# Next-to-minimal dark matter @ LHC

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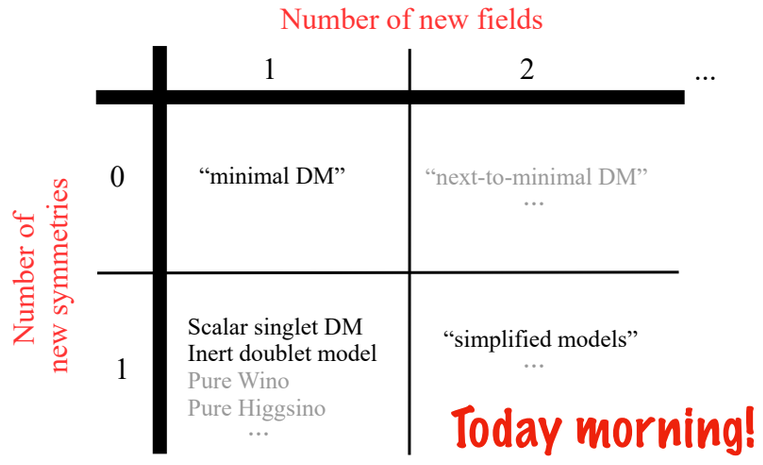
**Dark Matter makes up ~20% of our universe; an EW scale particle seems to be a good fit**

$$\Omega h^2 \sim 0.1 \Rightarrow \langle \sigma v \rangle \sim 1 \text{ pb} \cdot c$$

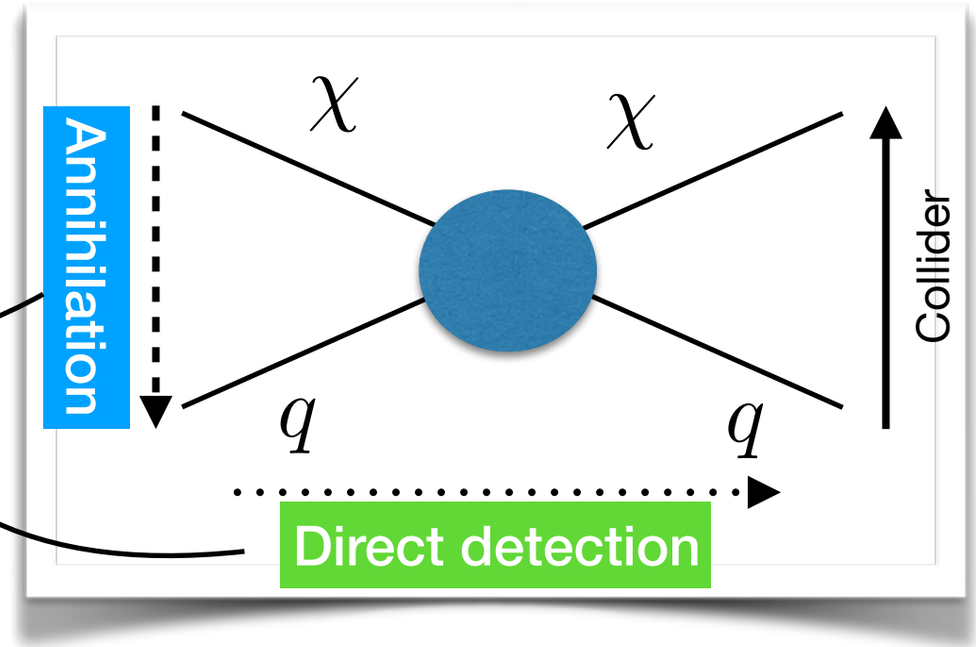
$$\Rightarrow m_\chi \sim O(10^2 - 10^3) \text{ GeV}; g \sim g_{\text{EW}}$$

Classification of models (according to minimality)




**What are minimal EW possibilities?**

- SU(2) doublet fermion (a.k.a. Higgsino) ⇒ ~ 1.2 TeV
- SU(2) triplet fermion (a.k.a Wino) ⇒ 2.7 TeV
- SU(2) 5-plet fermion (MDM) ⇒ ~10 TeV
- SU(2) 7-plet scalar (MDM) ⇒ ~10 TeV **100 TeV?**



# What about next-to-minimal scenarios?

- One SU(2) x U(1) singlet $\chi$ + one SU(2) N-plet $\psi$
- $\mathbb{Z}2$ stabilises the lightest state

$$\mathcal{L}_{\rm DM} = i\,\psi^\dagger\overline{\sigma}^\mu D_\mu\psi + i\,\chi^\dagger\overline{\sigma}^\mu\partial_\mu\chi - \left(\frac{1}{2}M\psi\psi + \frac{1}{2}m\chi\chi + \text{ h.c.}\right) + \mathcal{L}_{\rm quartic} + \mathcal{L}_{\rm mix}$$

$$\mathcal{L}_{\rm quartic} = \frac{1}{2}\frac{\kappa}{\Lambda}\phi^\dagger\phi\chi\chi + \frac{1}{2}\frac{\kappa'}{\Lambda}\phi^\dagger\phi\psi^A\psi^A$$

**Strong limits from DD**

N=3

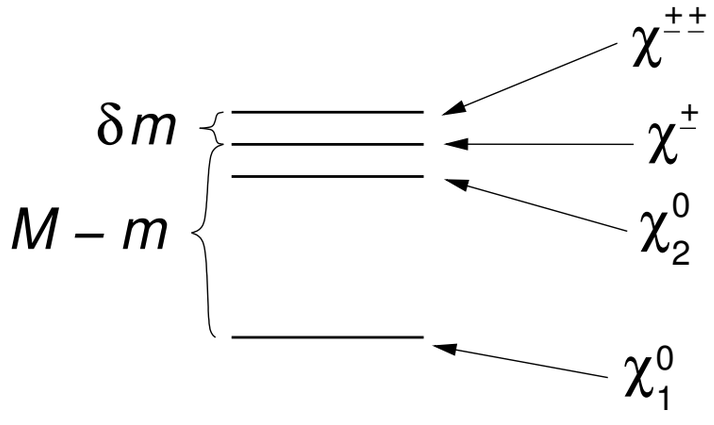
$$\mathcal{L}_{\rm mix} = \frac{\lambda}{\Lambda}\phi^\dagger\tau^a\phi\;\psi^a\chi + \text{ h.c.} \quad\longrightarrow\quad \theta \approx \frac{\sqrt{2}\lambda v^2}{\Lambda(M-m)}$$

N=5

$$\mathcal{L}_{\rm mix} = \frac{\lambda}{\Lambda^3}\,C^{j\ell}_{Aik}\;\phi^{\dagger i}\phi_j\phi^{\dagger k}\phi_\ell\psi^A\chi + \text{ h.c.} \quad\longrightarrow\quad \theta \approx \sqrt{\frac{2}{3}}\frac{\lambda v^4}{\Lambda^3(M-m)}\,.$$

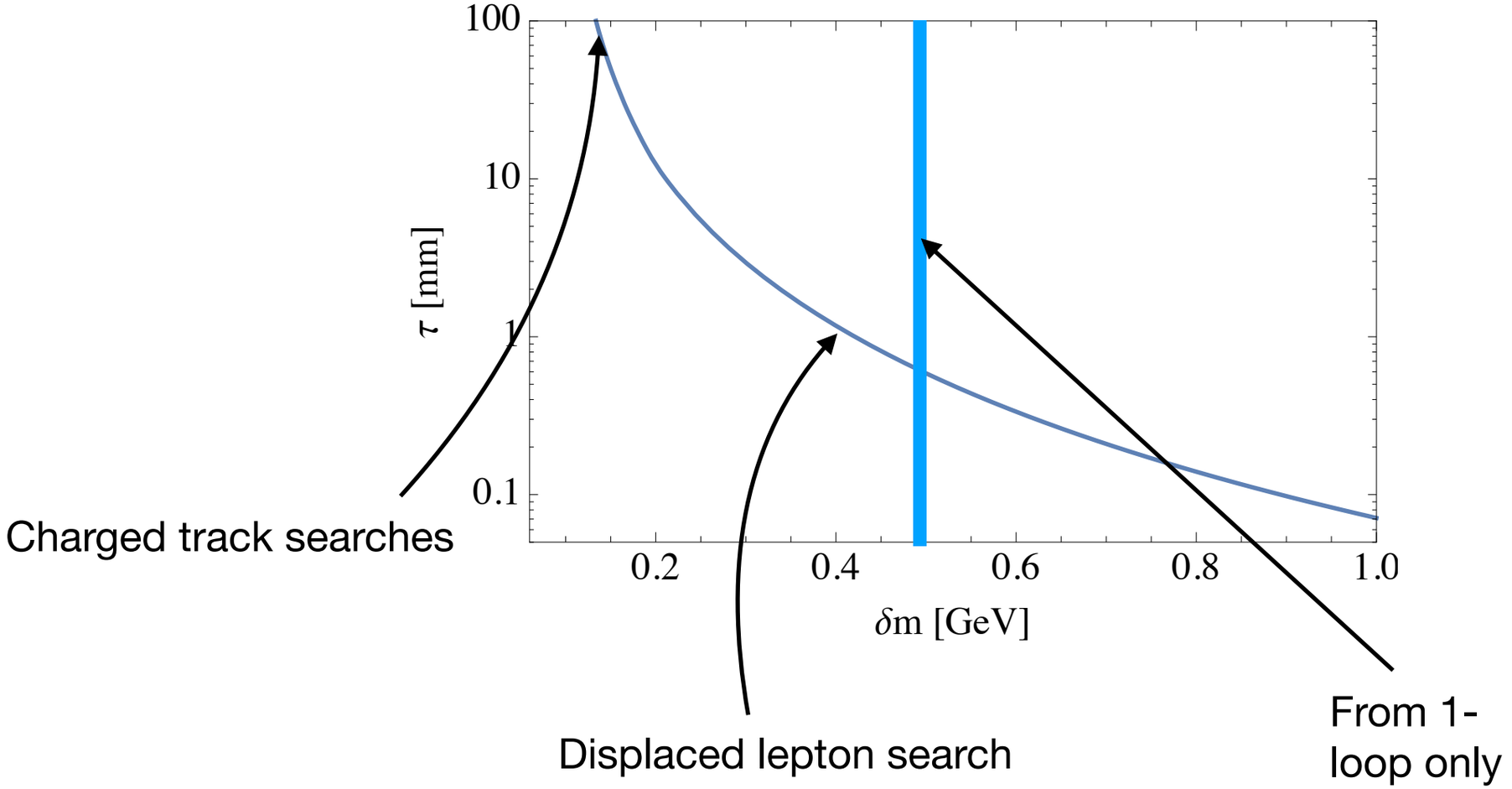
Bruemmer, Desai, Bharucha (in prep.)

# Collider searches: Quintuplet model

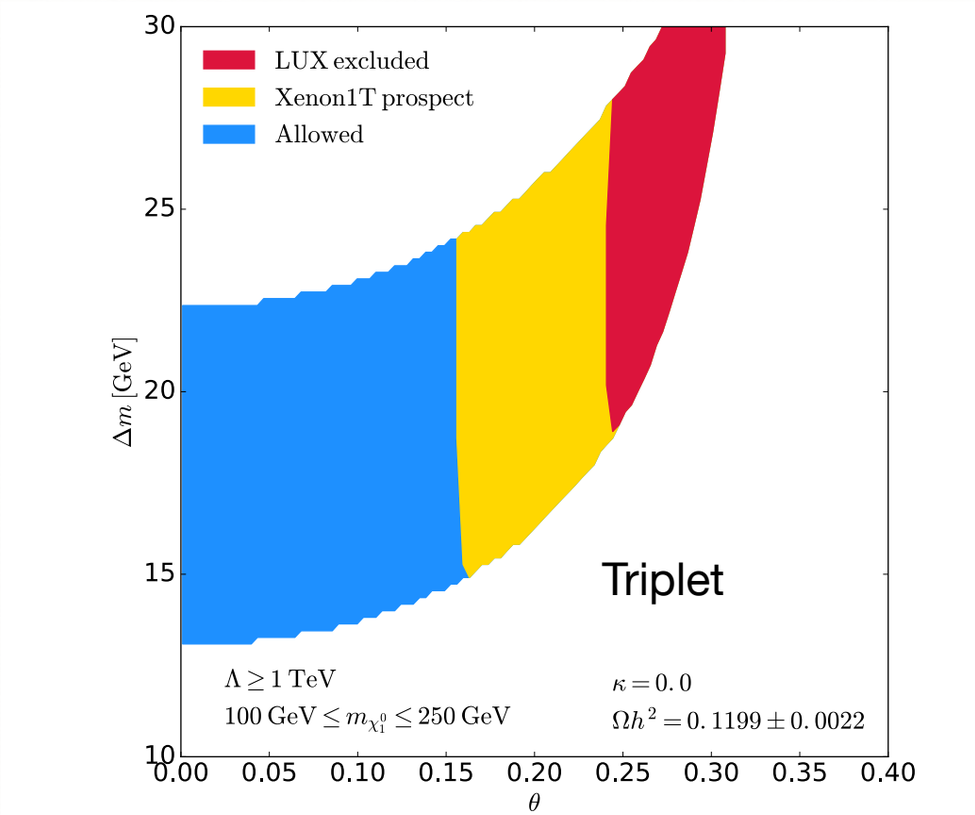


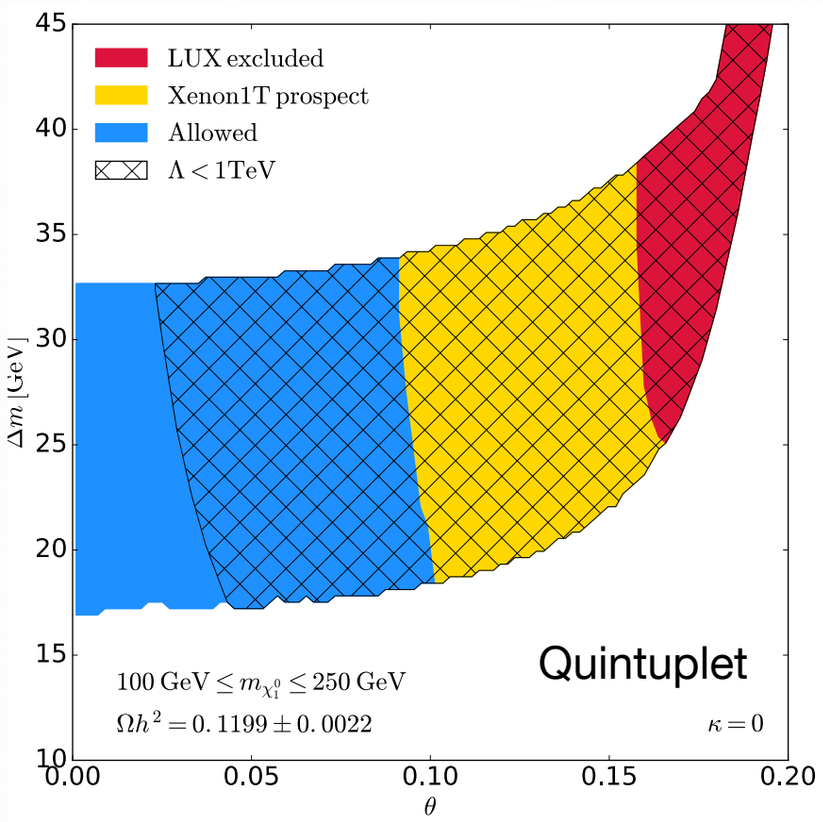

$$\chi^{++} \to \chi^{+}\pi^{+}$$
$$\chi^{+} \to \chi_1^0 W^* \to \ell\nu\chi_1^0$$
$$\chi_2^0 \to \chi_1^0 h^* \to b\bar{b}\chi_1^0$$

**Large lifetime for the doubly charged partner**



# DIRECT DETECTION CONSTRAINTS

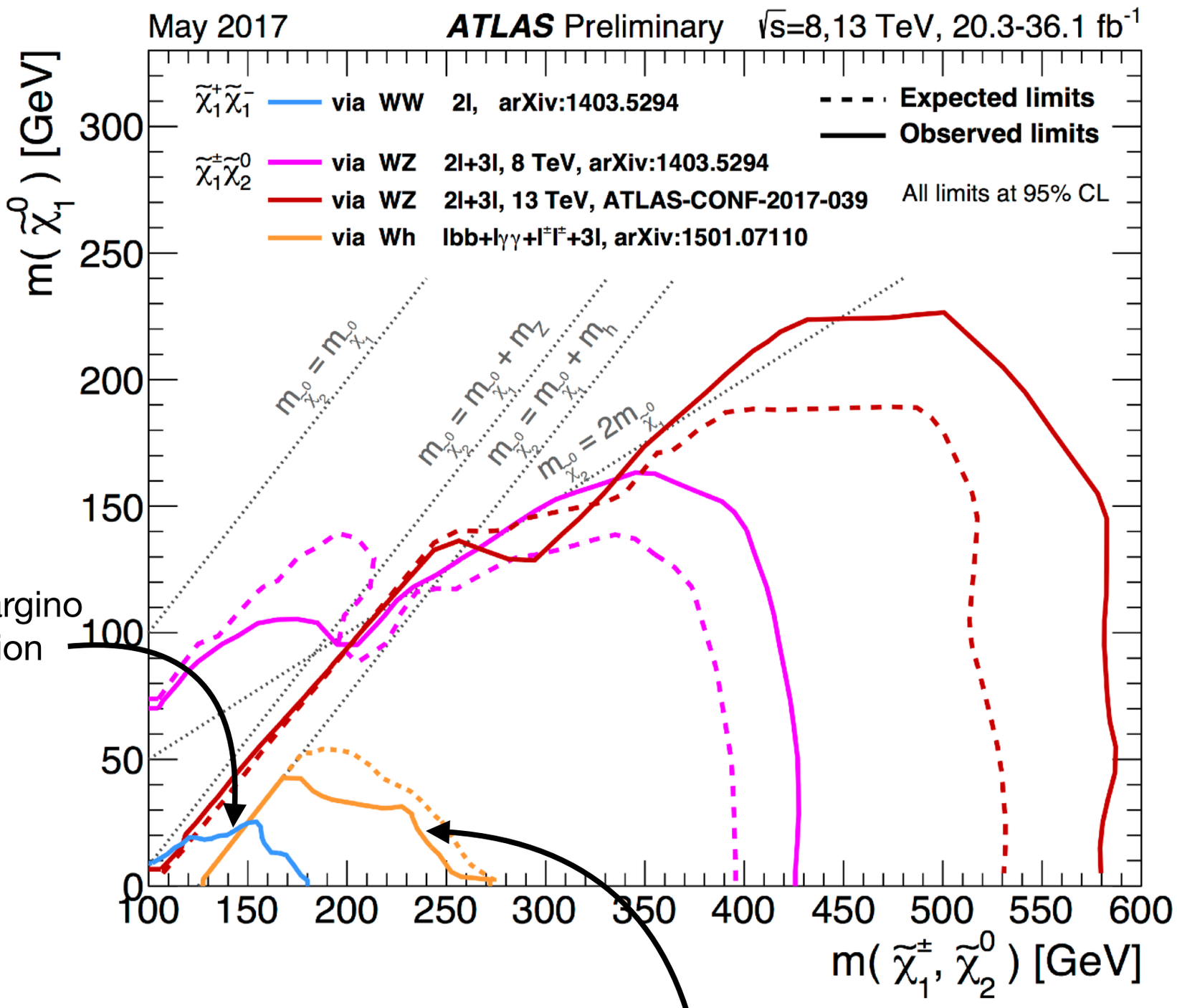



- Look at parameters that gives right relic density
- Low mixing angle gives low DD cross section; however, not a problem at the LHC because production is primarily Drell-Yan!

Bruemmer, Bharucha, Ruffault (2017)
Bruemmer, Desai, Bharucha (in prep.)

# Prompt search limits: SUSY searches

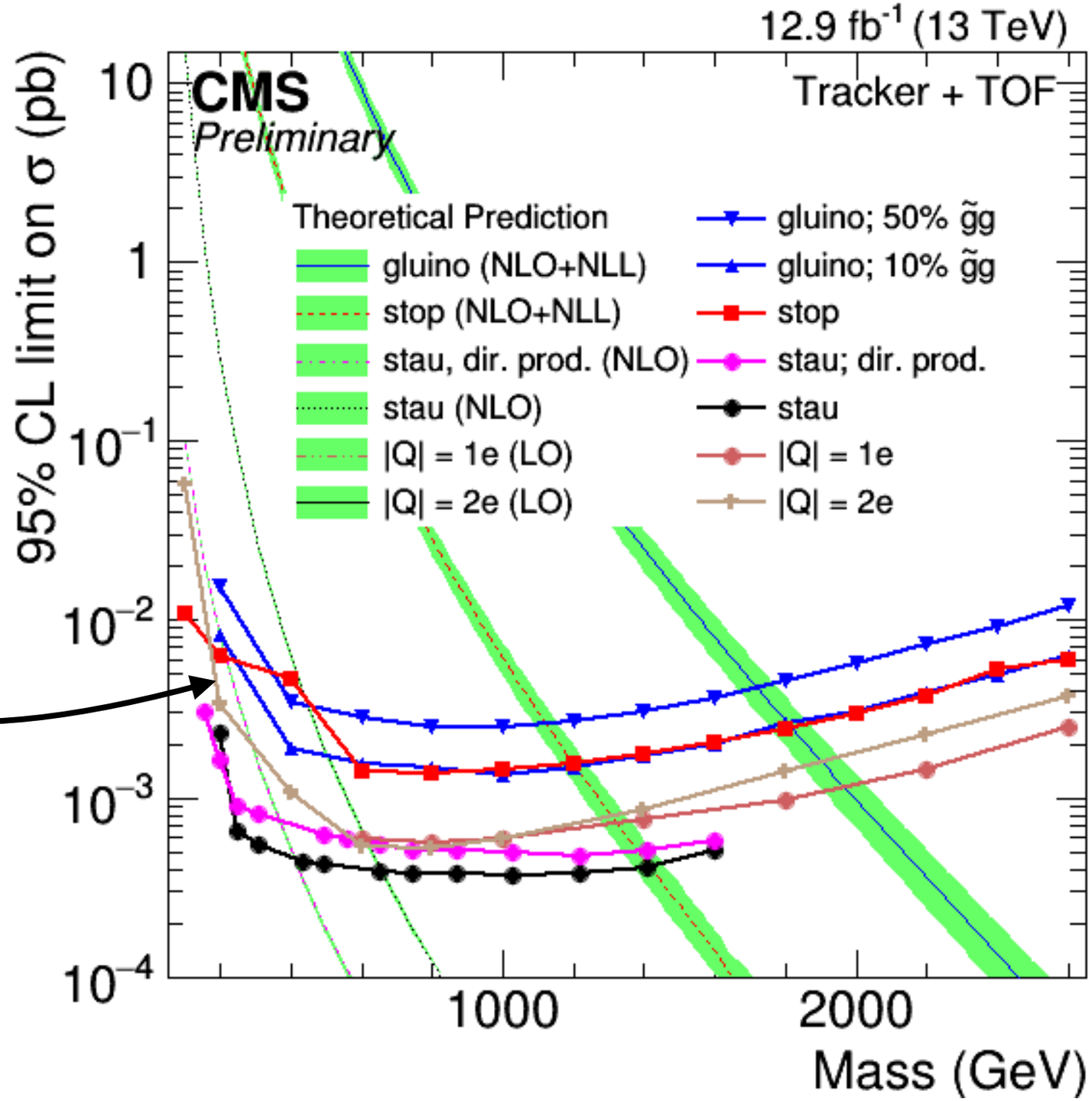



Limit on Chargino pair production

LHC limit on WH final state; not stronger than displaced leptons

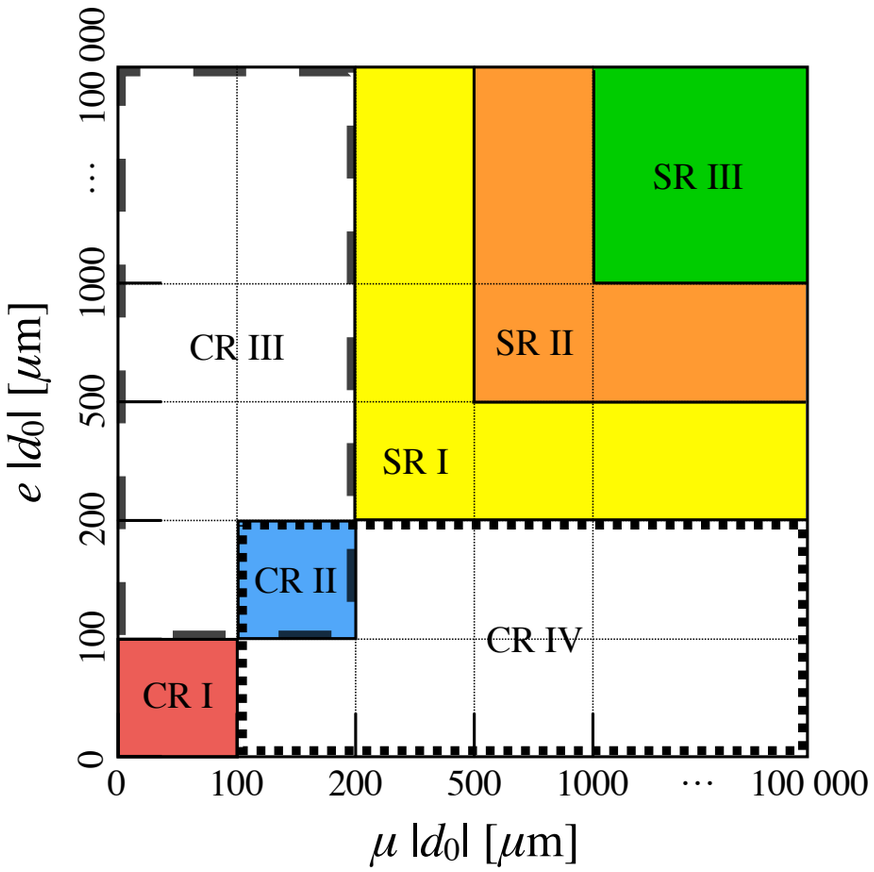
# Other possible limits: charged track searches

Doubly charged



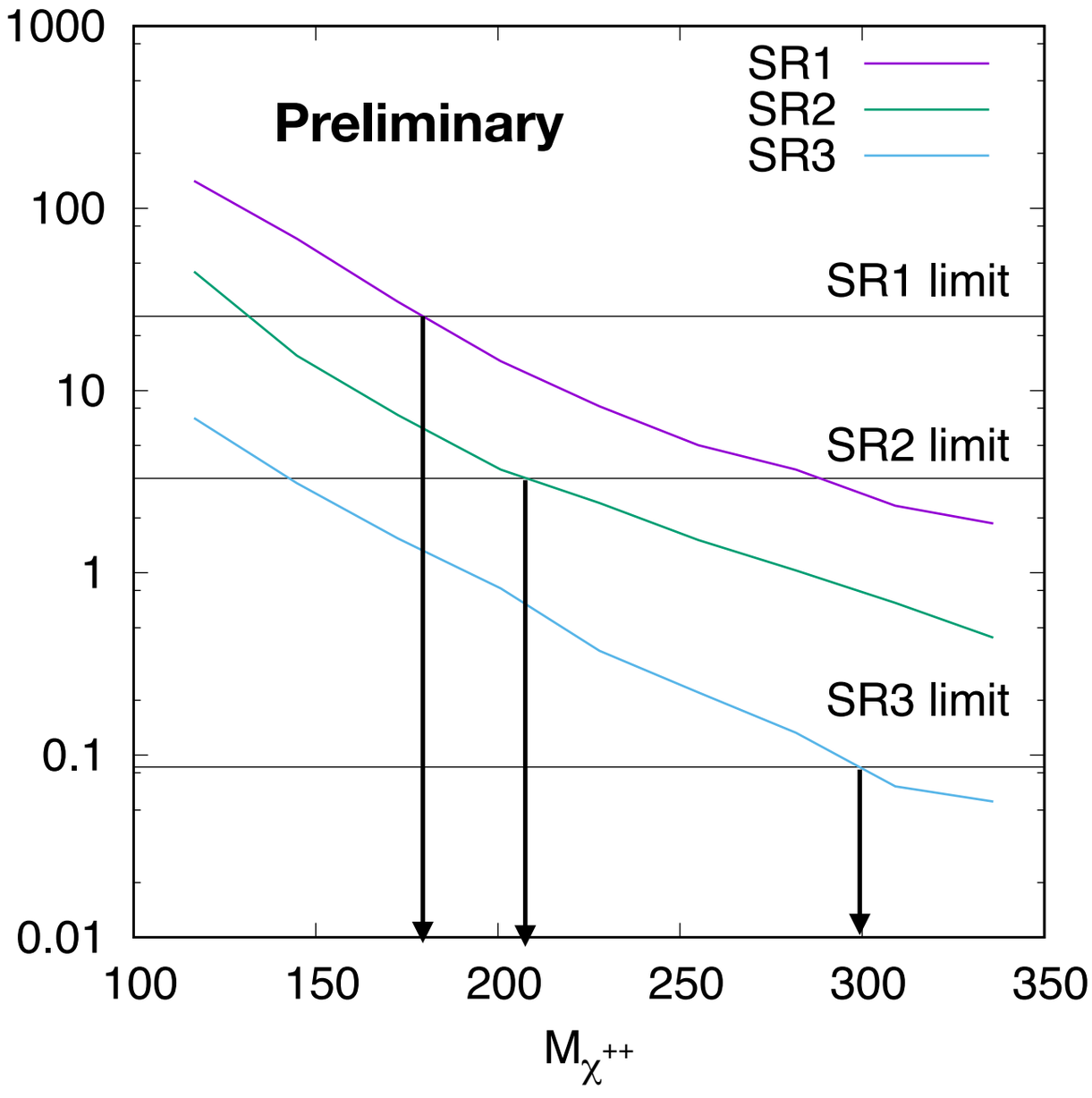

**Rule out long-lived region i.e. when mass difference is smaller than pion mass**

# The CMS displaced lepton search (arXiv:1409.4789)

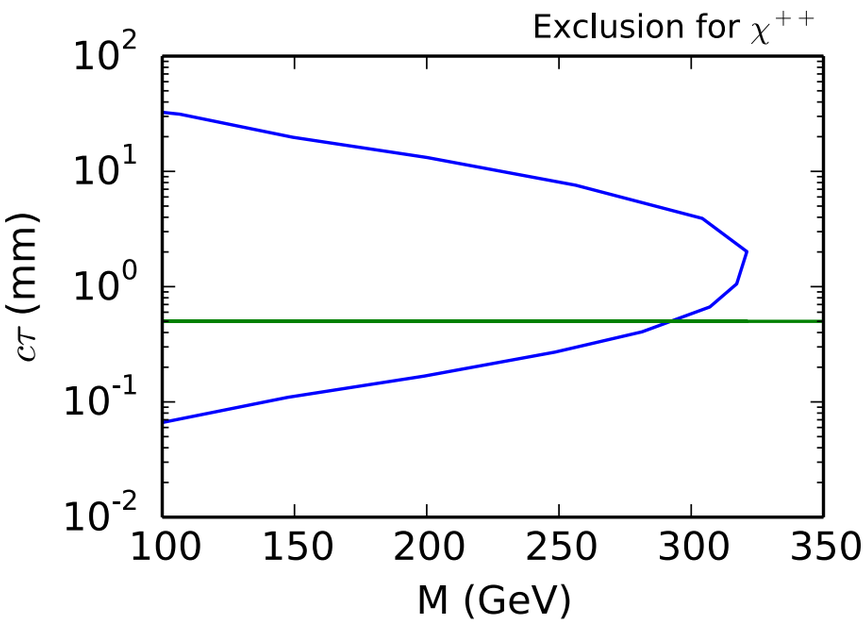


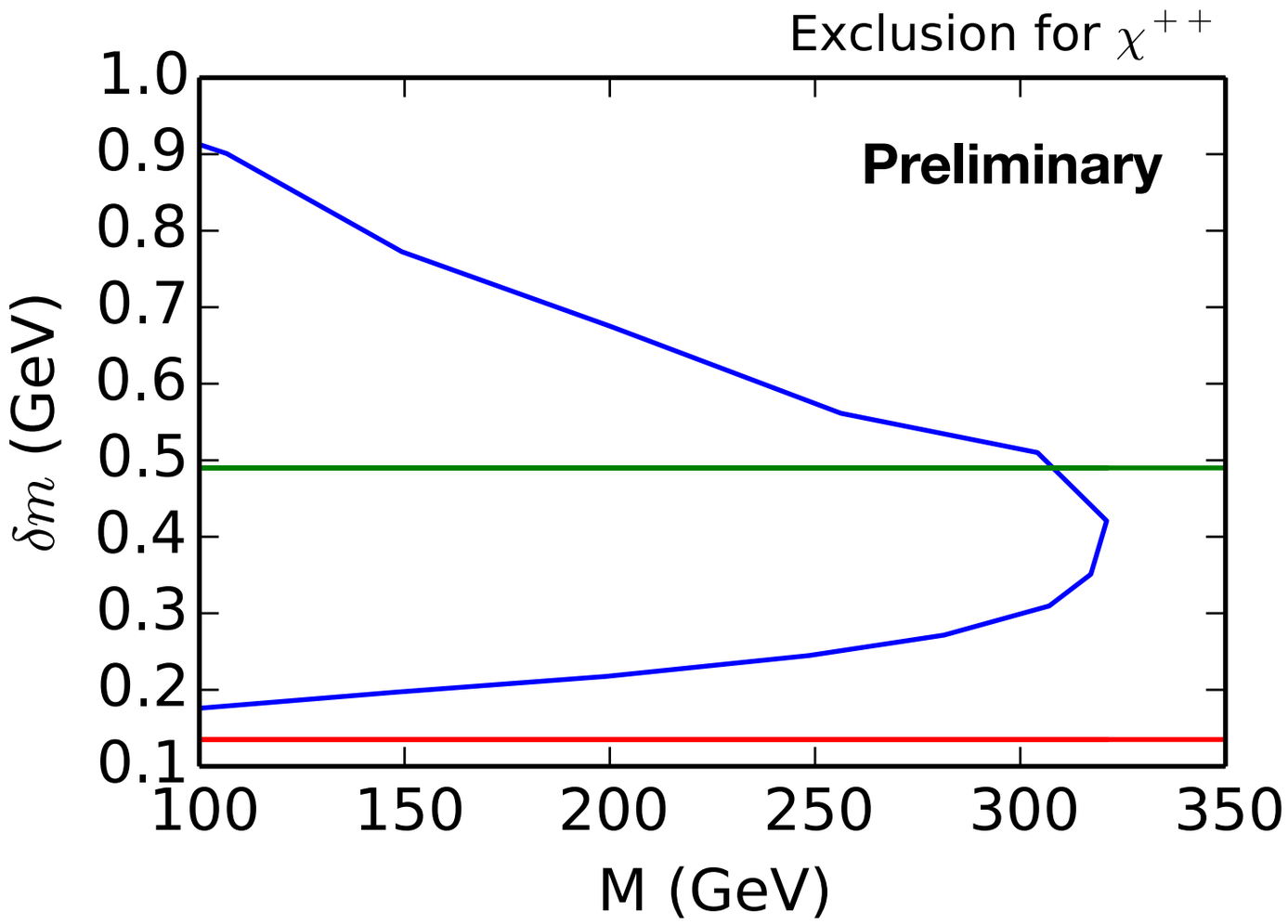

Validation

| Lifetime | 1 mm | 10 mm | 100 mm |
|---|---|---|---|
| SR1 | 34.4 (30 ± 5) | 28.3 (35 ± 7) | 4.83 (4 ± 1) |
| SR2 | 8.76 (6.5 ± 1) | 24.6 (30 ± 5) | 5.73 (5 ± 1) |
| SR3 | 1.69 (1.3 ± 0.3) | 53.6 (51 ± 10) | 24.6 (26 ± 5) |



# Exclusions for displaced lepton search




**For currently published 13 TeV data (~ 2/fb), displaced searches give worse sensitivity at 13 TeV due to high $p_T$ cuts (to remove displaced leptons from heavy flavour)**

# Summary

- Next-to-minimal models (with relic density constraint) predict new particles in LHC discovery range

- In 5-plet model, lifetime of doubly charged particles imply displaced signatures/charged tracks

- Above pion mass threshold, current limit ~ 300 GeV (from displaced leptons)

- Below pion mass (lifetime > 1m), current limit ~ 600 GeV.

- Limits from chargino/neutralino production not significant