Hunting for long-lived exotica using jets and missing transverse momentum

Marc Thomas

In collaboration with Alexander Belyaev,
Stefano Moretti, Ian Tomalin and Kilian Nickel

Plan

- Background on displaced vertices
  - Analyses
  - Models
- Study method
  - Signal from particles that decay ***outside*** the detector
  - Look for missing transverse momentum (MET)
  - Extend current searches for long-lived particles to longer lifetimes
- Results
  - Method applied to 2 specific models already studied by CMS
- Summary

Displaced Vertices

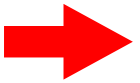
- Arise from long-lived particles with lifetimes in the nano – picosecond range.
- Reconstructed secondary vertex within detector.
- Multiple CMS/ATLAS searches in LHC run 1 (7, 8 TeV)
  - Decays in,
    - Inner detector, Hadronic calorimeter, Muon spectrometer
  - Signal searched for,
    - $e^+e^-, \mu^+\mu^-, q\bar{q}, jj$
    - Multi-track (5 or more charged particles)
- Would be missed without a dedicated search.

Models with Long-lived Particles

- Numerous models give rise to displaced vertices,
  - Split-SUSY
    - Scalars are heavy (squarks), Fermions are light (gluino)
    - Gluino can only decay via virtual *heavy* squarks
    - Long-lived gluino
  - “Hidden Valley” models
    - Additional non-abelian gauge group
    - Long-lived “v-hadrons”
  - Minimal B-L extension of the SM
    - Long-lived RH neutrinos.
  - R-parity Violating (RPV) SUSY
    - Long-lived neutrino
  - Non-SM Higgs models

Models with Long-lived Particles

- Numerous models give rise to displaced vertices,
  - Split-SUSY
    - Scalars are heavy (squarks), Fermions are light (gluino)
    - Gluino can only decay via virtual *heavy* squarks
    - Long-lived gluino
  - “Hidden Valley” models
    - Additional non-abelian gauge group
    - Long-lived “v-hadrons”
  - Minimal B-L extension of the SM
    - Long-lived RH neutrinos.
  - R-parity Violating (RPV) SUSY
    - Long-lived neutrino
  - Non-SM Higgs models



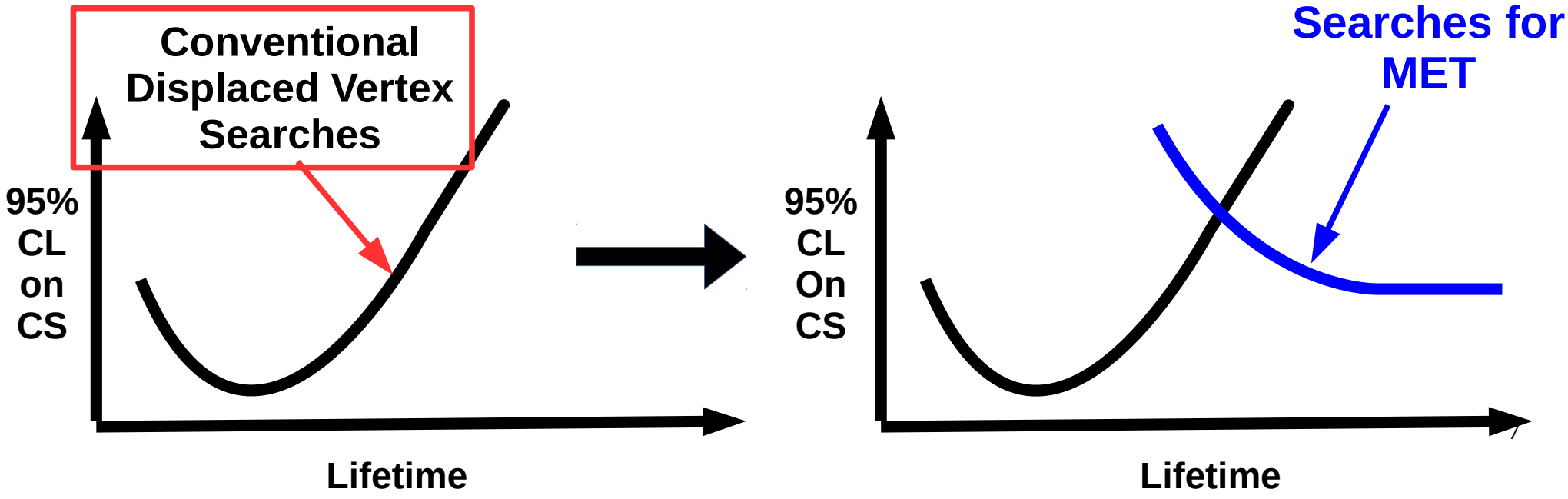
Models used in our study
(discussed more fully later)

Our Study Method

- Look for the signal from long-lived particles when they decays ***outside*** the detector
  - Large missing transverse energy signal.
  - Often associated jets.
- Multiple 7/8 TeV searches for MET signals by ATLAS/CMS
  - Usually in context of Dark Matter or Lightest Supersymmetric Particle (LSP).
  - Many different signal
    - MET + multiple jets, MET + monojet, MET + 1,2 leptons, etc.

Our Study Method

- Look for the signal from long-lived particles when they decays ***outside*** the detector
  - Large missing transverse energy signal.
  - Often associated jets.
- Multiple 7/8 TeV searches for MET signals by ATLAS/CMS
  - Usually in context of Dark Matter or Lightest Supersymmetric Particle (LSP).
  - Many different signal
    - MET + multiple jets, MET + monojet, MET + 1,2 leptons, etc.



Models

- Concentrate on 2 models used in specific CMS displaced vertex papers (CMS-EXO-12-037,CMS-EXO-12-038).

Simplified Heavy Higgs model

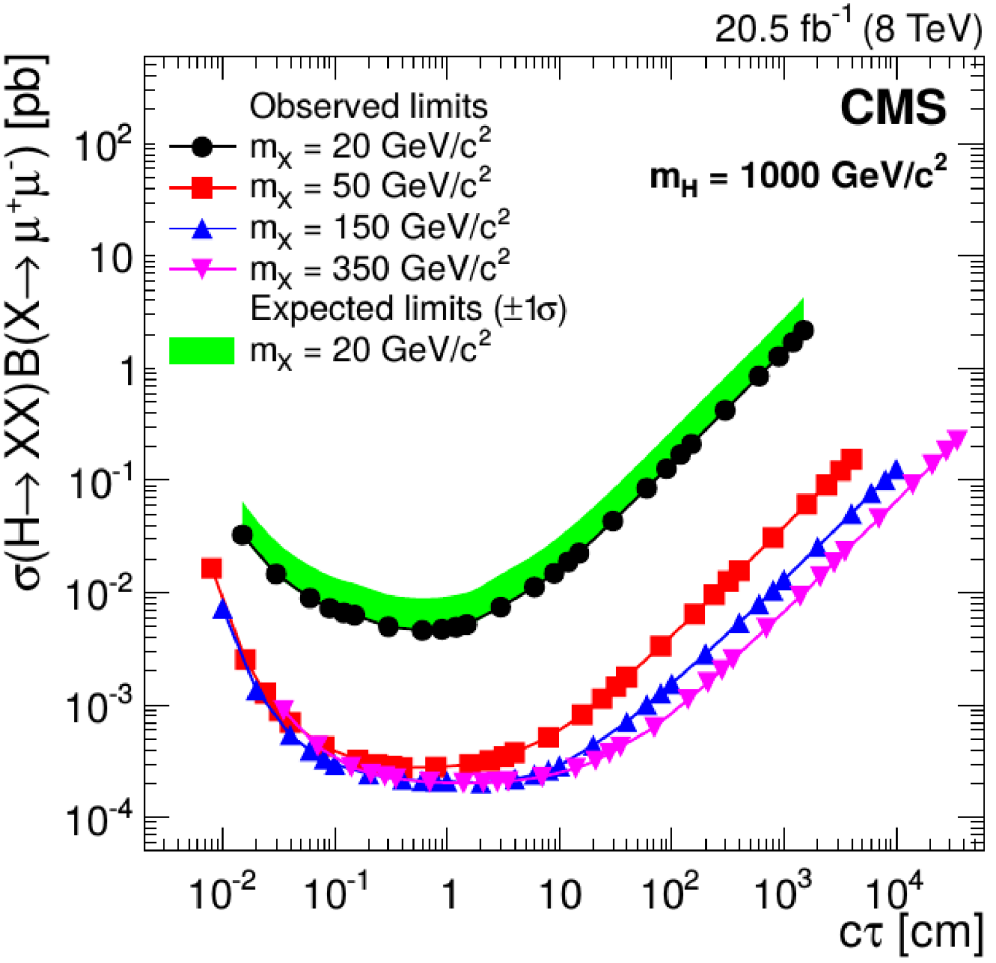
- Non-SM heavy Higgs H^0 decays to pair of long-lived scalars X

$$gg \to H^0 \to XX$$
$$X \to e^+e^-, \mu^+\mu^-, q\bar{q}$$

RPV-SUSY

$$(\lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}_k, \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}^c_k)$$
$$pp \to \tilde{q}\tilde{q}^*, \quad \tilde{q} \to q\tilde{\chi}^0$$
$$\tilde{\chi}^0 \to \ell^+\ell^-\nu, \tilde{\chi}^0 \to ud\mu$$

Example of what we will extend



Models

- Concentrate on 2 models used in specific CMS displaced vertex papers (CMS-EXO-12-037,CMS-EXO-12-038).

Simplified Heavy Higgs model

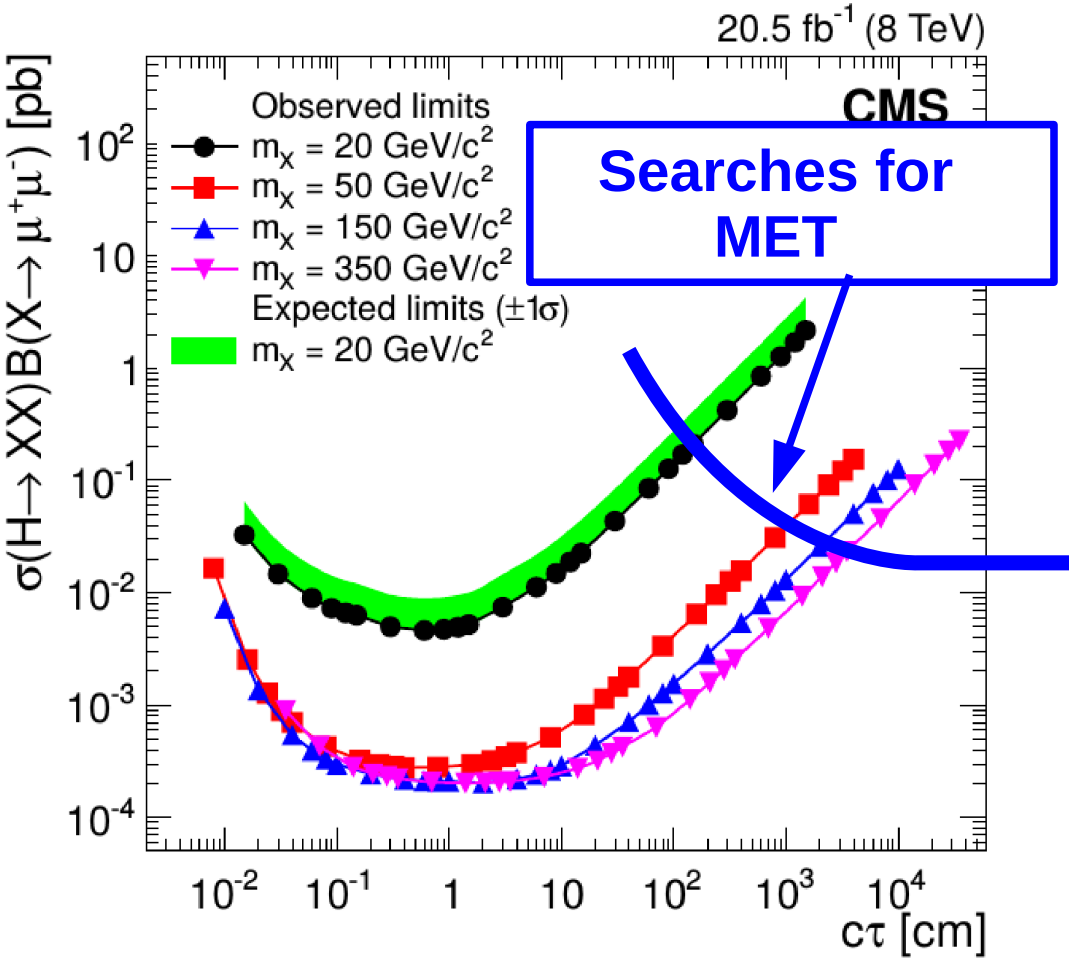
- Non-SM heavy Higgs H^0 decays to pair of long-lived scalars X

$$gg \to H^0 \to XX$$
$$X \to e^+e^-, \mu^+\mu^-, q\bar{q}$$

RPV-SUSY

$$(\lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}_k, \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}^c_k)$$
$$pp \to \tilde{q}\tilde{q}^*, \quad \tilde{q} \to q\tilde{\chi}^0$$
$$\tilde{\chi}^0 \to \ell^+\ell^-\nu, \tilde{\chi}^0 \to ud\mu$$

Example of what we will extend



Signal Generation and Analysis

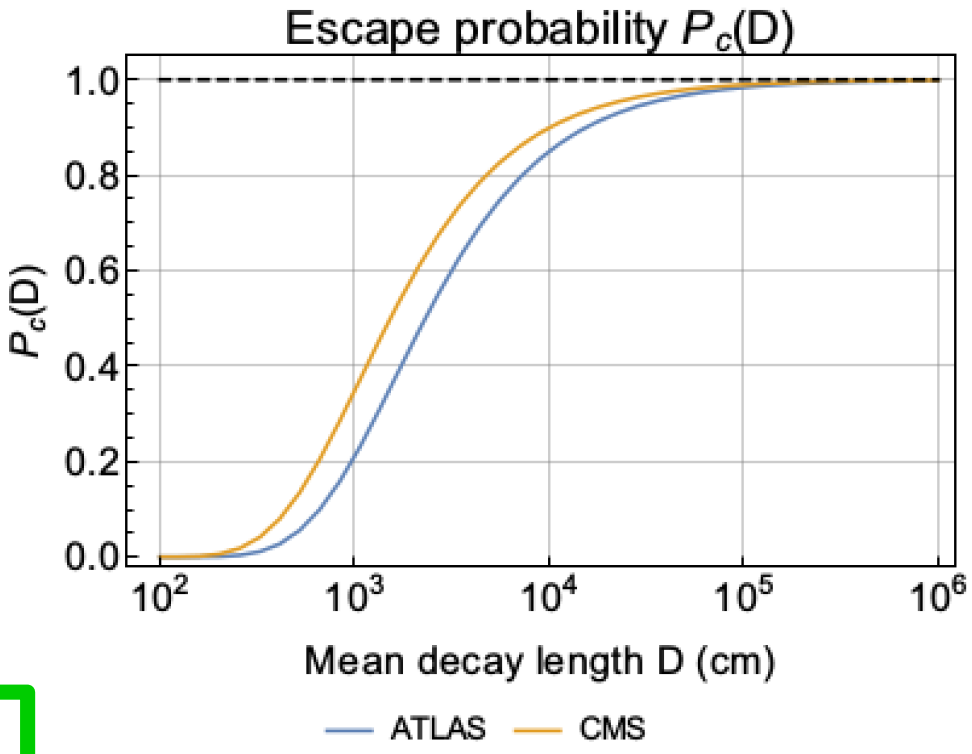
- Model created in **LanHEP**.
- Signal generation, showering, hadronisation, detector simulation.
  - **MadGraph5** → **Pythia** → **Delphes-3**.
- Analysis using **CheckMATE**.
  - Multiple 7/8 TeV LHC analyses already implemented.
  - Applies any/all implemented analyses to event file.
  - Compares to published observed signal.
  - Gives best analysis and enables to calculate **95% upper limit on cross-section, for stable particle**.
  - Multiple analyses useful as different analyses will give best limits for different models and areas of parameter space.

Limits for finite lifetimes

Probability of particle leaving detector

$$f(r, D) = \frac{1}{4\pi r^2} \exp\left(\frac{-r}{D}\right)$$

$$P_{\mathrm{c}}(D) = \int_{\mathrm{bar}} f(r, D) dS + \int_{\mathrm{end}} f(r, D) dS$$



$$\bar{P}_{\mathrm{c}} = \text{ averaged over Energy}$$

$$\sigma^{95\%}(c\tau/m) = \sigma^{95\%}_{\mathrm{stable}} \times [\bar{P}_{\mathrm{c}}(c\tau/m)]^{-2}.$$

Limits for finite lifetimes calculated from limits for stable particle.

- Mass of long-lived particle enters due to time-dilation.
- ATLAS: length 46m, diameter 25m.
- CMS: length 21m, height 18m, width 15m.

Our Results from CheckMATE

Simplified Heavy Higgs model – limits for stable particle

Heavy Higgs Mass (GeV)	Mass of long-lived X scalar (GeV)	95% CL cross section limit (pb)	Best Analysis and SR
125	20	38.9	atlas_1502_01518 - SR4
125	50	38.7	atlas_1502_01518 - SR4
200	20	16.9	atlas_1502_01518 - SR4
200	50	17.2	atlas_1502_01518 - SR4
400	20	3.16	atlas_1502_01518 - SR6
400	50	3.16	atlas_1502_01518 - SR6
400	150	3.15	atlas_1502_01518 - SR6
1000	20	0.95	atlas_1502_01518 - SR7
1000	50	0.95	atlas_1502_01518 - SR7
1000	150	0.96	atlas_1502_01518 - SR7
1000	350	0.95	atlas_1502_01518 - SR7

Our Results from CheckMATE

Simplified Heavy Higgs model – limits for stable particle

Heavy Higgs Mass (GeV)	Mass of long-lived X scalar (GeV)	95% CL cross section limit (pb)	Best Analysis and SR
125	20	38.9	atlas_1502_01518 - SR4
125	50	38.7	atlas_1502_01518 - SR4
200	20	16.9	atlas_1502_01518 - SR4
200	50	17.2	atlas_1502_01518 - SR4
400	20	3.16	atlas_1502_01518 - SR6
400	50	3.16	atlas_1502_01518 - SR6
400	150	3.15	atlas_1502_01518 - SR6
1000	20	0.95	atlas_1502_01518 - SR7
1000	50	0.95	atlas_1502_01518 - SR7
1000	150	0.96	atlas_1502_01518 - SR7
1000	350	0.95	atlas_1502_01518 - SR7

Our Results from CheckMATE

Simplified Heavy Higgs model – limits for stable particle

Heavy Higgs Mass (GeV)	Mass of long-lived X scalar (GeV)	95% CL cross section limit (pb)	Best Analysis and SR
125	20	38.9	atlas_1502_01518 - SR4
200	20, 50	16.9	atlas_1502_01518 - SR4
400	20,50,150	3.16	atlas_1502_01518 - SR6
1000	20,50,150,350	0.95	atlas_1502_01518 - SR7

- Limits independent of mass of X-scalar as Heavy Higgs has a narrow width and decays to invisible only.
- Only one particular monojet analysis best for every benckmark point in this model.
  - Occurs because long-lived X-scalars come out back to back so no MET unless recoil against jet.
- Limits of order 1 pb.

Our Results from CheckMATE

RPV-SUSY – limits for stable particle

Squark Mass (GeV)	Long-lived neutralino mass (GeV)	95% CL cross section limit (pb)	Best Analysis and SR
120	48	31.4	cms_1303_2985 - 4j_0b_325
350	148	0.57	cms_1303_2985 - 23j_0b_325
1000	148	0.0086	atlas_conf_2013_047 - AM
1500	494	0.0024	atlas_conf_2013_047 - CT

- Limits heavily dependent on masses, can be down to order fb.
- 2 studies give best limits,

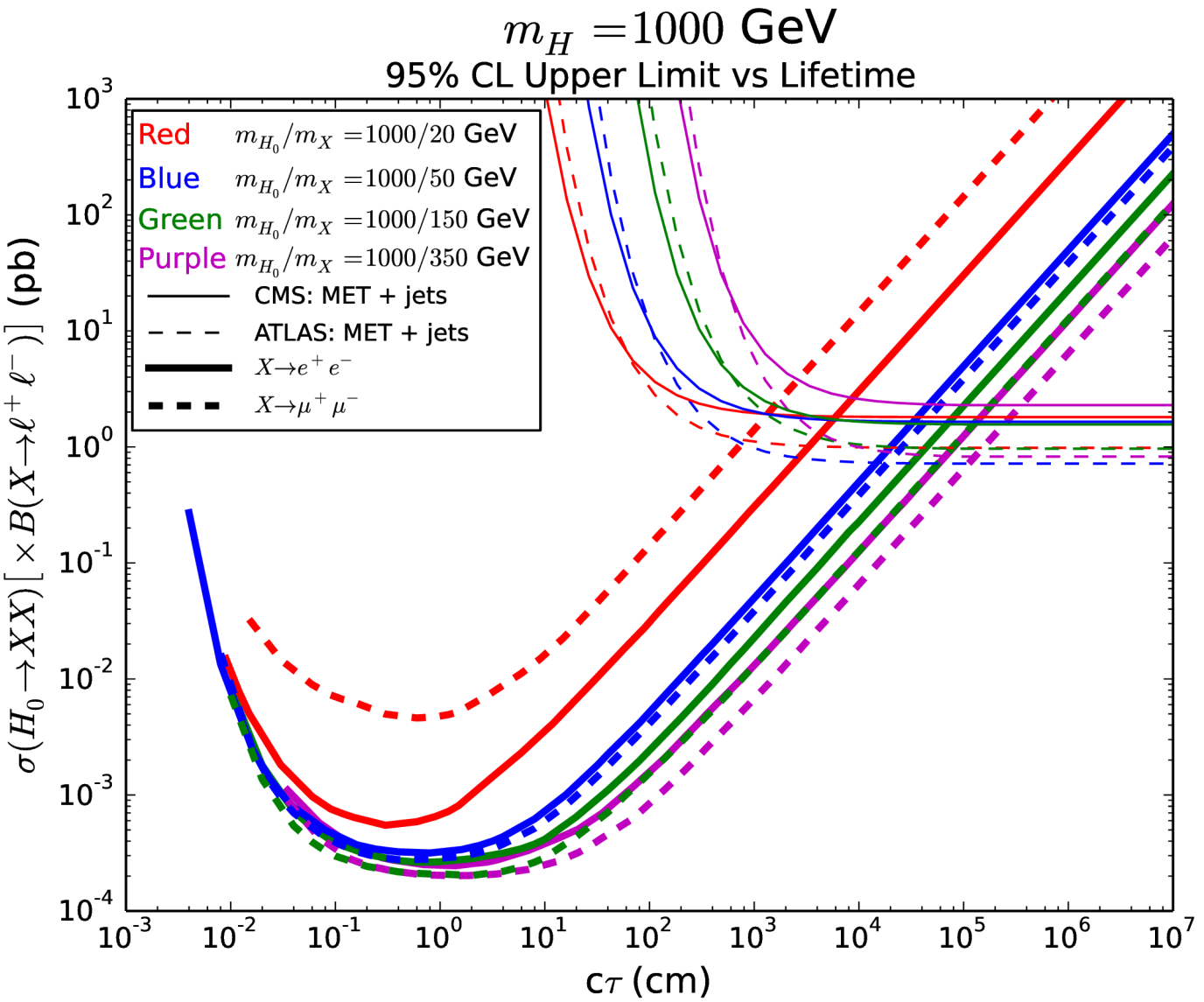
atlas_conf_2013_047

- MET + jets, designed for MSSM neutralino LSP
- Best for large mass gaps between squark and neutralino.

cms_1303_2985

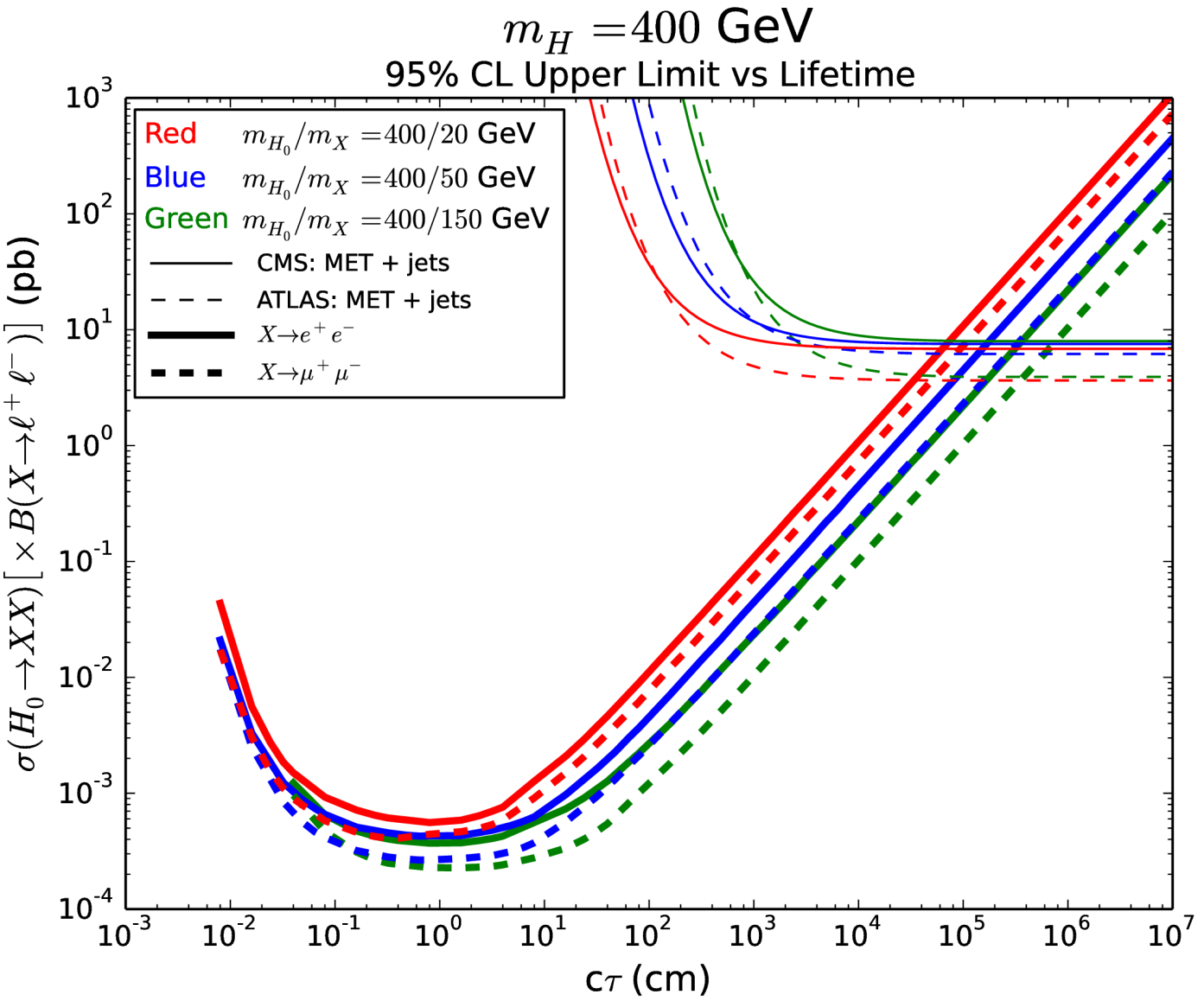
- Main discriminating variable $\alpha_T = \frac{E_T^{j_2}}{M_T}$ $M_T =$ Transverse Mass of j_1,j_2
  $\alpha_T > 0.5$ when large MET

Results – Heavy Higgs model



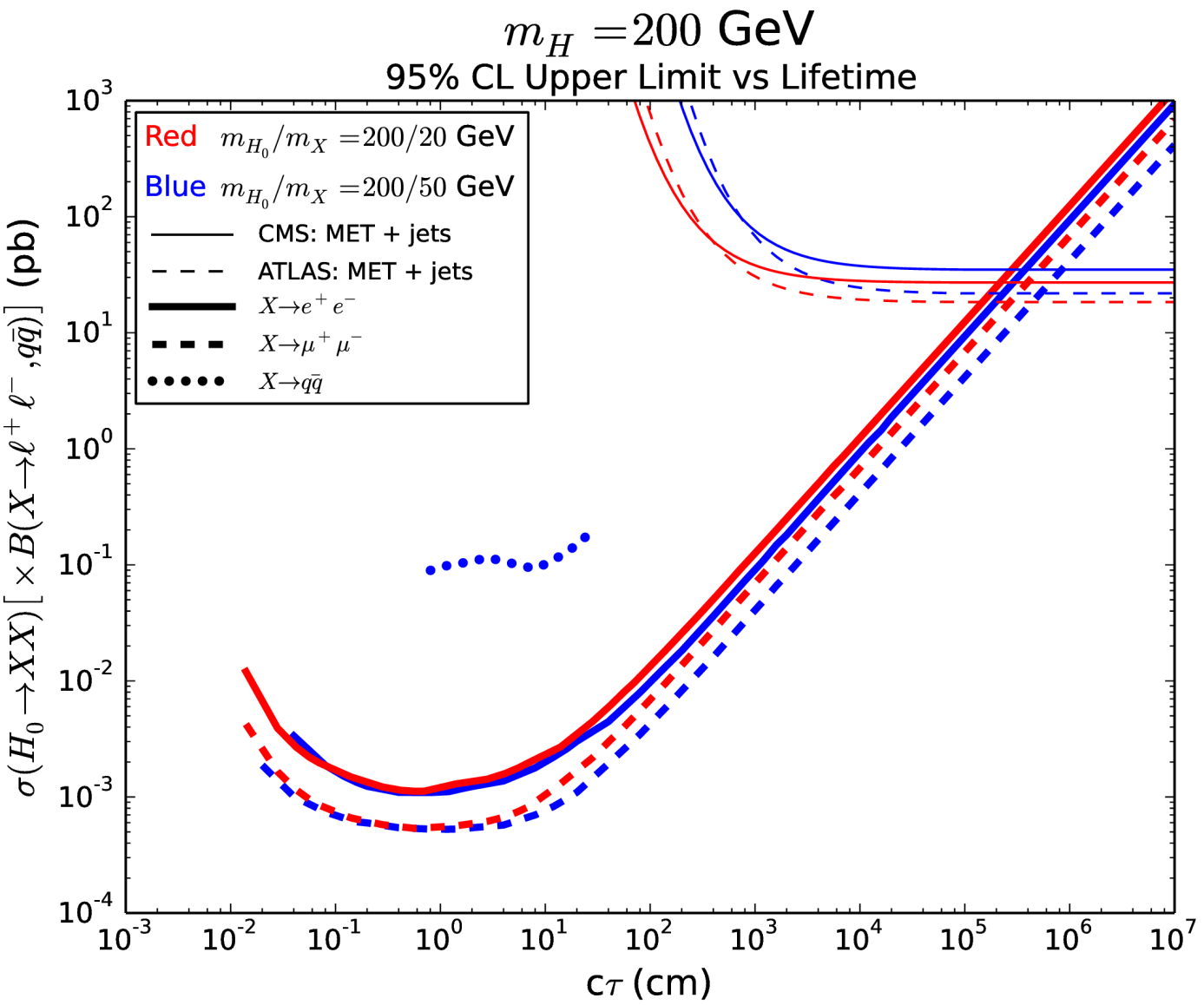
- MET searches better for proper decay distances from as low as a few meter up to around a km
- Effect of detector size visible
- Larger time-dilation effect on smaller masses
- Extends limits
  - Now from ~100 micrometers to arbitrary long lifetimes.

Results – Heavy Higgs model



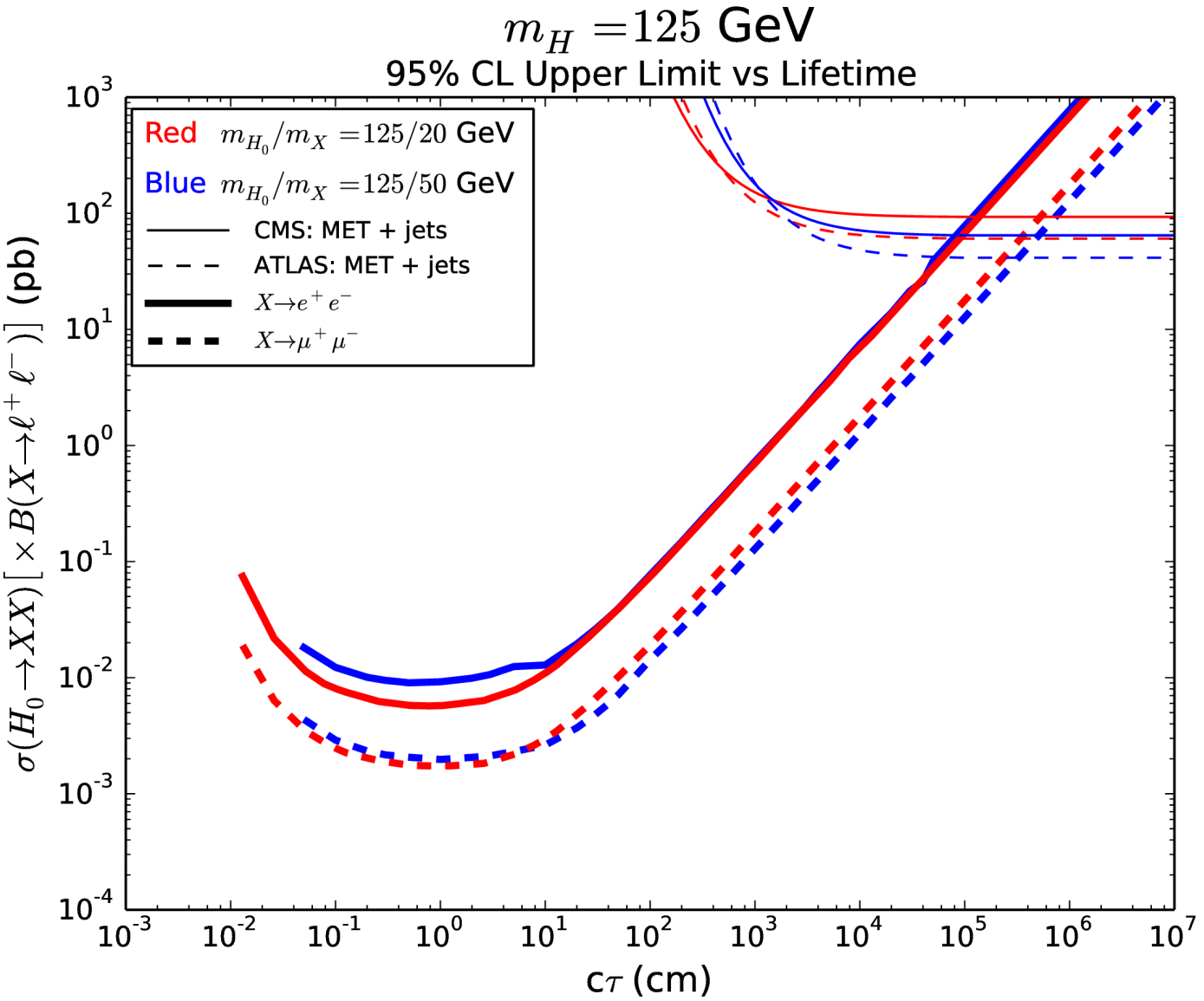
- Limits weaker as Heavy Higgs mass reduces because smaller MET

Results – Heavy Higgs model



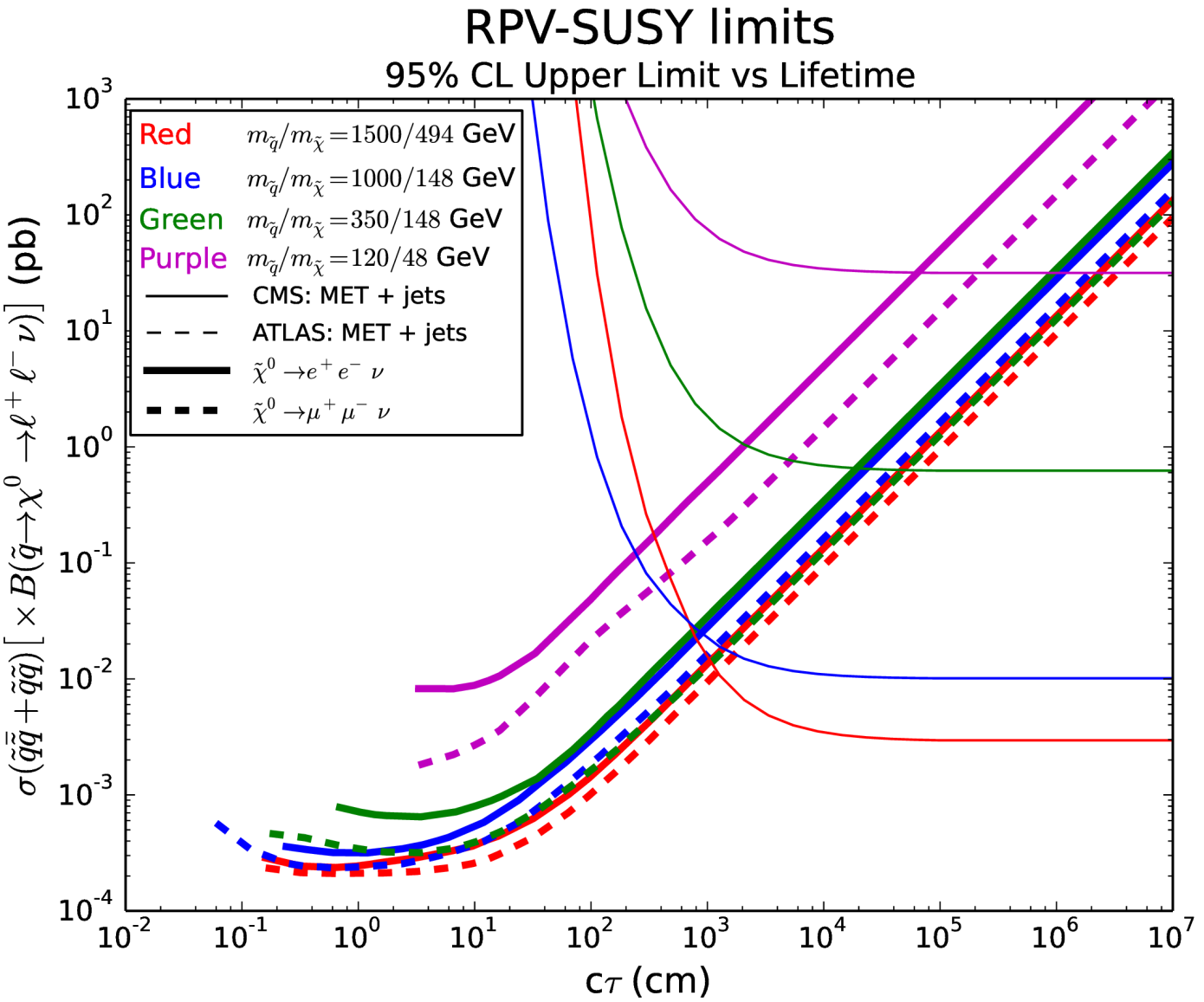
- Limits weaker as Heavy Higgs mass reduces because smaller MET

Results – Heavy Higgs model



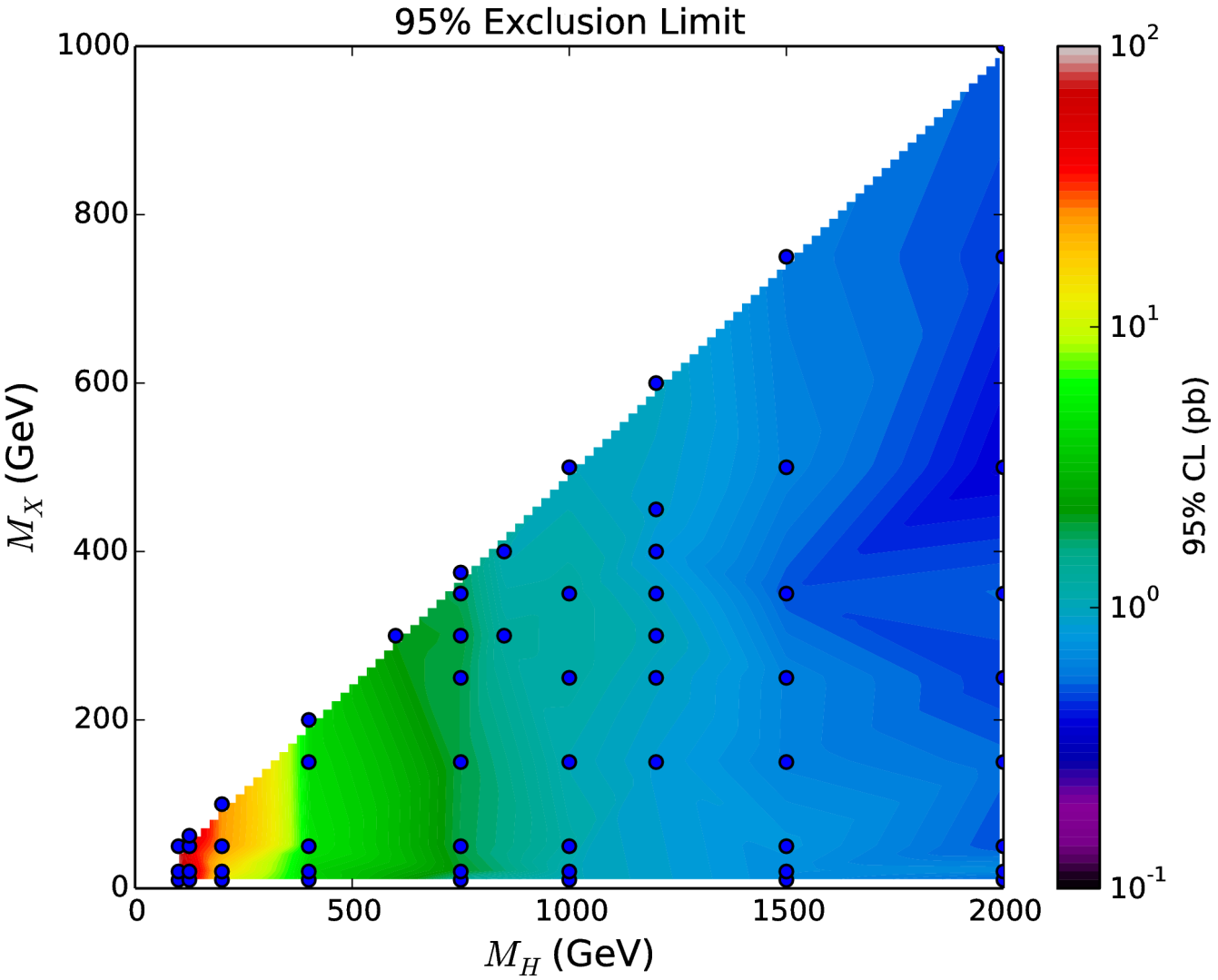
- Limits weaker as Heavy Higgs mass reduces because smaller MET

Results – RPV-SUSY model



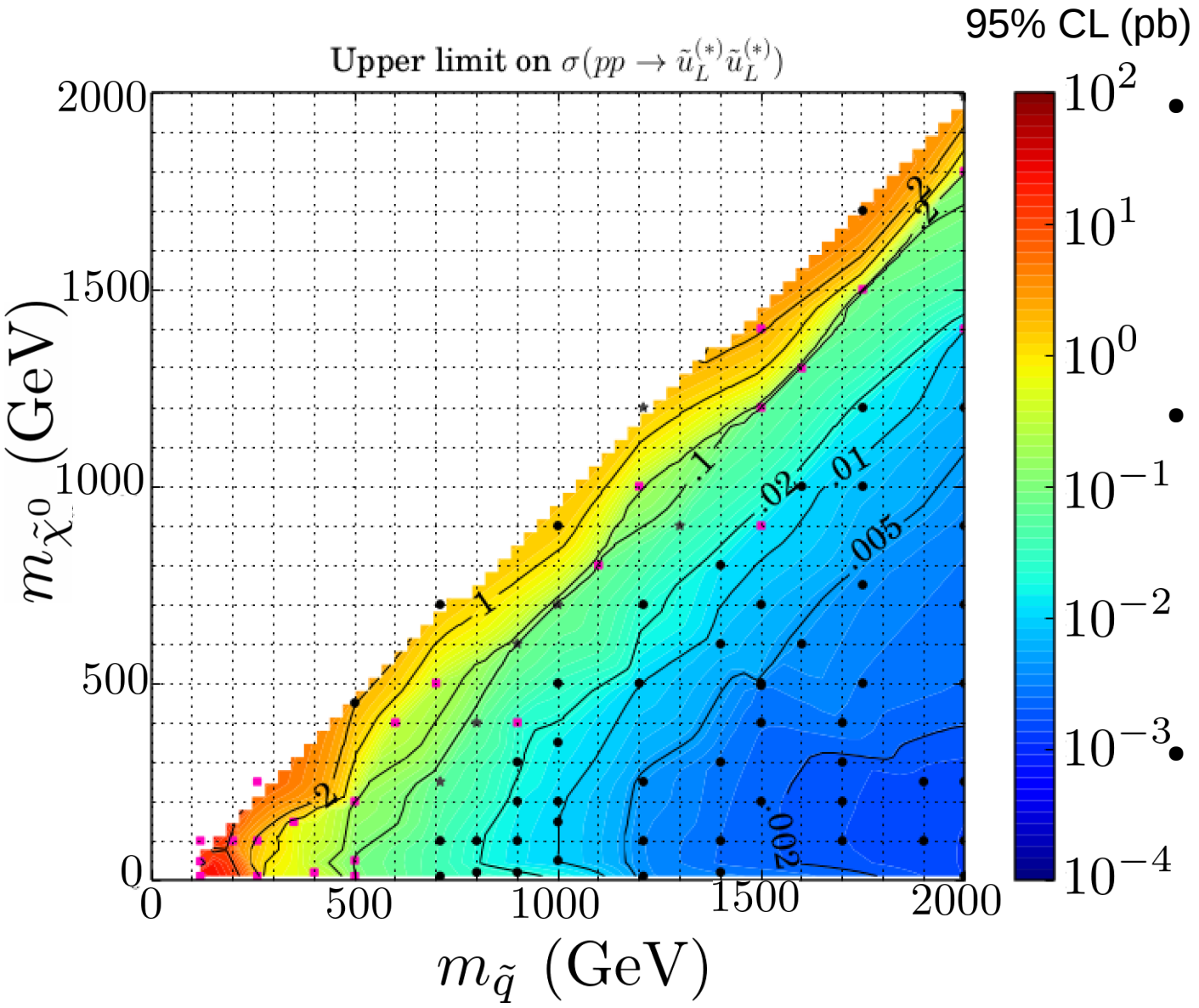
- Generally better limits than for the Heavy Higgs model.
- Especially for heavy squarks.
- Good signal as many jets.
- Studies for the heavier squarks (**red**/**blue**) specifically designed for this model.

Results – Heavy Higgs model



- Little dependence on mass of long-lived X-scalar.
- Strong dependence on mass of heavy Higgs – doesn't occur for traditional displaced vertex searches.
- Better limits for heavier Higgs.
- Results valid independent of spin of X particle

Results – RPV-SUSY model



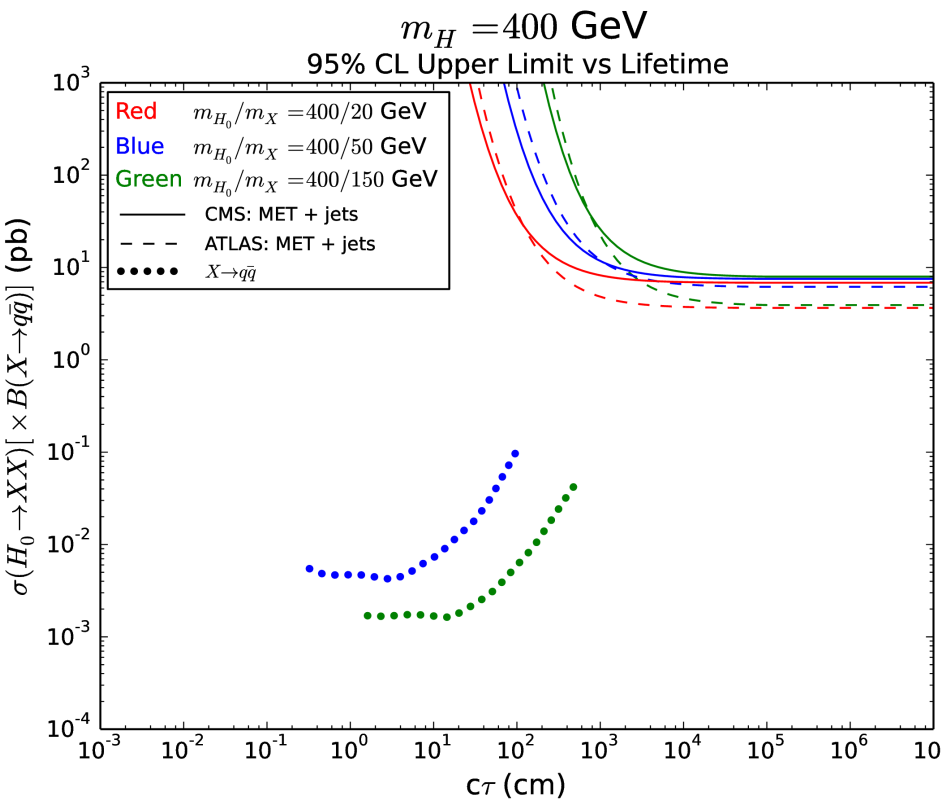
- Limits mainly depend on mass gap $\Delta m = m_{\tilde{q}} - m_{\tilde{\chi}^0}$
- Explained as larger gaps gives larger MET and higher transverse momentum to jets.
- Other than in small Δm region, limits stronger than for heavy Higgs model.

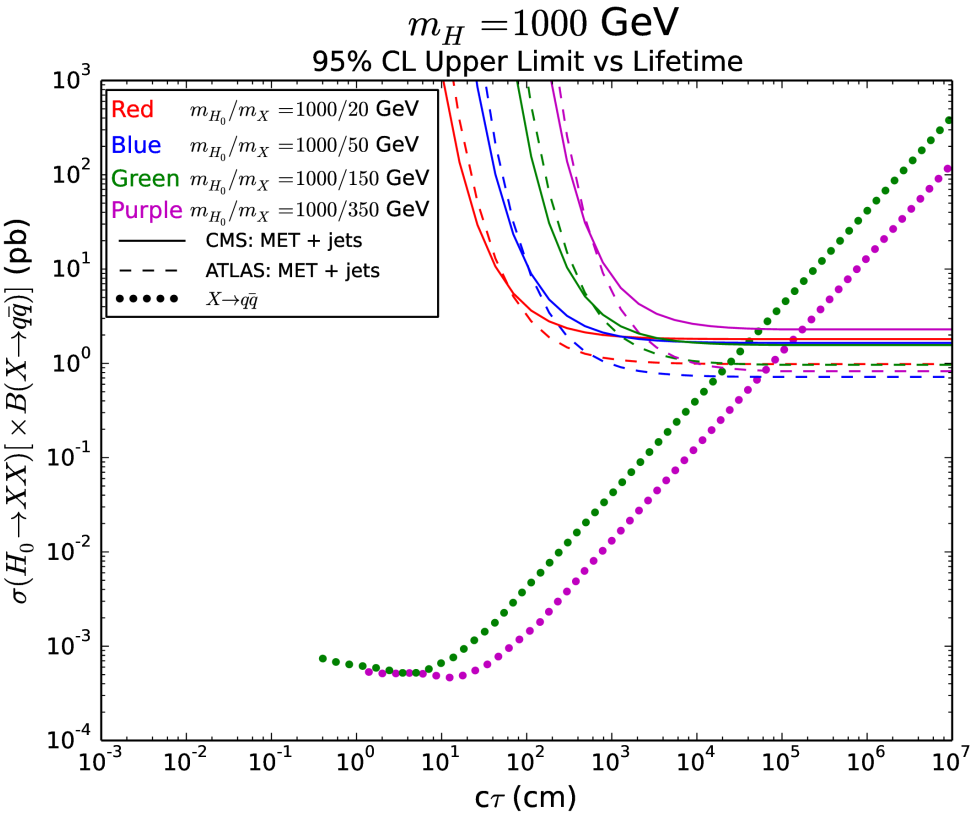
Summary

- Using MET searches can usefully extend analyses for long-lived particles.
  - Means limits are set for proper decay distances from micrometers to kilometers.
- The decay distance at which the limits from MET searches improve on those from displaced vertices can be as small as a few metres, or as large as a few km.
- Combining multiple analyses allows to cover the whole parameter space more effectively.
- We have extended the limits to arbitrary long lifetimes for 2 models studied by CMS.
- Also produced results in 2D $m_{med} - m_{long}$ parameter space.

Spare Slides

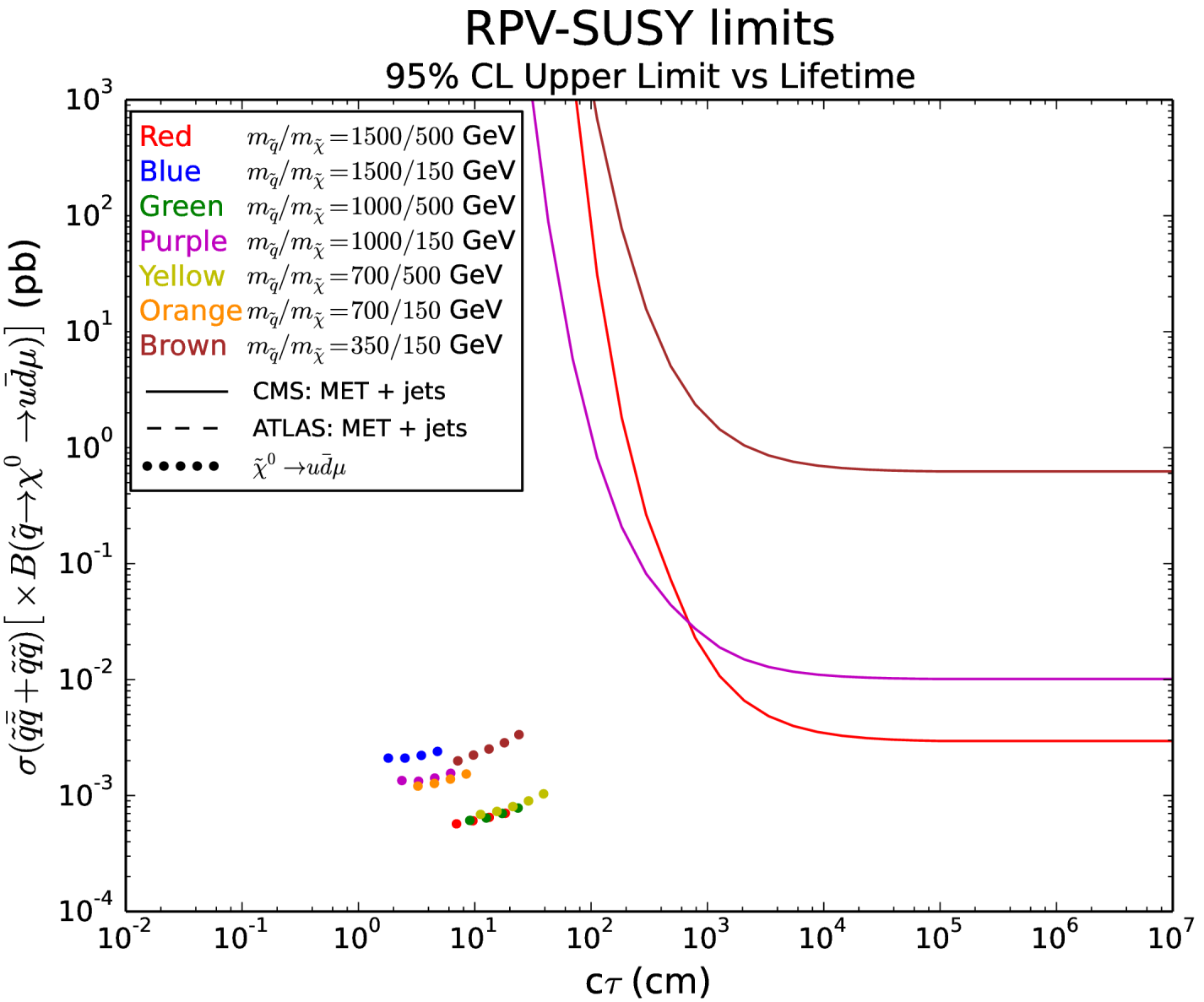
Results – Heavy Higgs model





- For decays to quark-antiquark, we can't always extrapolate CMS limits until they cross.

Results – RPV-SUSY model



- Neutralino decaying to jets $(u\bar{d}\mu)$