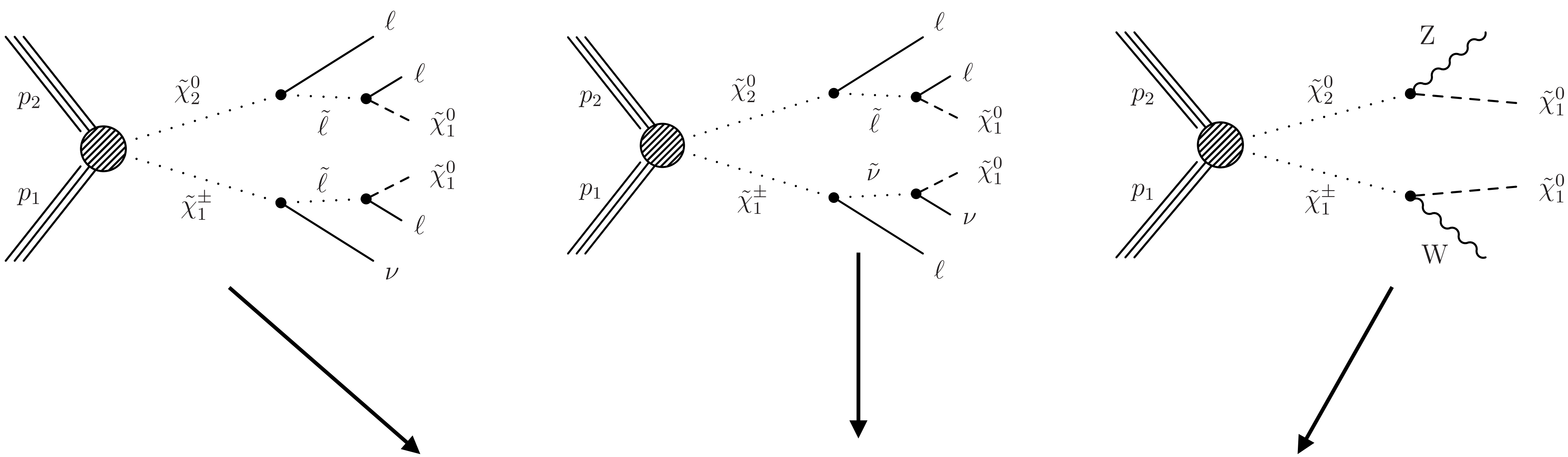
arXiv:1405.7570

Testing SUSY spectrum

- Final state with 3 leptons

FastLim
EPJC74 (2014) 11, 3163

Characterising efficiencies



$$N_{evts}^{th} = \mathcal{L} \times [(\mathcal{A} \times \epsilon)_1 \times (\sigma \times \mathcal{B})_1^{th} + (\mathcal{A} \times \epsilon)_2 \times (\sigma \times \mathcal{B})_2^{th} + (\mathcal{A} \times \epsilon)_3 \times (\sigma \times \mathcal{B})_3^{th}]$$

SModelS upcoming