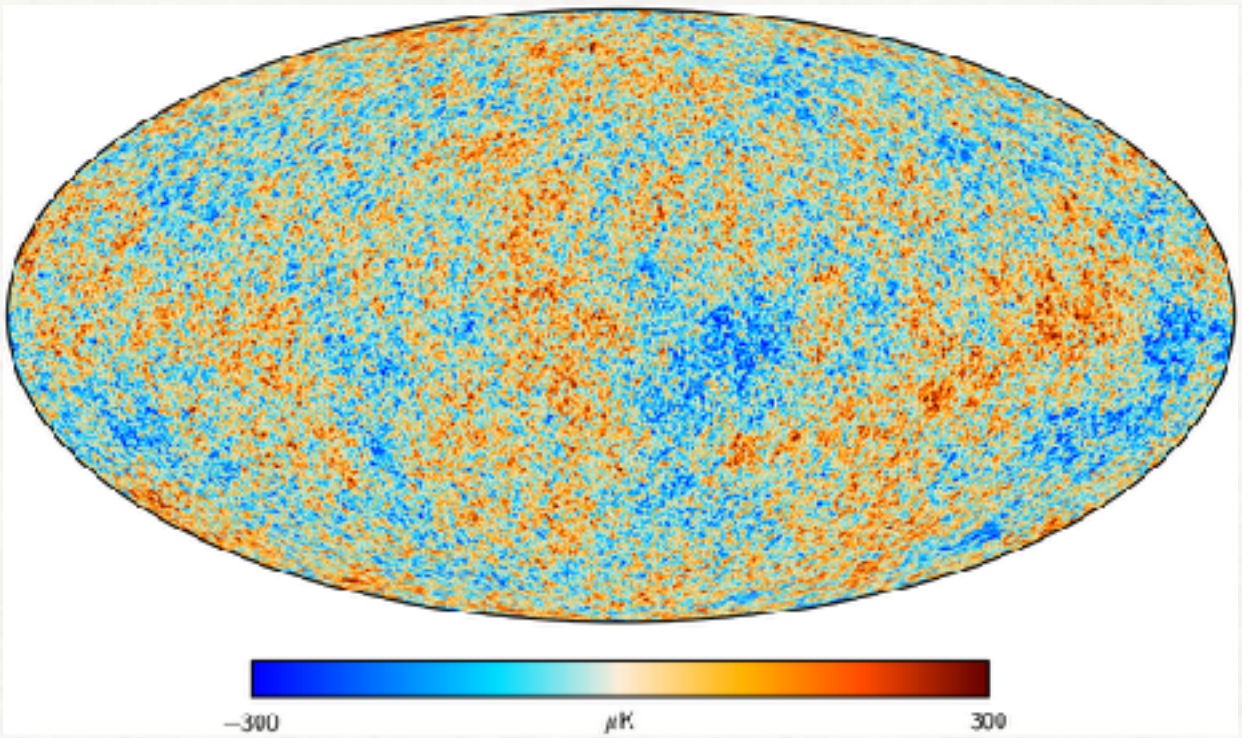
NISHITA DESAI • LUPM, MONTPELLIER

DARK MATTER @ LHC

Collaborators:
B. Allanach, M. Badziak, D. Barducci, M. Bauer, A. Butter, A. Bharucha, J. Bramante, G. Cottin, J. Ellis, M. Frigerio, P. Fox, B. Fuks, J. Gonzalez-Fraile, A. Goudelis, C. Hugonie, F. Luo, S. Kulkarni, J. Marrouche, U. Maitra, A. Martin, B. Mukhopadyaya, B. Ostdiek, T. Plehn, G. Polesello, D. Sengupta, P. Skands, R. Ziegler

21 November 2017 • ICTS, Bengaluru

MANIFOLD EVIDENCE FOR DARK MATTER



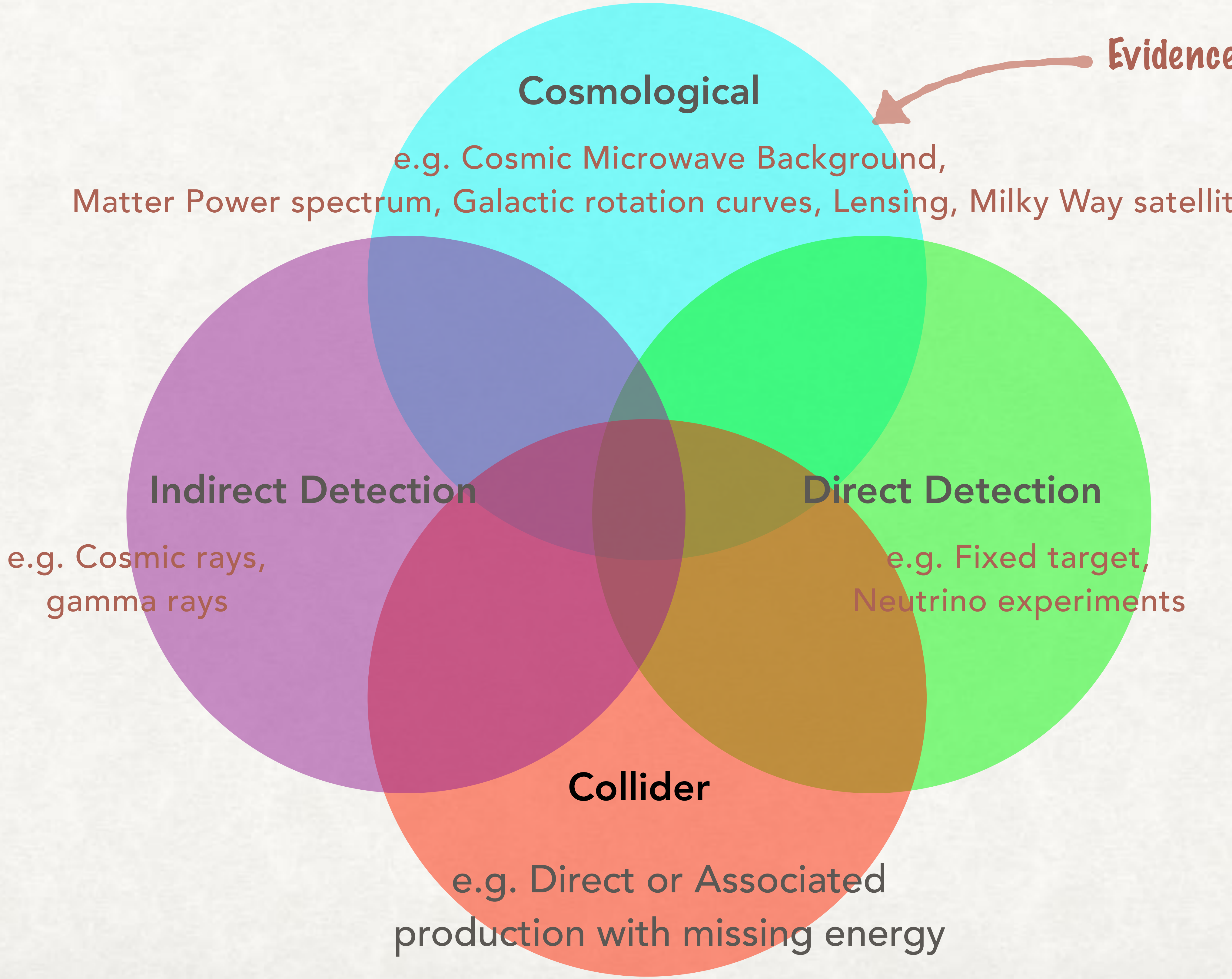
PLANCK Collaboration (2015)

Bullet Cluster

$$
\begin{aligned}
\Omega_m h^2 &= 0.1415 \pm 0.0019 \\
\Omega_b h^2 &= 0.02226 \pm 0.00023 \\
\Omega_c h^2 &= 0.1186 \pm 0.0020
\end{aligned}
$$

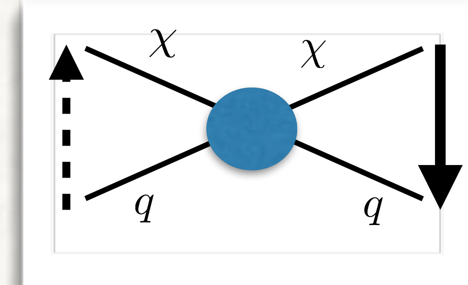
A Dark Matter particle should be: <u>massive</u>, <u>neutral</u>, <u>non-relativistic</u> at present time

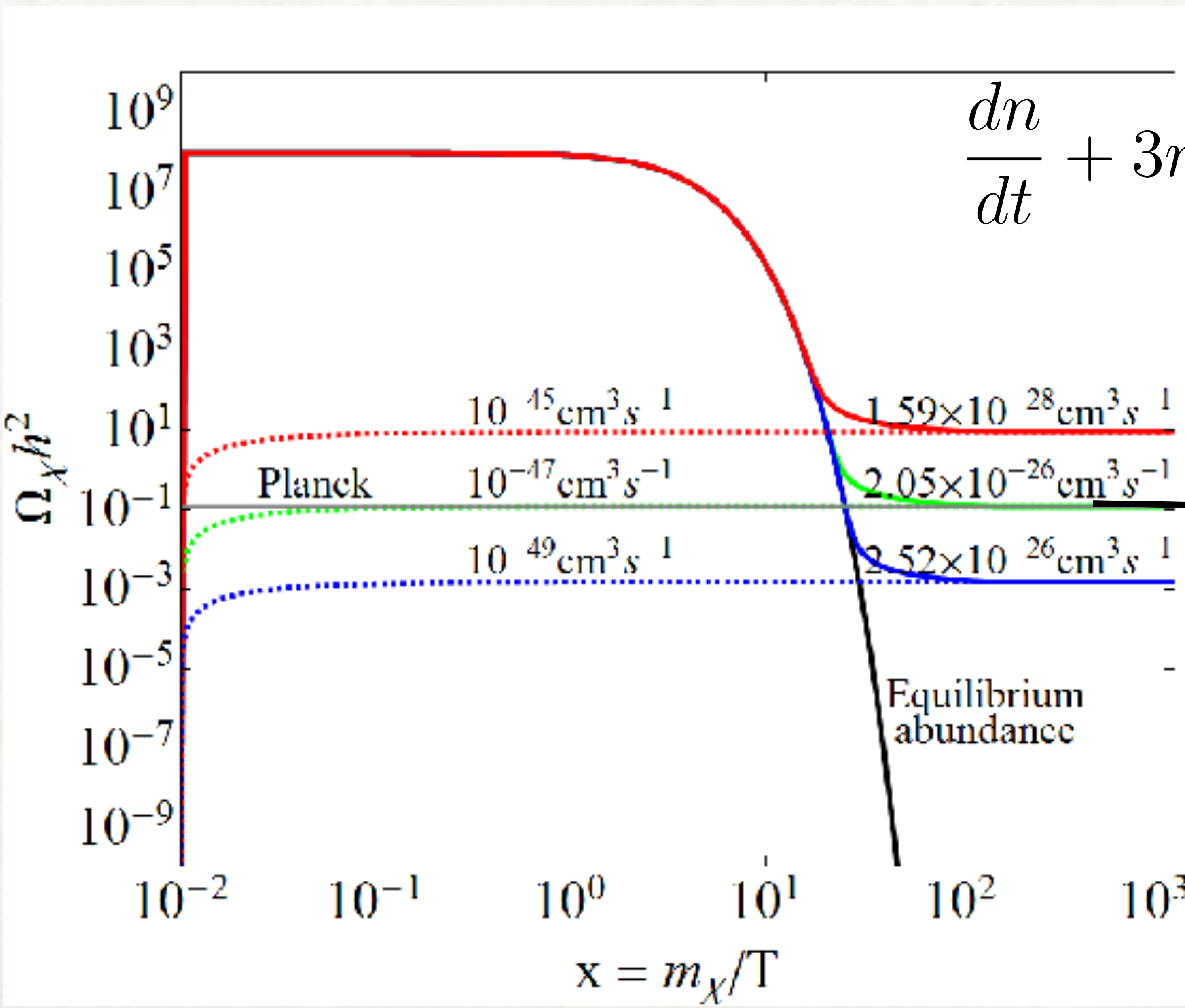
COMPLEMENTARITY OF SEARCHES



RELIC DENSITY VIA THE "WIMP MIRACLE"

How does the DM density change with the expanding universe?
Simple assumption: Start with thermal equilibrium



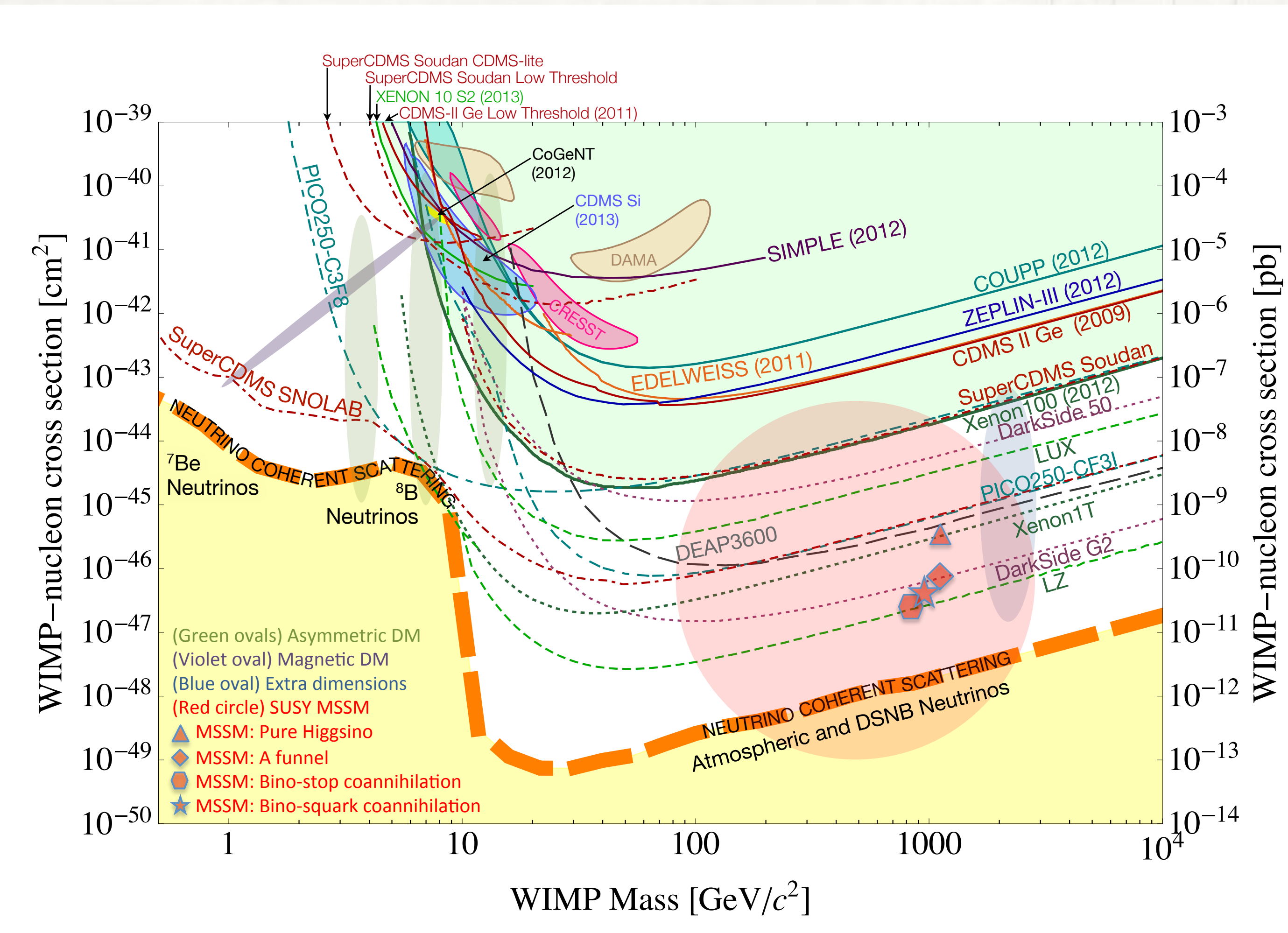


$$\frac{dn}{dt} + 3nH = -\frac{1}{2}\langle\sigma v\rangle\left(n^2 - (n^{eq})^2\right)$$

$$m_\chi \sim 100 \text{ GeV}$$

$$g \sim g_{EW}$$

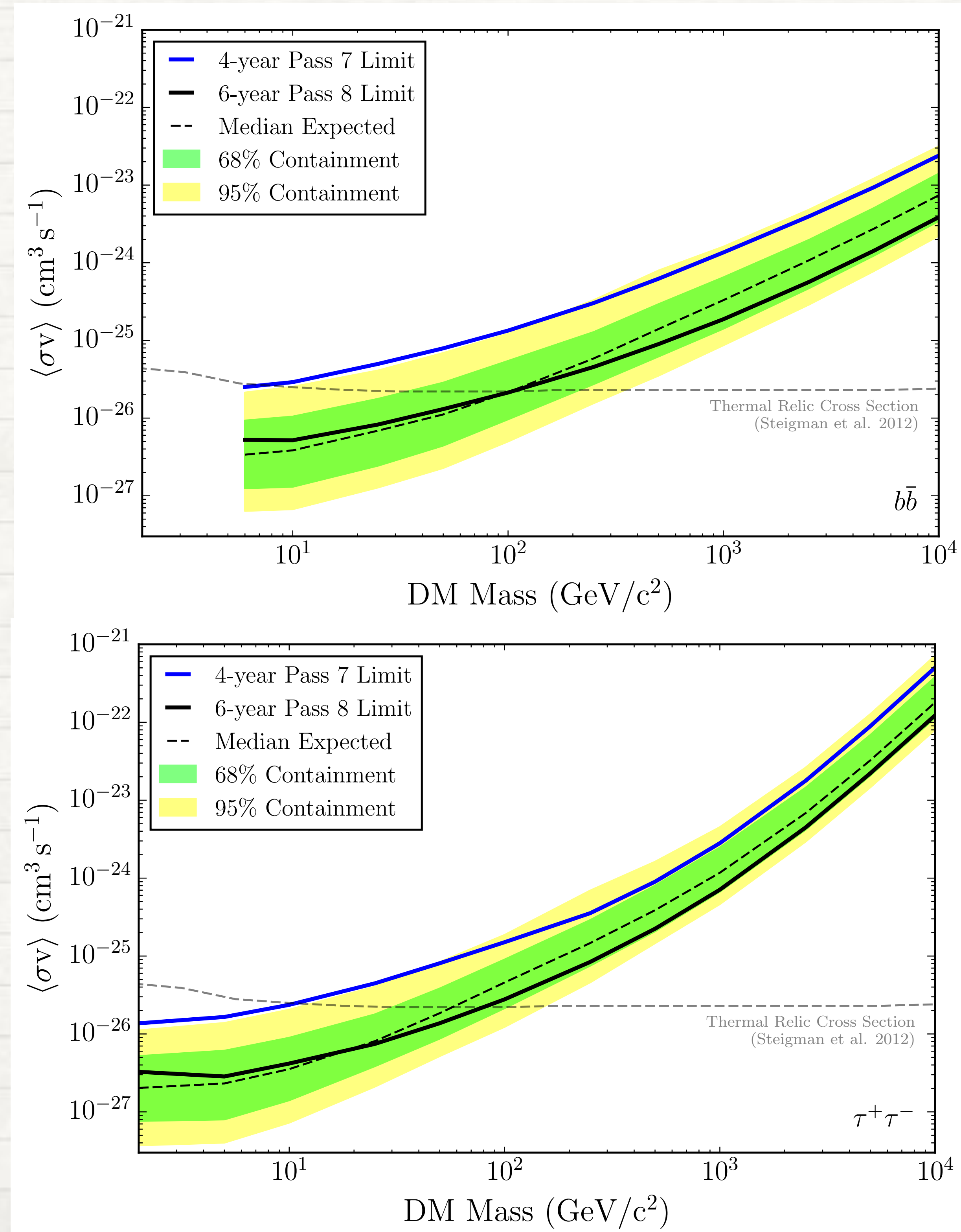
DIRECT DETECTION



- Direct observation of nuclear recoil from dark matter particle
- Best sensitivity ~ 100 GeV mass
- Loss of sensitivity for mass < 10 GeV
- Neutrino floor (from solar neutrinos) will be a bottleneck for future.
- Current best limits from LUX and PandaX

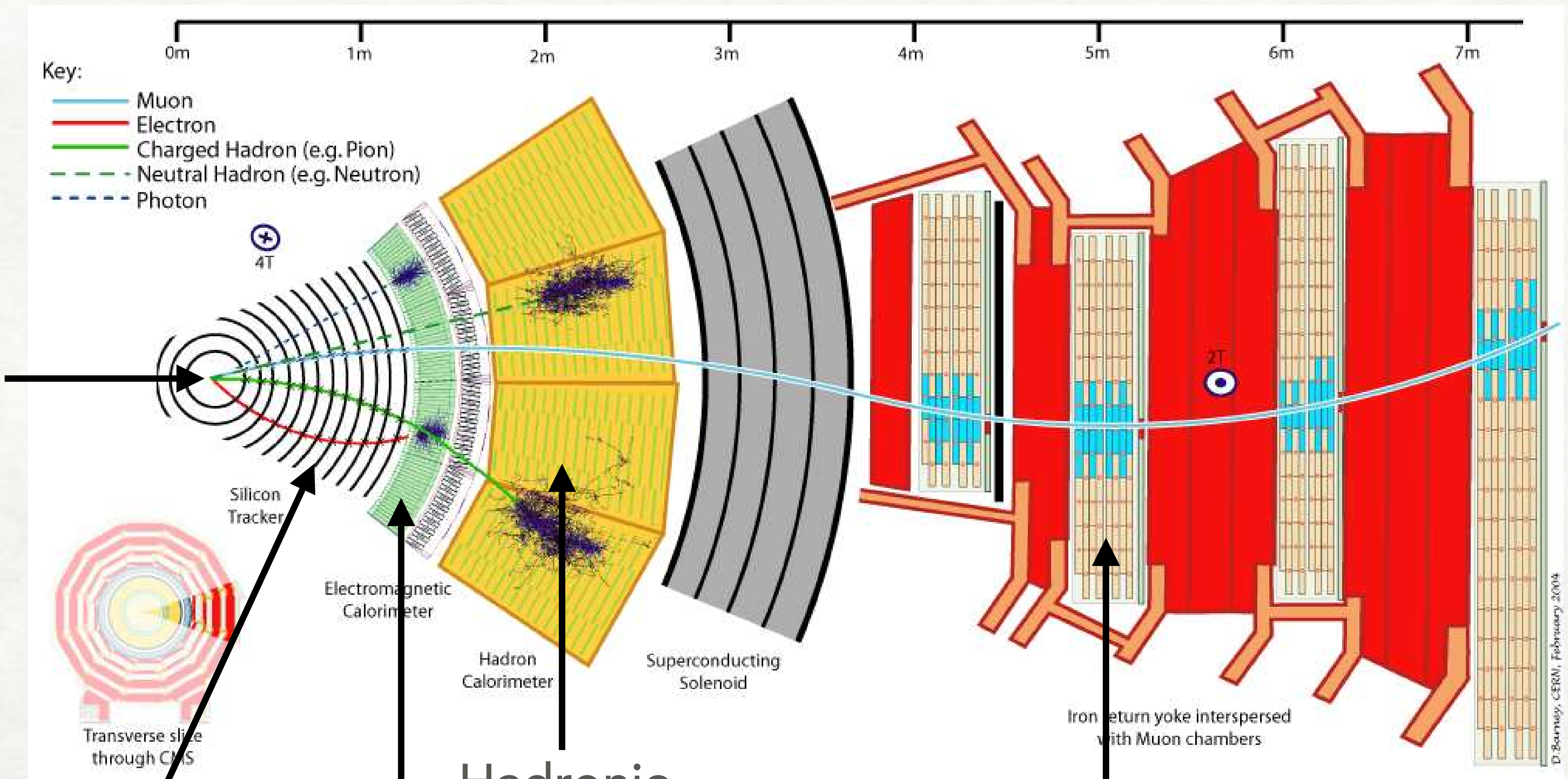
INDIRECT DETECTION

- Gamma rays from annihilation of dark matter into SM
- Observe flux of gamma-ray photons from dark matter dominated regions (i.e. galactic centre and dark spheroidal galaxies)
- Other possibility: observe cosmic rays (mainly charged particle); but prone to uncertainties in propagation models.



Fermi-LAT collaboration (1503.02641)

ANATOMY OF A TYPICAL DETECTOR @ LHC



Collision point

Tracker

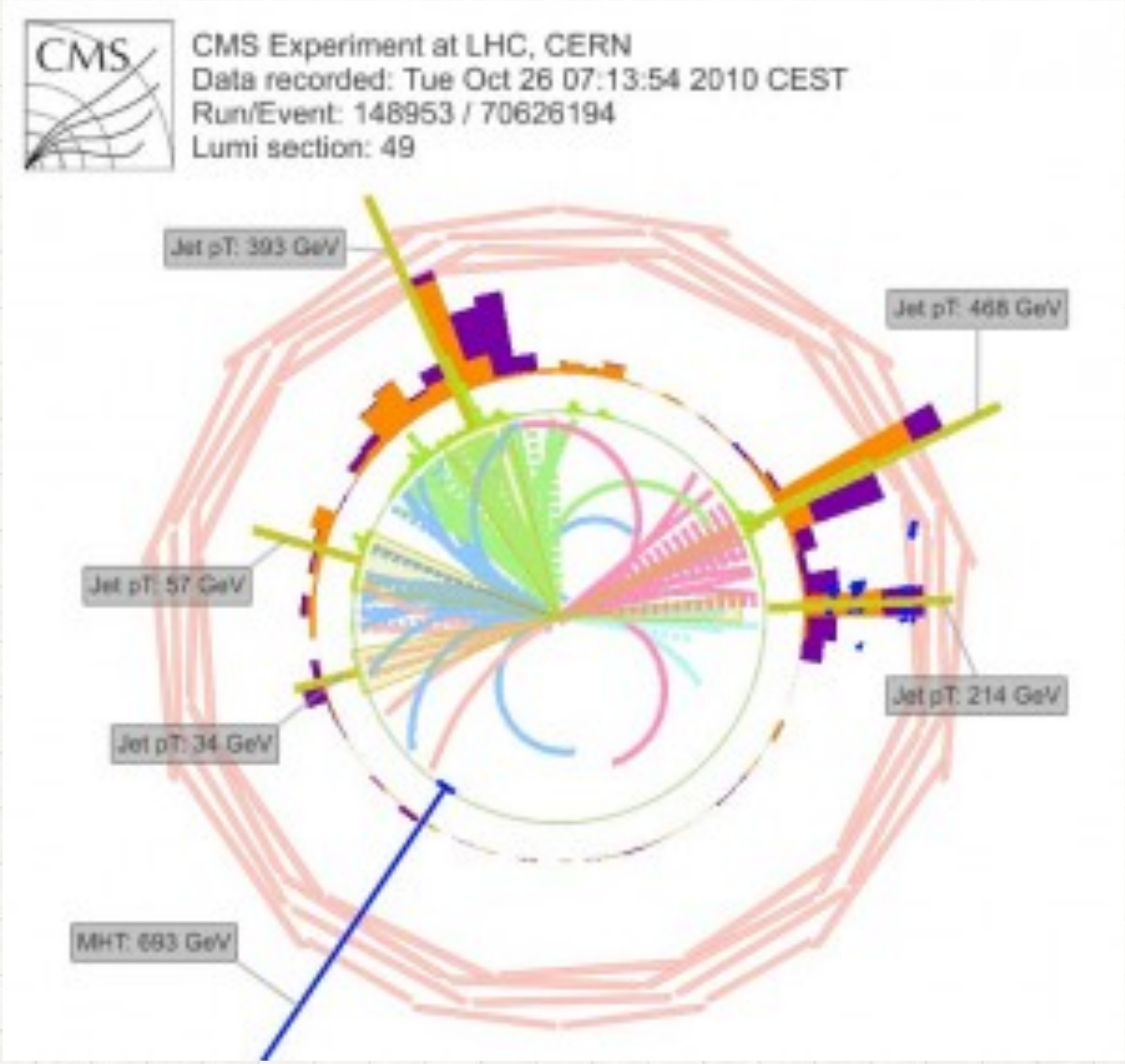
Electo-Magnetic Calorimeter

Hadronic Calorimeter

Muon Chambers

WHAT DOES A COLLISION EVENT LOOK LIKE?

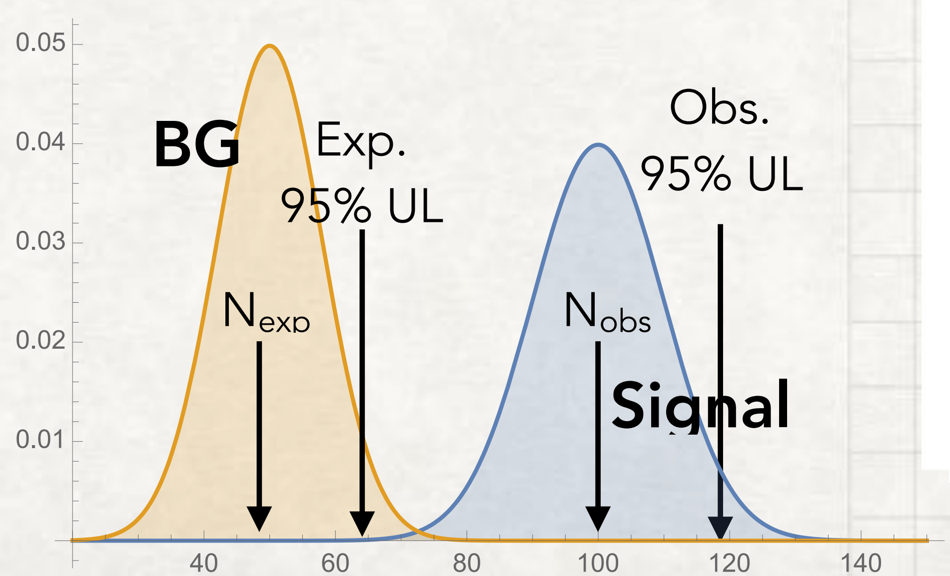
- Detectable objects are **photons**, **electrons**, **muons**, hadrons (which form **jets**), and invisible neutrinos (in the form of **missing momentum or MET**)
- Most new particles will decay into SM particles
- We use **kinematic distributions** of detectable objects to define **signal** (i.e. new physics) and **background** (i.e. SM physics)

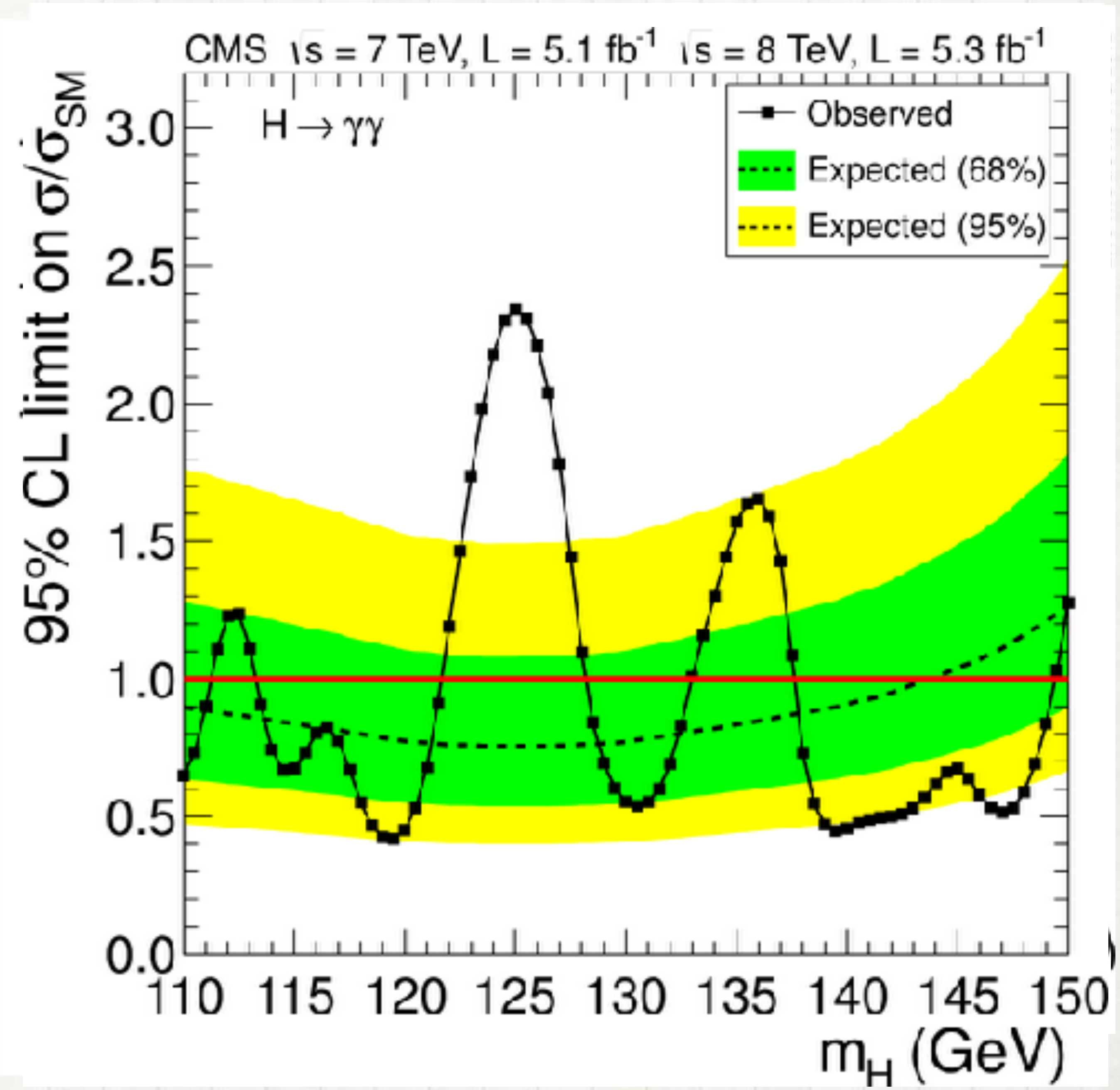


PREDICTING A NEW PARTICLE

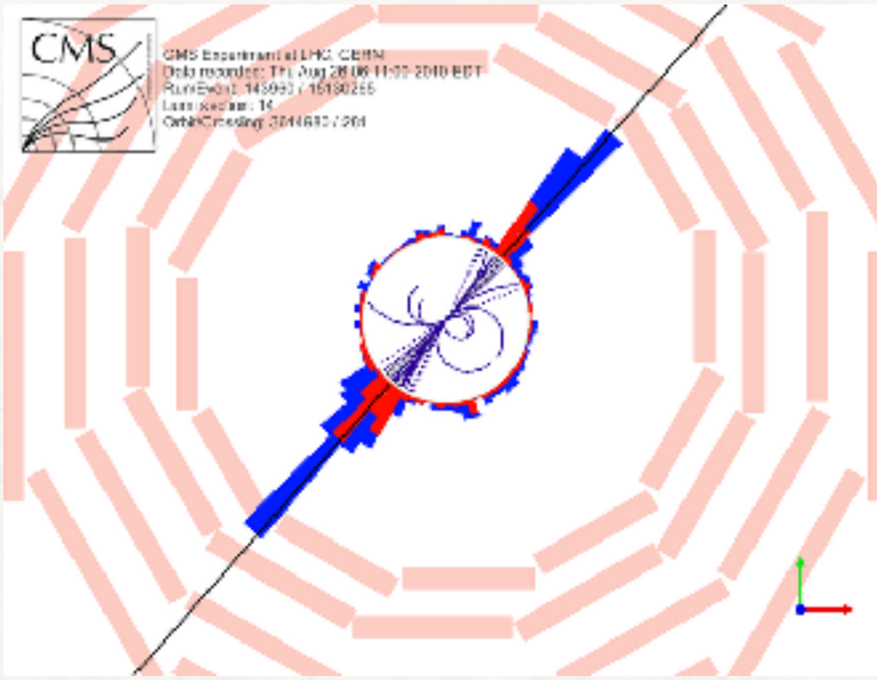
What is

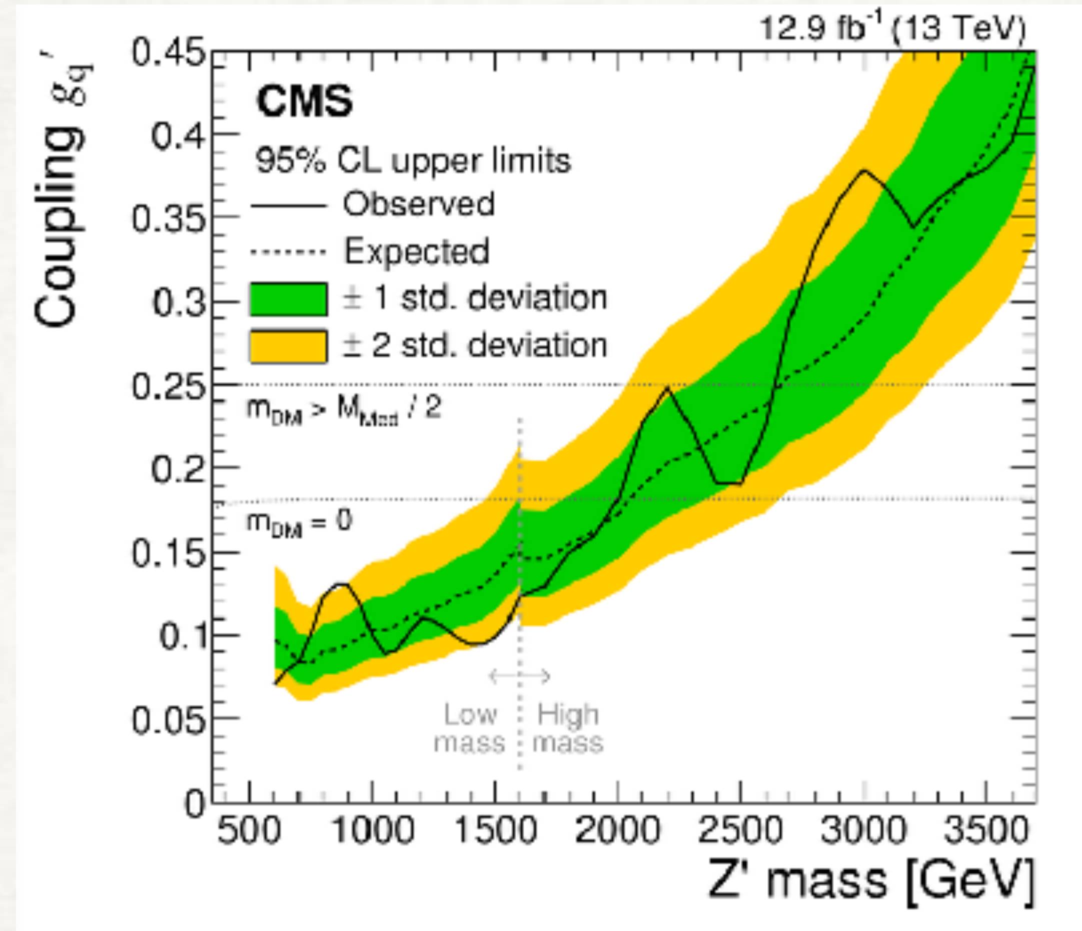
1. the production cross section?
2. its decay into?
3. the best observable channel?
   (i.e. what is the SM background? Is it well understood?)
4. the signal significance?
5. the upper limit (p-value > 0.05)





DATA FROM EXPERIMENTS





A. Experiments provide "high-level" information, e.g. **number of observed events** with X jets + Y electrons/muons + large MET; **signal strength** in a particular channel, etc.

B. Kinematic requirements (a.k.a **cuts**) are placed to discriminate new physics "signal" from Standard Model "background". Experiments provide **cut flows**, **efficiency maps**.

C. Complex statistical machinery used — likelihoods, MVA, Neural Nets etc. to get best **upper limits**, **signal strengths**, or **cross section measurements**.

REVIEW: ALGORITHM TO RECAST SEARCHES

1. Write down Lagrangian
2. Generate signal & background event samples
3. Simulate detector effects
4. Apply analysis cuts & validate
5. Compare surviving signal cross section with 95% upper limits from experiment.

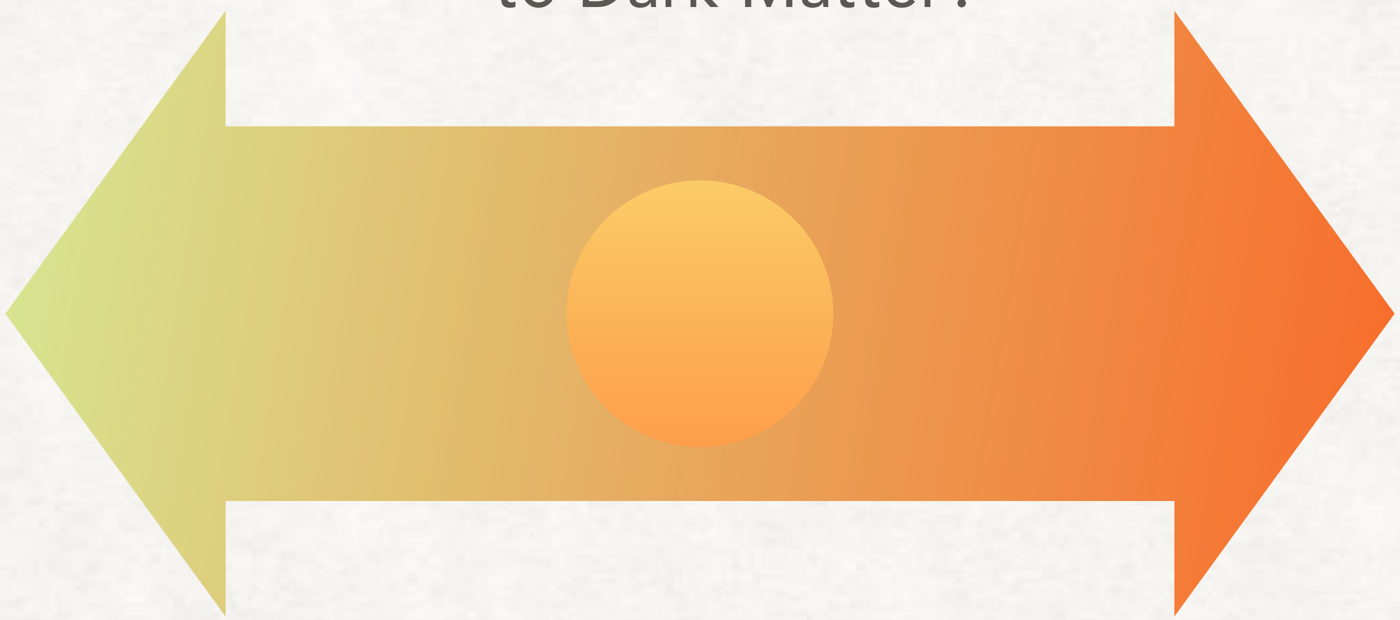
Pythia 8; Sjöstrand, Desai et al. (2015)
CheckMATE2; Dercks, Desai et al (2017)

WRITING DOWN A MODEL FOR DM

Is it a Scalar? Vector? Dirac or Majorana Fermion?

Does it couple directly to some SM particle (Z, h) ?
If there is a mediator, how does the mediator couple to SM?
to Dark Matter?

Effective Field Theory



Complete Models

eg. SUSY, Universal Extra Dim,
Little Higgs,…

PRO: Simple, Easy to relate observables

CON: bad high-energy behaviour

Simplified models

Trying to get the best of both worlds

IDEA: write down the simplest field content (often a DM field + one mediator)

PRO: Theoretically well motivated, fully calculable, extra particles

CON: Model Prejudices, complicated to understand

LIST OF EFT OPERATORS

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

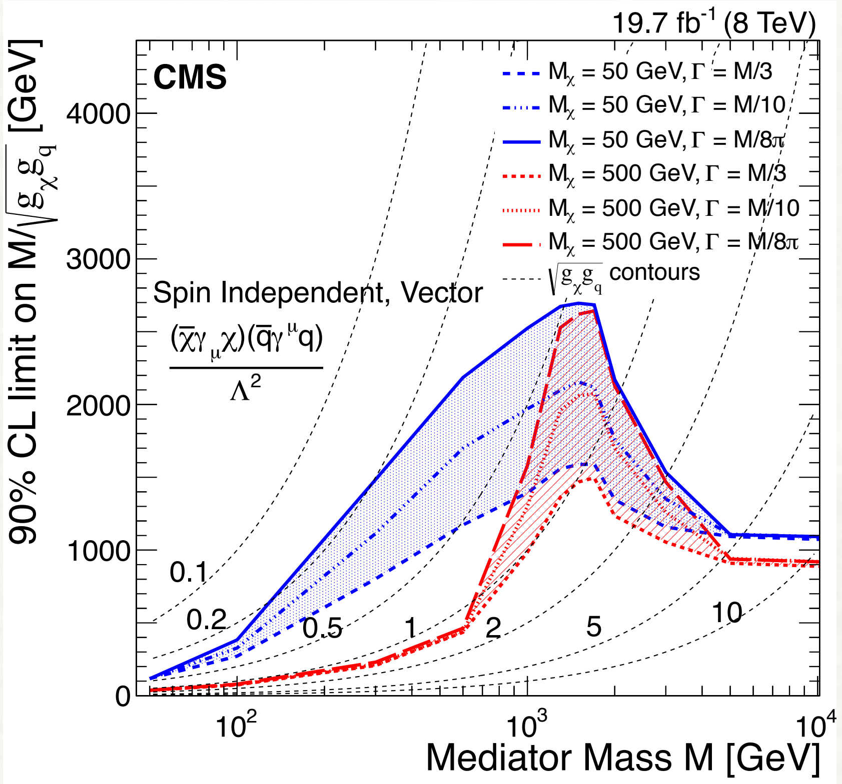
Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

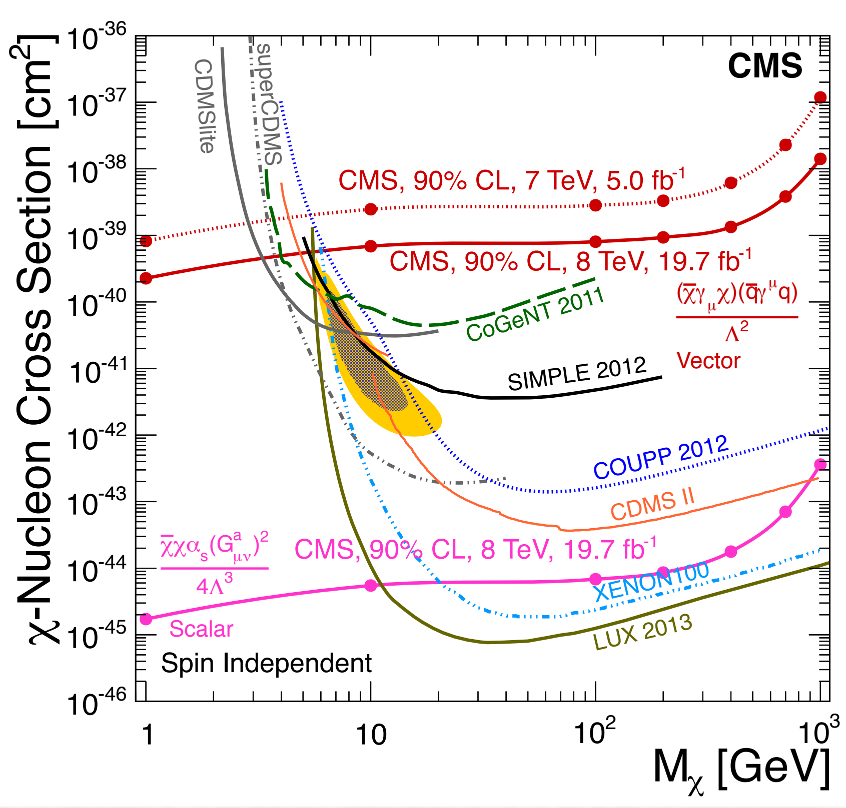
Goodman et al. (2010)

CMS LIMITS ON EFT OPERATORS

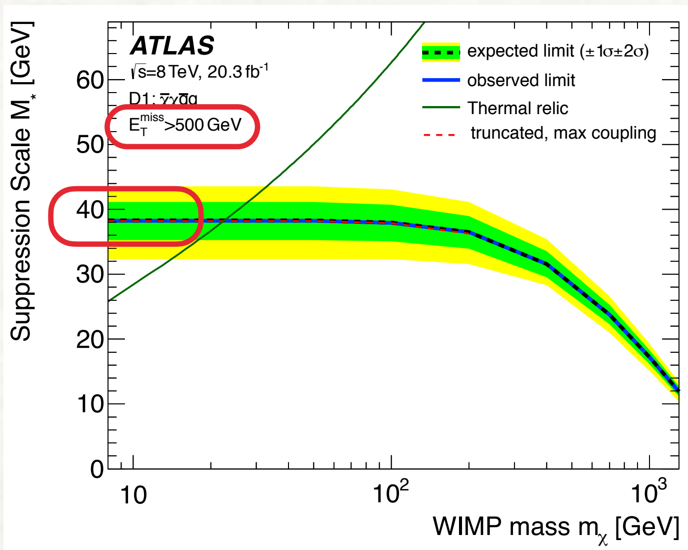
- Can be interpreted both in terms of mediator mass and in terms of DD cross section
- Relatively insensitive to underlying Lorentz structure (i.e. “axial-vector” or “pseudo-scalar” operators does not suffer from suppression)
- Strong limits in low mass region (where DD loses sensitivity)

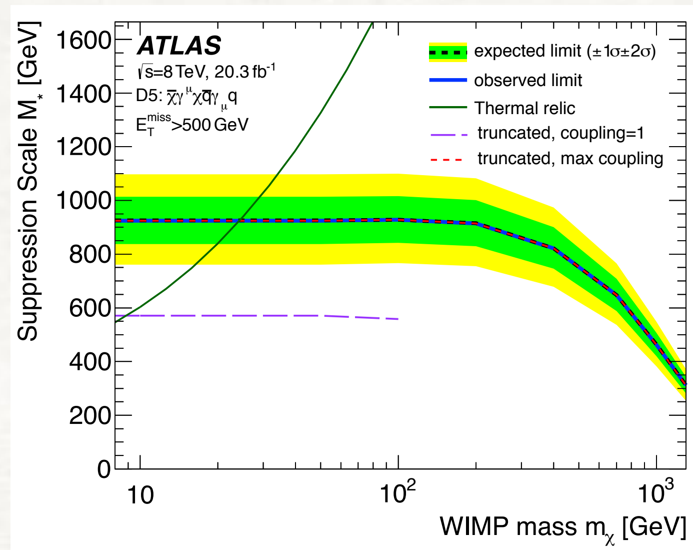
Truly complementary to DD searches!

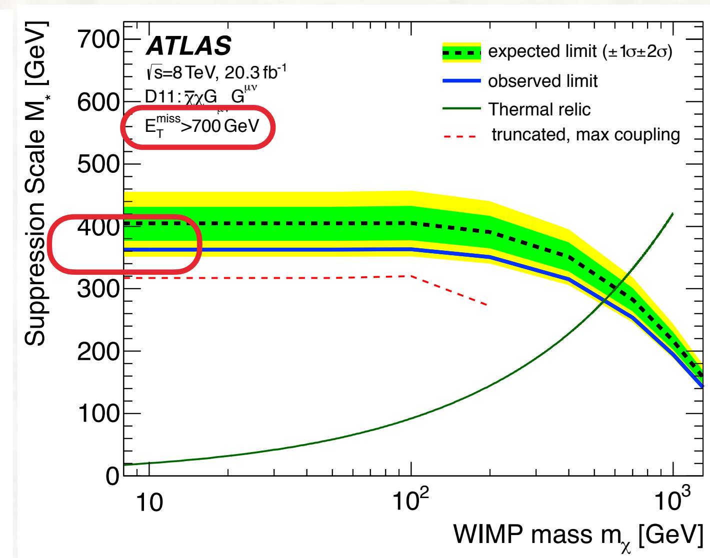


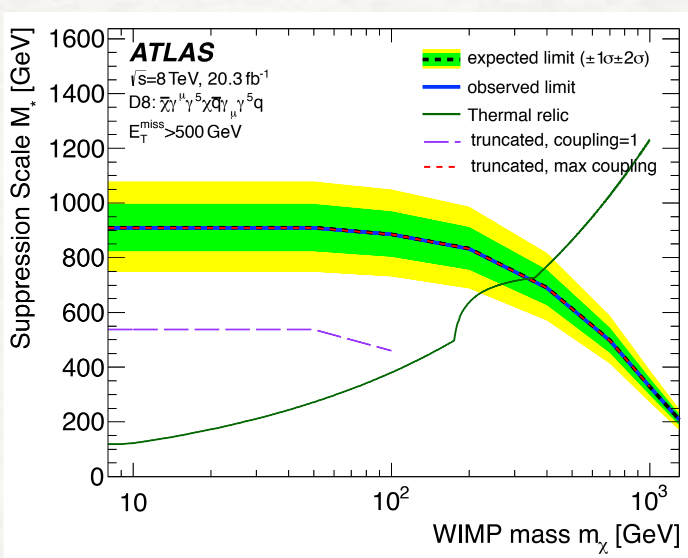


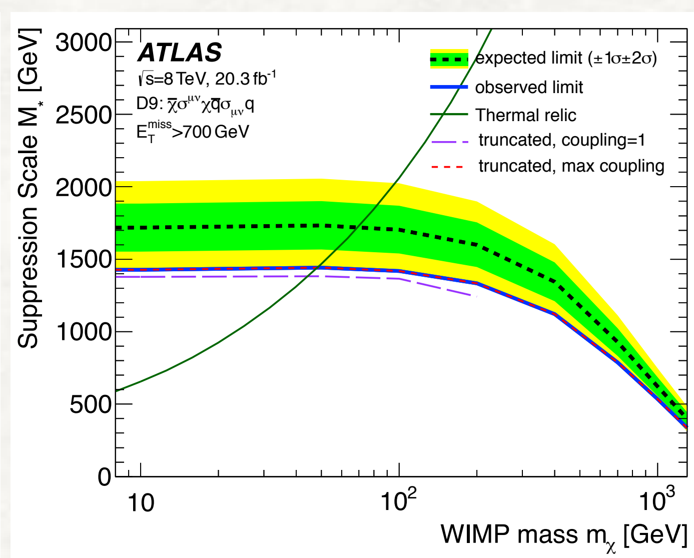
THE PROBLEM WITH NAIVE EFT USAGE

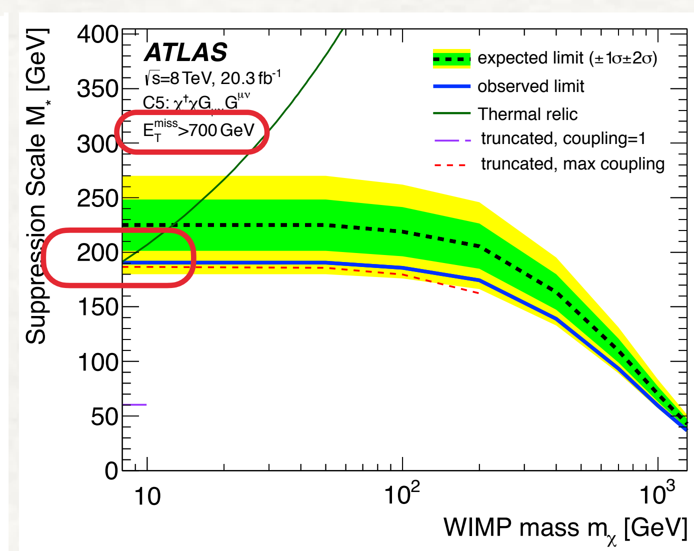








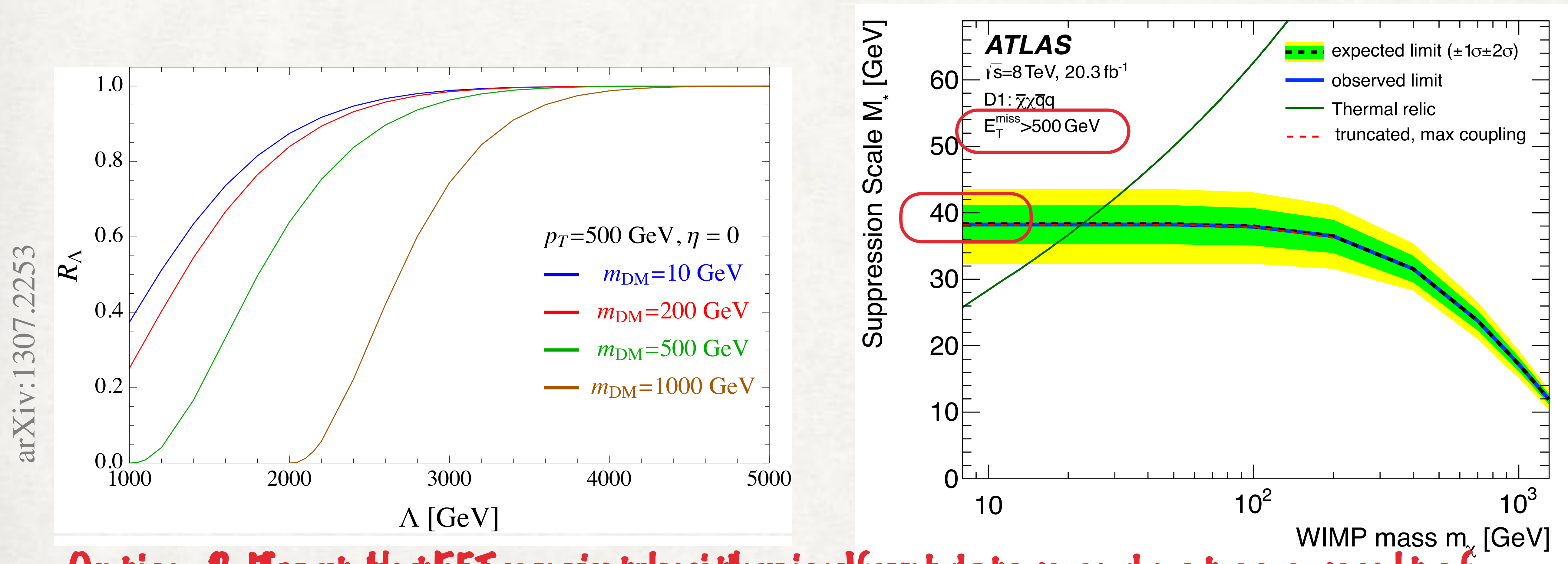




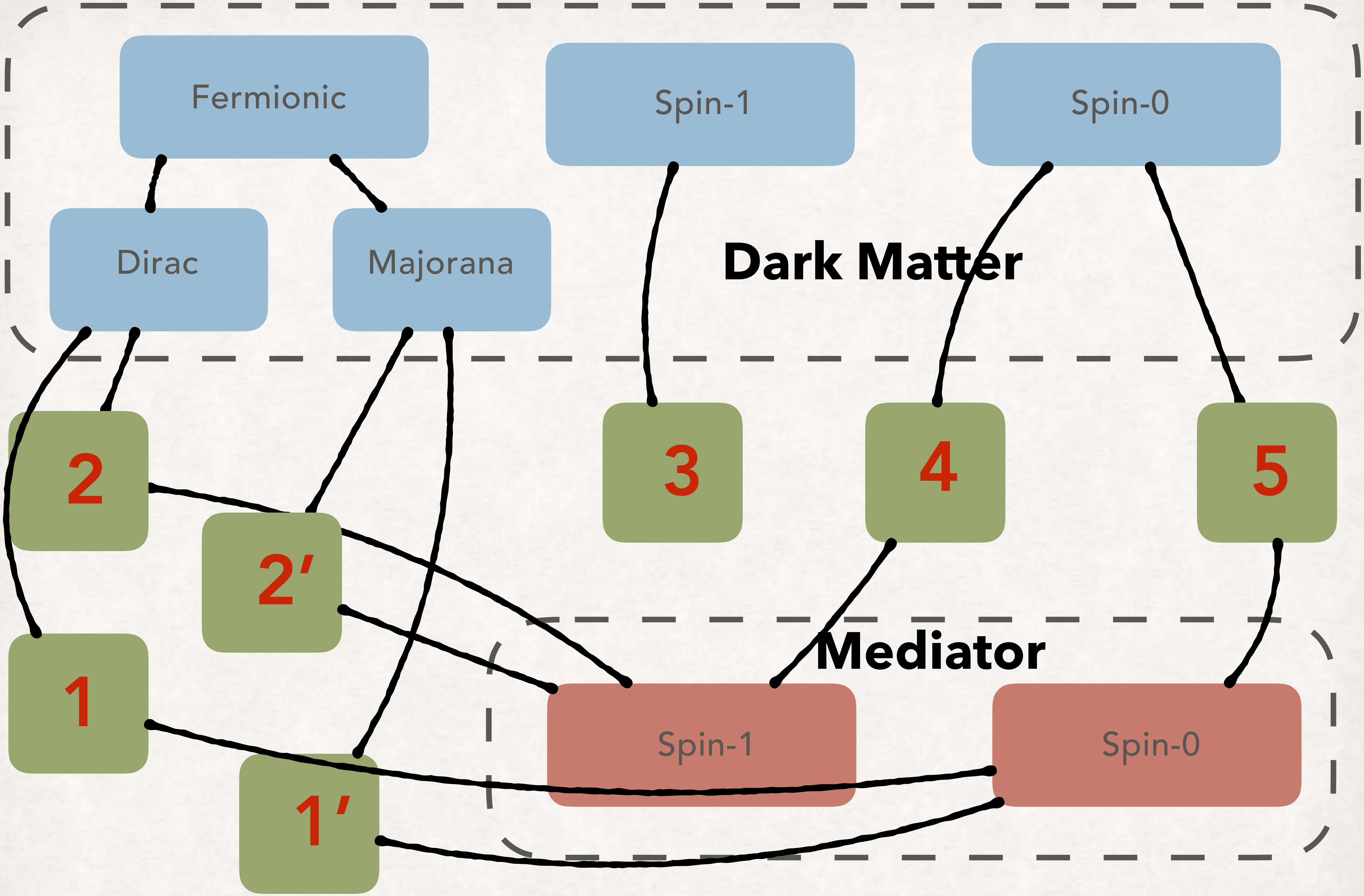
INTERPRETING RESULTS IN EFT

$$\bar{q}q \frac{g}{p^2 - M^2} \bar{\psi}\psi \xrightarrow{M \gg p} \frac{g}{M^2} \bar{q}q\bar{\psi}\psi$$

So how does one live with:



Option 1: Treat the EFT as simply a basis of operators and not as a result of integrating out massive particles.



HOW TO WRITE A SIMPLIFIED MODEL?

SIMPLIFIED MODELS WITH FERMIONIC DM

1

$$\mathcal{L}_S = \frac{1}{2}\partial_\mu S \partial^\mu S - m_S^2 S^2 + \sum g_{s\chi\bar{\chi}}\bar{\chi}\chi S + \sum g_{sq\bar{q}}\bar{q}qS + \bar{\chi}(i\partial_\mu\gamma^\mu - m_\chi)\chi$$

$$\mathcal{L}_P = \frac{1}{2}\partial_\mu P \partial^\mu P - m_P^2 P^2 + \sum g_{s\chi\bar{\chi}}\bar{\chi}\gamma^5\chi P + \sum g_{sq\bar{q}}\bar{q}\gamma^5 qP + \bar{\chi}(i\partial_\mu\gamma^\mu - m_\chi)\chi$$

$$\begin{aligned}\mathcal{L}_T &= \frac{1}{2}D_\mu T D^\mu T - m_T^2 T^2 + \sum g_{T\chi\bar{\chi}}(\bar{\chi}qT^* + \text{c.c.}) \\ &\quad + \bar{\chi}(i\partial_\mu\gamma^\mu - m_\chi)\chi\end{aligned}$$

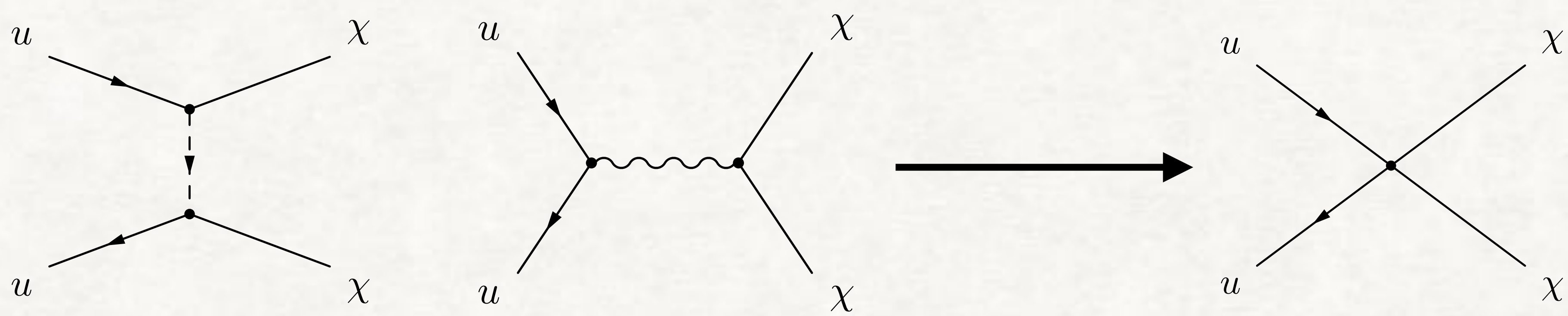
2

$$\begin{aligned}\mathcal{L}_{Z'} &= \sum g_{Z'\chi\bar{\chi}}\bar{\chi}\gamma^\mu\chi Z'^\mu + \sum g_{Z'q\bar{q}}\ \bar{q}\gamma^\mu q Z'^\mu \\ &\quad + \bar{\chi}(i\partial_\mu\gamma^\mu - m_\chi)\chi + \text{gaugeterms}\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{A'} &= \sum g_{A'\chi\bar{\chi}}\bar{\chi}\gamma^\mu\gamma^5\chi A'^\mu + \sum g_{A'q\bar{q}}\ \bar{q}\gamma^\mu\gamma^5 q A'^\mu \\ &\quad + \bar{\chi}(i\partial_\mu\gamma^\mu - m_\chi)\chi + \text{gaugeterms}\end{aligned}$$

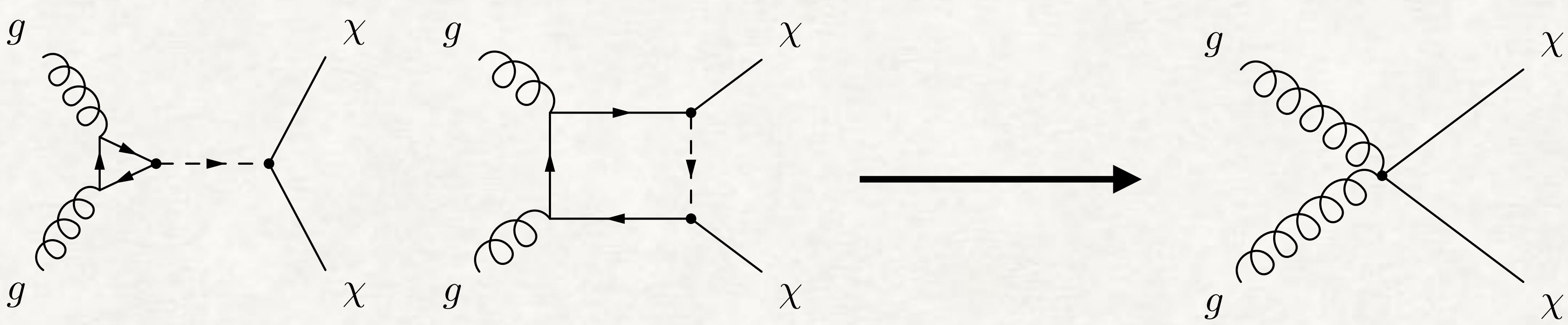
EFTS
VS.
SIMPLIFIED MODELS FOR FERMIONIC DM

EFT TO SIMPLIFIED MODELS



$$\mathcal{L}_{eff} \sim \frac{c_1}{\Lambda^2}(\bar{f}f)(\bar{\chi}\chi) + \frac{c_2}{\Lambda^2}(\bar{f}\gamma_\mu f)(\bar{\chi}\gamma^\mu\chi) + \frac{c_3}{\Lambda^2}\Lambda^2(\bar{f}\gamma_5 f)(\bar{\chi}\gamma_5\chi) + \frac{c_4}{\Lambda^2}\Lambda^2(\bar{f}\gamma_\mu\gamma_5 f)(\bar{\chi}\gamma^\mu\gamma_5\chi)$$

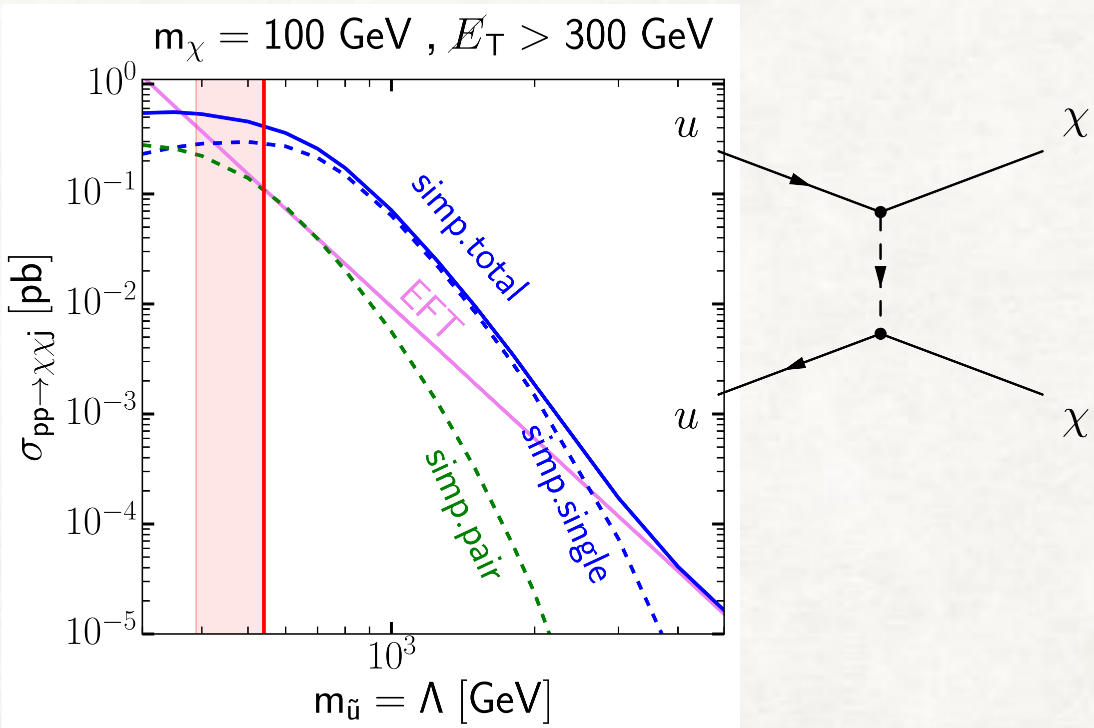
Scalar s-channel — Vector s-channel — Pseudo-scalar s-channel — Axial Vector s-channel

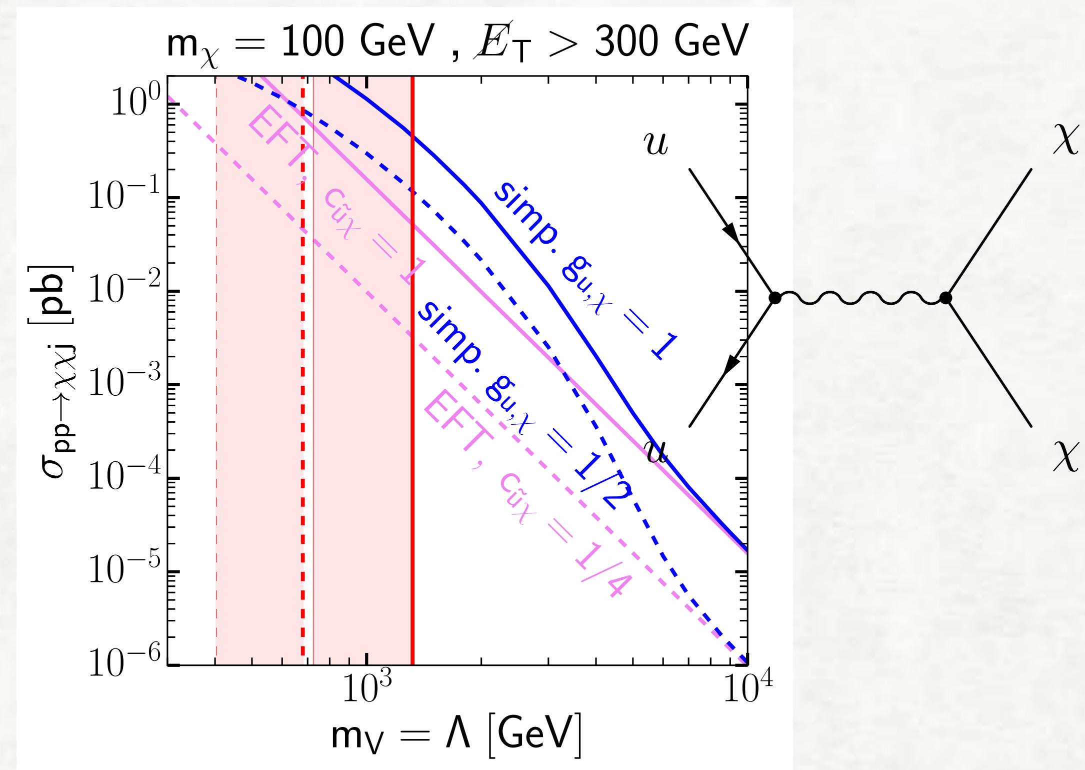


$$\mathcal{L}_{eff} \sim \frac{c_5}{\Lambda^3}(\bar{\chi}\chi)G_{\mu\nu}G^{\mu\nu} + \frac{c_6}{\Lambda^3}(\bar{\chi}\chi)G_{\mu\nu}\tilde{G}^{\mu\nu}$$

Desai, et al (2014)

COMPARISON OF EFT WITH UV COMPLETION



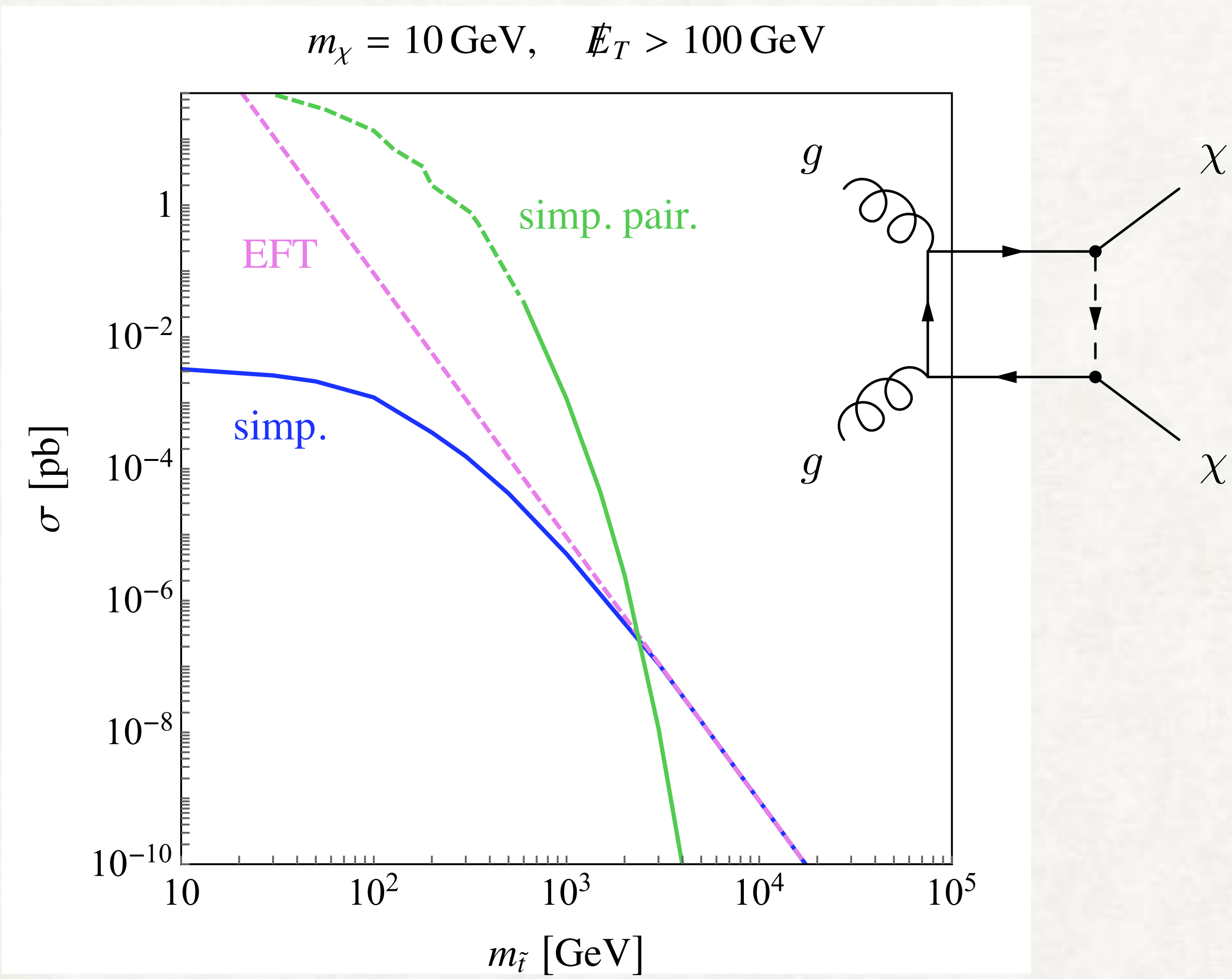


- Need large missing energy cuts to discriminate from SM backgrounds ⇒ large momentum transfer
- This brings into question the idea of “EFT” where the requirement is p≪M (some solutions proposed for this e.g. truncation).
- Cross section does not match even when

Bauer, Desai, et al (2016)

COMPARISON OF EFT WITH UV COMPLETION

What about the loop-mediated completions?



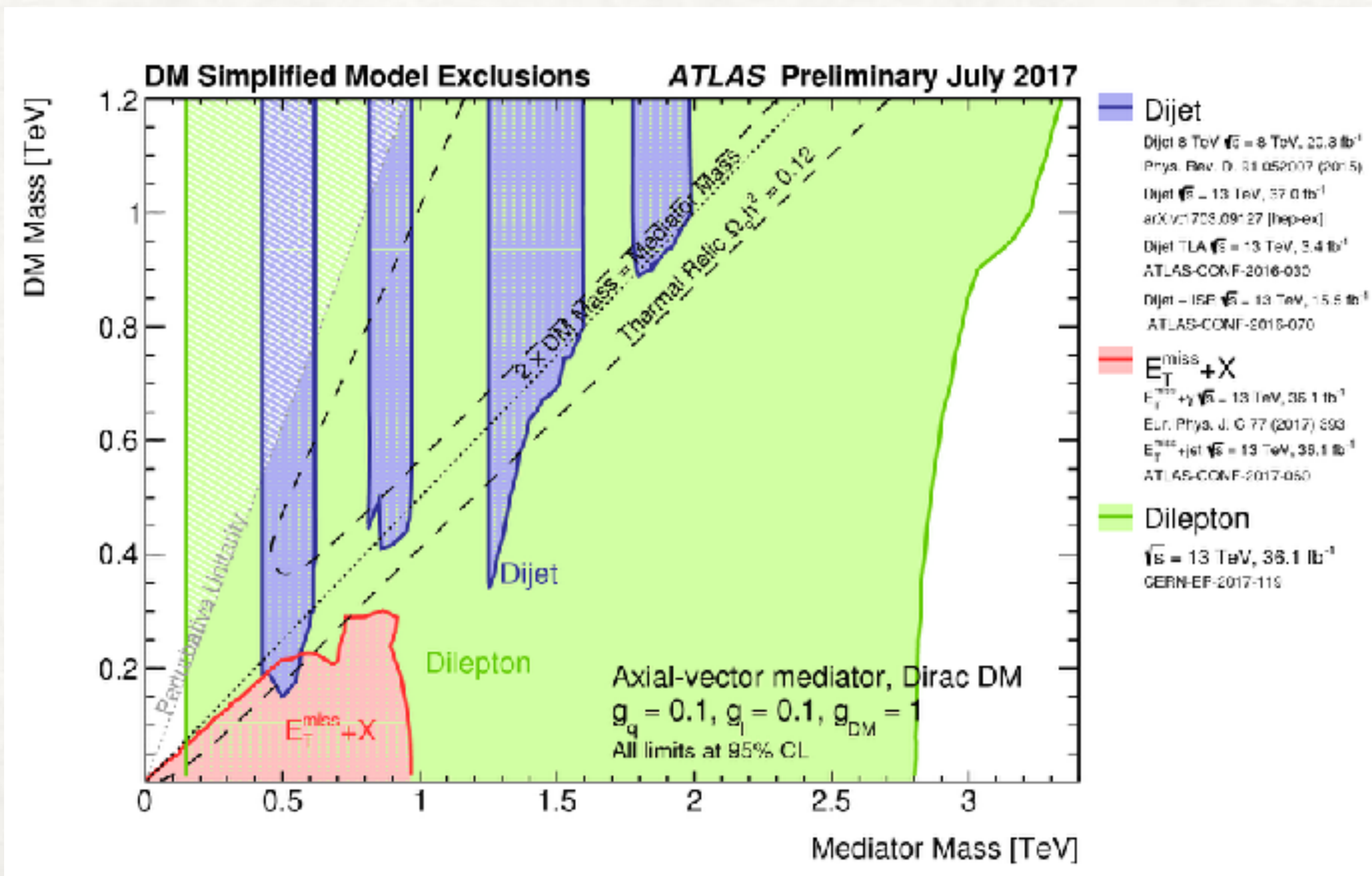
- EFT operator:

$$\mathcal{L}_{\rm eff} \supset \frac{c_{\tilde{t}\chi}}{\Lambda^2}(\bar{t}_R\chi)(\bar{\chi}t_R),$$

- Even worse behaviour for MET < M_{med} compared to normal t-channel
- Much better cross section in the mediator-pair production
- Best limits come from SUSY stop searches

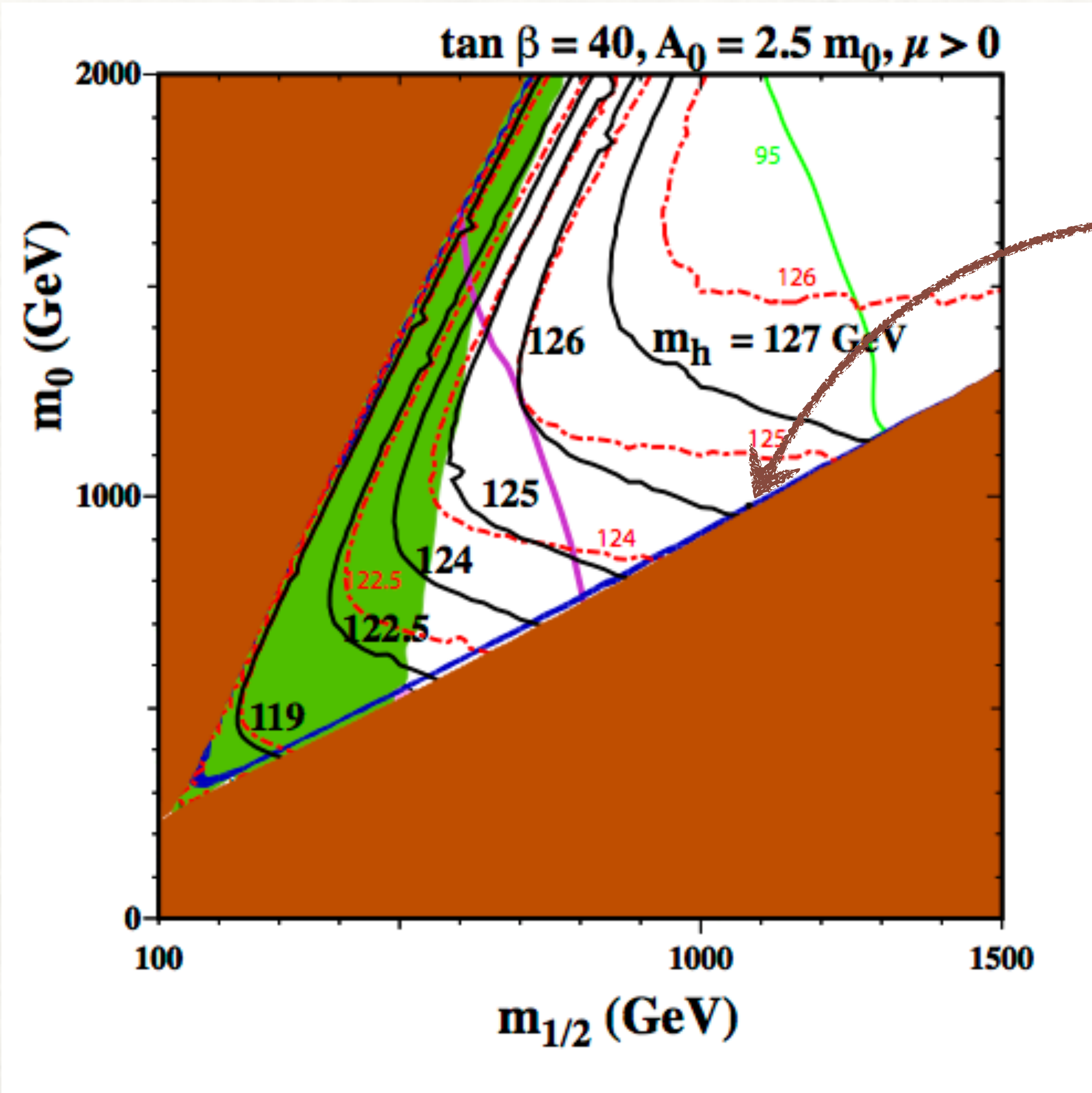
Desai, et al (2014)

LOOKING FOR THE MEDIATOR



STAU CO-ANNIHILATION

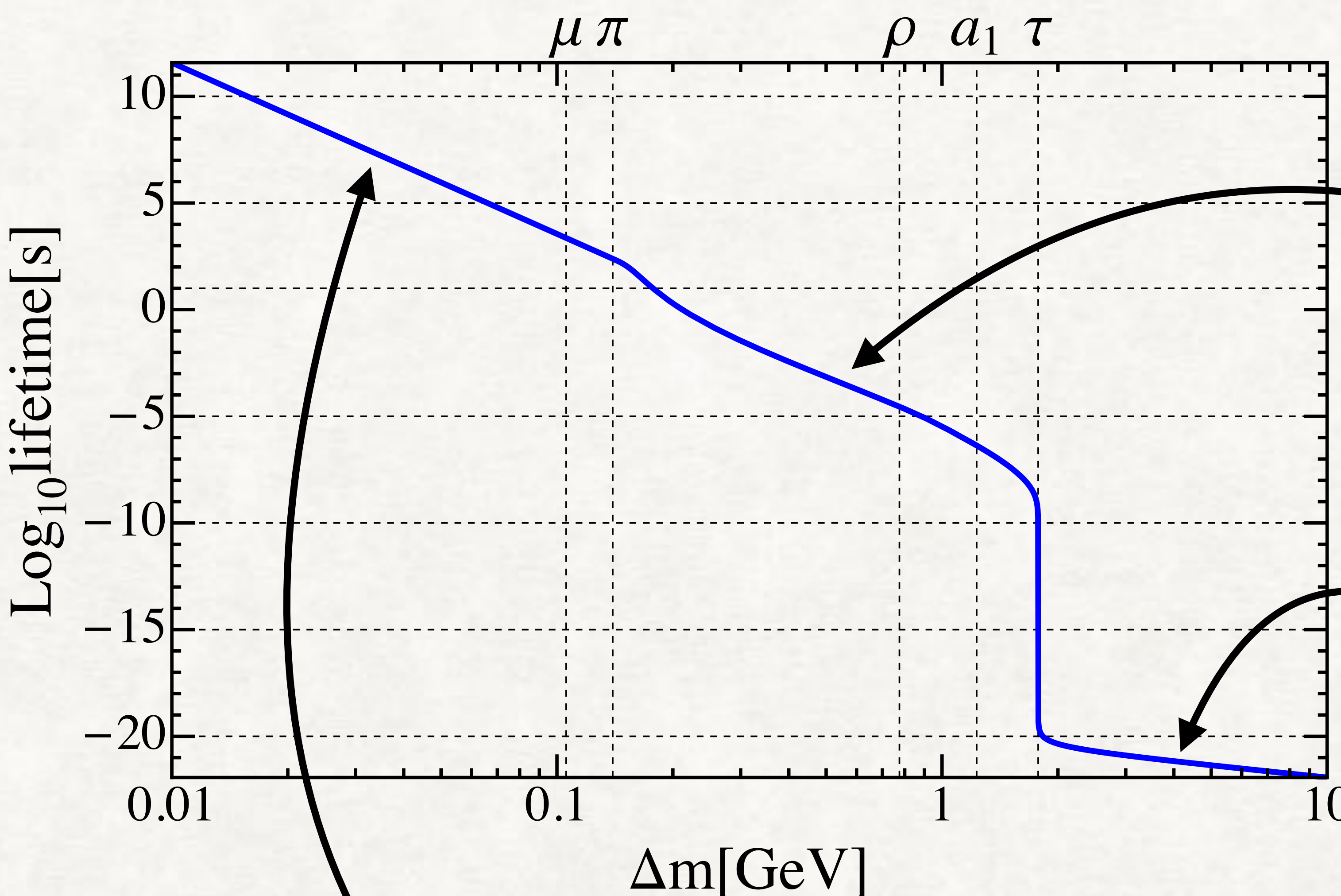
STAU CO-ANNIHILATION STRIP



Compressed stau and neutralino

Desai, et al (2014)

LIFETIME OF THE STAU



Combination of stable and disappearing tracks

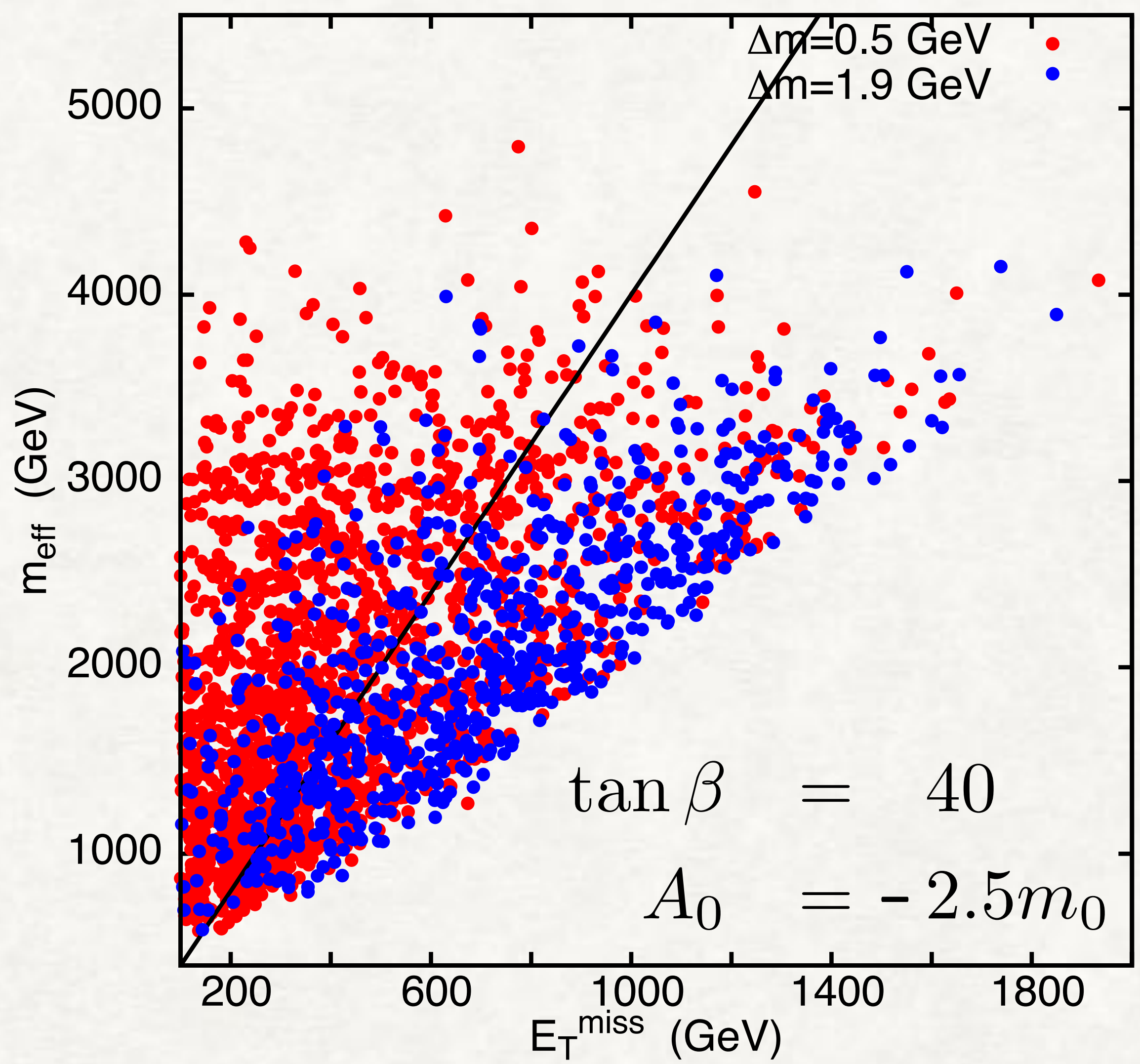
MET definitely works

Long-lived; charge tracks

Desai, et al (2014)

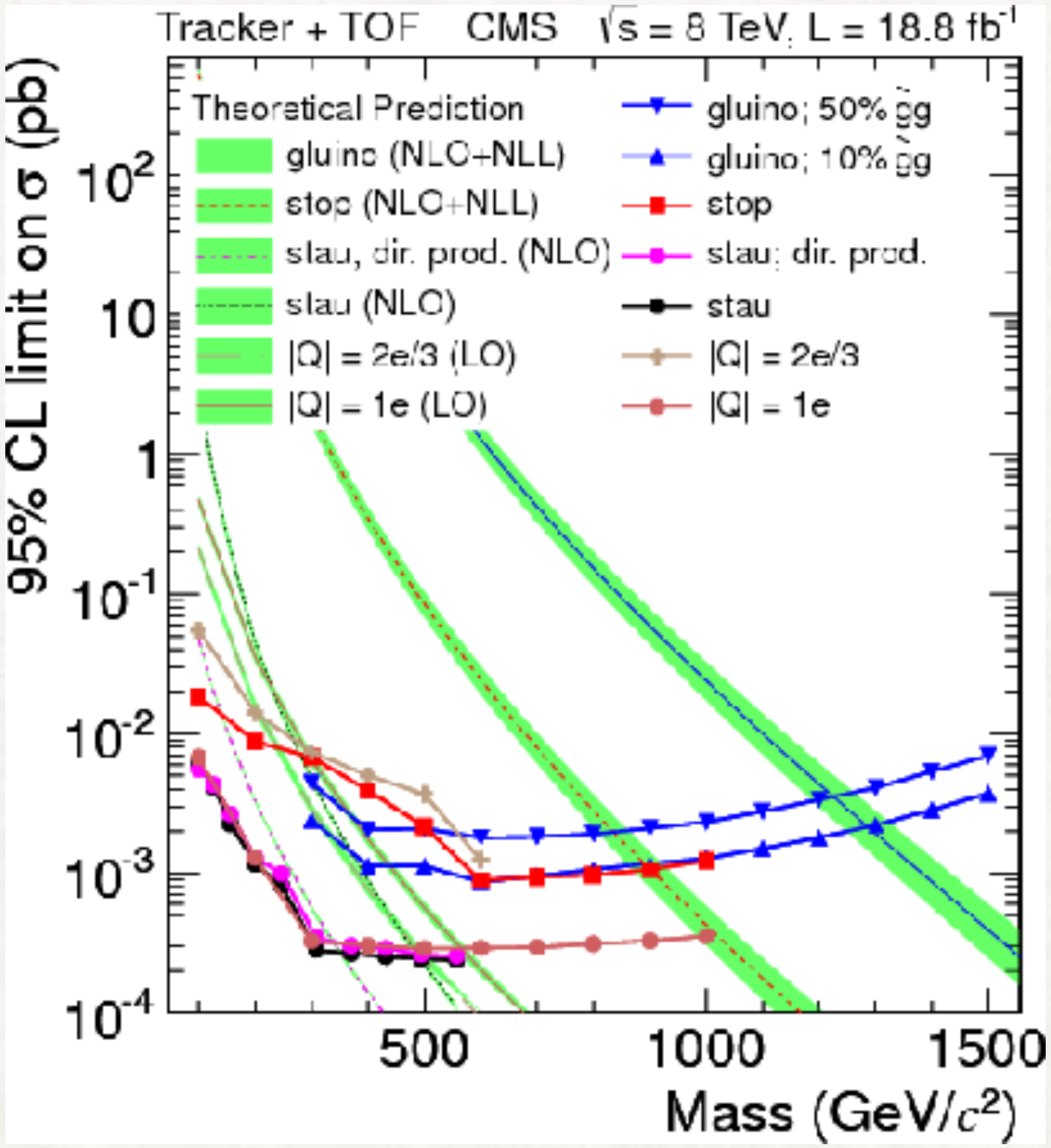
NOT ENOUGH MISSING ENERGY!

Requirement	Signal Region	
	2jW	**3j**
E_T^{miss}[GeV] >	160	
$p_T(j_1)$ [GeV] >	130	
$p_T(j_2)$ [GeV] >	60	
$p_T(j_3)$ [GeV] >		60
$p_T(j_4)$ [GeV] >		
$\Delta\phi(\text{jet}_{1,2,(3)}, \mathbf{E}_T^{miss})_{min} >$	0.4	
$\Delta\phi(\text{jet}_{i>3}, \mathbf{E}_T^{miss})_{min} >$		
W candidates	$2(W \to j)$	–
$E_T^{miss}/\sqrt{H_T}$ [GeV$^{1/2}$] >		
$E_T^{miss}/m_{eff}(N_j)$ >	0.25	0.3
m_{eff}(incl.) [GeV] >	1800	2200



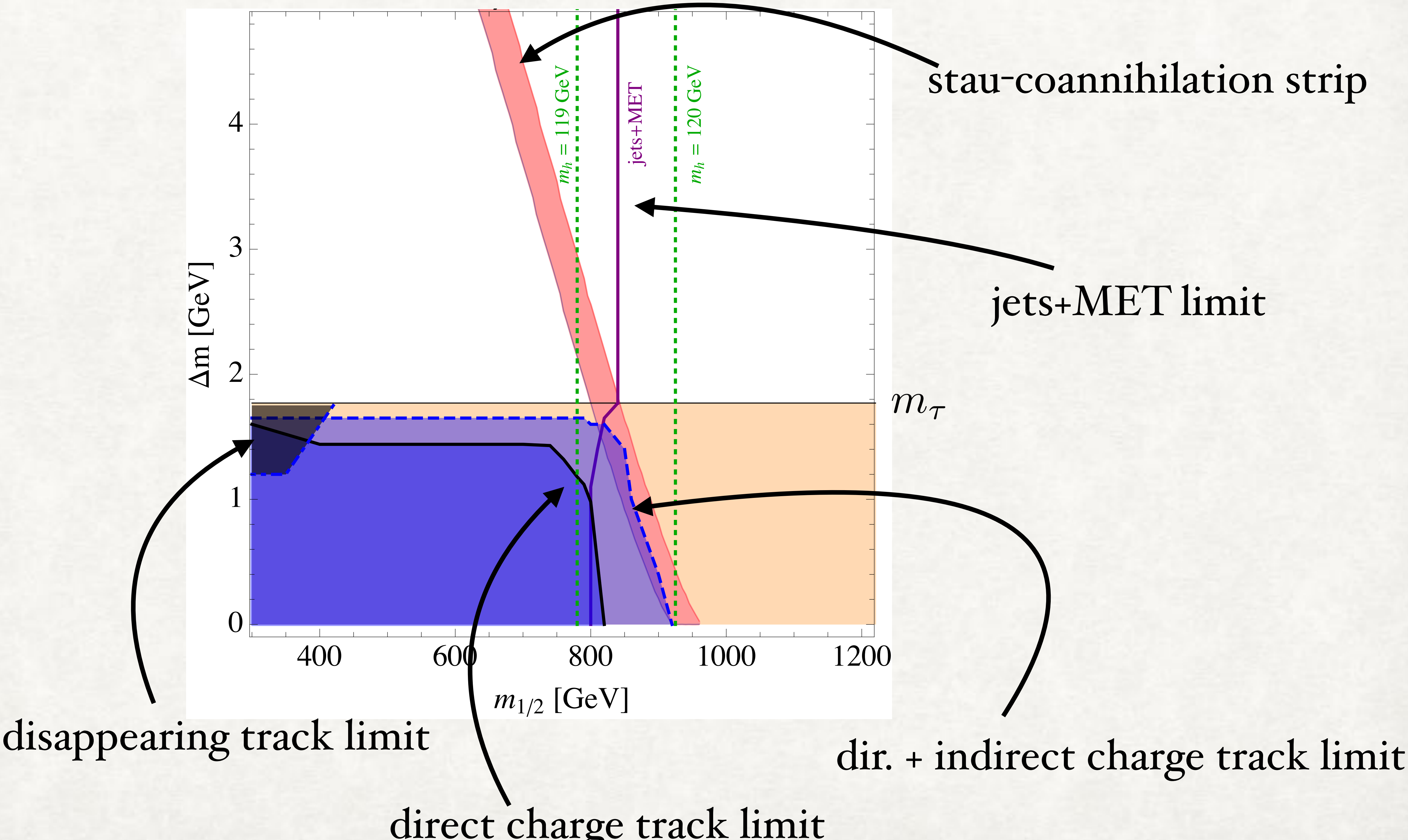
Desai, et al (2014)

LONG-LIVED CHARGE TRACKS



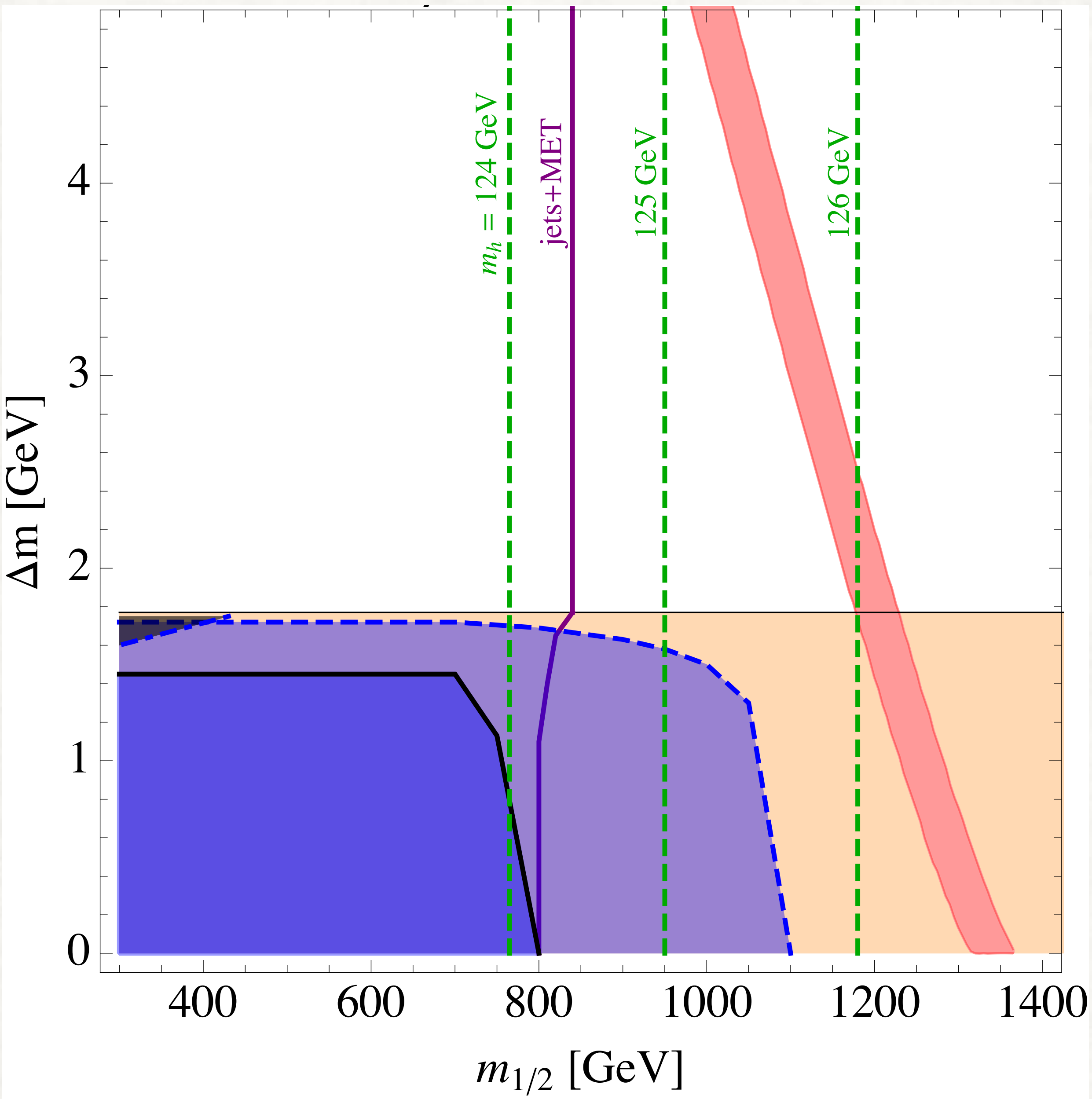
- Charged particle searches are specialised to take time of flight into account
- Fraction of staus that are stable on the detector scale decreases with increasing mass difference
- Run I limit on fully stable staus is ~550 GeV; since not all our staus exit the detector, we get a limit ~300 GeV.

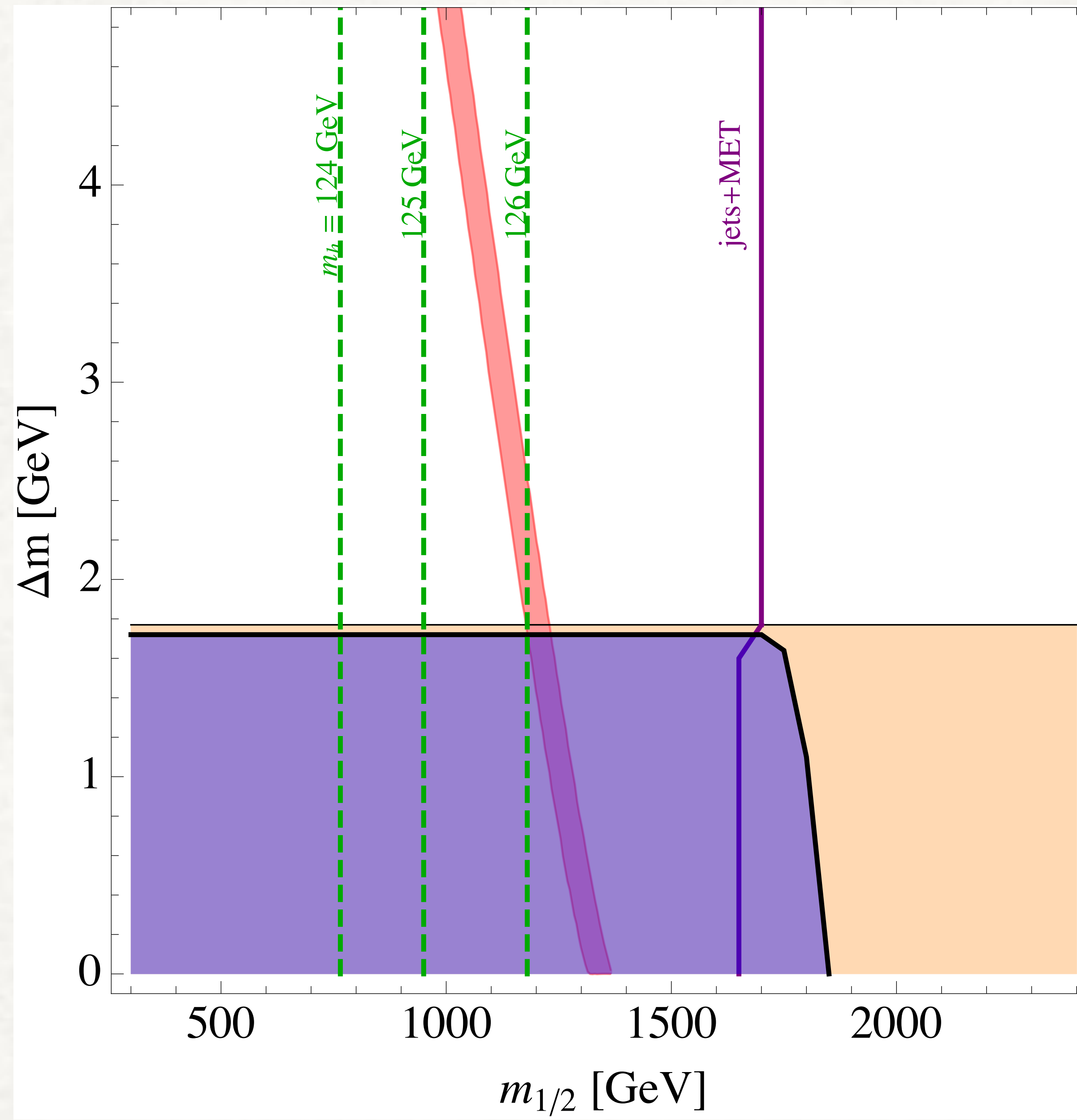
COMBINING MULTIPLE SEARCHES



Desai, et al (2014)

ELIMINATING STAU CO-ANNIHILATION





Coannihilation region not fully probed at 8 TeV; we await 13 TeV data results in this Winter to discover (or exclude!) the final part of the co-annihilation strip

Desai, et al (2014)

WELL-TEMPERED DM

HOW TO BUILD A "WELL-TEMPERED" MODEL?

- One SU(2) x U(1) singlet χ + one SU(2) N-plet ψ
- $\mathbb{Z}_2$ stabilises the lightest state
- Interactions with SM using Higgs-portal-like interactions

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

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

N=3

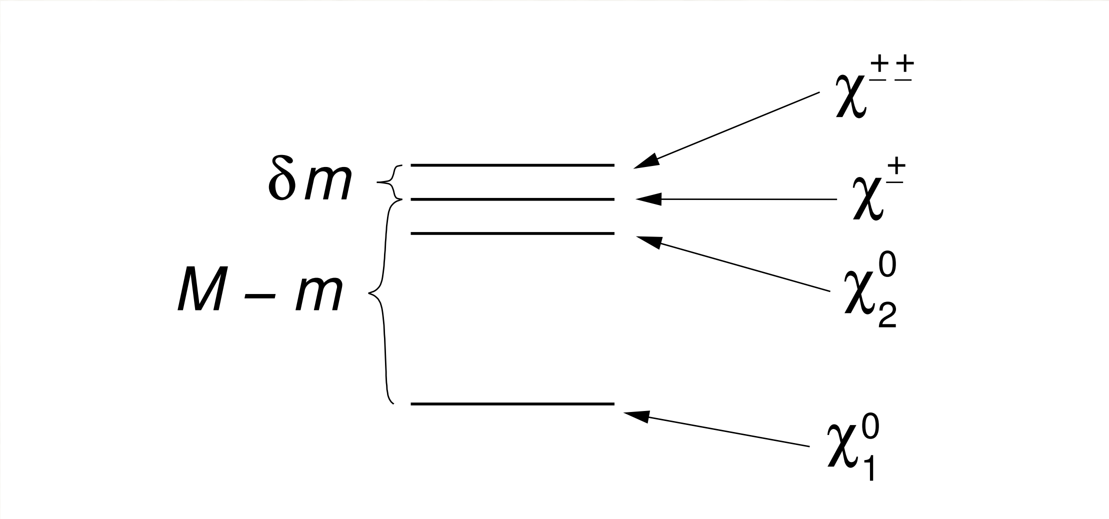
$$\mathcal{L}_{\rm mix} = \frac{\lambda}{\Lambda}\phi^\dagger\tau^a\phi\;\psi^a\chi + \text{ h.c.} \longrightarrow \theta \approx \frac{\sqrt{2}\lambda v^2}{\Lambda(M-m)}$$

N=5

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

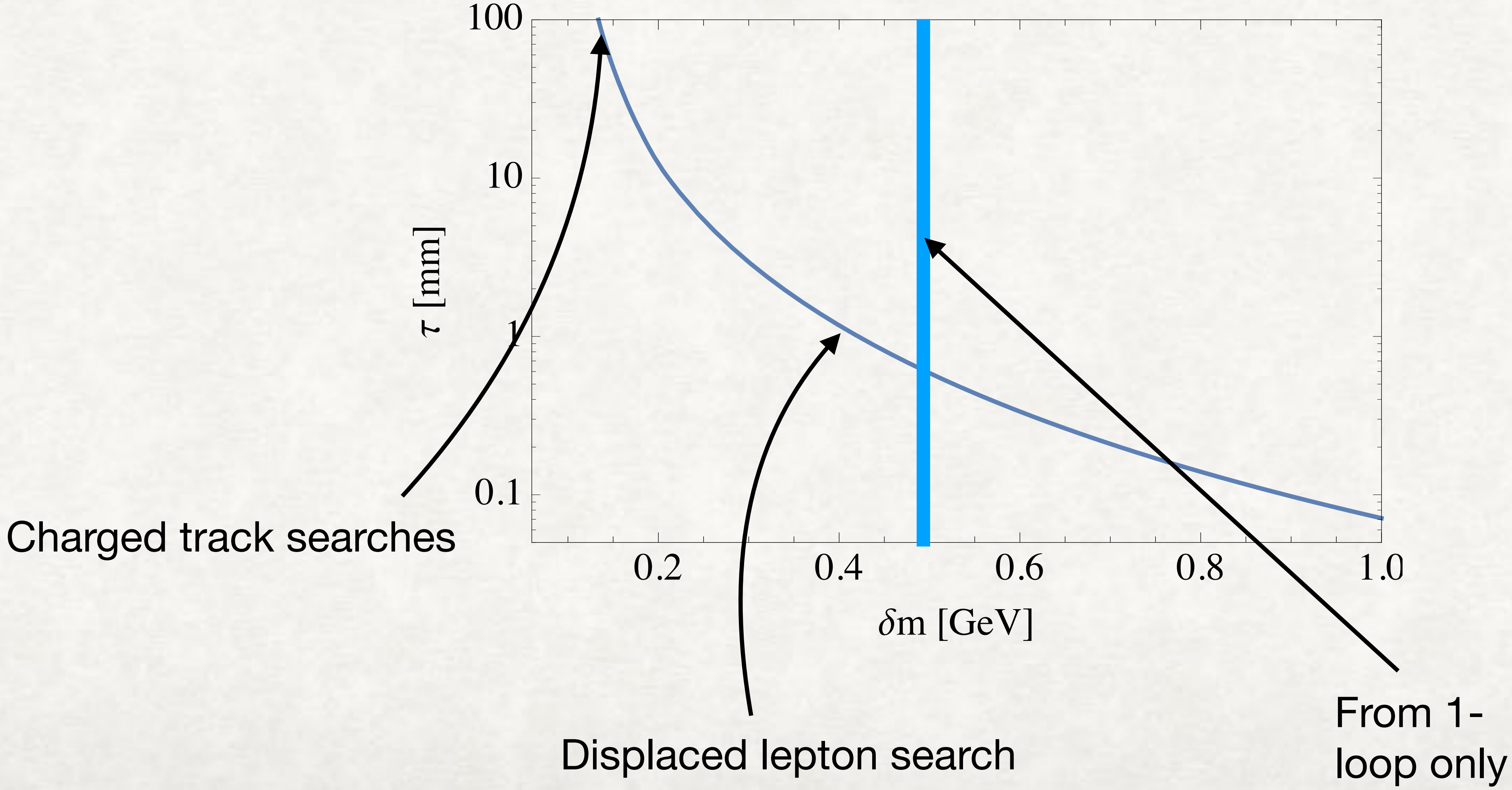
Bruemmer, Desai, Bharucha (in prep.)

POSSIBLE LHC SEARCHES: DISPLACED LEPTONS

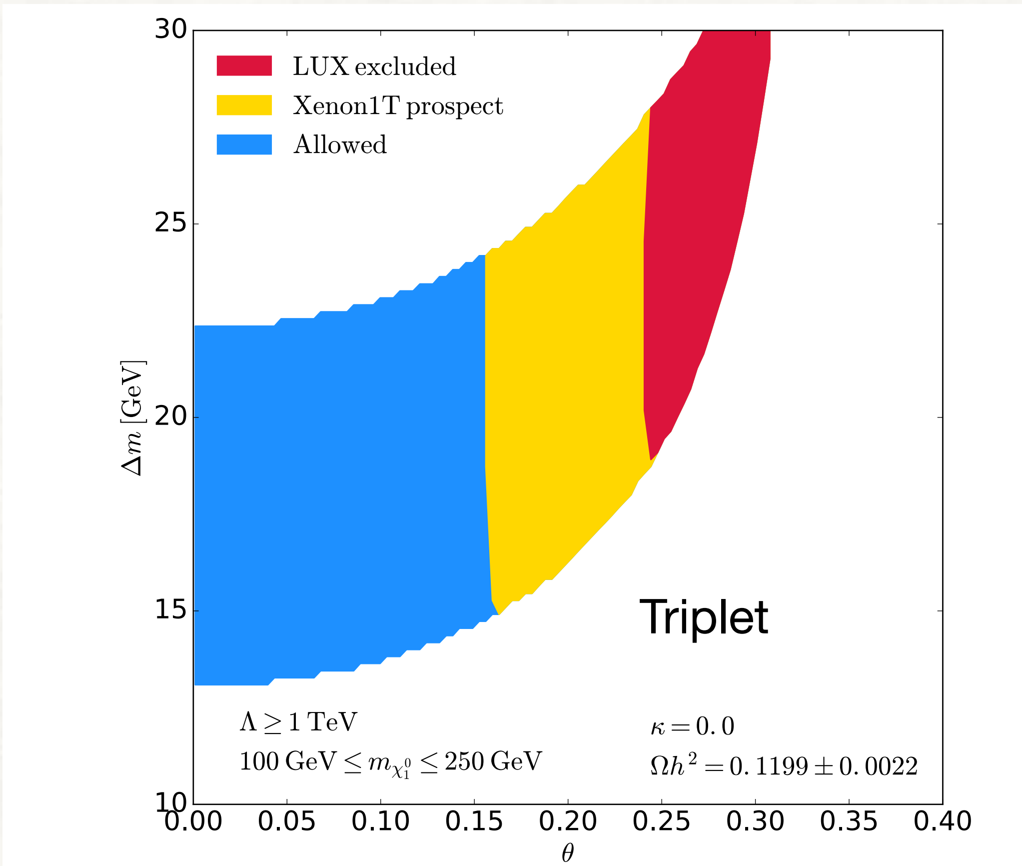


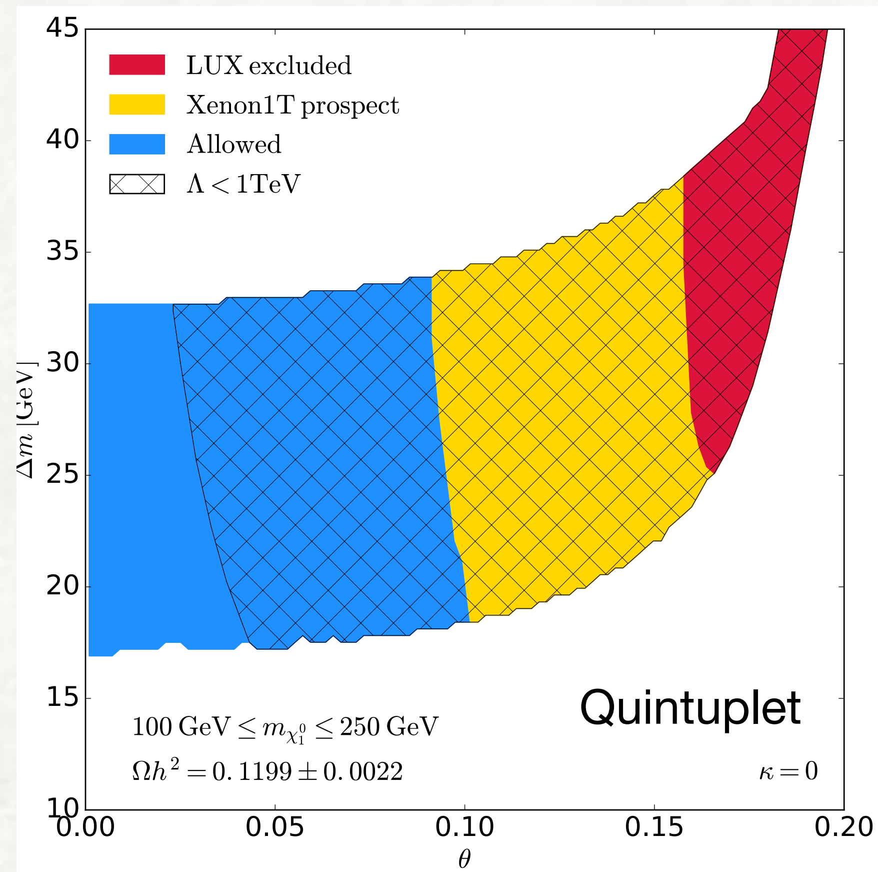
$$\chi^{++} \to \chi^{+}\pi^{+}$$
$$\chi^{+} \to \chi_1^0 W^* \to \ell\nu\chi_1^0$$
$$\chi_2^0 \to \chi_1^0 h^* \to b\bar{b}\chi_1^0$$

Large lifetime for the doubly charged partner



DIRECT DETECTION CONSTRAINTS

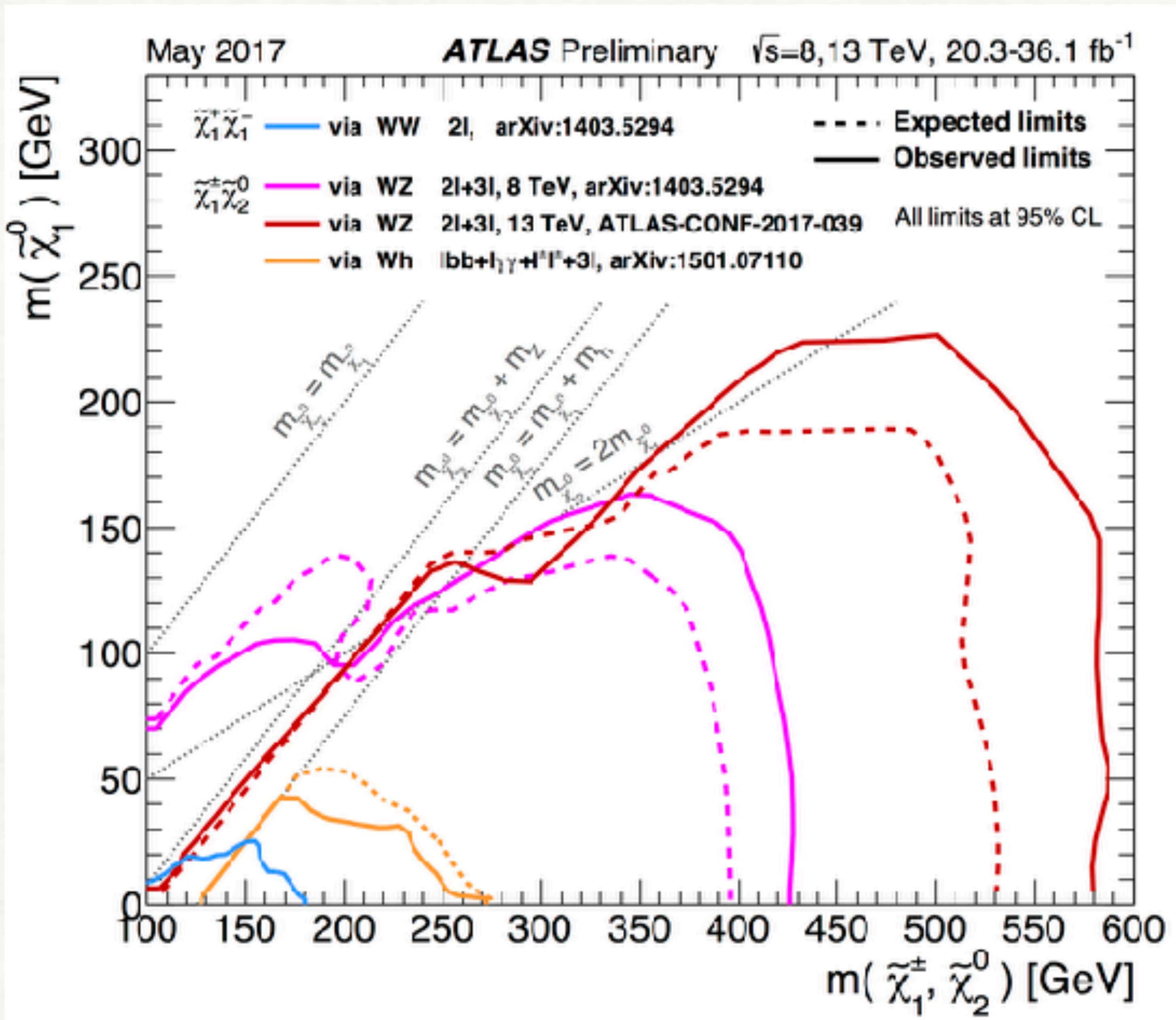




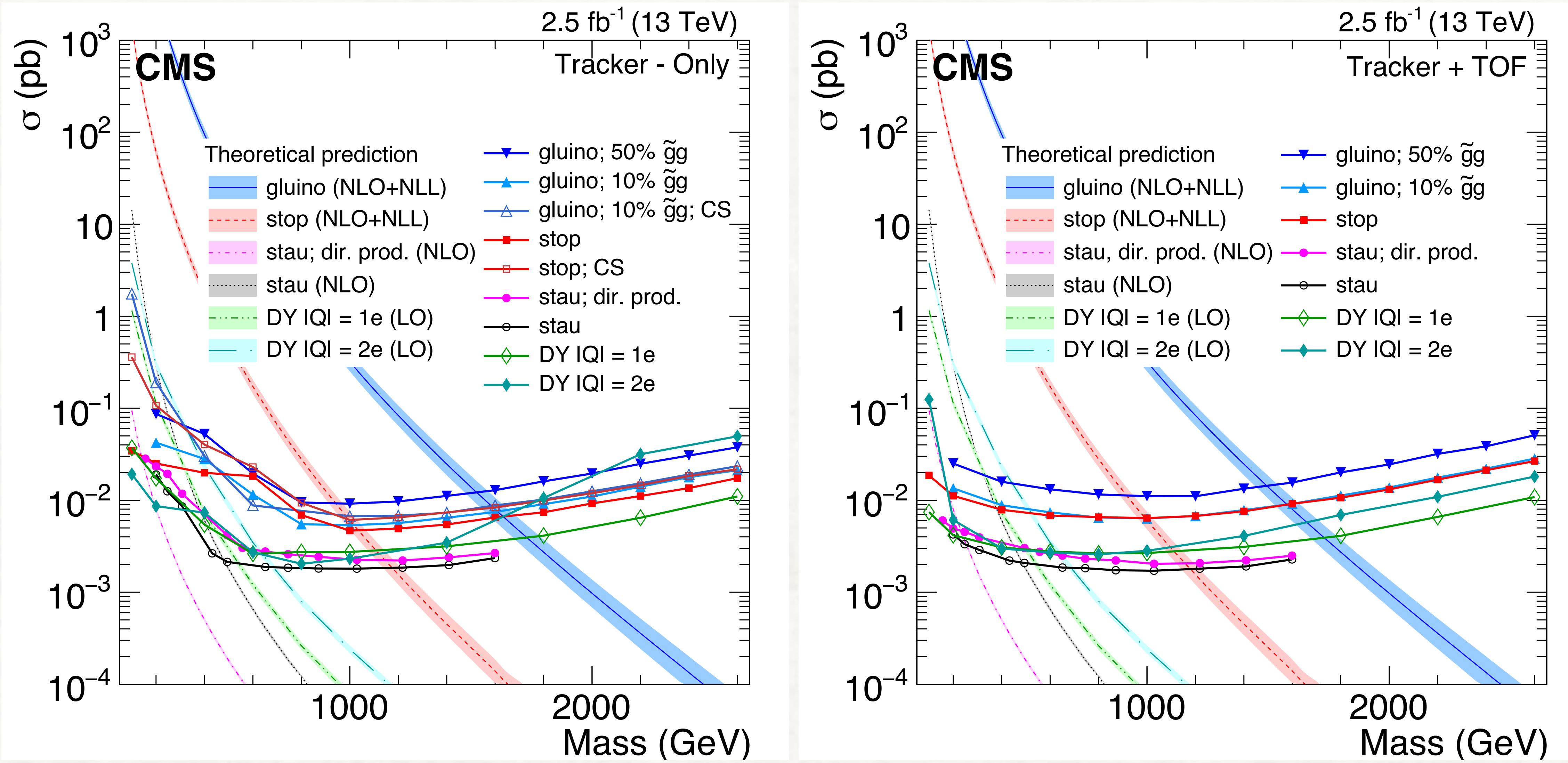
- Look at parameters that gives right relic density
- Low mixing angle gives low DD cross section; however, not a problem at the LHC because production is primarily Drell-Yan!

Bruemmer, Desai, Bharucha (in prep.)

POSSIBLE LHC SEARCHES: CHARGINOS



OTHER POSSIBLE LIMITS: CHARGED TRACK SEARCHES

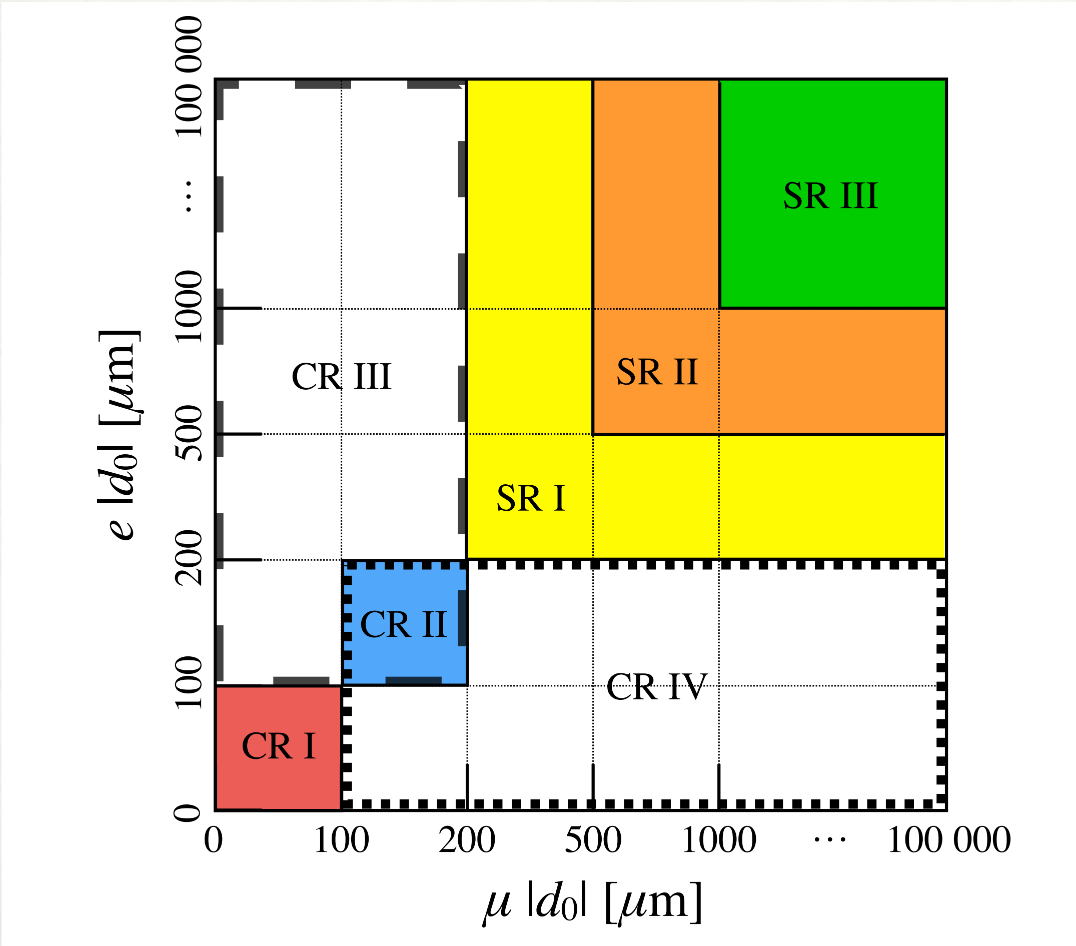


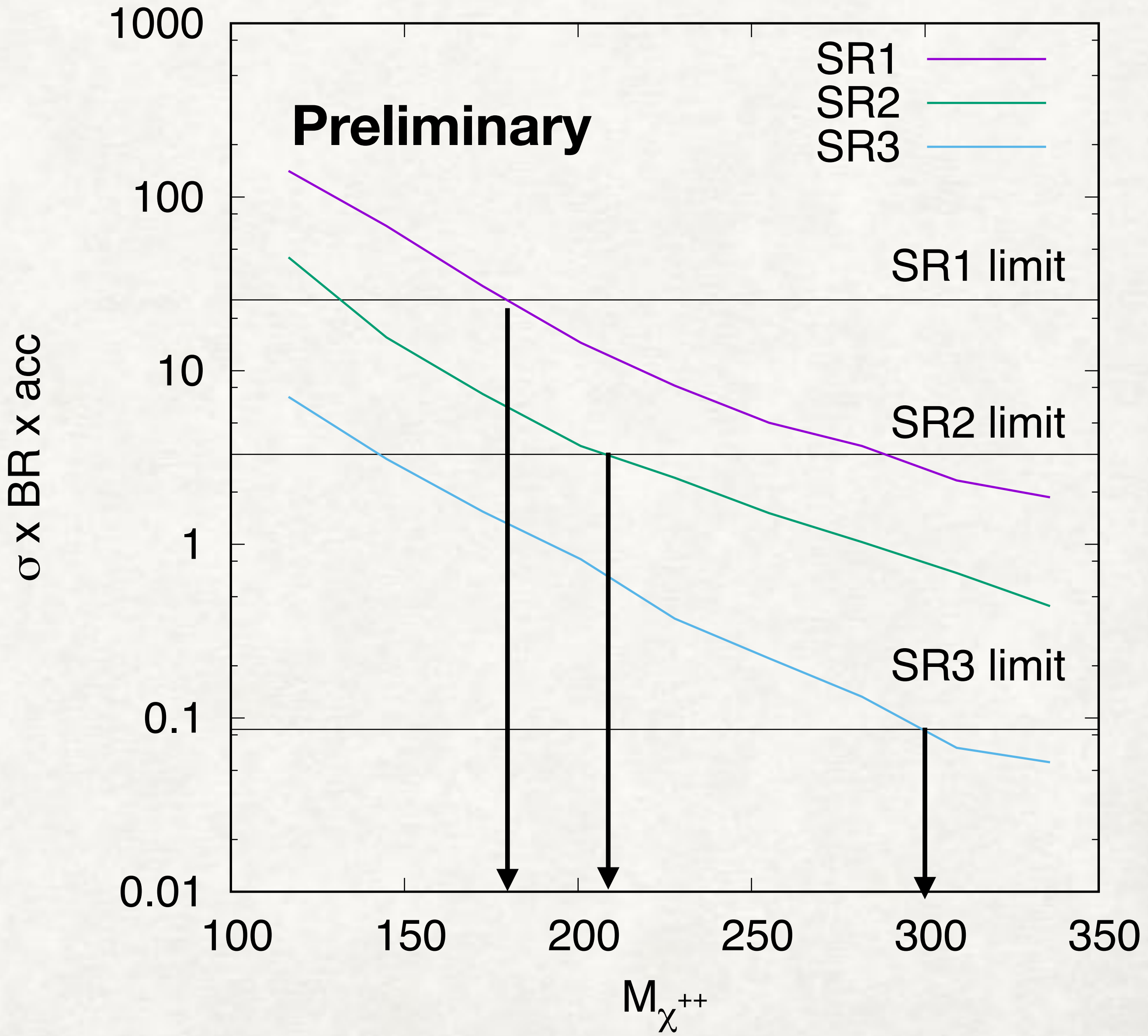
RESULTS FOR QUINTUPLET

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)

The CMS displaced lepton search (arXiv:1409.4789)





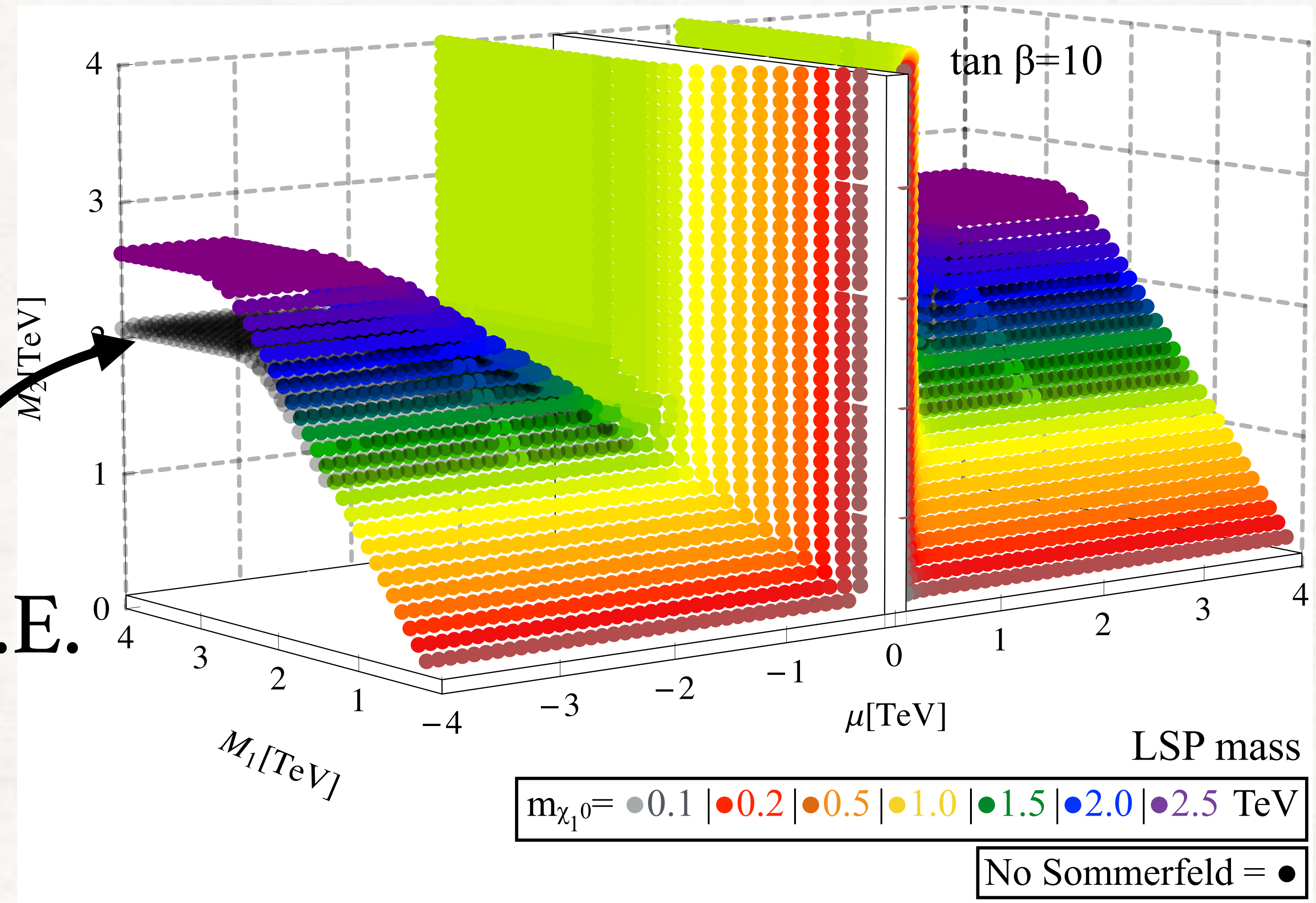
Bruemmer, Desai, Bharucha (in prep.)

UV-COMPLETE MODEL: SUPERSYMMETRY

SUPERSYMMETRIC PARAMETER SPACE

- What kinds of interactions?
- Co-annihilation
- Sommerfeld enhancement
- Direct detection constraints
- Indirect detection constraints

No S.E.



$$\Omega_{\tilde{W}} h^2 \simeq 0.12 \left(\frac{m_{\tilde{\chi}}}{2.1 \text{ TeV}}\right)^2 \xrightarrow{\text{SE}} 0.12 \left(\frac{m_{\tilde{\chi}}}{2.6 \text{ TeV}}\right)^2 .$$

$$\Omega_{\tilde{H}} h^2 \simeq 0.12 \left(\frac{m_{\tilde{\chi}}}{1.13 \text{ TeV}}\right)^2 \xrightarrow{\text{SE}} 0.12 \left(\frac{m_{\tilde{\chi}}}{1.14 \text{ TeV}}\right)^2 .$$

Bramante, Desai et al. (2015)

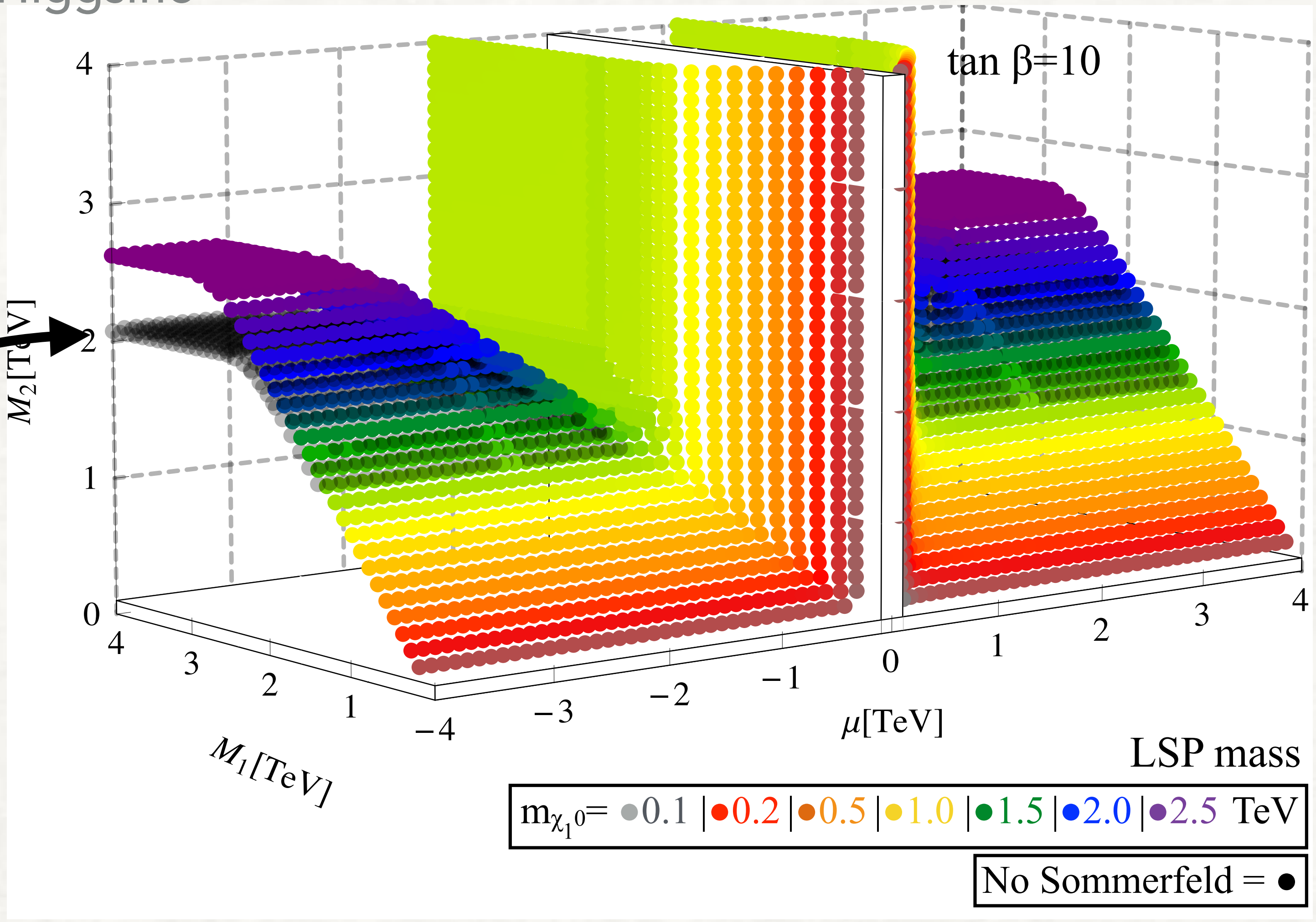
RELIC SURFACE WITH SE

M_1, M_2, μ, and $\tan\beta$

Bino Wino Higgsino

$$\Omega h^2 = 0.120 \pm 0.005$$

No S.E.

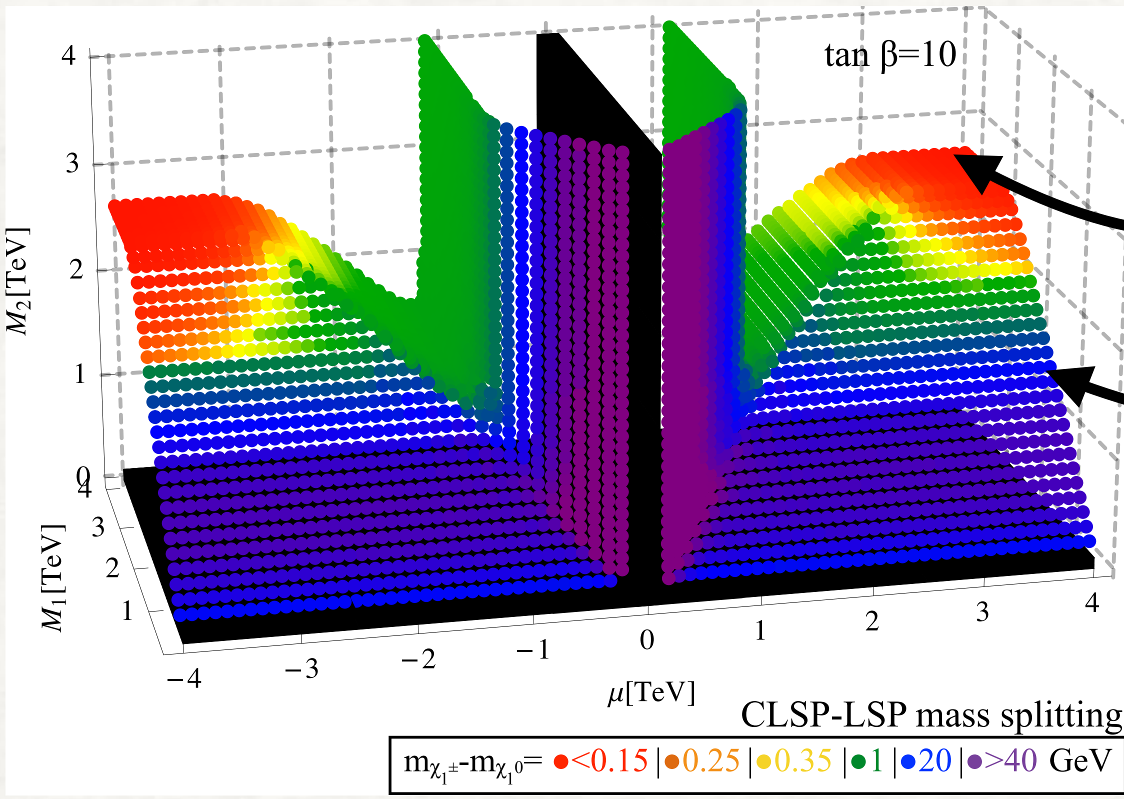


$$\Omega_{\tilde{W}} h^2 \simeq 0.12 \left(\frac{m_{\tilde{\chi}}}{2.1 \text{ TeV}}\right)^2 \xrightarrow{\text{SE}} 0.12 \left(\frac{m_{\tilde{\chi}}}{2.6 \text{ TeV}}\right)^2 .$$

$$\Omega_{\tilde{H}} h^2 \simeq 0.12 \left(\frac{m_{\tilde{\chi}}}{1.13 \text{ TeV}}\right)^2 \xrightarrow{\text{SE}} 0.12 \left(\frac{m_{\tilde{\chi}}}{1.14 \text{ TeV}}\right)^2 .$$

Bramante, Desai et al. (2015)

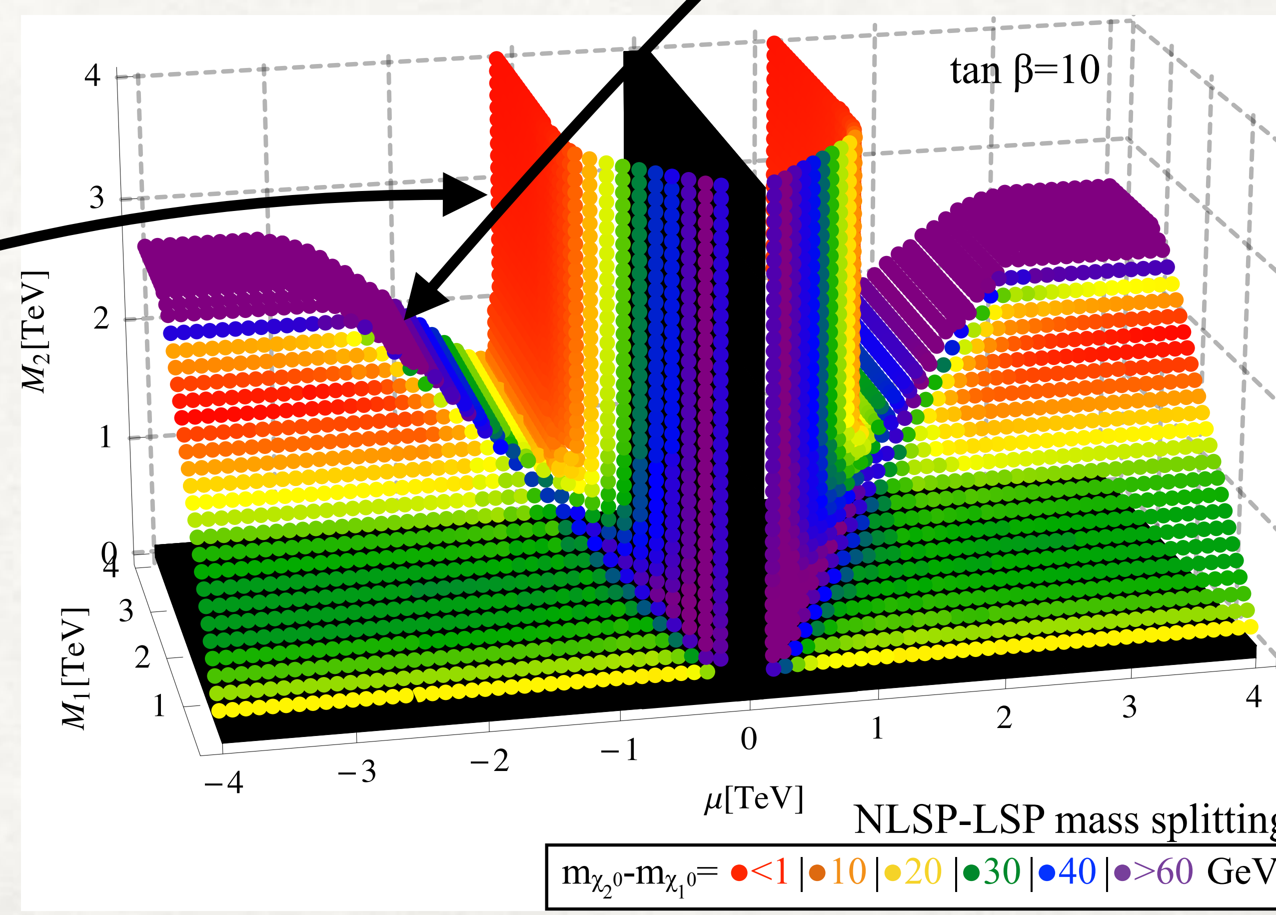
MASS SPLITTING



pure Wino => co-annihilation with chargino

Wino-Higgsinos

Bino-Winos



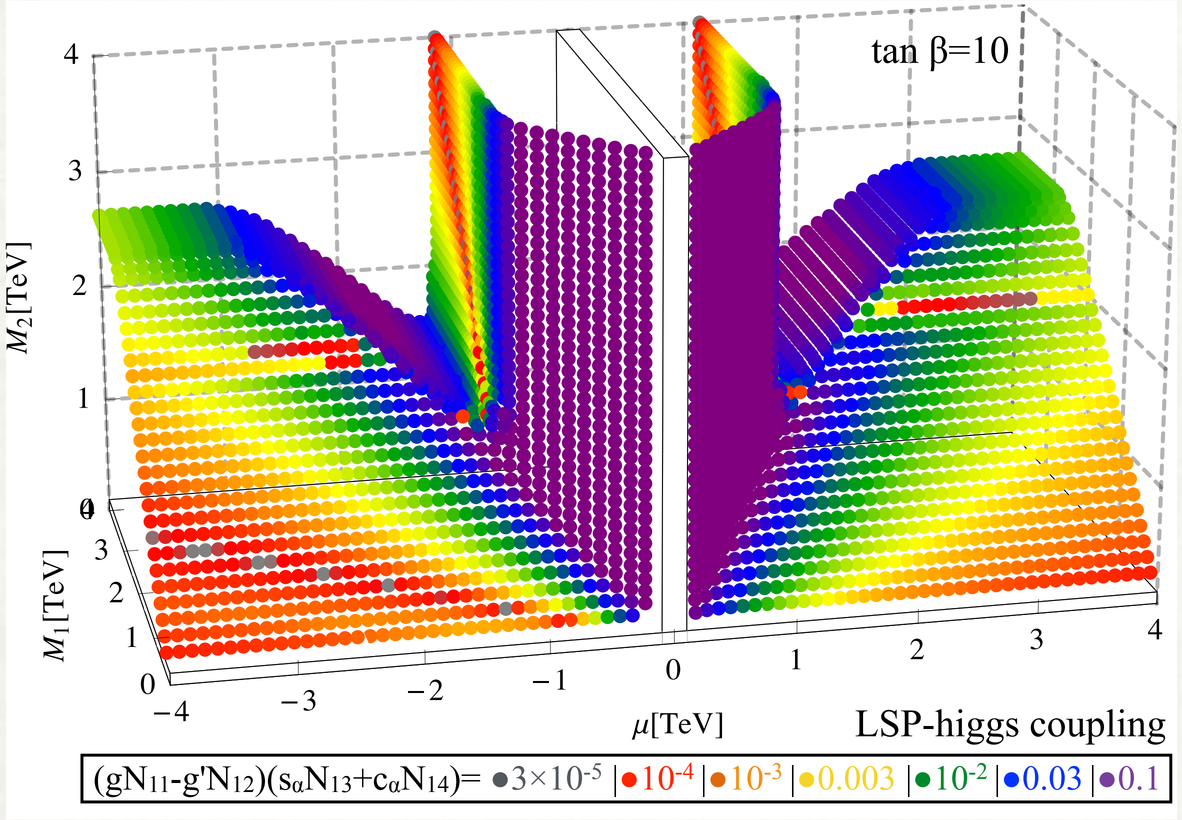
pure Higgsinos => co-annihilation with second neutralino + chargino

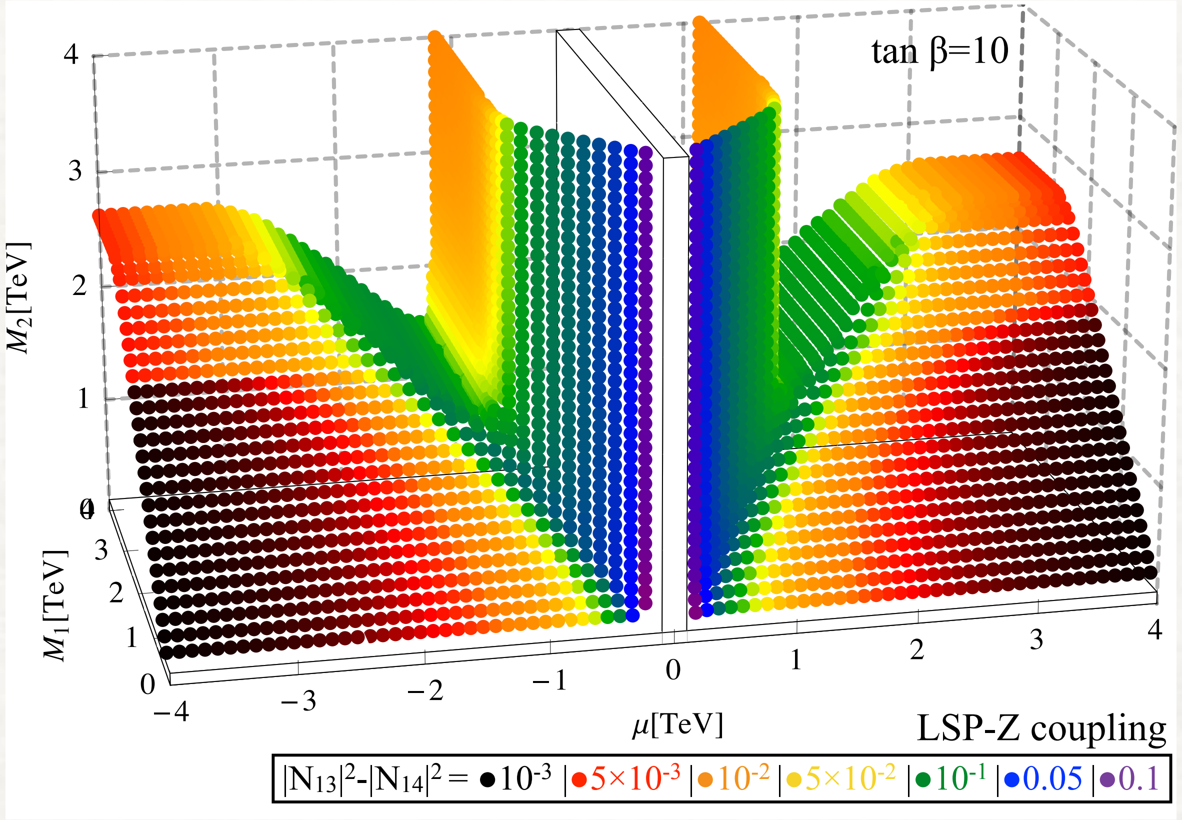
COUPLINGS

$$g_{Z\tilde{\chi}_1^0\tilde{\chi}_1^0} = \frac{g}{2\cos\theta_w} \left(|N_{13}|^2 - |N_{14}|^2\right)$$

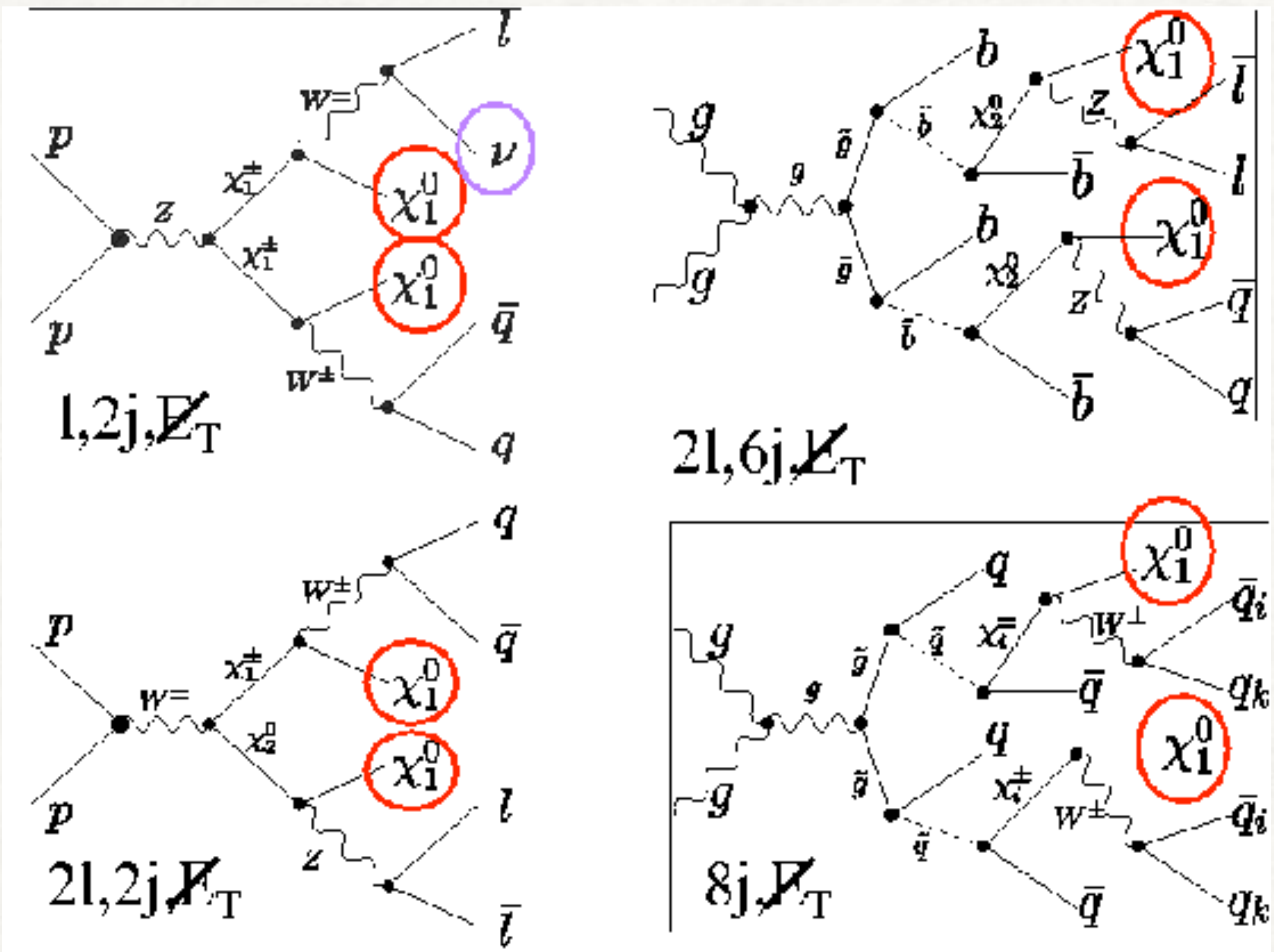
$$g_{h\tilde{\chi}_1^0\tilde{\chi}_1^0} = (gN_{11} - g'N_{12}) \; (\sin\alpha \; N_{13} + \cos\alpha \; N_{14})$$

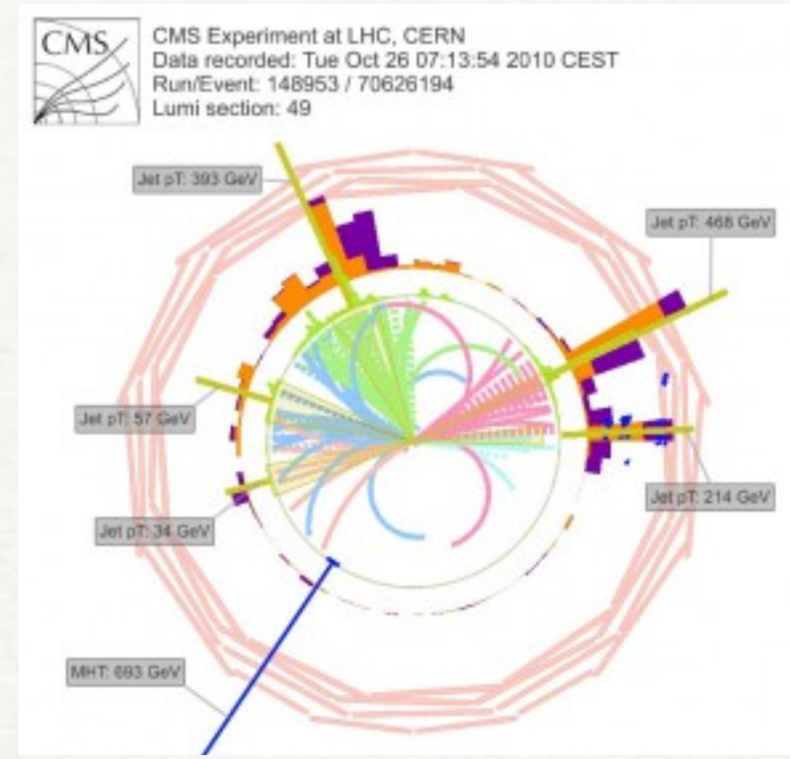
$$g_{W\tilde{\chi}_1^0\tilde{\chi}_1^+} = \frac{g\sin\theta_w}{\sqrt{2}\cos\theta_w} \left(N_{14}V_{12}^* - \sqrt{2}N_{12}V_{11}^*\right) \; ,$$





OBSERVING LSP PRODUCTION AT THE LHC: JETS + MET

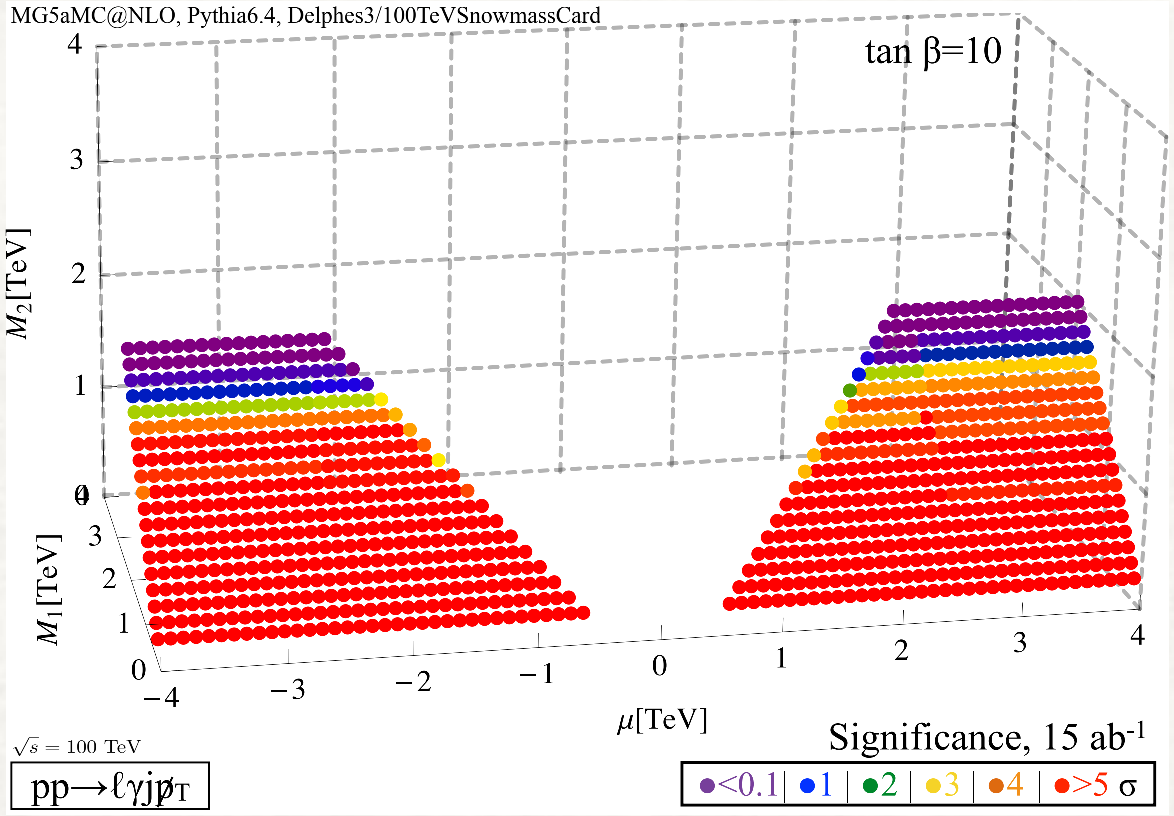


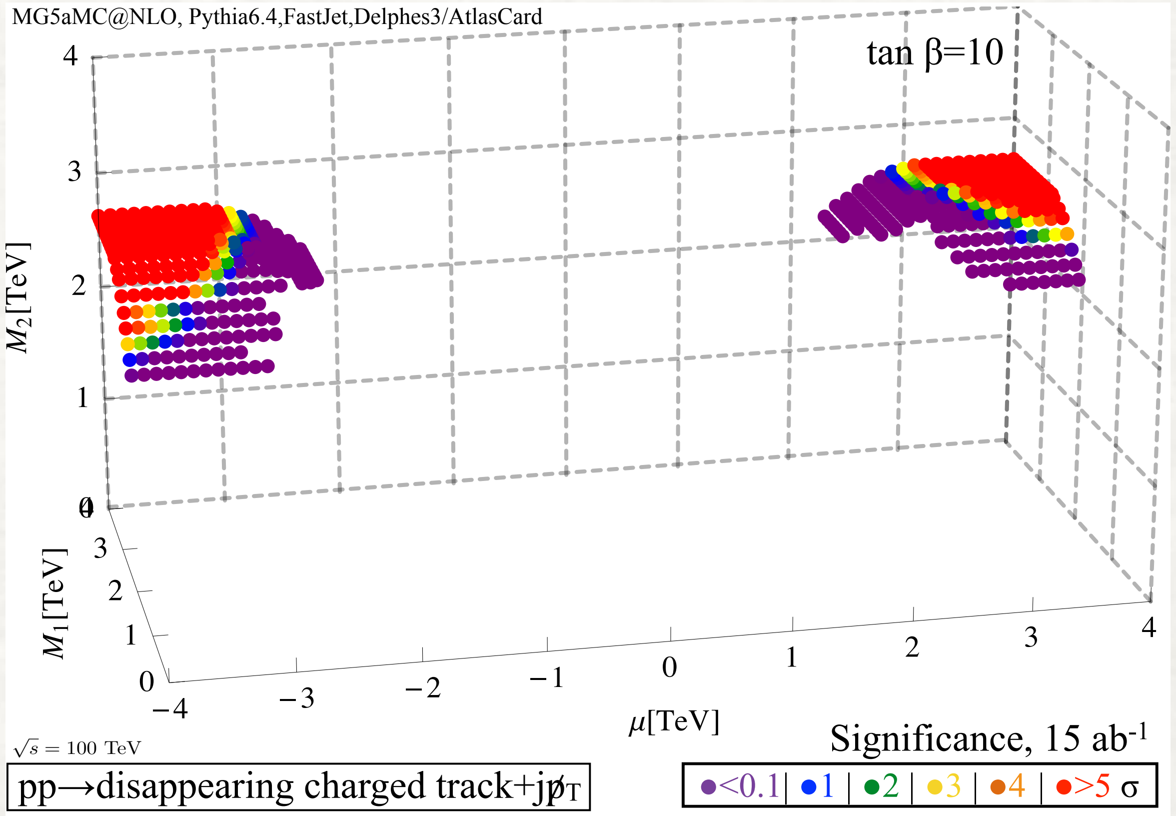


- Generic searches: jets + leptons + MET
- Compressed searches: soft jets/leptons, maybe photons, low MET (but have more background)

(POTENTIAL) COLLIDER SEARCHES

$$pp \to (\tilde{\chi}_2^0 \to \gamma \tilde{\chi}_1^0)\,(\tilde{\chi}_1^\pm \to \ell^\pm \nu_\ell \tilde{\chi}_1^0) j \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^\pm \nu_\ell \gamma j\,,$$

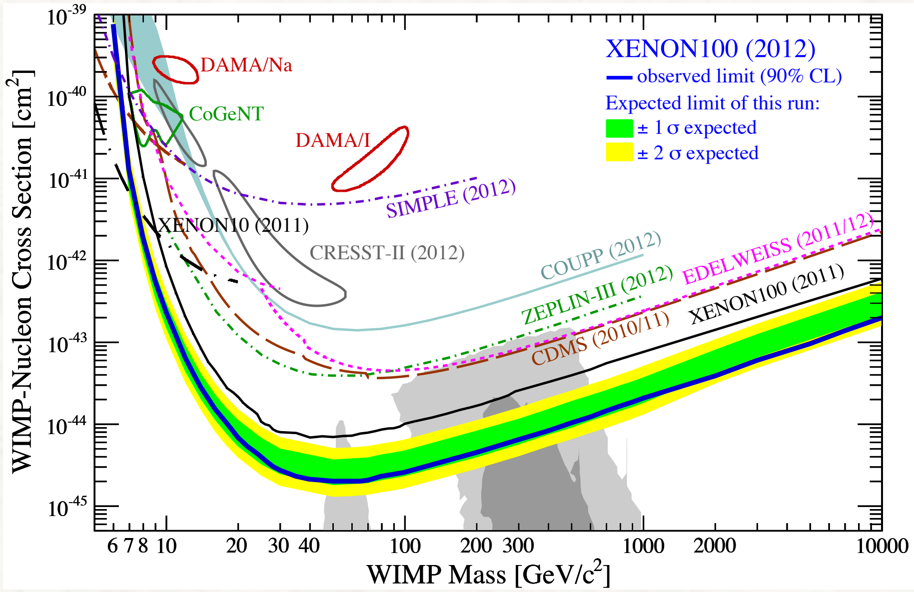


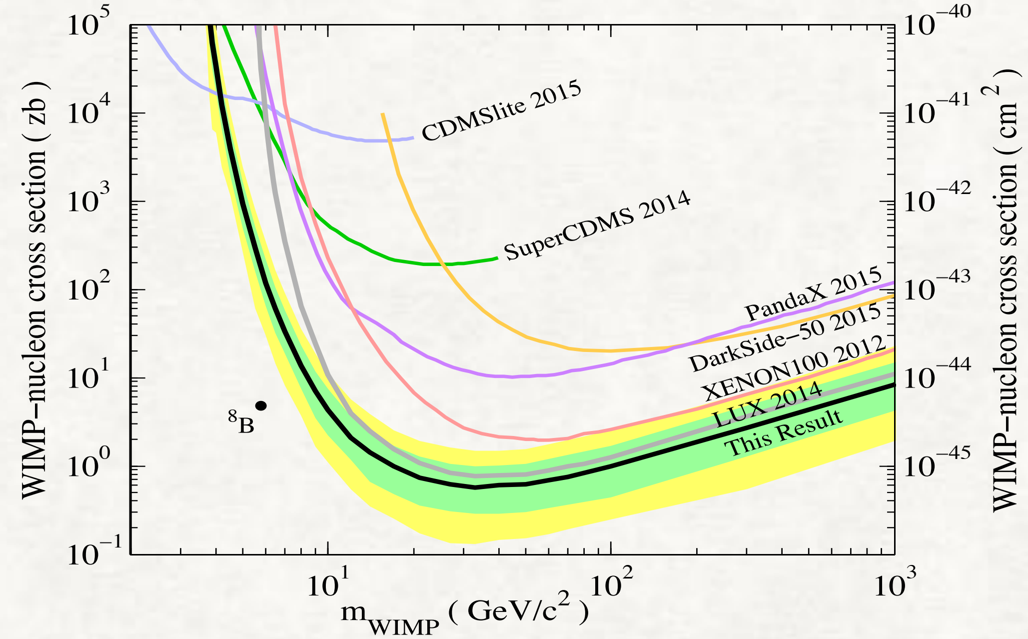


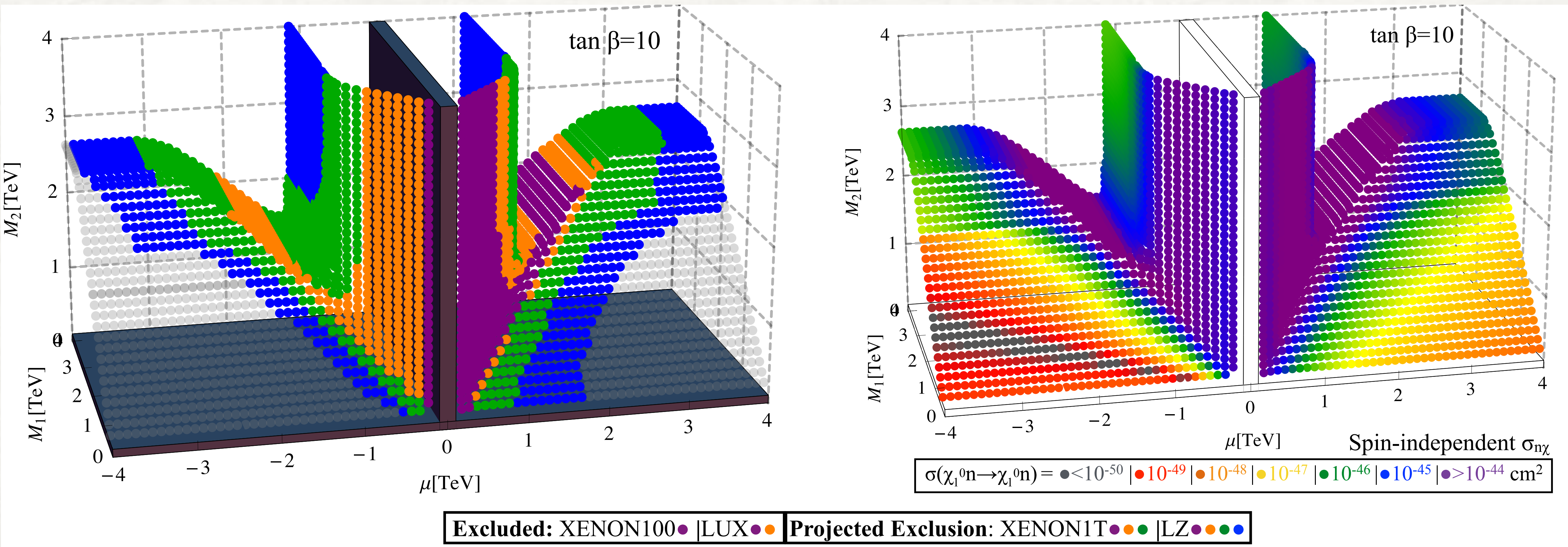
$$pp \to \chi_1^+ \chi_1^-\,,\ \chi_1^0 \chi_1^+$$

Bramante, Desai et al. (2015)

DIRECT DETECTION

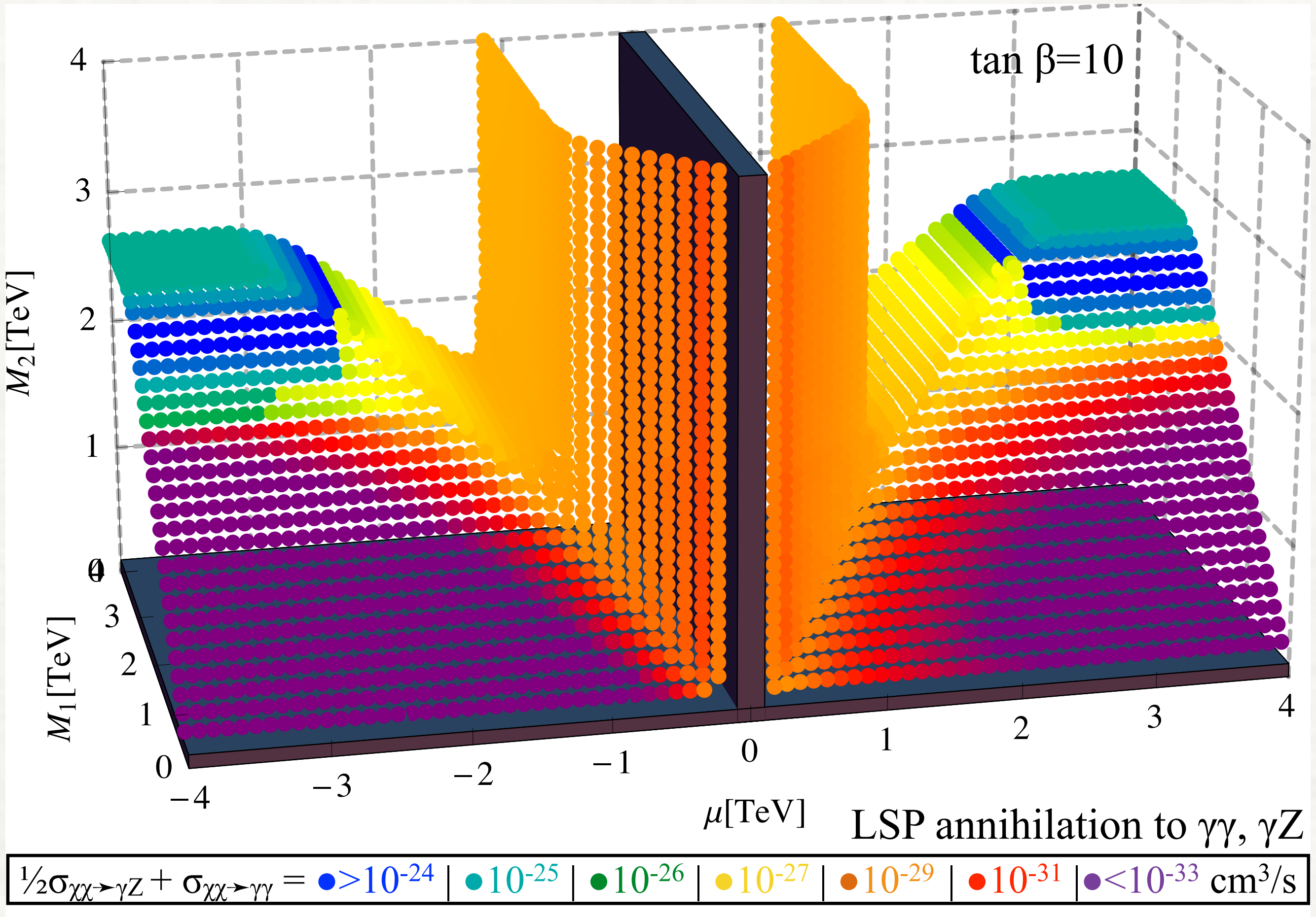


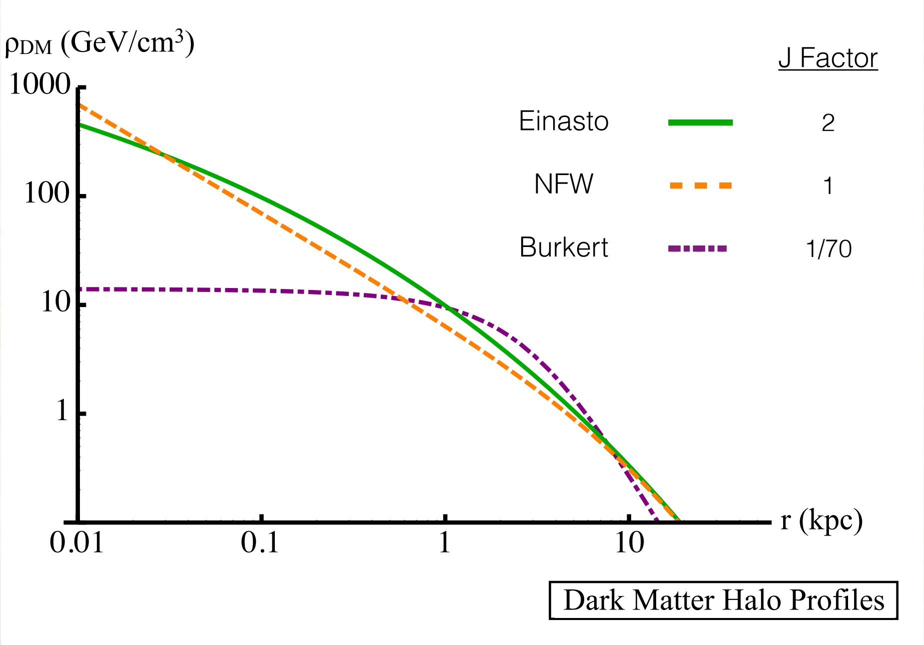




Bramante, Desai et al. (2015)

INDIRECT DETECTION



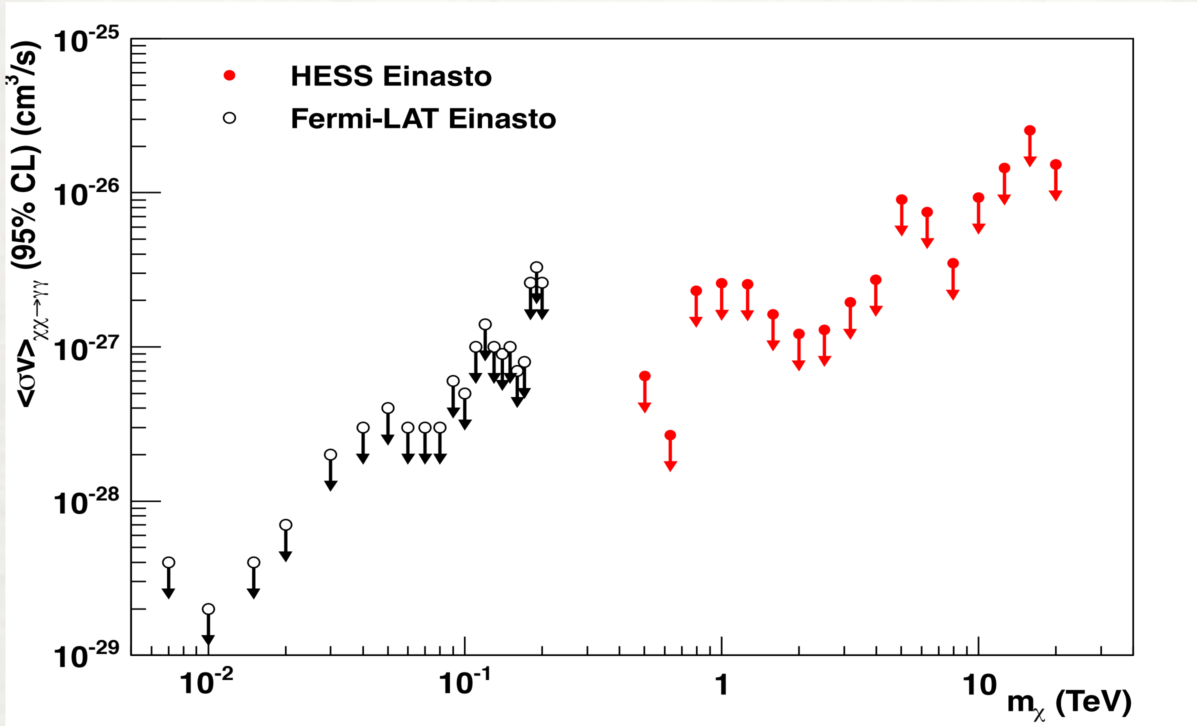


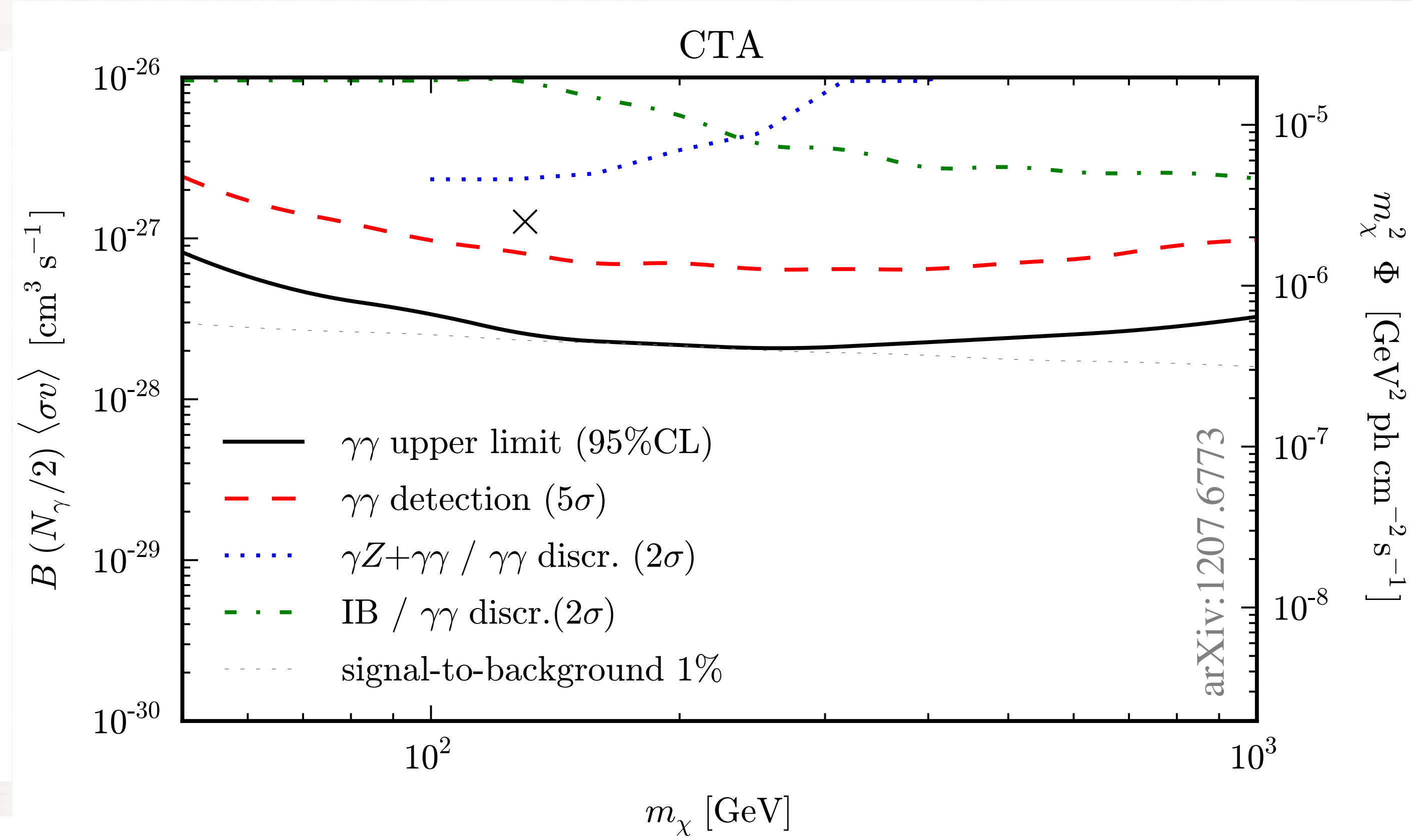
$$\rho_{\rm NFW}(r) = \frac{\rho_\odot}{(r/R)\,(1+r/R)^2},$$

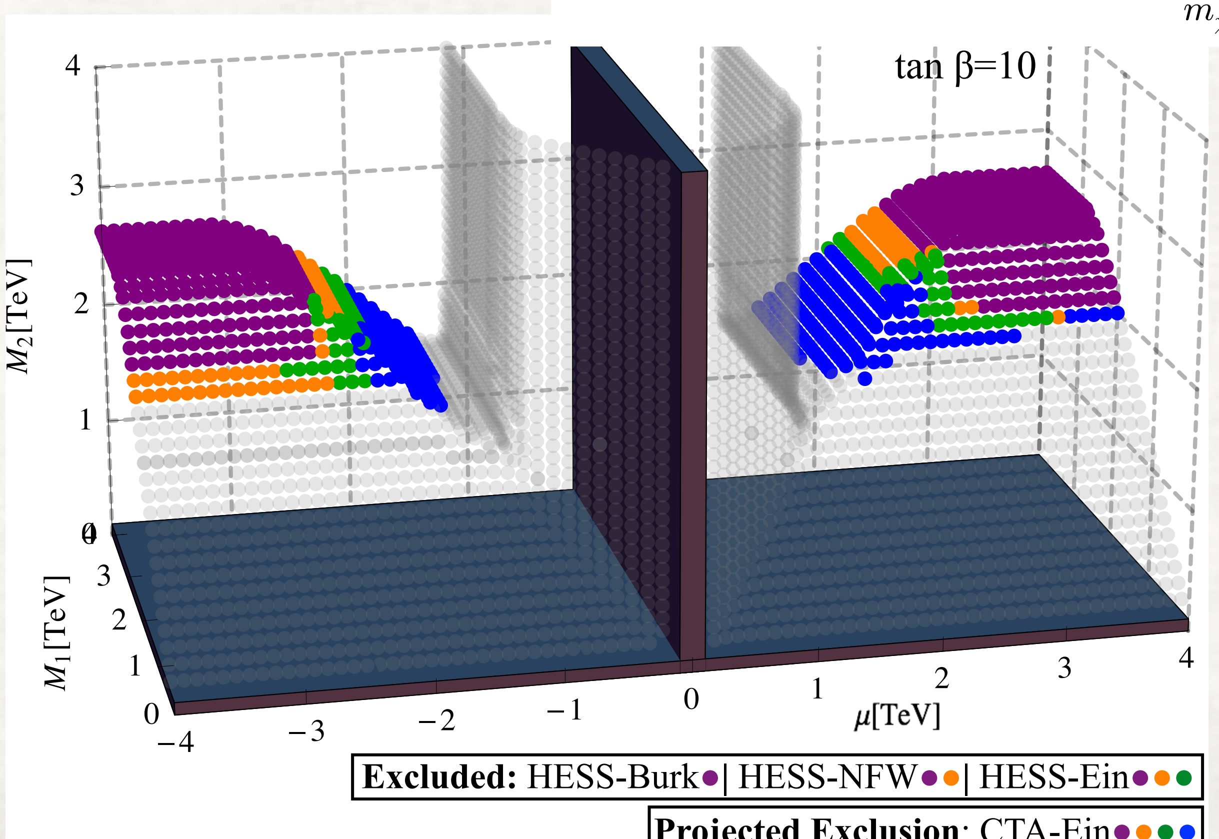
$$\rho_{\rm Ein}(r) = \rho_\odot\ \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{R}\right)^\alpha - 1\right)\right],$$

$$\rho_{\rm Burk}(r) = \frac{\rho_\odot}{(1+r/r_c)\,(1+(r/r_c)^2)},$$

ANNIHILATION INTO PHOTONS

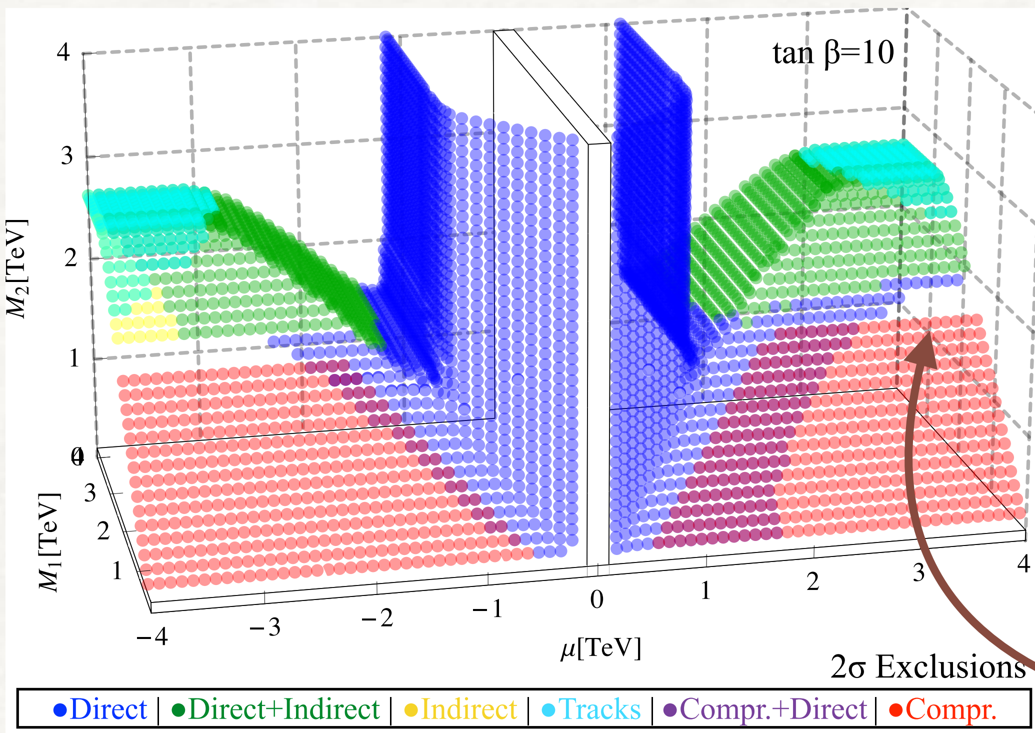






Bramante, Desai et al. (2015)

PUTTING IT ALL TOGETHER



- Pure winos can best be detected with tracks + indirect detection
- Pure Higgsinos as well as Wino-Higgsinos can be detected with direct (and/or) indirect detection
- Bino-Winos can only be detected with collider searches
- Last gap to be filled with displaced object searches?

ALMOST ALL OF SUSY DM CAN BE DETECTED WITHIN NEXT 10-20 YEARS ONLY IF WE HAVE A HIGHER ENERGY COLLIDER

Bramante, Desai et al. (2015)

FUTURE OF DM SEARCHES

- Collider searches are an important component to confirm DM, especially in case of WIMPs
- Simplified Models the way to go for searches, but mediator searches more constraining than direct DM production
- For weakly charged (i.e. SU(2) multiplet) DM, collider searches are crucial since not all parameter space can be probed by other techniques
- Long-lived particle searches needed to cover parameter space of many models
- A future collider would be necessary to completely rule out all SUSY parameter space