Hunting scalar lepton partners

- an example of direct BSM searches at lepton colliders -

Sebastian Baum

Stanford Institute for Theoretical Physics

Stanford University

Also known as sleptons
to the members of a
particular BSM sect...

Hunting scalar lepton partners

- an example of direct BSM searches at lepton colliders -

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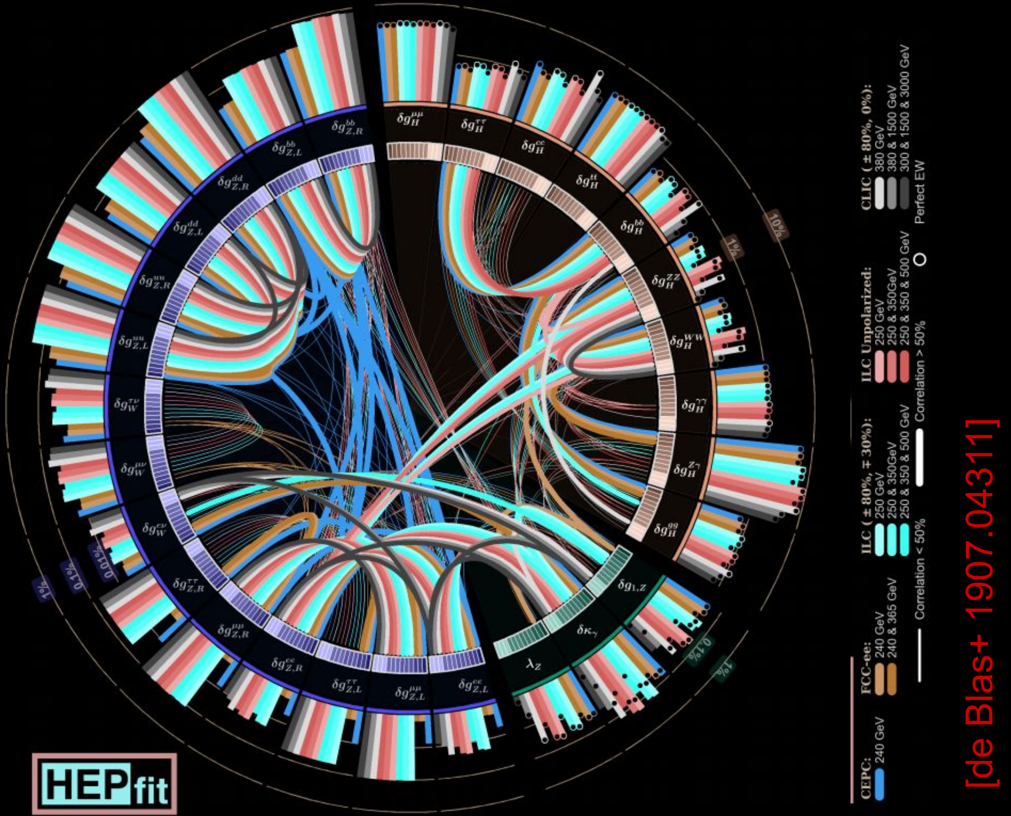
Lepton colliders are great for precision physics...



[de Blas+ 1907.04311]

… but what about direct searches for new physics?

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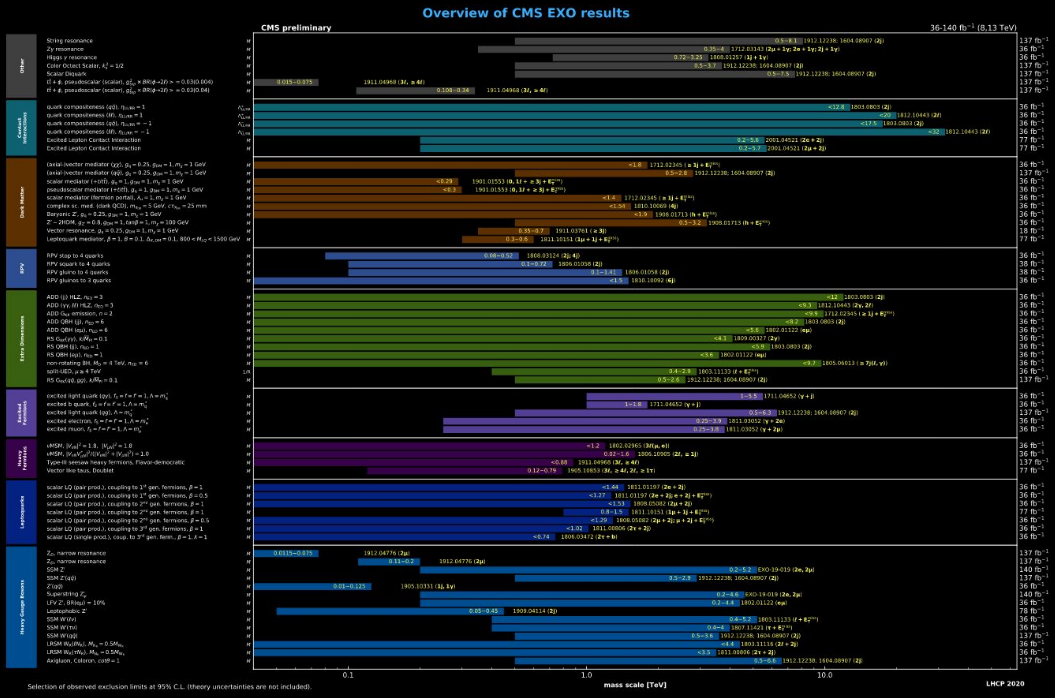
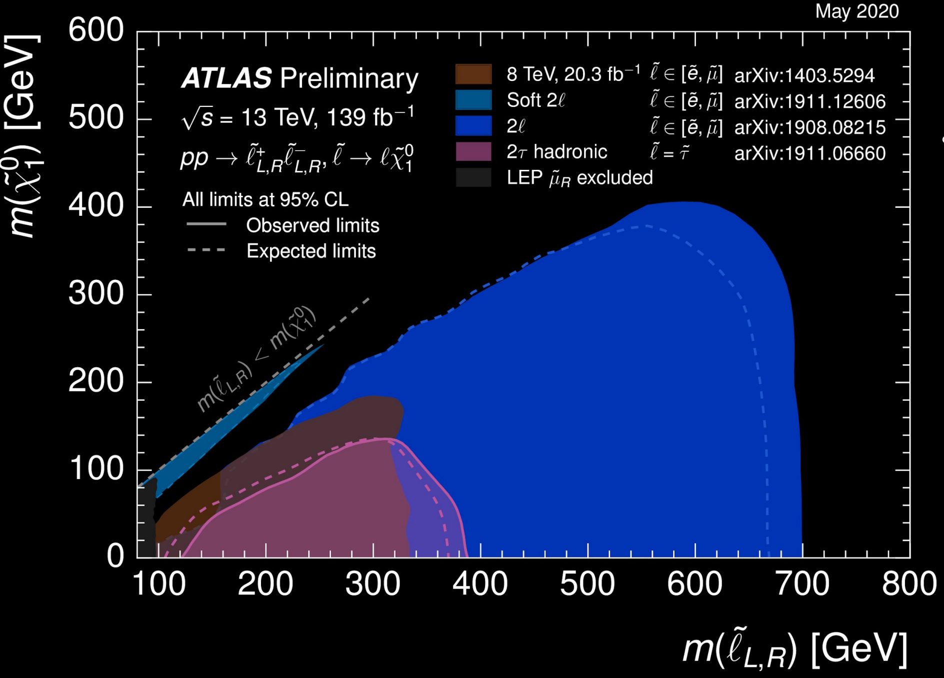
LHC sets strong bounds on lots of BSM scenarios!

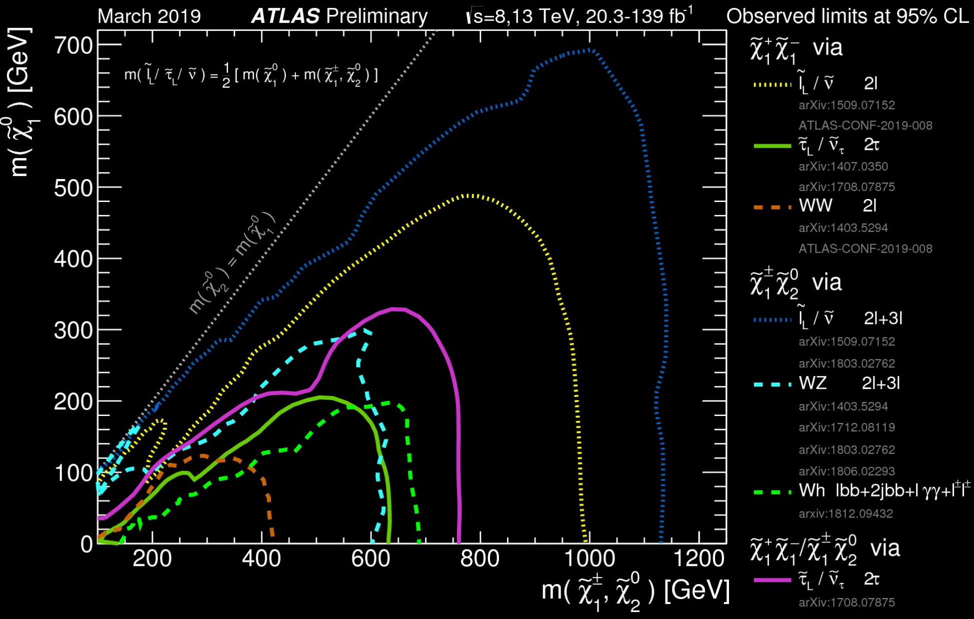


… but what about direct searches for new physics?

Sleptons (~ EW charged scalars)



Electroweakinos (~EW charged fermions)



Electro(weak) colliders for new electroweak physics!

Electro(weak) colliders for new electroweak physics!

PHYSICAL REVIEW D **102,** 015026 (2020)

Hunting for scalar lepton partners at future electron colliders

Sebastian Baum,[1,2,*] Pearl Sandick,[3,†] and Patrick Stengel[2,‡]

[Farrar&Fayet '80; Tsukamoto+ '95;
Nojiri '95; Feng&Peskin '01;
Freitas+ '03; Boos+ '03;
Freitas, v. Manteufel&Zerwas '04;
Martyn '04; Battaglia+ '05;
Buckley+ '08;
Ellis, Olive&Sandick '08;
Bechtle+ '10; Berggren '13;
Endo+ '13]

A "simplified" model

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Standard Model +

- Spin-zero state with $Q = -e$ and lepton (flavor) number

“slepton” “smuon”

$$\tilde{\ell} = \tilde{e}, \tilde{\mu}, \tilde{\tau}$$

“selectron” “stau”

A “simplified” model

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- Spin-zero state with Q = -e and lepton (flavor) number
- Q = 0 fermion without lepton number (“neutralino”)

“slepton” “smuon”

$$\tilde{\ell} = \tilde{e}, \tilde{\mu}, \tilde{\tau}$$

“selectron” “stau”

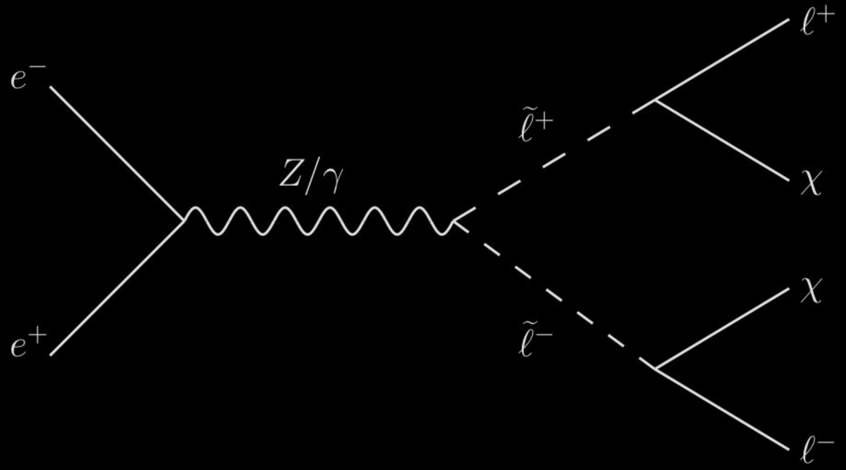
Opens decay channel

$$(\tilde{\ell}^{\pm} \to \chi \ell^{\pm})$$

$$\mathcal{L} \supset |D_\mu \tilde{\ell}|^2 - m^2_{\tilde{\ell}_i} |\tilde{\ell}_i|^2 + \bar{\chi}(i\not{D} - m_\chi)\chi - (\kappa \tilde{\ell}^\dagger_i \bar{\chi} \ell_i + \text{H.c.})$$

Standard Model +

- Spin-zero state with *Q* = -*e* and lepton (flavor) number
- *Q* = *0* fermion without lepton number (“neutralino”)
- $$\begin{pmatrix} \tilde{\ell}_1 \\ \tilde{\ell}_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \tilde{\ell}_L \\ \tilde{\ell}_R \end{pmatrix}$$



$$\mathcal{L} \supset |D_\mu \tilde{\ell}|^2 - m^2_{\tilde{\ell}_i} |\tilde{\ell}_i|^2 + \bar{\chi}(i\not{D} - m_\chi)\chi - (\kappa \tilde{\ell}_i^\dagger \bar{\chi} \ell_i + \text{H.c.})$$

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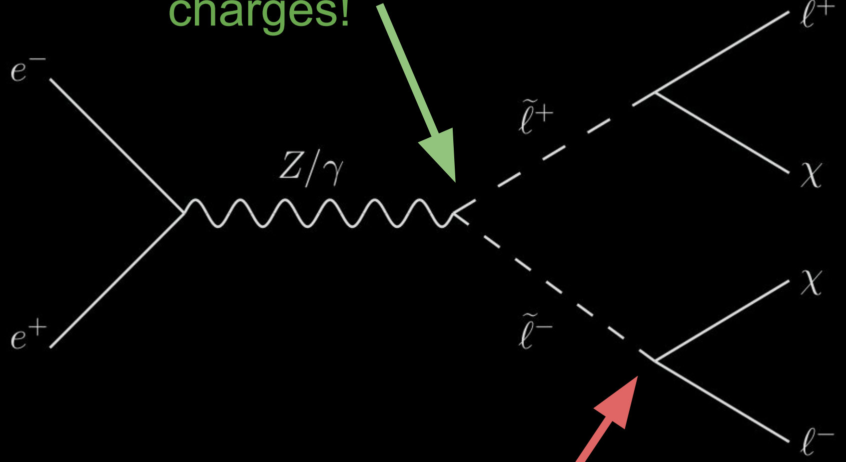
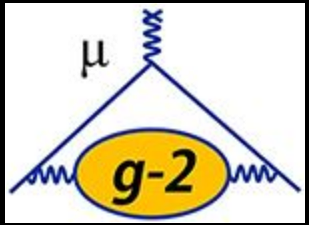
Fixed by gauge charges!



Model dependent (if multiple decay channels allowed) "slepton" + "neutralino"

Is this good for anything?

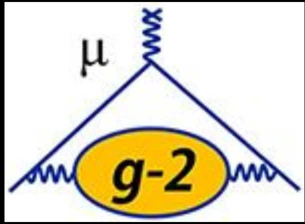


“slepton” + “neutralino”

Appear in well-motivated more complete (supersymmetric) UV models

Dark Matter Model Building
- Slepton co-annihilation
- left-right mixed slepton enhances neutralino pair-annihilation (incredible bulk)

[Ellis+ ‘98, ‘01; Buckley, Hooper&Kumar ‘13; Pierce, Shah&Freese ‘13; Fukushima+ ‘14; Baker&Thamm ‘18; Duan+ ‘19]



“slepton” + “neutralino”

Appear in well-motivated more complete (supersymmetric) UV models

Dark Matter Model Building
- Slepton co-annihilation
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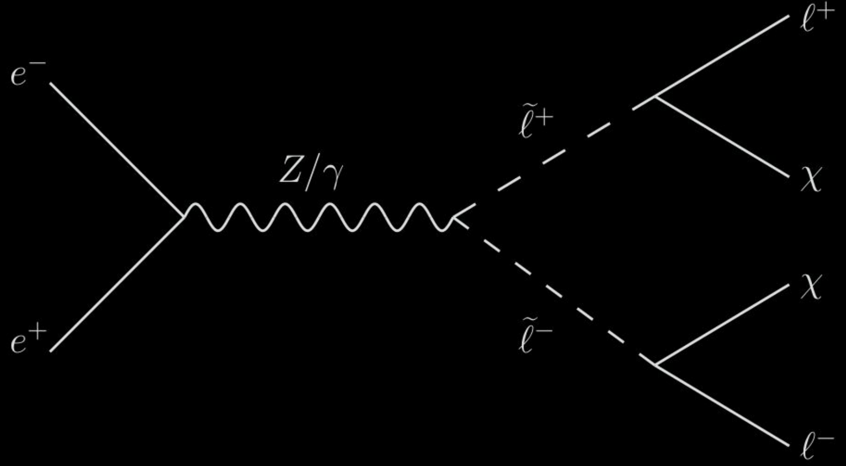
(focus on smuons and staus!)

Crank the collider simulation...

Simple final state:

- two charged leptons
  + missing energy



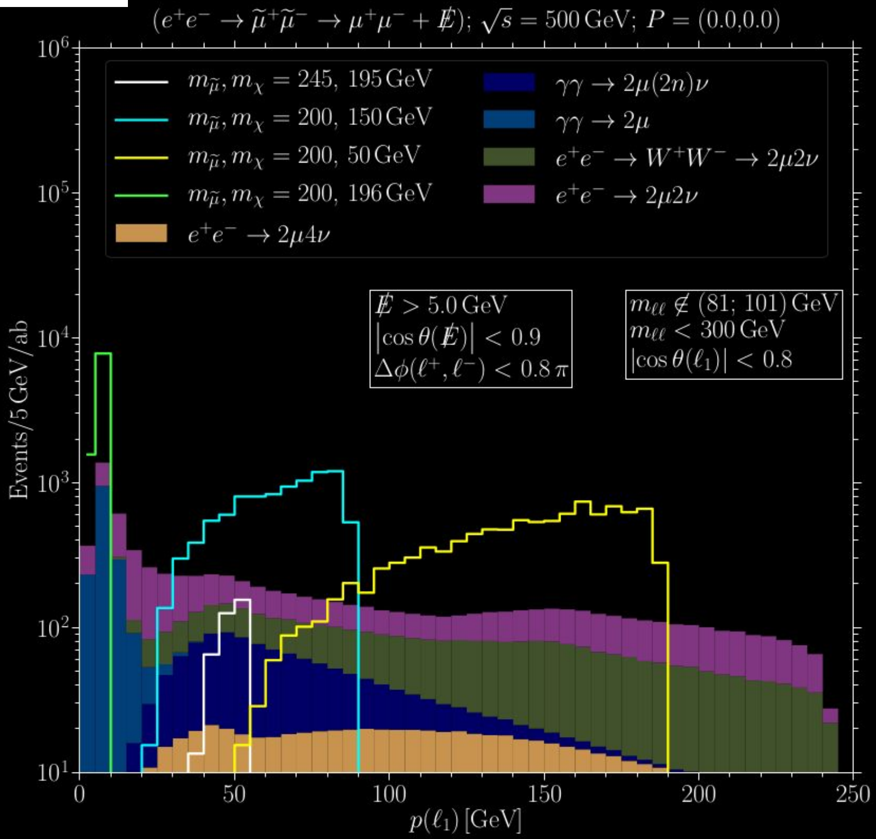
Crank the collider simulation...

[SB+ 2004.02834]

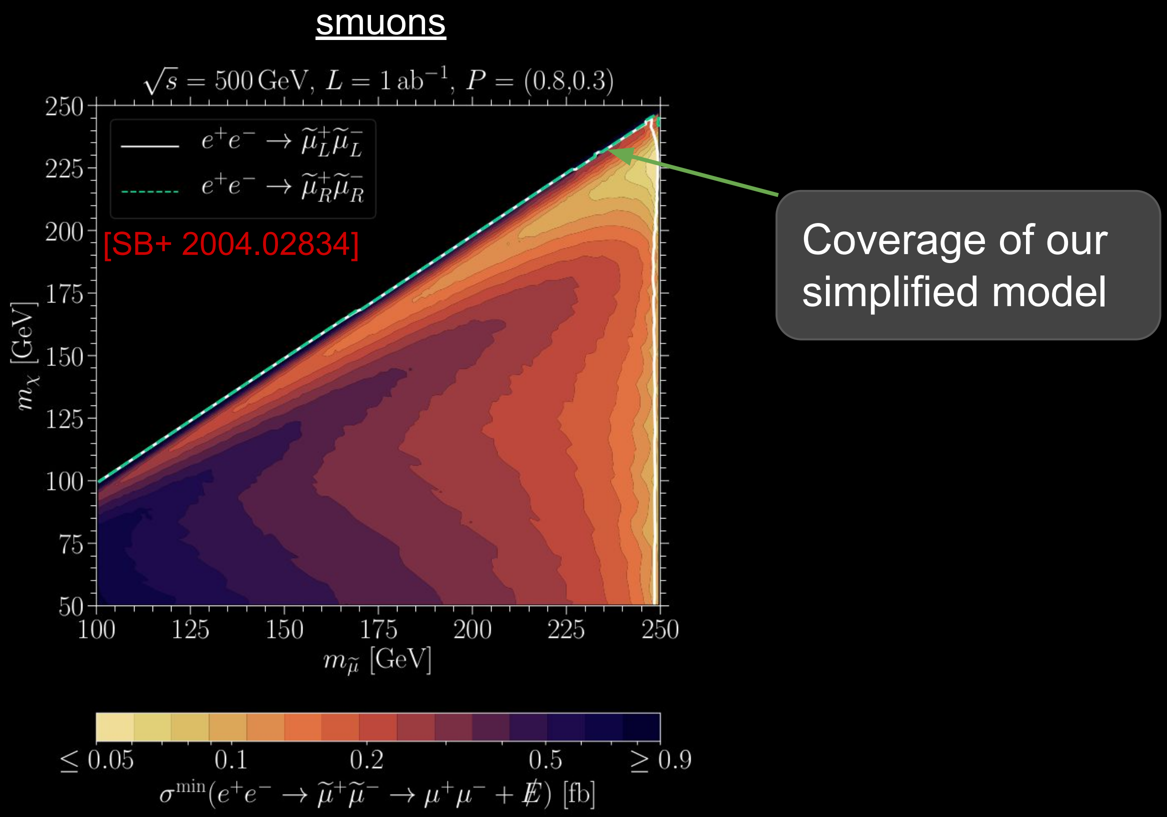
Simple final state:

- two charged leptons
  + missing energy

Background process	No. of samples
$e^+e^- \to \mu^+\mu^-$	10^7
$e^+e^- \to \mu^+\mu^- + 2\nu$	10^7
$e^+e^- \to \mu^+\mu^- + 4\nu$	5×10^6
$\gamma\gamma \to \mu^+\mu^-$	10^9
$\gamma\gamma \to \mu^+\mu^- + 2\nu$	10^7
$\gamma\gamma \to \mu^+\mu^- + 4\nu$	10^7

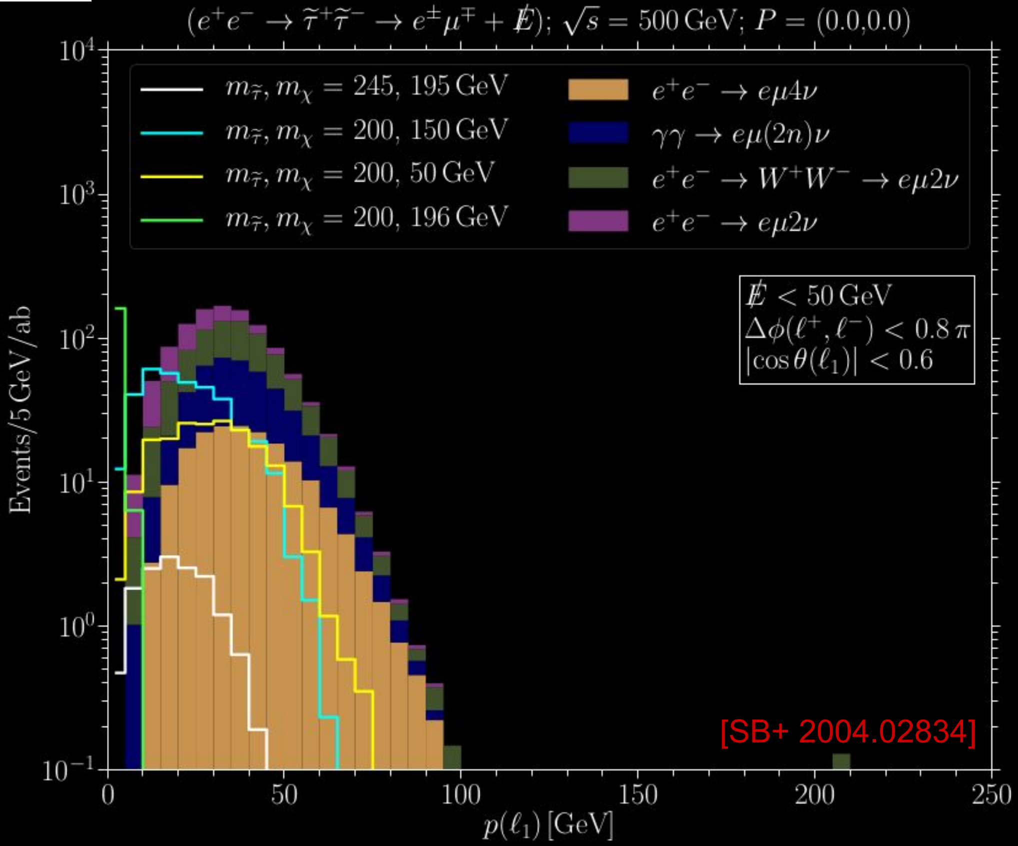


Sensitivity for this simple cut & count analysis:



And what about staus?

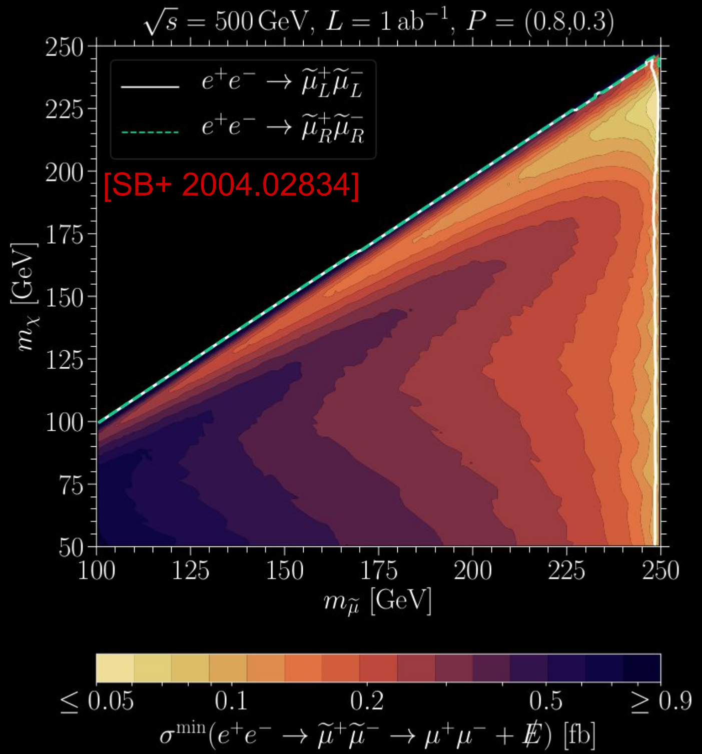
Use $(e^\pm \mu^\mp + \not{E})$ final state!



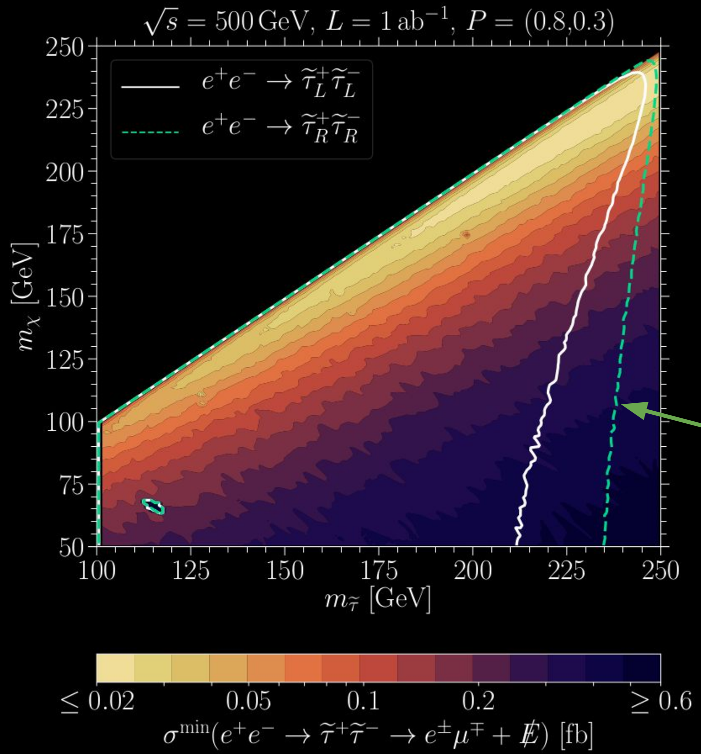
[SB+ 2004.02834]

Sensitivity for this simple cut & count analysis:

smuons

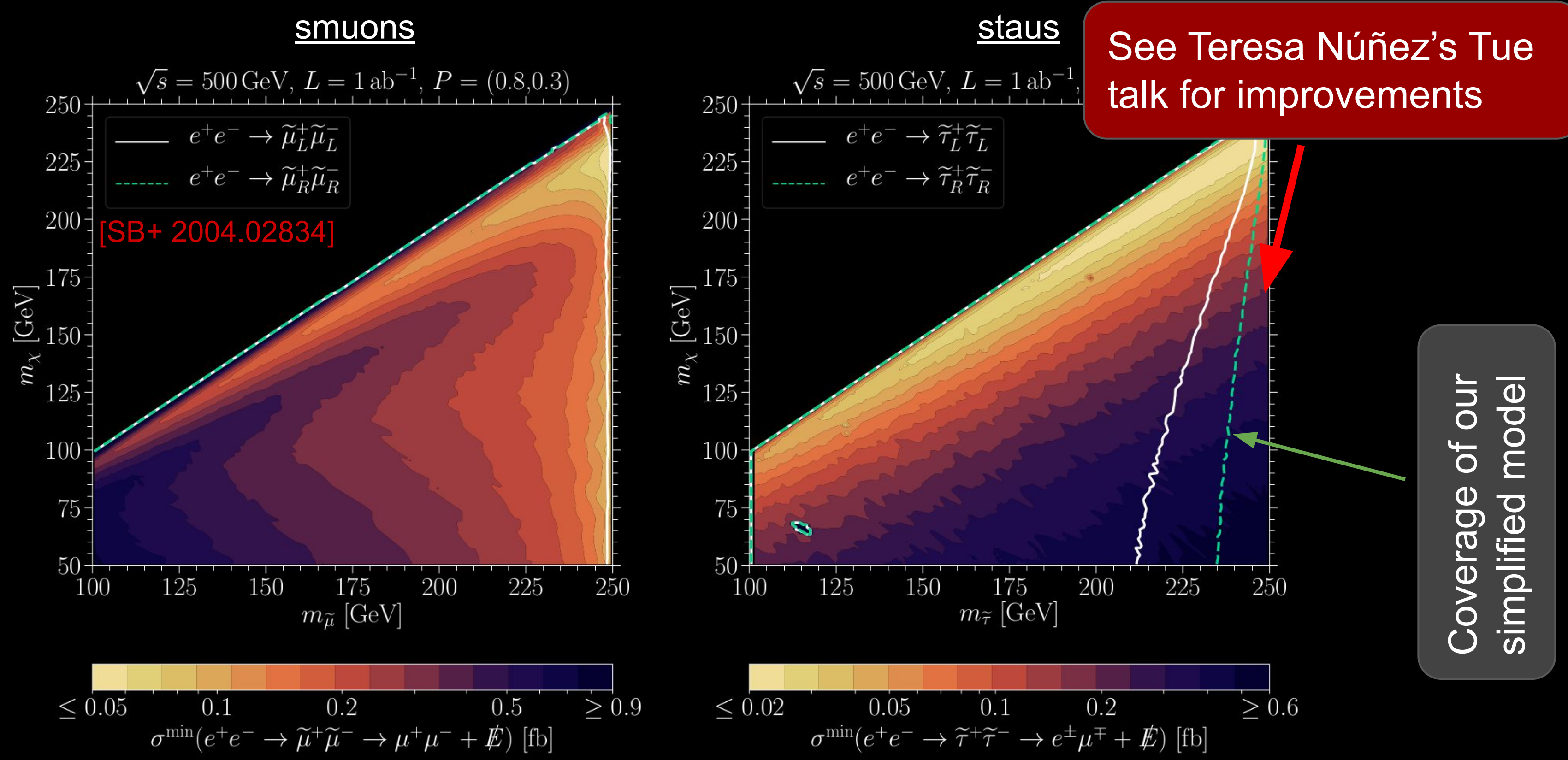


staus



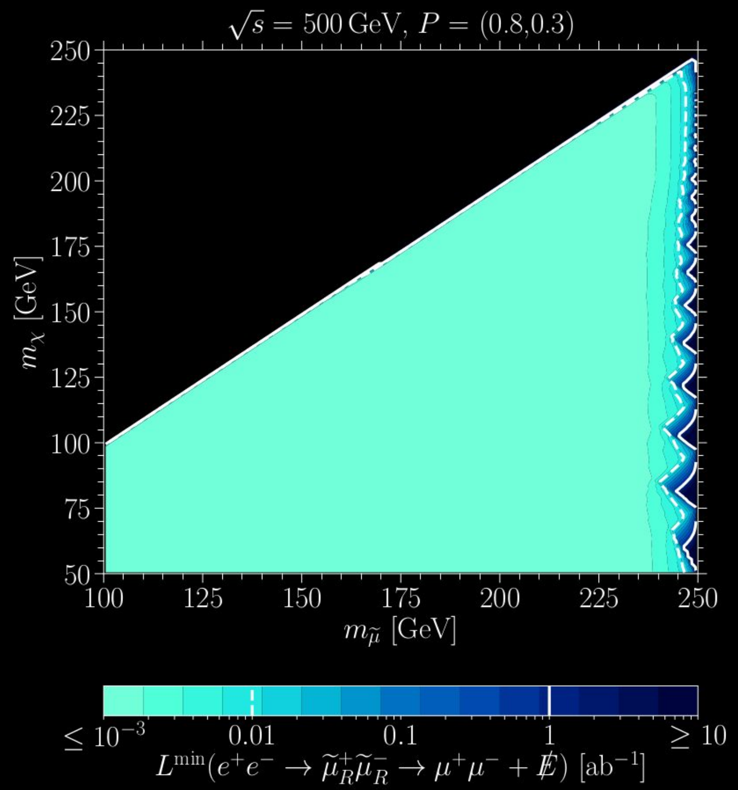
Coverage of our simplified model

Sensitivity for this simple cut & count analysis:

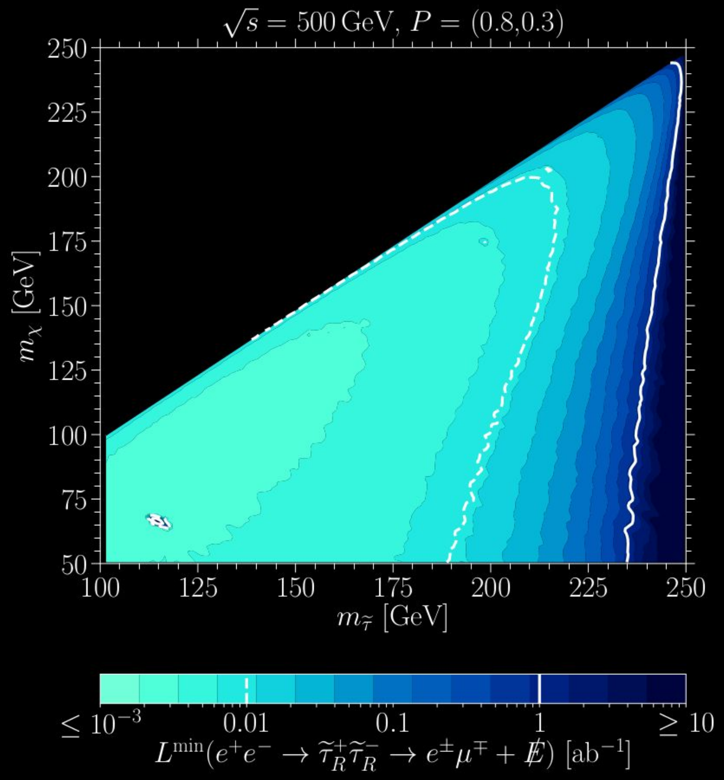


How much luminosity is needed?

smuons with mostly right-handed beams

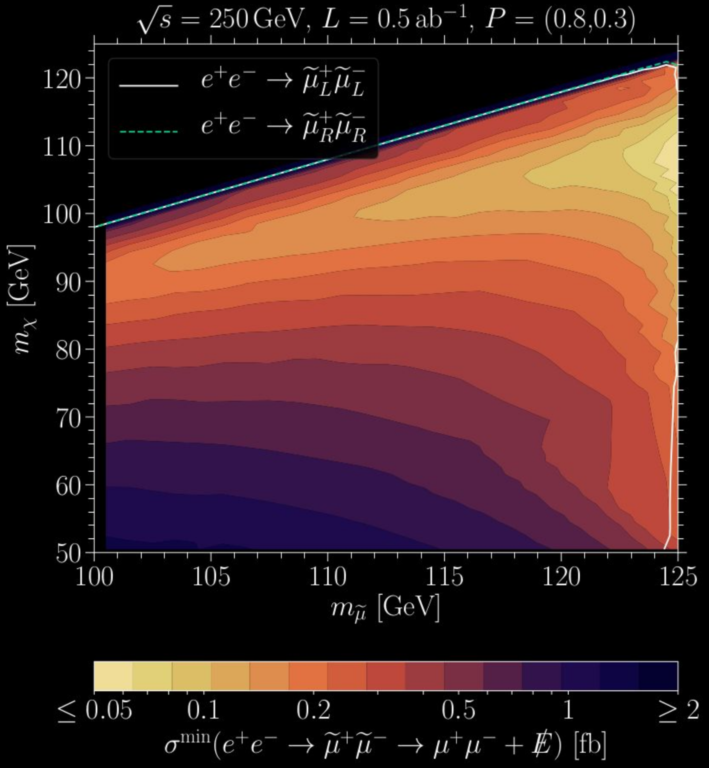


staus with mostly right-handed beams

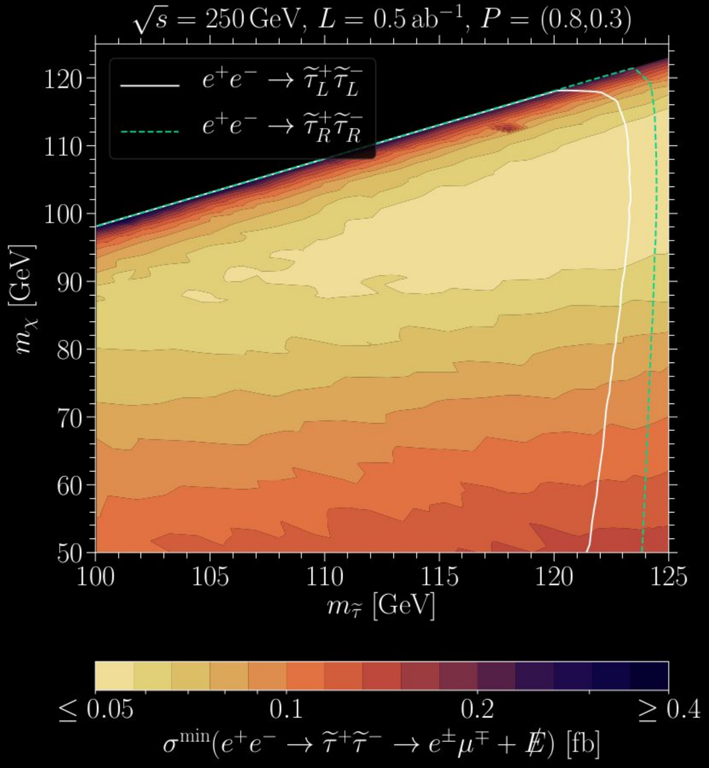


Reach at √s = 250 GeV

smuons



staus



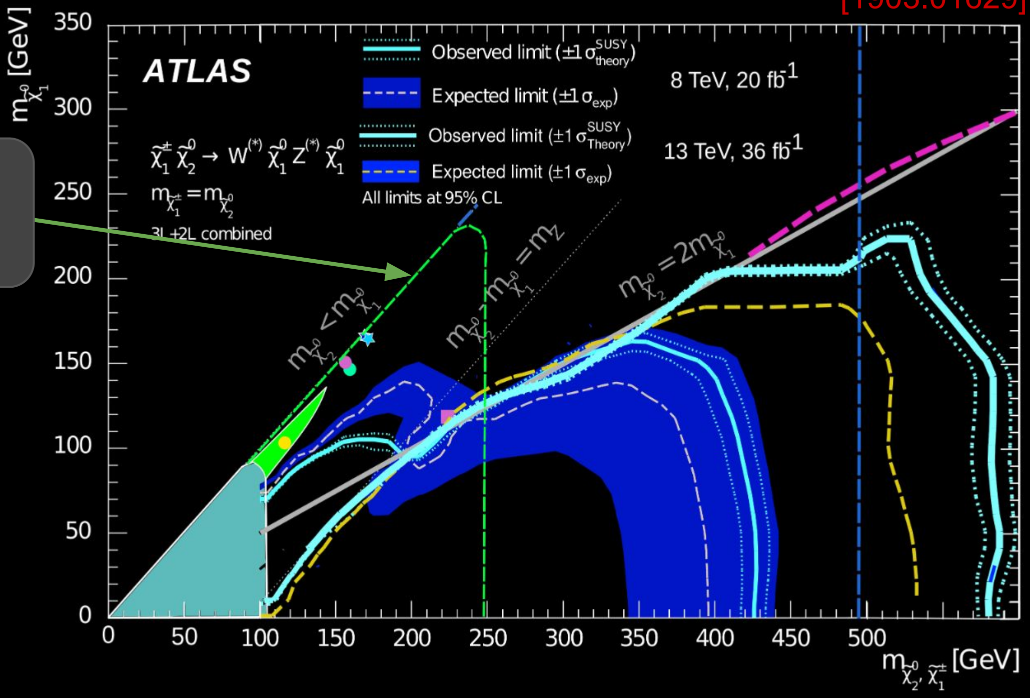
(electroweakinos)

[ILC 1506.05992; d'Enterria '17; CEPC 1811.10545; CLIC 1812.02093; Baer+ '20; Habermehl+ '20]

Similar story for new charged fermions…

[1903.01629]

Direct coverage to √s/2 at a lepton collider

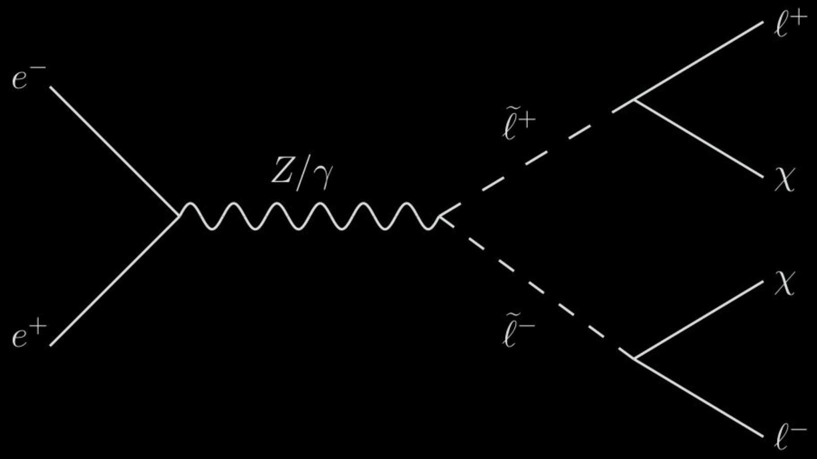


Conclusions

- Any future electron collider would have ~immediate reach to new (EW-) charged physics up to √s/2

  ➡️ fills some important holes left by the LHC
  (even at rather low √s!)

- Polarization would be very helpful!

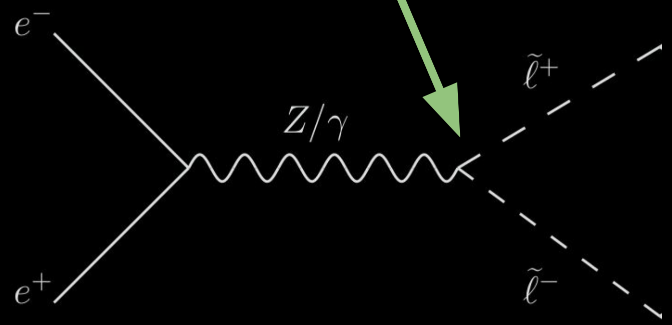


Smuon/stau pair production cross sections

Polarized pair-production cross section

$$\frac{d\sigma_{LL/RR}(e^+e^- \to \tilde{\ell}_i\tilde{\ell}_i)}{d\cos\theta} = \frac{\pi\alpha_{\rm EM}^2}{2s}\left[1 + g_{\tilde{\ell}}^{ii} g_{LL/RR}\frac{s}{s-m_Z^2}\right]^2 \times \left(1 - \frac{4m_{\tilde{\ell}}^2}{s}\right)^{3/2}\sin^2\theta,$$

Fixed by gauge charges!



Effective slepton-slepton-Z coupling

$$g_{\tilde{\ell}}^{ii} = \begin{cases} \frac{\cos^2\alpha}{\sin(2\theta_W)} - \tan\theta_W & \text{for } \tilde{\ell}_i = \tilde{\ell}_1, \\ \frac{\sin^2\alpha}{\sin(2\theta_W)} - \tan\theta_W & \text{for } \tilde{\ell}_i = \tilde{\ell}_2, \end{cases}$$

Effective electron-electron-Z coupling

$$g_{LL} = \frac{1}{2}(\cot\theta_W - \tan\theta_W),$$

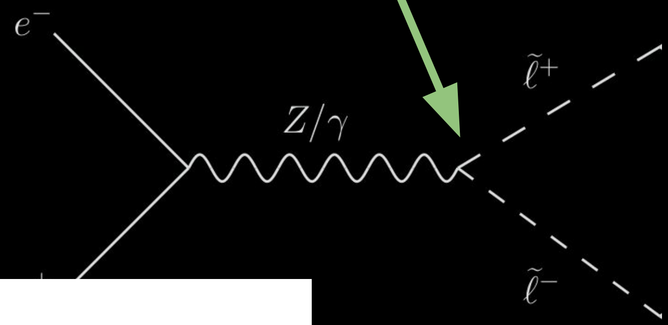
$$g_{RR} = -\tan\theta_W.$$

Smuon/stau pair production cross sections

Polarized pair-production cross section

$$\frac{d\sigma_{LL/RR}(e^+e^- \to \tilde{\ell}_i\tilde{\ell}_i)}{d\cos\theta} = \frac{\pi\alpha_{\rm EM}^2}{2s}\left[1 + g_{\tilde{\ell}}^{ii} g_{LL/RR}\frac{s}{s-m_Z^2}\right]^2 \times \left(1 - \frac{4m_{\tilde{\ell}}^2}{s}\right)^{3/2} \sin^2\theta,$$

Fixed by gauge charges!



Kinematic shape independent of beam polarization, left-right mixing, etc.!

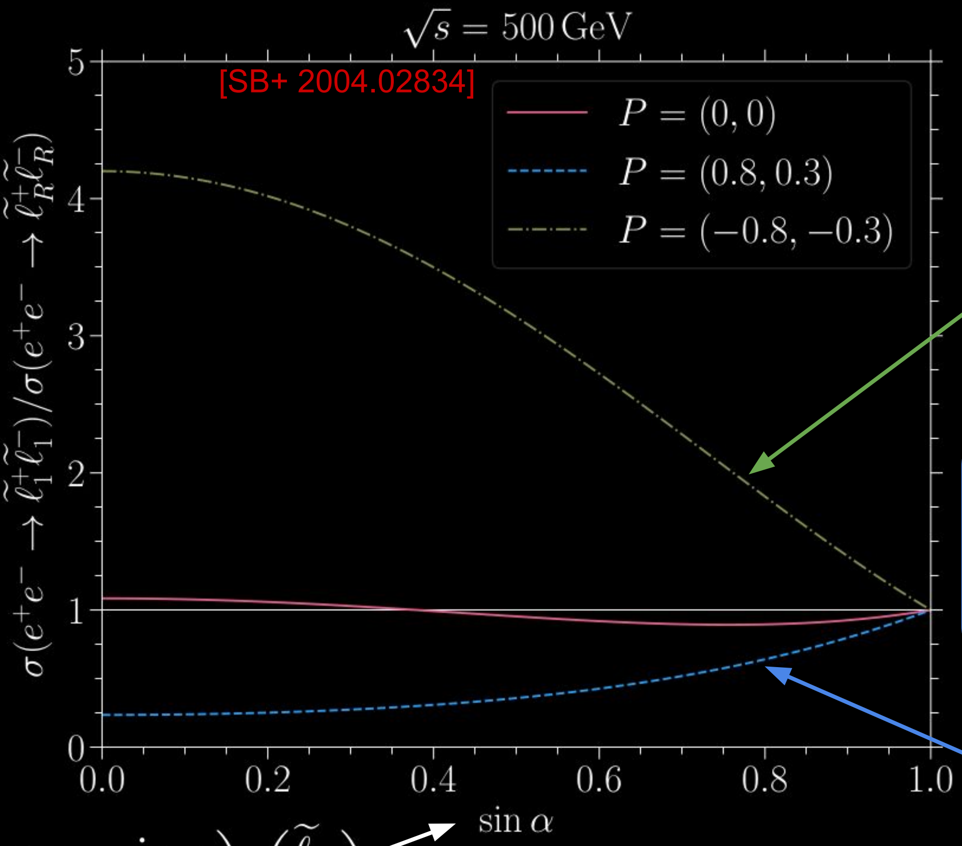
Effective slepton-slepton-Z cou

$$g_{\tilde{\ell}}^{ii} = \begin{cases} \frac{\cos^2\alpha}{\sin(2\theta_W)} - \tan\theta_W & \text{for } \tilde{\ell}_i = \tilde{\ell} \\ \frac{\sin^2\alpha}{\sin(2\theta_W)} - \tan\theta_W & \text{for } \tilde{\ell}_i = \tilde{\ell}_2, \end{cases}$$

coupling

g_{LL} … 2 …

$$g_{RR} = -\tan\theta_W.$$



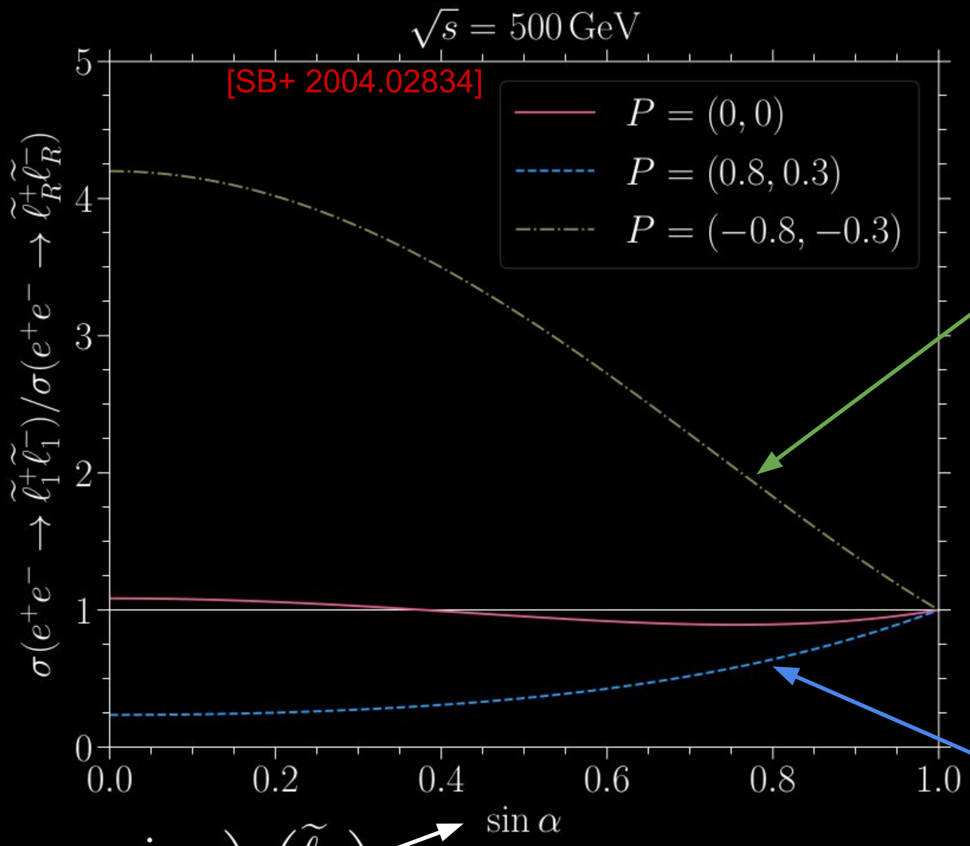
Mostly left-handed beam configuration

$$P_R = f_R - f_L,$$

$$f_L = \frac{n_L}{n_L + n_R}, \qquad f_R = \frac{n_R}{n_L + n_R},$$

Mostly right-handed beam configuration

$$\begin{pmatrix} \tilde{\ell}_1 \\ \tilde{\ell}_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \tilde{\ell}_L \\ \tilde{\ell}_R \end{pmatrix}$$



Mostly left-handed beam configuration

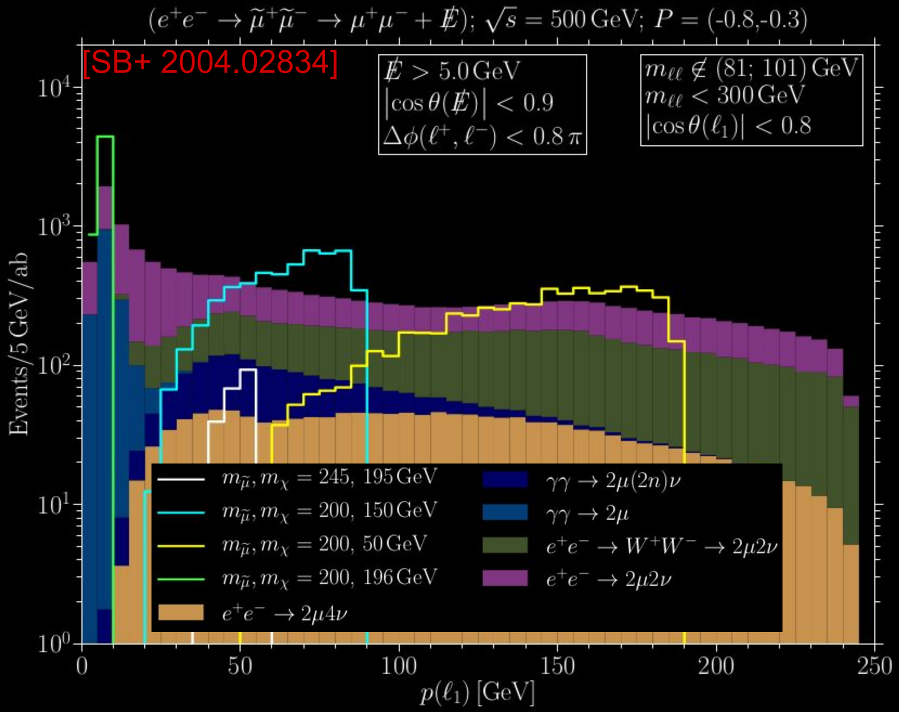
Most important back-ground for this search: W pair production

Mostly right-handed beam configuration

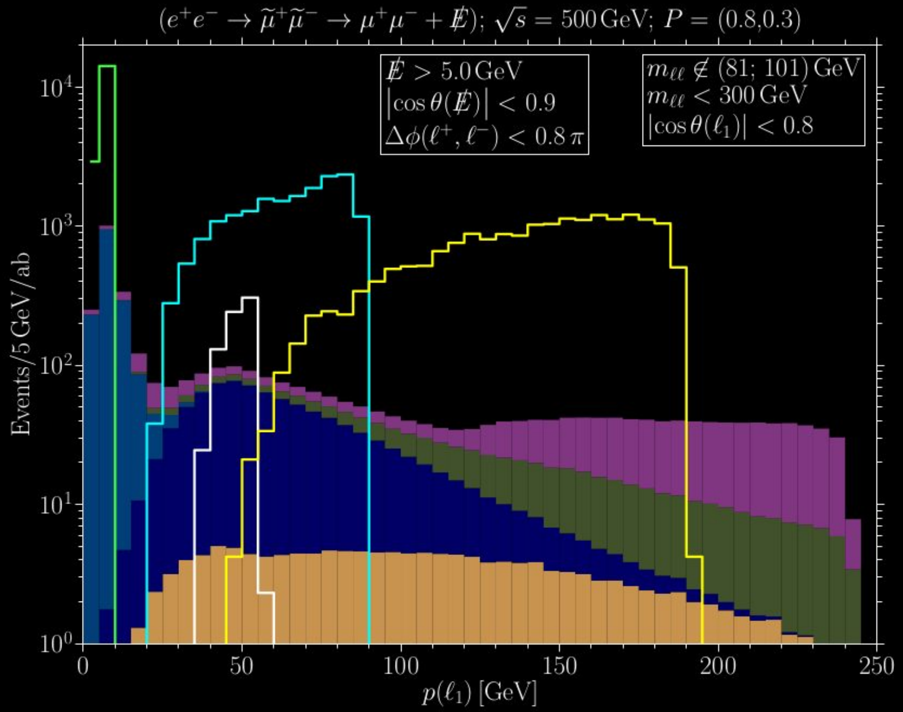
$$\begin{pmatrix} \tilde{\ell}_1 \\ \tilde{\ell}_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \tilde{\ell}_L \\ \tilde{\ell}_R \end{pmatrix}$$

Beam polarization matters! (for right-handed sleptons)

Mostly left-handed beams

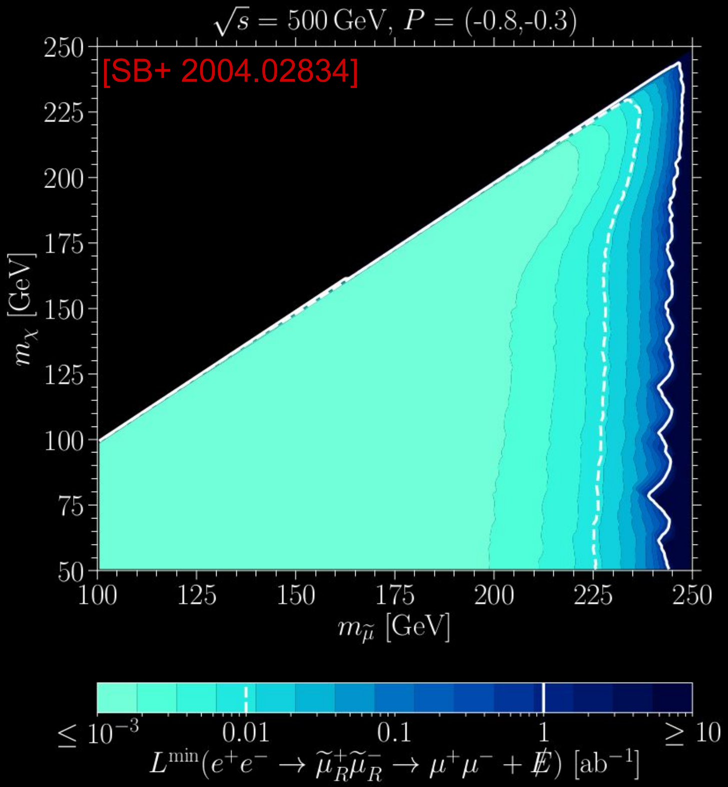


Mostly right-handed beams

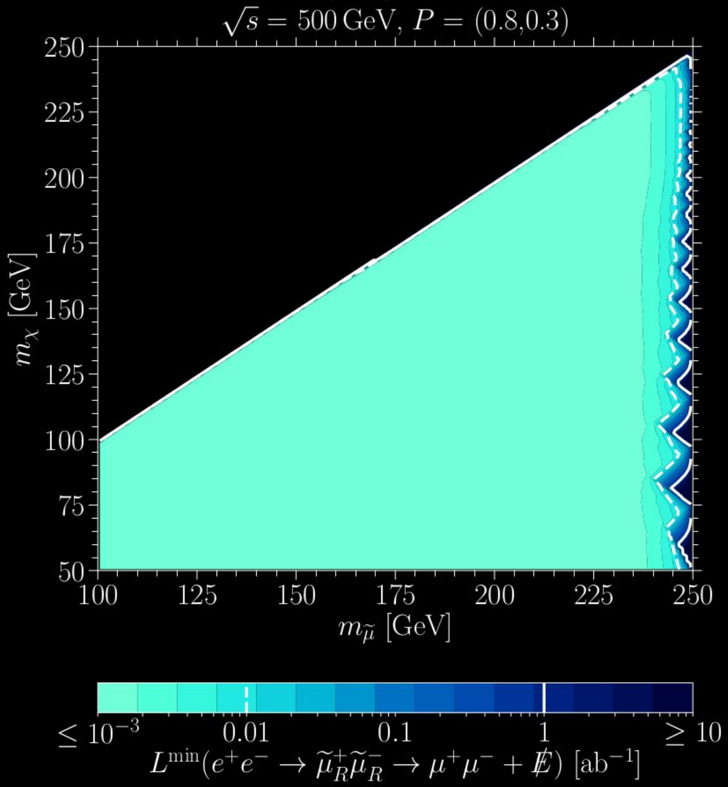


How much luminosity is needed?

smuons with mostly left-handed beams

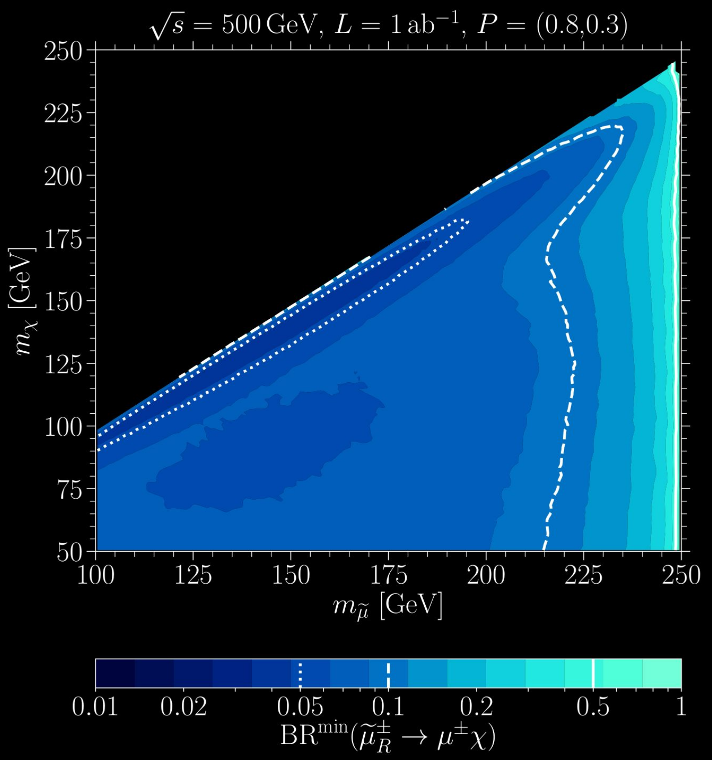


and with mostly right-handed beams

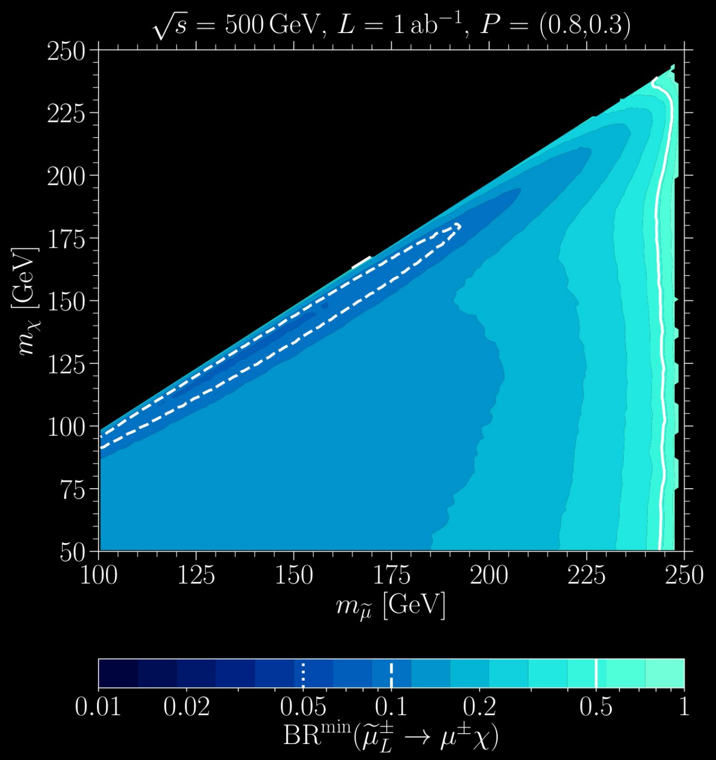


Or, in terms of the branching ratio:

right-handed smuons



left-handed smuons



How much luminosity is needed for staus?