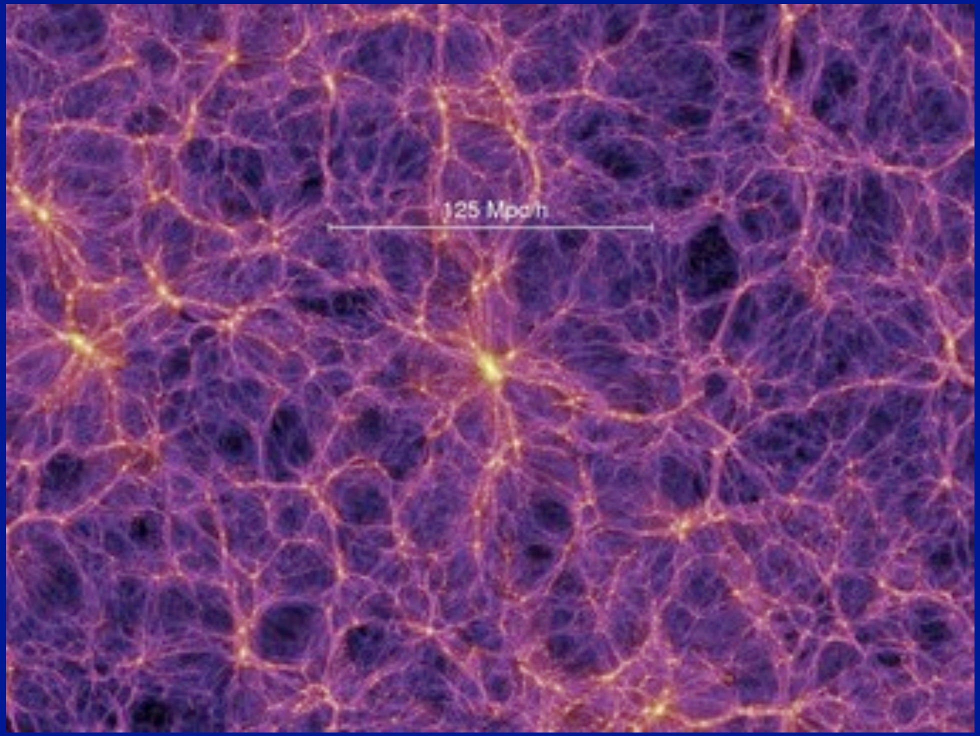
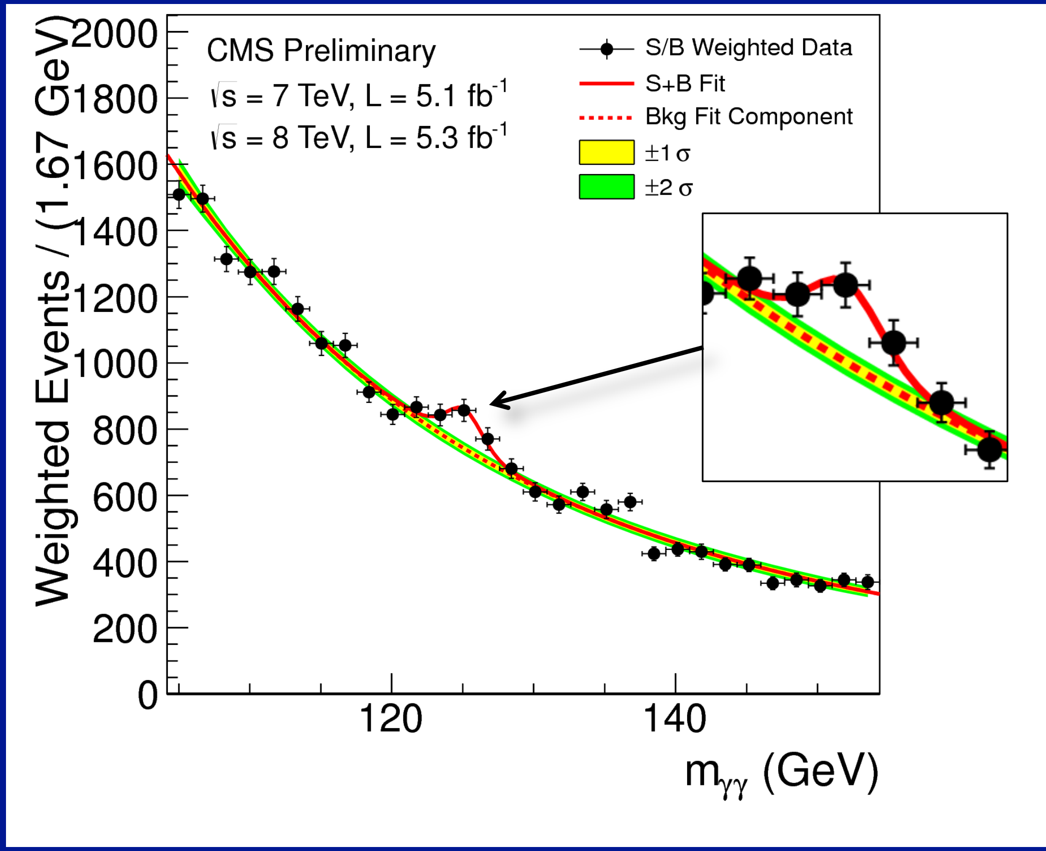


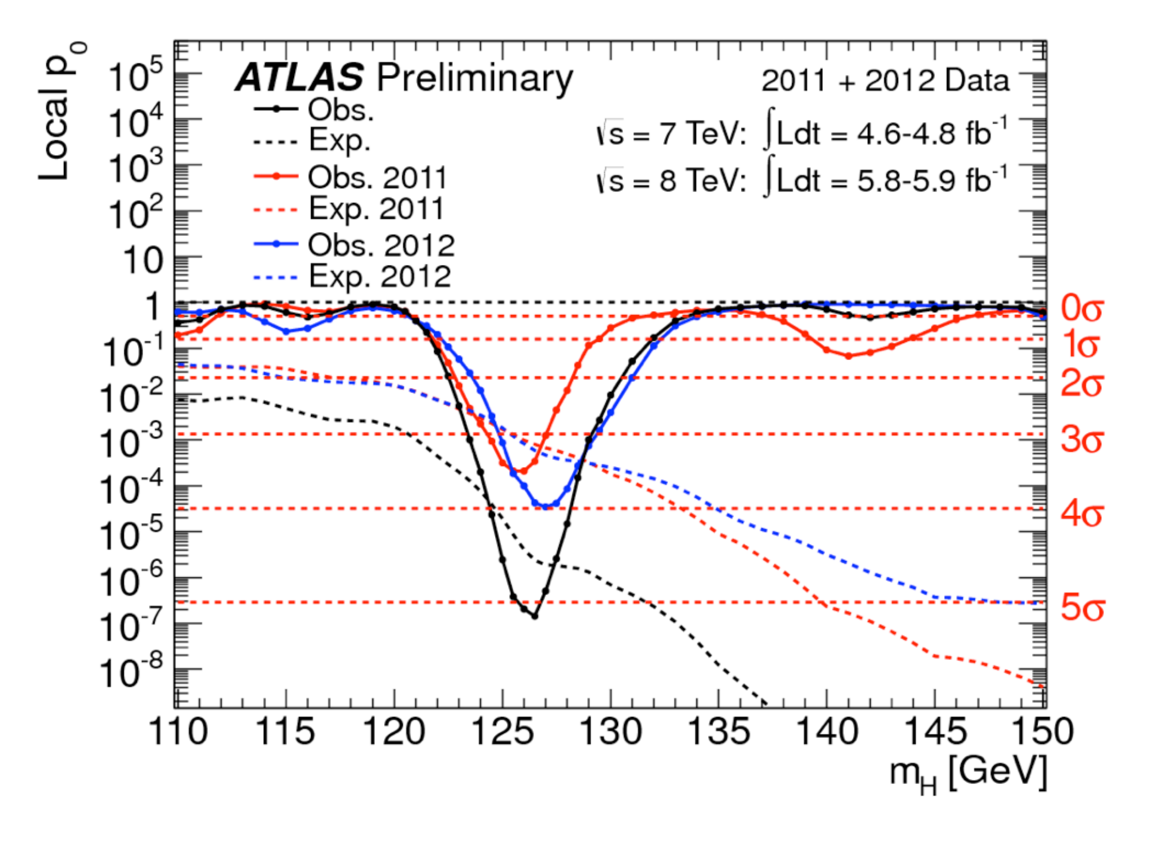
Long-lived higgsinos as probes of gravitino dark matter at the LHC

Sara Rydbeck

Based on JHEP 02(2013)133 (arXiv:1211.5584) with Jan Hajer and Sergei Bobrovskyi.

The Large Hadron Collider (LHC)





- Only discovery so far.

- If no new strongly interacting physics is found, how can we further test for new electroweak physics at the LHC?

- How might the new physics be hiding from current searches?

The light-higgsino scenario (LHS)

- The only new parameter introduced in the minimal supersymmetric standard model (MSSM) is the higgsino mass parameter μ:

$$W = \mu H_u H_d + h^u_{ij} Q_i U_j H_u + h^d_{ij} D_i Q_j H_d + h^e_{ij} L_i E_j H_d$$

- Supersymmetry breaking introduces many more:

$$\begin{aligned} -\mathcal{L}_{\rm soft} = {} & m_u^2 H_u^\dagger H_u + m_d^2 H_d^\dagger H_d + (B H_u H_d + \text{h.c.}) \\ & + \widetilde{m}^2_{li} \tilde{l}_i^\dagger \tilde{l}_i + \widetilde{m}^2_{ei} \widetilde{\bar{e}}_i^\dagger \widetilde{\bar{e}}_i + \widetilde{m}^2_{qi} \widetilde{q}_i^\dagger \widetilde{q}_i + \widetilde{m}^2_{ui} \widetilde{\bar{u}}_i^\dagger \widetilde{\bar{u}}_i + \widetilde{m}^2_{di} \widetilde{\bar{d}}_i^\dagger \widetilde{\bar{d}}_i \\ & + \frac{1}{2}\left(M_1 \tilde{B}\tilde{B} + M_2 \tilde{W}\tilde{W} + M_3 \tilde{g}\tilde{g} + \text{h.c.}\right) + \text{trilinear } A \text{ terms} \end{aligned}$$

- In general no connection between the *μ* and the soft mass parameters...

The light-higgsino scenario (LHS)

- Why split spectrum? The soft supersymmetry breaking terms introduces sources of flavour- and CP violation. Alleviated if superparticles heavy.
- Easy to explain 126 GeV scalar boson ($\delta m_h \sim \log \frac{m_{\tilde{t}}}{m_t}$) and no signals of squarks and gluinos.
- Why weak-scale μ? Chargino searches tell us μ > ~100 GeV,
- Obtaining the electroweak symmetry breaking scale

$$-\frac{m_Z^2}{2} = \left(|\mu|^2 + m_{H_u}{}^2\right)\Big|_{\text{high scale}}$$

Supersymmetric,
running does not depend
on the soft parameters

Polynomial dependence
on all soft parameters

- In hybrid models of supersymmetry breaking from extra dimensional GUTs, μ is gravity mediated and the soft masses are gauge mediated...

Brümmer & Buchmüller (2011)

The light-higgsino scenario (LHS)

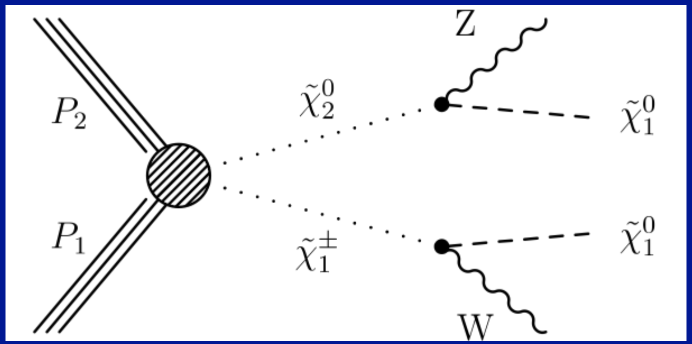
- This leads to an MSSM spectrum where the lightest chargino and neutralinos are higgsino-like and the rest of the superpartners have >TeV masses.

$$\mu \ll |M_{1,2}|$$

- The lightest higgsino is a neutralino.

$$m_{\chi_1^\pm} - m_{\chi_1^0} \approx \frac{1}{2} m_Z^2 \left(\frac{M_1 c_1 + M_2 c_2}{M_1 M_2} + \mu \frac{M_1^2 c_1 + M_2^2 c_2}{M_1^2 M_2^2} \right)$$ (*c*'s positive)

- Small mass differences between all the higgsinos $\sim m_Z^2 / M_{1,2}$
  - Difficult to detect at the LHC. Baer, Barger & Huang (2011)



  - Very low thermal relic densities of neutralino WIMP dark matter candidate, due to coannihilation.

Dark matter in the LHS? (Not to mention baryogenesis and neutrino masses)

- Possible solutions: moduli decays to WIMPs Gelmini *et al* (2006) , axions Baer *et al* (2011) - or **decaying gravitino dark matter**:

www.particlezoo.net

  - Local supersymmetry leads to the prediction of the gravitino.
  - Thermal leptogenesis requires high reheating temperature.
    Fukugita, Yanagida (1986); Davidson, Ibarra (2002); Buchmüller, Di Bari, Plümacher (2004); Buchmüller, Peccei, Yanagida (2005)
  - Thermal production of gravitinos depends on the reheating temperature. Potential cosmological problems with overclosure and big bang nucleosynthesis...
    Weinberg (1982); Ellis, Nanopoulos, Sarkar (1985); Kawasaki, Kohri, Moroi (2005); Jedamzik (2006); Bolz, Brandenburg, Buchmüller (2008)
  - With small R-parity violation, gravitino dark matter can be made consistent with big bang nucleosynthesis and leptogenesis (with see-saw generated neutrino masses).
    Buchmüller, Covi, Hamaguchi, Ibarra, Yanagida (2007)

R-parity violation

- R-parity distinguishes between standard model and supersymmetric particles. It is imposed to ensure the stability of the proton and also results in the lightest supersymmetric particle being stable.

- Allowing for R-parity violating terms in the MSSM in general introduces many new parameters:

$$\Delta W = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \frac{1}{2}\lambda''_{ijk} U_i D_j D_k$$

$$-\Delta\mathcal{L} = B_i H_u \tilde{l}_i + \left(m^2_{id} \tilde{l}^\dagger_i H_d + \text{h.c.} \right) + \text{trilinear terms}$$

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- Consider extension of the MSSM with only the bilinear terms; trilinear L-violating couplings are always generated at loop level anyway but B is conserved so that the proton is stable. Very few parameters.

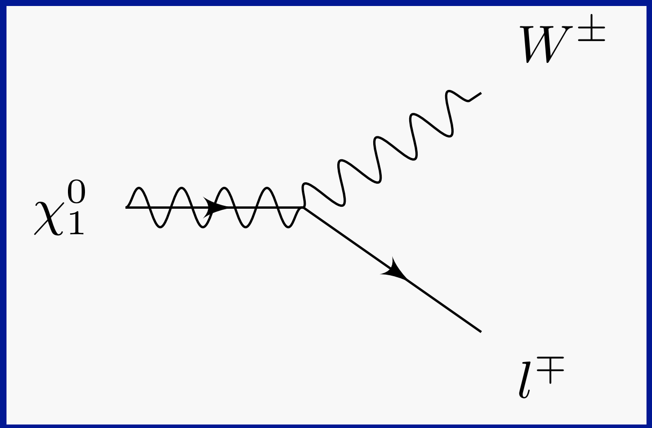
Bilinear R-parity violation

- To facilitate calculations, the fields can be rotated twice to trade the bilinear couplings in both the superpotential and the soft part for L-violating trilinear terms proportional to the Yukawa couplings.

Bobrovskyi, Buchmüller, Hajer & Schmidt (2010)

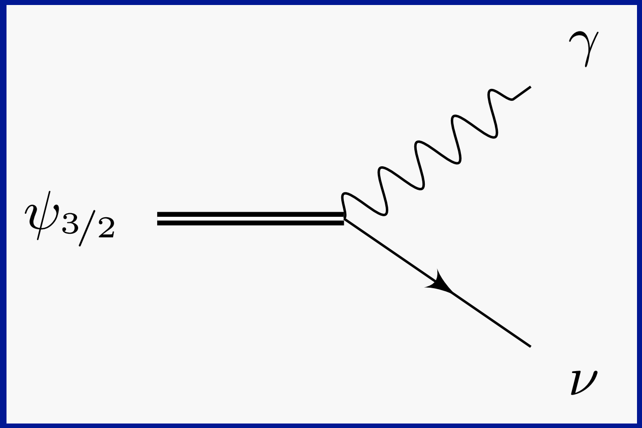
- μ_i, B_i, m_{id}^2 are thus traded for the rotation parameters $\epsilon, \epsilon', \epsilon''$, and the new interactions will depend linearly on the parameters:

$$\zeta_i = \frac{\epsilon' v_d + \epsilon'' v_u}{v}$$

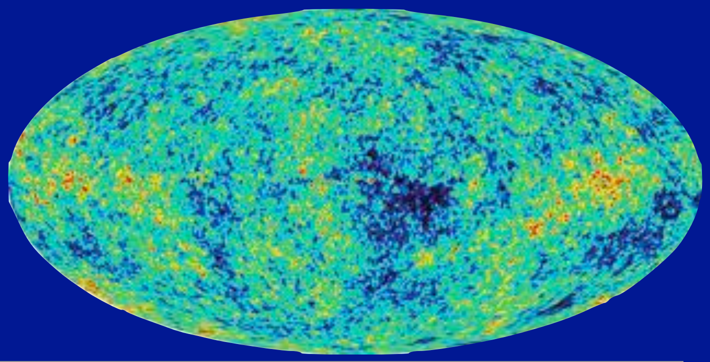


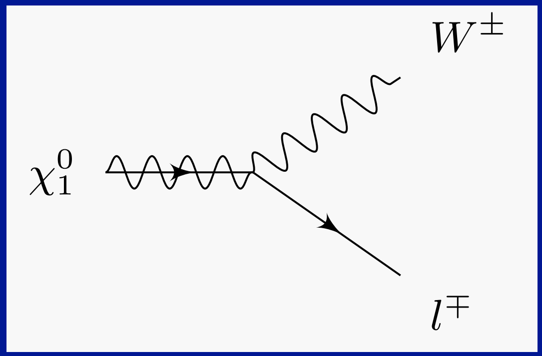
- For the phenomenology of interest, one can introduce an overall R-parity breaking parameter ζ:

$$\zeta = \sum_i \zeta_i$$



Constraints on ζ from cosmology





- How much R-parity violation do we need?
  - All higgsinos decay before BBN if $\boxed{\zeta \gtrsim 10^{-12}}$
- Can we get the right relic abundance of gravitinos?

$$\Omega_{3/2} \propto \frac{T_R m_{\tilde{g}}^2}{m_{3/2}}$$

  - Scenario with spontaneous breaking of B-L in the early universe allows for lower reheating temperature than in thermal leptogenesis: 1 TeV gluino gives a minimum gravitino mass of 10 GeV.
    This bound scales as:

Buchmüller, Domcke, Schmitz (2012)

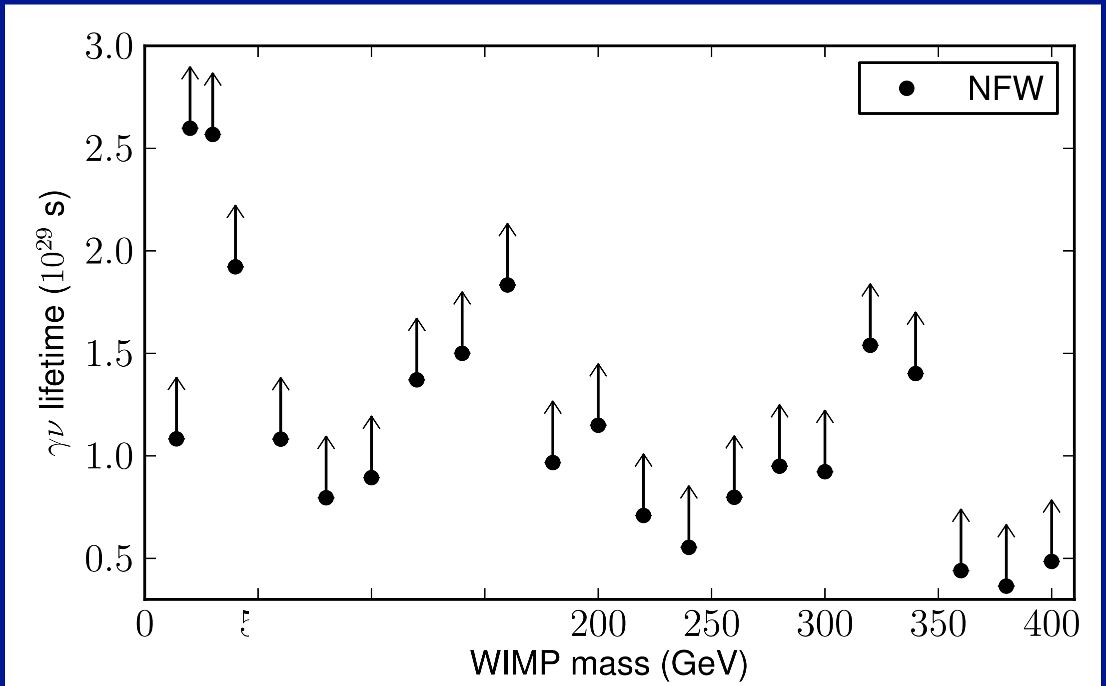
$$m_{3/2}^2 = (10\ \mathrm{GeV}) \left(\frac{m_{\tilde{g}}}{1\ \mathrm{TeV}}\right)^2$$

  - Can have 40 GeV gravitino with 2 TeV gluino and thus higgsino masses from 100 GeV (and up to allow for heavier gluinos).

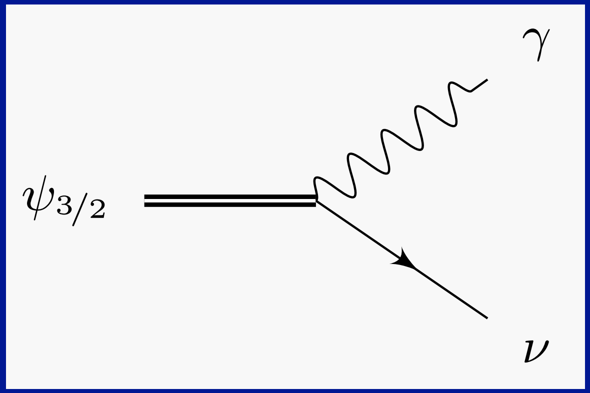
Constraint on ζ from astrophysics

- How large R-parity violation can we have?

$$\zeta = 4 \times 2^{3/4} \sqrt{\frac{G_F}{\alpha}} \frac{M_{\rm P}}{\sqrt{m_{3/2}^3 \tau_{3/2}}} \frac{M_1 M_2}{M_2 - M_1}$$



Ackermann *et al* (2012)

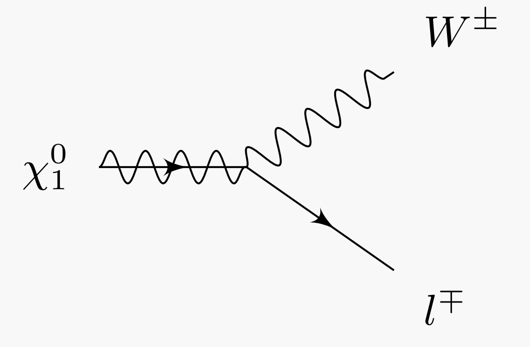


- Fermi-LAT bound on the lifetime of decaying dark matter leads to:

$$\boxed{\zeta \lesssim 10^{-8}}$$

LHC signature: (very) displaced muons

- In the LHS with R-parity violation, the lightest higgsino dominantly decays to a W boson and a charged lepton, but not promptly.

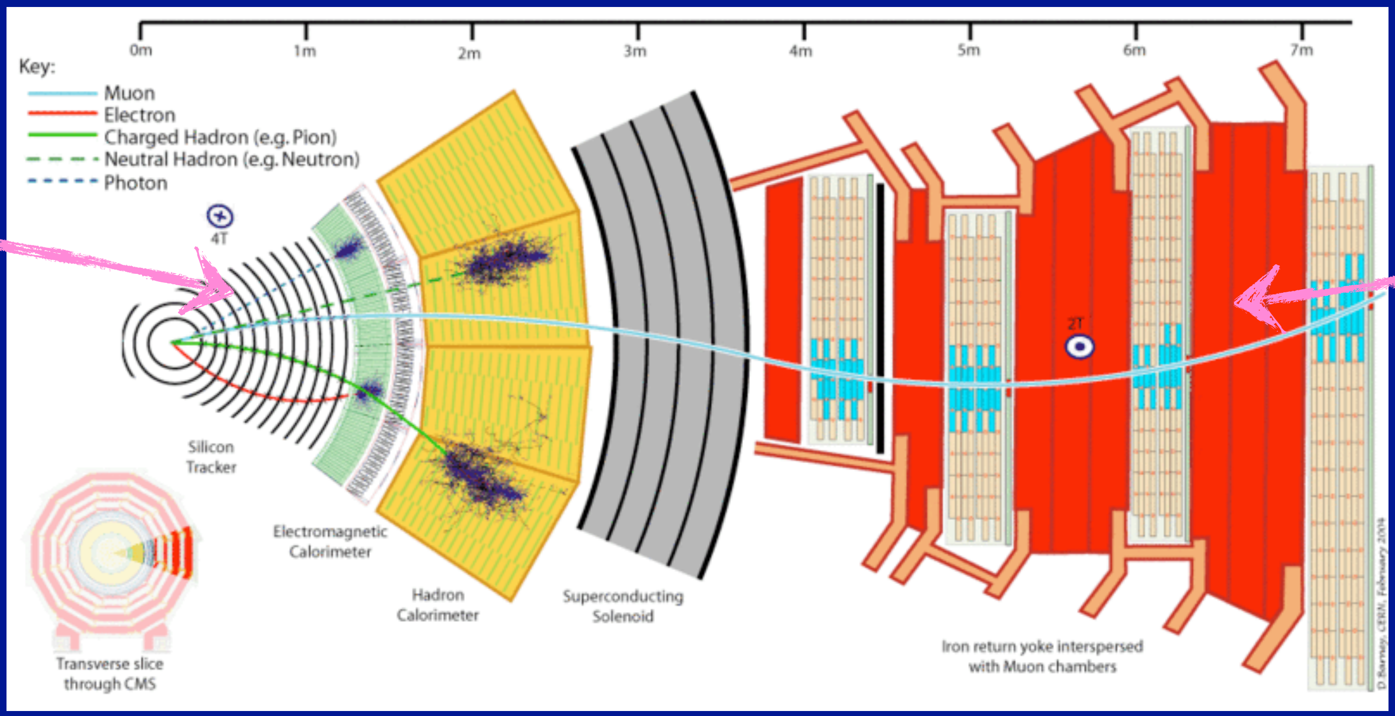


- Fermi bound on ζ leads to lower bound on the higgsino NLSP decay length:

$$c\tau_{\chi_1^0} \gtrsim 6.5\,\mathrm{m}\left(\frac{m_{\chi_1^0}}{400\,\mathrm{GeV}}\right)^{-1}\left(\frac{m_{3/2}}{40\,\mathrm{GeV}}\right)^{3}\left(\frac{\tau_{3/2}(\gamma\nu)}{10^{28}\,\mathrm{s}}\right) f_W(m_{\chi_1^0})^{-1}$$

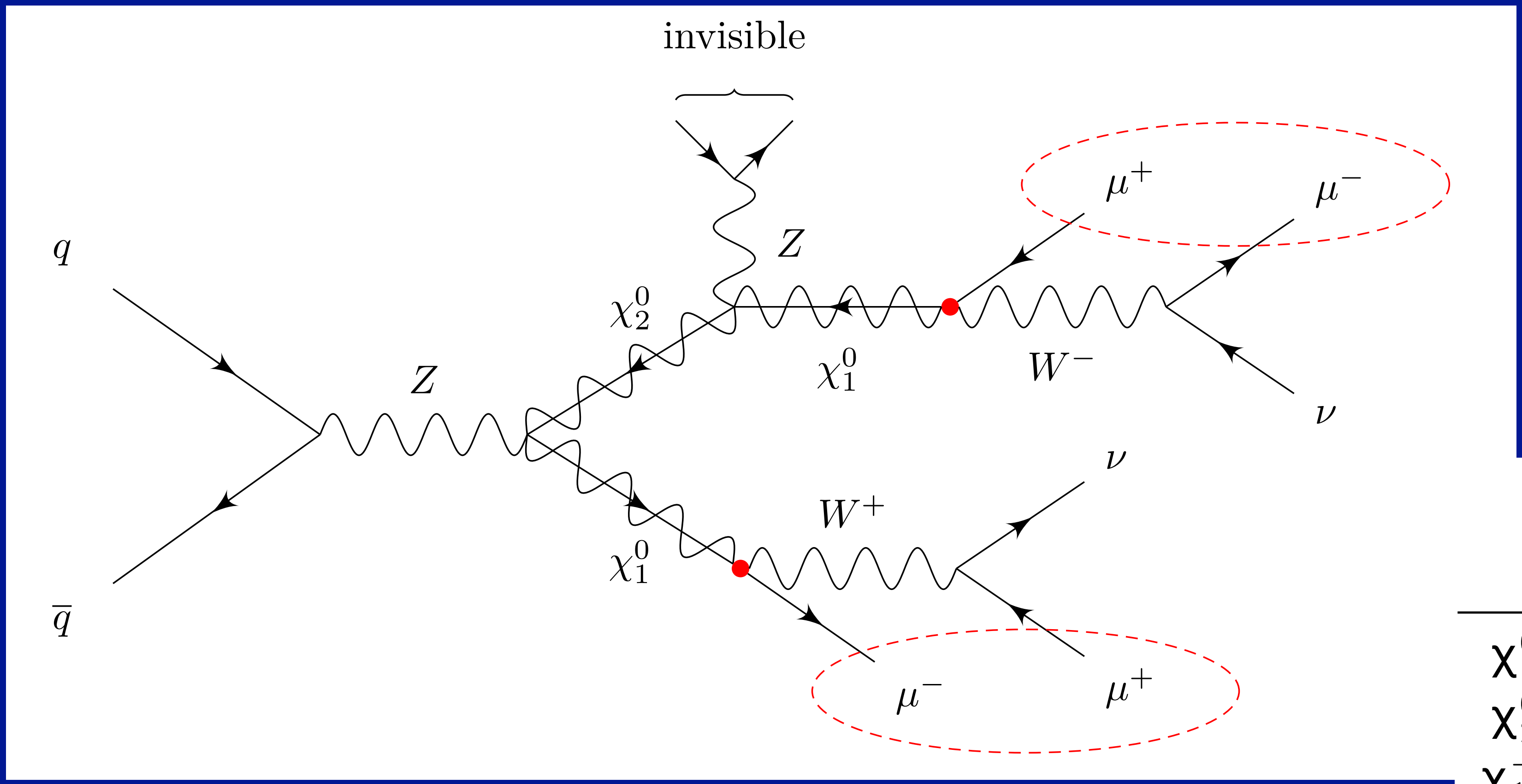
1 m   4 m   7 m

Inner detector: Tracker



Outer detector: Muon chambers

LHC signature: (very) displaced muons



higgsino	μ			
	100	200	300	400
χ_2^0	106	209	311	413
$\chi_1^\pm$	104	207	309	411
χ_1^0	102	205	307	408

masses in GeV

	μ			
	100	200	300	400
$\chi_1^0\chi_1^+$	1640	121	22.8	6.28
$\chi_2^0\chi_1^+$	1530	116	22.2	6.15
$\chi_1^-\chi_1^+$	1300	94.8	17.2	4.58
$\chi_1^0\chi_1^-$	918	55.9	9.23	2.29
$\chi_2^0\chi_1^-$	851	53.6	8.94	2.24
$\chi_1^0\chi_2^0$	1410	91.3	16.1	4.19
σ^{tot}	7649	532.6	96.47	25.73

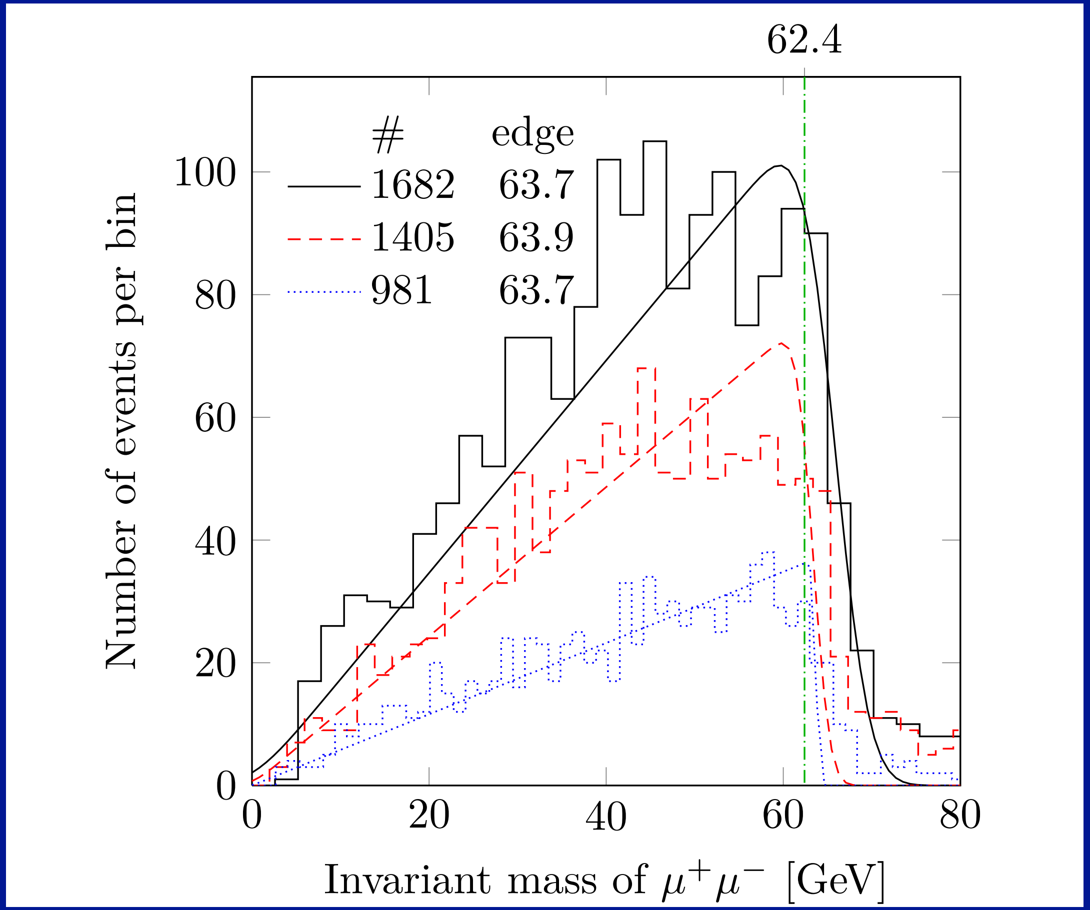
production cross sections in fb

- Consider pair production of charged and neutral higgsinos for μ=100-400 GeV at 8 TeV proton collisions at the LHC.
- Look for pair of muons with opposite sign (OS) from the same displaced vertex.

LHC signature: (very) displaced muons

- Analysis: Madgraph/Madevent+Pythia for event generation and Delphes for detector simulation.
  Radial information taken into account as worked out in Bobrovskyi, Buchmüller, Hajer, Schmidt (2011)
- Cuts:
  - 2 OS isolated muons (created before the muon system) with p_T>10 GeV,
  - If the muons have tracks (muon created within the 1st 3d of the tracker):
    - *d*(vertex) > 5 mm,
    - Δ*d*(vertices) < 1 mm,
  - Invariant mass *m*(μ+μ-) > 5 GeV.

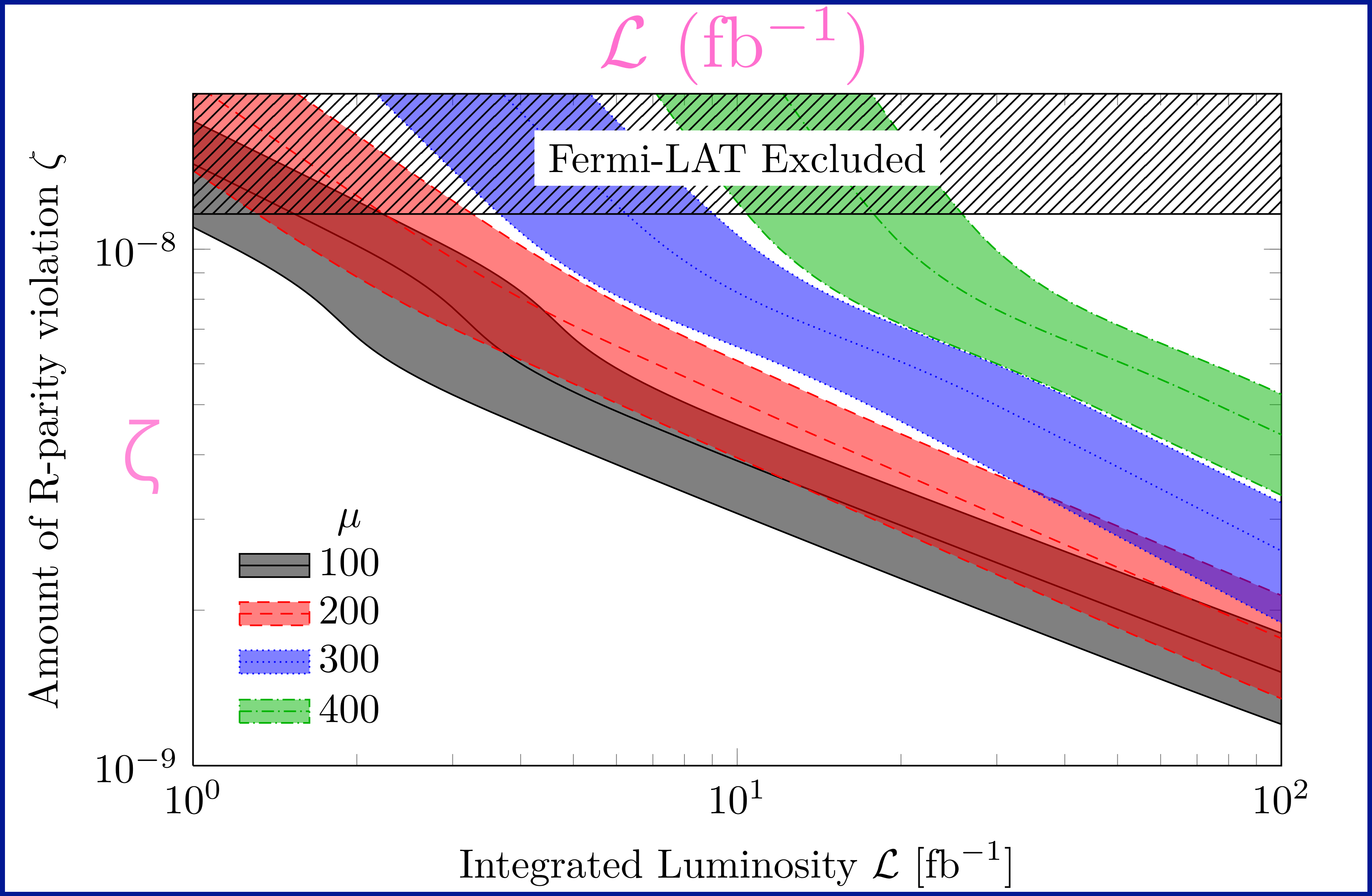
$$m_{ll}^2 \approx m_{\chi_1^0}^2 - m_W^2$$



Test with neutralino mass of 102 GeV.

Discovery reach @ LHC 8 TeV

- The cuts effeciently remove all simulated background (SM dimuon and detector effects) and are expected to remove background from cosmic muons, decay-in-flight, punch-throughs and pile-up.

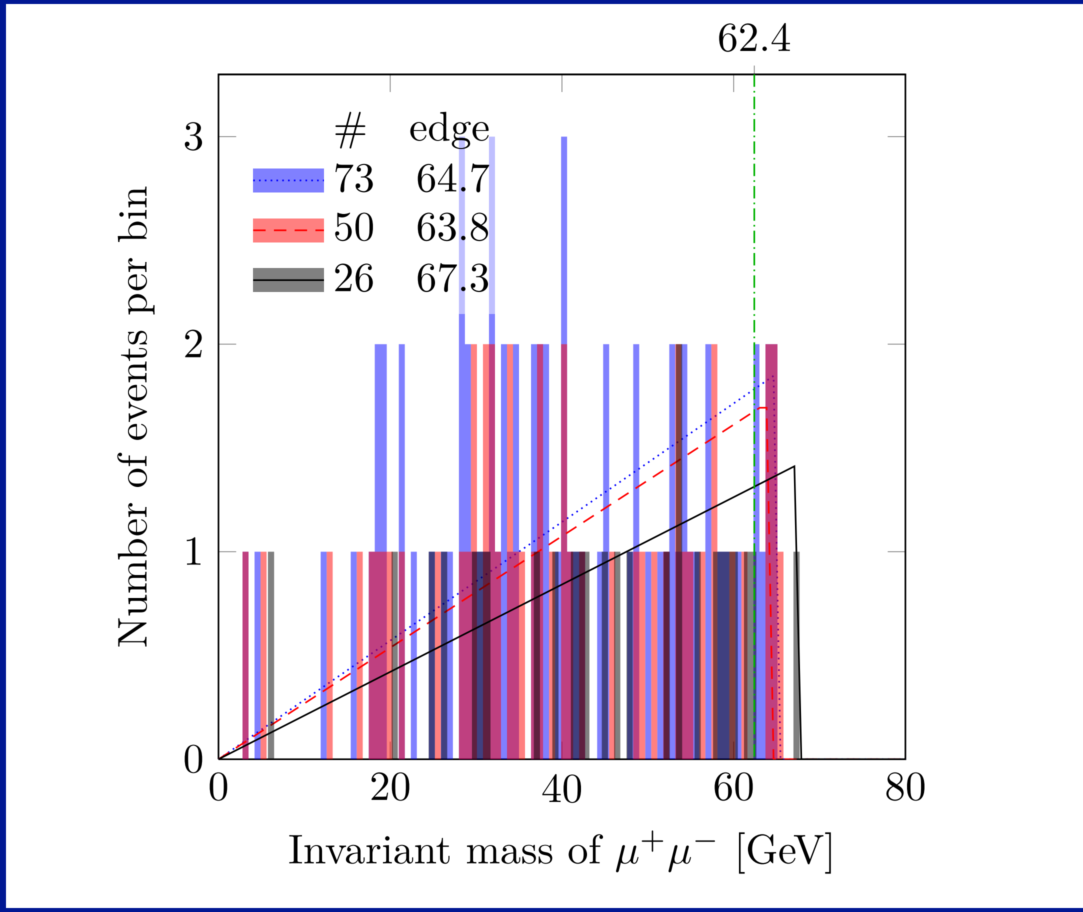


Requiring an expectation of at least 5 events and 50%, 90% or 99% probability to observe such a signal (assuming a Poisson distribution).

Higgsino mass determination

- The higgsino mass can be determined using the edge in the dimuon invariant mass distribution:

$$m_{ll}^2 \approx m_{\chi_1^0}^2 - m_W^2$$



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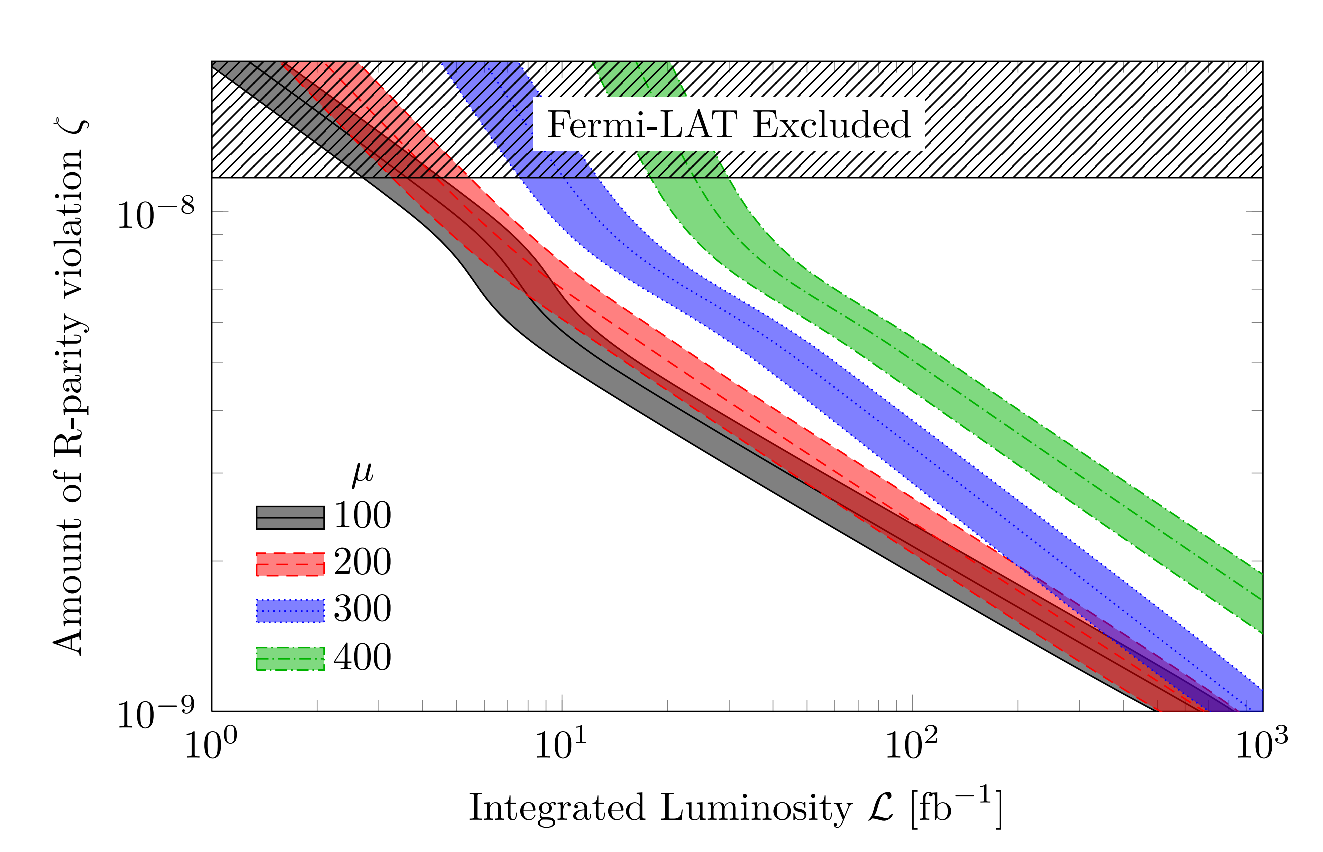

Estimation of mass determination prospects at 14 TeV if 30, 40 or 50 events are needed to reconstruct the mass edge correctly.

Summary & conclusion

- An MSSM light-higgsino scenario is an interesting theoretical possibility.
- Extended with small R-parity violating couplings we can also have a consistent cosmology and gravitino dark matter.
- The bounds on decaying dark matter from the Fermi-LAT motivates a search for displaced higgsino-like neutralino decays at the LHC.
- With the 8 TeV data, LHC searches can extend the reach in the RPV parameter ζ as compared to current gamma-ray searches, and a signal can show up at integrated luminosities of 10-30/fb.
- In the case of a signal, the displaced dimuon signature allows for reconstruction of the higgsino mass. For this, we might have to wait for the 13 TeV run.