Title: TBA

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Abstract: <p>Abstract TBA</p>

Windows for Light Charged Particles

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arXiv:1711.soon

with Daniel Egana-Ugrinovic *and* Joshua Ruderman

LEP Quiz

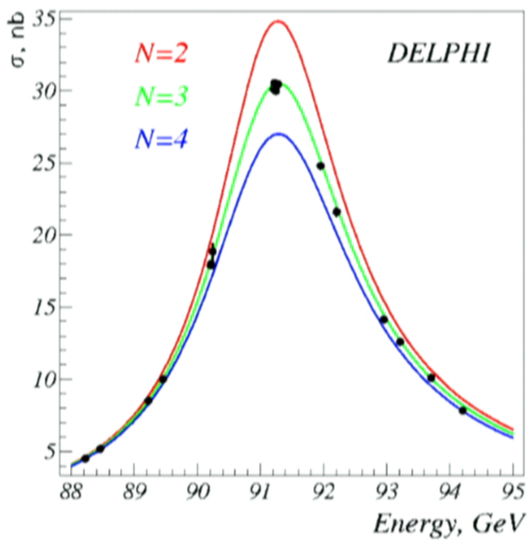
- Which of the following statements is true?
  - a LEP says weakly-charged particles $m > M_Z/2$
  - b LEP says electrically-charged particles $m > 94$ GeV
  - c LEP says $N_\nu = 3$

LEP Quiz

a LEP says weakly-charged particles $m > M_Z/2$

$$\Gamma_Z = 2.4952 \pm 0.0023 \text{ GeV}$$

c LEP says $N_\nu = 3$



http://delphiwww.cern.ch/delfigs/export/pubdet4.html

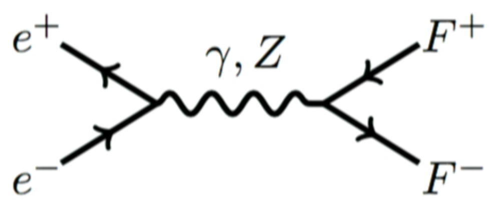
LEP Review

- LEP says electrically-charged particles $m > 94$ GeV

$\widetilde{\chi}_i^{\pm}$ — charginos (mixtures of $\widetilde{W}^{\pm}$ and $\widetilde{H}_i^{\pm}$) Mass $m_{\widetilde{\chi}_1^{\pm}} > 94$ GeV, CL = 95% [$\tan\beta < 40$, $m_{\widetilde{\chi}_1^{\pm}} - m_{\widetilde{\chi}_1^0} > 3$ GeV, all m_0]

http://pdg.lbl.gov/2017/tables/rpp2017-sum-searches.pdf

- Contribution from s-channel photon and Z

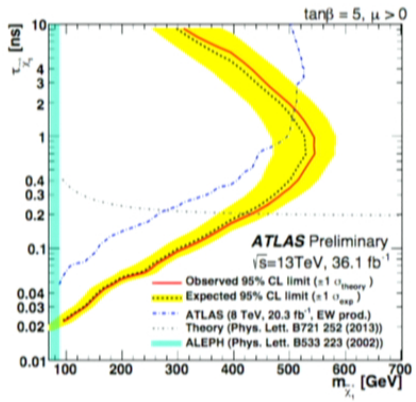


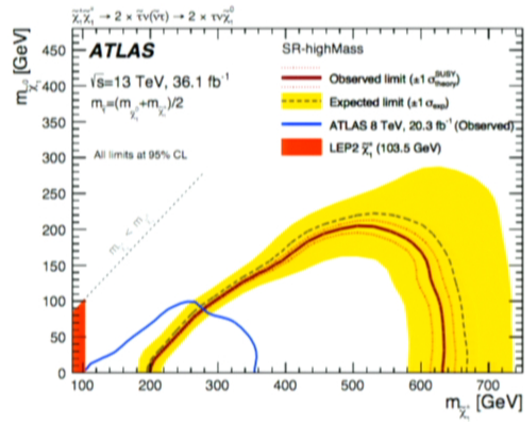
$$\sigma_\gamma = \frac{4\pi\alpha^2}{3s} Q_F^2$$

$$\sigma_Z = \frac{4\pi\alpha^2}{3s}(0.35)(v_F^2 + a_F^2)$$

LEP Review

- Results below 94 GeV – 103.5 GeV often not shown at LHC





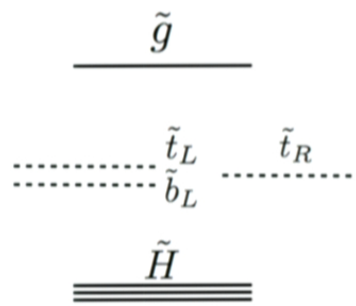
- In fact, this bound is not robust
- The rest of this talk will make this quantitative

Outline

- Motivation
- LEP Archeology
- Mechanisms
- LHC Limits
- Conclusions

Motivation

- Why do we care about light charged particles?
  - Important to be precise
  - LHC triggers are rising
  - Model building tool
  - Light charginos are possible



natural SUSY

LEP Archeology

- LEP II Factsheet
  - Ran from 1995 – 2000
  - Ran at $\sqrt{s} = 130.3$ GeV – 208.0 GeV
  - Four detectors: ALEPH, DELPHI, L3, OPAL
  - Collected $\approx 3\ \text{fb}^{-1}$ total

pb^{-1}	ALEPH	DELPHI	L3	OPAL
189 GeV	174.2	153.4	176.4	167.6
196 GeV	236.9	224.7	233.2	204.9
206 GeV	216.8	221.1	212.6	197.5

LEP Archeology

- LEP II SUSY limits on charginos

$\widetilde{\chi}_i^{\pm}$ — charginos (mixtures of $\widetilde{W}^{\pm}$ and $\widetilde{H}_i^{\pm}$)

Mass $m_{\widetilde{\chi}_1^{\pm}} > 94$ GeV, CL = 95%

[$\tan\beta < 40$, $m_{\widetilde{\chi}_1^{\pm}} - m_{\widetilde{\chi}_1^0} > 3$ GeV, all m_0]

Mass $m_{\widetilde{\chi}_1^{\pm}} > 500$ GeV, CL = 95%

[simplified model, $2\ell^{\pm} + \not{E}_T$, $m_{\widetilde{\chi}_1^0} = 0$ GeV]

http://pdg.lbl.gov/2017/tables/rpp2017-sum-searches.pdf

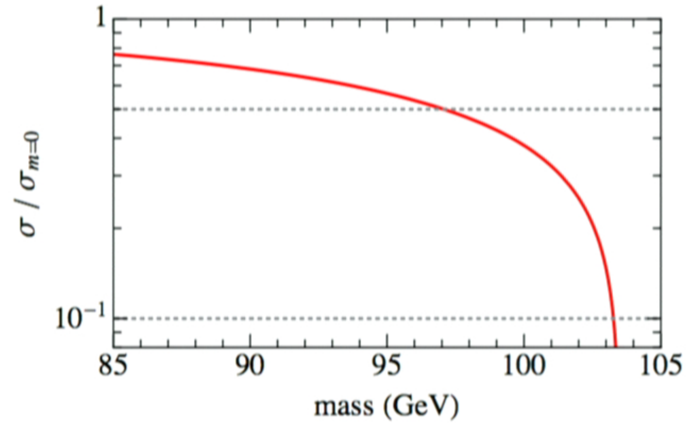
Channel	M(obtained) >	M(expected) >
Chargino	103.5 GeV	103.3 GeV

http://lepsusy.web.cern.ch/lepsusy/www/inos_moriond01/charginos_pub.html

LEP Archeology

- Mass threshold

$$\sigma_\gamma = \frac{4\pi\alpha^2}{3s}\sqrt{1-\frac{4m_{\tilde{\chi}}^2}{s}}\left(1+\frac{2m_{\tilde{\chi}}^2}{s}\right)$$

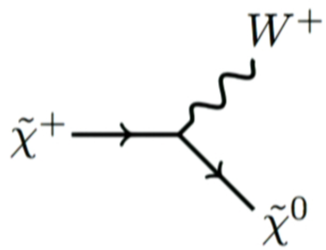


- Lepton collider asymptotic limit

$$m_{\tilde{\chi}} \to \frac{\sqrt{s}}{2}$$

LEP Archeology

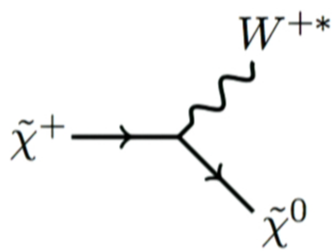
- Decay modes
  - Splitting $> m_W$



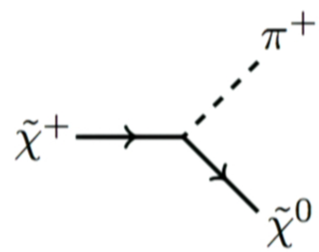
$\mathrm{BR}(\ell\nu_\ell) \approx 33\%$

$\mathrm{BR}(jj) \approx 67\%$

  - Splitting $< m_W$



  - Splitting $< \Lambda_{\mathrm{QCD}}$



LEP Archeology

- Decay modes
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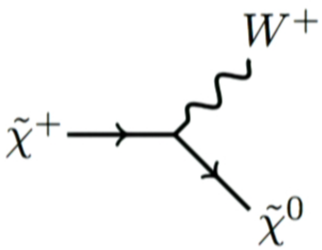

$$\text{BR}(\ell\nu_\ell) \approx 33\%$$

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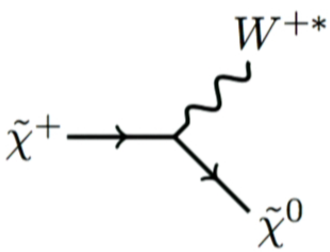
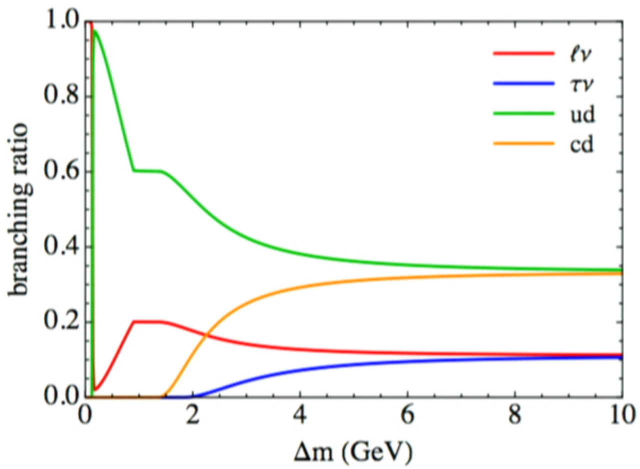




LEP Archeology

- Mass splitting: $\Delta m \equiv m_{\tilde{\chi}^\pm} - m_{\tilde{\chi}^0}$
  - Determines branching ratios
  - Sets energy of daughters
    - *e.g.* two-body decay $\tilde{\chi}^\pm \to \tilde{\chi}^0 \pi^\pm$

$$|p_\pi| = \frac{1}{2m_{\tilde{\chi}^\pm}} \sqrt{(m^2_{\tilde{\chi}^\pm} - (m_{\tilde{\chi}^0} + m_\pi)^2)(m^2_{\tilde{\chi}^\pm} - (m_{\tilde{\chi}^0} + m_\pi)^2)}$$

$$|p_\pi| = \frac{m^2_{\tilde{\chi}^\pm} - m^2_{\tilde{\chi}^0}}{2m_{\tilde{\chi}^\pm}} + \mathcal{O}\left(\frac{m_\pi^2}{m_{\tilde{\chi}}^2}\right)$$

$$|p_\pi| \approx \Delta m$$

- three-body decay daughters have even less energy

LEP Archeology

- Divide regions by Δm
  - $\Delta m > 3$ GeV: bulk region

    leptons, jets, missing energy

  - 300 MeV $< \Delta m <$ 3 GeV: compressed region

    ISR + leptons, jets, missing energy

  - 140 MeV $< \Delta m <$ 300 MeV: displaced region

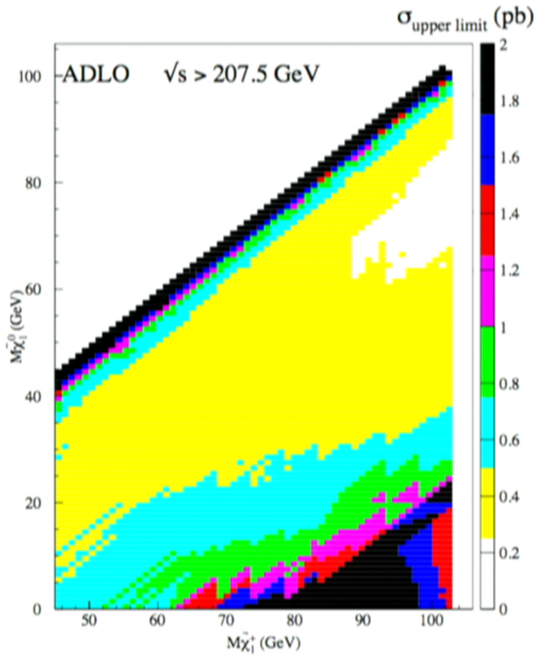
    impact parameter, kinks

  - $\Delta m <$ 140 MeV: long-lived region

    tracks

LEP Archeology

- LEP combinations separate into two categories
  1. Charginos, at large m_0 (bulk region)



- Based on $\sim 210\ \text{pb}^{-1}$ / experiment
- Quoted $m_{\tilde{\chi}^\pm} > 103.5$ GeV
- Other category focuses on compression line
- Weakest σ-limit in bottom-right
- Properly $m_{\tilde{\chi}^\pm} >$ **88 GeV**

LEP Archeology

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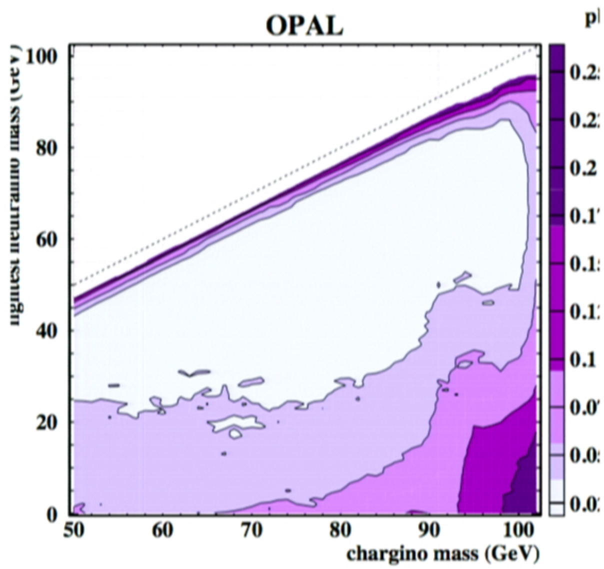
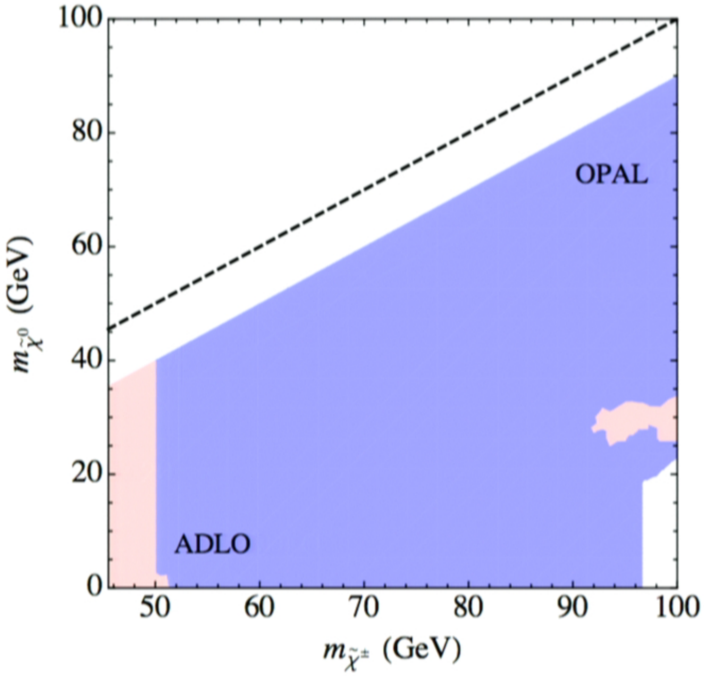
  1. Charginos, at large m_0 (bulk region)



- OPAL multilepton search (hep-ex/0309014)
- Uses 680 pb^{-1}
- Two OS leptons and $\not{E}_T$
- Limit on $\sigma \times \text{BR}(\tilde{\chi}^0 \ell \nu)^2$
- Stronger than ADLO in much of the parameter space

LEP Archeology

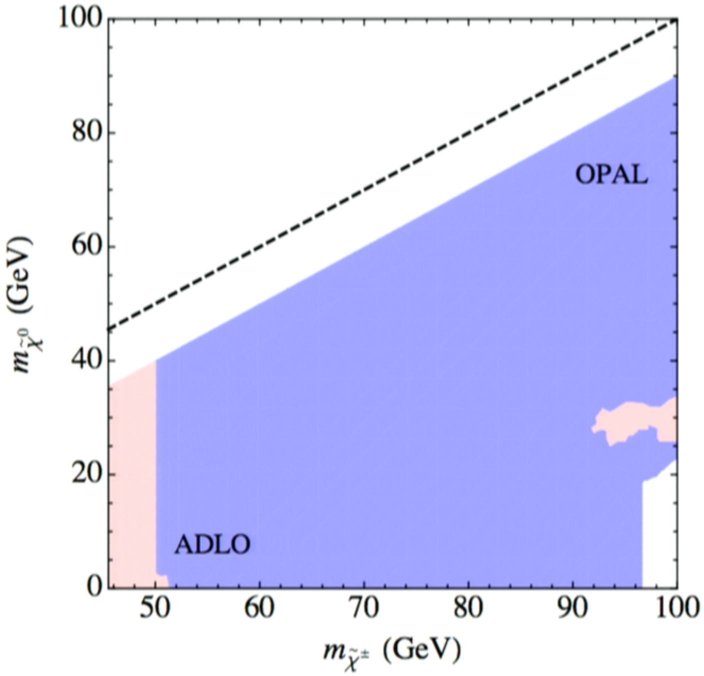
- LEP combinations separate into two categories
  1. Charginos, at large m_0 (bulk region)



- Compare strongest limit over parameter space
- Complementary coverage
- $m_{\tilde{\chi}^\pm} >$ **96 GeV**
- $\mathcal{O}(1)$ coverage for large $m_{\tilde{\chi}^\pm}$

LEP Archeology

- LEP combinations separate into two categories
  1. Charginos, at large m_0 (bulk region)



- Compare strongest limit over parameter space
- Complementary coverage
- $m_{\tilde{\chi}^{\pm}} >$ **96 GeV**
- $\mathcal{O}(1)$ coverage for large $m_{\tilde{\chi}^{\pm}}$

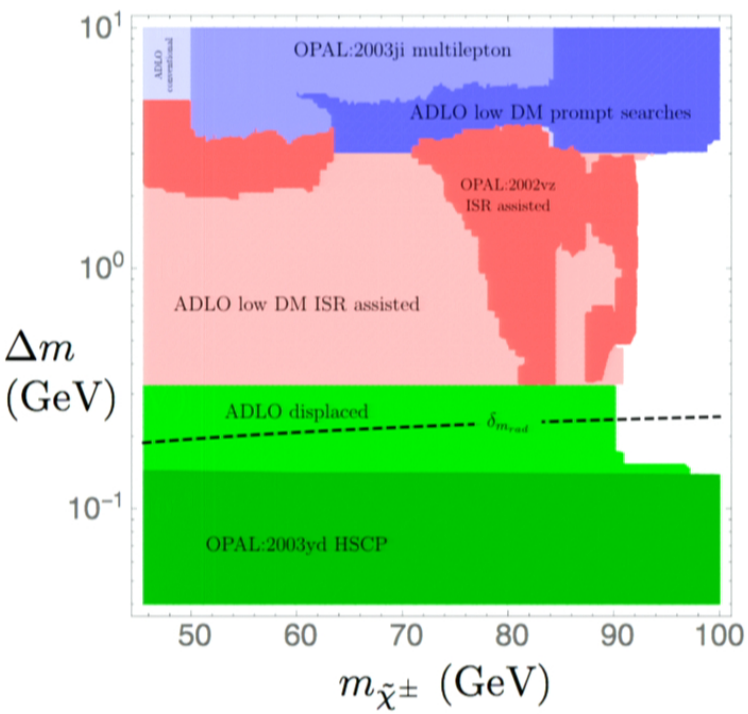
LEP Archeology

- LEP combinations separate into two categories
  2 Charginos, at small Δm (compressed region)
  - OPAL single photon search (hep-ex/0210043)
    - Uses 570 pb^{-1}
    - Looked for ISR photon
  - OPAL HSCP search (hep-ex/0305031)
    - Uses 693 pb^{-1}
    - Looked for detector-stable particles

LEP Archeology

- LEP combinations separate into two categories

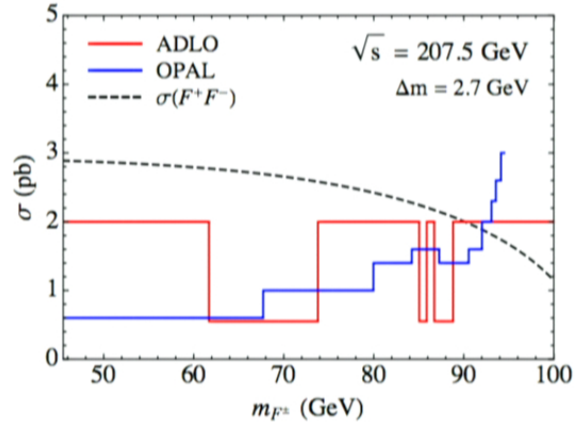
  2 Charginos, at small Δm (compressed region)



- Divide by strongest search
- A few better OPAL searches
- $m_{\tilde{\chi}^\pm} >$ **92 GeV**
- $\mathcal{O}(1)$ coverage for large $m_{\tilde{\chi}^\pm}$

Mechanisms

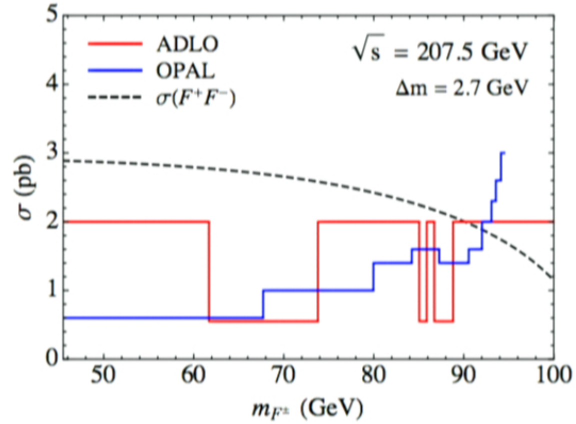
- Parts of parameter space are $\mathcal{O}(1)$ excluded



- Varying electroweak charges gives positive contributions
- Coupling to other particles can give negative contributions
- *e.g.* An electron sneutrino exchanged in the t-channel

Mechanisms

- Parts of parameter space are $\mathcal{O}(1)$ excluded



- Varying electroweak charges gives positive contributions
- Coupling to other particles can give negative contributions
- *e.g.* An electron sneutrino exchanged in the t-channel

Mechanisms

- Consider a simplified model
  - Fermion doublet F (hypercharge $Y = \pm 1/2$), scalar singlet S

$$\mathcal{L} \supset \mathcal{L}_{\text{kin}} - \frac{m_S^2}{2} S^2 - m_F \bar{F} F + \kappa L_E \bar{F} S + \text{h.c.}$$

  - F has electron number (different than chargino case)
  - Fermion splitting from 1-loop IR effect

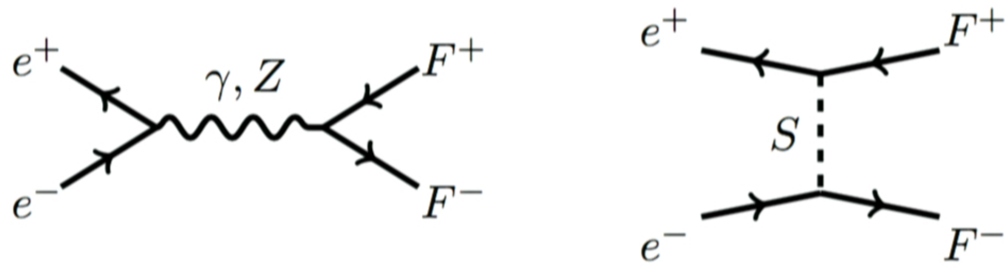
$$\Delta m = \frac{\alpha_2}{2}((Q^2 s_w^2 - Q^2 + 2YQ)m_Z + (Q^2 - 2YQ)m_W)$$

  - Additional splitting from Weinberg operator

$$\mathcal{L} \supset \frac{c_5}{\Lambda}(FH)(\bar{F}H^c)$$

Mechanisms

- Pair production has additional contribution



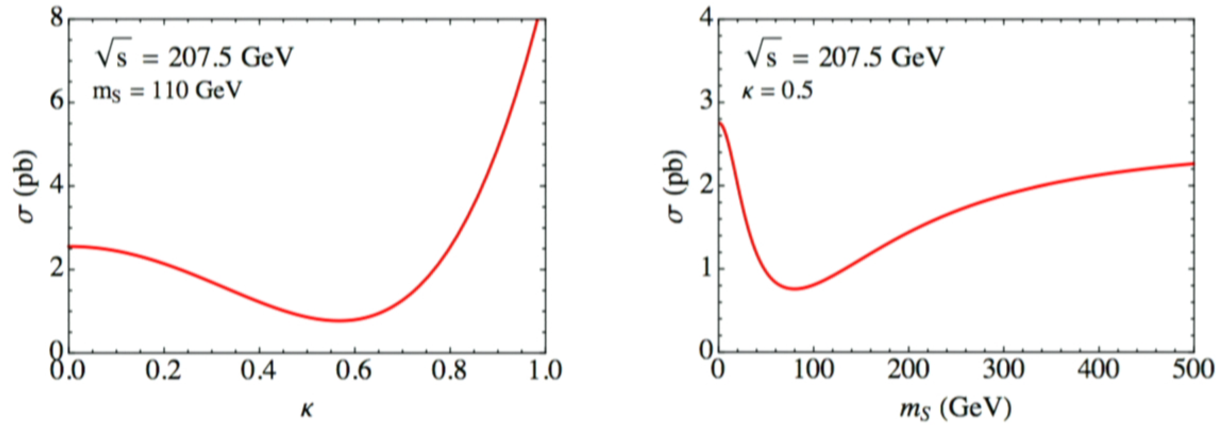
- Interference between diagrams

$$\mathcal{M} \sim \frac{2e^2}{s} + \left(\frac{g^2(1-2s_w^2)c_{2w}}{2c_w^2}\right)\frac{1}{s-m_Z^2} + \frac{\kappa^2}{t-m_S^2}$$

- Reduces cross section by $\mathcal{O}(1)$ as a function of (m_S, κ)

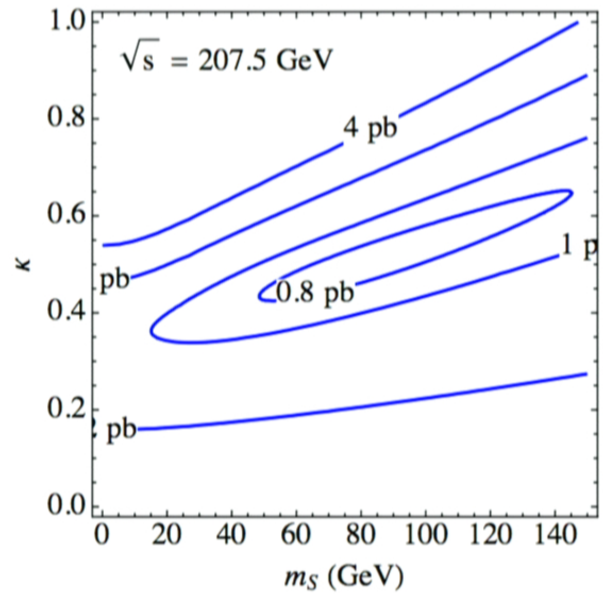
Mechanisms

- Variation of cross section with (m_S, κ)



Mechanisms

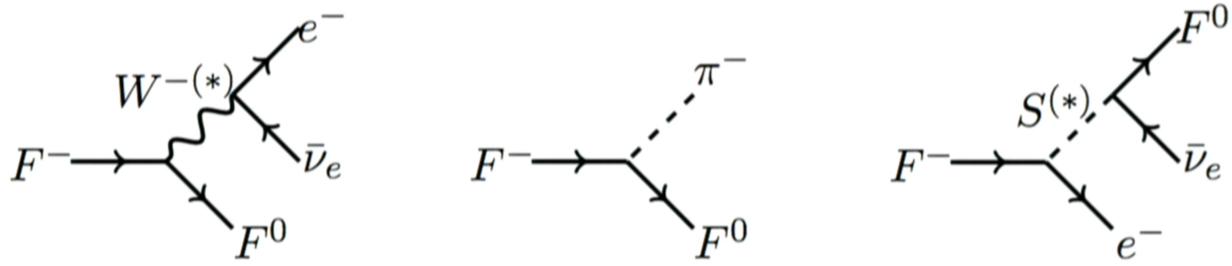
- Variation of cross section with (m_S, κ)



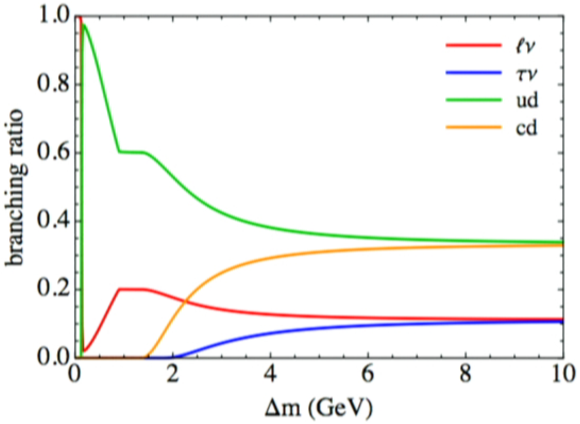
- Reduction by $\times 3$ at $(m_S = 81\ \mathrm{GeV}, \kappa = 0.5)$

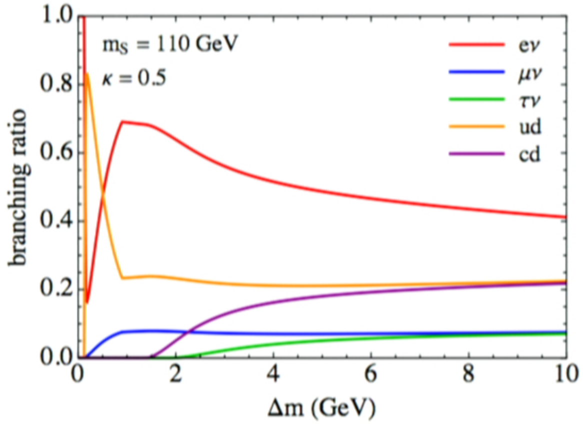
Mechanisms

- Width and branching ratios modified



- Enhanced branching ratio to electrons





Mechanisms

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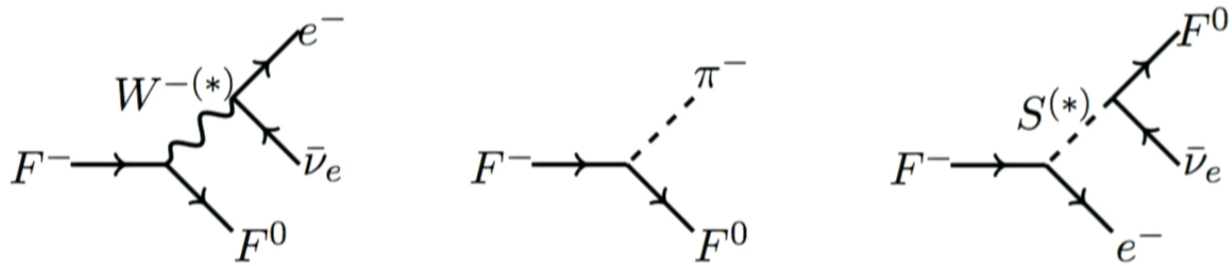
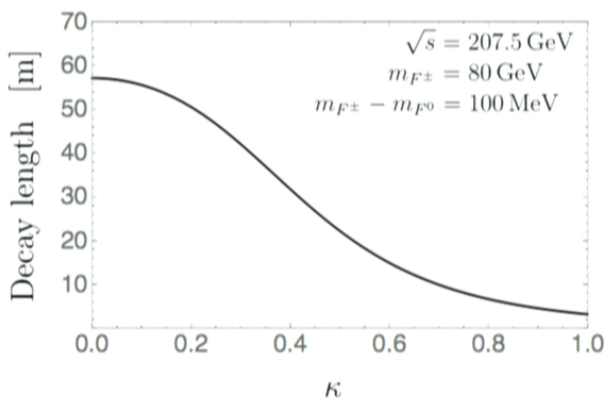
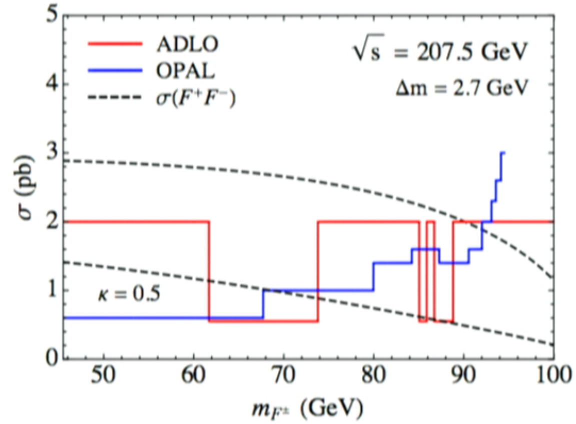


- Width increased (and lifetime decreased)



Mechanisms

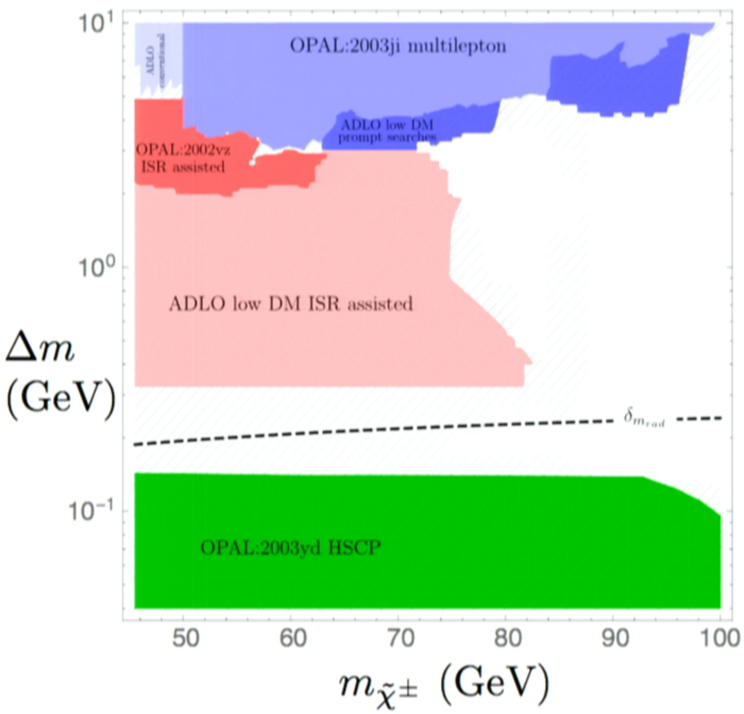
- Use benchmark of $(m_S = 110\ \text{GeV}, \kappa = 0.5)$



- Window above 74 GeV is now opened
- Are there other windows now?

Mechanisms

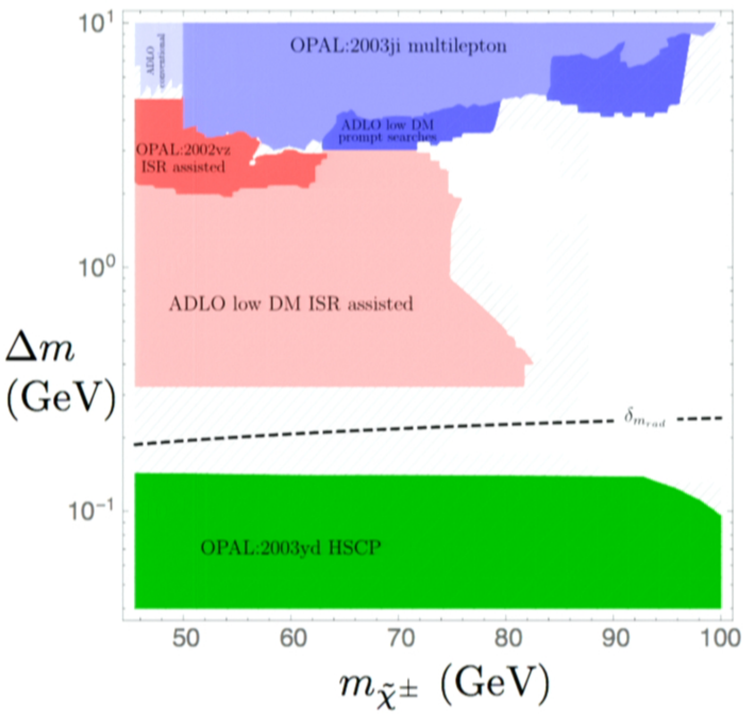
- Use benchmark of $(m_S = 110\ \text{GeV}, \kappa = 0.5)$



- More windows in compressed region
- 74 GeV is now possible (via LEP)
- Hatched region assumes same efficiencies (despite change in BR)
- (Some windows remain after current LHC searches)

Mechanisms

- Use benchmark of $(m_S = 110 \text{ GeV}, \kappa = 0.5)$



- More windows in compressed region
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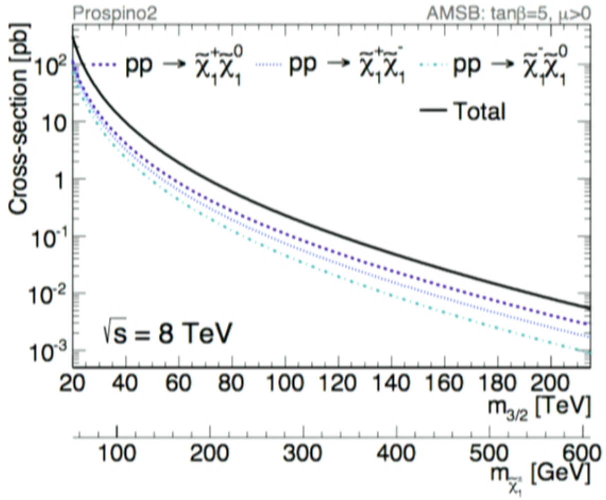
LHC Limits

- Typically LHC does not show search results below 100 GeV



- Rates at LHC are $\mathcal{O}$(pb)
- LHC can produce heavy particles (which decay to charged particles)
- LHC has much higher luminosity

- *e.g.* the wino cross section

LHC Limits

- Charged-neutral splitting arises from Weinberg operator

$$\mathcal{L} \supset \frac{c_5}{\Lambda}(FH)(\bar{F}H^c)$$

- Induces coupling of F^0 to Higgs

$$g_{hF^0F^0} = c_5\frac{v}{\Lambda} = \frac{2}{v}(m_{F^\pm} - m_{F^0})$$

- Partial width of the Higgs is

$$\Gamma = \frac{m_h}{8\pi}g^2_{hF^0F^0}\left(1 - \frac{4m^2_{F^0}}{m^2_h}\right)^{3/2}$$

- Invisible width $\mathrm{BR}_{h\to\mathrm{inv}} \leq 0.24$ rules out $m_{F^0} < 62.5$ GeV
- Closes uncompressed window

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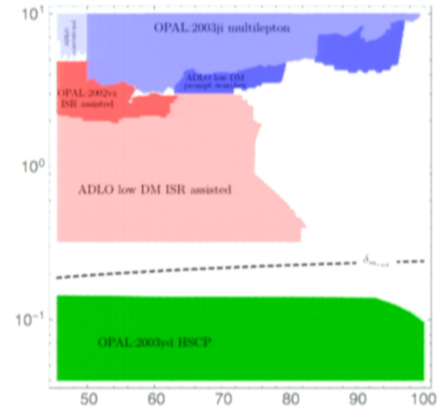
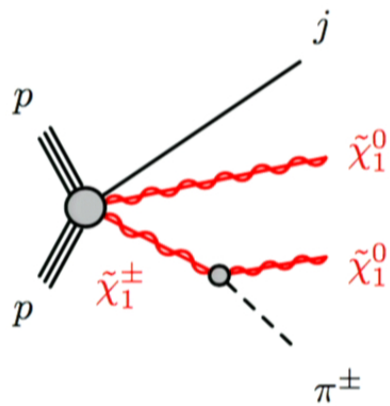
LHC Limits

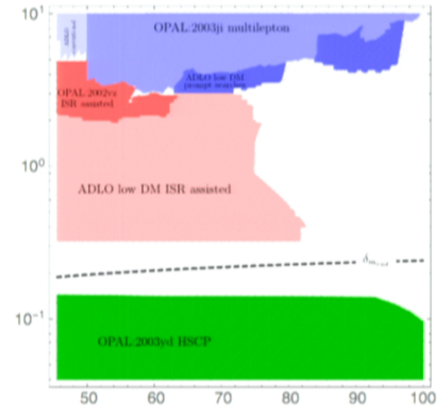
- Recall compressed window at ≈ 200 MeV
- Long-lived LHC searches may cover region
- Disappearing tracks cover $\mathcal{O}(0.1 \text{ m})$ range

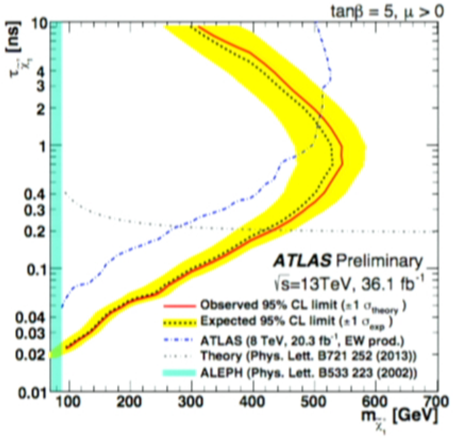




LHC Limits

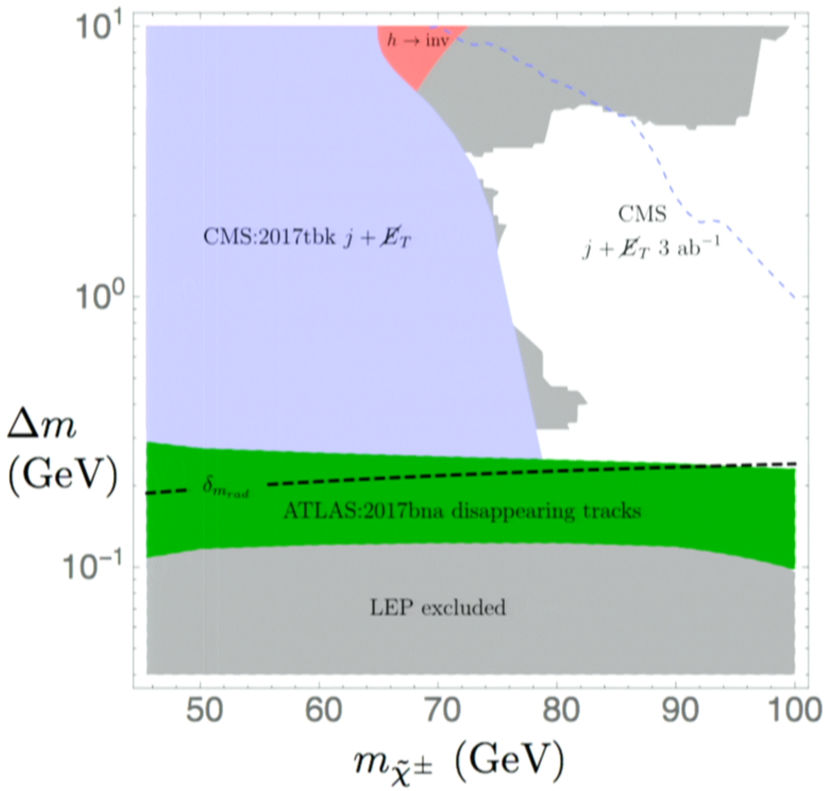
- Recall compressed window at ≈ 200 MeV
- Long-lived LHC searches may cover region
- Disappearing tracks cover $\mathcal{O}(0.1\text{ m})$ range
  - ATLAS provides reconstruction efficiency as a function of distance
  - Compute $\epsilon(m_{F^\pm}, c\tau)$ in Monte Carlo
  - Match remaining $\epsilon(m_{F^\pm}, c\tau)$ to ATLAS
  - Compare simplified model signal to N_{95}





LHC Limits

- LHC and LEP limits



- Currently $m_{\tilde{\chi}} >$ **74 GeV**
  - with scalar singlet
  - and compressed

Conclusions

- Including the LHC increases these
  - $m_{\tilde{\chi}^{\pm}} >$ **103 GeV** (uncompressed)
  - $m_{\tilde{\chi}^{\pm}} >$ **74 GeV** (compressed)