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Gudrid Moortgat-Pick, Sven Heinemeyer

Direct and indirect searches in the MSSM

Minimal Supersymmetric Standard Model

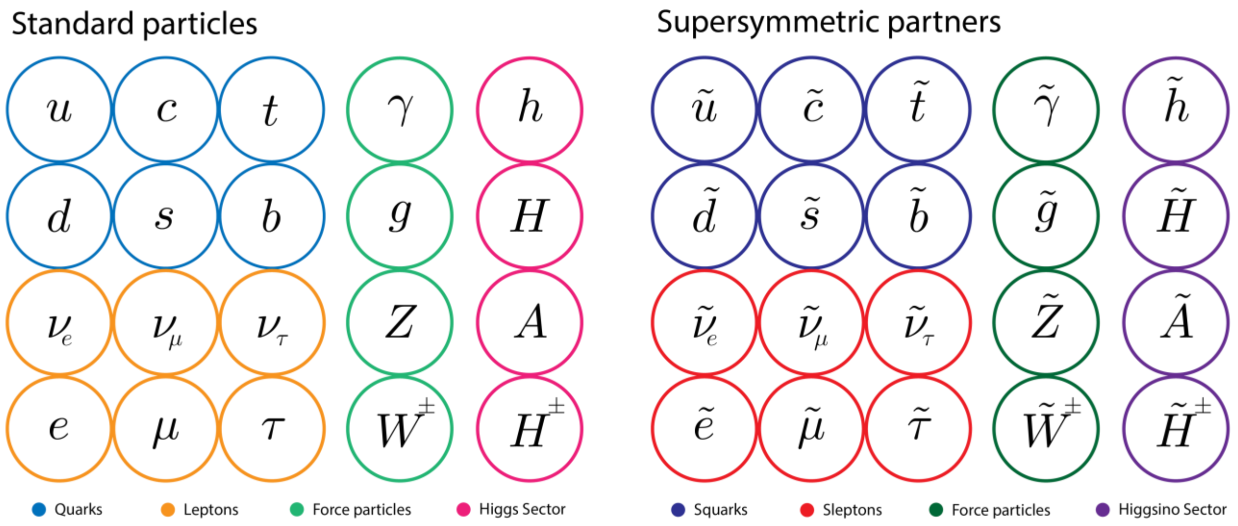
Gaugino and higgsino fields mix into mass eigenstates

1. Neutralinos

$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$

2. Charginos

$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$



Neutralino Sector

- SUSY-Parameters $M_1, M_2, \mu, \tan\beta$
- M_1 can only be determined with Neutralinos
- $M_2, \mu, \tan\beta$ are determined using chargino data

$$\mathcal{M}_N = \begin{pmatrix} M_1\cos^2\theta_W + M_2\sin^2\theta_W & (M_2 - M_1)\sin\theta_W\cos\theta_W & 0 & 0 \\ (M_2 - M_1)\sin\theta_W\cos\theta_W & M_1\cos^2\theta_W + M_2\sin^2\theta_W & m_Z & 0 \\ 0 & m_Z & \mu\sin 2\beta & -\mu\cos 2\beta \\ 0 & 0 & -\mu\cos 2\beta & -\mu\sin 2\beta \end{pmatrix}$$

$$x_i M_1^2 + y_i M_1 - z_i = 0, \quad \text{for} \quad i = 1, 2, 3, 4$$

$$\begin{aligned} x_i &= -m^6_{\tilde{\chi}^0_i} + a_{41} m^4_{\tilde{\chi}^0_i} - a_{21} m^2_{\tilde{\chi}^0_i} + a_{01}, \\ y_i &= a_{42} m^4_{\tilde{\chi}^0_i} - a_{22} m^2_{\tilde{\chi}^0_i} + a_{02}, \\ z_i &= m^8_{\tilde{\chi}^0_i} - a_{63} m^6_{\tilde{\chi}^0_i} + a_{43} m^4_{\tilde{\chi}^0_i} - a_{23} m^2_{\tilde{\chi}^0_i} + a_{03}, \end{aligned}$$

a_{kl} with $k = 0{,}2{,}4{,}6$; $l = 1{,}2{,}3$ coefficients depending on $M_2, \mu, \tan\beta$

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Chargino Sector

- Two unitary transformations for chargino mixing $U_{L,R}$
- Two mixing angles $\Phi_{L,R}$

$$\mathcal{M}_C = \begin{pmatrix} M_2 & \sqrt{2} m_W \cos\beta \\ \sqrt{2} m_W \sin\beta & \mu \end{pmatrix}$$

$$\begin{pmatrix} \tilde{\chi}_1^- \\ \tilde{\chi}_2^- \end{pmatrix}_{L,R} = U_{L,R} \begin{pmatrix} \tilde{W}^- \\ \tilde{H}^- \end{pmatrix}_{L,R}$$

$$U_{L,R} = \begin{pmatrix} \cos\Phi_{L,R} & \sin\Phi_{L,R} \\ -\sin\Phi_{L,R} & \cos\Phi_{L,R} \end{pmatrix}$$

Goal:

- Use $\Phi_{L,R}$, $m_{\tilde{\chi}_1^\pm}$, $m_{\tilde{\chi}_2^\pm}$ to recalculate SUSY-parameters

$$m^2_{\tilde{\chi}^\pm_{1,2}} = \frac{1}{2}(M_2^2 + \mu^2 + 2m_W^2 \mp \Delta_C)$$

$$\cos 2\phi_{L,R} = -(M_2^2 - \mu^2 \mp 2m_W^2 \cos 2\beta)/\Delta_C$$

$$\Delta_C = [(M_2^2 - \mu^2)^2 + 4m_W^4 \cos^2 2\beta + 4m_W^2(M_2^2 + \mu^2) + 8m_W^2 M_2 \mu \sin 2\beta]^{1/2}$$

Chargino Sector

- $M_2, \mu, \tan\beta$ can be calculated using p, q, r with $r^2 = \frac{m^2_{\tilde{\chi}^\pm_1}}{m^2_W}$
- Sign of p is ambiguous since $\sigma^\pm\{ij\}$ is calculated using $\cos(2\Phi_{L,R})$

$$p = \pm\left|\frac{\sin 2\Phi_L + \sin 2\Phi_R}{\cos 2\Phi_L - \cos 2\Phi_R}\right|$$

$$q = \frac{1}{p}\frac{\cos 2\Phi_L + \cos 2\Phi_R}{\cos 2\Phi_L - \cos 2\Phi_R}$$

$$M_2 = \frac{m_W}{\sqrt{2}}\left[(p+q)\sin\beta - (p-q)\cos\beta\right]$$

$$\mu = \frac{m_W}{\sqrt{2}}\left[(p-q)\sin\beta - (p+q)\cos\beta\right]$$

$$\tan\beta = \left[\frac{p^2 - q^2 \pm \sqrt{r^2(p^2+q^2+2-r^2)}}{(\sqrt{1+p^2} - \sqrt{1+q^2})^2 - 2r^2}\right]^\eta$$

$$\sigma^\pm\{ij\} = c_1\cos^2 2\Phi_L + c_2\cos 2\Phi_L + c_3\cos^2 2\Phi_R + c_4\cos 2\Phi_R + c_5\cos 2\Phi_L\cos 2\Phi_R + c_6$$

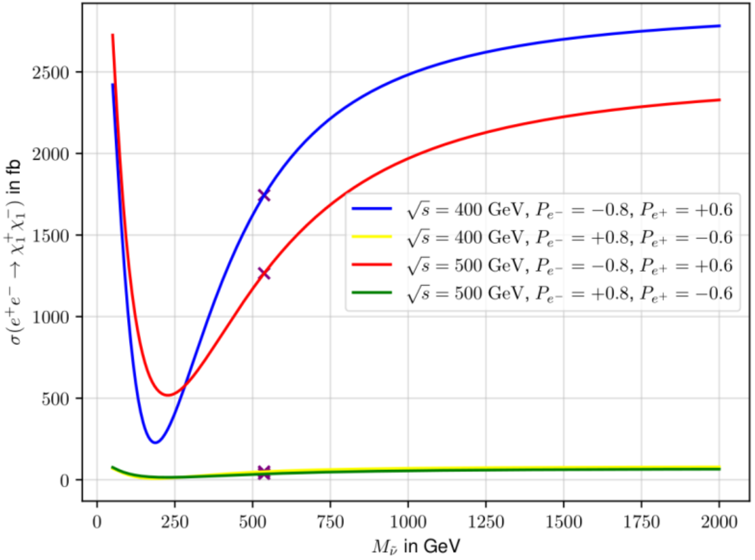
$$\sigma^\pm\{ij\} = \sigma(e^+e^- \to \tilde{\chi}^\pm_i\tilde{\chi}^\mp_j)$$

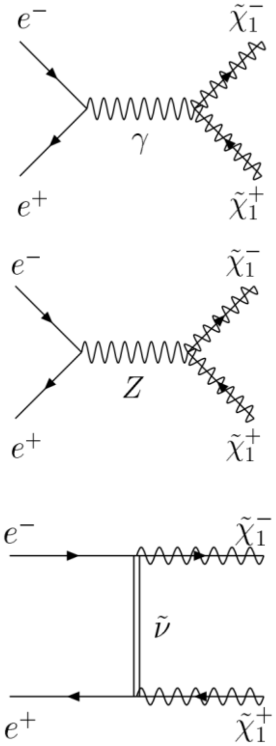
M_1	175.09 GeV	$\sigma^{400}_{-0.8,+0.6}$	1744.2519 fb
M_2	178.25 GeV	$\sigma^{400}_{+0.8,-0.6}$	49.8956 fb
μ	1215.85 GeV	$\sigma^{500}_{-0.8,+0.6}$	1265.4737 fb
$\tan\beta$	34.81	$\sigma^{500}_{+0.8,-0.6}$	35.6168 fb
$M_{\tilde{\nu}}$	536.9 GeV	$m_{\chi_1^\pm}$	177.1484 GeV

Cross sections

- Sneutrino mass $M_{\tilde{\nu}}$ relevant in t-channel propagator

→ Finding sensible limit becomes important objective





Strategy

- Take a parameter point with correct dark matter relic density
- Determine $\sigma(e^+e^- \to \tilde{\chi}_1{}^+\tilde{\chi}_1{}^-)$ and chargino masses
  - at $\sqrt{s} = 400\ \mathrm{GeV},\ 500\ \mathrm{GeV}$
  - With $P_{e^-} = \mp 0.8$ and $P_{e^+} = \pm 0.6$
  - Considering necessary uncertainties especially from $M_{\tilde{\nu}}$
- Calculate chargino mixing angles
- Redetermine chargino SUSY parameters – $M_2, \mu, \tan\beta$,
- Calculate neutralino masses
- Redetermine neutralino SUSY parameters – M_1
- Recalculate DM relic density including all uncertainties

Dataset

- Bino/Wino dark matter with $\tilde{\chi}_1^{\pm}$-coannihilation

Constraints:

- Muon $(g-2)$ – *BNL* and *Fermilab*
- Vacuum stability – stable and correct EW vacuum
- LHC constraints – all relevant SUSY searches
- Dark matter relic density constraints – *Planck 2018*
- Direct dark matter detection – *XENON1T*

$100\ \text{GeV}$	$\leq$	M_1	$\leq$	$1\ \text{TeV}$
M_1	$\leq$	M_2	$\leq$	$1.1M_1$
$1.1M_1$	$\leq$	μ	$\leq$	$10M_1$
5	$\leq$	$\tan\beta$	$\leq$	60

Manimala Chakraborti, Sven Heinemeyer, Ipsita Saha
arXiv:2104.03287v1

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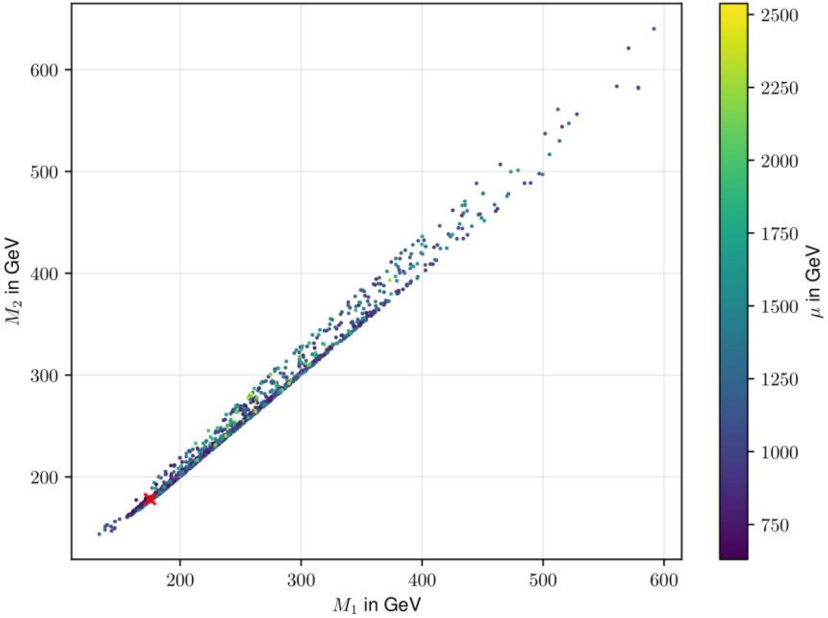
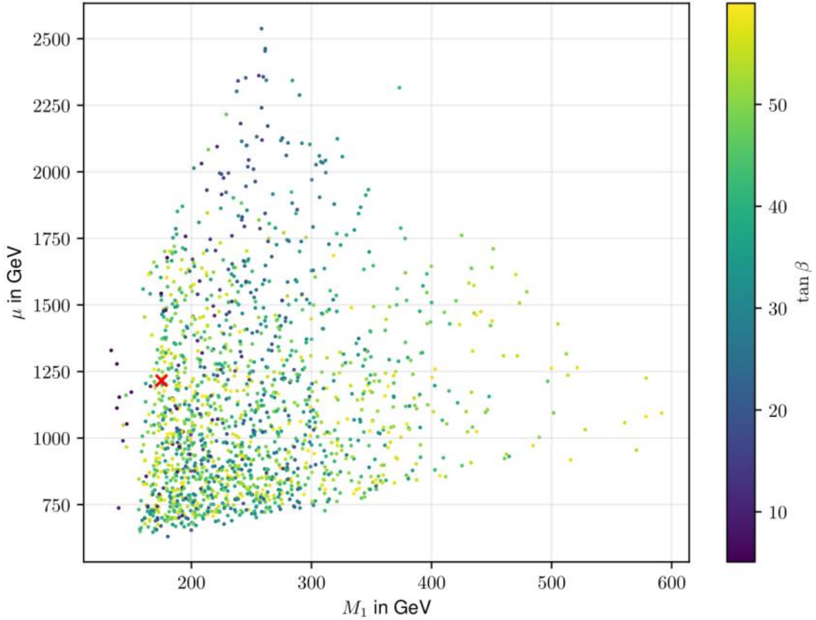
Dataset





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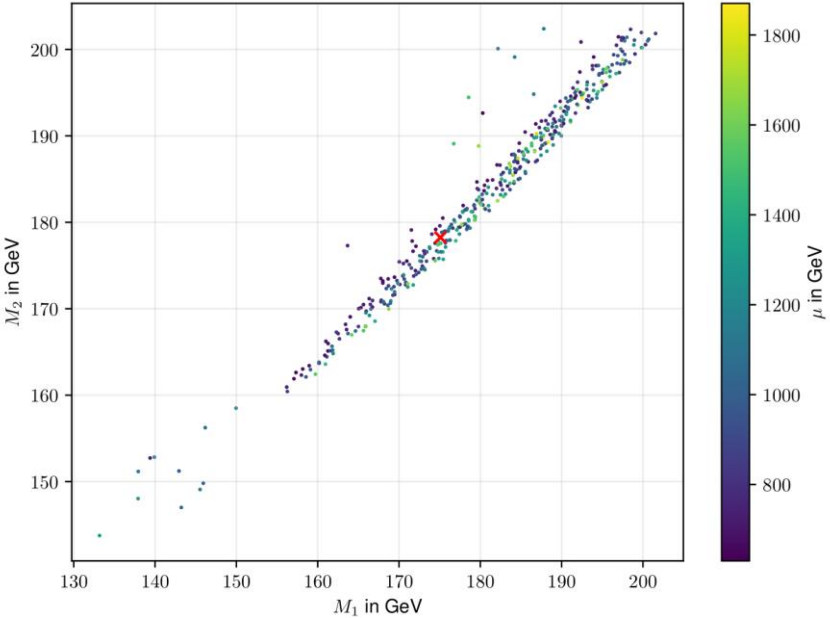
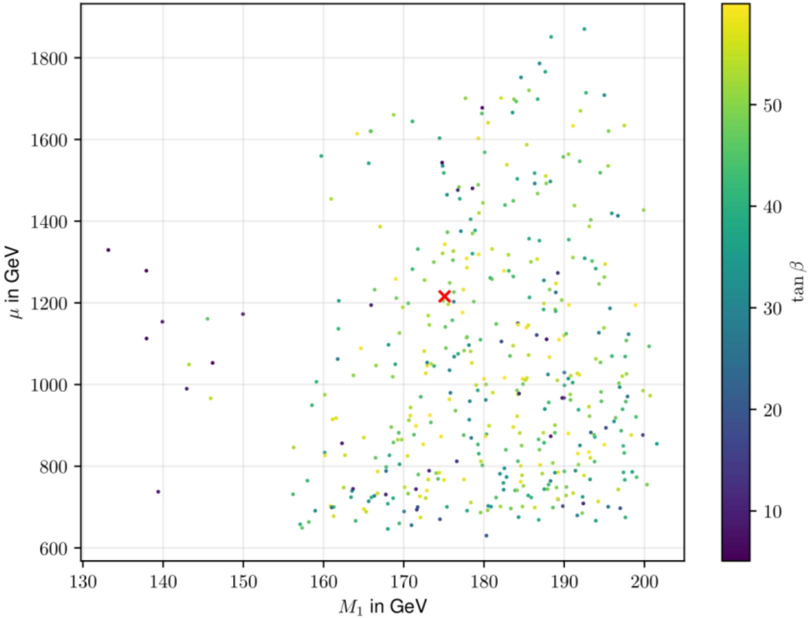
Dataset – kinematically allowed





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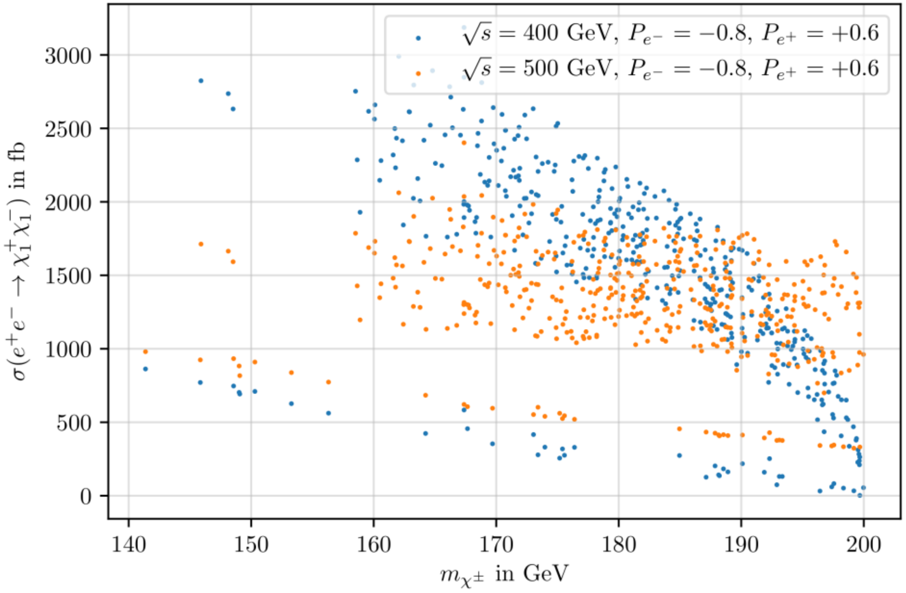
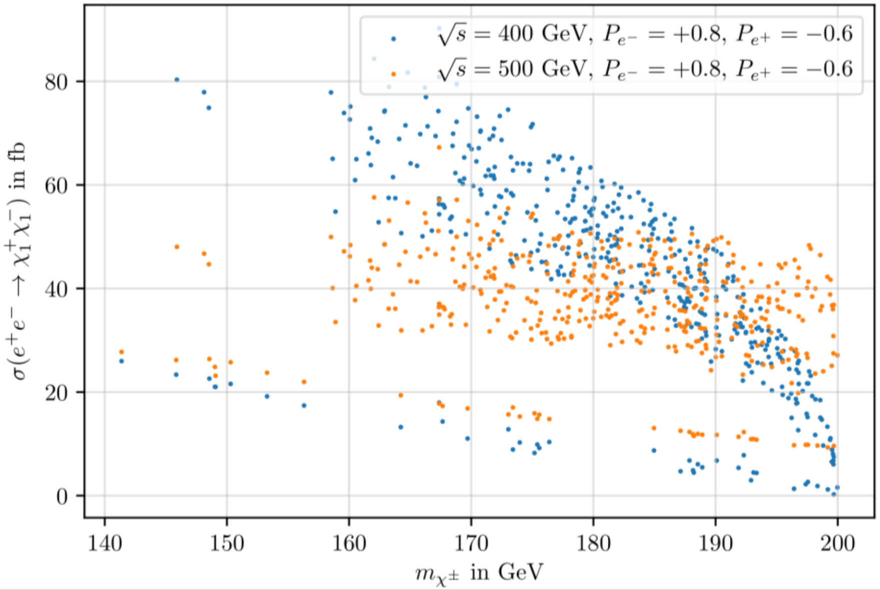
Dataset – Cross sections





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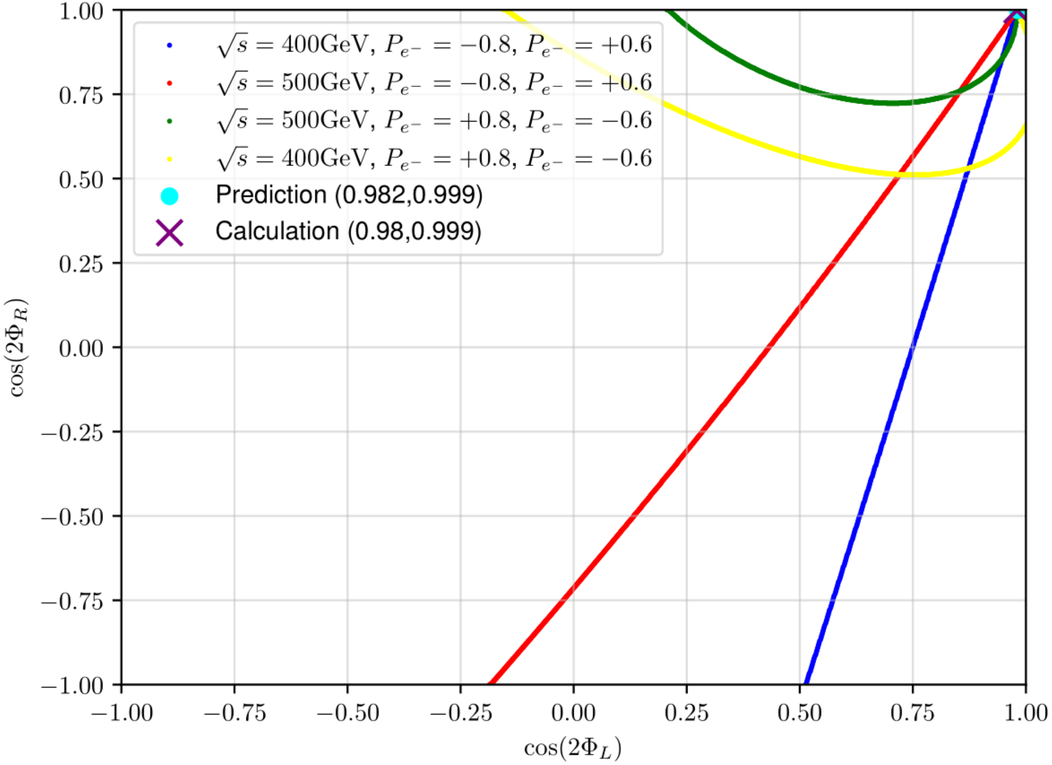
Mixing angles

- Single beam energy causes ambiguities

→ two energies remove ambiguity

- Direct vs. Indirect approach
- Indirect approach has slight ambiguities in intersection coordinates



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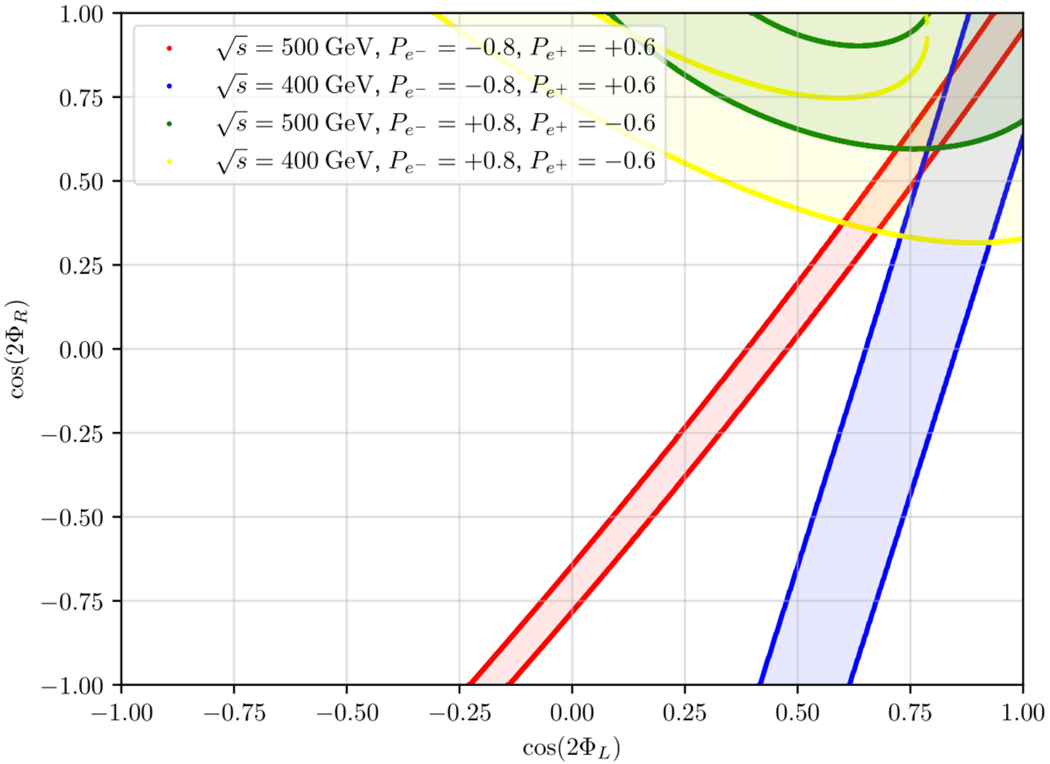
Mixing angles

- Adding uncertainties
  - 0.5% on chargino mass
  - Gaussian error on cross section
  - 0.5% on polarisation
  - → Sneutrino mass error not included
- 1D Curves now become 2D bands
- Intersection becomes 2D area



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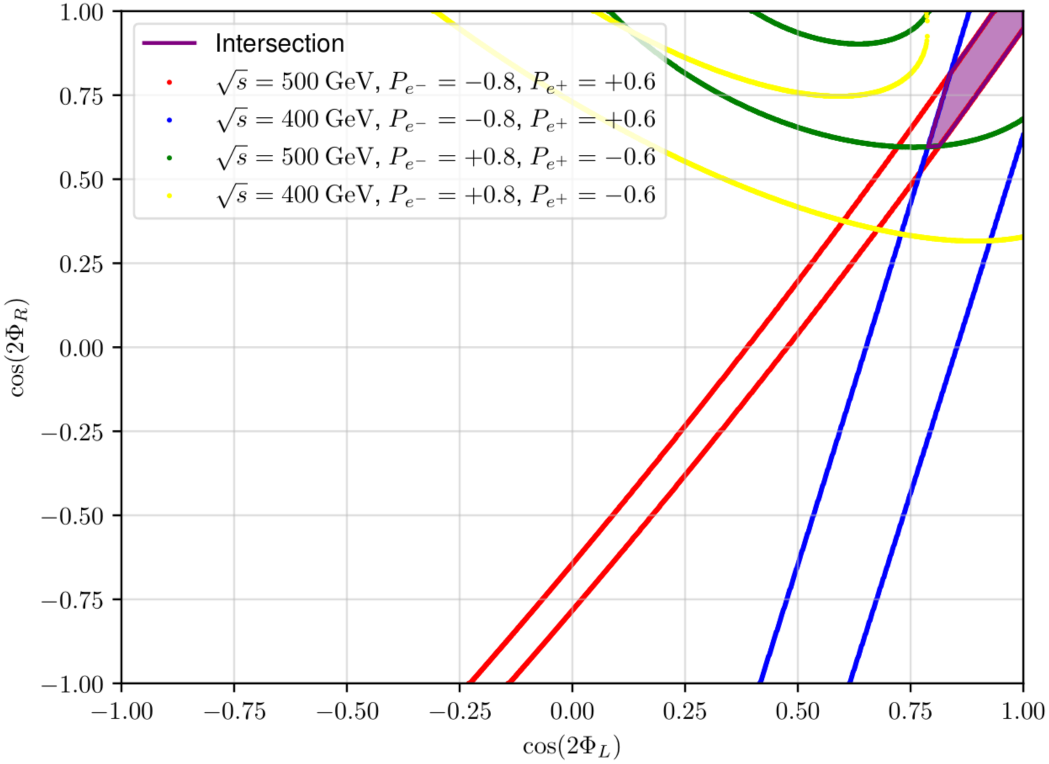
Mixing angles

- Set theory approach
  - Mixing angle bands are defined as polygons using the *shapely* Python libary
  - Intersection of polygons is calculated
- Accurately describes all the points within and on the boundary
- Calculation is easier, more efficient and less ambiguous compared to 1D case



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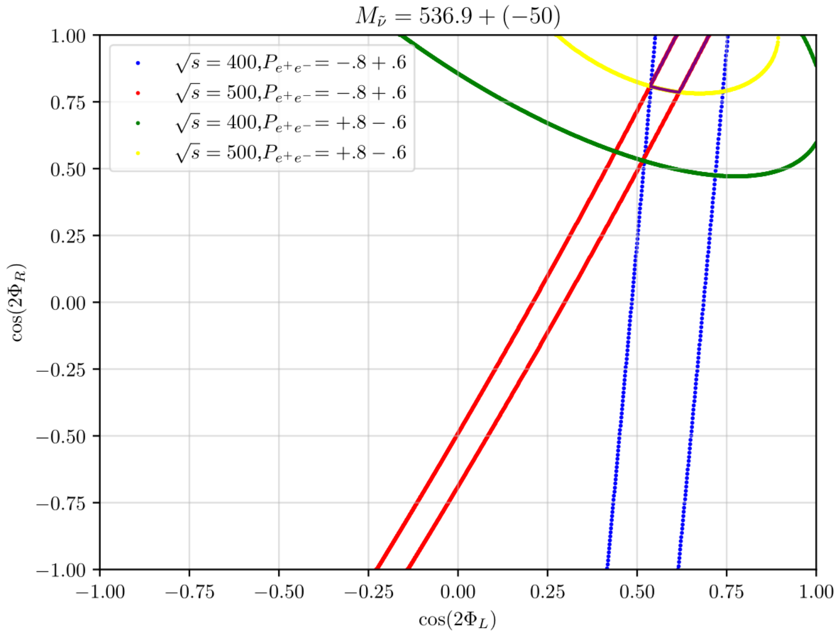
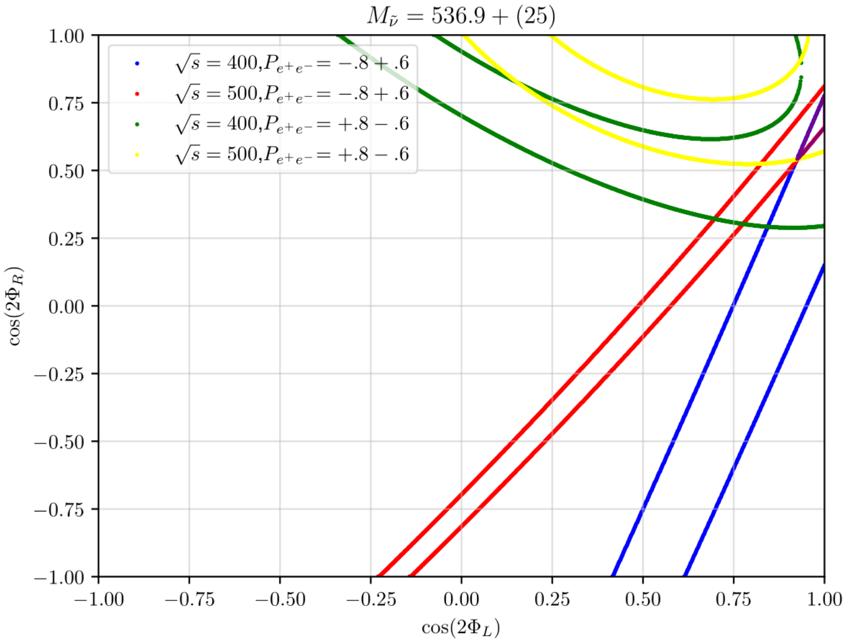
Mixing angles - $M_{\tilde{\nu}}$





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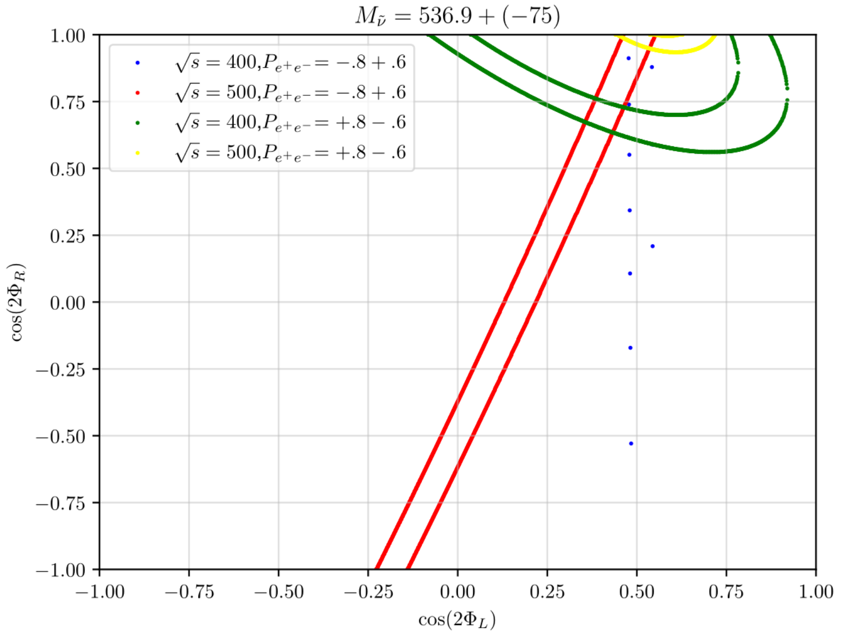
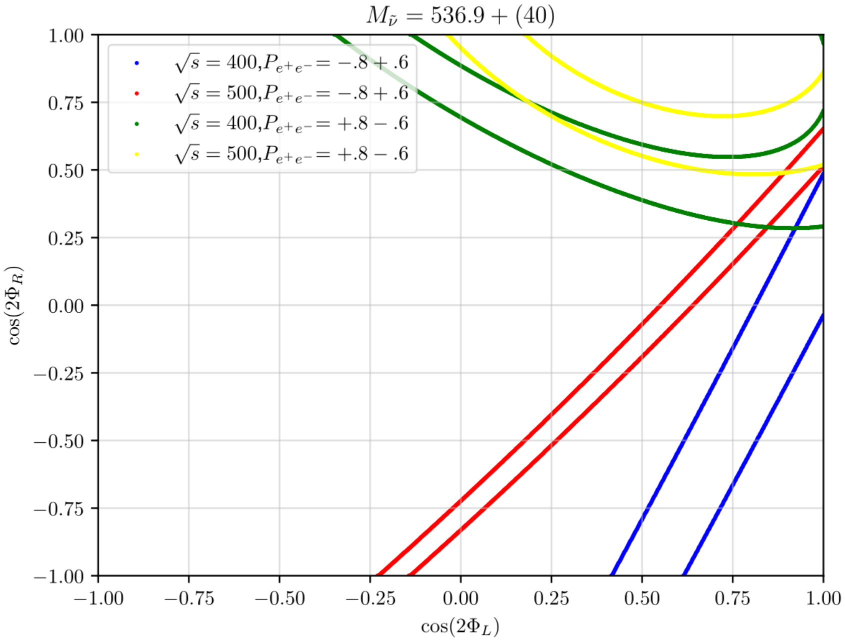
Mixing angles - $M_{\tilde{\nu}}$





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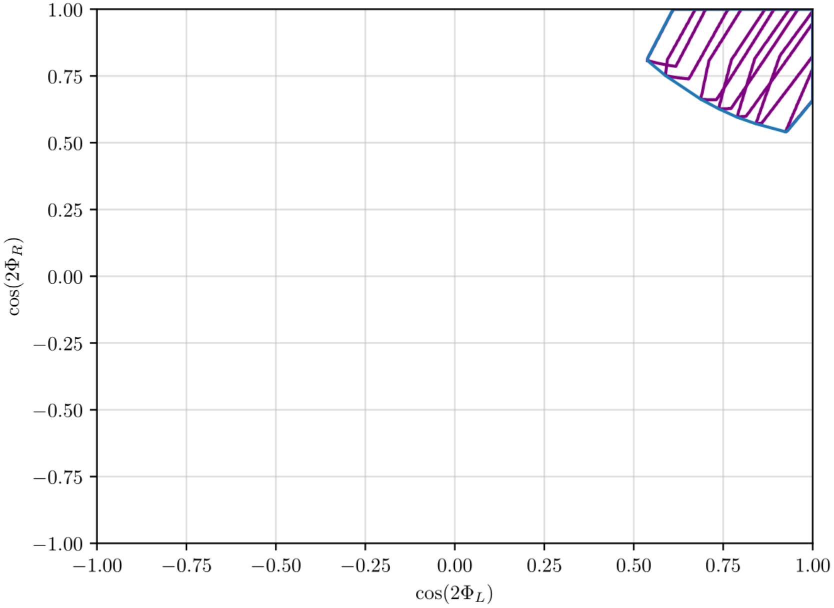
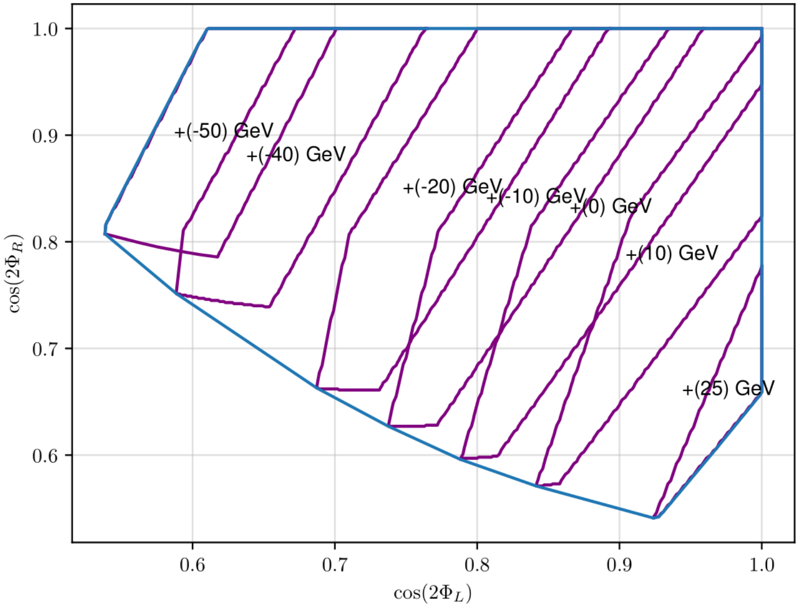
Mixing angles - $M_{\tilde{\nu}}$

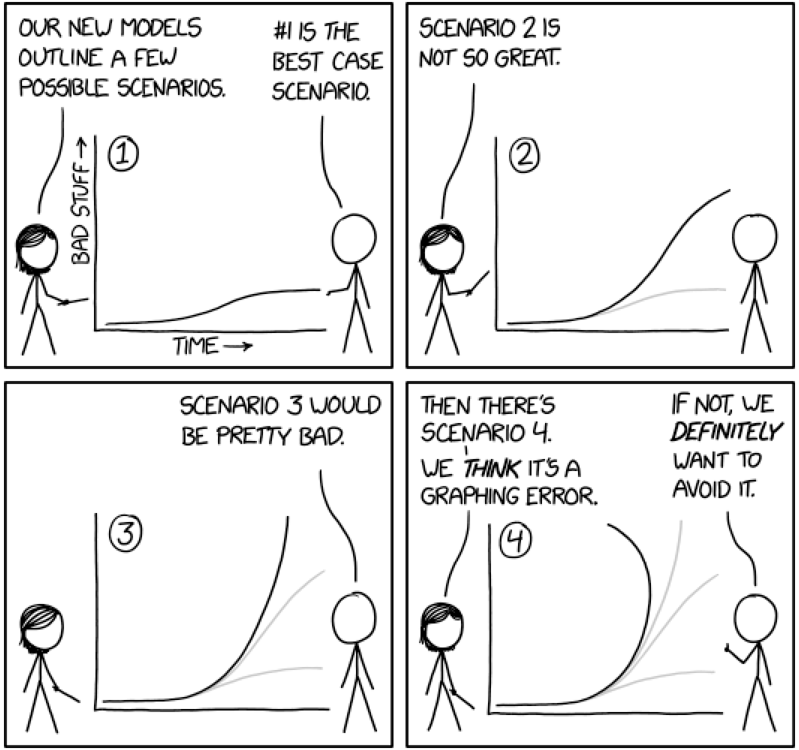




Next Steps

- Automate uncertainties resulting from Sneutrino mass
- Neutralino mass calculations
- Describe SUSY-parameters using chargino and neutralino calculations
- Relic Density

Thank you



https://xkcd.com/2289/