(Dis) appearing tracks at CLIC

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Physics at CLIC workshop
CERN
July 18, 2017

Outline

- Motivation for LLPs
- Signatures
- Disappearing tracks - LHC to CLIC
  - Side remark: above threshold reach at lepton coll.
- Appearing (emerging) tracks
  - Side remark: Id of exotic objects inside jets?

Lifetimes and track lengths

- Rest frame lifetime

$$\tau = \frac{\hbar}{\Gamma}$$

- Nominal decay length $\ell_0 = c\tau$

- Lab frame $\ell = \beta\gamma c\tau$

- To touch tracker

$$\text{cm - m} \;\sim\; (10^{-9} - 10^{-7})\,\frac{1}{\text{eV}}$$

Small coupling or small phase space!

Lifetimes and track lengths

- Decay law

$$N(d) = N_0\, e^{-d/\ell}$$

$$dN(d) \propto -\frac{1}{\ell} N(d)$$

- Long lifetime

$$N_{\text{tracker}} \sim \frac{\text{meter}}{\ell}$$

- Short lifetime

$$N_{\text{tracker}} \sim e^{-\frac{\text{few cm}}{\ell}}$$

More boost beats more luminosity (enters exponent)!

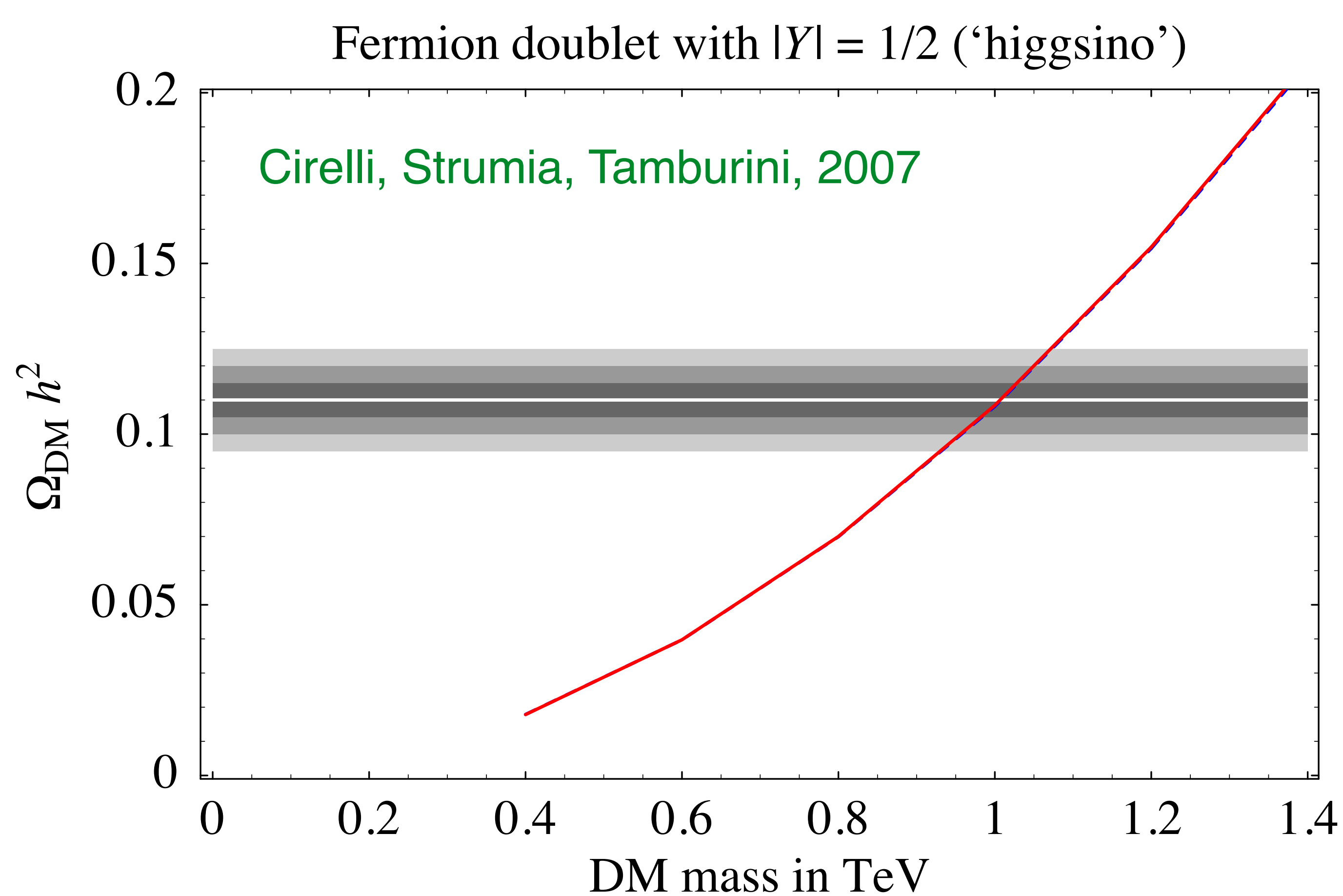
Motivation

- Minimal models (of dark matter)
- Freeze in (dark matter)
- Dark Sectors (dark matter)
- Twin Higgs (dark matter?)
- RPV SUSY

Minimal (Higgsino) DM

- SM + single weak multiplet (with neutral state)
- Relic abundance function of mass only
- Radiative mass splitting

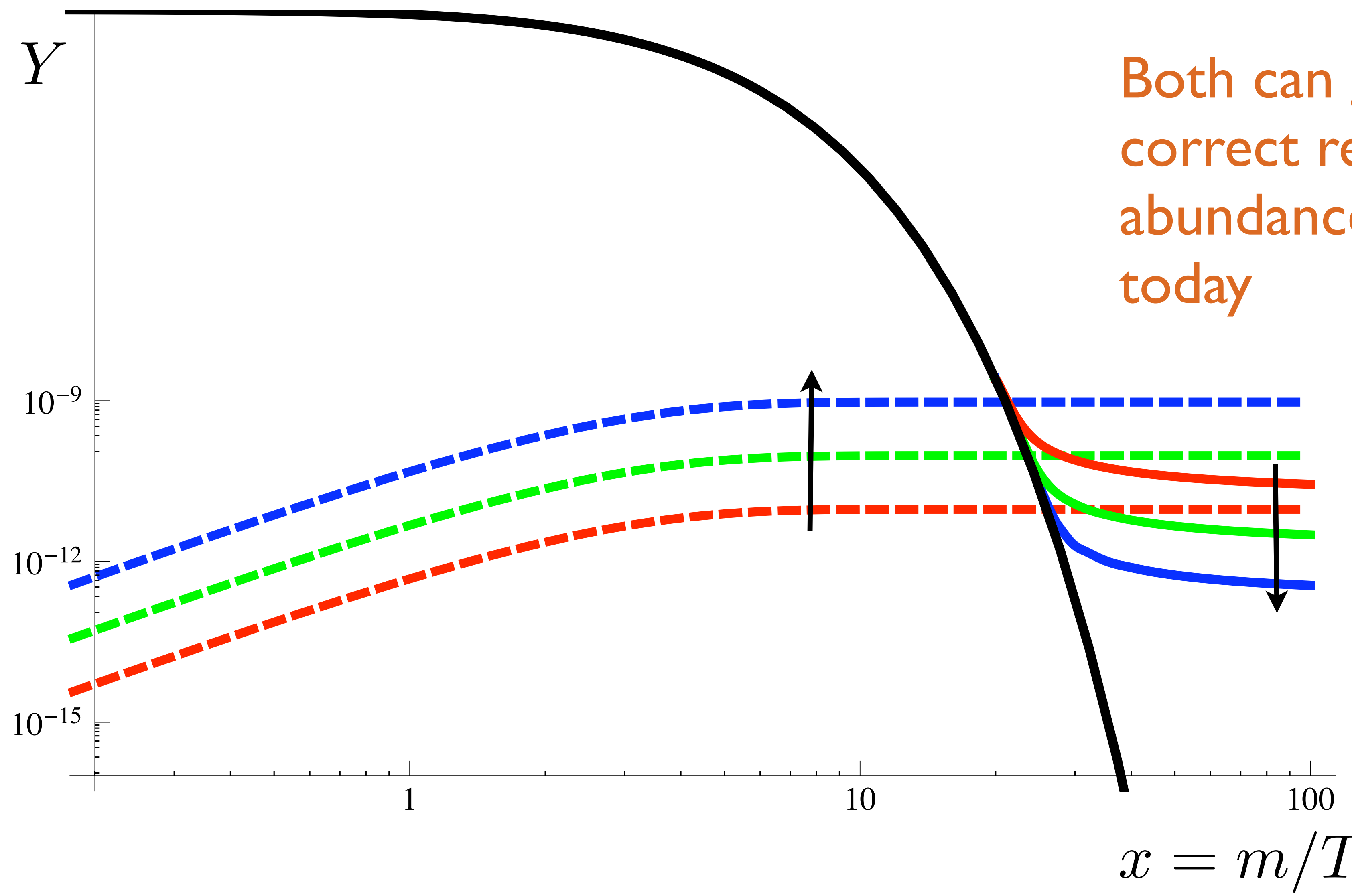
$$\Delta m \approx 166\,\mathrm{MeV}\,(1 + 2Y/c_w)$$



- Order cm lifetime of charged state

Freeze-in DM

WIMP
Thermal abundance in early universe



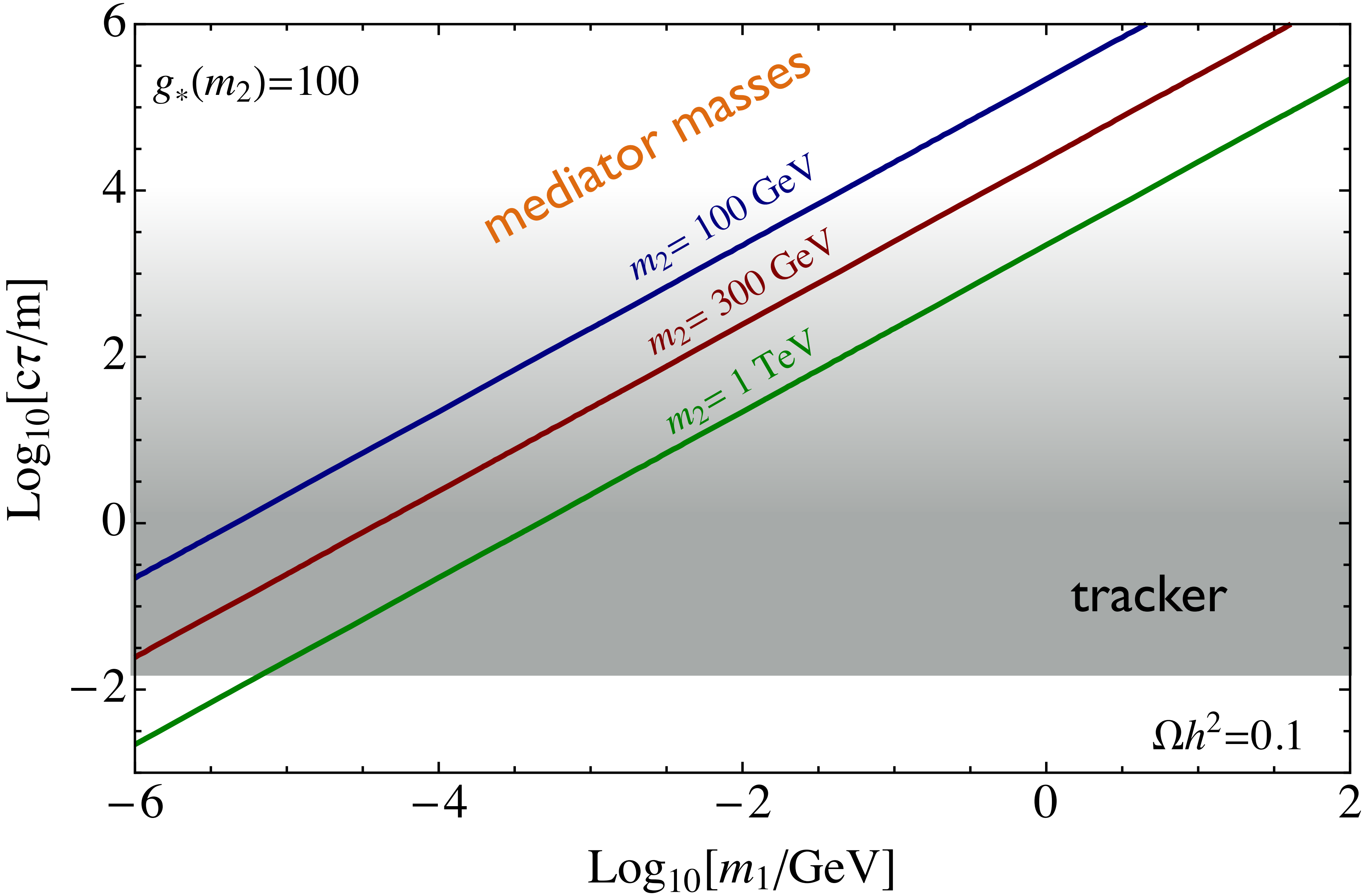
Both can give correct relic abundance today

"FIMP"
Never in thermal equilibrium
= tiny coupling!

Hall, Jedamzik, March-Russell, West, 2009

Freeze-in DM

Mediator lifetime in meters



1 keV

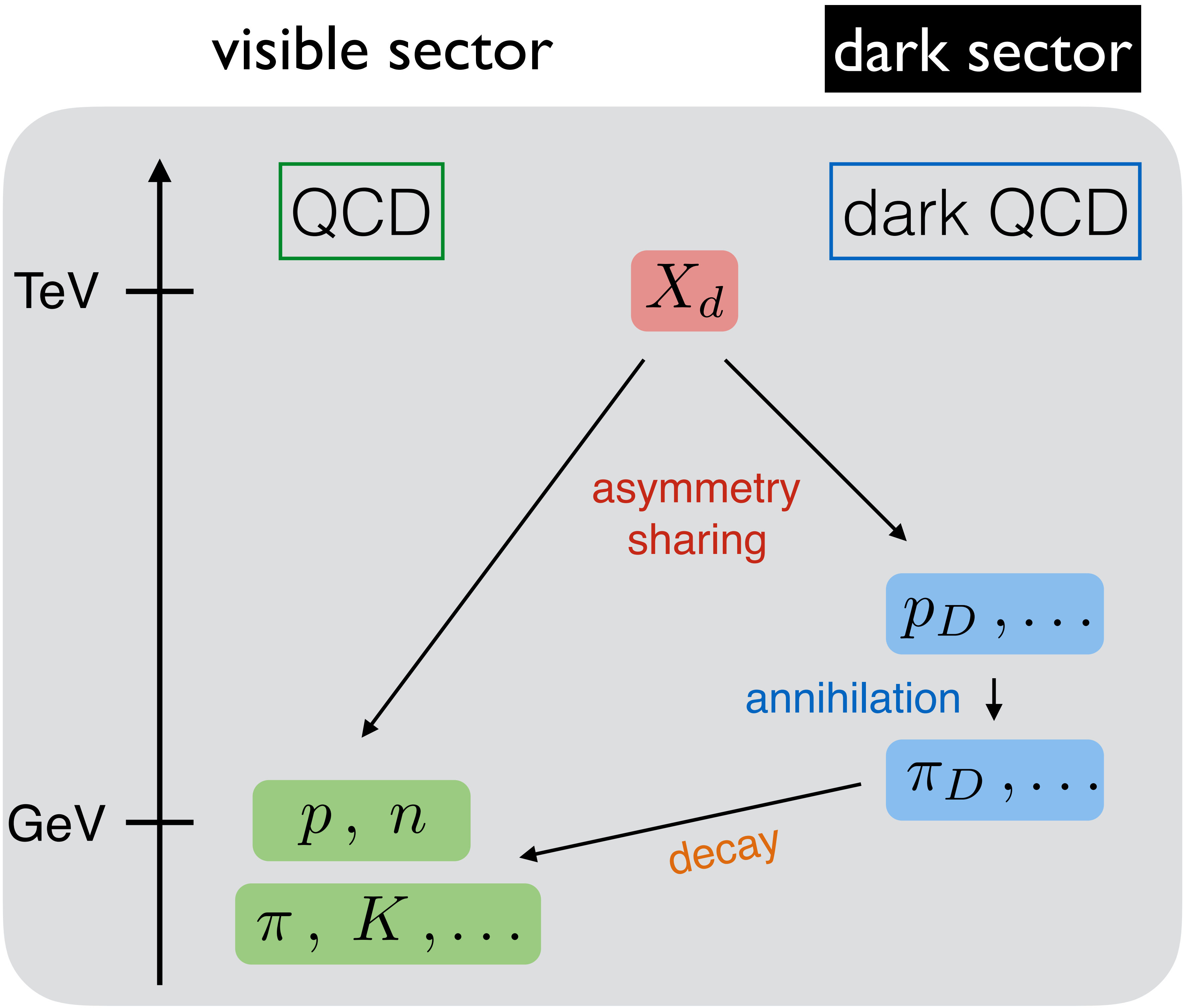
DM mass

100 GeV

Buchmuller, De Roeck, Hahn, McCullough, PS, Sung, Yu, 2017

Bai, PS, PRD, 2014

Dark Sector



- Asymmetric dark matter
- DM mass and stability
- Many similar models, e.g. hidden valleys (Strassler, Zurek), twin Higgs (Chacko, Goh, Harnik)

Dark Sector

- Asymmetric DM motivates $\Lambda_{\mathrm{Dark}} \sim \mathrm{few\ GeV}$
  - e.g.

$$\frac{\Omega_{\mathrm{DM}}}{\Omega_{\mathrm{B}}} \sim \frac{M_{\mathrm{DM}}}{M_{\mathrm{B}}}$$

- Dark pion lifetime possibly macroscopic

$$c\tau(\pi_D \to \mathrm{SM}) \sim \frac{M_X^4}{m_{\pi_D}^5} \sim \mathrm{cm} \times \left(\frac{\mathrm{M_X}}{\mathrm{TeV}}\right)^4 \left(\frac{\mathrm{GeV}}{\mathrm{m}_{\pi_\mathrm{D}}}\right)^5$$

Others

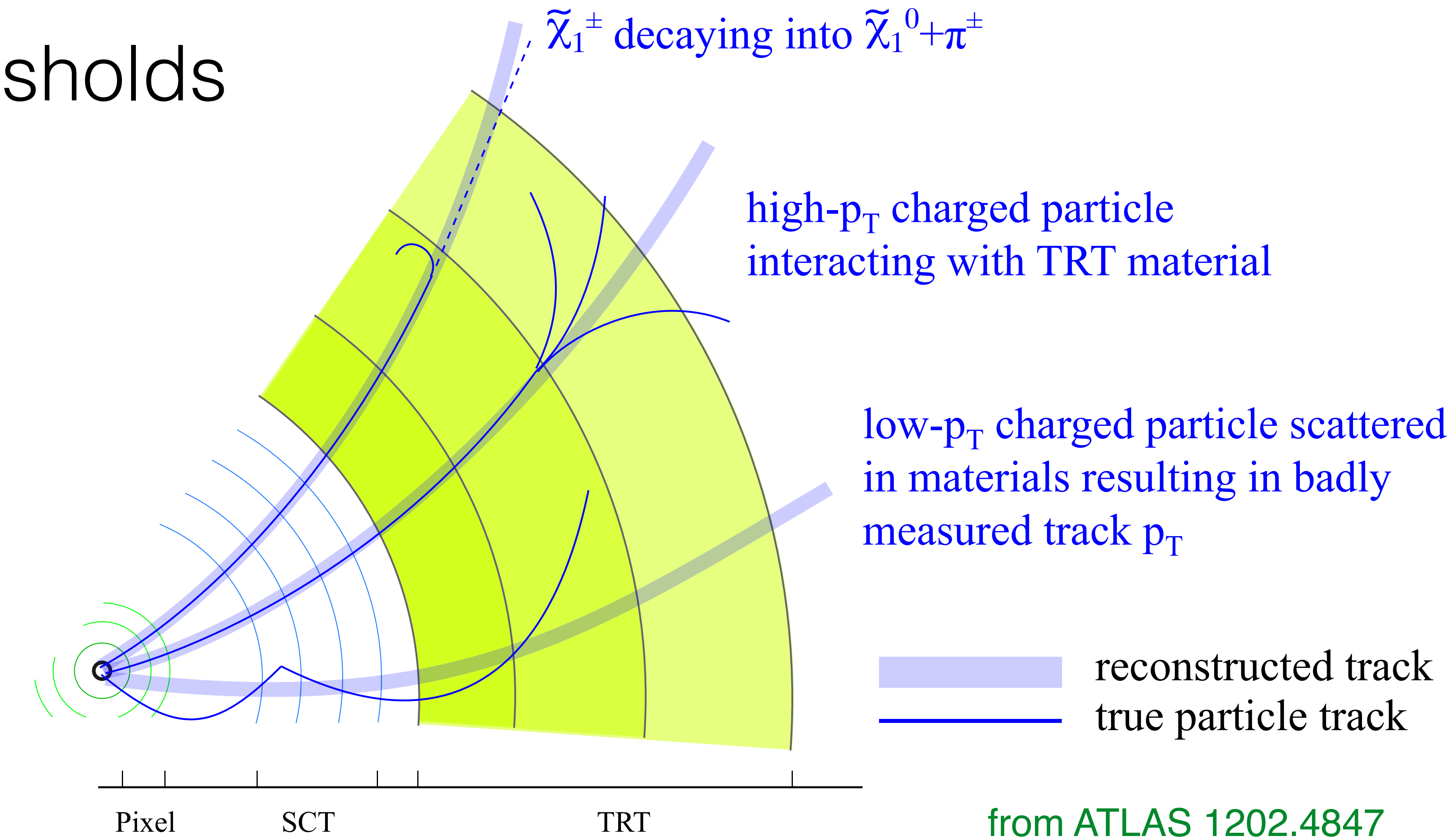
- Twin Higgs
  - long lived twin-glueballs through the Higgs portal
- RPV SUSY
  - long lived states if breaking is small, many possible signatures
- Co-annihilation
  - e.g. long lived gluinos, staus, …

Disappearing Tracks
(kinked tracks)

How does a track disappear?

How does a track disappear?

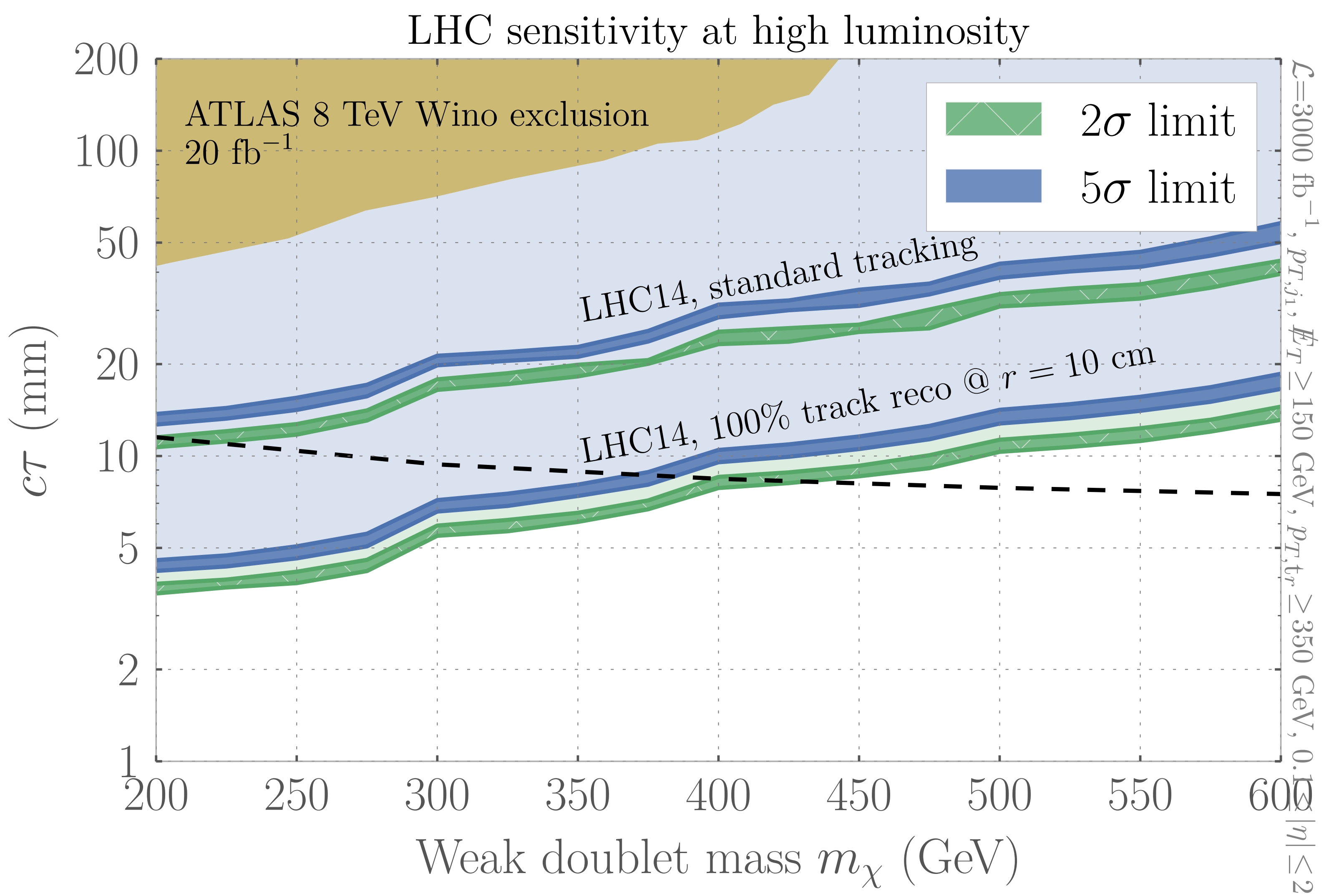
- Depends on detector thresholds
- B-field off data (ok this is old now)
- But first we have to see it!



from ATLAS 1202.4847

Fig. 2 Origins of disappearing high-p_T tracks.

Higgsino projections

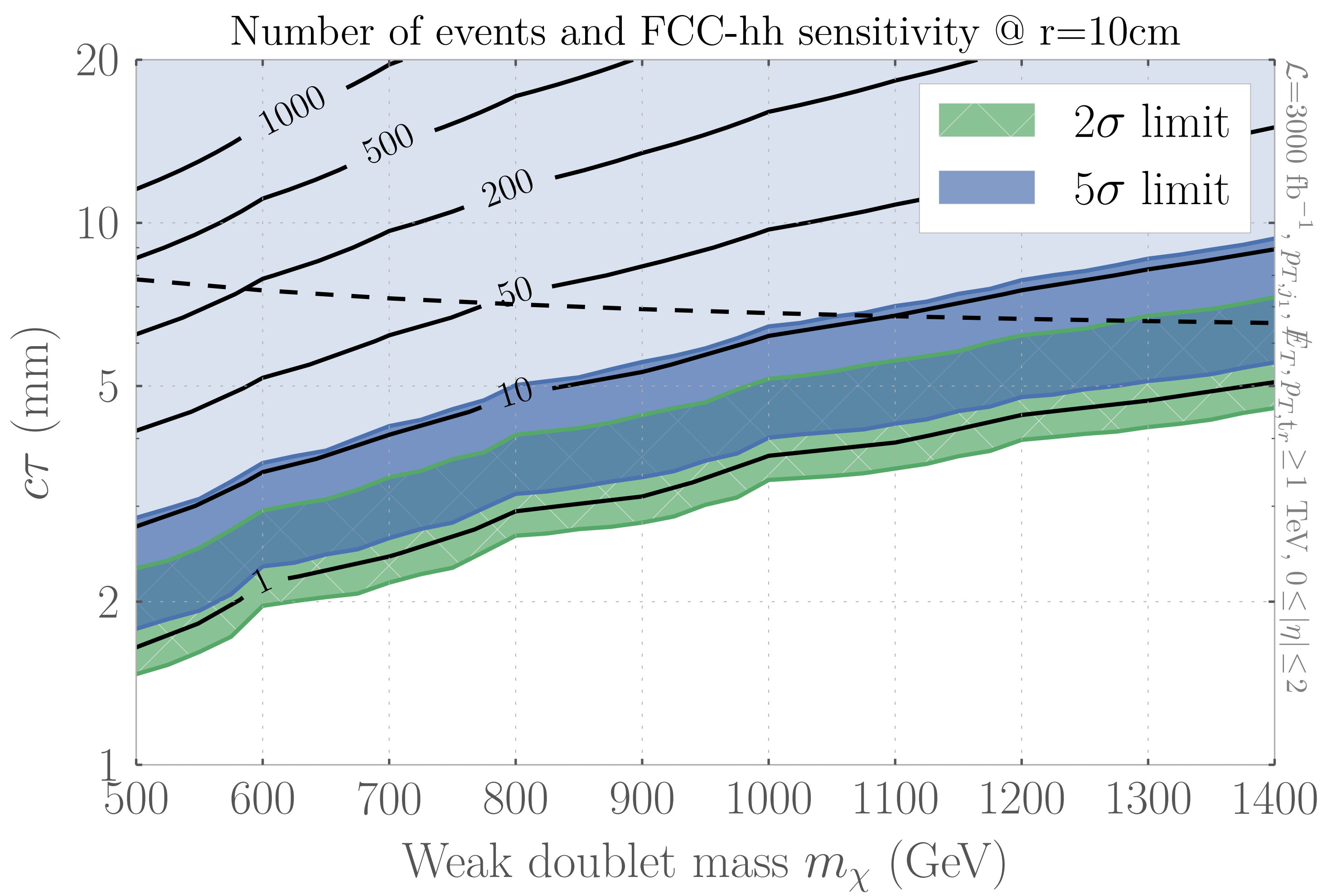


Higgsino

- Assumption: 100% track efficiency at 10cm
  Moriond a week later: 12 cm is possible!

Mahbubani, PS, Zurita, 2017

Higgsino projections

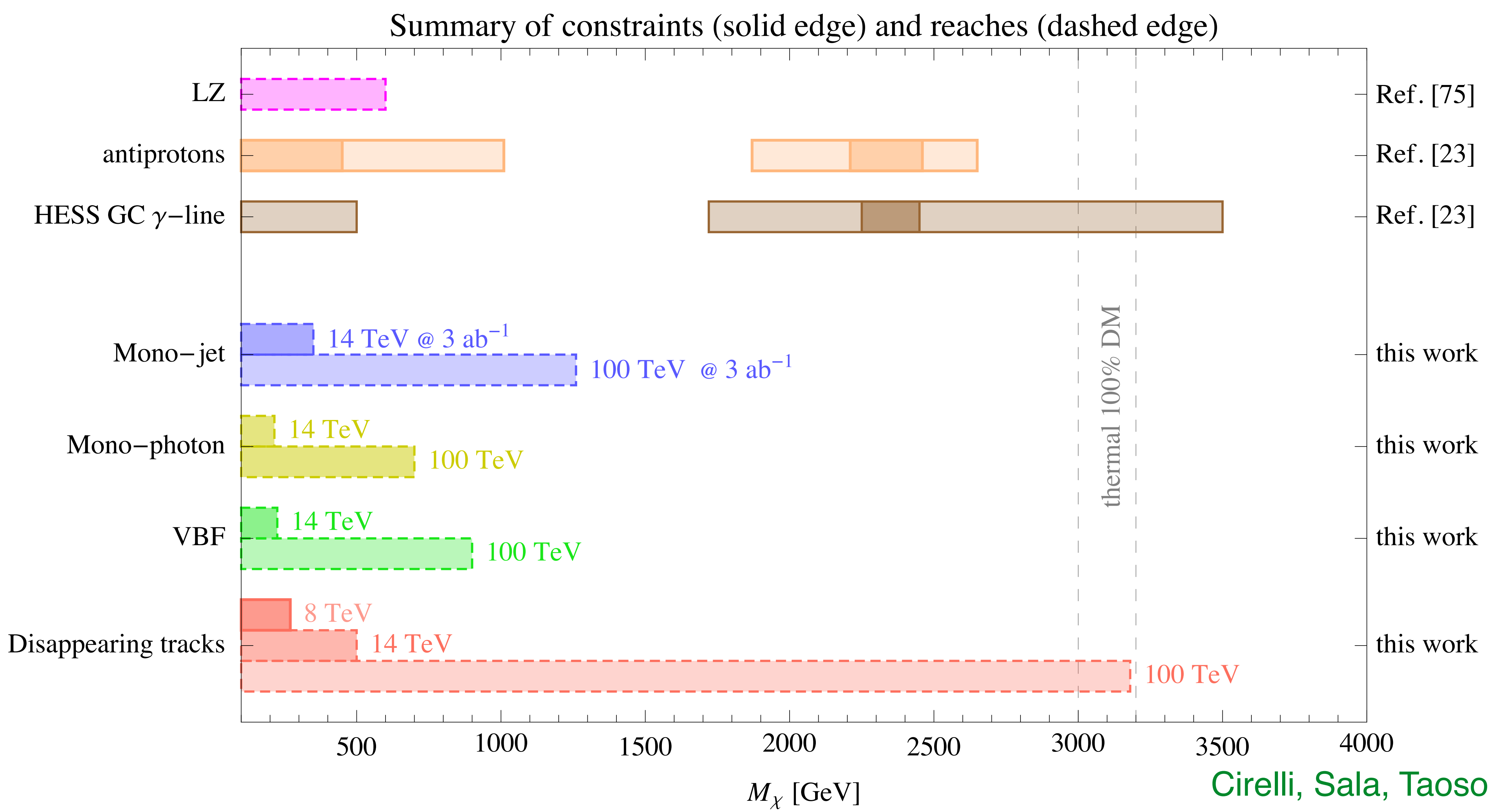


- Can cover thermal Higgsino mass range at FCC-hh
- Mono-jet seems to fall short

Mahbubani, PS, Zurita, 2017

Wino (triplet)

- Thermal DM mass range ~ 3 TeV in reach of FCC-hh, requires disappearing tracks



Cirelli, Sala, Taoso, 2014
see also Low, Wang, 2014

CLIC thoughts

- Disappearing tracks are essential for mass reach at hadron colliders
- For CLIC, the reach is probably close to $\frac{\sqrt{s}}{2}$
- No boost near threshold, bad for < cm lifetimes
- Tracklets to see all states, measure mass difference?
- Alternative? photon energy scan?
- How many tracker layers do we have to hit? dE/dx to discriminate from lighter charged tracks?
- Can we see the soft pion?

Precision constraints

- Can we constrain masses above $\sqrt{s}/2$

- Vector-like multiplets don't contribute to S & T parameters, but to W,Y

	universal form factor ($\mathcal{L}$)
W	$-\frac{\mathrm{W}}{4m_W^2}(D_\rho W^a_{\mu\nu})^2$
Y	$-\frac{\mathrm{Y}}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$

- Need below percent precision on $e^+e^- \to e^+e^-$ at threshold Azatov, PS, Zurita

- Contribution grows with energy - scan to cancel systematics?

See Harigaya et al, 1504.03402, for full form factor dependence

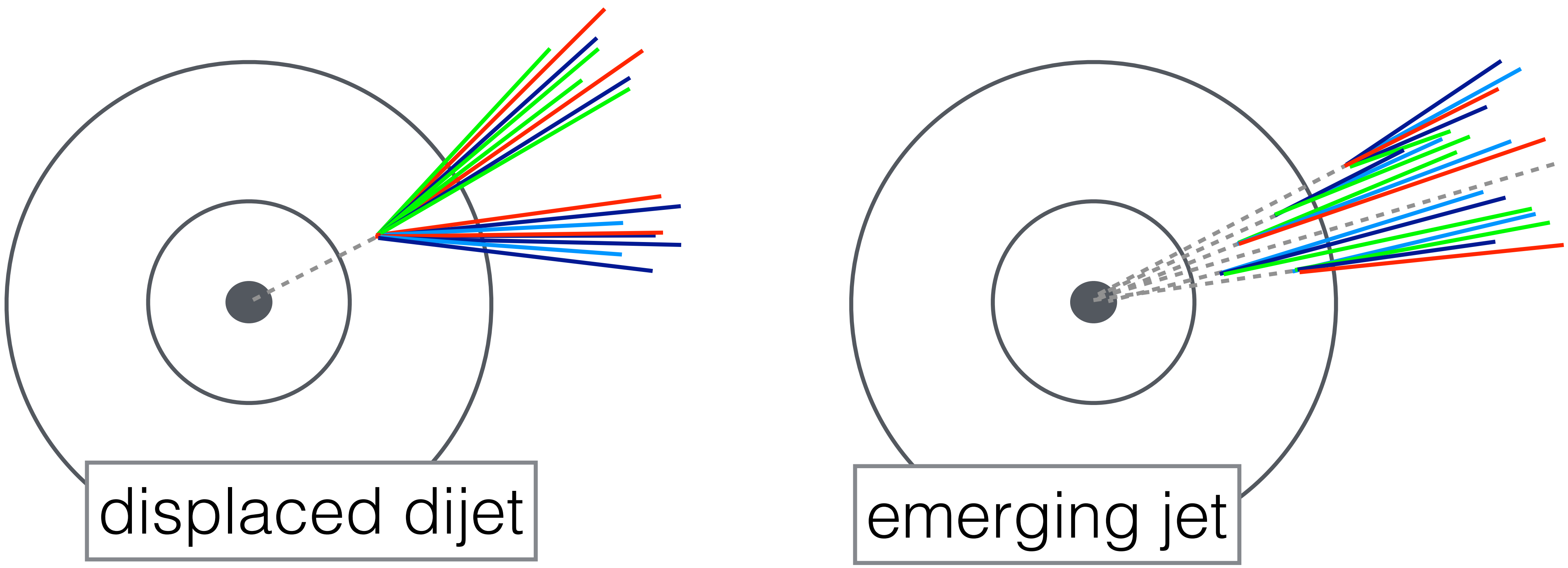
Appearing Tracks

(displaced vertices, emerging jets, etc)

PS, Stolarksi, Weiler, JHEP 2015

Signatures

$$R = \frac{\text{mediator mass}}{\text{dark pion masses}}$$



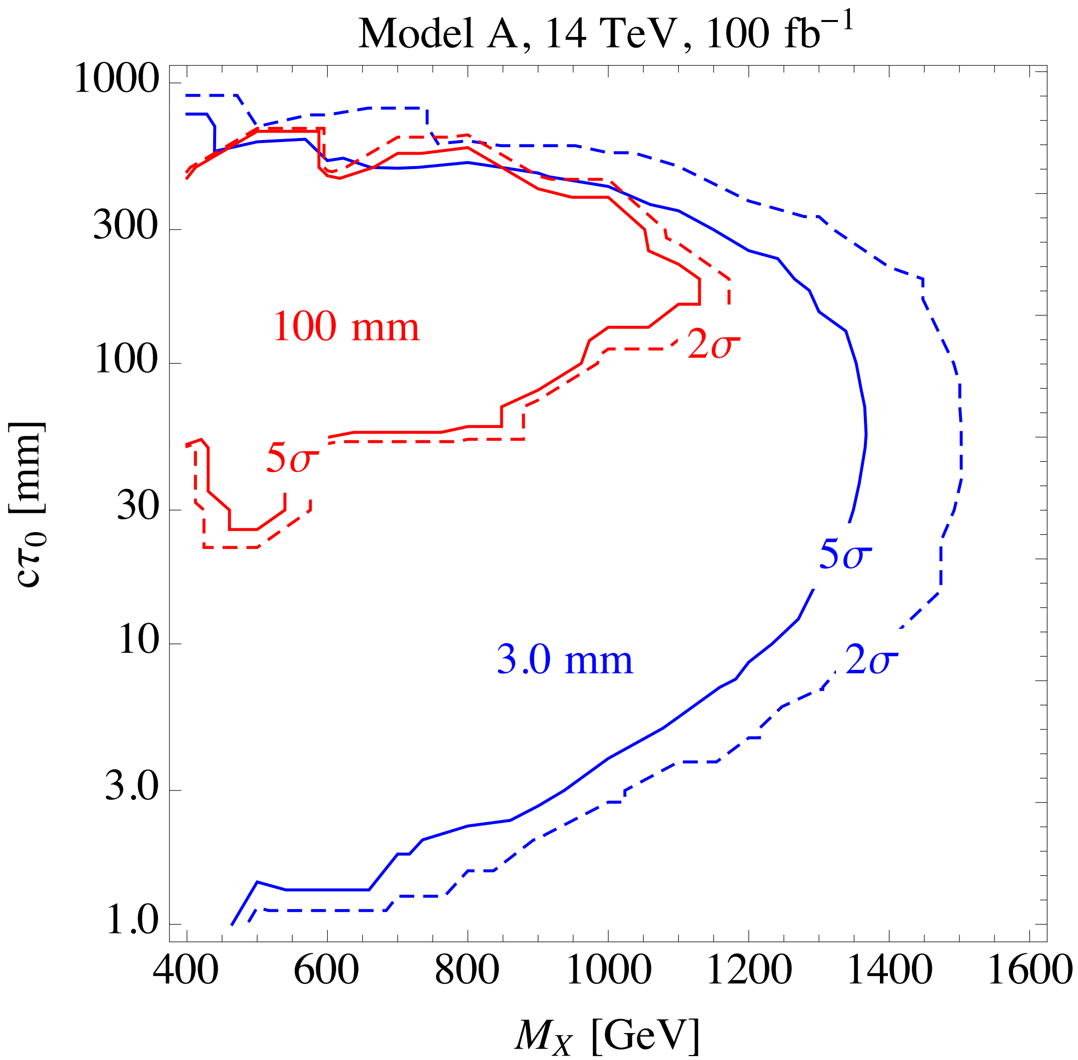
$R \gtrsim 1$ $\qquad$ $R \gg 1$

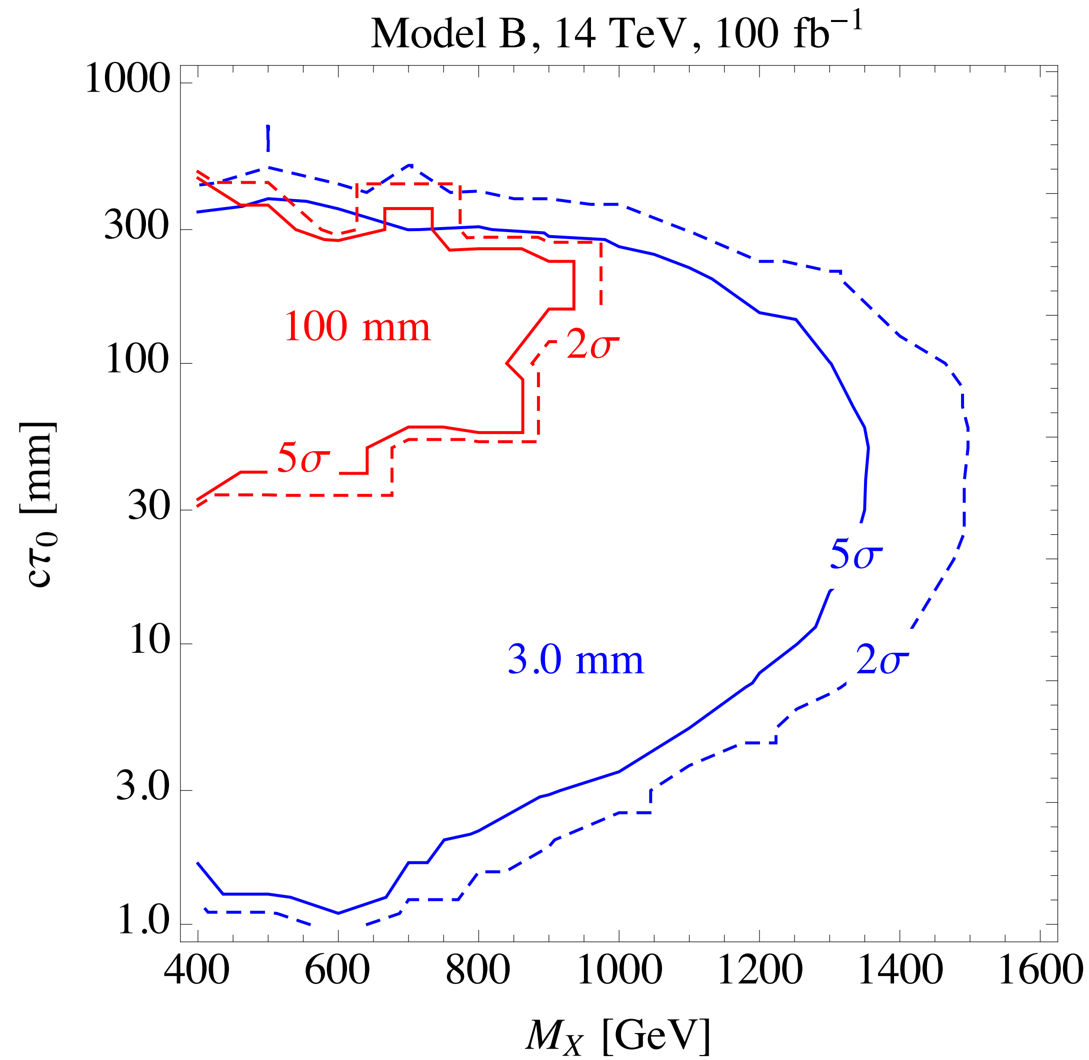
- Third direction: Conformal behaviour, spherical “jets”

AKA soft bombs, see Knapen, Pagan Griso, Papucci, Robinson, 2016

PS, Stolarksi, Weiler, JHEP 2015

Reach ATLAS/CMS





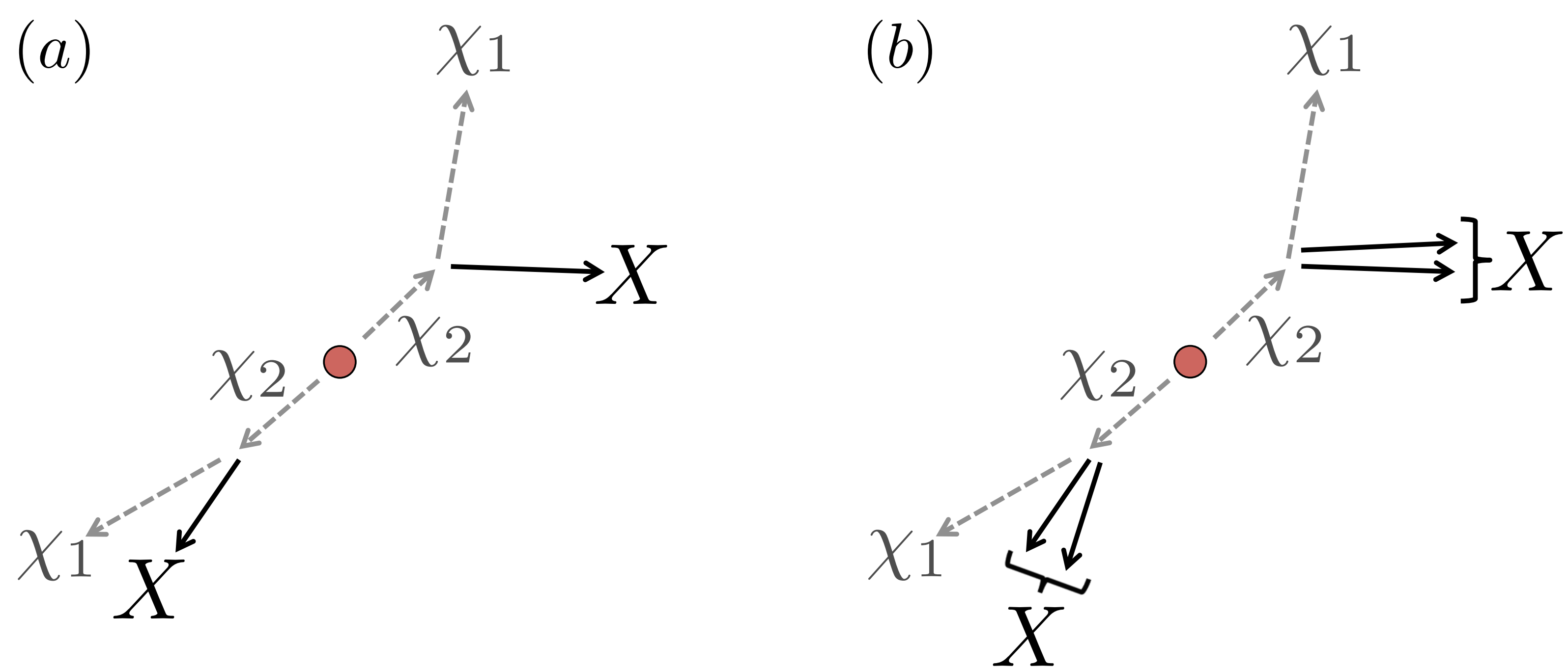
- Optimistic scenario (no non-collisional BGs)
- More realistic studies under way at ATLAS/CMS

Simplified models

- Successful way to present collider searches in a less model dependent way
  - Two masses (DM & mediator) and two couplings
- Minimal extension to include displaced decays
  - Add second “dark” state with mass $m_2 > m_{\rm DM}$
  - Lifetime $\Gamma(\chi_2 \to \chi_1 X)$
- Underlying models e.g. “GMSB SUSY”, freeze-in DM, twin Higgs dark sectors

Buchmuller, De Roeck, Hahn, McCullough, PS, Sung, Yu, 2017

Signatures



- X can be any set of SM particles
- Can also imagine charged χ_2
- UFO files available, download and start doing CLIC studies!

Buchmuller, De Roeck, Hahn, McCullough, PS, Sung, Yu, 2017

Typical LHC problems

- Triggering
  - Conventional triggers (e.g. ISR). Efficiencies unclear due to cleaning cuts
  - Dedicated LLP triggers (lower bandwidth, efficiency)
- Pile-up
- Large QCD backgrounds, can look like almost anything

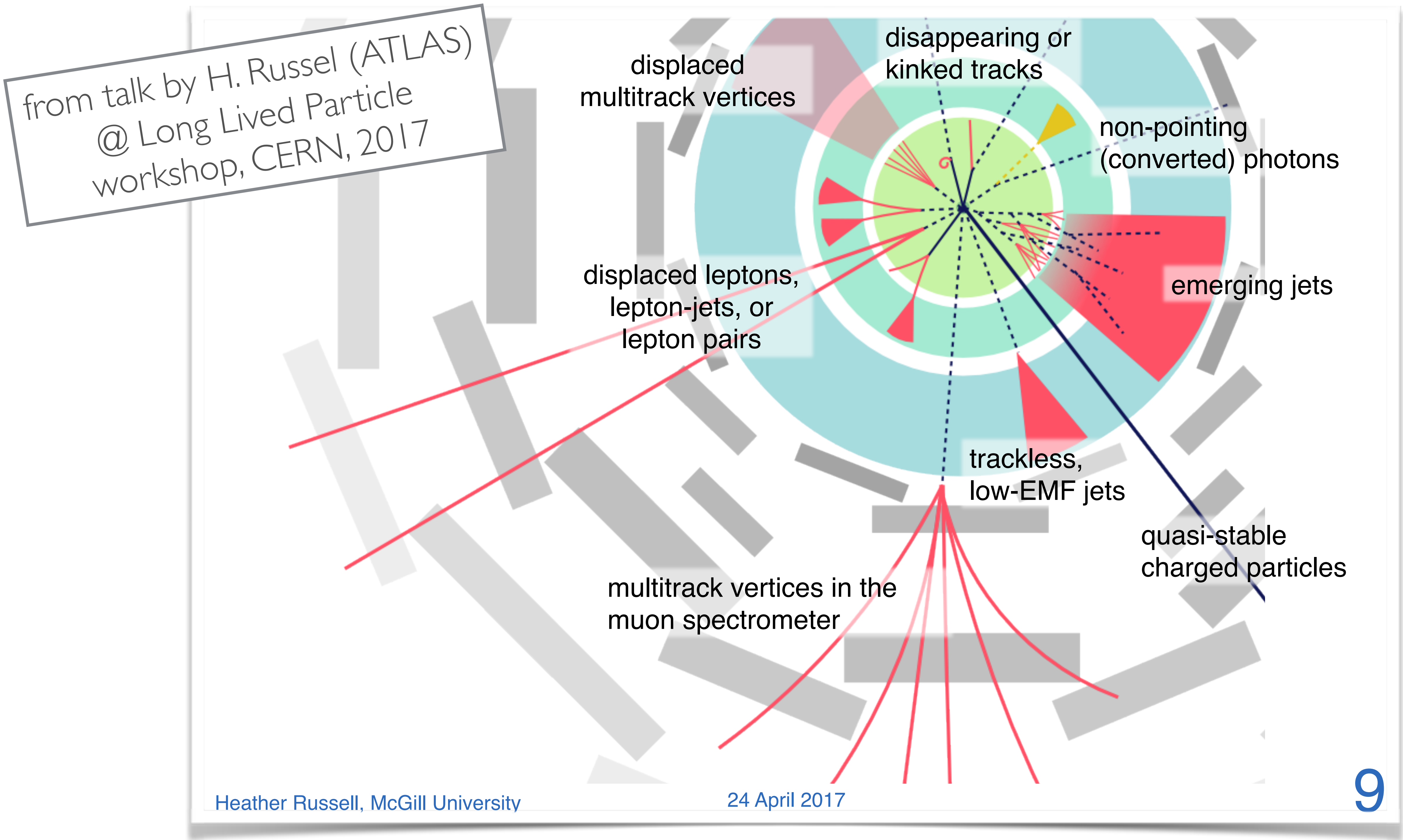
Opportunities at CLIC

- Drop distinction between single displaced objects and displaced jets
  - Find each dark pion!
- No triggers - find anything which is not SM?
- Segmented calorimeters, ideal to find displaced energy deposits
- Non-resonant or light, weakly coupled mediators?
- Study dark sector properties, dark sector spectroscopy, …

Summary

- Long lived particles appear in many BSM scenarios, often related to dark matter or baryogenesis (not discussed)
- Unconventional collider signatures - dedicated searches can be very sensitive, background free
- CLIC detector design looks very good:
    - no triggers
    - close to beam line
    - segmented calorimeters (also granular ecal?)
- MC implementations available, for detailed studies!

Signatures


from talk by H. Russel (ATLAS)
@ Long Lived Particle
workshop, CERN, 2017
displaced
multitrack vertices
disappearing or
kinked tracks
non-pointing
(converted) photons
displaced leptons,
lepton-jets, or
lepton pairs
emerging jets
trackless,
low-EMF jets
quasi-stable
charged particles
multitrack vertices in the
muon spectrometer
Heather Russell, McGill University
24 April 2017
9

Where does LHC struggle

- Higgs portal DM
  - Above threshold ($m_{\mathrm{DM}} > m_h/2$) very limited reach even for 100 TeV pp collider
- Weakly interacting DM
  - Minimal DM
  - Wino, Higgsino, Bino; mixed scenarios
  - Difficult regions often covered by direct or indirect detection - even then a laboratory production of DM would be highly beneficial

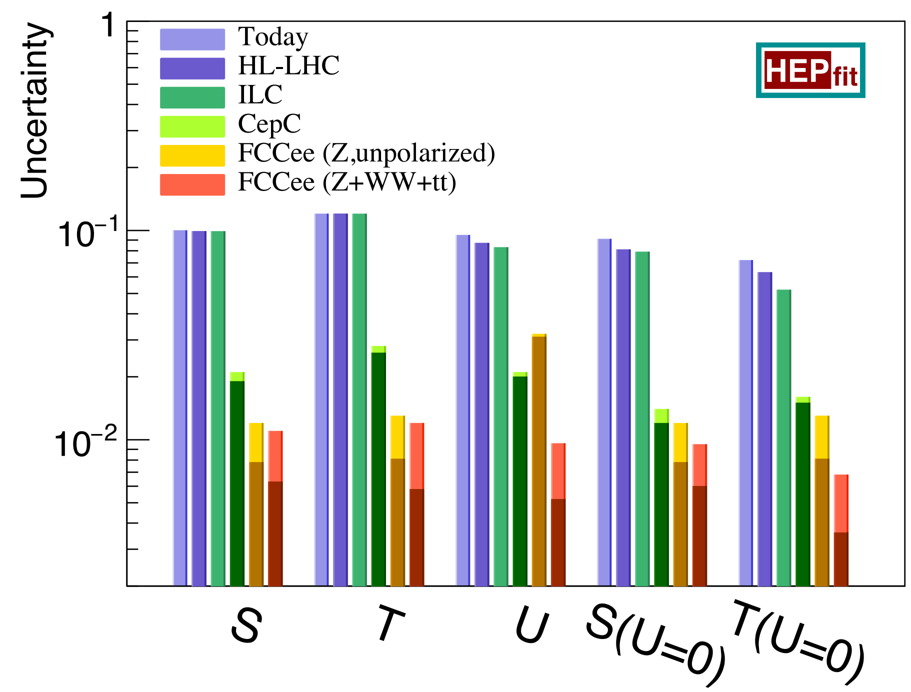
Where does LHC struggle II

- Annihilation mostly into leptons, e.g.
  - gauged lepton number portal (1305.1108)
  - leptophilic DM
  - gauged $L_{\mu\text{-}\tau}$ portal
- Light, very weakly coupled mediators (dark photon…)
- Flavoured DM(?)
- sterile neutrinos (and axions etc…)

Weakly coupled states

- Direct reach usually close to $\sqrt{s}/2$ at FCC-ee

- Not enough to cover e.g. thermal Higgsino region (1.1 TeV)



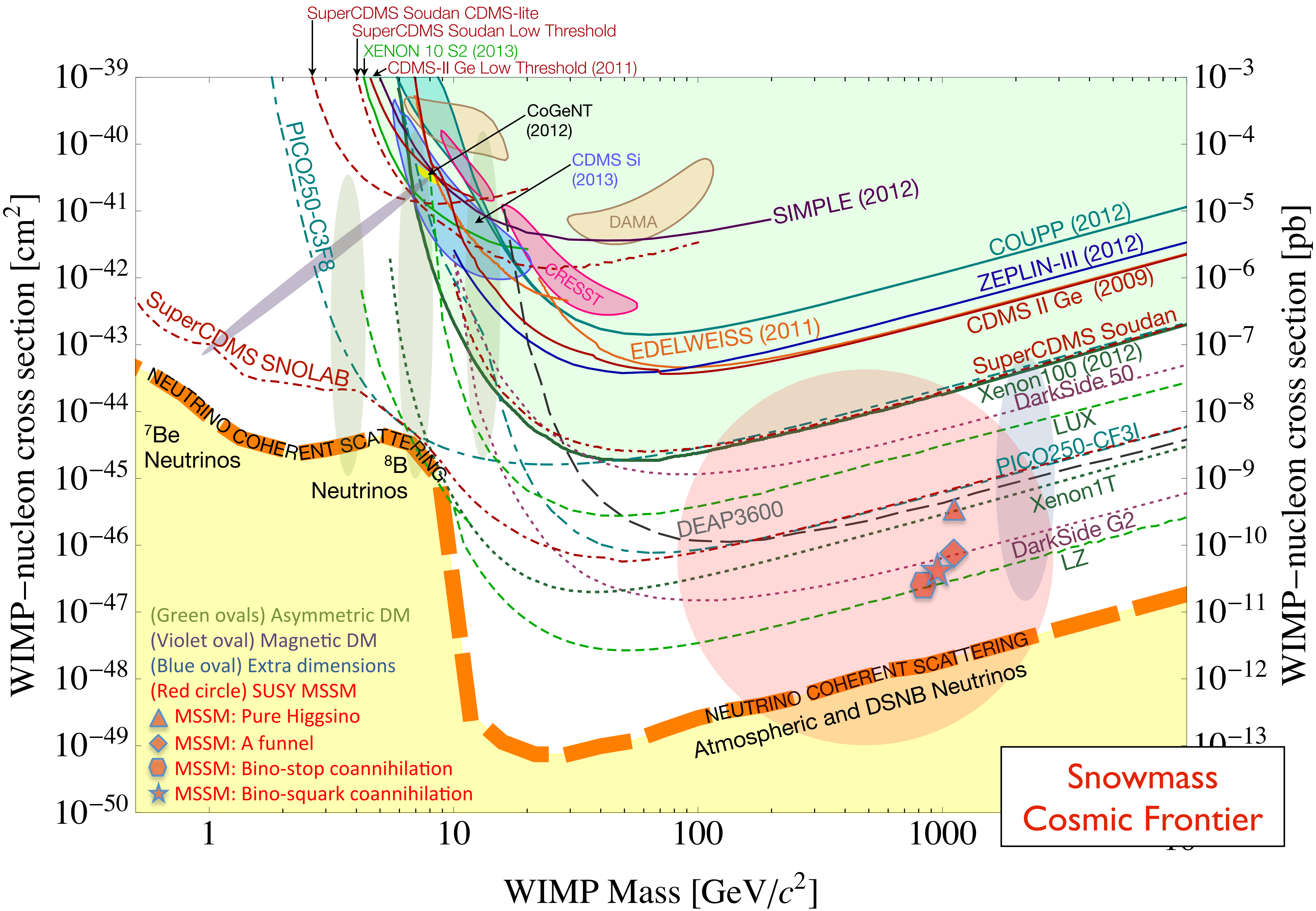
- Use precision instead? Factor 10 improved constraints on STU parameters
    - e.g. 1404.4398, could probe new vector-like states up to 500 GeV or more

- Precision also in pp machines (e.g. 1609.08157)

Once more the challenges

- Higgs portal
- Electroweak production, small mass splitting
- Leptophilic interactions
- Light, weakly coupled mediators
- Flavour sensitive interactions
- Beyond-WIMP scenarios severely un-studied

ALSO DIRECT DETECTION GETS HARDER



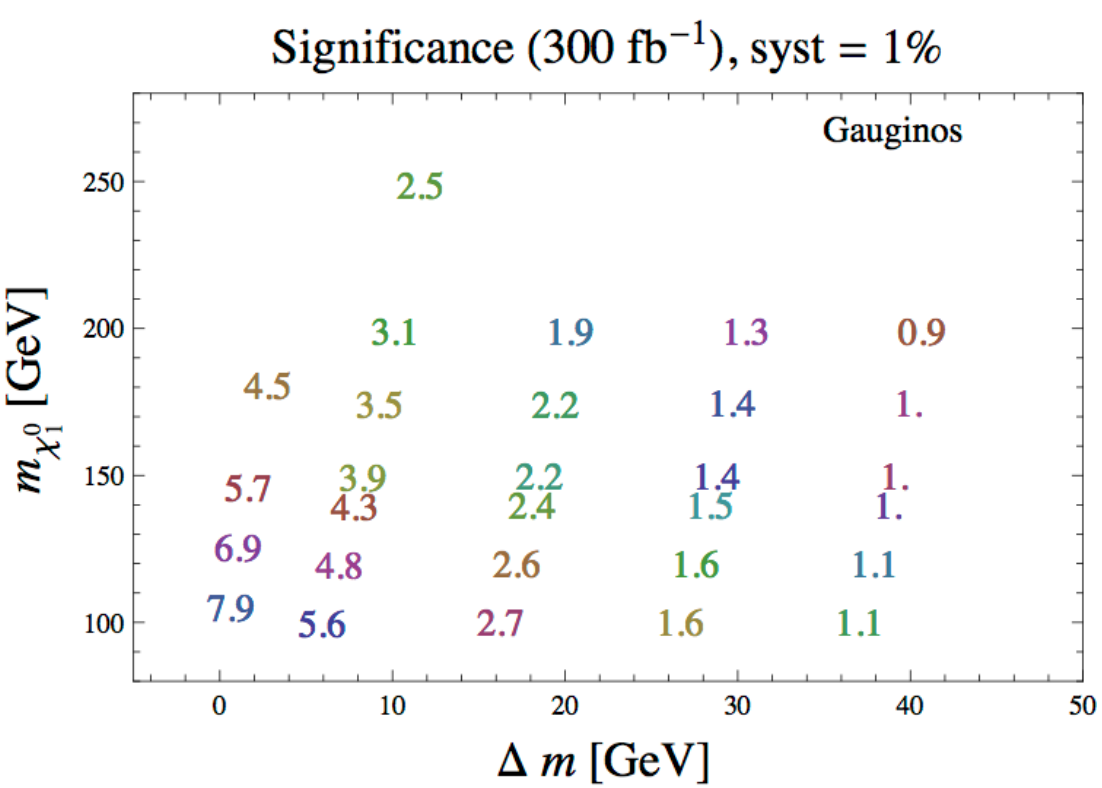
WIMP AT COLLIDER?

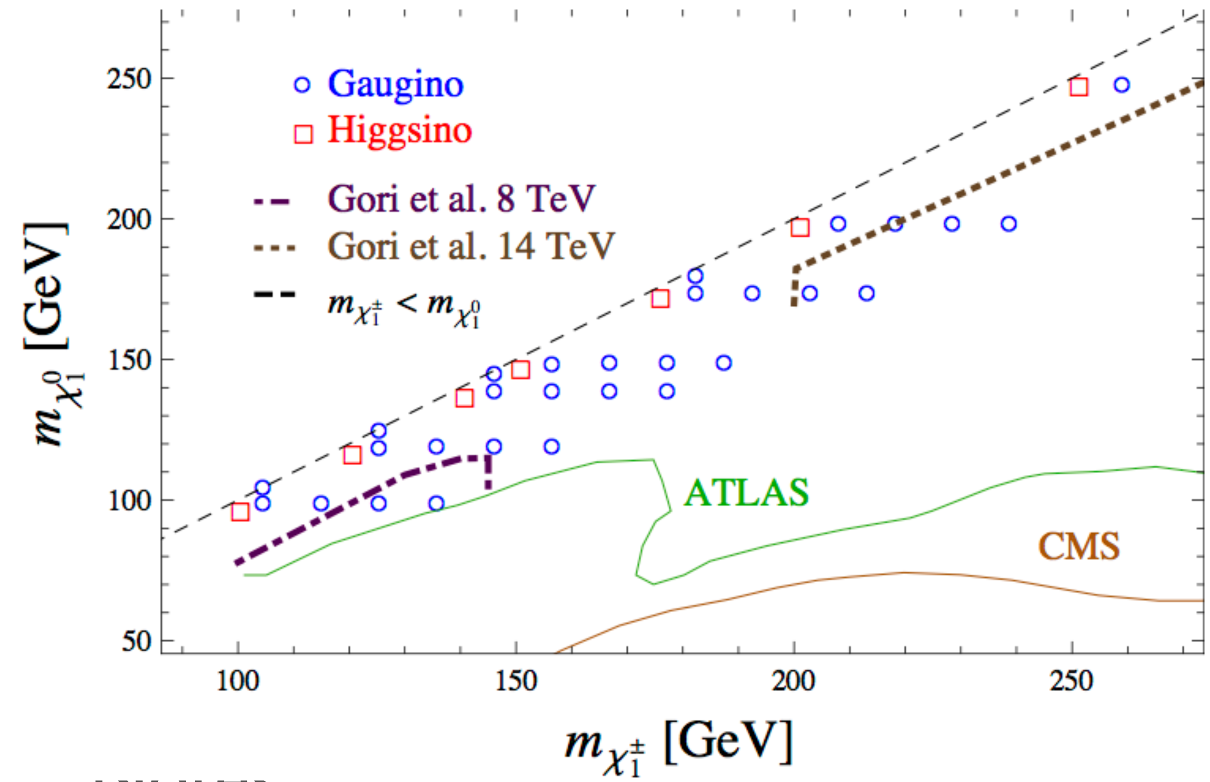
full model	minimal model	effective theory
e.g. MSSM, UED couplings depend on model structure Signals: X+MET, from production of heavy states, mono jets, model specific	e.g. minimal DM DM is gauge singlet or multiplet single (or few) mediators Signals: mono jet, mediator specific, multiplet specific	only SM + DM couple via effective operators Signals: mono jet

DEGENERATE ELECTROWEAKINOS

PS, Zurita, 1312.7350
see also:
C. Han et al, 1310.4274
Baer et al, 1401.1162
Z. Han et al, 1401.1235

- Simplified SUSY: Only higgsino or bino/wino light
- Searches difficult when masses are degenerate
- Mono jets? Impossible at 8 TeV, low masses testable with 14 TeV:





Notes:

- Assumed 1% systematics
- Includes soft leptons (more later)
- Cuts not optimal for $\Delta m \gtrsim 15\ \mathrm{GeV}$

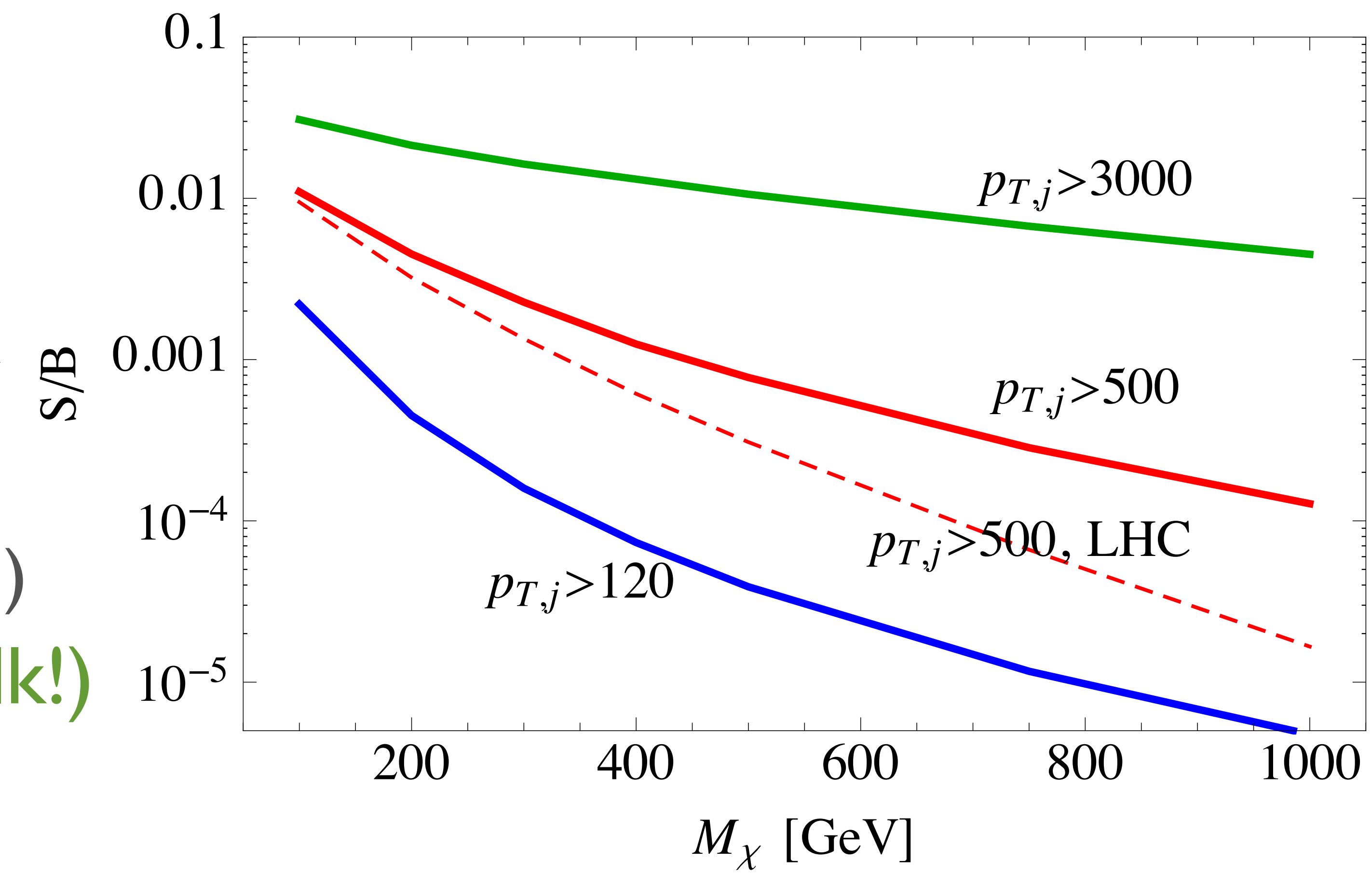
SOFT LEPTONS

Giudice, et al, 1004.4902
...
PS, Zurita, 1312.7350
Z. Han et al, 1401.1235

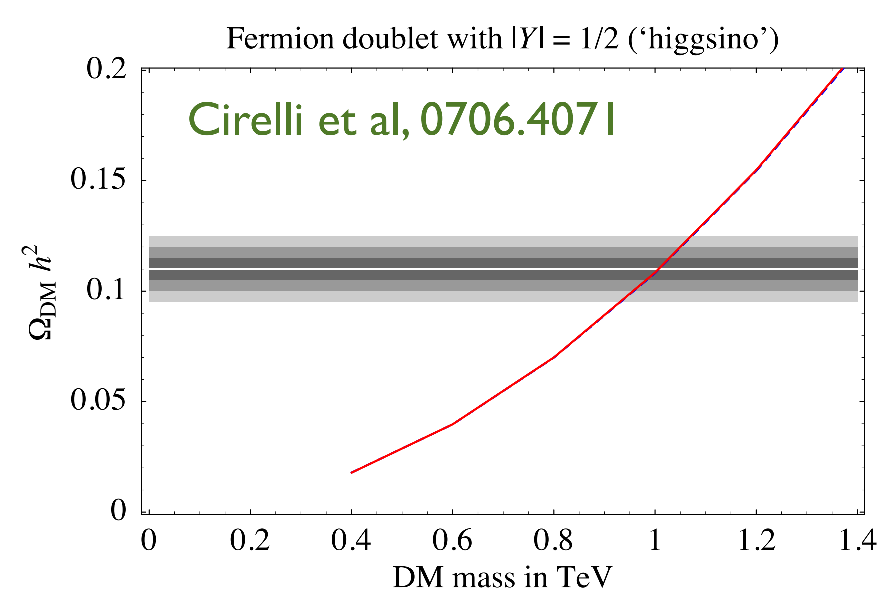
- Chargino decay: $C_1 \to N_1 W^* \to N_1 \ell \nu_\ell$
- With $\Delta M \sim 1-10\ \mathrm{GeV}$ have $p_{T,\ell} \sim$ few GeV in rest frame: below detector limits
  At LHC: mono jet recoil can boost it above threshold
- 100 TeV: boost factor 10-20
  - Low muon thresholds give access to even smaller Δm
    (can we find a 1 GeV muon? and have precision for 25 TeV muons?)
  - Also a problem: mono jet searches veto leptons above 20 GeV. will loose a lot of signal! Similar issue with soft jets from W decays

GOING TO 100 TEV

- Reach TeV scale, with better S/B
  (pure Higgsino, divided by Z(νν) background, just jet pT cut, generator level)
  (See also LT Wang's talk!)



- Important?
  - pure Higgsino has correct relic density for M = 1.1 TeV
  - very simple model, testable!



MINIMAL DM (HEAVY WIMPS)

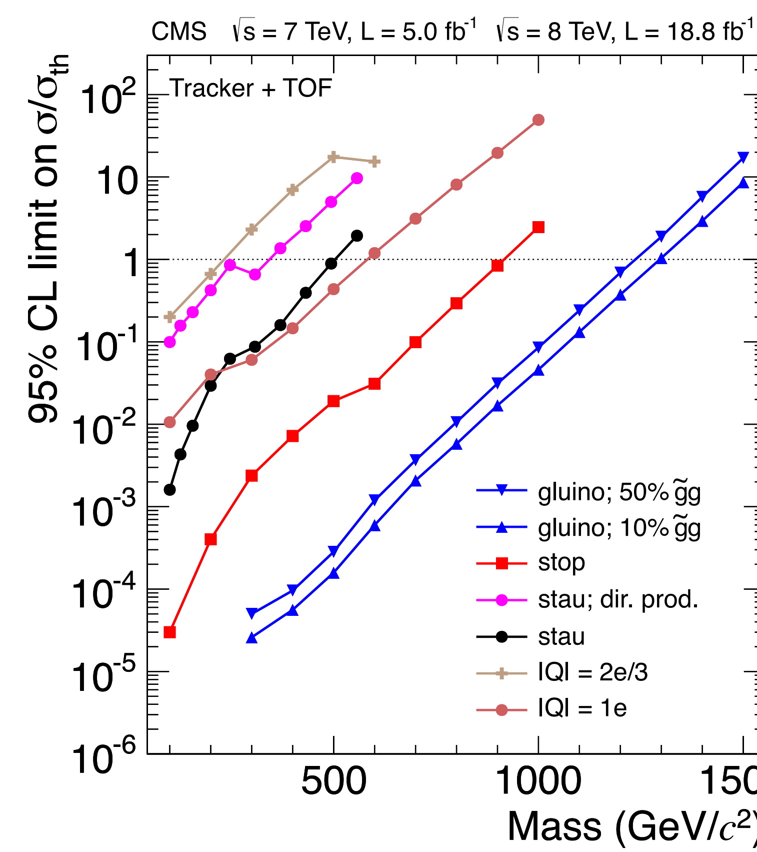
Cirelli, Fornengo, Strumia, hep-ph/0512090

- DM part of weak gauge multiplet

$$\mathscr{L} = \mathscr{L}_{\rm SM} + c \begin{cases} \bar{\mathcal{X}}(i\not{D} + M)\mathcal{X} \\ |D_\mu \mathcal{X}|^2 - M^2|\mathcal{X}|^2 \end{cases}$$

- e.g. triplet with Y=0 (wino) correct relic density for M~2.8 TeV
- too heavy for mono jets :(
- But: Tiny mass splitting, charged components long lived (~50 cm)
- weak production, too heavy for LHC
  FHC will do it (detector!)
- Larger splitting (e.g. from mixing): soft leptons again?

(see T. Cohen's talk for more details)



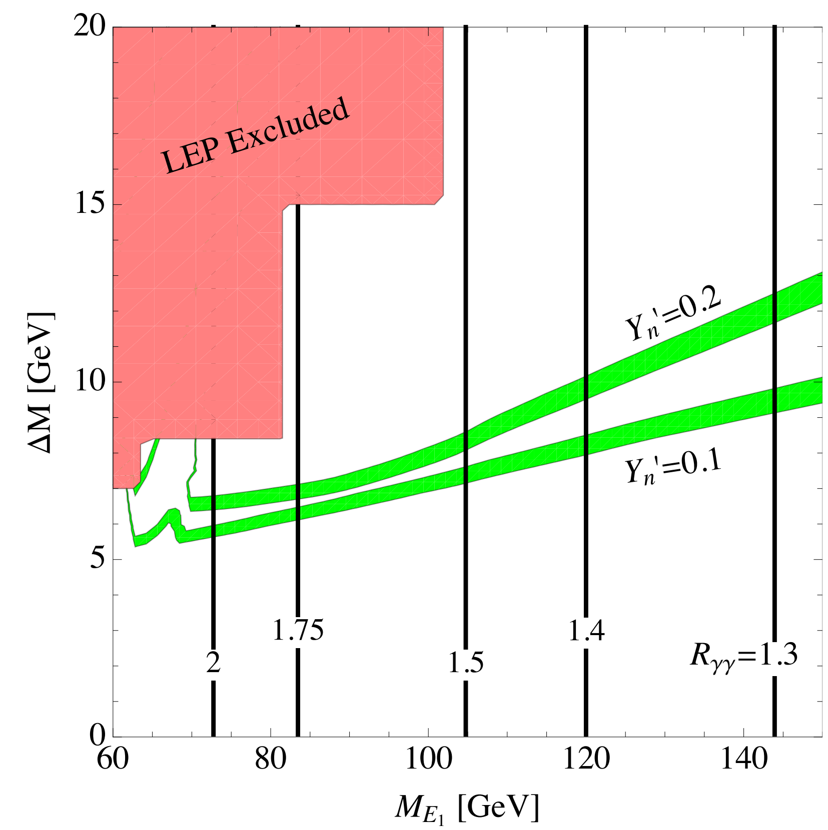
MIXED DM, CO-ANNIHILATION

e.g.
Joglekar, PS, Wagner, 1207.4235
Cheung & Sanford, 1311.5896

- Mixing e.g. of singlet DM candidate with gauge doublet

  (e.g. bino-wino, extended Higgs sector, vectorlike leptons)

- V-leptons example:
  - Co-annihilation preferred, good relic density with ~ 10 GeV mass splitting for weak (0.1) coupling
  - Search strategy? (mono jet etc...)



- Also with colored states

  (e.g. stop, sbottom co-annihilation, see LT Wang's talk)

HIGGS PORTAL DARK MATTER

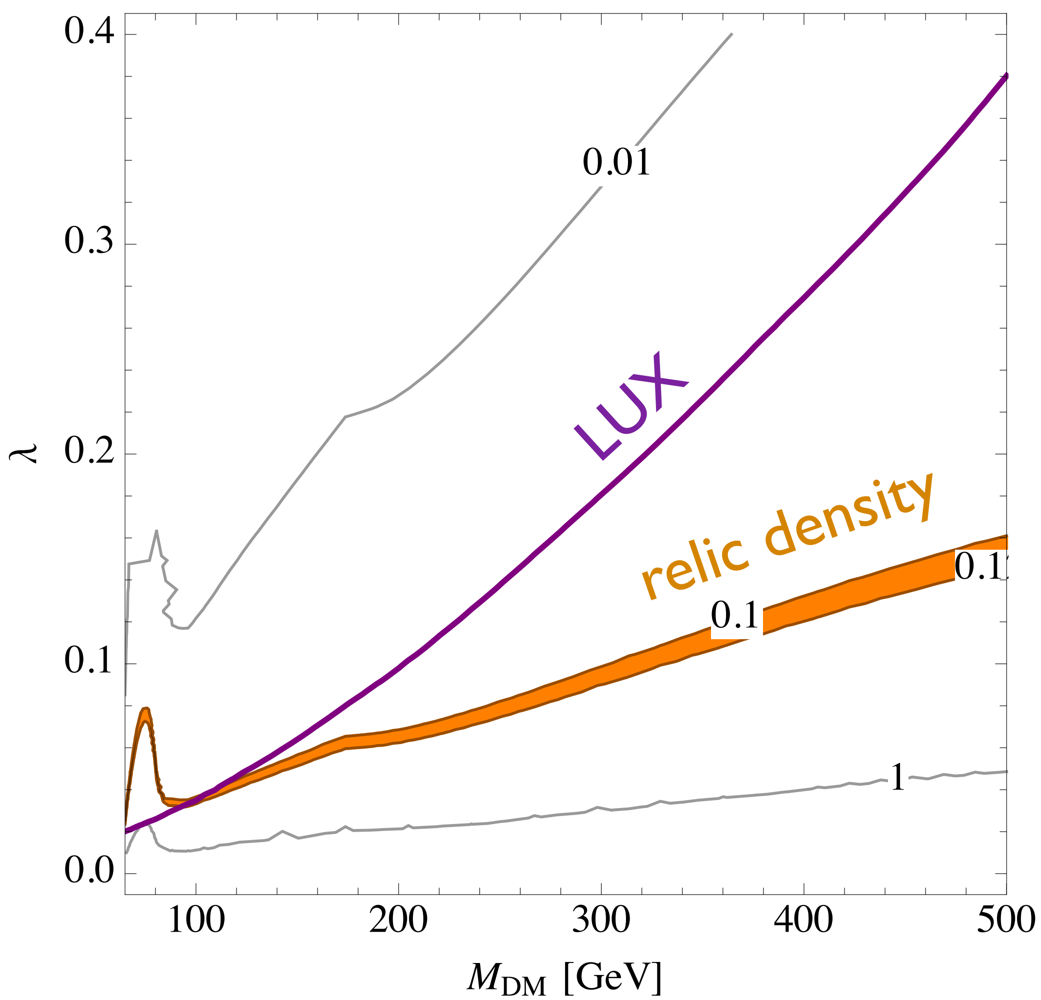
see e.g.
Kanemura, Matsumoto, et al, PRD82, 055026
Low, PS, Shaughnessy, Wagner, PRD85, 015009

- Simple DM models, scalar is even renormalizable

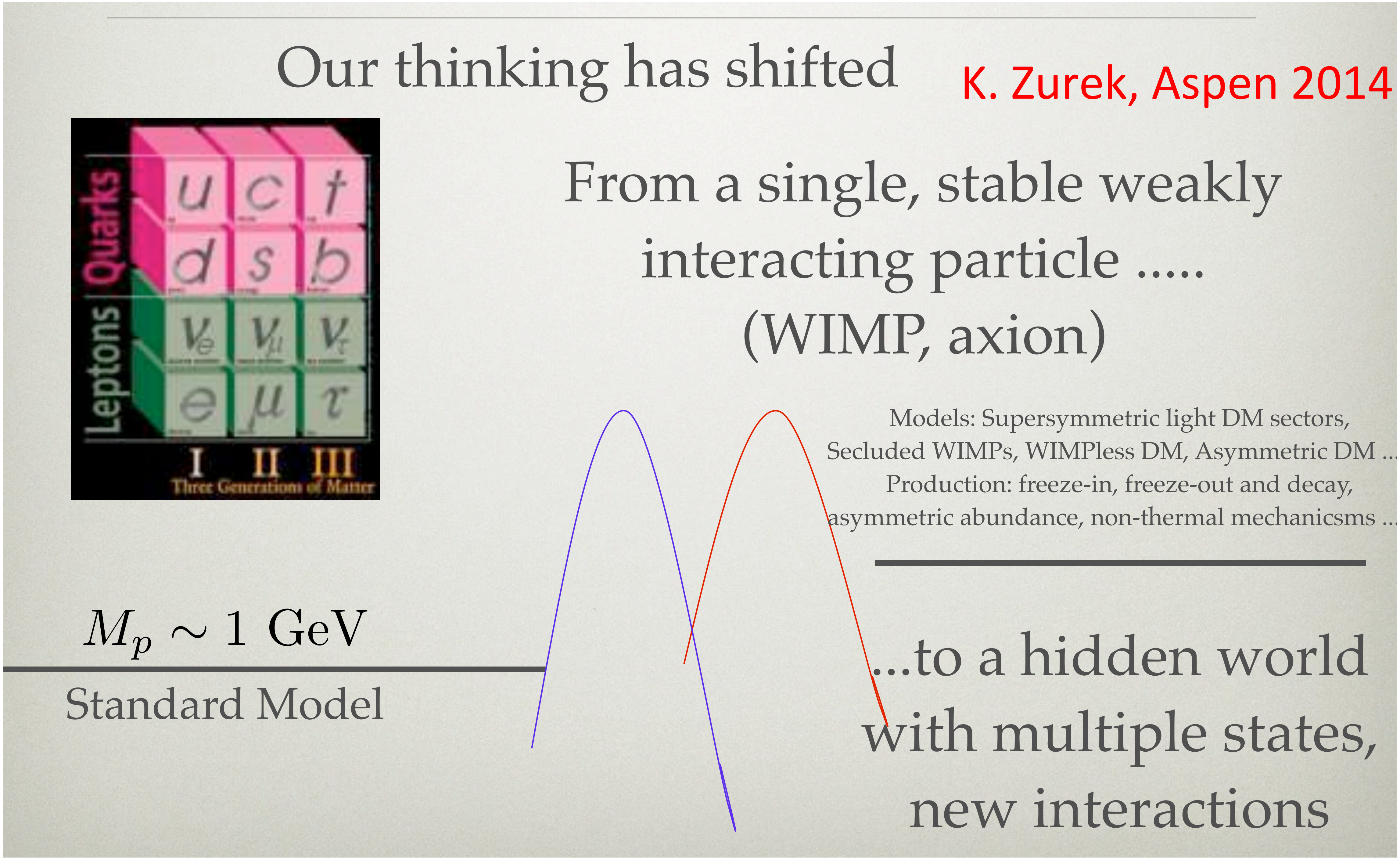
$$\mathcal{L} = \delta_c m_s^2 |S|^2 + \delta_c \lambda_s H^\dagger H |S|^2$$

- Direct detection & relic density:
- Testable at colliders?

Nightmare scenario?



NON WIMPS

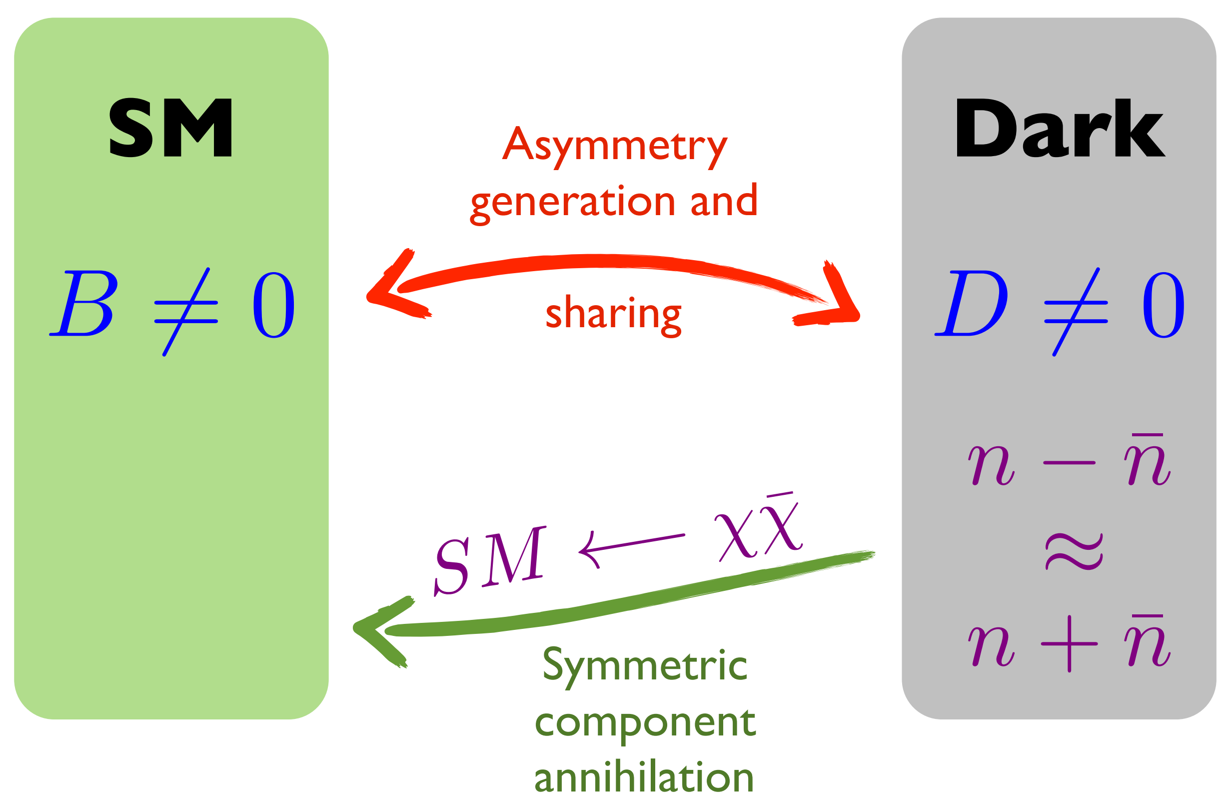


- Asymmetric DM, hidden valleys, mirror worlds, SUSY dark sectors, non-thermal DM

ASYMMETRIC DM

- Motivated by $\rho_{\mathrm{DM}} \sim \rho_{\mathrm{Baryon}}$
  relic density related to baryon asymmetry?

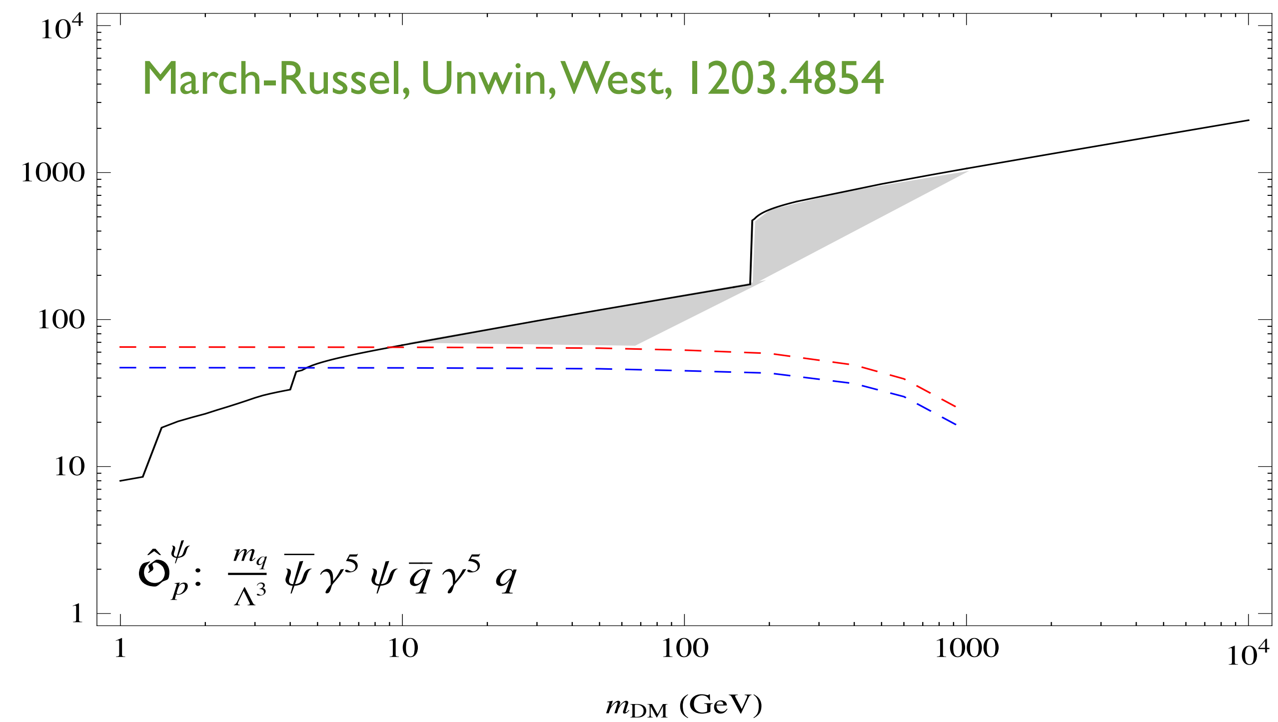
- Important components (collider perspective):
  - asymmetry sharing mechanism
  - efficient annihilation of symmetric relic density to SM



SYMMETRIC COMPONENT ANNIHILATION

- Requires stronger annihilation than thermal relic

- Already strongly constrained by mono jets



- Simple mediator models should be testable reliably at 100 TeV; should have more detailed study (beyond EFT)!

ASYMMETRY MEDIATOR

- Chances more model dependent
  - Leptogenesis like mechanisms: Typically high scale, unlikely in reach of current/next-gen colliders
  - Dark sphalerons: Z' and W' signals. TeV scale possible, but not guaranteed
  - Via weak scale baryogenesis: Requires extended Higgs sector (N. Craigs talk)

    e.g. Cheung, Zhang, 1306.4321
  - Dark baryogenesis: Also requires mediator, model dependent

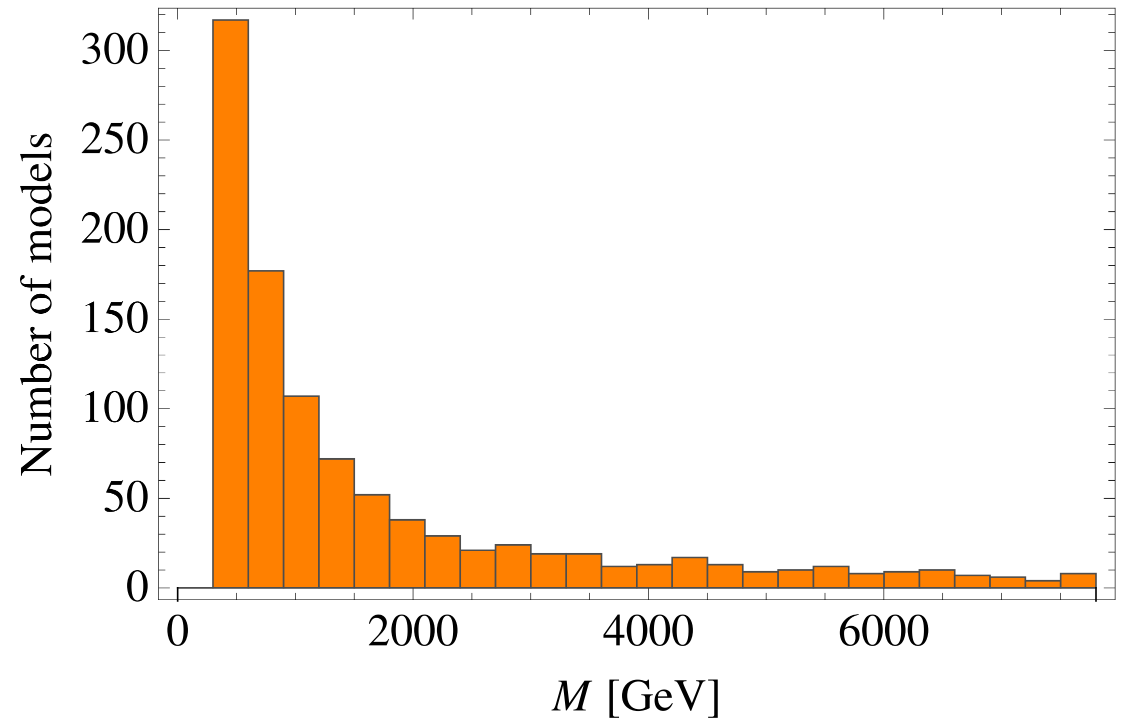
(DARK) HIDDEN VALLEYS

Strassler & Zurek, hep-ph/0604261

- One example: Hidden sector with dark QCD DM is dark baryon, $M_{DM} \sim M_p$ from IRFP

Bai, PS, 1306.4676

- Bi-fundamental mediators decouple at scale M



$M \sim \text{few TeV}$ required by IRFP and dark pion lifetime

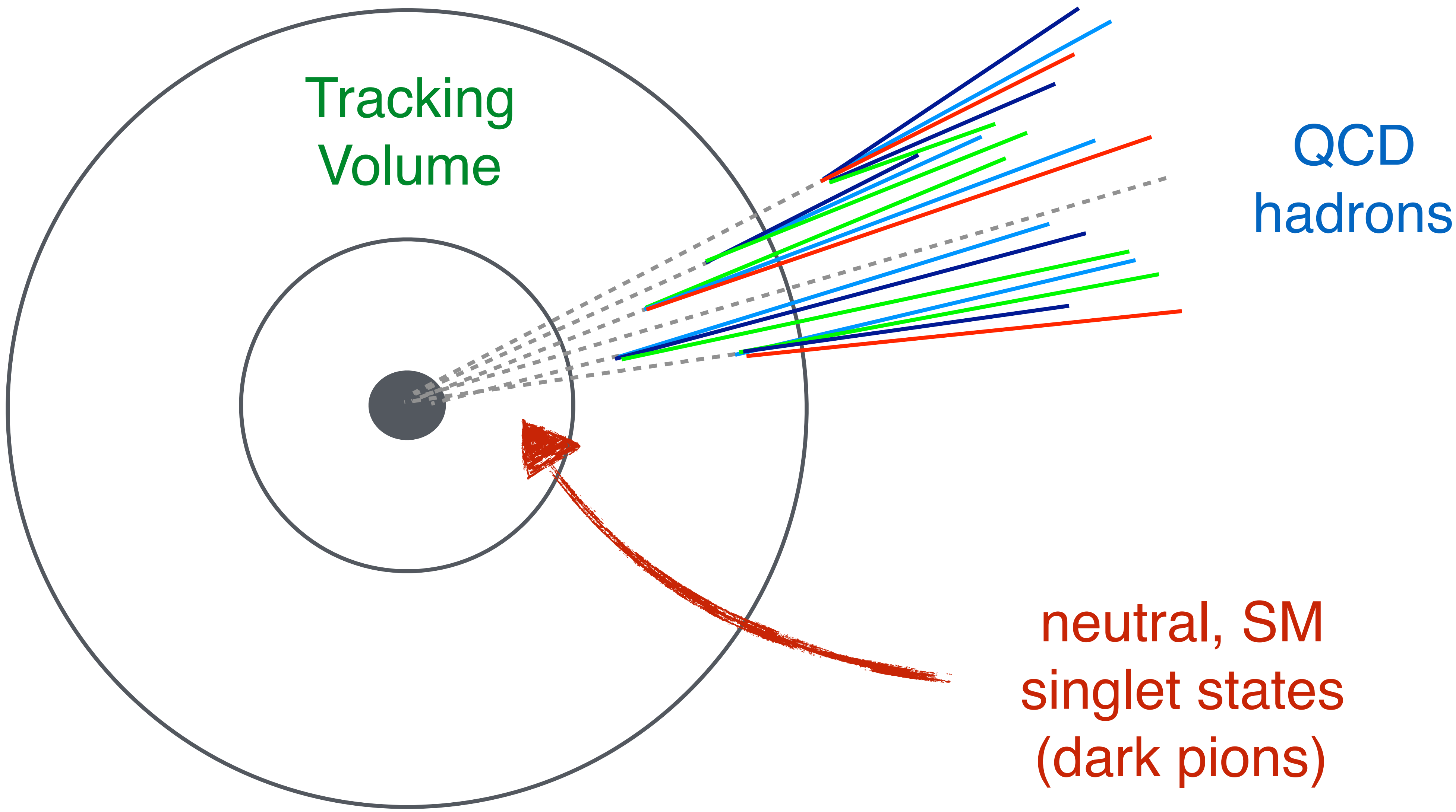
- Jets + dark jets/MET signatures, most models testable at 100 TeV collider

Many other interesting models… no time :(

SUMMARY

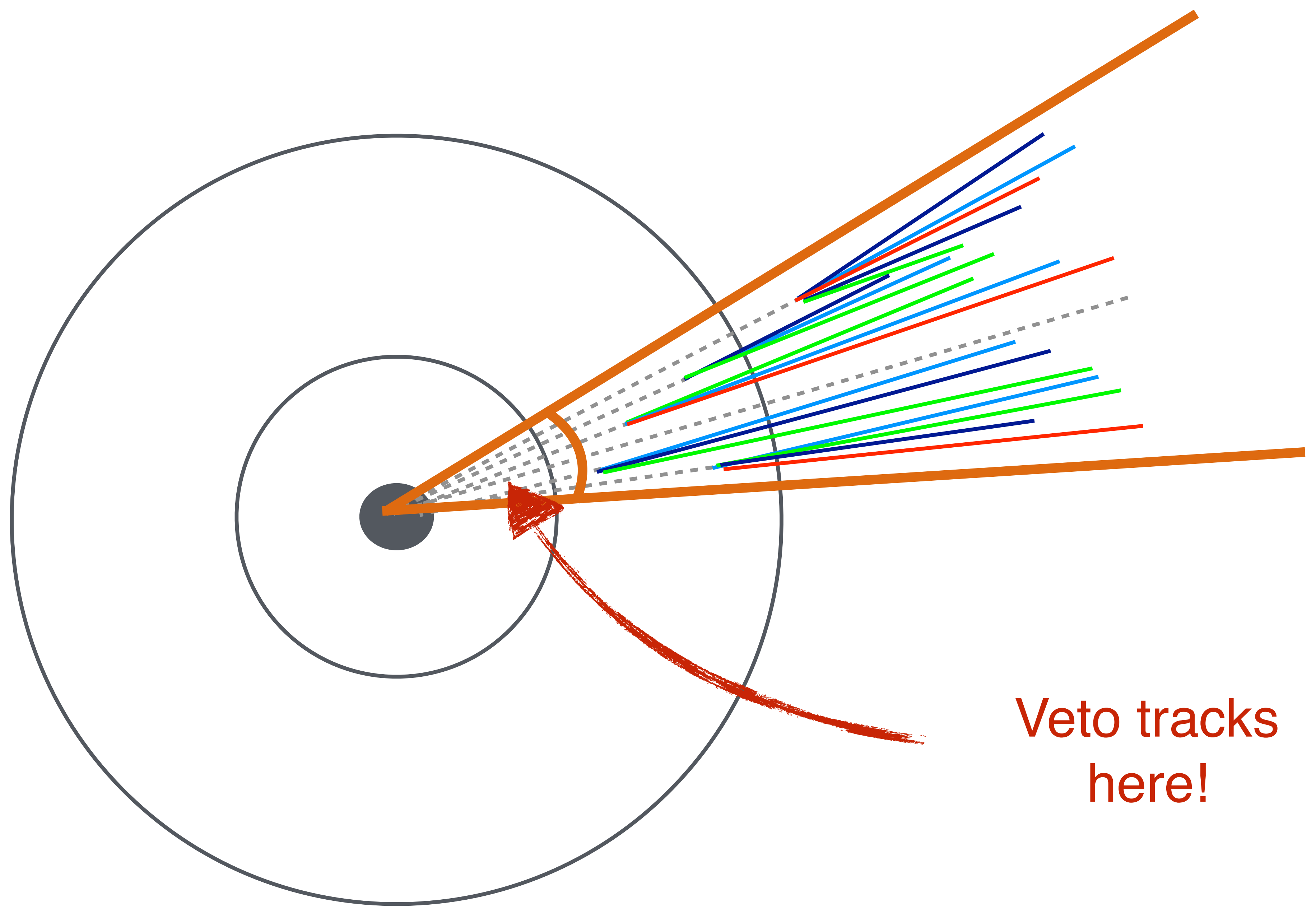
- WIMP paradigm strongly suggests DM at or below the few TeV scale - many models in reach of FHC/FCC/100 TeV
- Mono jets everywhere. Don't forget, DM not always a singlet:
  - soft leptons
  - displaced vertices/charged tracks
  - mono-Higgs , Z , γ (also mono Z')
  - quark/gluon jet discrimination (e.g. 1312.5325)
- non-WIMP DM can have spectacular signatures
  - few TeV scale motivated in some scenarios, e.g. many models of asymmetric DM
  - Exotic signatures from complex dark sectors, e.g. dark jets, long cascades, displaced vertices (and maybe baryon number violation???)

Emerging Jets



PS, Stolarksi, Weiler, JHEP 2015

Strategy



PS, Stolarksi, Weiler, JHEP 2015