A new variant of dark matter freeze-out predicting long-lived particles at the LHC

[based on Garny, JH, Lülf, Vogl, 1705.09292, *to appear in PRD*]

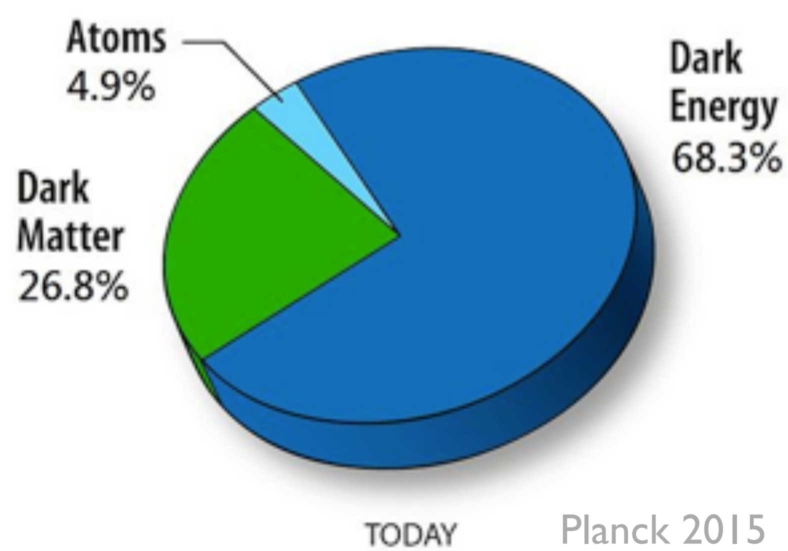
Jan Heisig (RWTH Aachen University)

Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

Among key scientific goals of LHC:

- Pinpoint the nature of dark matter!

Energy density of the universe:



Planck 2015

<u>Needed</u>: Predictions for possible signatures of dark matter models

Vanilla WIMP (Weakly Interacting Massive Particle)

Nice features:

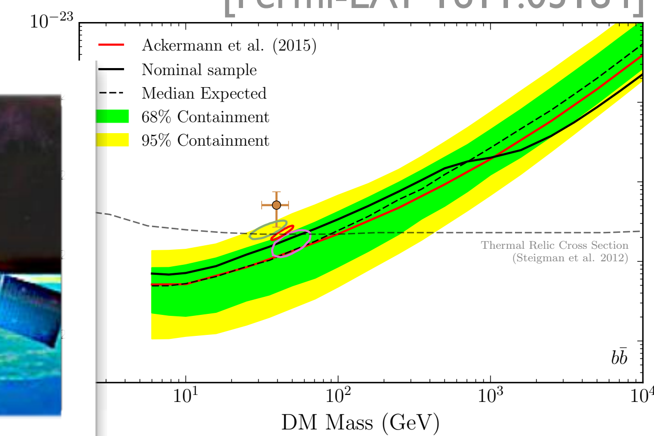
- Works with simple models ✓
- Not sensitive to initial thermal conditions (reheating) ✓
- Allows us to directly connect relic density (freeze-out) and experimental observables ⇒ clear predictions ✓

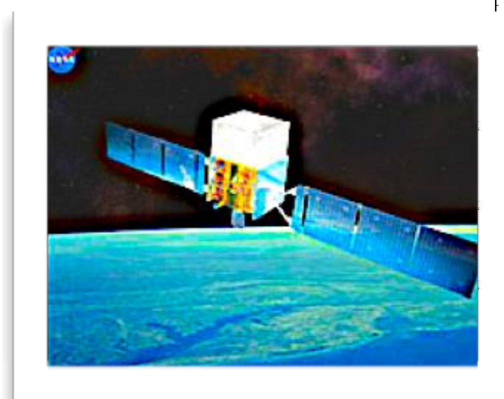
LHC WIMP-program: MET-searches

Vanilla WIMP (Weakly Interacting Massive Particle)

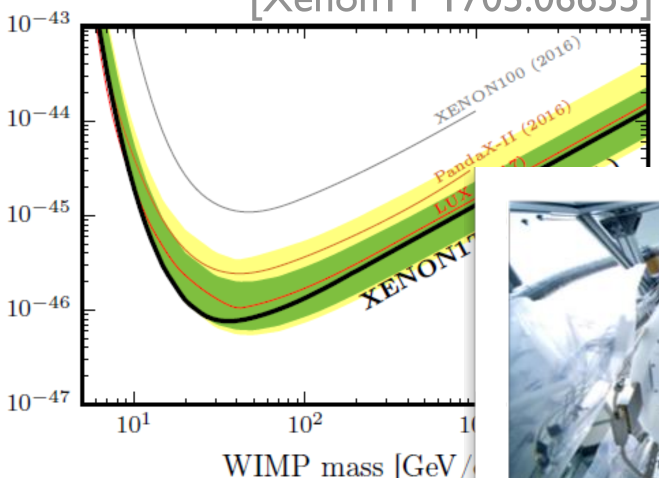
Less nice features:

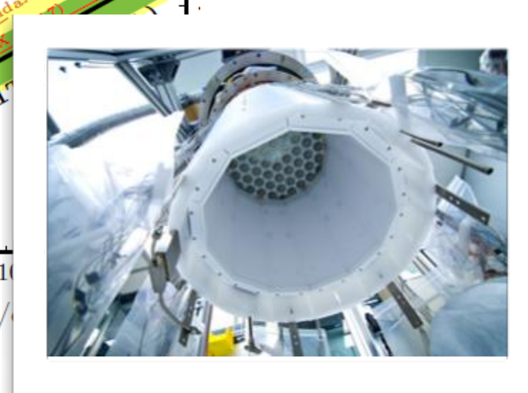
[Fermi-LAT 1611.03184]

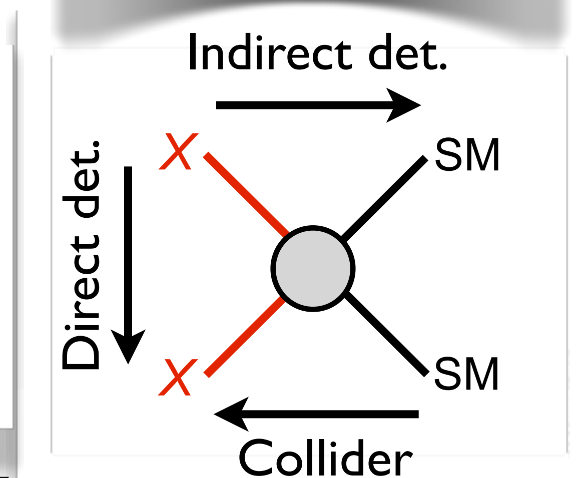




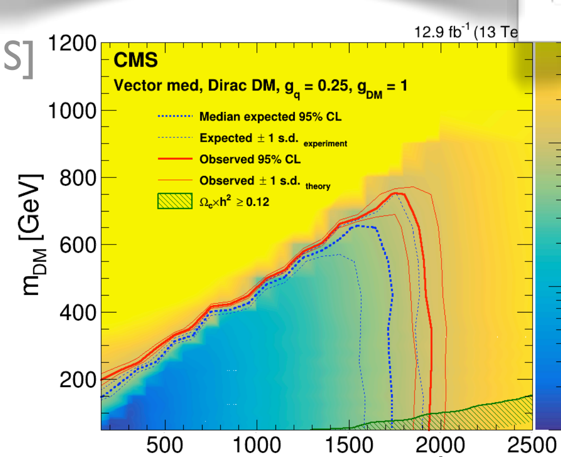
[XenonIT 1705.06655]

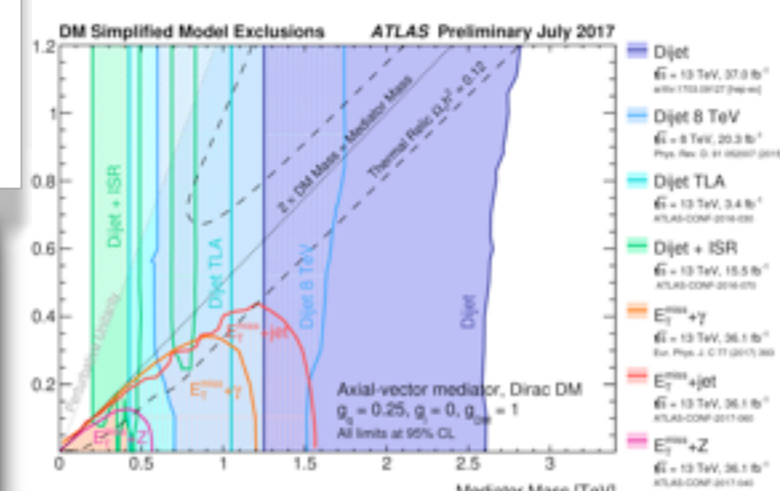






[CMS]





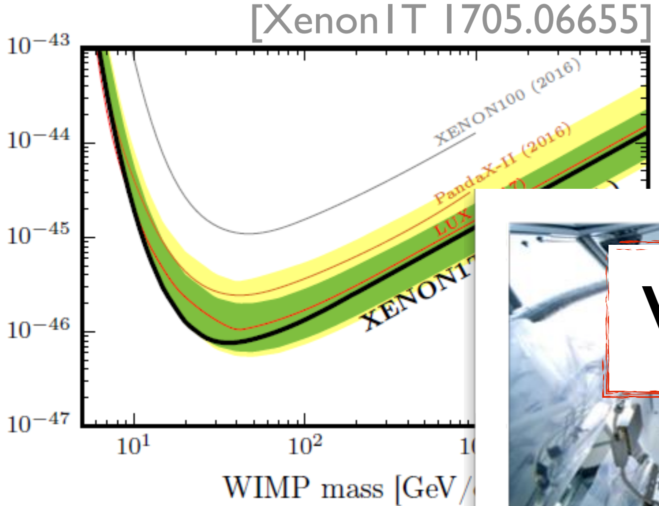
[ATLAS]

DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.5 TeV	g_q=0.25, g_χ=1.0, $m(\chi)$ < 400 GeV	ATLAS-CONF-2017-060
	Vector mediator (Dirac DM)	0 e, μ, 1 γ	≤ 1 j	Yes	36.1	m_{med} 1.2 TeV	g_q=0.25, g_χ=1.0, $m(\chi)$ < 480 GeV	1704.03848
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi)$ < 150 GeV	1608.02372

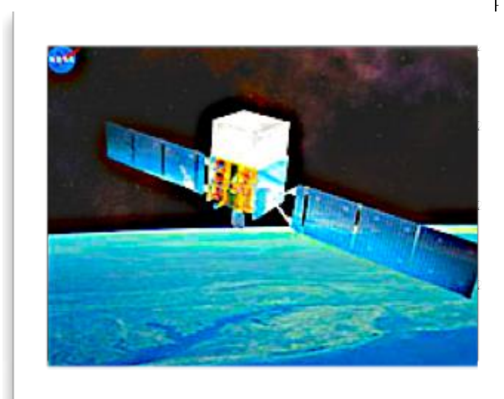
Vanilla WIMP (Weakly Interacting Massive Particle)

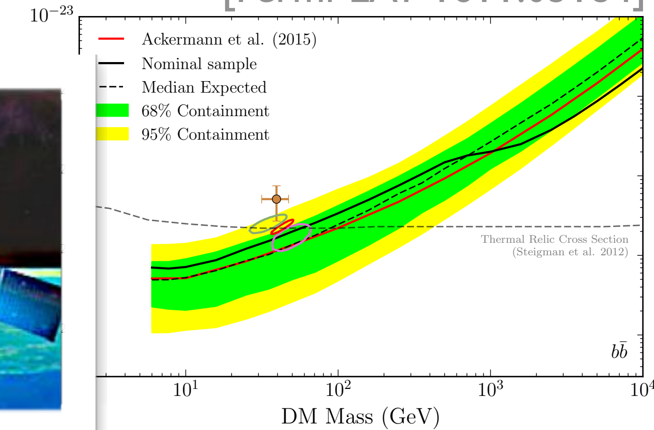
Less nice features:

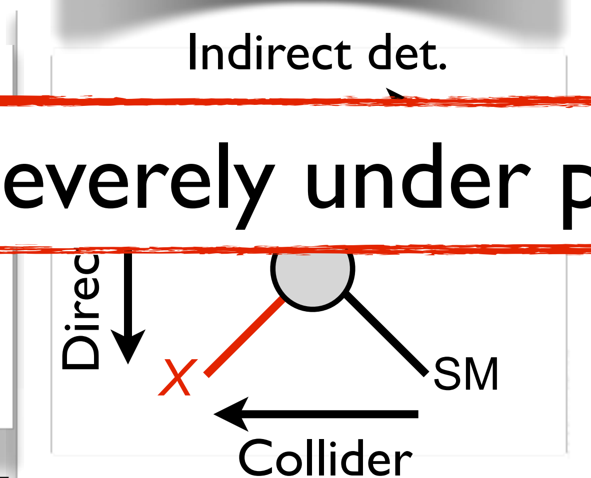
[Xenon1T 1705.06655]



[Fermi-LAT 1611.03184]

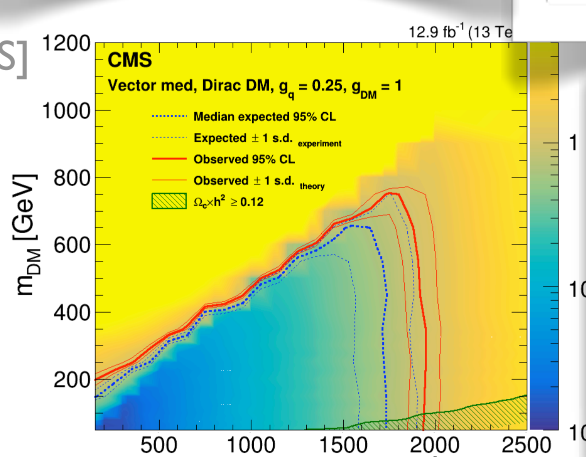


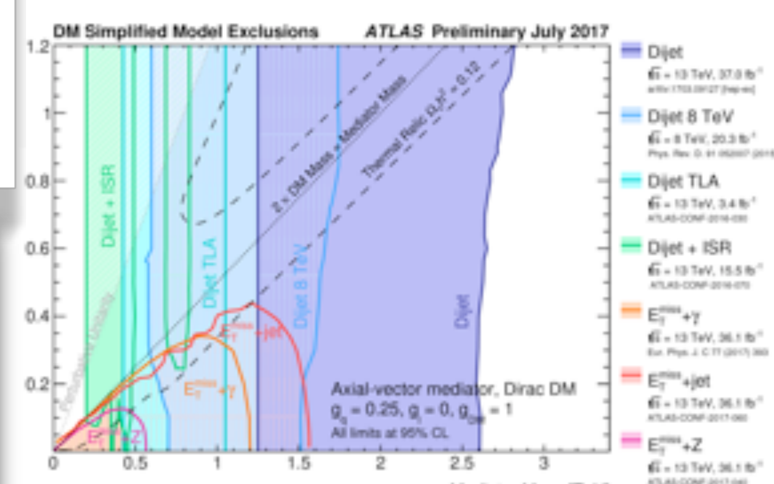




WIMPs severely under pressure

[CMS]





[ATLAS]

DM	Axial-vector mediator (Dirac DM)	0 e,μ	$1-4$ j	Yes	36.1	m_{med} 1.5 TeV	g_q=0.25, g_χ=1.0, $m(\chi)$ < 400 GeV	ATLAS-CONF-2017-060
	Vector mediator (Dirac DM)	0 e,μ, 1 γ	≤ 1 j	Yes	36.1	m_{med} 1.2 TeV	g_q=0.25, g_χ=1.0, $m(\chi)$ < 480 GeV	1704.03848
	$VV\chi\chi$ EFT (Dirac DM)	0 e,μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi)$ < 150 GeV	1608.02372

Other ways to produce dark matter with same nice features?

Other ways to produce dark matter with same nice features?

Yes!

This talk: Consider slight departure from WIMP co-annihilation scenario

➔ A new variant of dark matter production:

"Conversion-driven freeze-out"

[Garny, JH, Lülf, Vogl 2017]

[see also D'Agnolo, Pappadopulo, Ruderman, 2017]

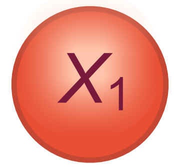
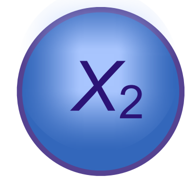
Conversion-driven freeze-out

- Works with simple models ✓
- Not sensitive to initial thermal conditions (reheating) ✓
- Allows us to directly connect relic density (freeze-out) and experimental observables ⇒ clear predictions, ✓

namely: <u>Long-lived particles at LHC</u>

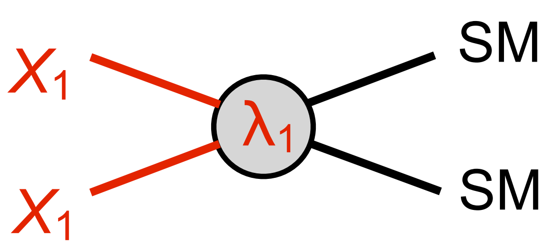
Other avenues beyond WIMPs: Secluded dark matter [Pospelov, Ritz, Voloshin 2007; Feng, Kumar 2008], Asymmetric dark matter [Kaplan, Luty, Zurek, 2009], Freeze-in [Hall, Jedamzik, March-Russell, West, 2009], SIMPs [Hochberg, Kuflik, Volansky, Wacker, 2014], Co-Decaying dark matter [Dror, Kuflik, Ng, 2016], Forbidden dark matter [Griest, Seckall, 1991; D'Agnolo, Ruderman, 2015], Pseudo-Dirac dark matter [Davolia, De Simone, Jacquesa, Sanz 2017], ELDERs [Kuflik, Perelstein, Rey-Le Lorier, Tsai, 2016 & 2017], superWIMPs [Feng, Rajaraman, Takayama 2003], ...

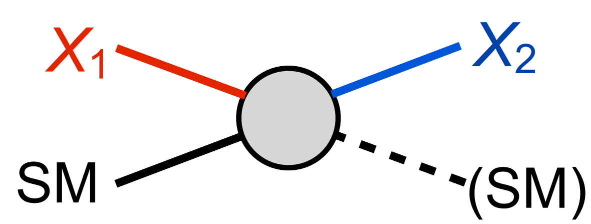
Revisiting WIMP co-annihilation

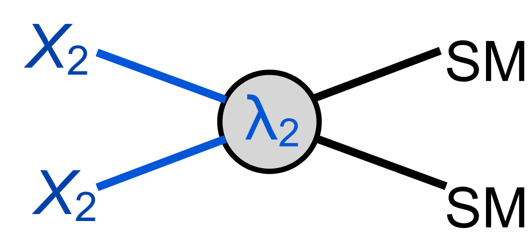
dark matter  $m_1 < m_2$  co-annihilation partner

λ_1 $\quad \Delta m \ll m_{1,2} \quad$ λ_2

Annihilation	Conversion	+	Co-annihilation
$X_1 \rightarrow \mathrm{SM}$	$X_1 \rightarrow X_2$		$X_2 \rightarrow \mathrm{SM}$







Usually (SUSY): $\lambda_1 \sim \lambda_2 \sim g_{\mathrm{SM}}$ $\Rightarrow$ conversion always efficient

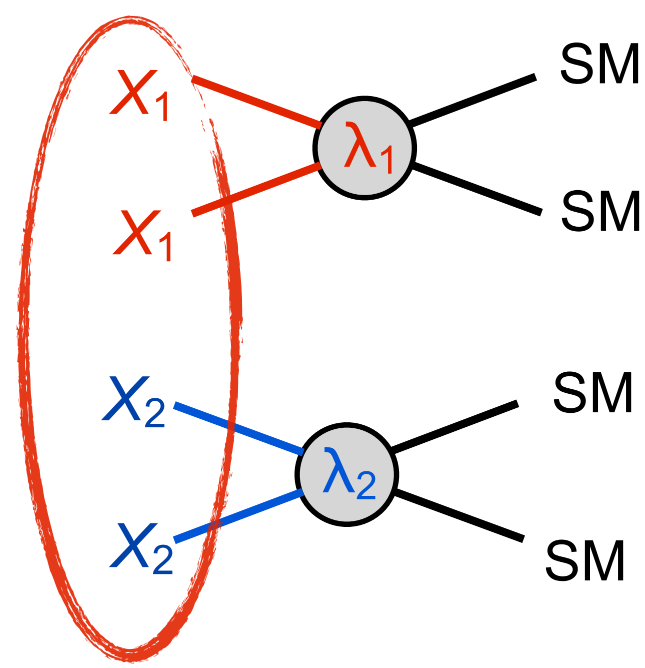
$$X_1 \overset{\text{eq.}}{\longleftrightarrow} X_2$$

Revisiting WIMP co-annihilation

Usually (SUSY): $\lambda_1 \sim \lambda_2 \sim g_{SM}$ $\Rightarrow$ conversion always efficient

$$X_1 \overset{\text{eq.}}{\longleftrightarrow} X_2$$

Annihilation+
Co-annihilation
in dark sector
$X_1, X_2 \rightarrow$ SM



Larger effective annihilation cross section helps to reduce relic density: $\Omega h^2 \propto \dfrac{1}{\langle \sigma v \rangle_{\text{eff}}}$

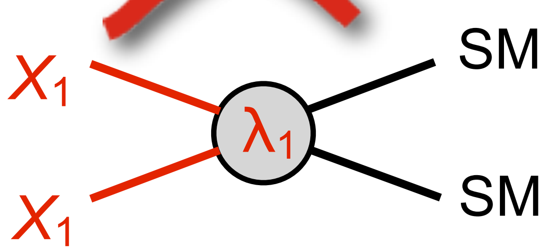
Conversion-driven freeze-out

[Garny, JH, Lülf, Vogl 2017]

Consider $\lambda_1 \ll \lambda_2$: $X_1 \overset{\text{eq.?}}{\longleftrightarrow} X_2$

~~Annihilation~~

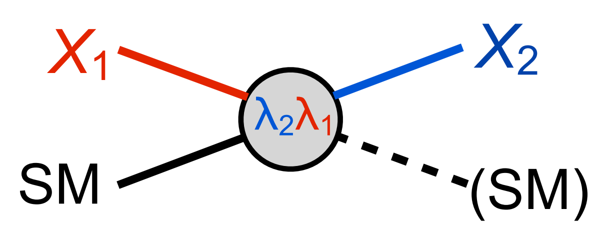
~~$X_1 \to$ SM~~



negligable

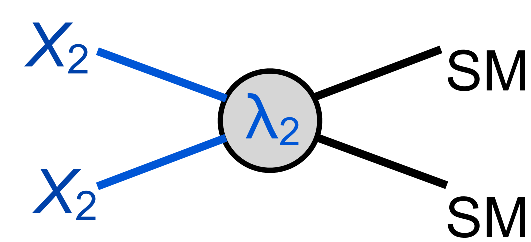
Conversion

$X_1 \to X_2$



Co-annihilation

$X_2 \to$ SM



large rate

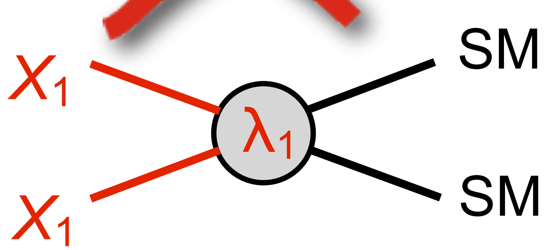
Conversion-driven freeze-out

[Garny, JH, Lülf, Vogl 2017]

Consider $\lambda_1 \ll \lambda_2$: $X_1 \overset{\text{eq.?}}{\longleftrightarrow} X_2$

~~Annihilation~~

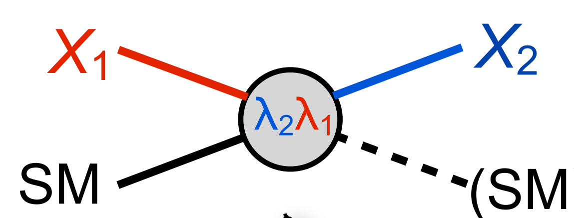
~~$X_1 \to$ SM~~



negligable

Conversion

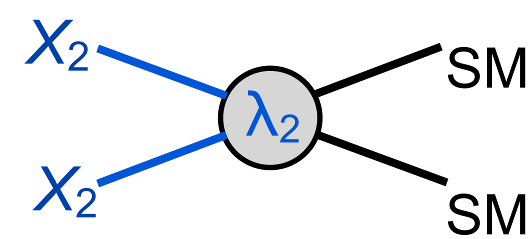
$X_1 \to X_2$



bottleneck!

Co-annihilation

$X_2 \to$ SM



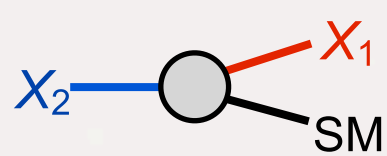
large rate

➔ Relic density is set by the size of the conversion rate

General back-of-the-envelope estimation:

Conversion rate (just) efficient at freeze-out:

$$\Gamma_{\mathrm{con}} \sim H\left(T_{\mathrm{f}} \simeq \frac{m_X}{30}\right)$$

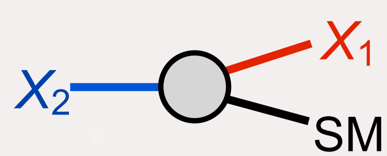
If (inverse) 2-body decay 

is allowed: $\Gamma_{\mathrm{con}} \sim \Gamma_{X_2}$

General back-of-the-envelope estimation:

Conversion rate (just) efficient at freeze-out:

$$\Gamma_{\mathrm{con}} \sim H\left(T_{\mathrm{f}} \simeq \frac{m_X}{30}\right)$$

If (inverse) 2-body decay 

is allowed: $\Gamma_{\mathrm{con}} \sim \Gamma_{X_2}$

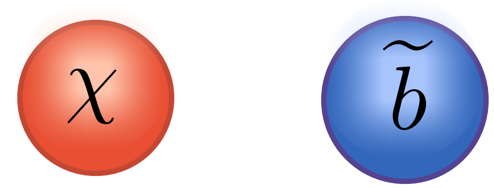
$\Rightarrow$ X_2 decay-length: $\dfrac{1}{\Gamma_{X_2}} \sim \dfrac{1}{H(T_{\mathrm{f}})} \sim 1\text{–}100\,\mathrm{cm}$

(for masses 100GeV to a few TeV)

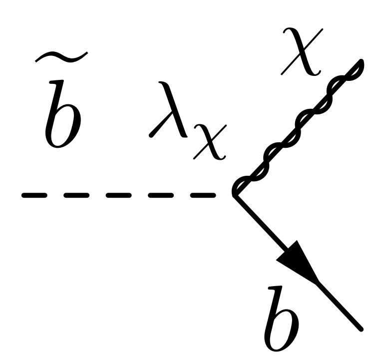
$\Rightarrow$ LHC: long-lived particles!

A concrete example

- Specific model: $\mathcal{L}_{\mathrm{int}} = |D_\mu \widetilde{q}|^2 - \lambda_\chi \widetilde{q}\bar{q}\frac{1-\gamma_5}{2}\chi + \mathrm{h.c.}$
- SUSY-inspired simplified model:
  Choose Majorana DM and scalar bottom-partner



- Yukawa-type interaction:

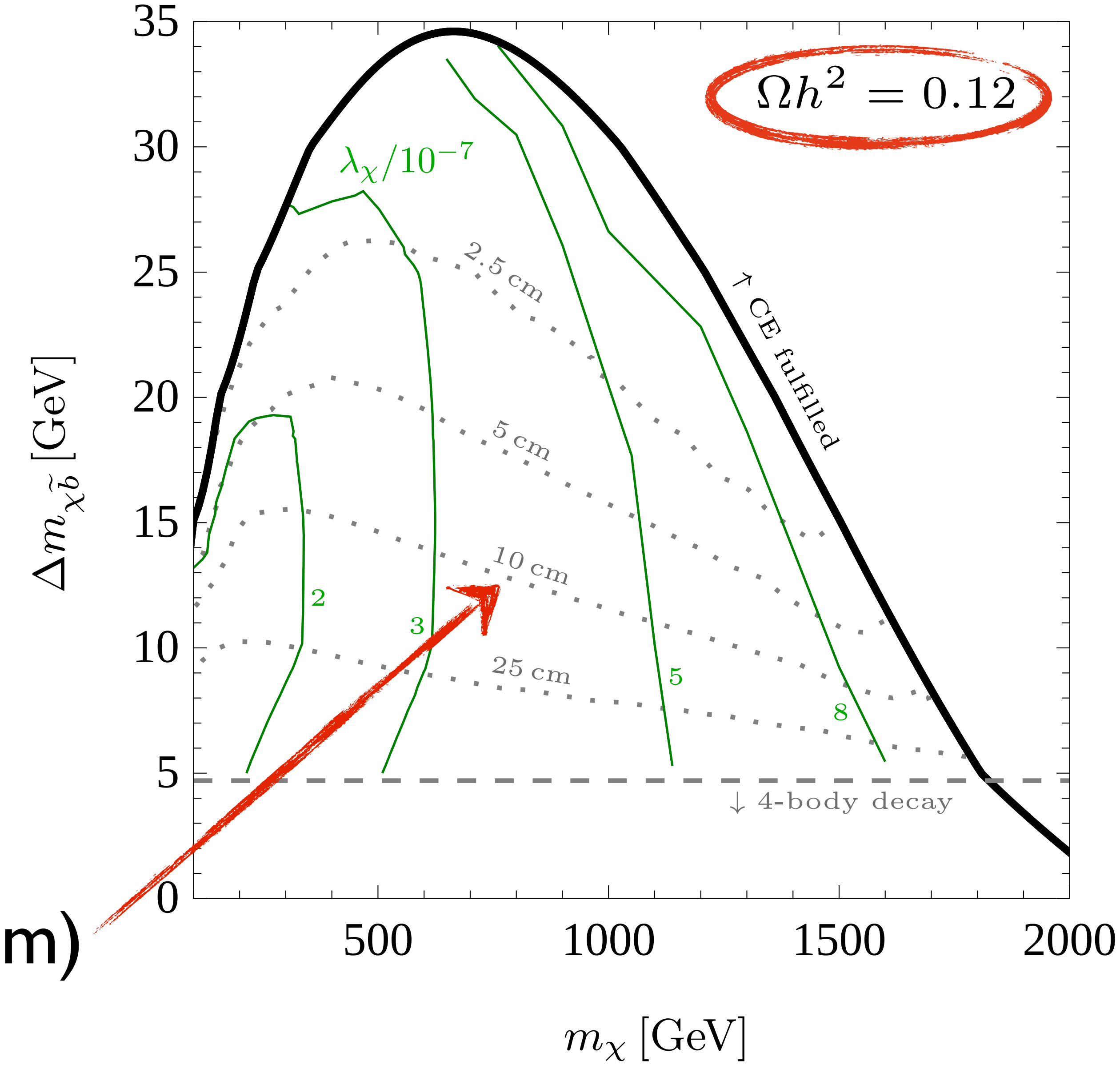


λ_χ is a free parameter here [see Ibarra et al. 2009 for SUSY realization]

Allowed parameter space

[Garny, JH, Lülf, Vogl 2017]

- Solve coupled set of Boltzmann equations
- Require Planck relic density



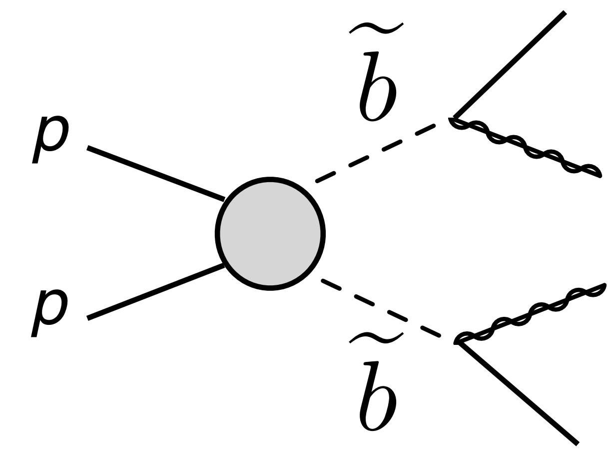
Decay length: *O*(1-100cm)

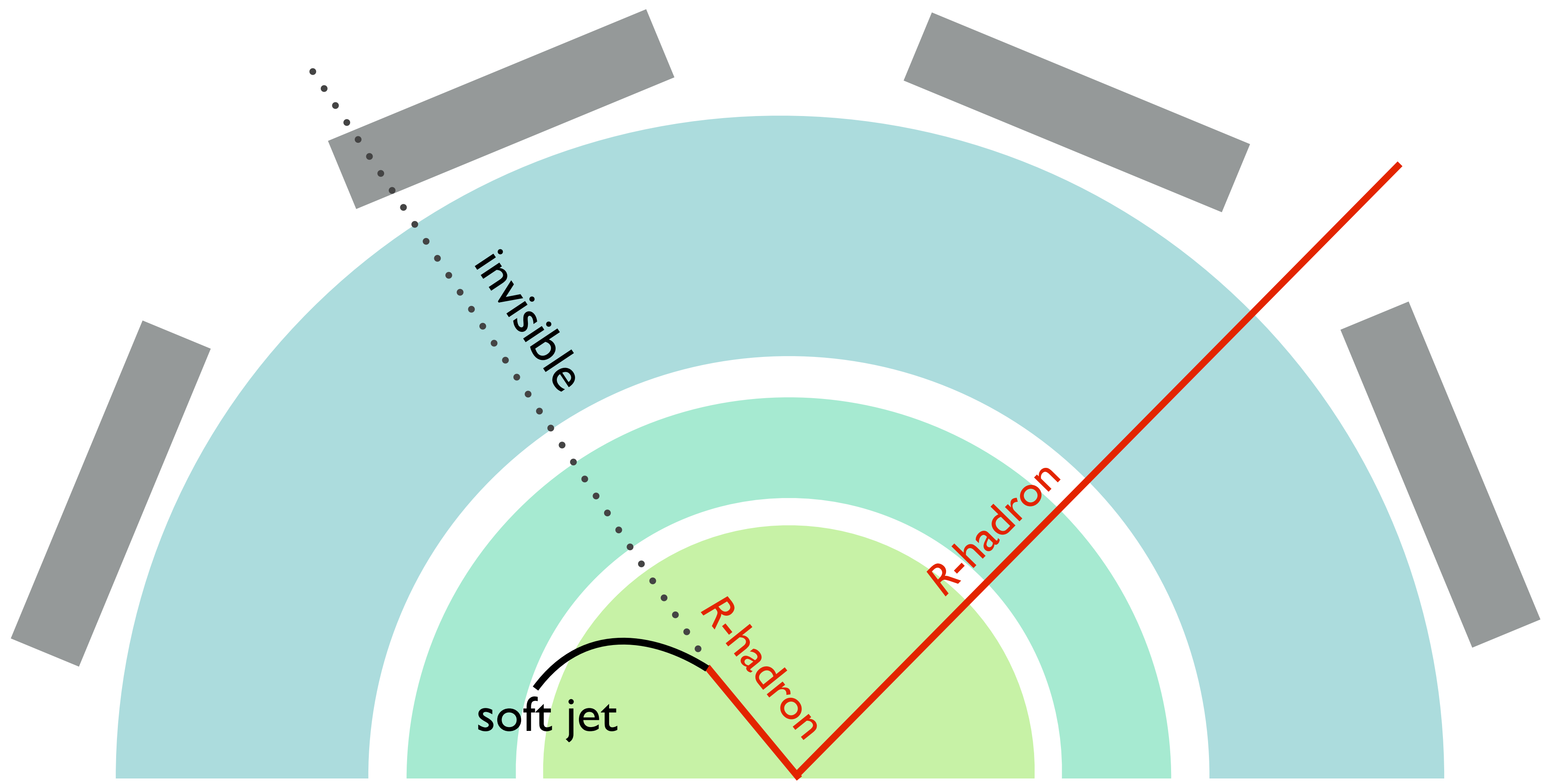
LHC constraints

Simplified model chapter:

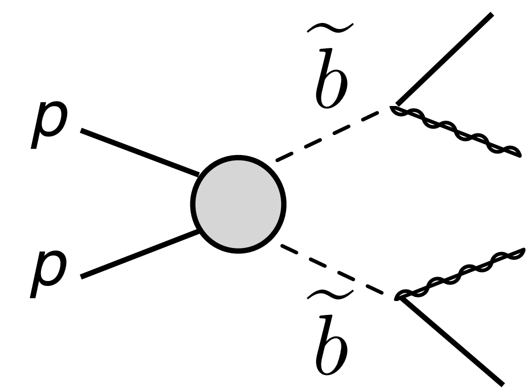
Production \ Decay	$j + \text{inv.}$	$jj(+\text{inv.})$	$j\ell$	$j\gamma$
DPP: squark pair or gluino pair	SUSY DM	SUSY	SUSY	

Table 1.3: **Simplified model channels for LLPs with color charge.**



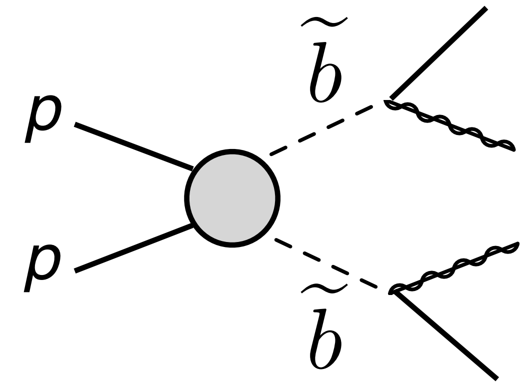


LHC constraints



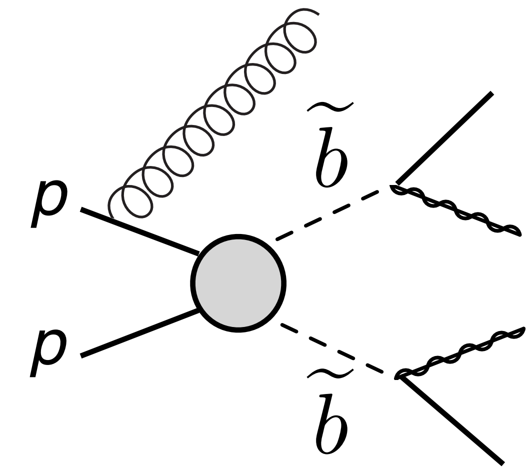
- Sbottom MET searches?

LHC constraints

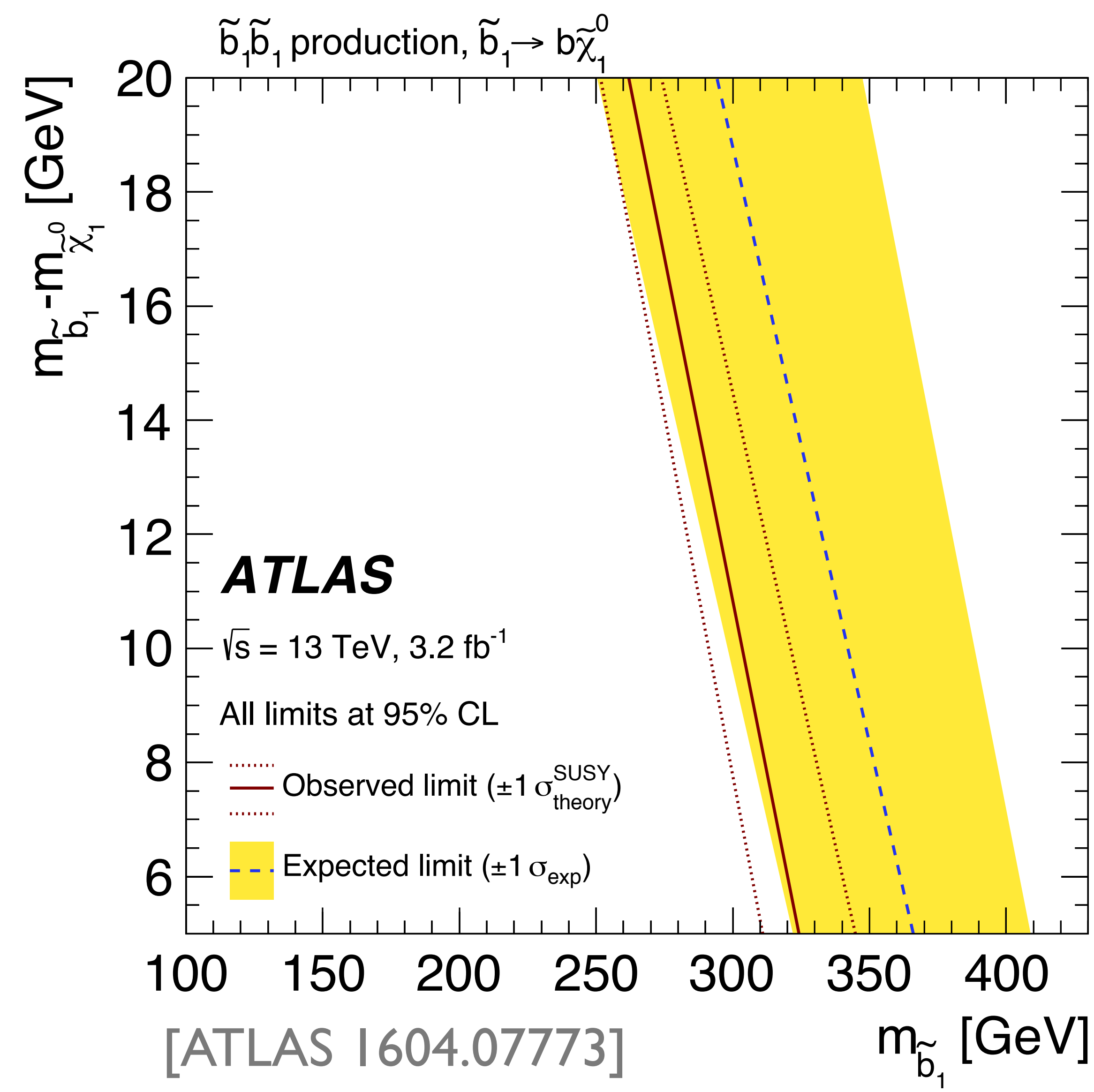


- Sbottom ~~MET~~ searches?   Non-prompt decay!

LHC constraints

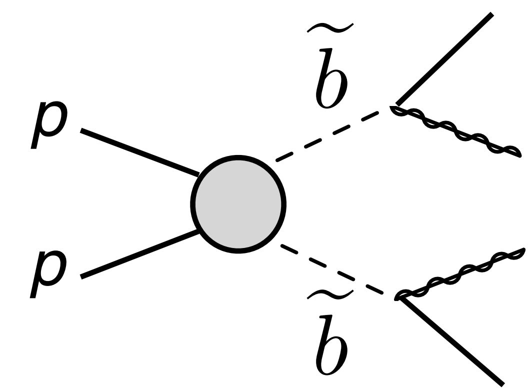


- Sbottom ~~MET~~ searches
- Mono-jet searches ✓



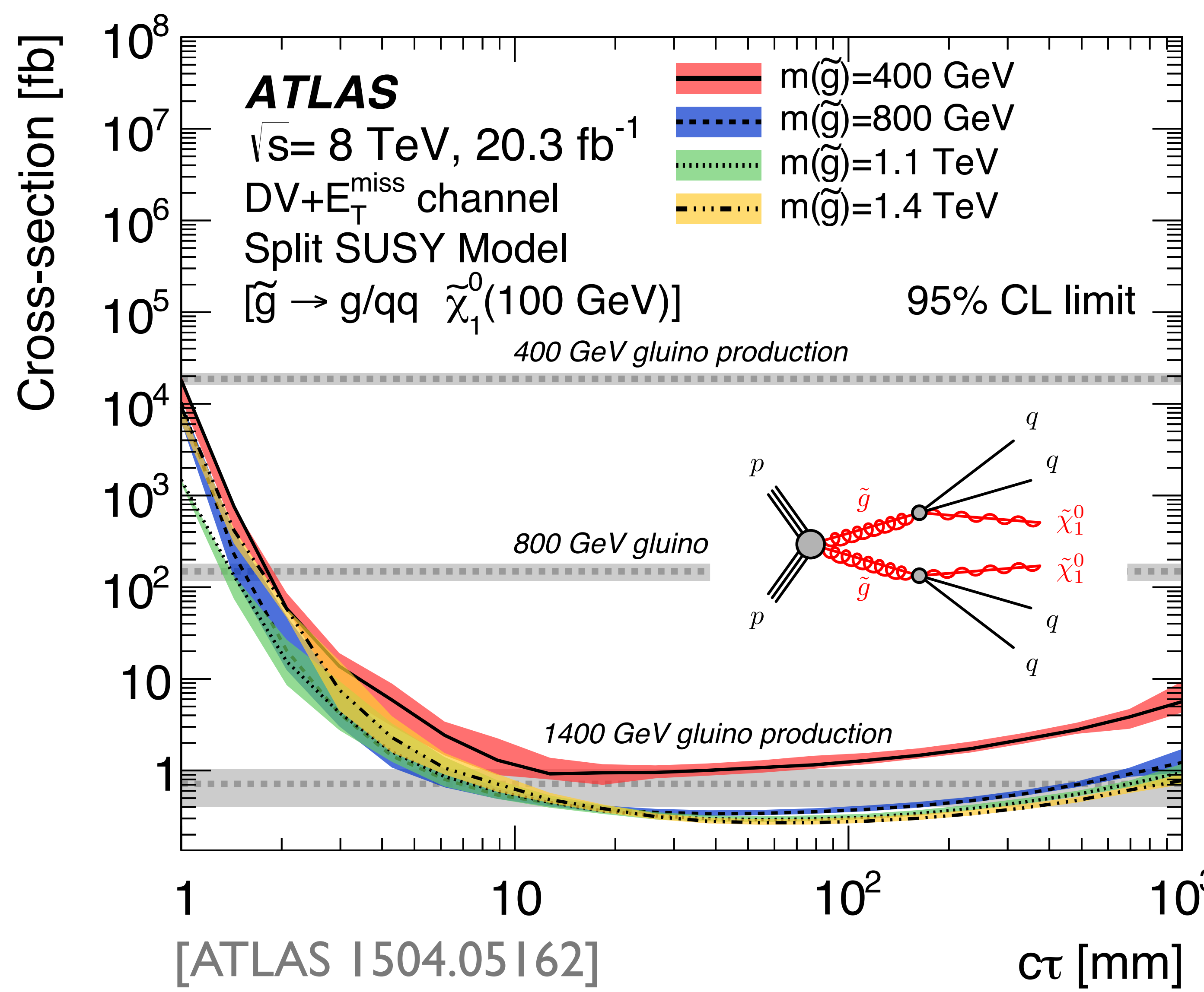
[ATLAS 1604.07773]

LHC constraints



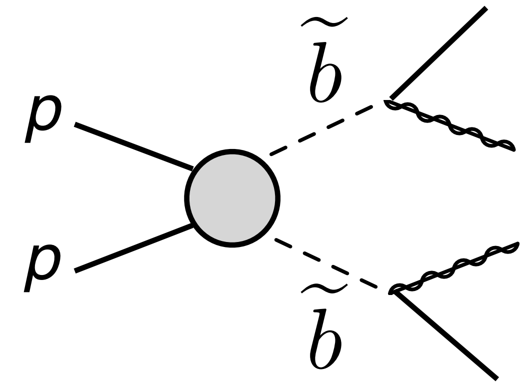
- Sbottom ~~MET~~ searches
- Mono-jet searches ✓
- Displaced jets ?

[see also ATLAS 1504.03634; as well as Davolia, De Simone, Jacquesa, Sanz 1706.08985 for a recent re-interpretation]



[ATLAS 1504.05162]

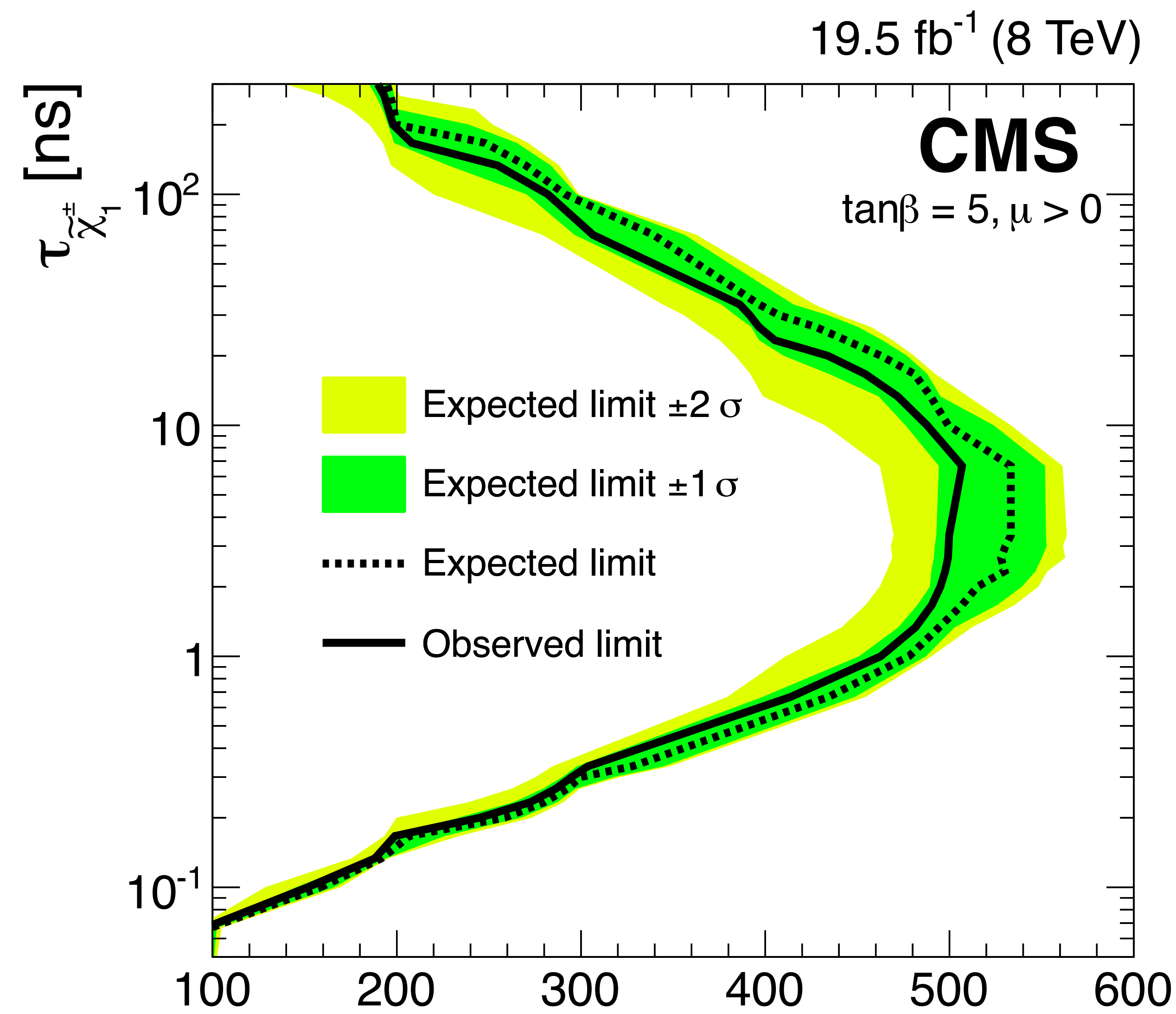
LHC constraints



- Sbottom ~~MET~~ searches
- Mono-jet searches ✓
- Displaced jets ?
- Disappearing tracks ?

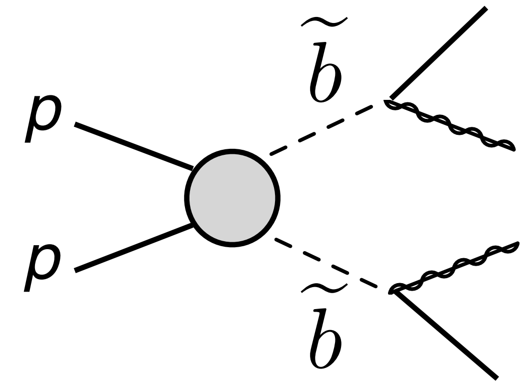
[see also ATLAS 1310.3675, ATLAS-CONF-2017-017]

Interpreted for chargino
➔ adapt to *R*-hadrons



[CMS 1411.6006]

LHC constraints



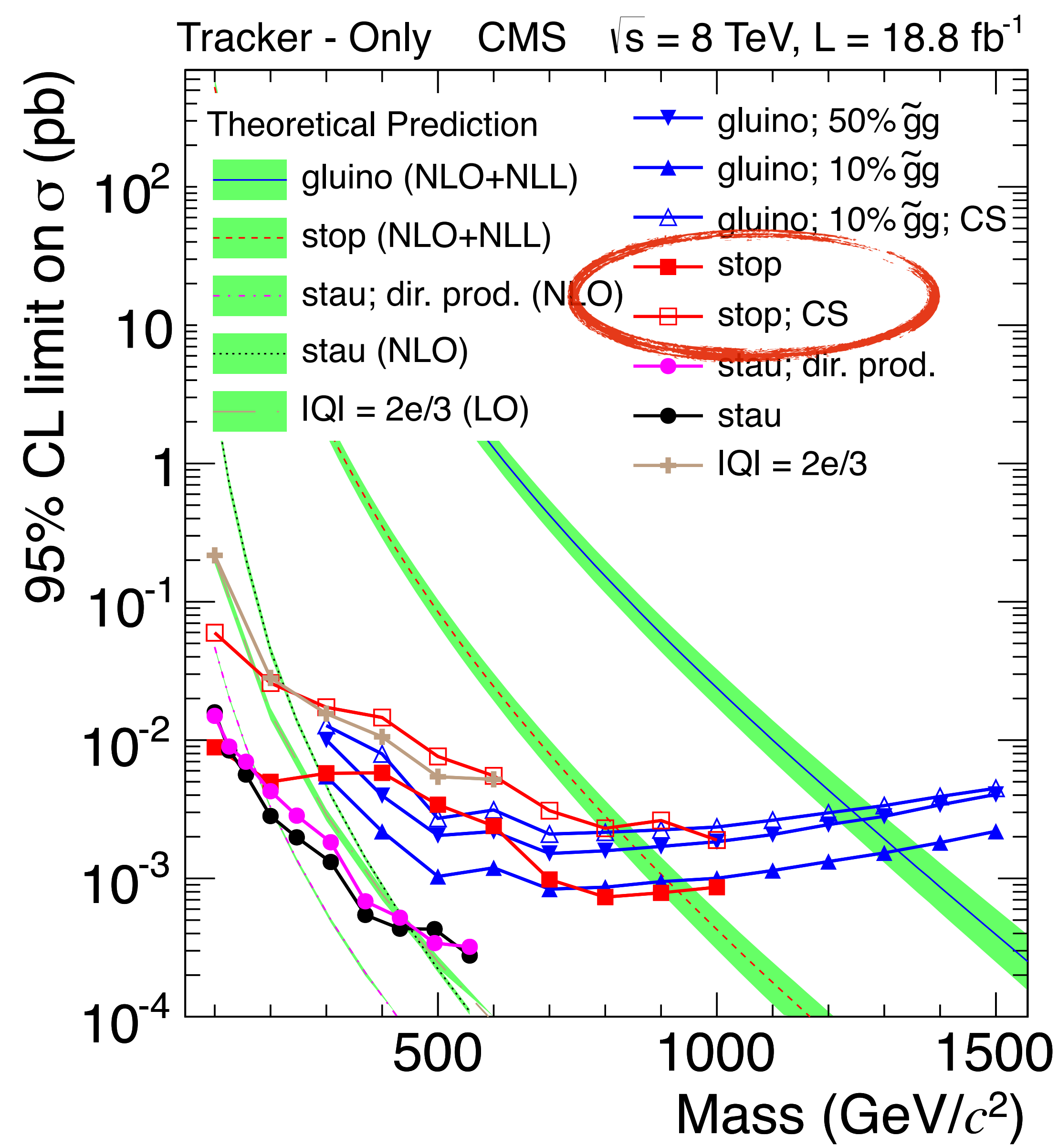
- Sbottom ~~MET~~ searches
- Mono-jet searches ✓
- Displaced jets ?
- Disappearing tracks ?
- HSCPs: search for detector-stable *R*-hadrons

➔ Reinterpretation for finite life-times

rescale signal by fraction passing the relevant detector parts:

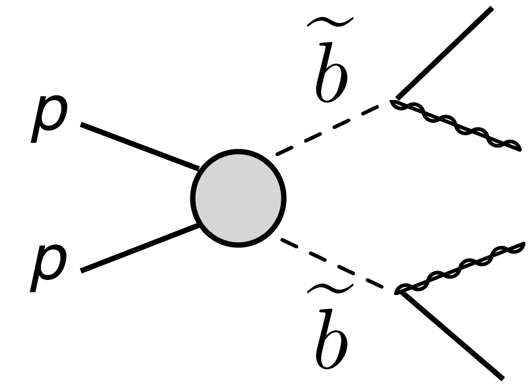
$$\sigma_{\text{pred}} \to \sigma_{\text{pred}} \times \overline{\mathcal{F}}_{\text{pass}}$$

Use [CMS 1502.02522] to estimate fraction



[CMS 1305.0491]

LHC constraints



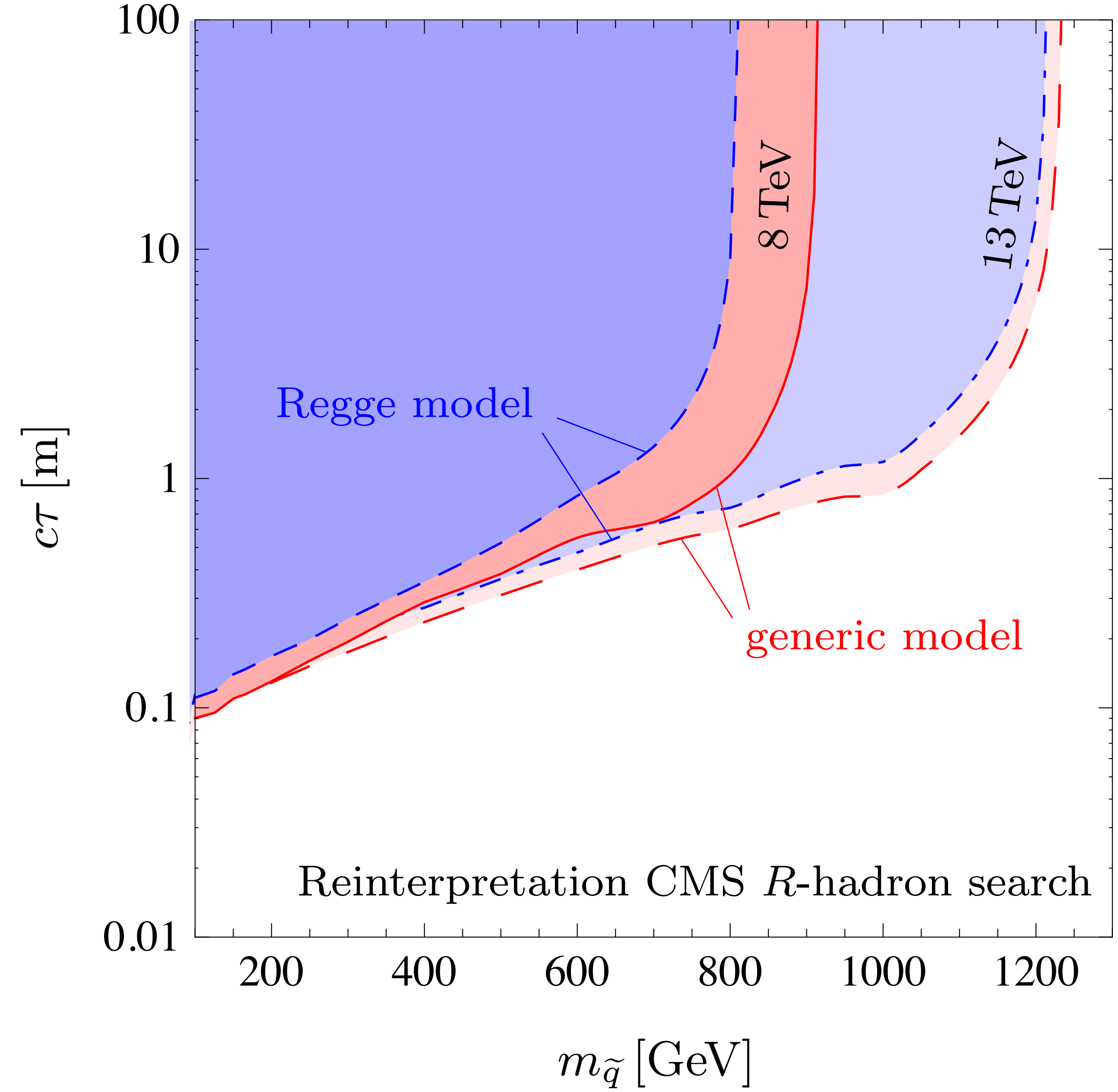
- Sbottom ~~MET~~ searches
- Mono-jet searches ✓
- Displaced jets ?
- Disappearing tracks ?
- HSCPs: search for detector-stable *R*-hadrons ✓

➔ Reinterpretation for finite life-times

rescale signal by fraction passing the relevant detector parts:

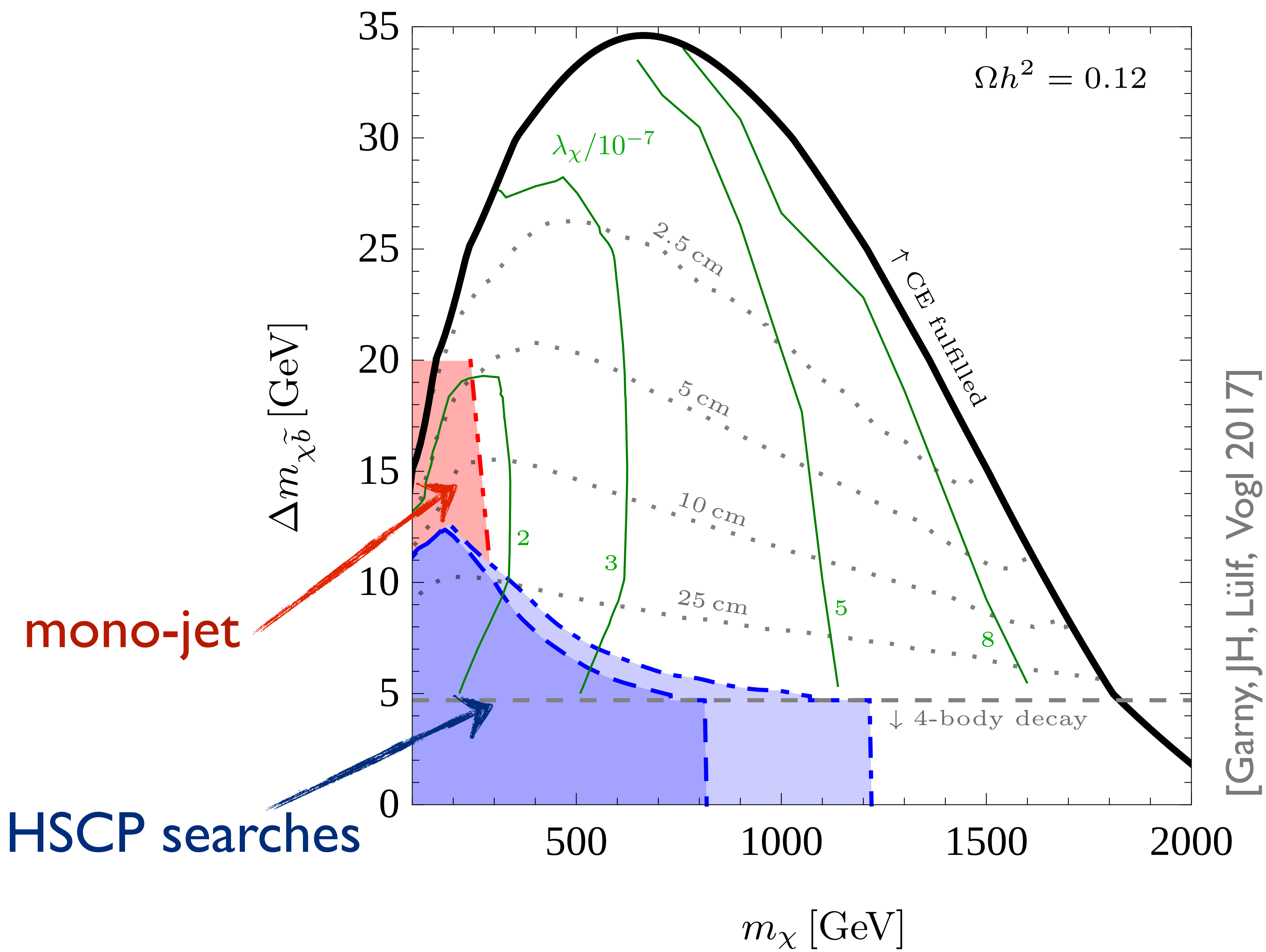
$$\sigma_{\text{pred}} \to \sigma_{\text{pred}} \times \overline{\mathcal{F}}_{\text{pass}}$$

Use [CMS 1502.02522] to estimate fraction

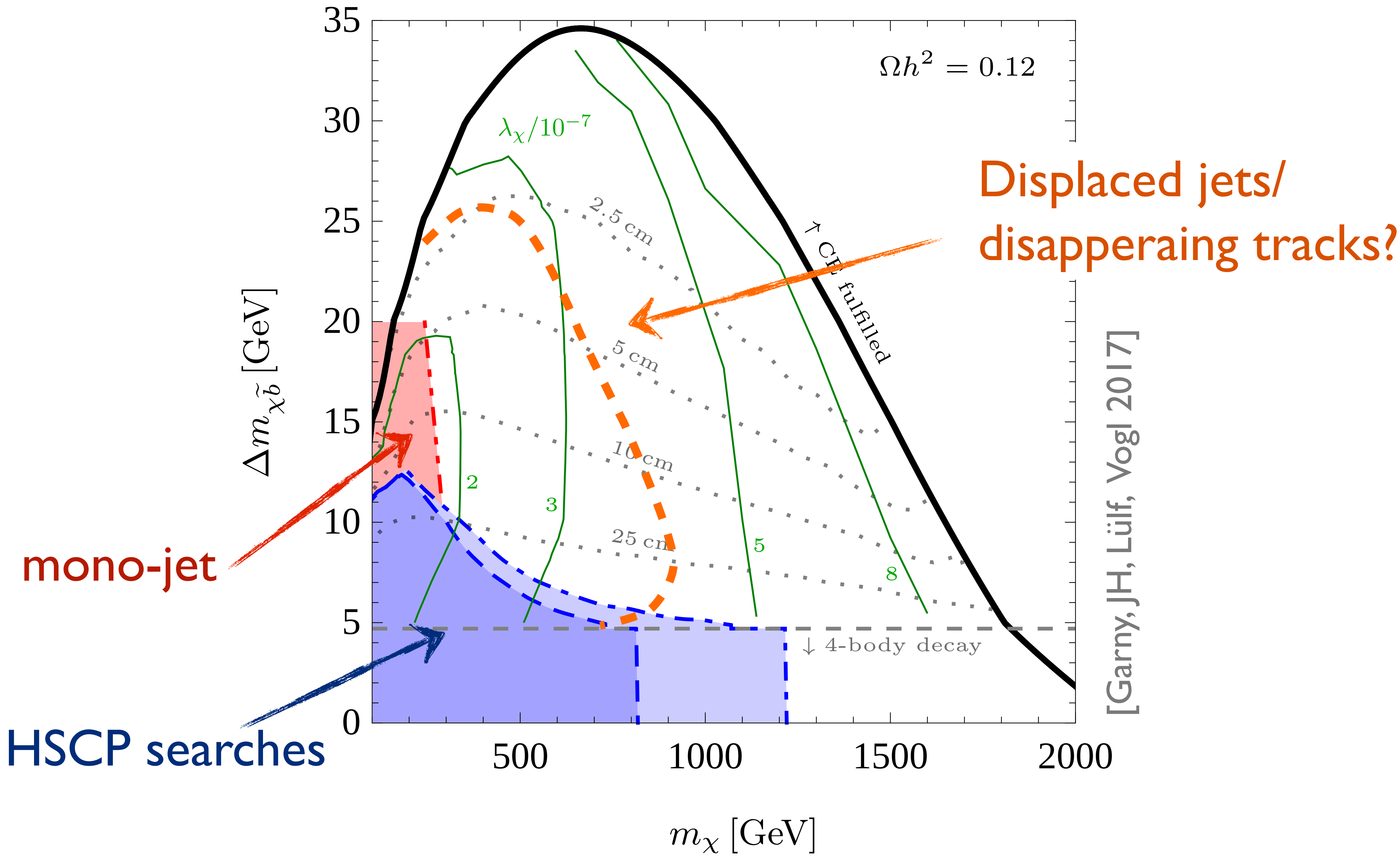


[Garny, JH, Lülf, Vogl 2017]

Allowed parameter space



Allowed parameter space



Summary

- Dark matter among key scientific goals for LHC
- Vanilla WIMP under pressure: Watch out for avenues beyond WIMPs with new LHC signatures!
- Conversion-driven freeze-out:
  - Shares nice features of WIMPs
  - Accommodates null-results from WIMP-searches
  - $H \sim \Gamma$: Lifetimes naturally O(1-100cm)

    $\Rightarrow$ Strong motivation for long-lived particles at LHC
- Our model: long-lived R-hadrons, other possibilities
- Interesting times for dark matter hunters lie ahead

Backup slide

Computation of the fraction of detector-stable *R*-hadrons:

$$\mathcal{F}^i_{\rm pass} = e^{-\ell/(c\tau\beta\gamma)} \ ,$$

$$\overline{\mathcal{F}}_{\rm pass} = \frac{\sum_i \mathcal{F}^i_{\rm pass}\mathcal{P}^i_{\rm on}\mathcal{P}^i_{\rm off}}{\sum_i \mathcal{P}^i_{\rm on}\mathcal{P}^i_{\rm off}}$$