Long-Lived Superparticles After LHC Run 1

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PITT PACC, University of Pittsburgh

@ ACFI Workshop:
LHC Searches for Long-Lived BSM Particles
12 November 2015

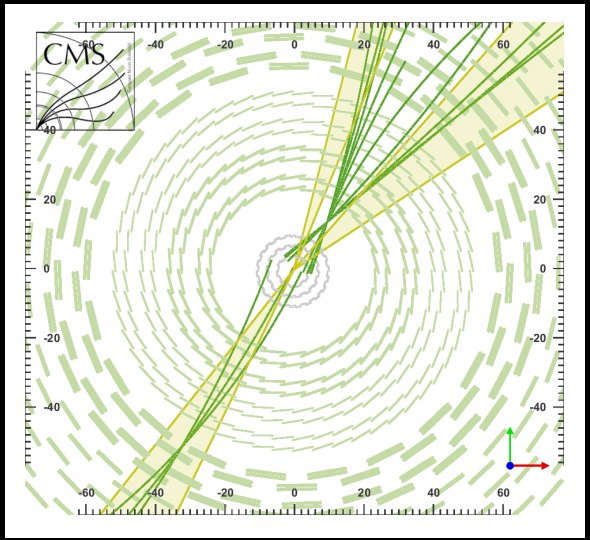
with Z Liu (1503.05923)
+ work by Yanou & Brian (1409.6729), Eric & collaborators (1505.00784)

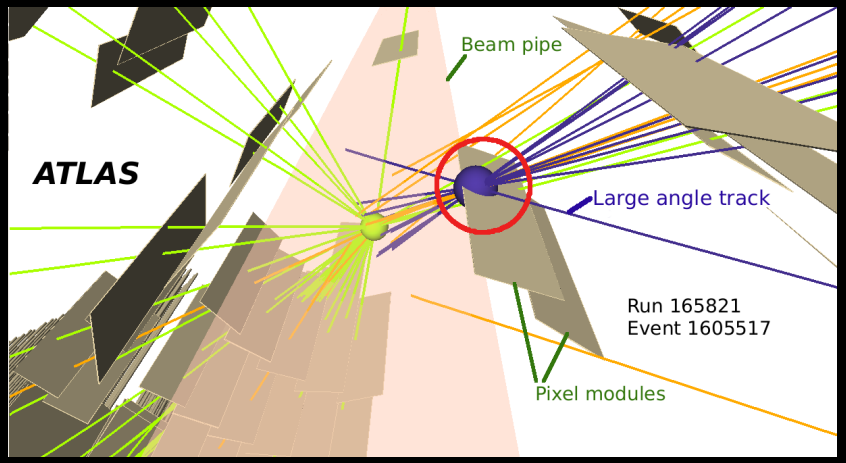
SUSY and Displacement

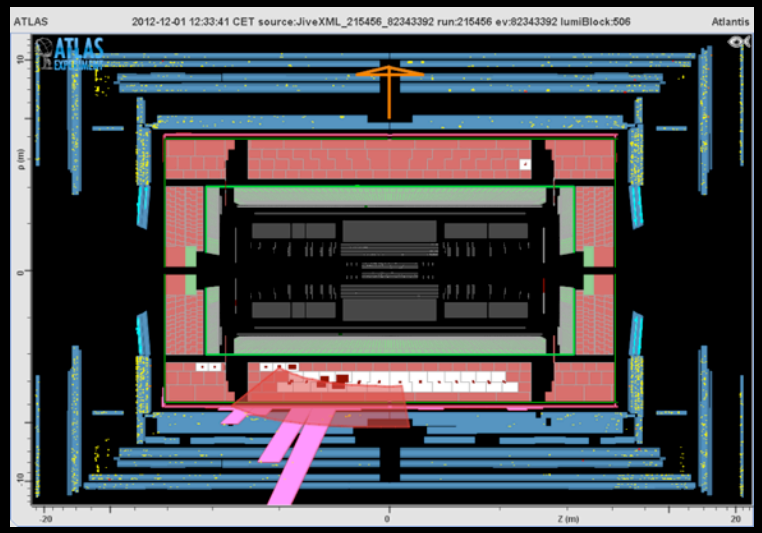
- R-Parity Violation $c\tau_{\rm RPV} \sim 0.1{\rm mm}\left(\frac{100\ {\rm GeV}}{\tilde{m}}\right)\left(\frac{10^{-6}}{\lambda}\right)^2$
  - final-stage decay controlled by B/L-violating couplings, favored small by precision tests & cosmology (displaced when RPV Yukawas < O(10^{-7}))
- Gauge mediation $c\tau_{\rm GMSB} \sim 0.1{\rm mm}\left(\frac{100\ {\rm GeV}}{\tilde{m}}\right)^5\left(\frac{\sqrt{F}}{100\ {\rm TeV}}\right)^4$
  - final-stage decay controlled by Goldstino coupling (displaced when sqrt(F) > O(100 TeV))
- Mini-split spectrum $c\tau \approx 10^{-5}\ {\rm m}\left(\frac{m_{\tilde{q}}}{\rm PeV}\right)^4\left(\frac{\rm TeV}{m_{\tilde{g}}}\right)^5$
  - gluino forced to decay through very heavy off-shell squarks (displaced when m($\tilde{q}$) > O(1000 TeV))
- Wino co-LSP's (e.g., anomaly mediation)
  - $m_\pm - m_0 \approx m(\pi)$
  - O(10 cm) long "disappearing track"
  - well-covered experimentally!

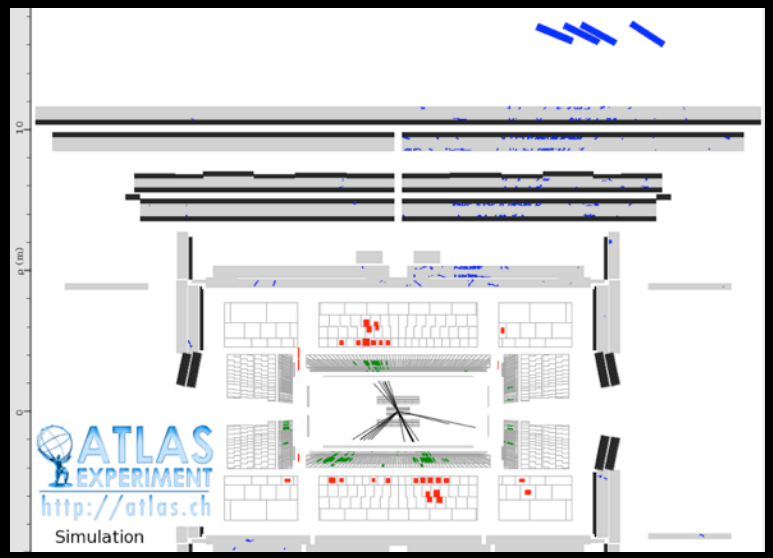
* Plus many other non-minimal models (stealth SUSY, etc)

LHC and Displacement

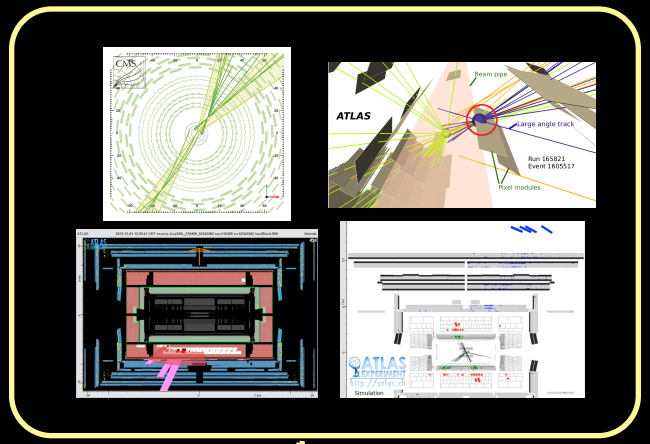


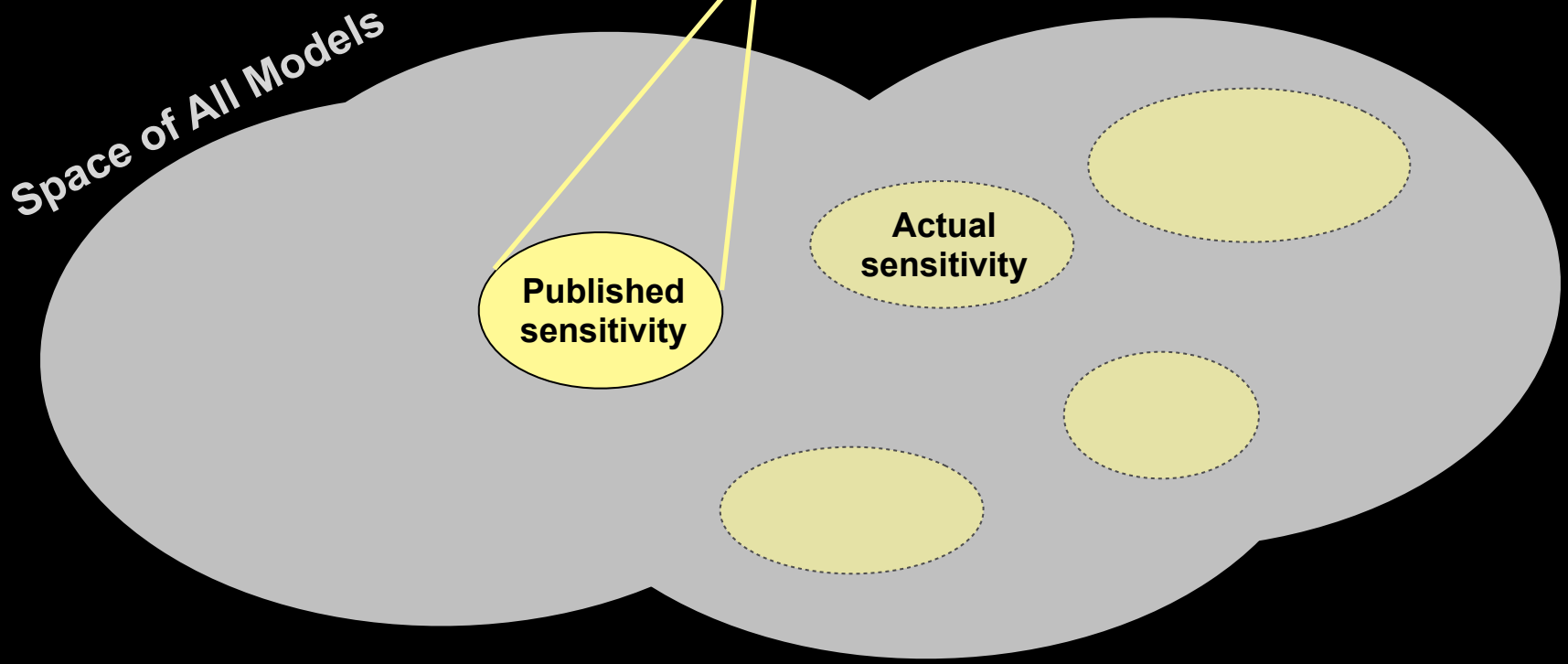






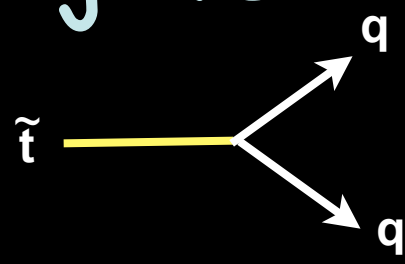
The Need to Recast



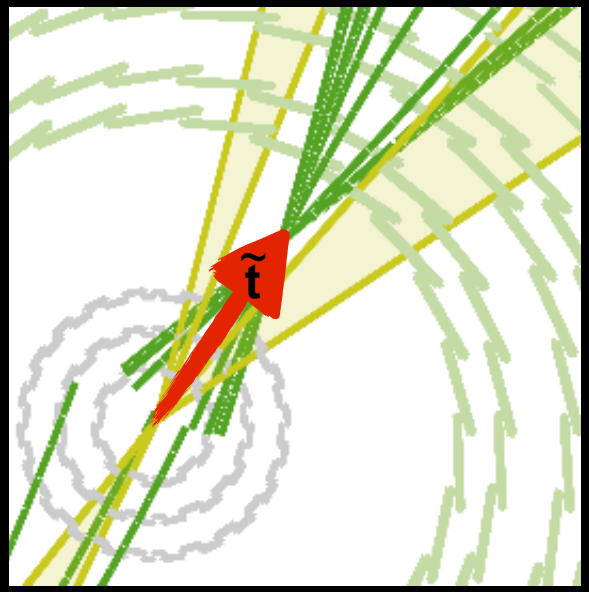


An Example: BRPV Stop from H -> aa -> Displaced Dijets

Motivated by **Barry, Graham, Rajendran (1310.3853)**:
"there are important factors that obfuscate the the relative efficiency of this search"



- $m(\tilde{t}) = 150$ & $\sqrt{\hat{s}} > 400$ $\Rightarrow$ $\sigma \sim 30$ pb via direct QCD pair production
- ~50% chance to get neutral stop-hadron
- ~50% pass basic acceptance, ~5% reco efficiency for $c\tau \sim 40$ cm
- ×2 stops per event
- luminosity ~ 20,000 pb^{-1}
- TOTAL: 30 * 0.5 * 0.5 * 0.05 * 2 * 20,000 = 15,000 candidates
- 1 background event $\Rightarrow$ limit is ~4 candidates



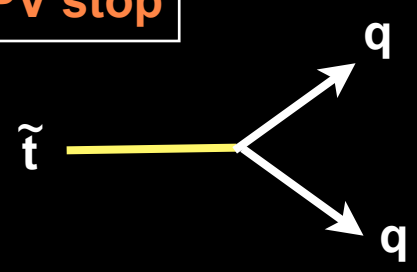
CMS PAS EXO-12-038
1411.6350

Loose Organizing Principles for Our First-Pass Survey

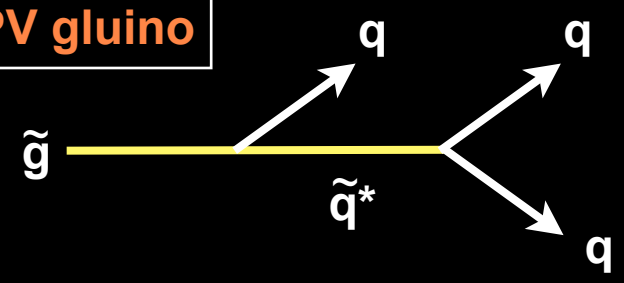
- Hadronic final states
  - can be difficult when decays are prompt
  - explicit displaced limits are limited (esp BRPV)
  - colored sparticles have big cross sections
- Naturalness
  - lightest sparticle tends to be stop or Higgsinos
  - gluino also can't be too heavy
- Simplified spectra
  - only one or two new particles
  - no long decay chains
  - minimize # parameters
  - conservative total rates

Some of the Models We Studied

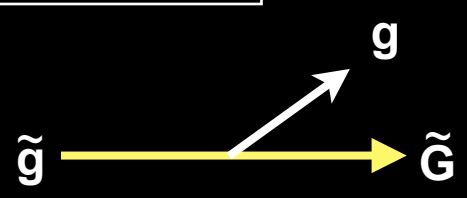
BRPV stop



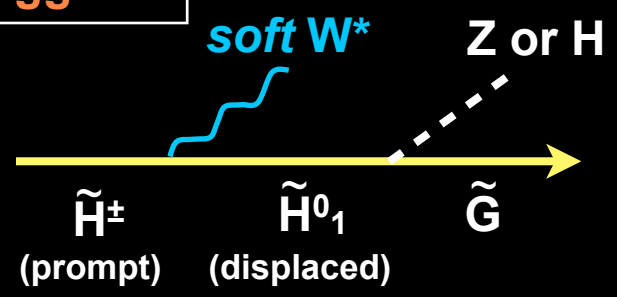
BRPV gluino



GMSB gluino

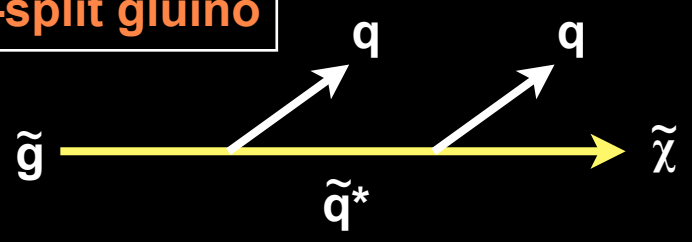


GMSB Higgsino



GMSB stop

Mini-split gluino



The Searches that We Recast

Applied to all models

- CMS displaced dijets (tracker)
- ATLAS low-EM jets (HCAL)
- ATLAS muon spectrometer vertices (7 TeV, 2 fb^{-1})
- CMS charged stable particles

Applied to models with leptonic decays

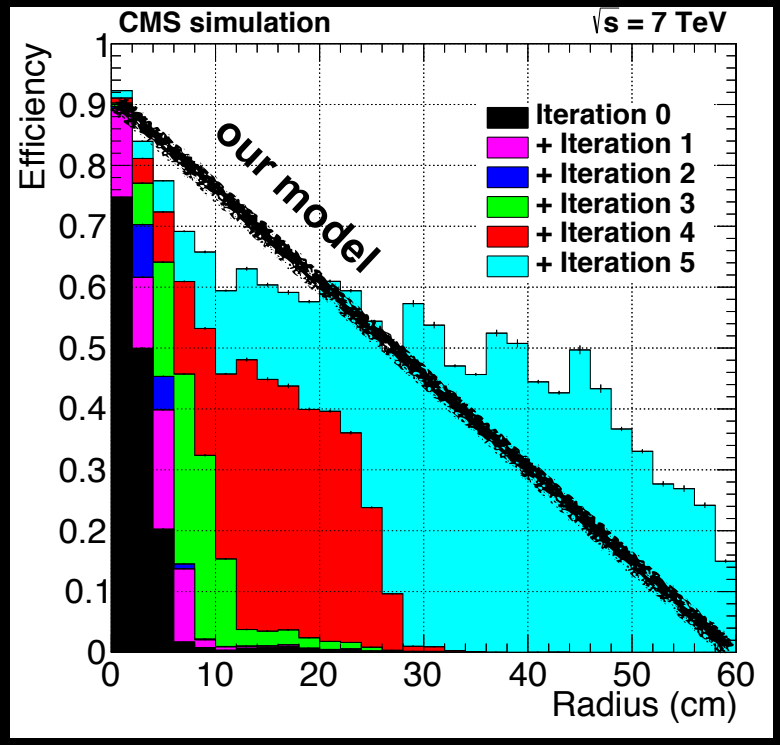
- CMS displaced dileptons
- CMS displaced electron & muon
- ATLAS displaced muon + tracks

*** For ATLAS displaced vertex+(l/j/MET) and lots more models, see Csaki, et al (1505.00784)**

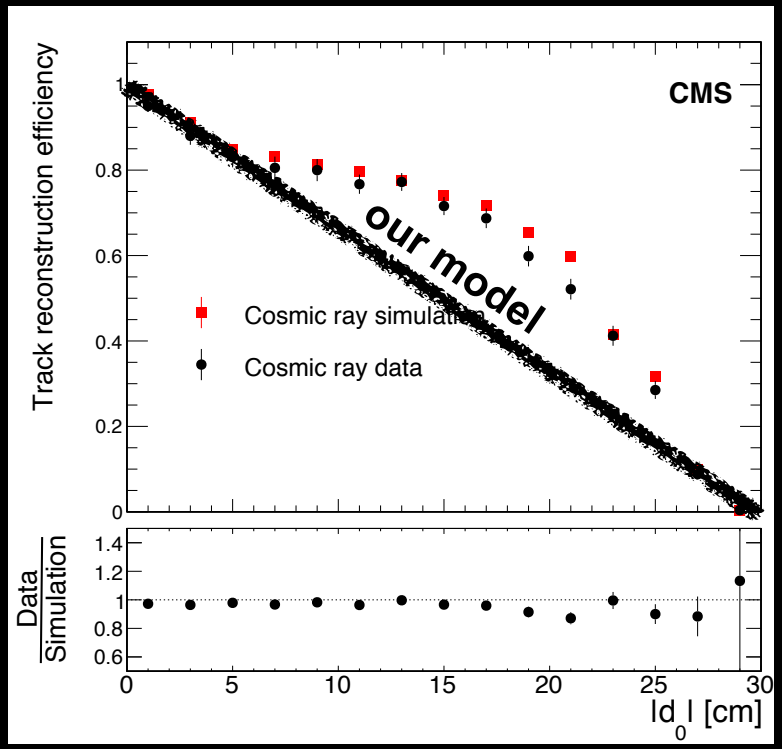
Detector Simulation Methodology

- Minimalistic
  - basic geometry, no detector granularity or energy smearing
  - perfect absorptive calorimeters
  - tracking/vertexing efficiencies with simple linear falloff models in radius, z, impact parameter
- Try to reproduce all explicitly studied models
  - employ constant fudge factors where necessary to mock up unreproducible reconstruction efficiencies
  - a (by now well-known) lesson for experimentalists: the broader the kinematic range of benchmarks tested, the better
- Even O(1) modeling errors can be acceptable
  - rapid evolution of rates near limit boundaries
  - but we try to do better where we can!

E.g., Tracking Efficiency at "CMS"



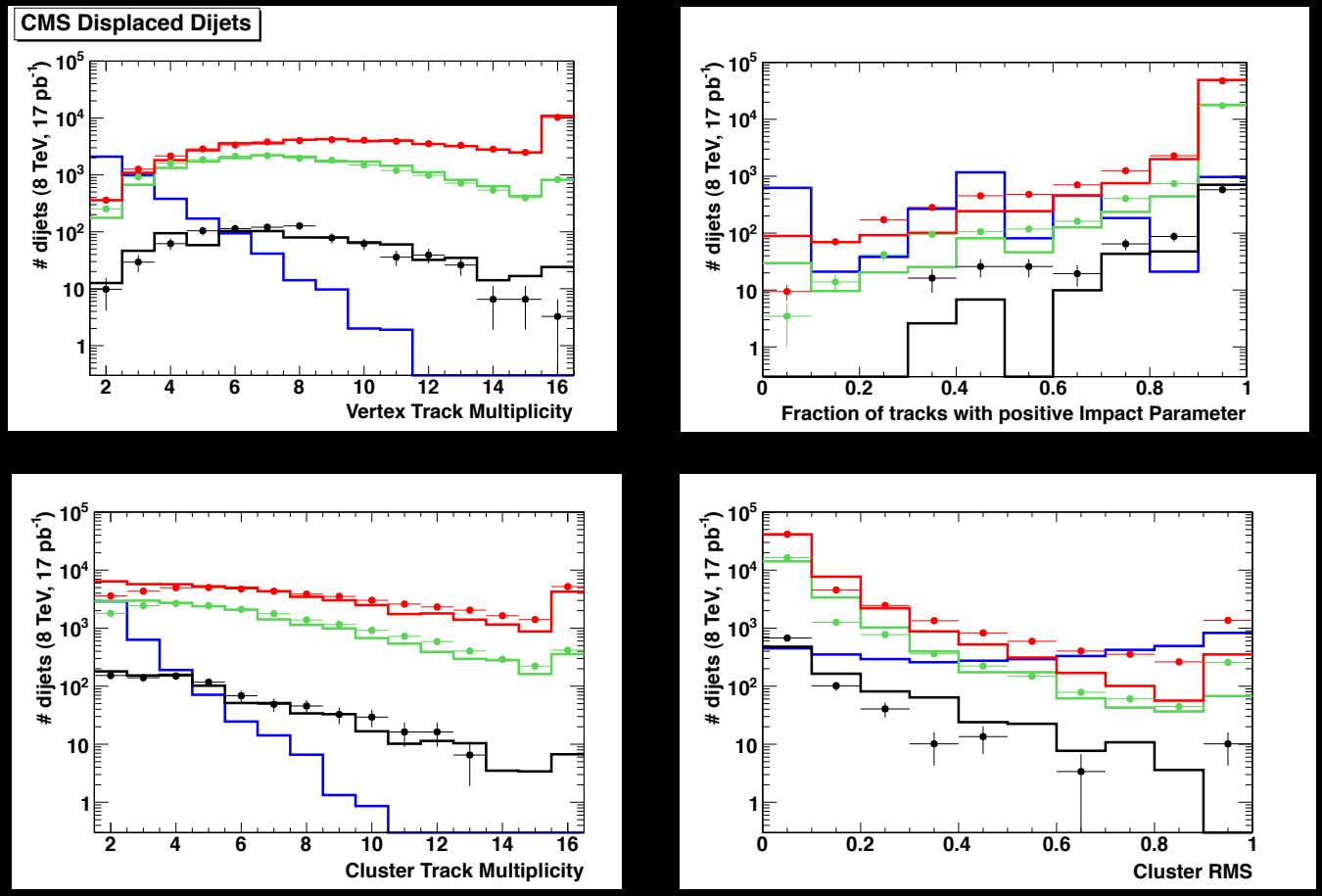
1405.6569



1411.6977

× linearly-falling inefficiency vs Lz (to 55 cm)

CMS Dijets Validation



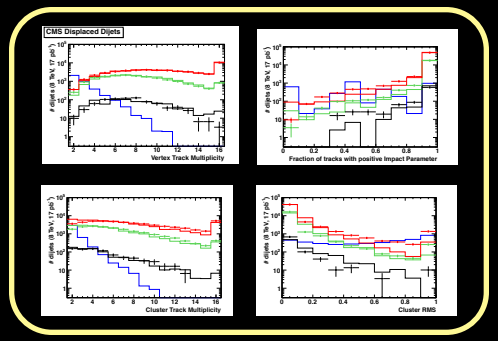
H(1000) → X(350) X(350), cτ = 35 cm

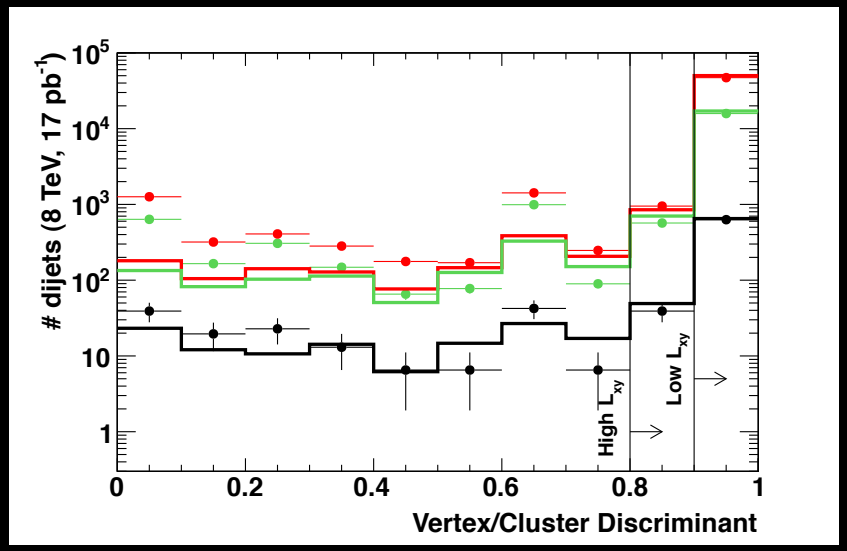
H(400) → X(150) X(150), cτ = 40 cm

H(200) → X(50) X(50), cτ = 20 cm

QCD background

CMS Dijets Validation





(Dominated by multiplicity variables)

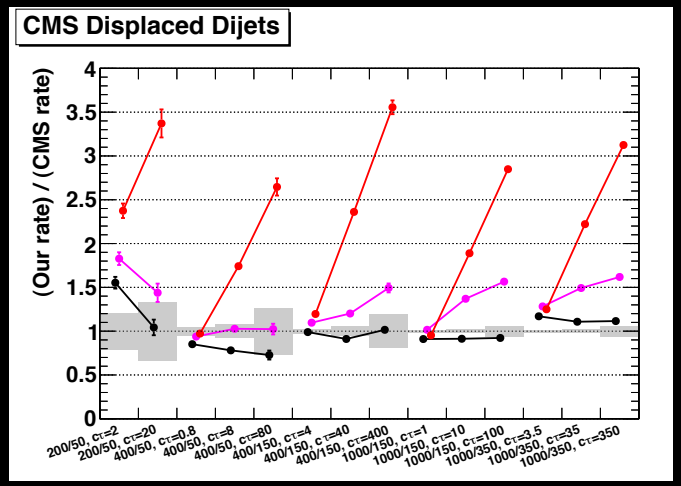
H(1000) → X(350) X(350), cτ = 35 cm

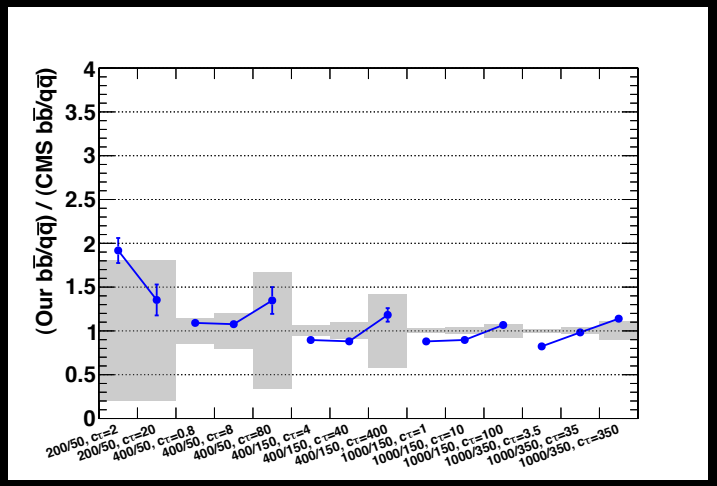
H(400) → X(150) X(150), cτ = 40 cm

H(200) → X(50) X(50), cτ = 20 cm

QCD background

Dijets Validation





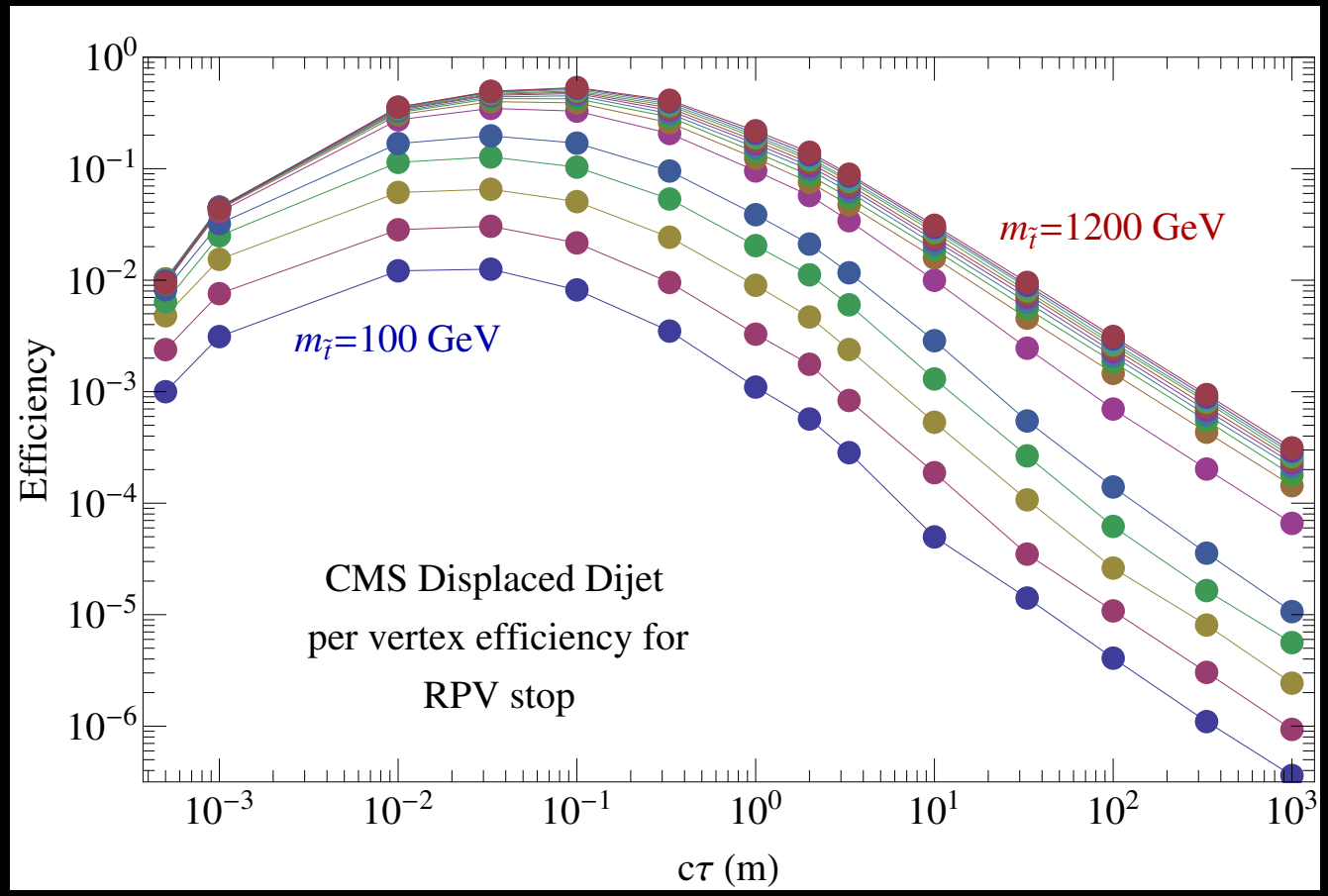
Perfect tracking & vertexing

Imperfect tracking, perfect vertexing

Imperfect tracking & vertexing

$X \rightarrow bb$ / $X \rightarrow qq$

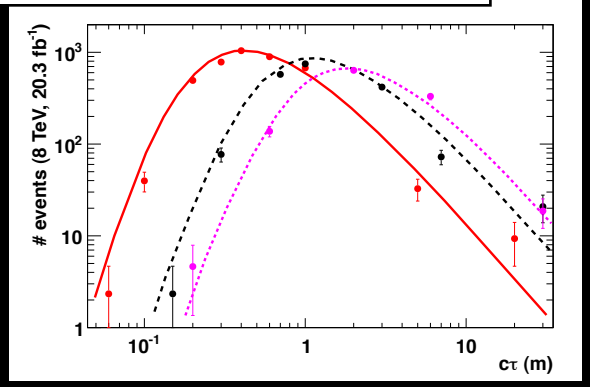
RPV Stop Efficiencies



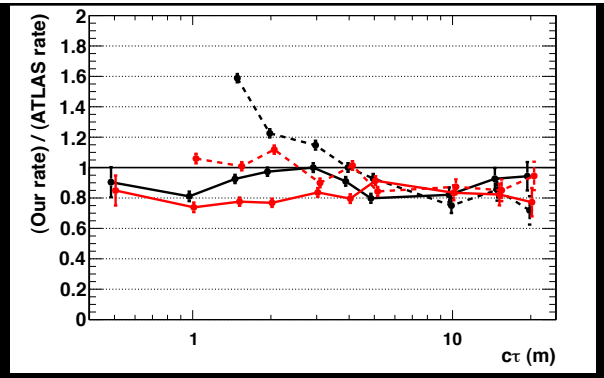
ATLAS HCAL & Muon Spectrometer Validations

ATLAS low-EM jets

* explicit max delay cut 5 ns



ATLAS muon spectrometer



* calibrated max delay 7 ns

H(126) → X(10) X(10)

H(126) → X(25) X(25)

H(140) → X(40) X(40)

H(120) → X(20) X(20) solid

H(120) → X(40) X(40) dashed

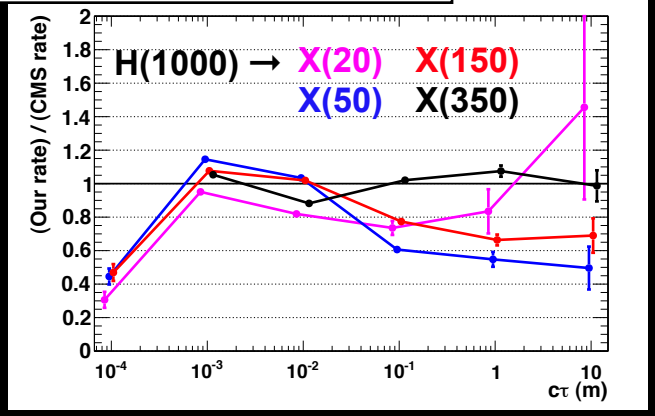
H(140) → X(20) X(20) solid

H(140) → X(40) X(40) dashed

Analyses specialized for low-mass scenarios
...We must blindly extrapolate to higher-mass SUSY models

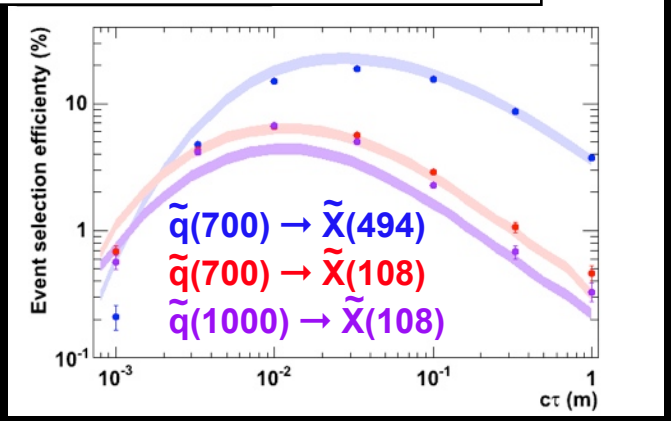
Lepton Validations

CMS dilepton



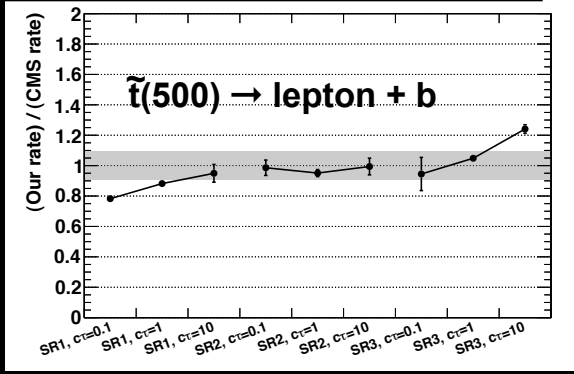
e^+e^-, one of several validations

ATLAS muon + tracks



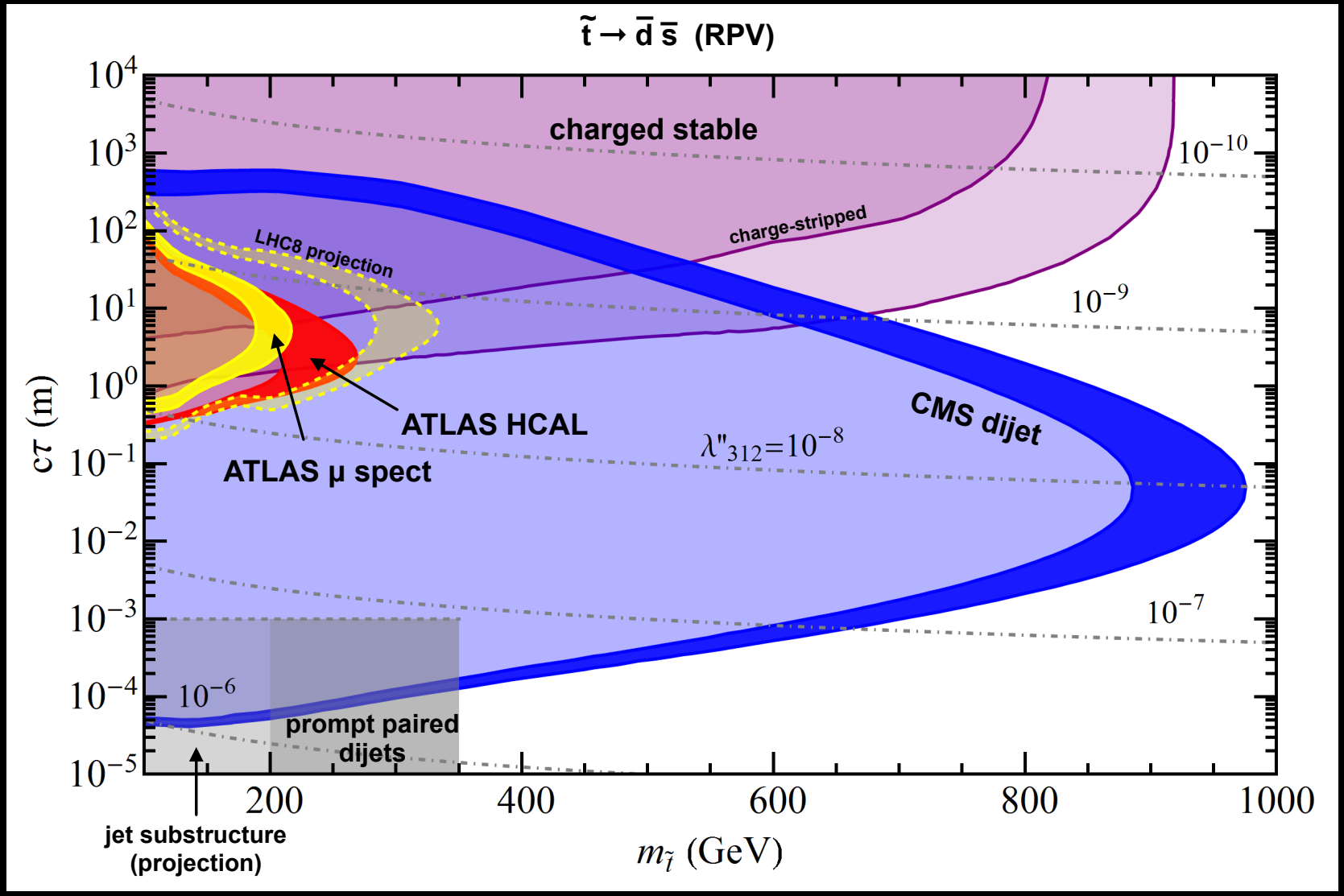
LSP decay to *μqq*

CMS electron & muon



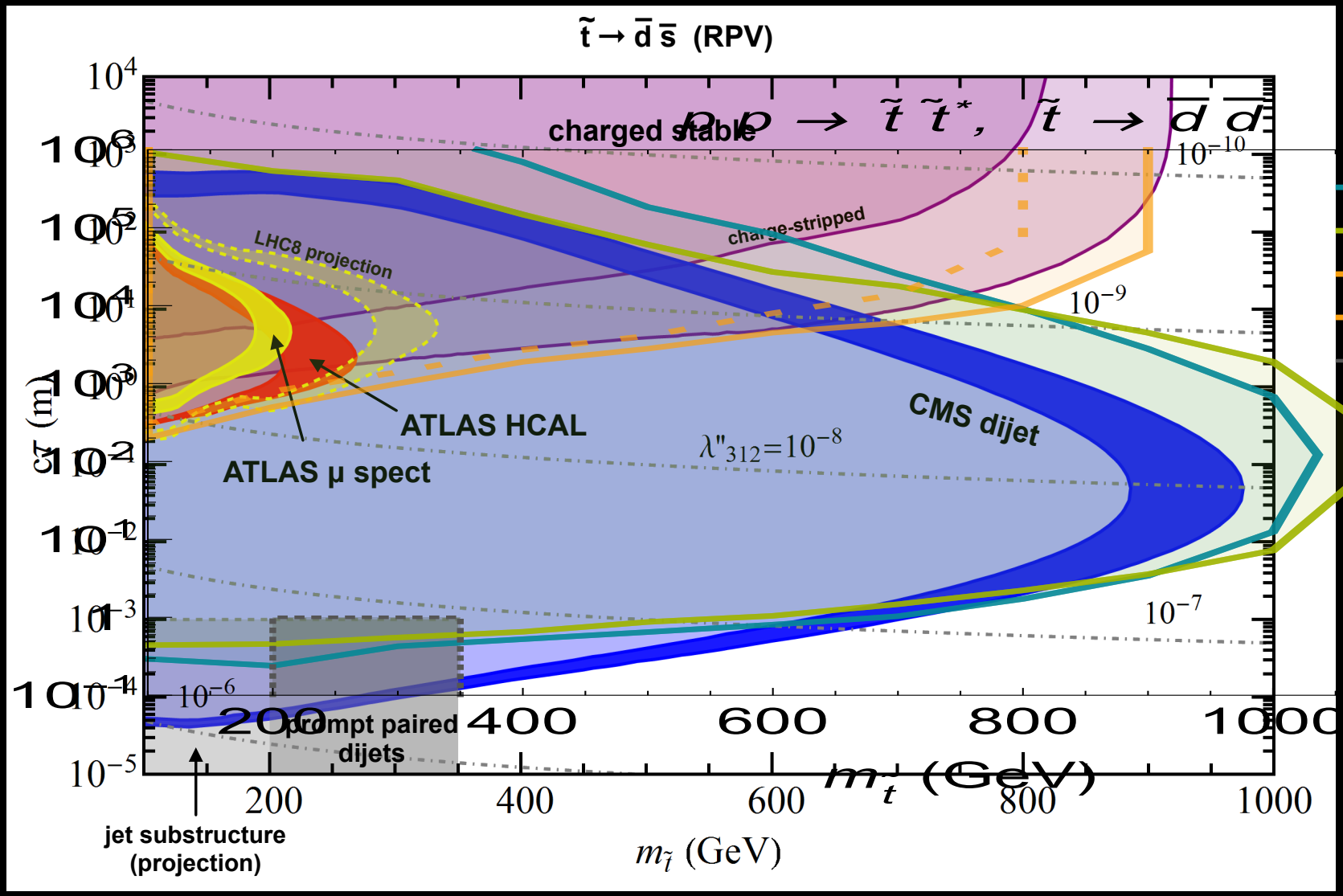
different impact pararameter regions

RPV Stop → 2q (Light Flavors)

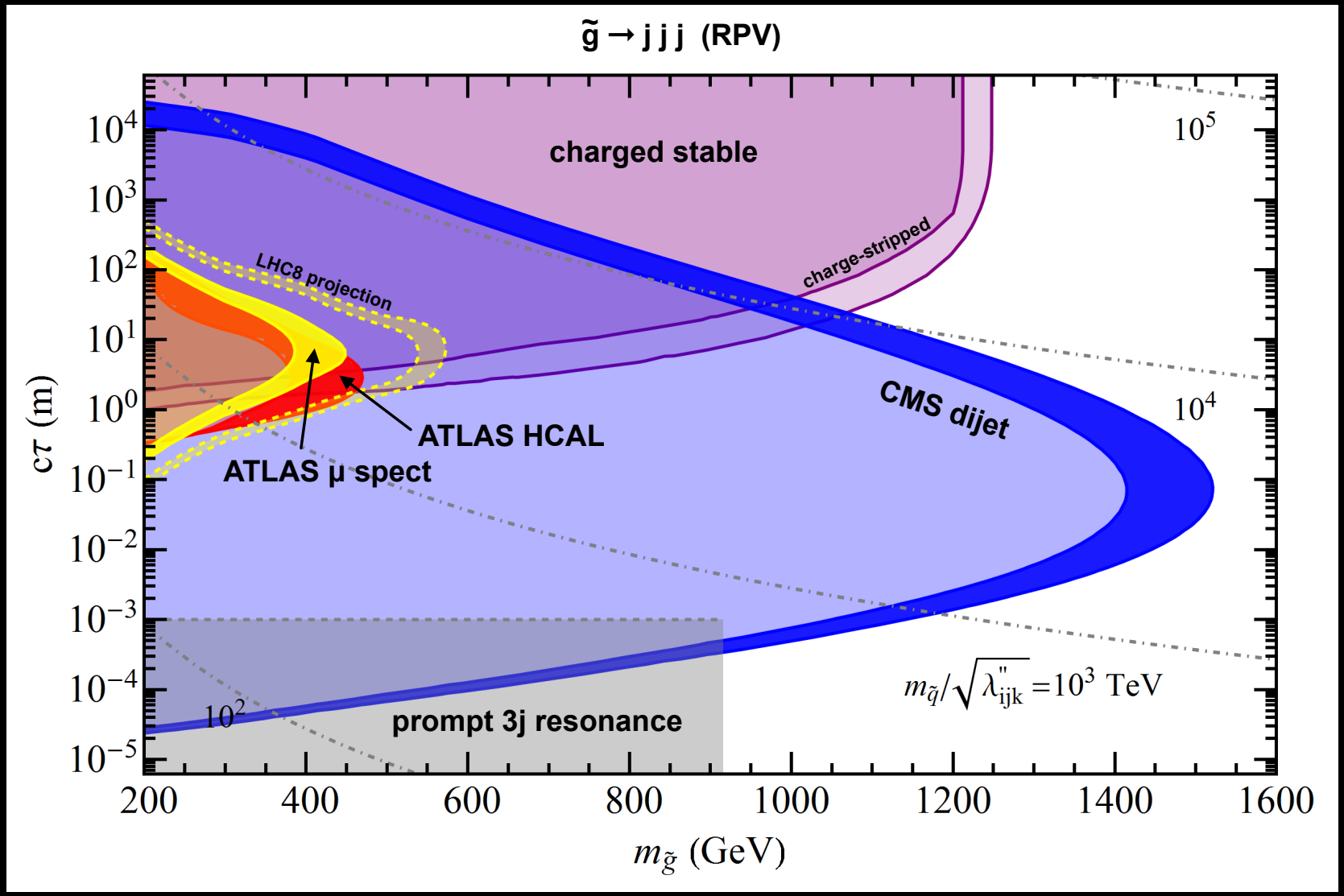


Csaki, et al (1505.00784) overlayed

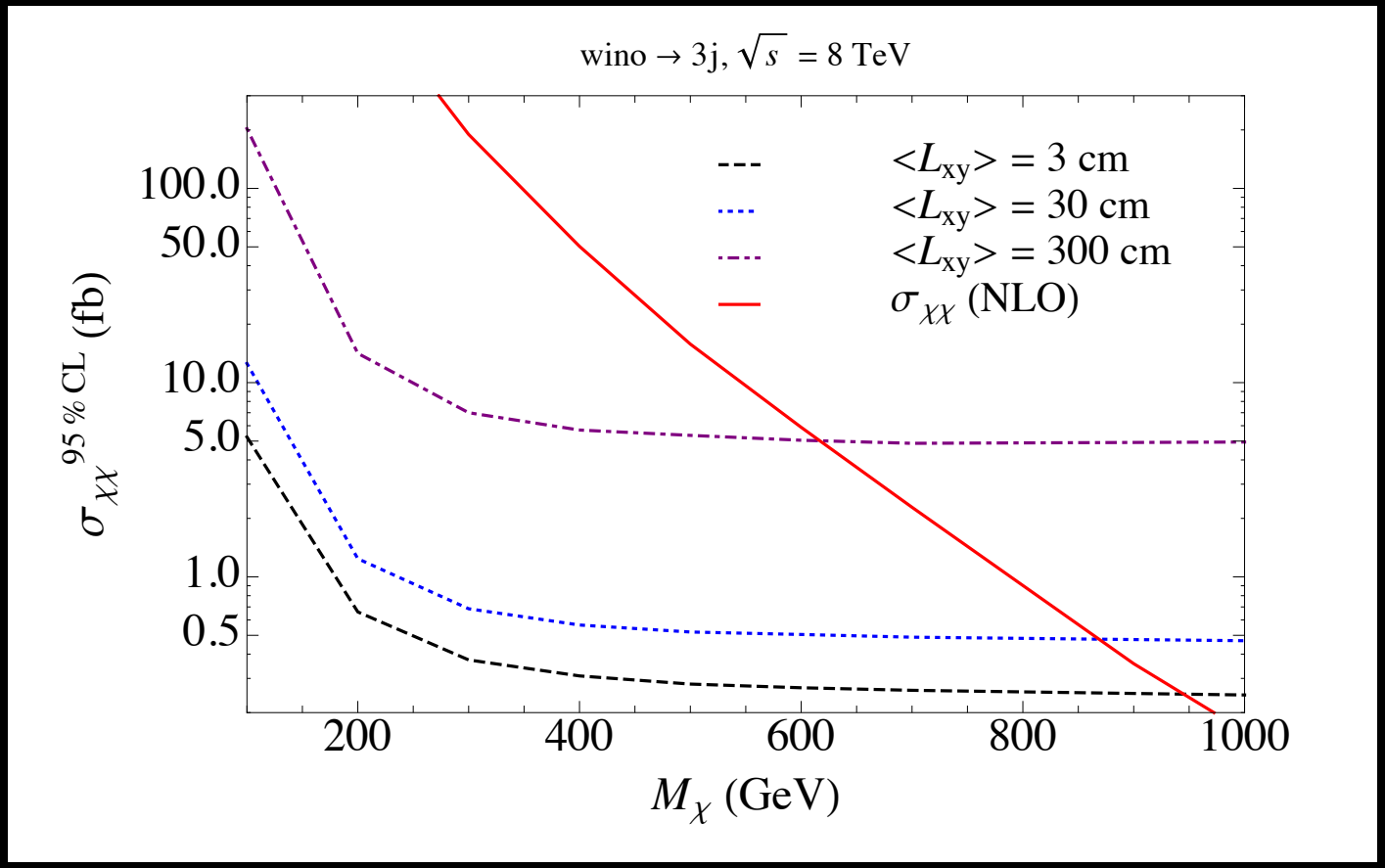
RPV Stop → 2q (Light Flavors)



RPV Gluino → 3q (Light Flavors)

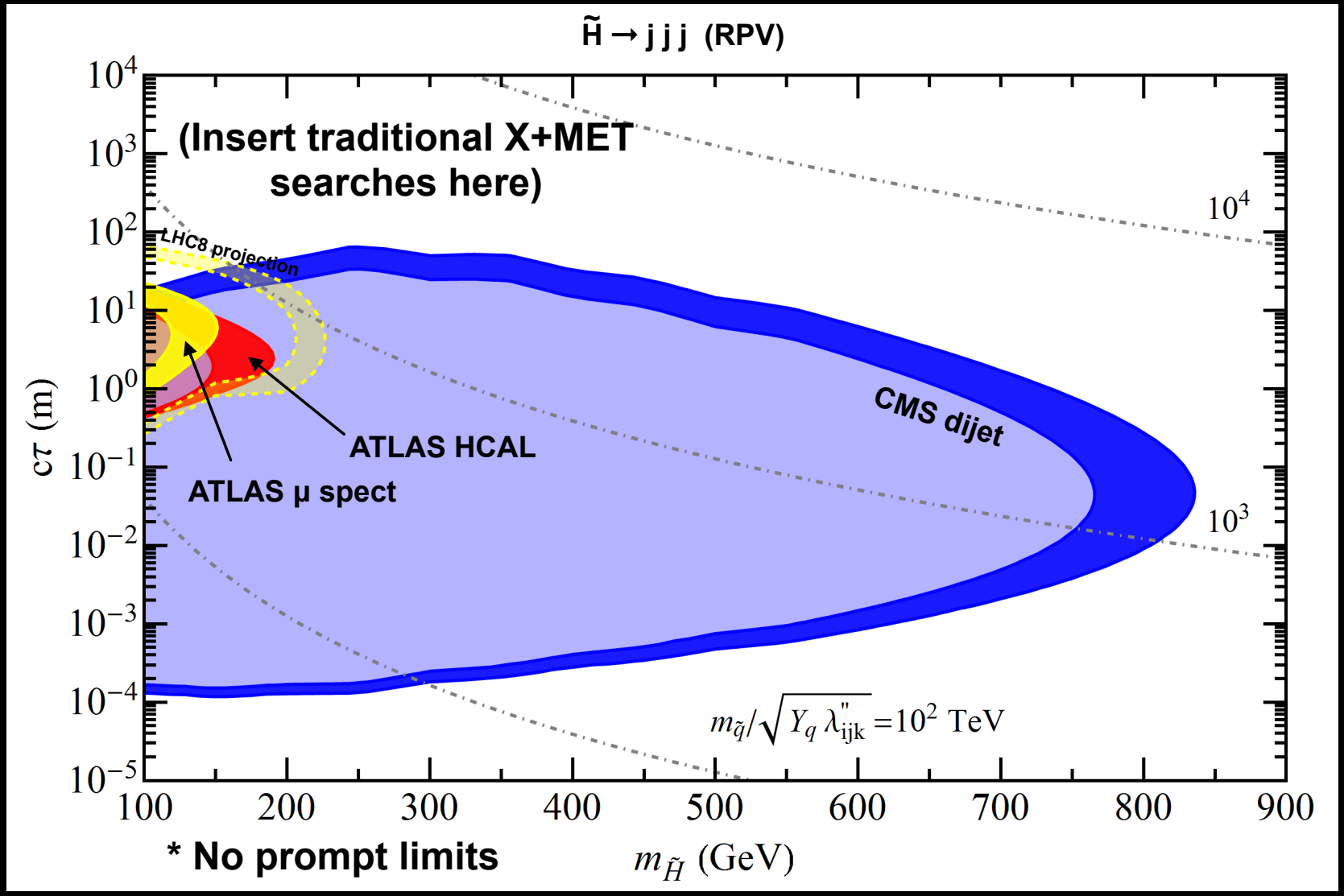


RPV Wino → 3q (Light Flavors)

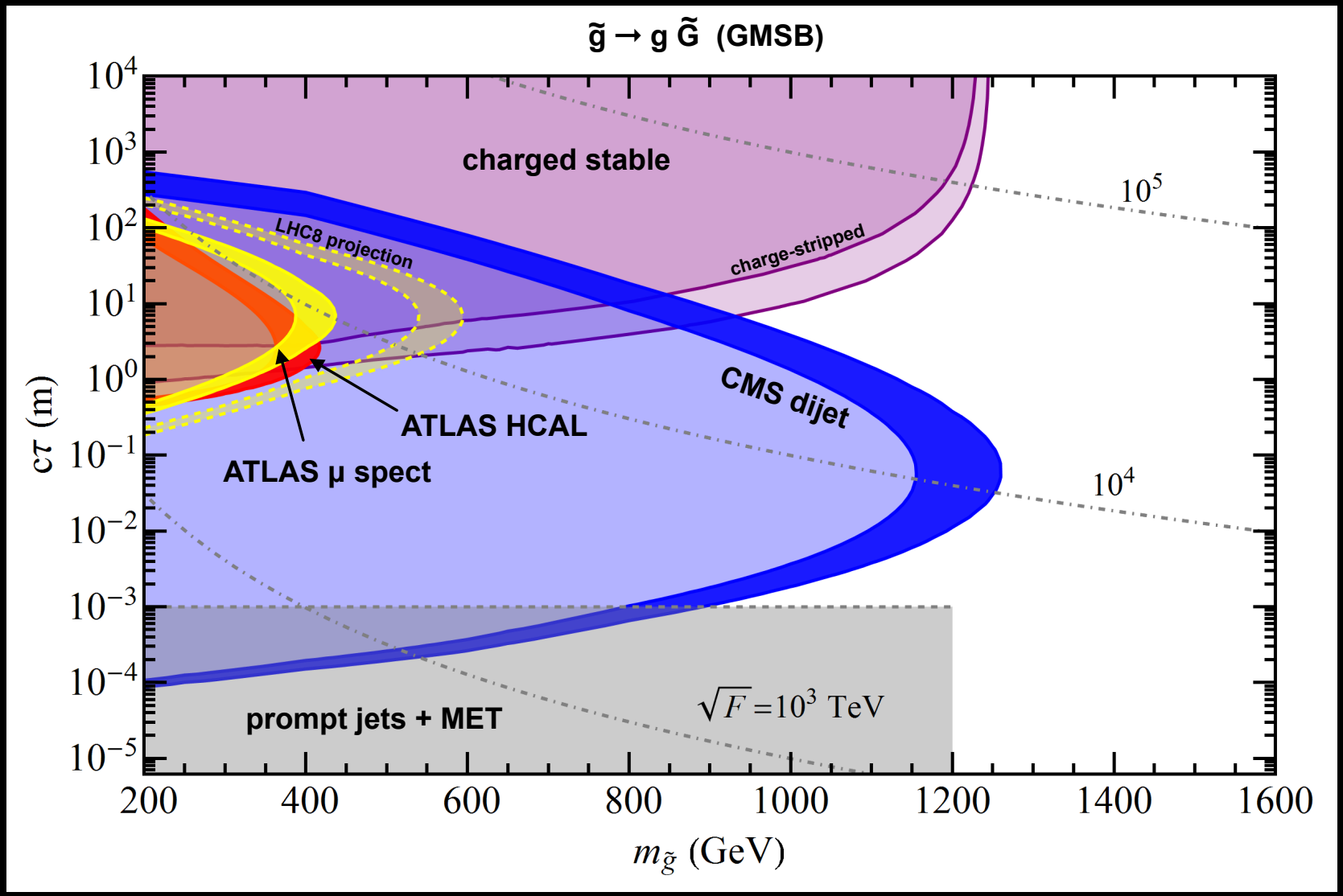


Cui & Shuve (1409.6729)

RPV Higgsino → 3q (Light Flavors)

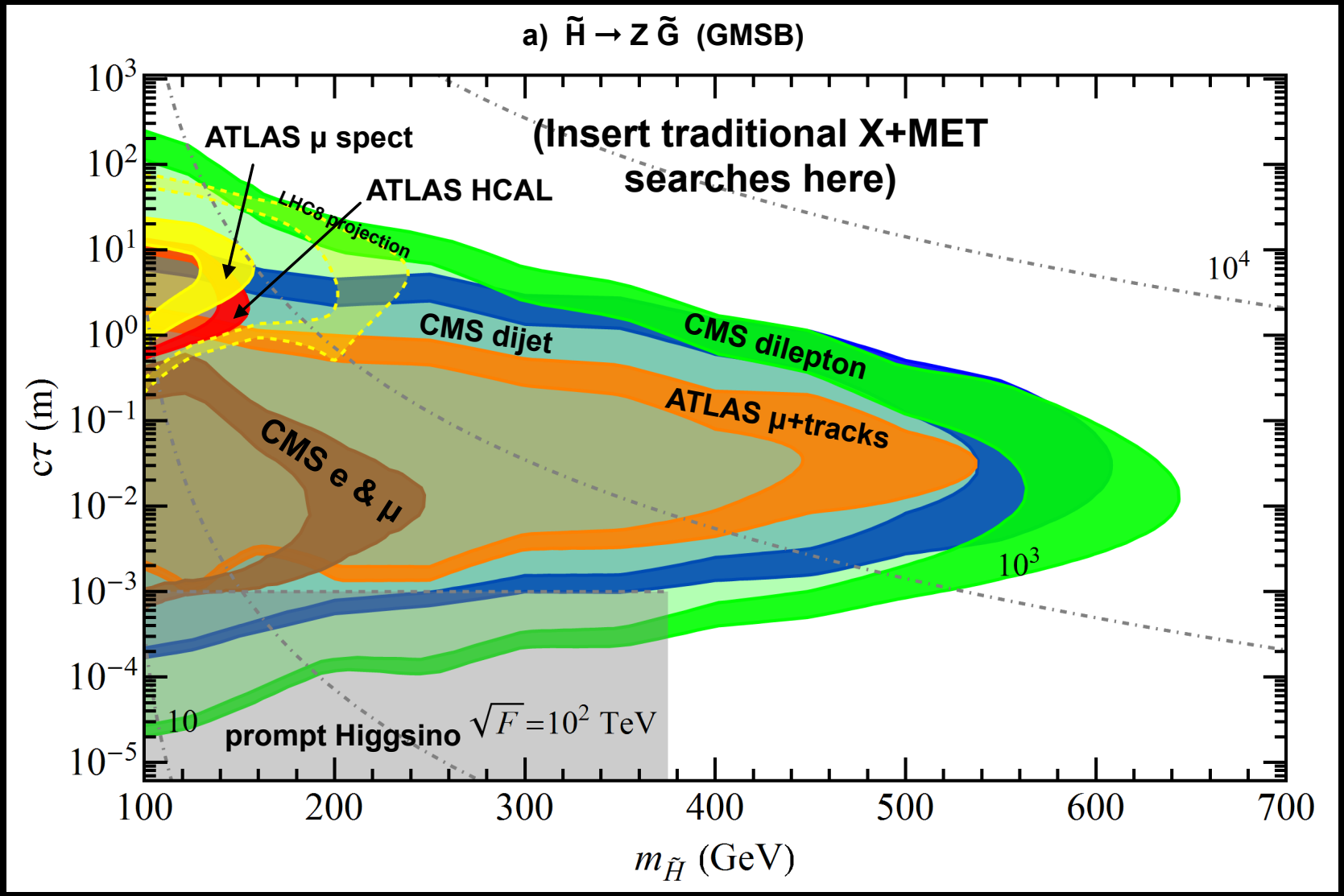


GMSB Gluino → g + Gravitino

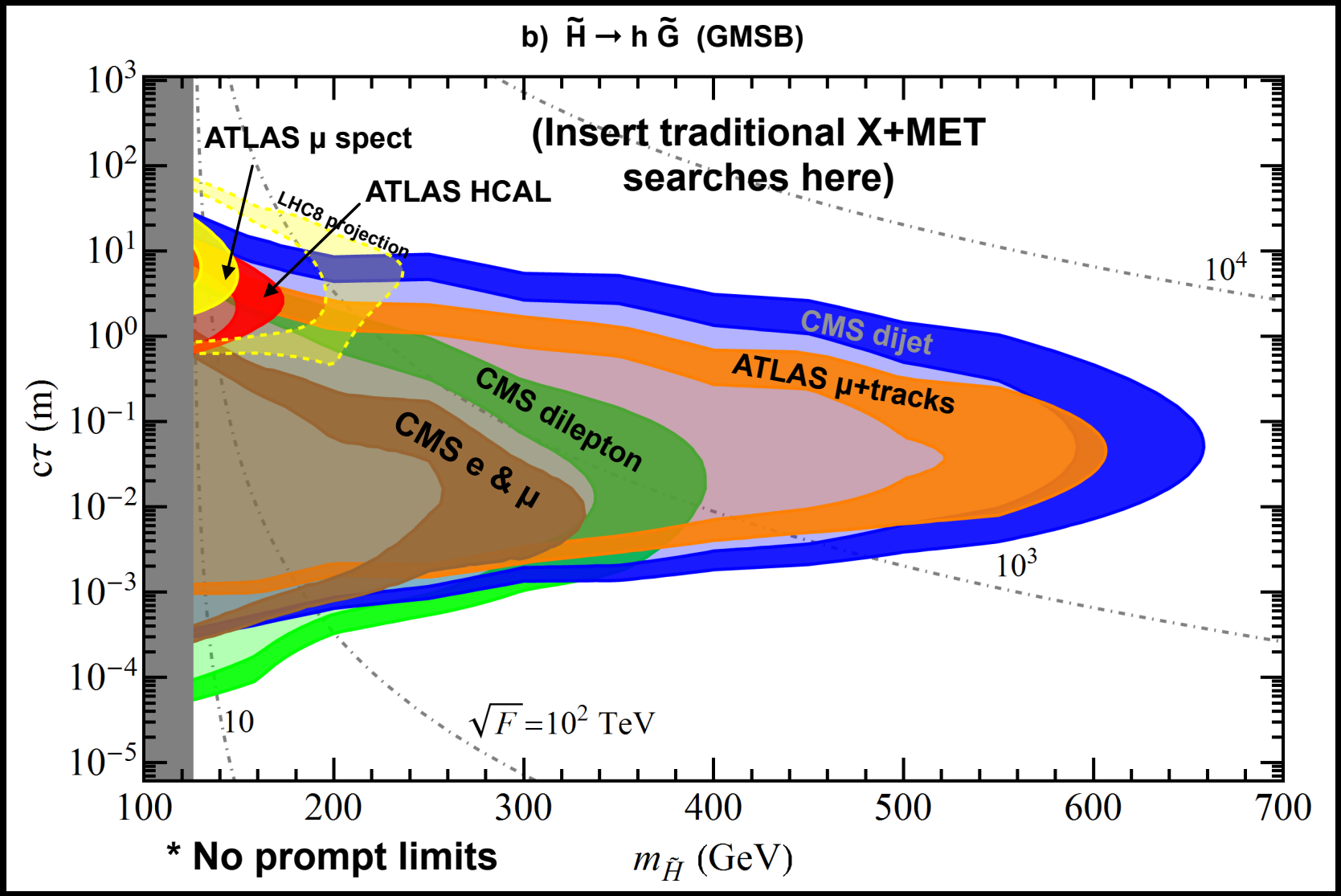


Needs to be re-evaluated with ATLAS DV+X!

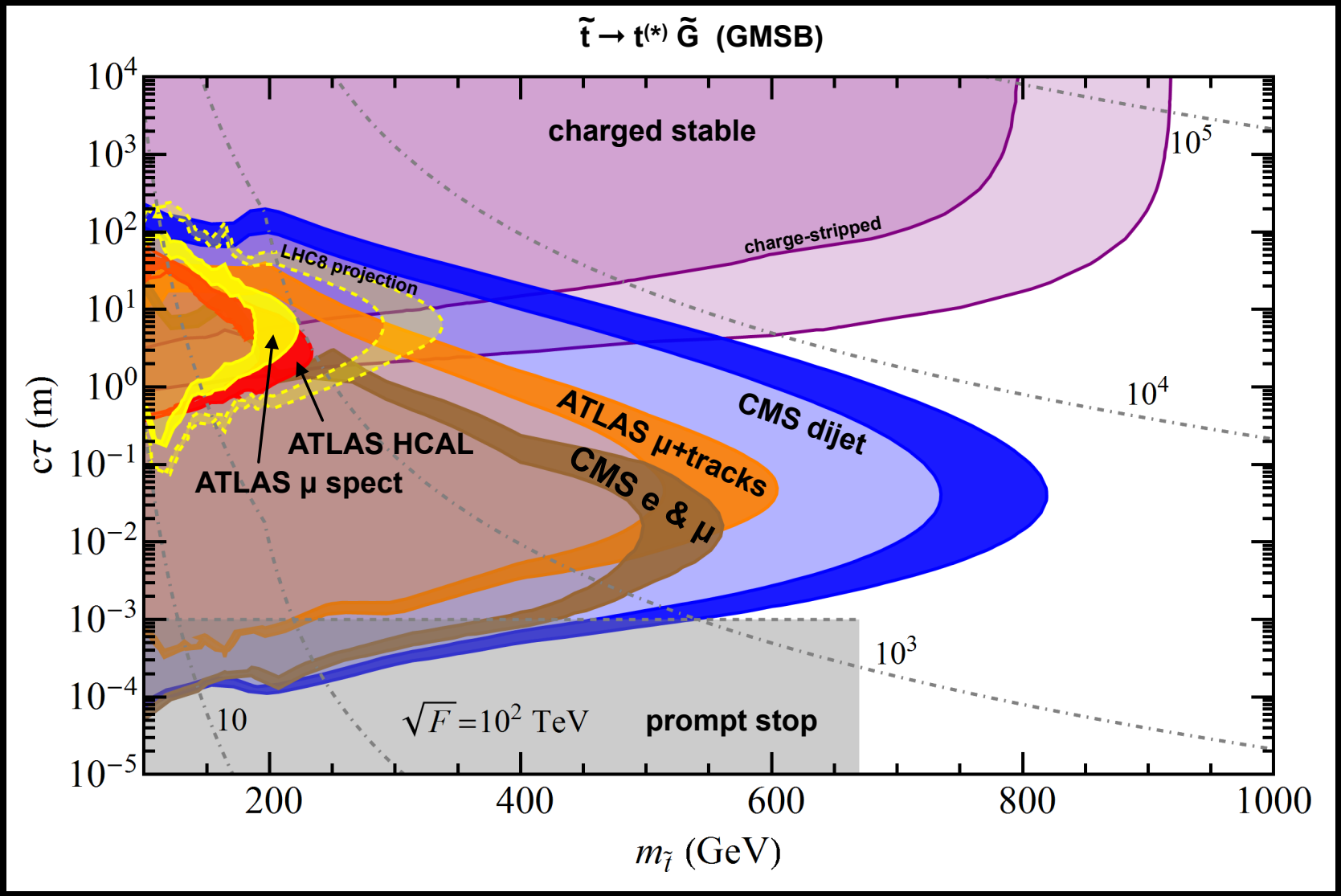
GMSB Higgsino → Z + Gravitino



GMSB Higgsino → H + Gravitino

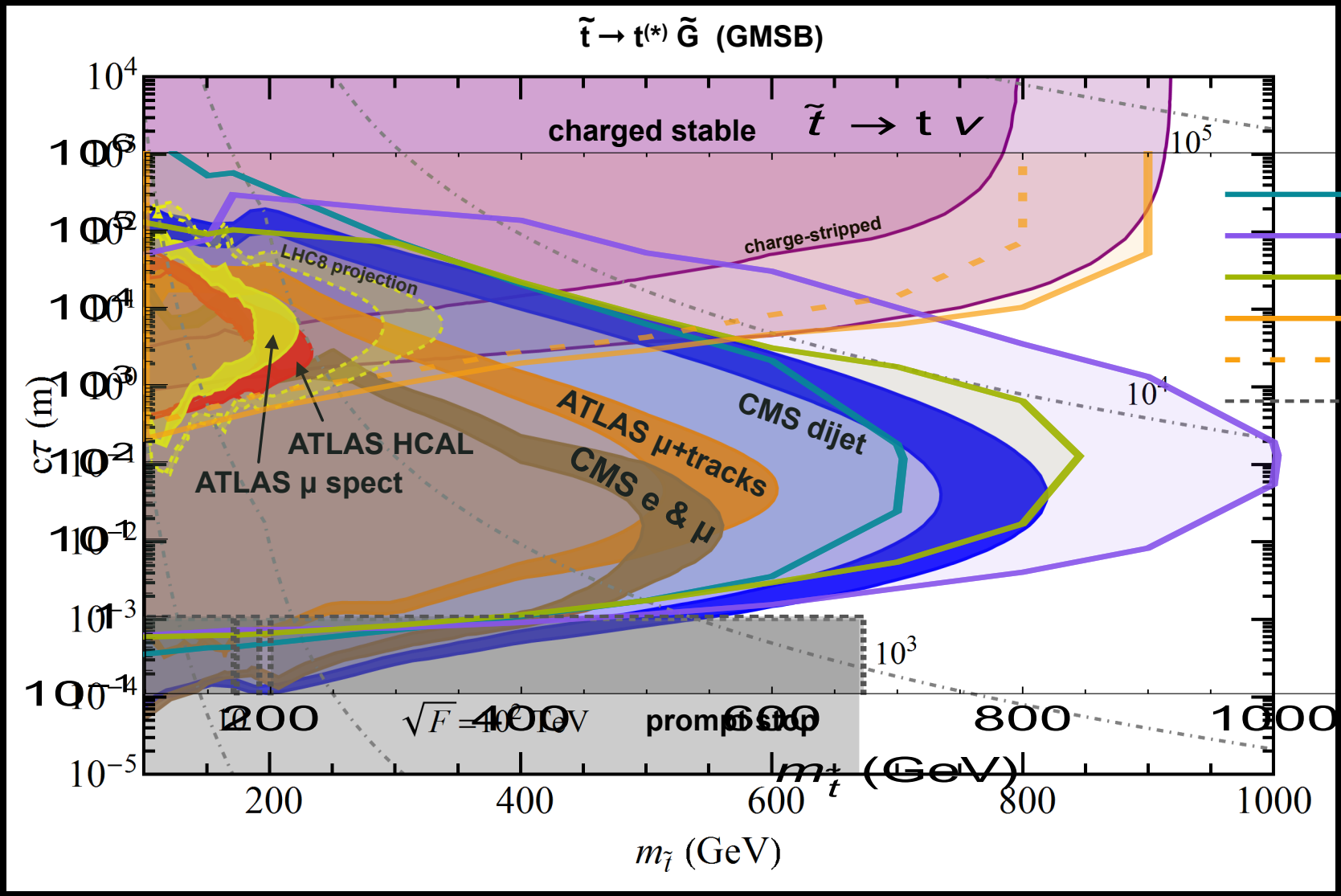


GMSB Stop → Top$^{(*)}$ + Gravitino

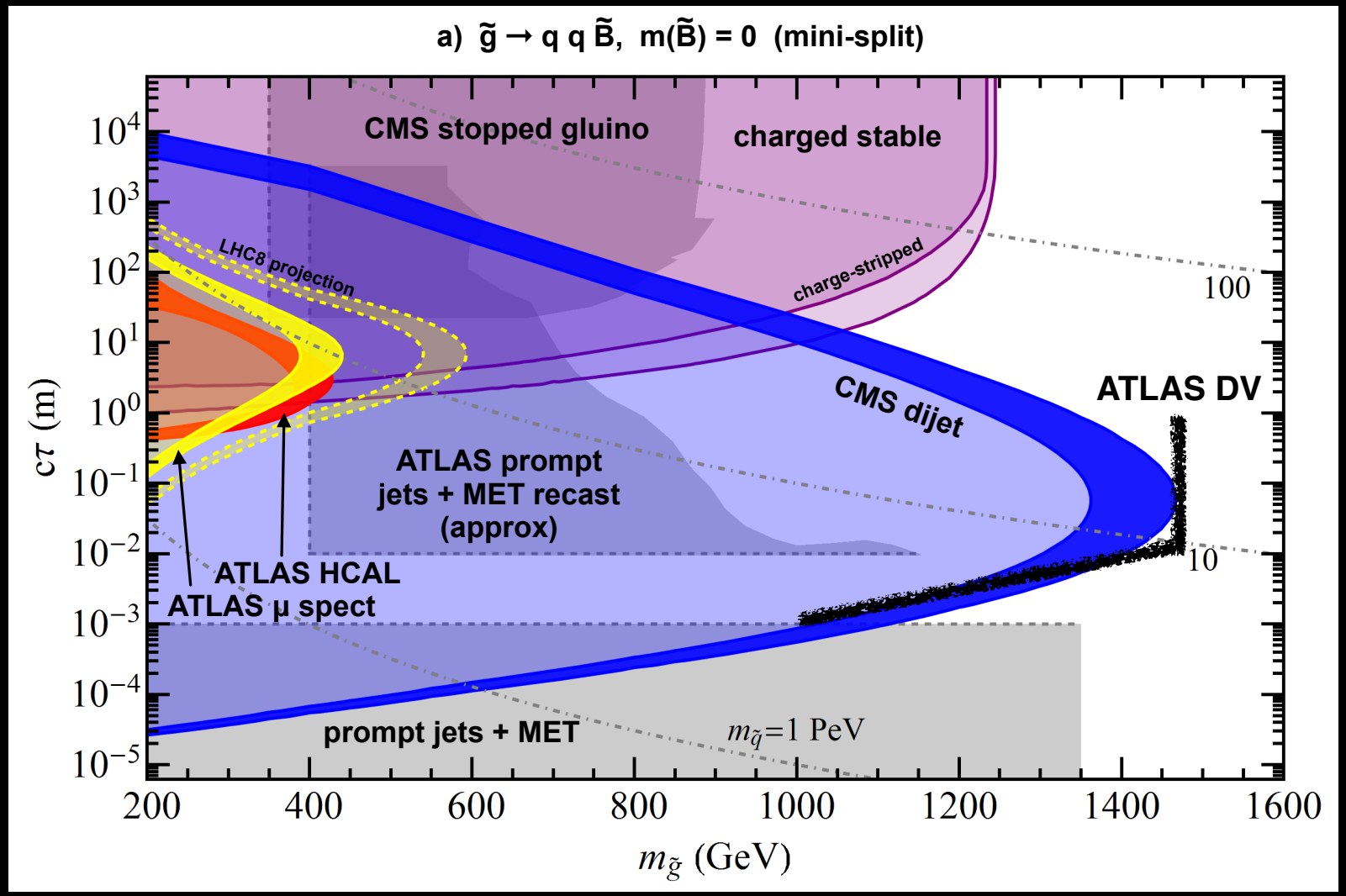


Csaki, et al (1505.00784) overlayed

GMSB Stop → Top$^{(*)}$ + Gravitino



Mini-Split Gluino → 2j + LSP



* m(LSP) = 0 (Also: Comparable limits from decays with tops)

Some Lessons

- Displaced SUSY is difficult to hide
  - non-dedicated displaced searches usually beat dedicated prompt searches in mass reach
  - strong complementarity across prompt/displaced/stable searches
  - “zero to infinity” lifetime coverage in many cases
  - when hadronic decays are active, CMS displaced dijets and ATLAS DV+X usually win
- Weak points at $c\tau \sim$ m and $c\tau \sim$ mm
  - ATLAS CAL/muon searches suffer multiple penalties: coincidence requirement, timing issues, strict isolation criteria, MET veto
  - more b-tag recasts might cover some space at low lifetime
  - prompt search reach is probably broader than we show
- Inner tracker seems to be the most sensitive instrument
  - small volume, but tons of detailed information for crafting cuts
  - still, more aggressive searches with CALs & MS seem possible

Comments on Model Space

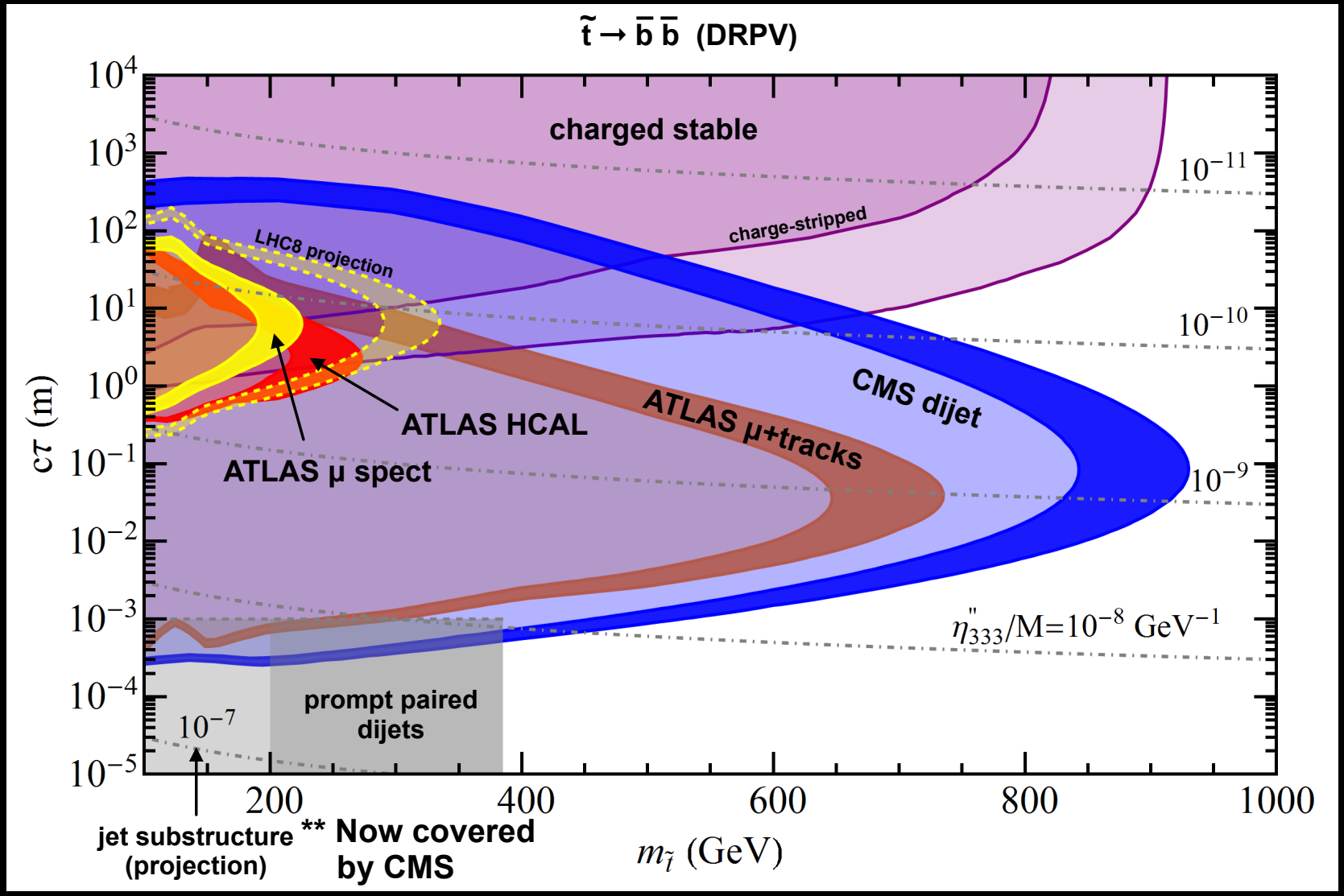
- It's big
  - as elsewhere, facilitating recasting seems mandatory
  - RPV in particular has O(b'gillion) parameters even in simplified spectra
  - we've just scratched the surface here (with lots of personal bias)
- Natural+displaced options generally in bad shape
  - possible escape hatches: prompt-ish BRPV stop at > 350 GeV, really short/long-lived Higgsinos (could still be seen in heavier sparticle prompt decays), decay modes very different from what we've shown, not-so-simplified spectra, ...
- Mini-split gluino is probably above a TeV
- GMSB simplified models have finite options
  - sleptons (staus): amenable to track-stub searches, di- displaced leptons; need/benefit from explicit "kinked track" search? displaced τ-jets?
  - Wino: neutral NLSP gives displaced Z/γ, charged NLSP (non-generic) gives displaced W's; both easy to see

Recaster's Wishlist

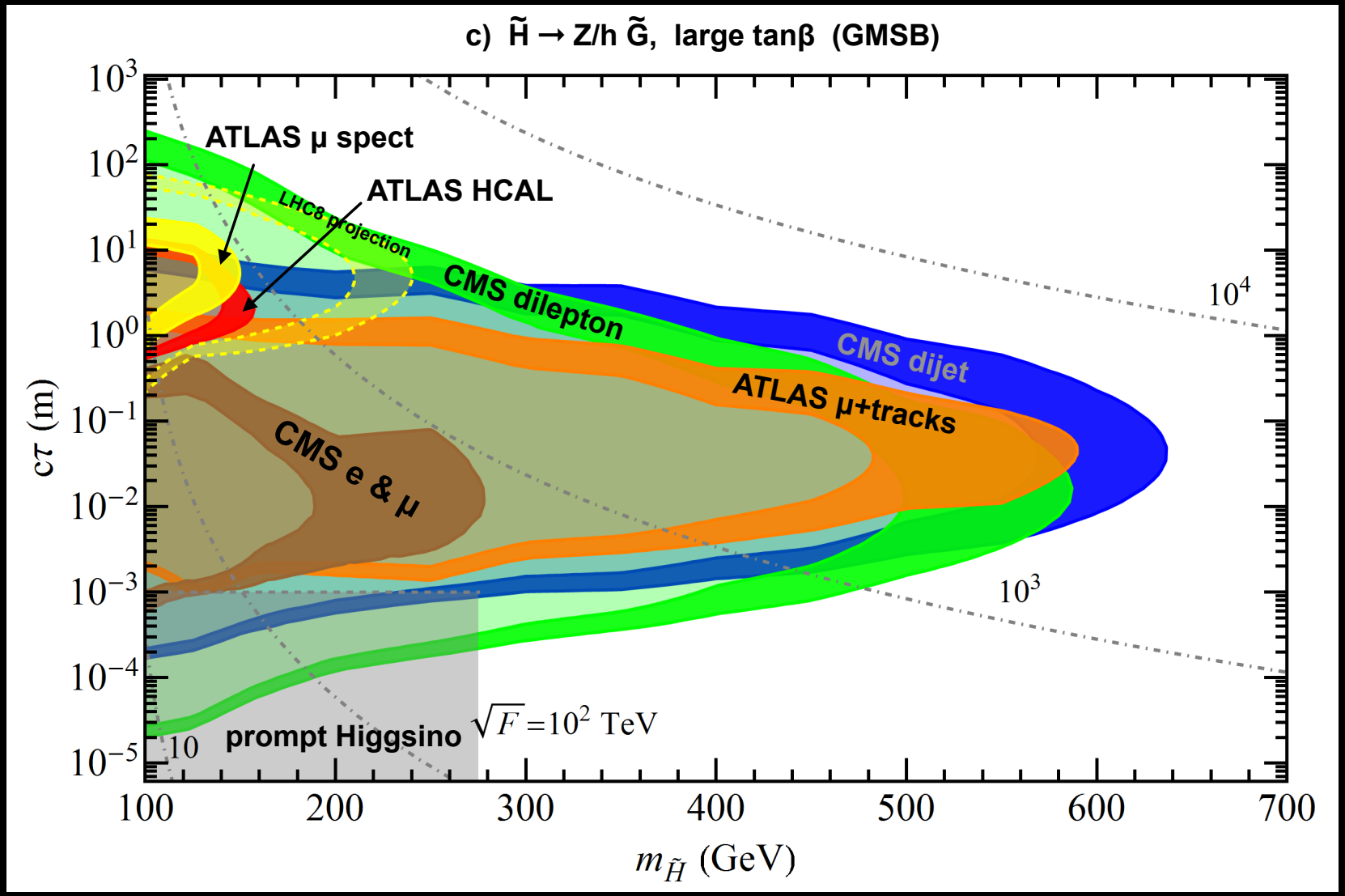
- More varied test models for calibration
  - higher/lower masses
  - different topologies
  - neutral & charged
- More details on detector efficiencies over broad ranges of kinematics, esp. tracking/vertexing
  - isolated tracks vs (η,r,z,IP)
  - transparent/parametrized vertexing criteria
  - fate of "exploding tracks"?
- Some "standard" detector/analysis emulation strategy?
  - but effective # of dials grows rapidly, often several new ones for each new analysis
  - is one experimentally-vetted toy detector per analysis too labor-intensive? (e.g., CMS HSCP recast map: **PAS EXO-13-006**)

More...

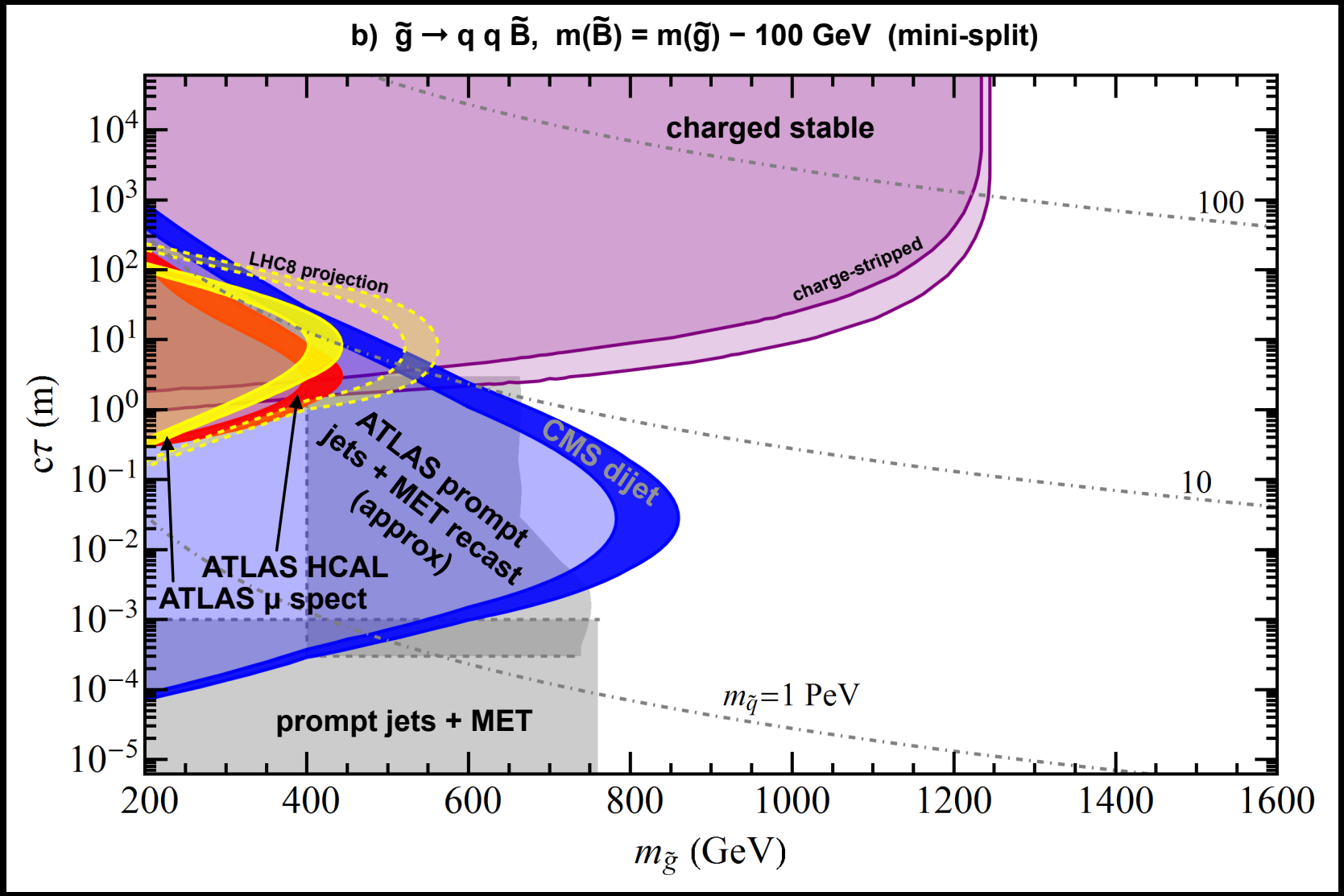
dRPV Stop → 2b


$\tilde{t} \to \bar{b}\,\bar{b}$ (DRPV)
charged stable
charge-stripped
LHC8 projection
ATLAS HCAL
ATLAS μ spect
ATLAS μ+tracks
CMS dijet
10^{-11}
10^{-10}
10^{-9}
10^{-7}
$\eta''_{333}/M=10^{-8}$ GeV^{-1}
prompt paired dijets
$c\tau$ (m)
$m_{\tilde{t}}$ (GeV)
jet substructure (projection)
** Now covered by CMS

GMSB Higgsino → Z/h + Gravitino
Large tanβ Limit

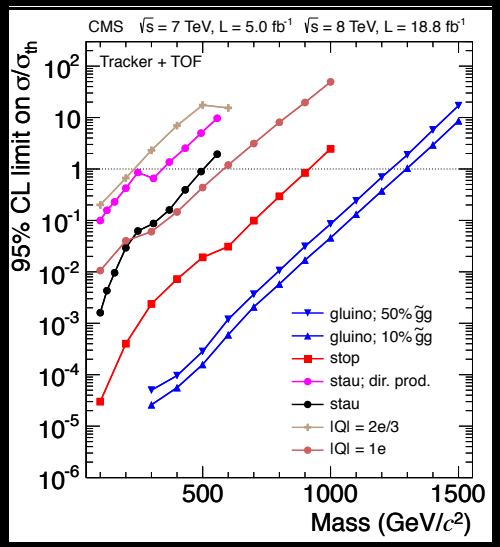


Mini-Split Gluino → 2j + LSP



A Few SUSY Limits

detector-stable charged



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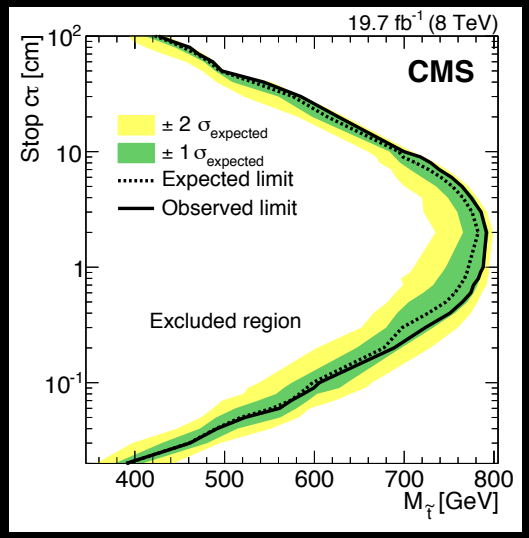
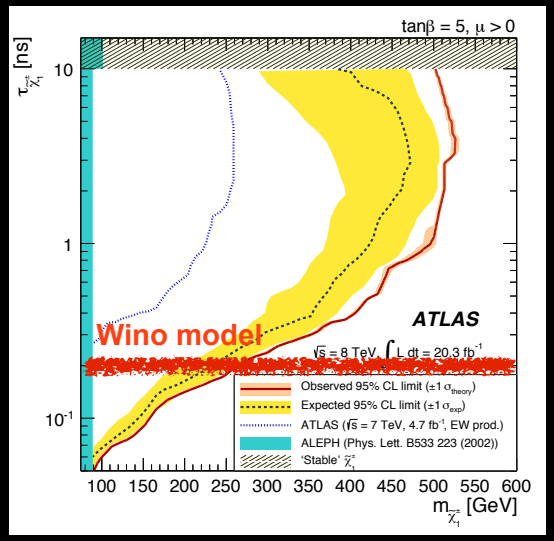
stop → lepton + bottom (LRPV)



1409.4789

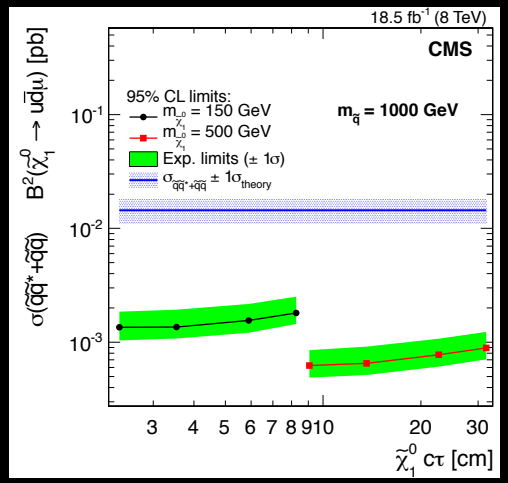
disappearing track (Wino co-LSPs)



1310.3675

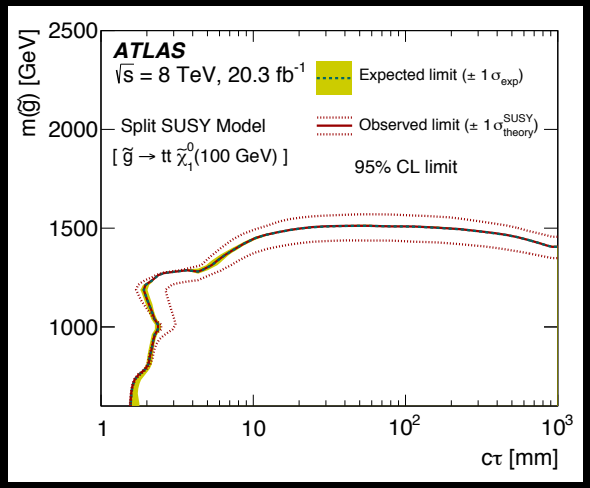
A Few More

displaced "dijet": neutralino → μ + jets (LRPV)



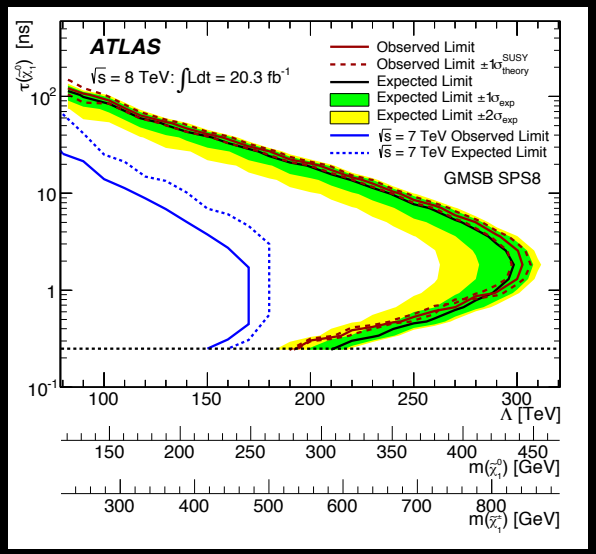
1411.6530

DV + jets/leptons/MET: gluino → tt + neutralino (Mini-split)



1504.05162

non-pointing photons (GMSB)



1409.5542