Compressed Stops and Displaced Superparticles

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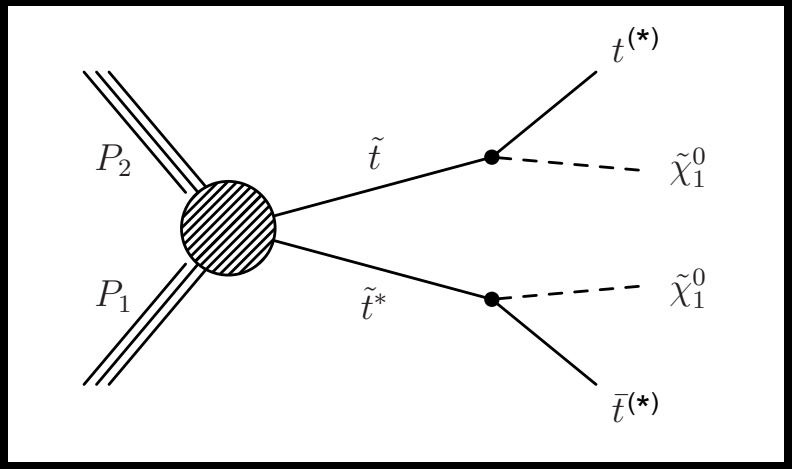
@ TRIUMF Workshop:
Discoveries at the Dawn of LHC Run 2
28 October 2015

Part I: Compressed Stops

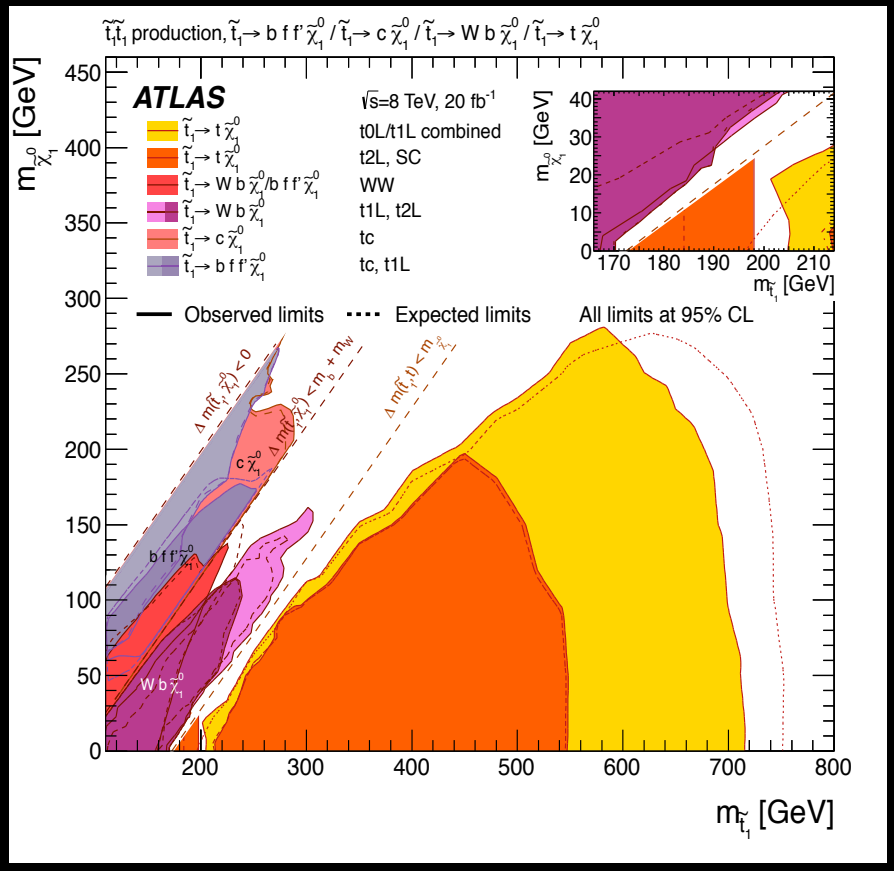
with S Macaluso, M Park, D Shih (1506.07885)

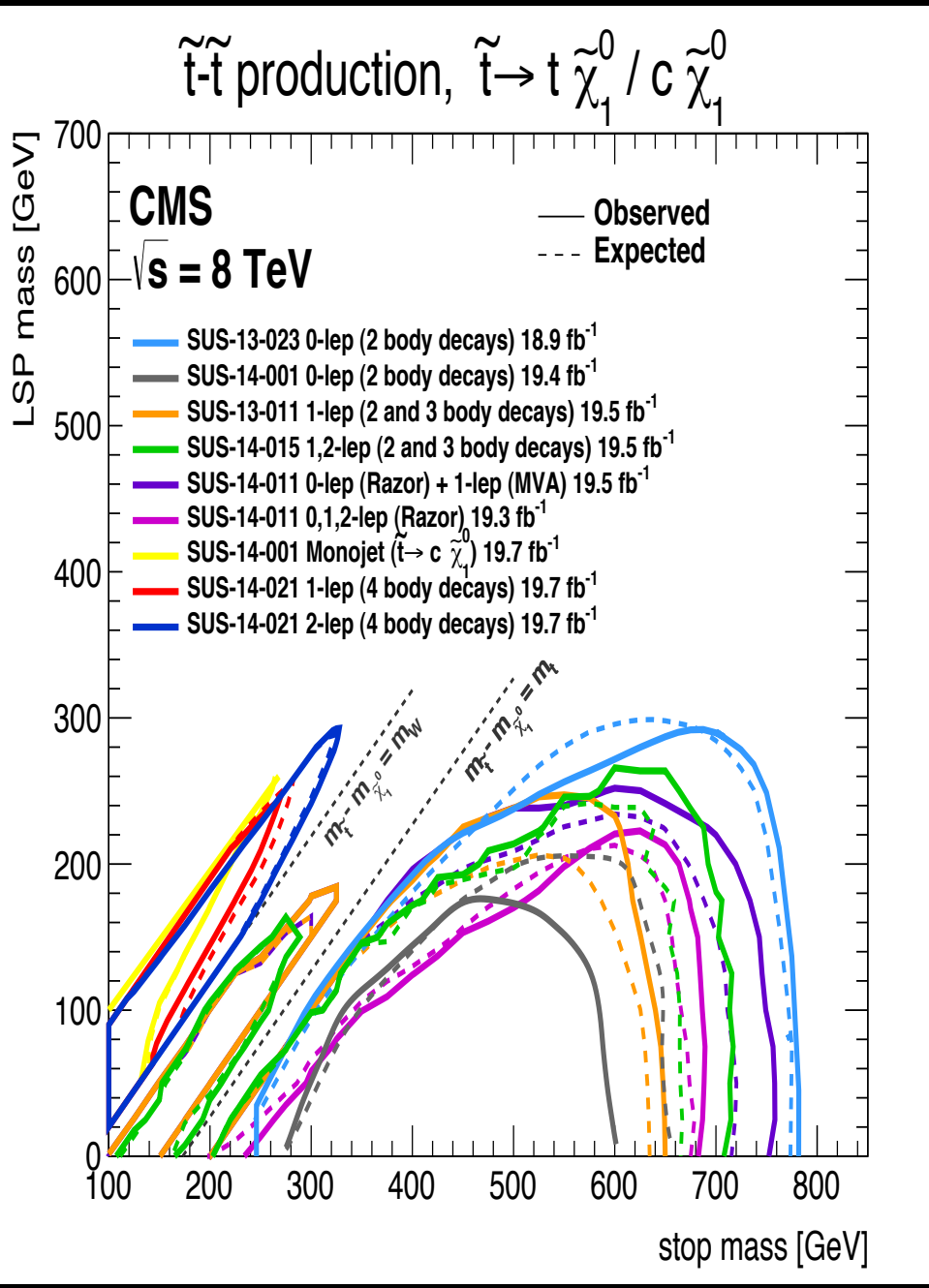
Stop-Neutralino Simplified Model



The minimalist's model of Natural SUSY

Run 1 Results

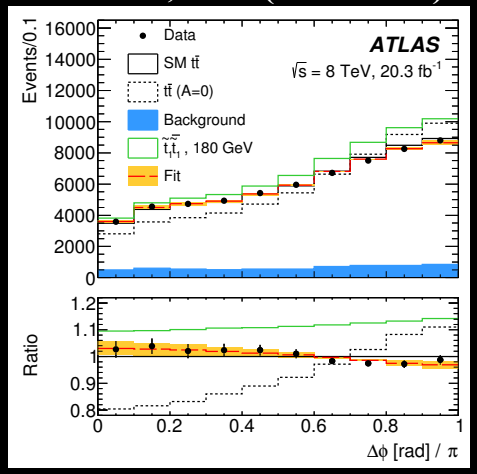




A Sampling of Ideas

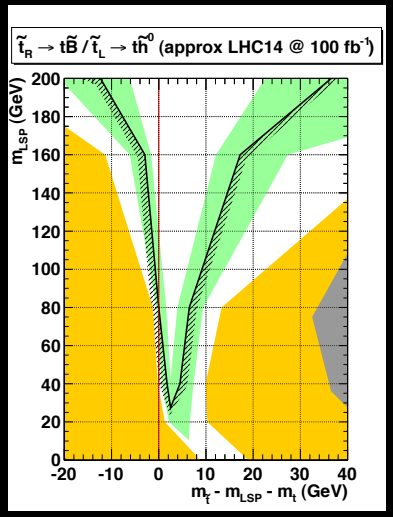
σ_{tt} + spin correlation

Han, Katz, Kroh, Reece (1205.5808)
Czakon, et al (1407.1043)



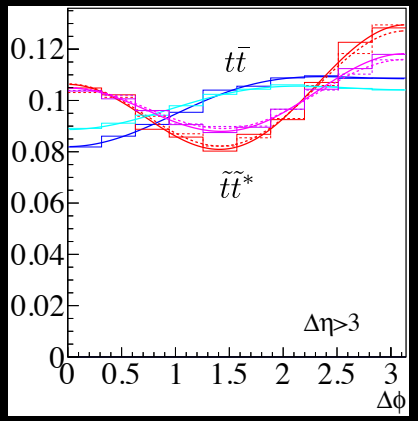
Careful kinematic tail measurements

Alves, et al (1205.5805)
Kilic & Tweedie (1211.6106)



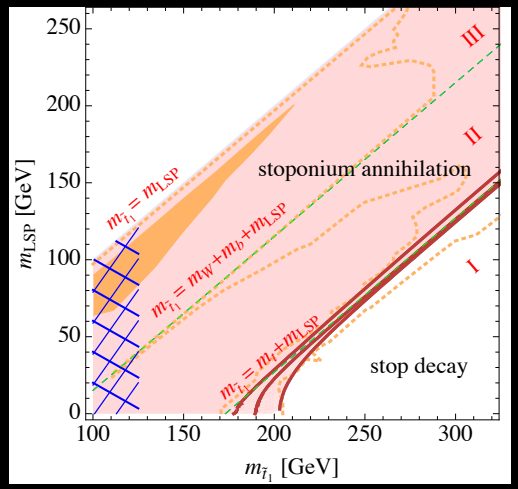
VBF

Dutta, et al (1312.1348)
Buckley, Plehn, Ramsey-Musolf (1403.2726)



Stoponium

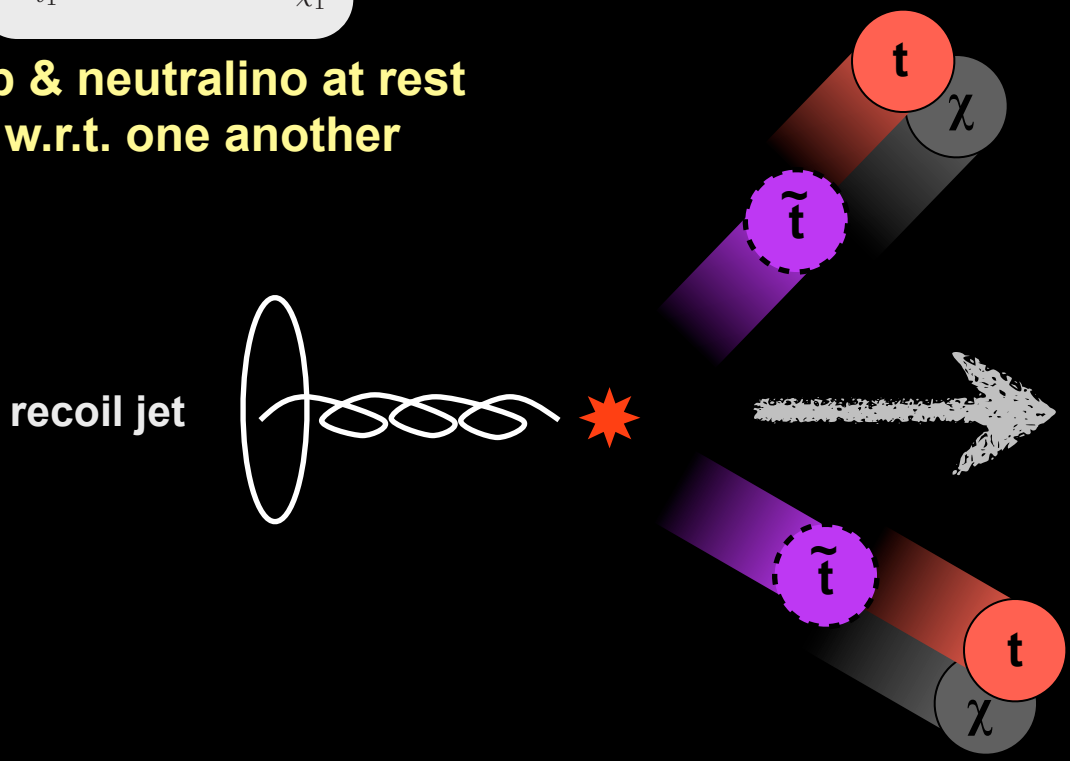
e.g., Batell & Jung (1504.01740)



"An Equal-Velocity Scenario for Hiding Dark Matter at the LHC"

$$m_{\tilde{t}_1} \simeq m_t + m_{\tilde{\chi}_1^0}$$

=> top & neutralino at rest w.r.t. one another



$$\vec{\not{E}}_T \simeq -\vec{p}_T(\text{jet}) \times \frac{m_{\tilde{\chi}}}{m_{\tilde{t}}}$$

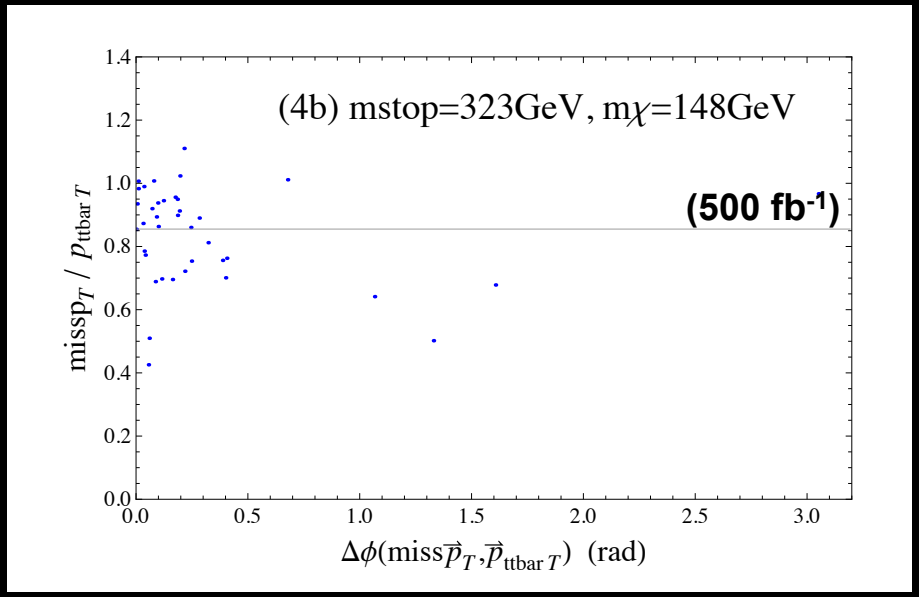
+ MET from top decay

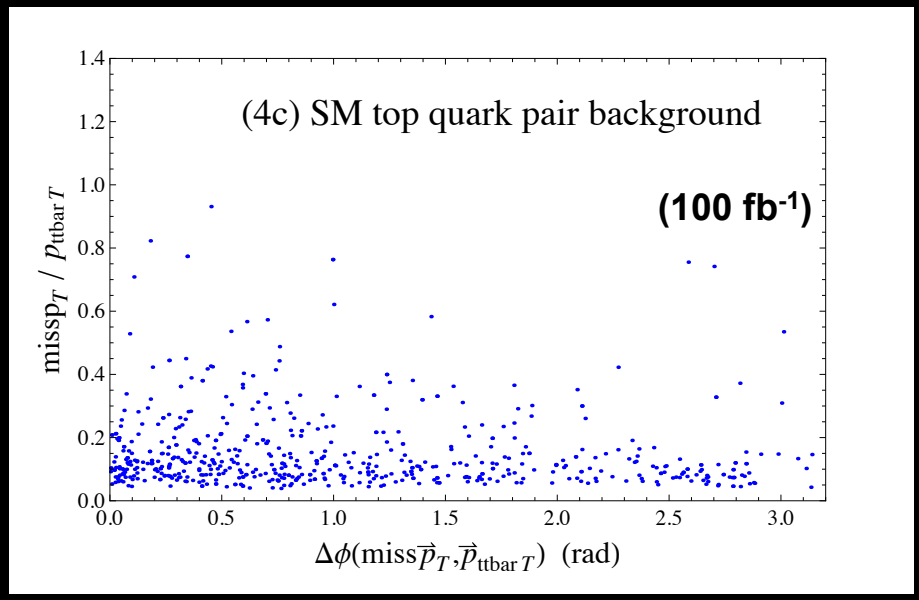
*** Correlation in both direction & magnitude ...Strongest if both tops decay hadronically**

Hagiwara & Yamada (1307.1553)

(Might this idea have appeared earlier?)

2D Distributions





All-hadronic analysis after showering & jet reco

Hagiwara & Yamada (1307.1553)

Our Approach

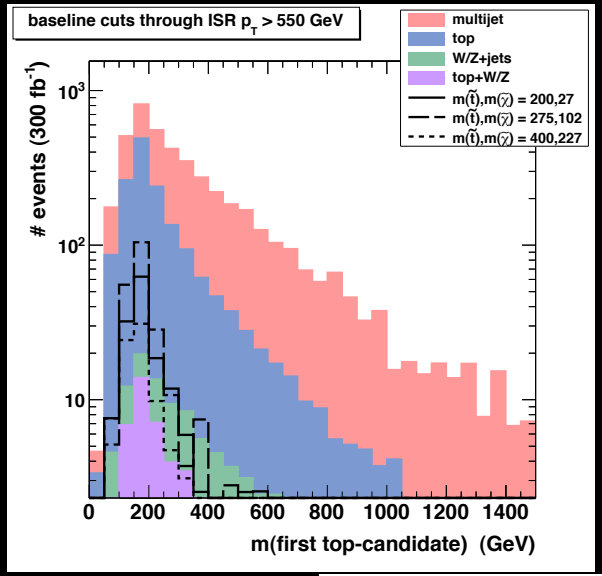
- Coarse modeling of (we hope) most relevant detector effects
  - lepton ID / isolation (no tau veto)
  - jet energy smearing (Snowmass projection with 50 pileup)
  - MET defined to balance jets (neglect out-of-jet corrections)
  - *assume* pileup jets can be efficiently removed/attenuated
- Simple reconstruction
  - ≥7 jets, 2 b-tags
  - "ISR-jet" identified (basically hardest jet), 550 GeV threshold
  - form top candidates through ΔR clustering of jets
- Incorporate major backgrounds
  - QCD starting from 4j at parton-level (≥ b- or c-quarks)
  - tt matched to +1j (all-hadronic) or +2j (l/τ+jets)
  - also tt+W/Z, W/Z+jets (single-t automatically subdominant to tt)
  - everything LO (good approx for tt, who knows for QCD...)

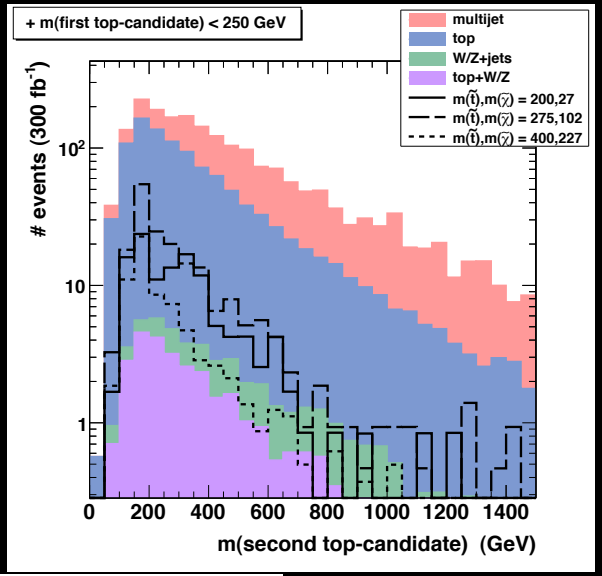
More Details

lepton veto	no isolated ID'ed leptons with $p_T(l) > 10$ GeV, $\|\eta(l)\| < 2.5$
jets	$p_T(j) > 20$ GeV, $\|\eta(j)\| < 2.8$; $N(j) >= 7$, $N(b\text{-tag}) >= 2$
ISR-jet	$p_T(\text{ISR-jet}) > 550$ GeV
tops	$m(\text{top-candidates}) < 250$ GeV
jet/$\not\!\!E_T$ alignment	$\|\Delta\phi(j_{1,2,3}, \not\!\!E_T)\| > 0.55$, $\|\Delta\phi(\text{ISR-jet}, \not\!\!E_T)\| > 2.95$
$\not\!\!E_T/\sqrt{H_T}$	optimized window (minimally $\not\!\!H_T/\sqrt{H_T} > 3$ GeV$^{1/2}$)

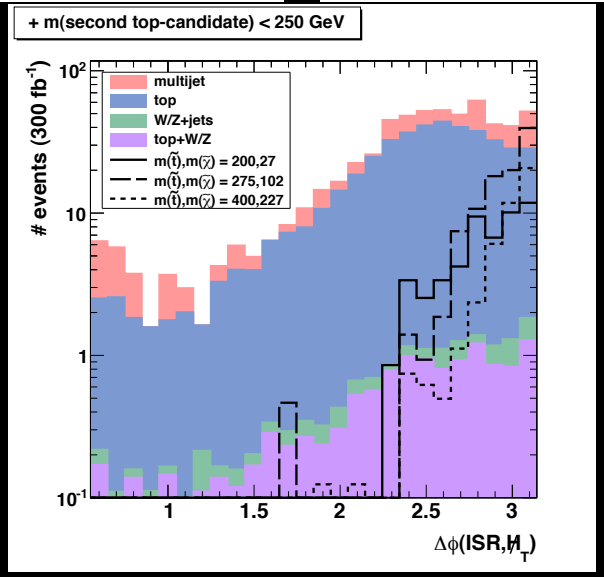
Sequential Kinematic Distributions

top #1 mass



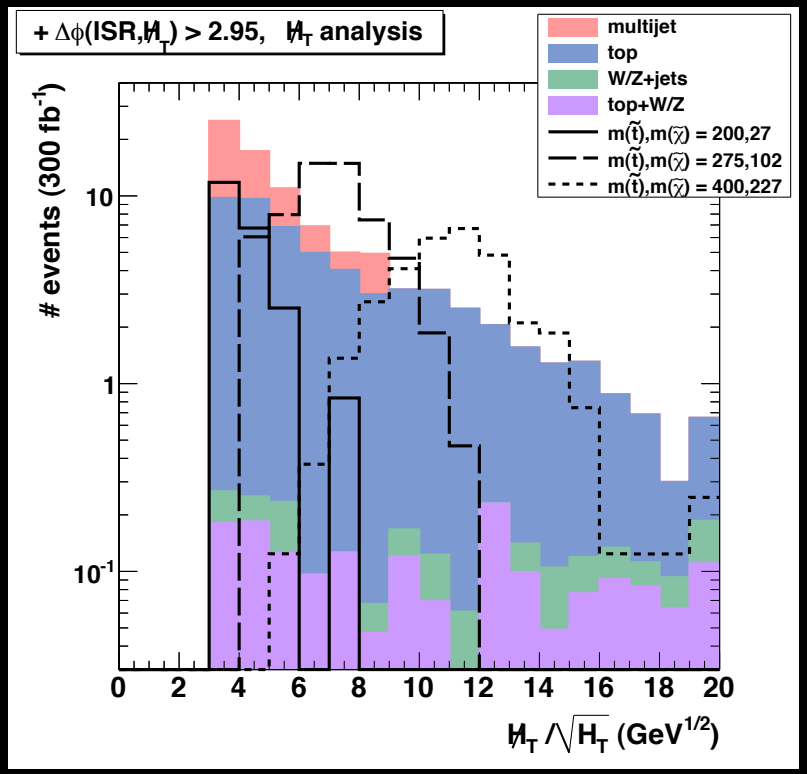


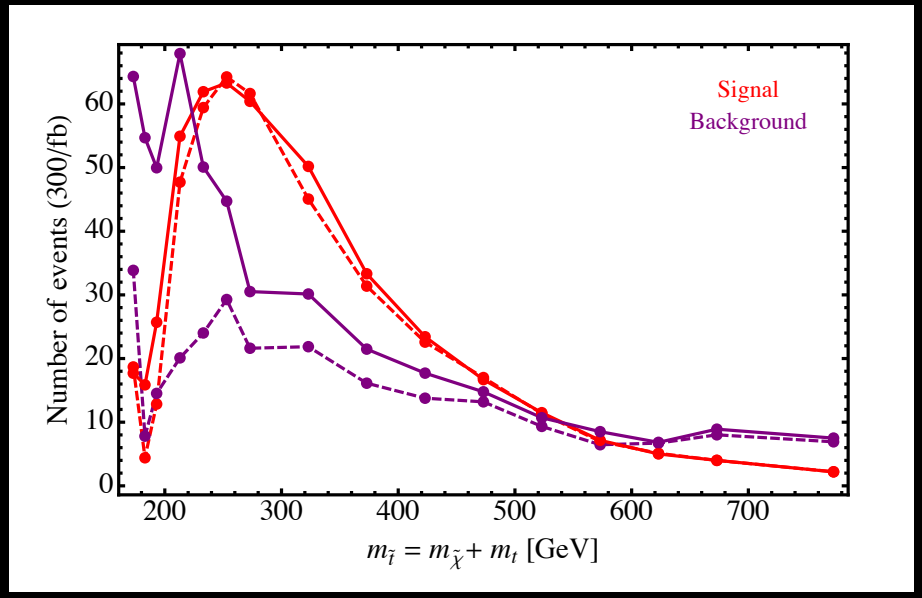
top #2 mass



Δφ between recoil-jet and MET

Final Cut on MET-Significance

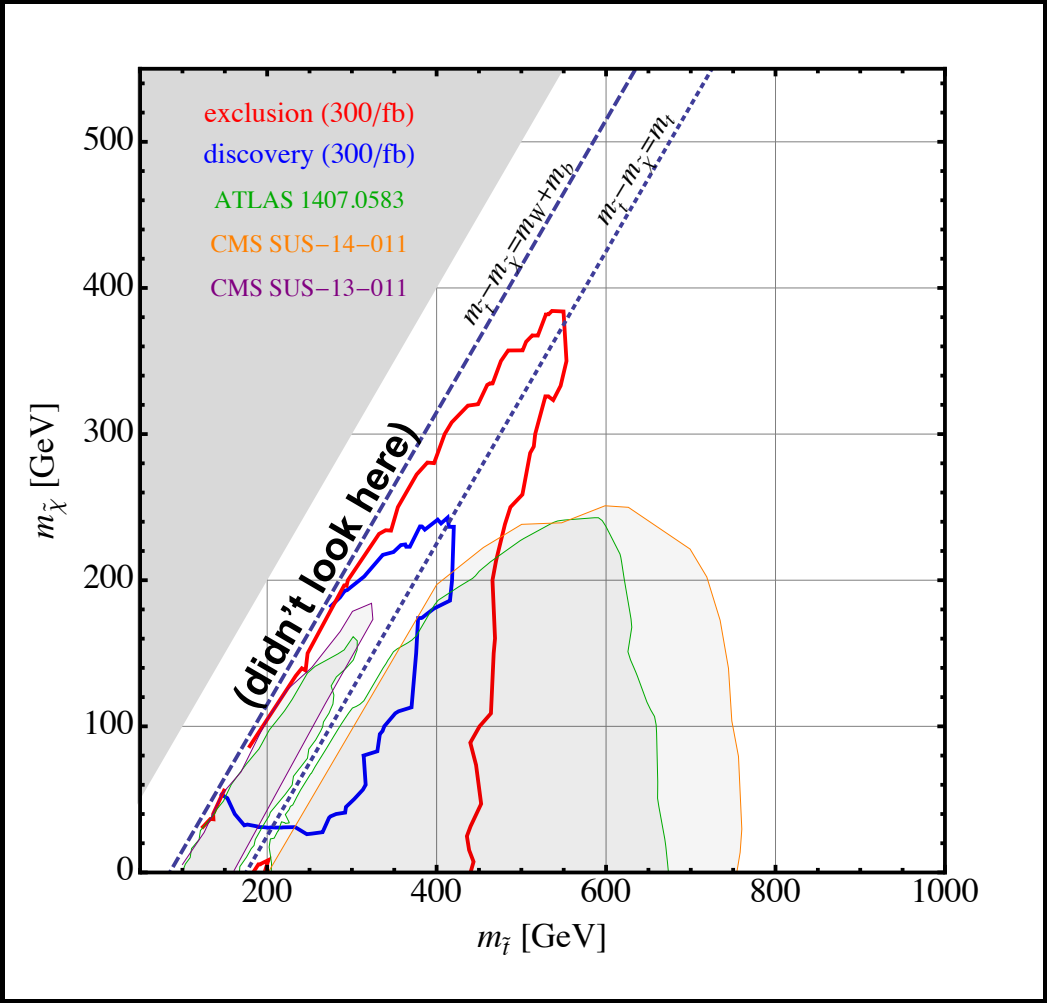




(Dashed lines => perfect MET)

Identify optimized window for each signal, cut & count (no systematics)

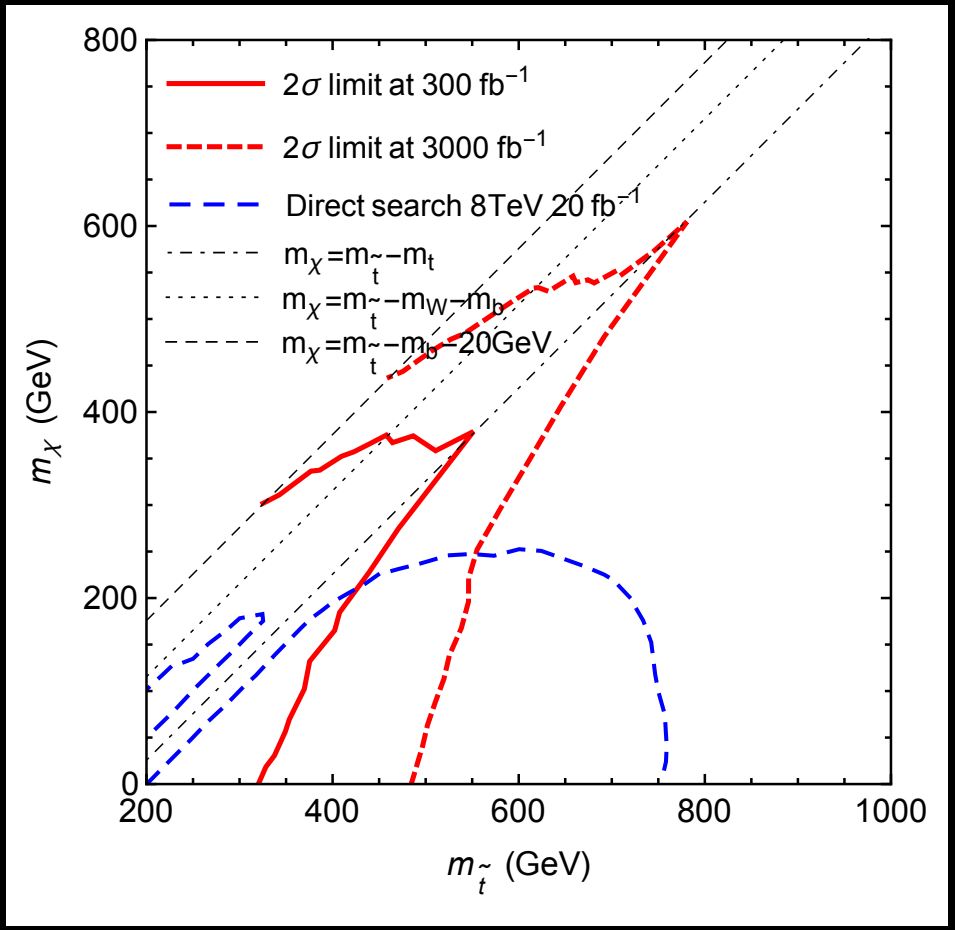
Coverage Projection, 300 fb^{-1}



Start getting exclusion coverage at 30 fb^{-1}
Scaling up to HL-LHC 3 ab^{-1}: Exclusion to 800 GeV
(However, pileup not accounted)

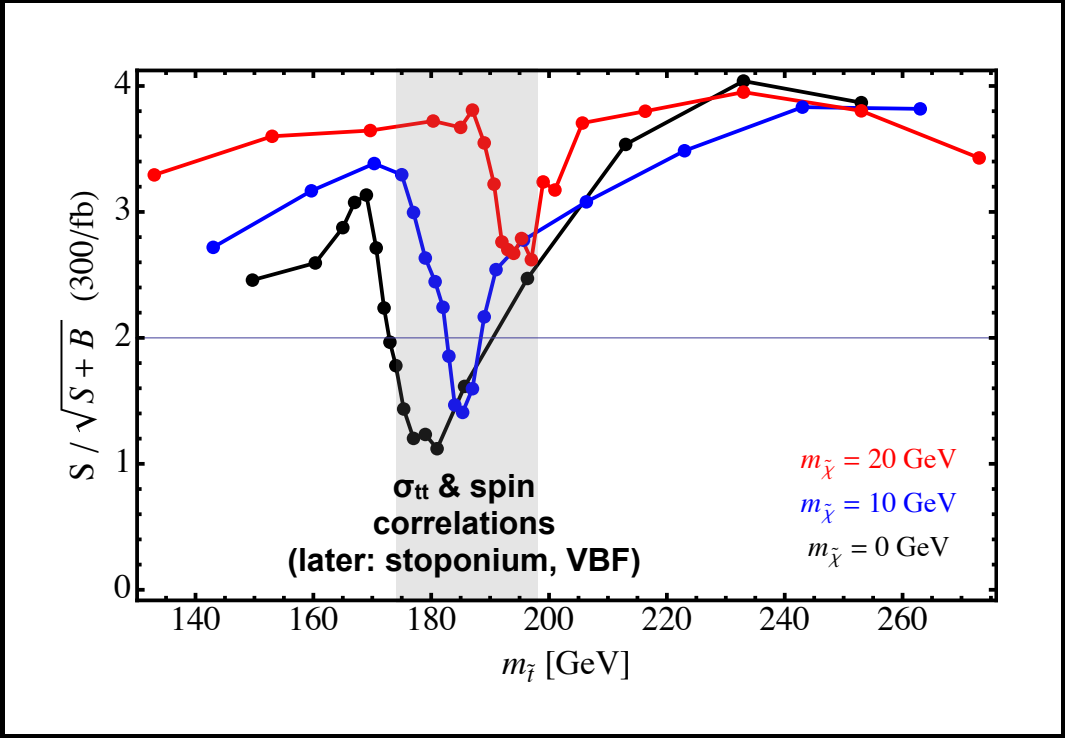
1506.00653

An & Wang



- Looser requirements on #jets (3) & #b's (1), no top reco, harder ISR-jet cut (700 GeV)
  - complementary phase space
- Final cut on MET/p_T(ISR)
  - almost same as MET-sig?
- Higher stats, lower S/B, extremely similar discovery & exclusion reach
- Good coverage of W compression line

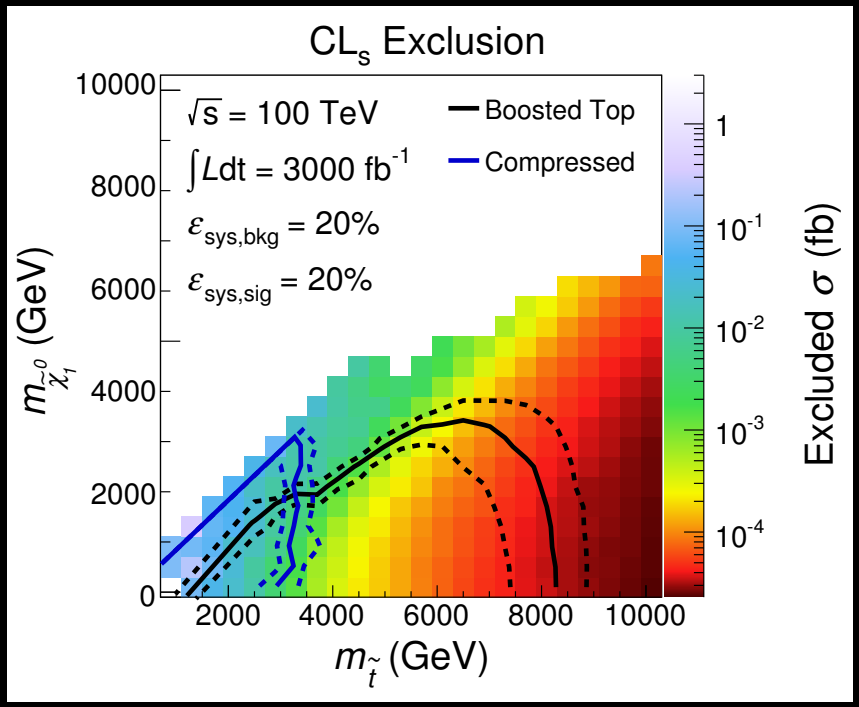
Approaching the Stealth Region



Nice complementarity and potentially unbroken coverage
Worth a closer look...

Much Longer Term...

Cohen, et al (1406.4512)



For m(stop) >> m(top), all compression lines sort-of merge

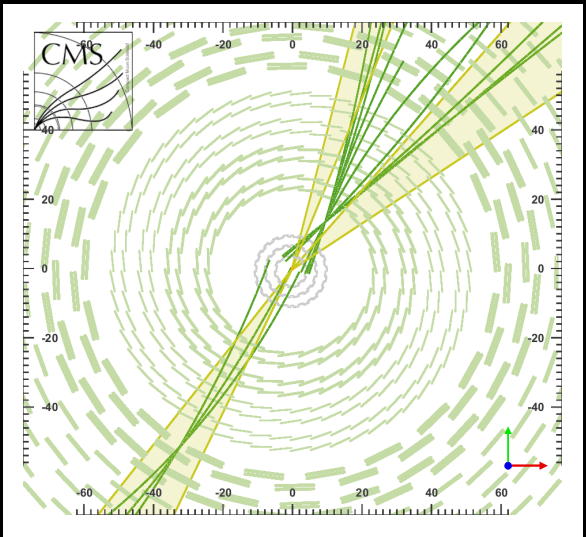
Back-of-the-envelope: Current fully-compressed “monojet” search with 8 TeV, 20 fb^{-1}, gets limit of 260 GeV. Scaling energy and lumi to 100 TeV machine would give limit of ~3.2 TeV.

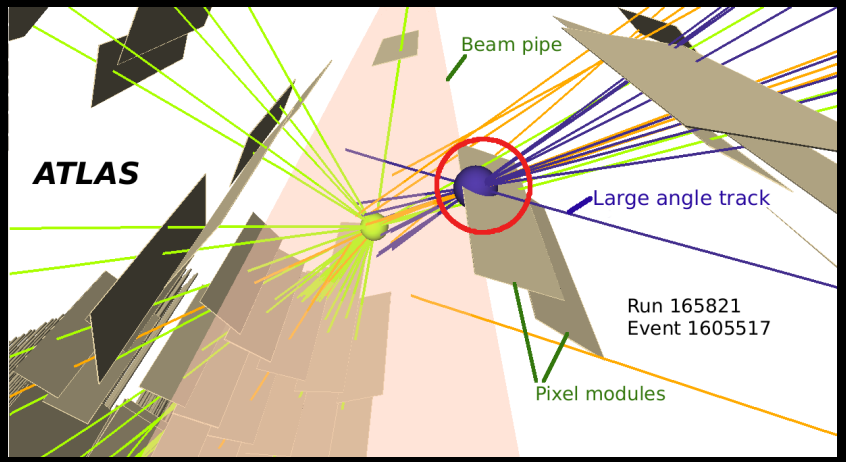
Part II: Displaced Superparticles

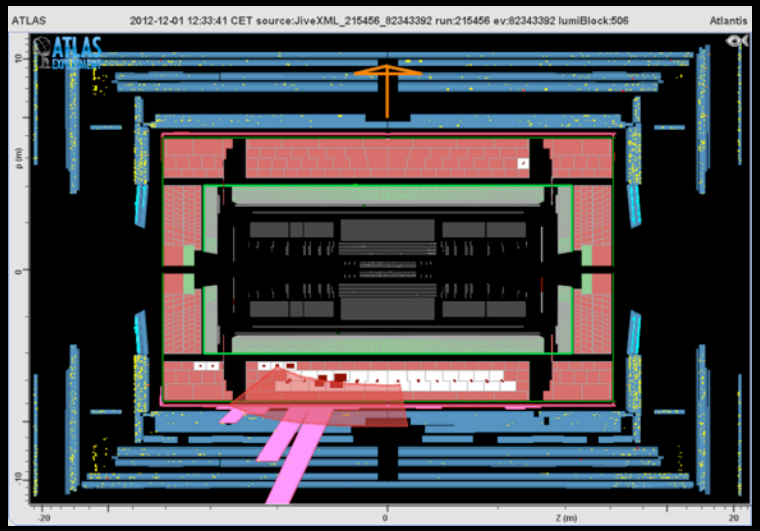
with Z Liu (1503.05923)

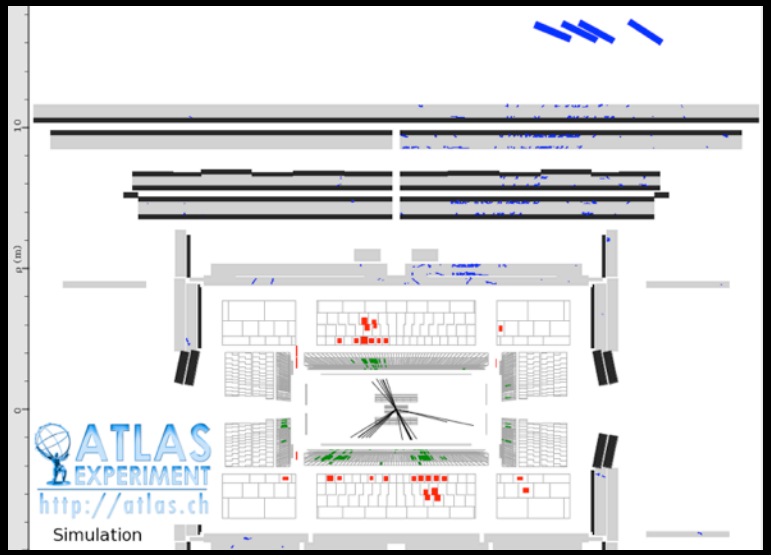
** See also Yanou's talk today!

Lots of Untapped Opportunities









SUSY and Displacement

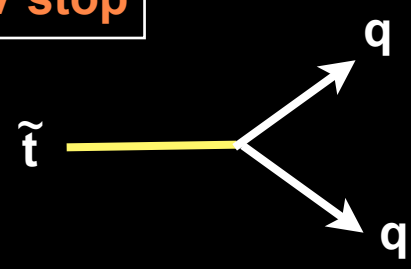
- R-Parity Violation
  - final-stage decay controlled by B/L-violating couplings, favored small by precision tests & cosmology (displaced when RPV Yukawas < $O(10^{-6})$)
- Gauge mediation
  - final-stage decay controlled by Goldstino coupling (displaced when sqrt(F) > O(100 TeV))
- Mini-split spectrum
  - gluino forced to decay through very heavy off-shell squarks (displaced when $m(\tilde{q})$ > O(1000 TeV))
- Anomaly mediation
  - co-LSP Winos with $\Delta m(\pm,0) \sim m(\pi)$
  - O(10 cm) long “disappearing track”
  - well-covered experimentally

Loose Organizing Principles for Our First-Pass Survey

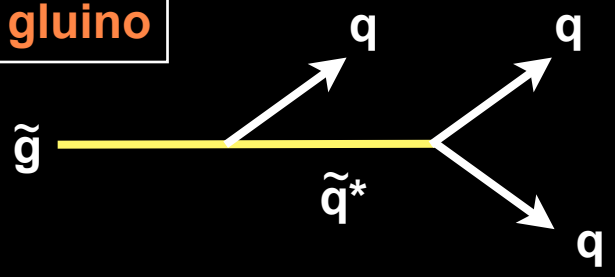
- Hadronic final states
  - can be difficult when decays are prompt
  - explicit displaced limits are largely nonexistant (except mini-split gluino)
  - colored sparticles have big cross sections
- Naturalness
  - lightest sparticle tends to be stop or Higgsinos
- Simplified spectra
  - only one or two new particles
  - no long decay chains
  - minimize # parameters
  - conservative total rates

Some of the Models We Studied

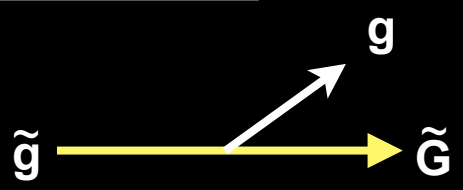
RPV stop



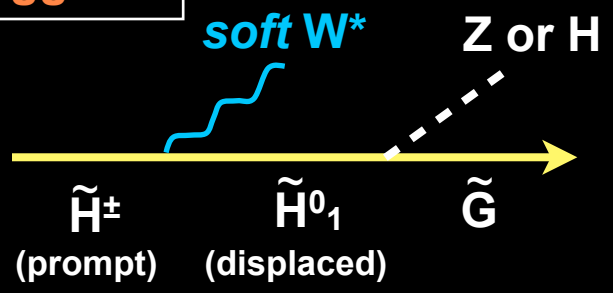
RPV gluino



GMSB gluino

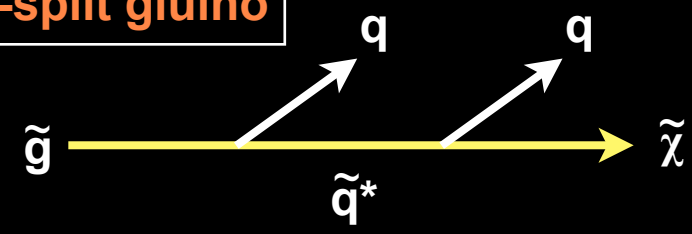


GMSB Higgsino



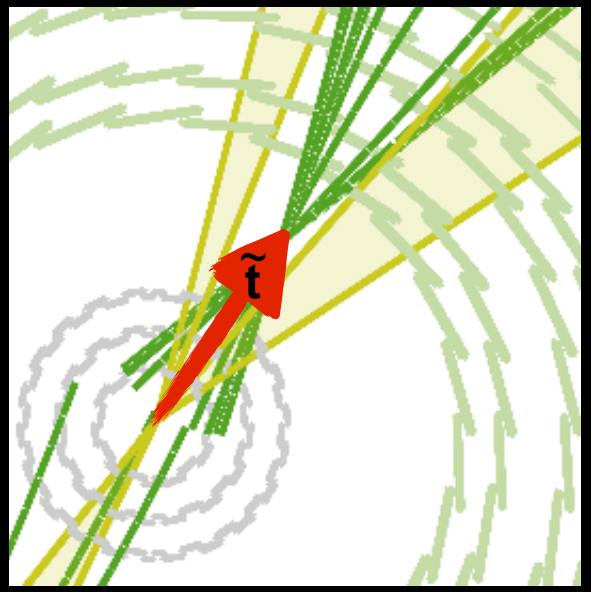
GMSB stop

Mini-split gluino



Displaced RPV Stop Back-of-the-Envelope

- $m(\tilde{t}) = 150$ & $\sqrt{\hat{s}} > 400$ $\Rightarrow$ $\sigma \sim 30$ 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
- luminosity ~ 20,000 pb^{-1}
- TOTAL: 30 * 0.5 * 0.5 * 0.05 * 20,000 = 7,500 events
- 1 background event $\Rightarrow$ limit is ~4 events



CMS PAS EXO-12-038
(Displaced dijets)

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

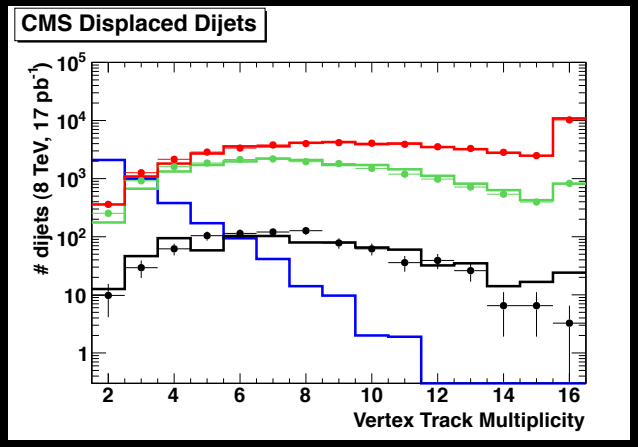
- CMS displaced dileptons
- CMS displaced electron & muon
- ATLAS displaced muon + tracks

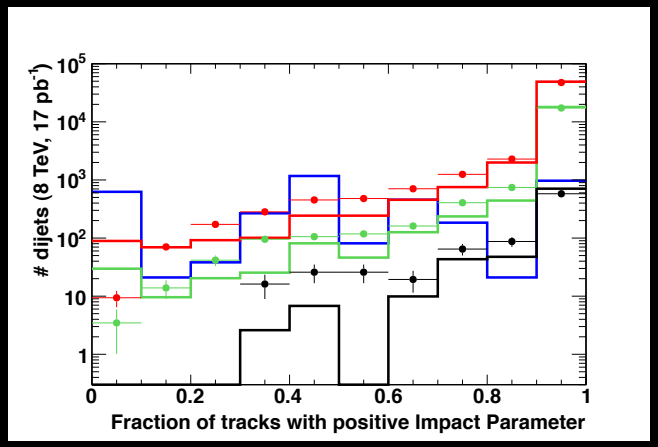
* for ATLAS displaced vertex+(l/j/MET) and more models, see **Csaki, et al (1505.00784)**

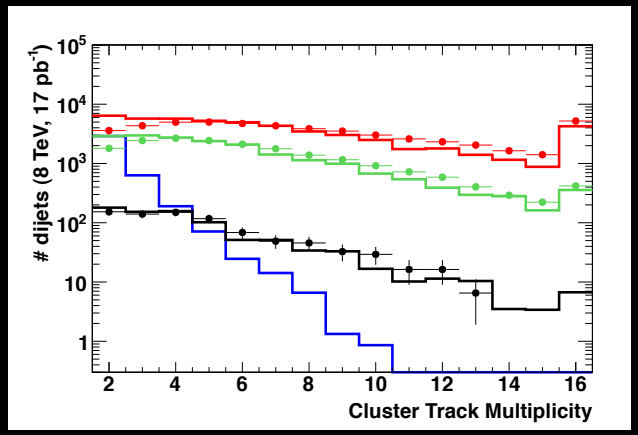
Detector Simulation Methodology

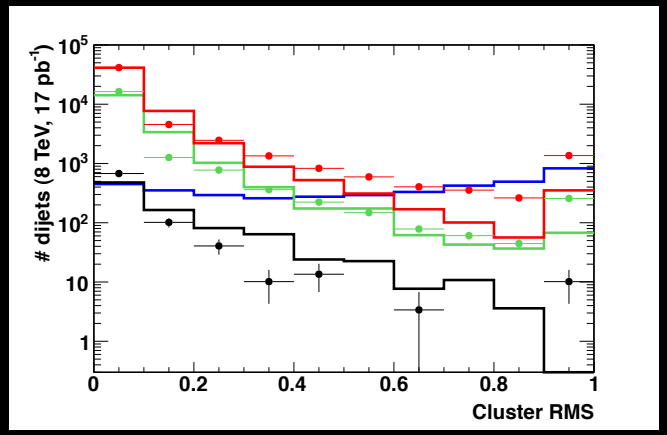
- Minimalistic
  - basic geometry, no detector granularity or energy smearing
  - perfect absorptive calorimeters
  - tracking/vertexing efficiencies with simple linear falloff models in radius, z, impact parameter
- Try to reproduce all explicitly studied models
  - employ constant fudge factors where 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!

CMS Dijets Validation









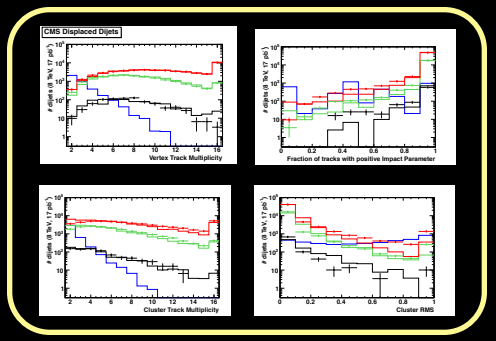
H(1000) → X(350) X(350), cτ = 35 cm

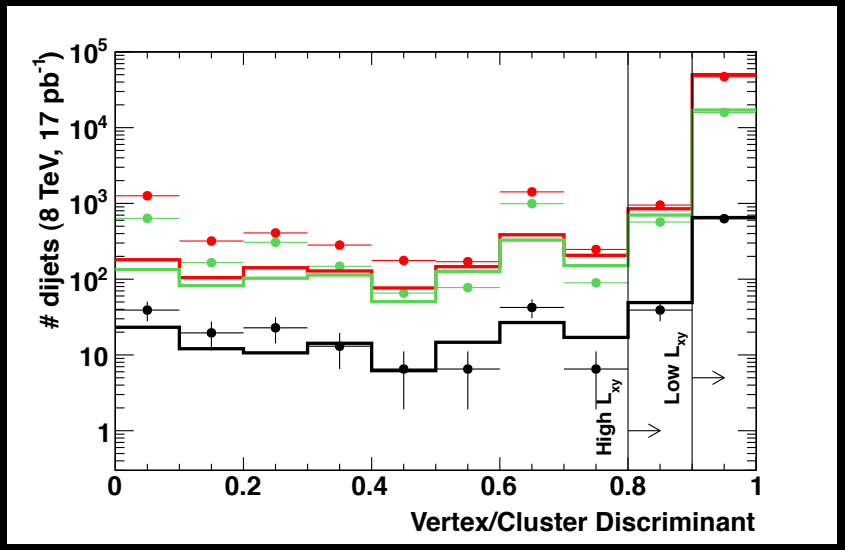
H(400) → X(150) X(150), , cτ = 40 cm

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

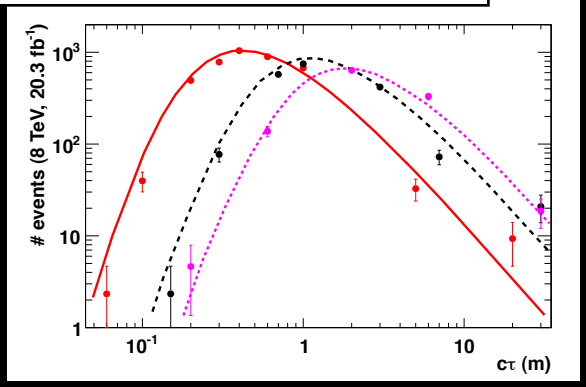
H(200) → X(50) X(50), cτ = 20 cm

H(400) → X(150) X(150), , cτ = 40 cm

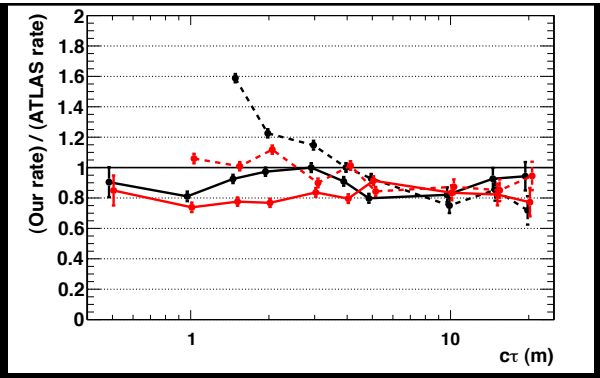
QCD background

ATLAS HCAL & Muon Spectrometer Validations

ATLAS low-EM jets



ATLAS muon spectrometer



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

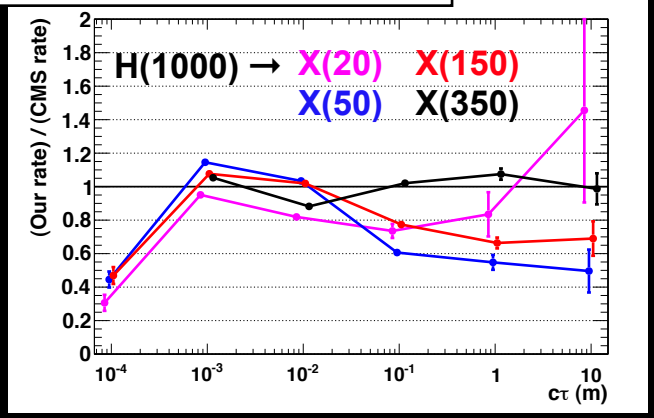
H(140) → X(20) X(20) solid

H(140) → X(40) X(40) dashed

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

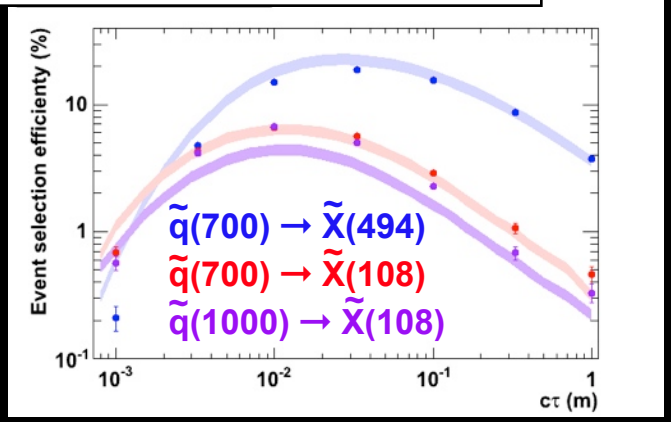
Lepton Validations

CMS dilepton



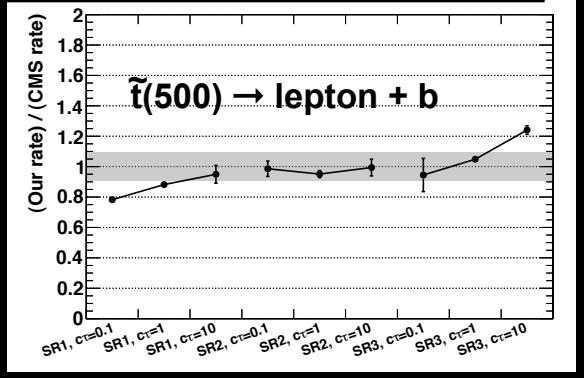
e^+e^-, one of several validations

ATLAS muon + tracks



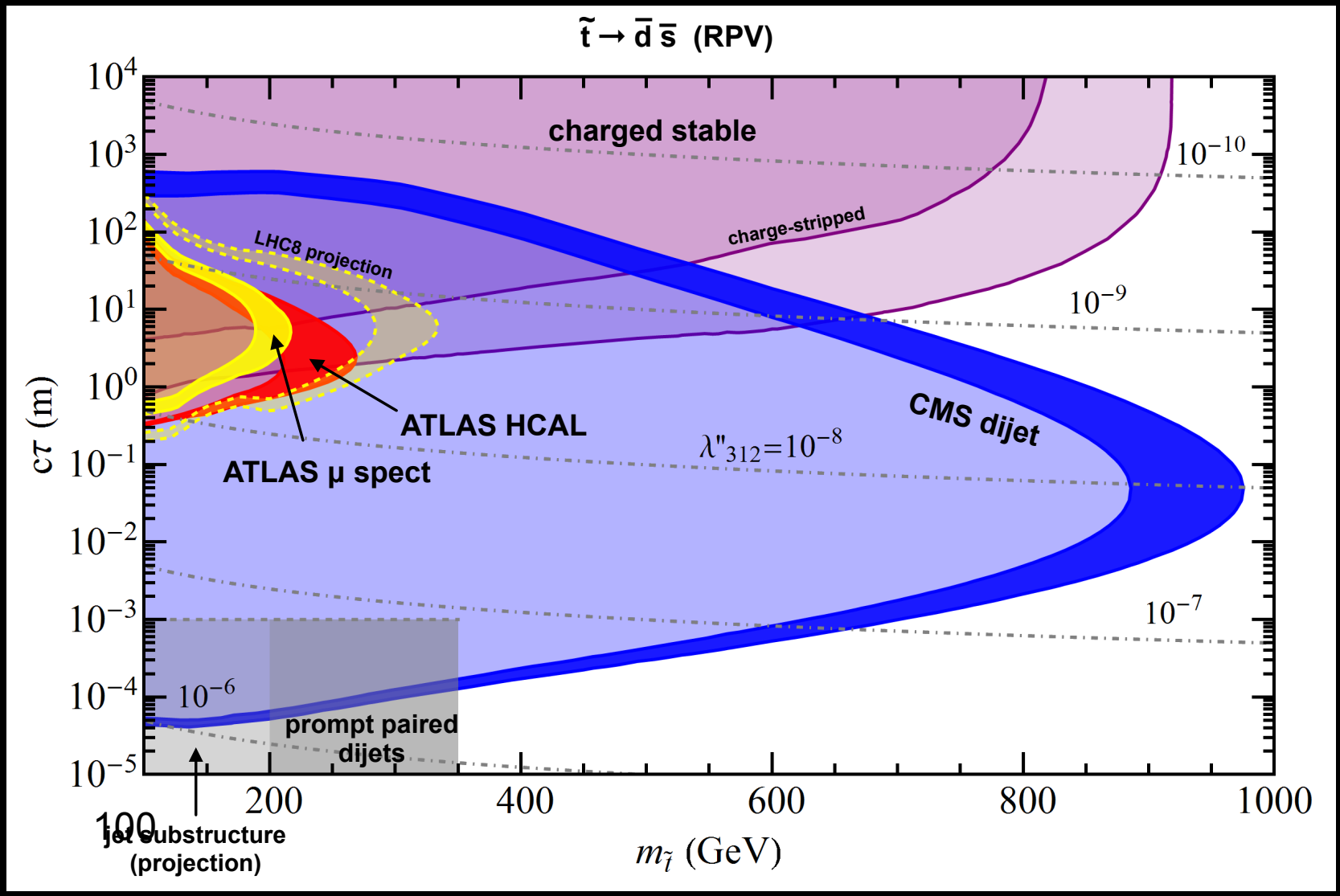
LSP decay to *μqq*

CMS electron & muon

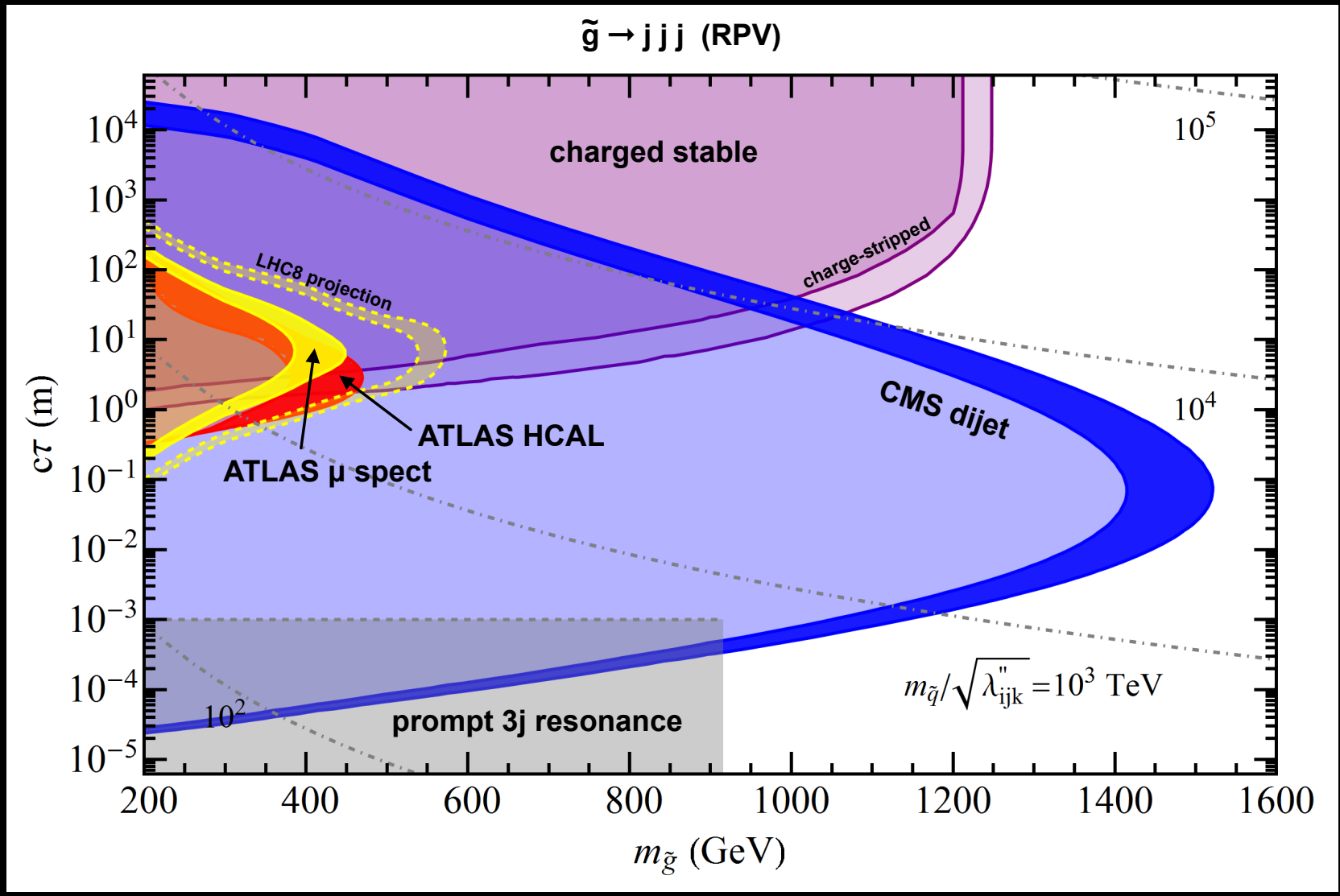


different impact pararameter regions

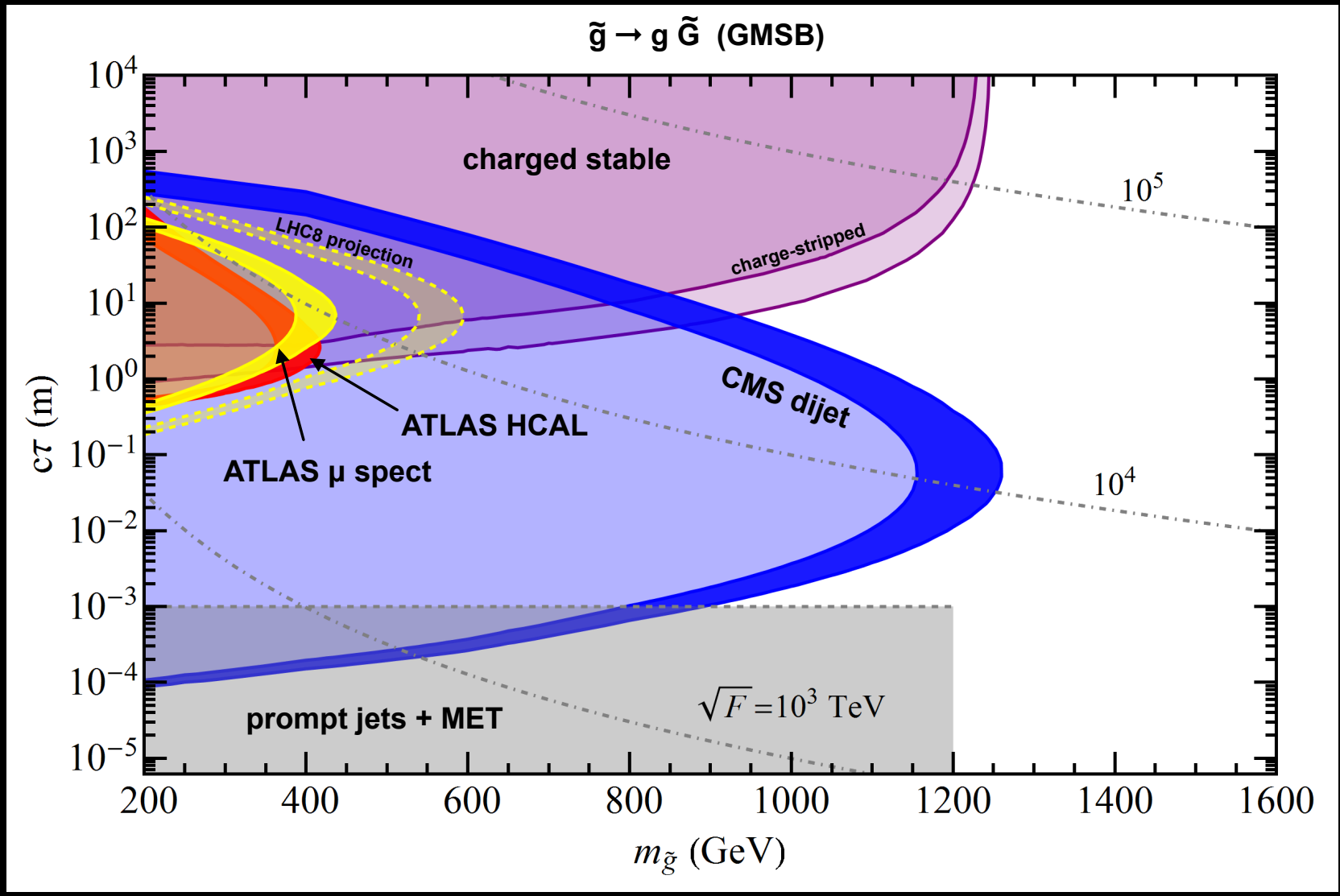
RPV Stop → 2q (Light Flavors)



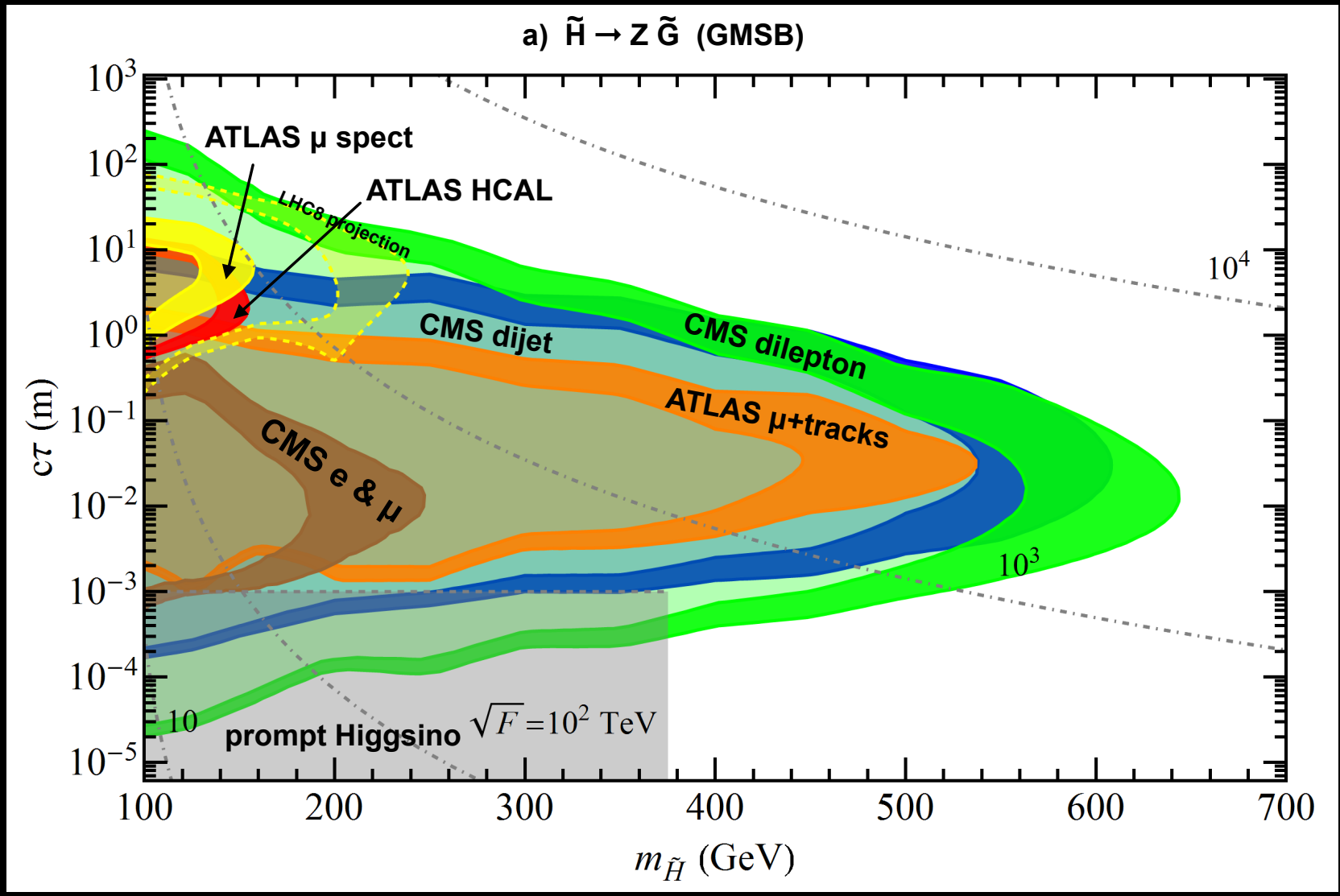
RPV Gluino → 3q (Light Flavors)



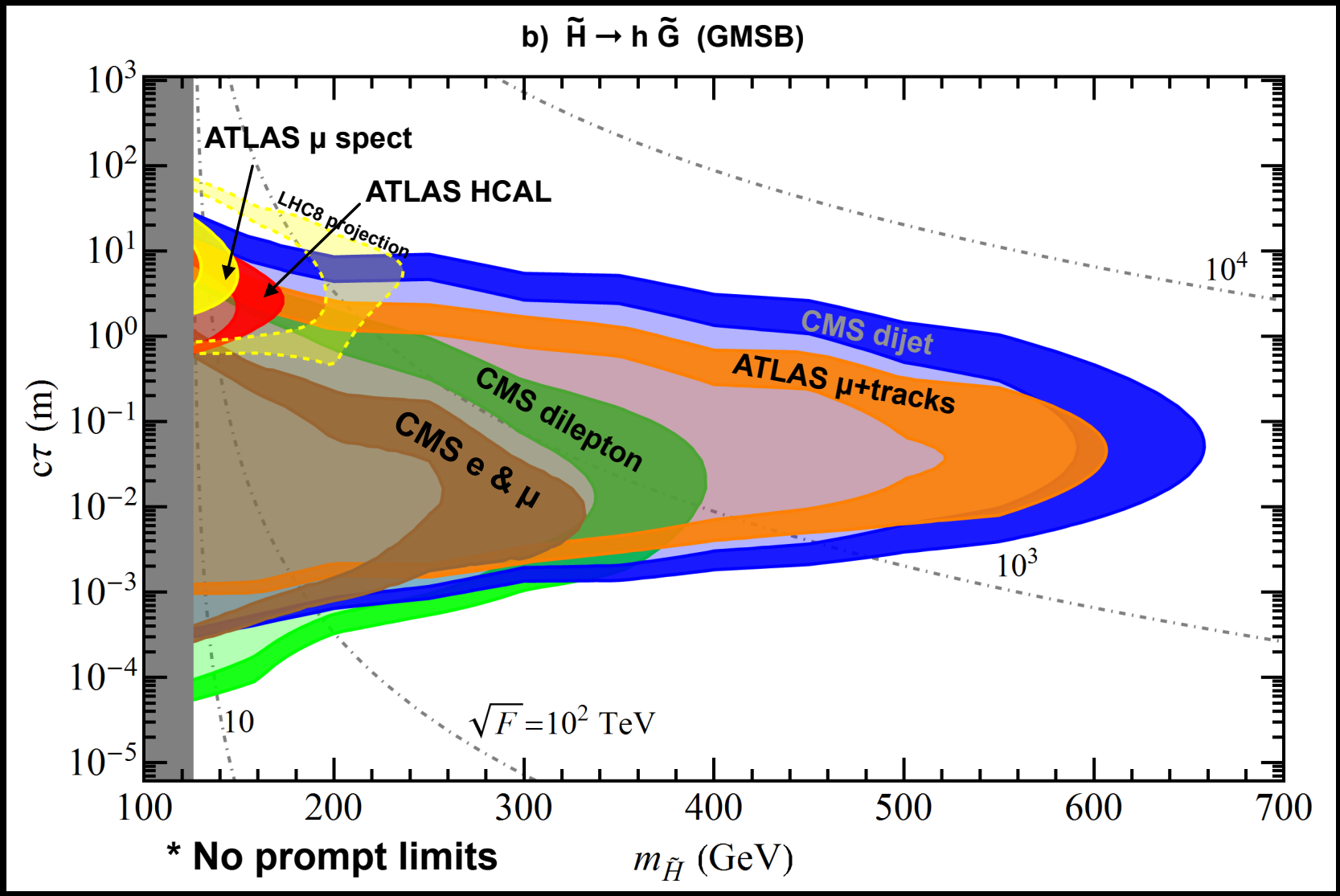
GMSB Gluino → g + Gravitino



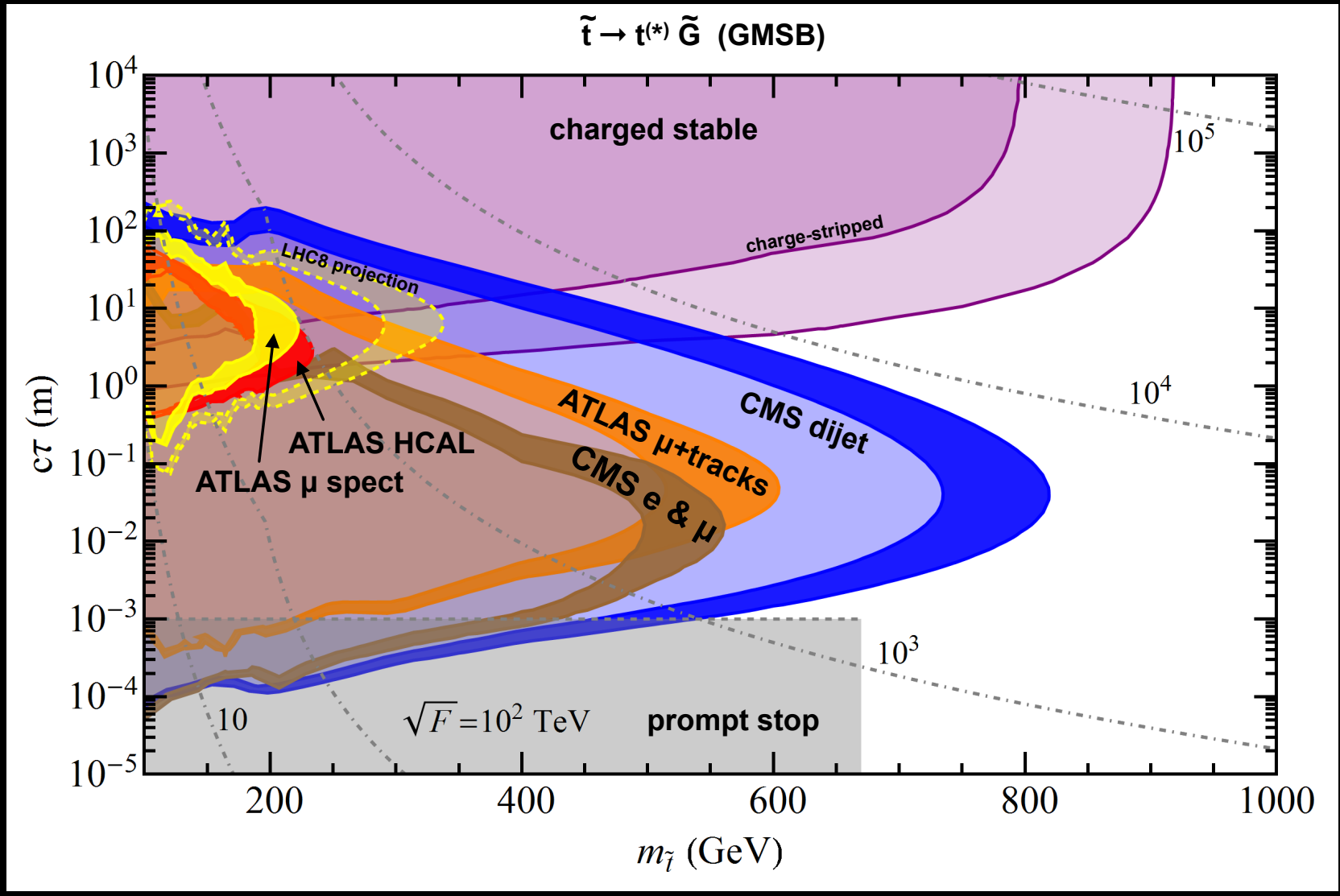
GMSB Higgsino → Z + Gravitino



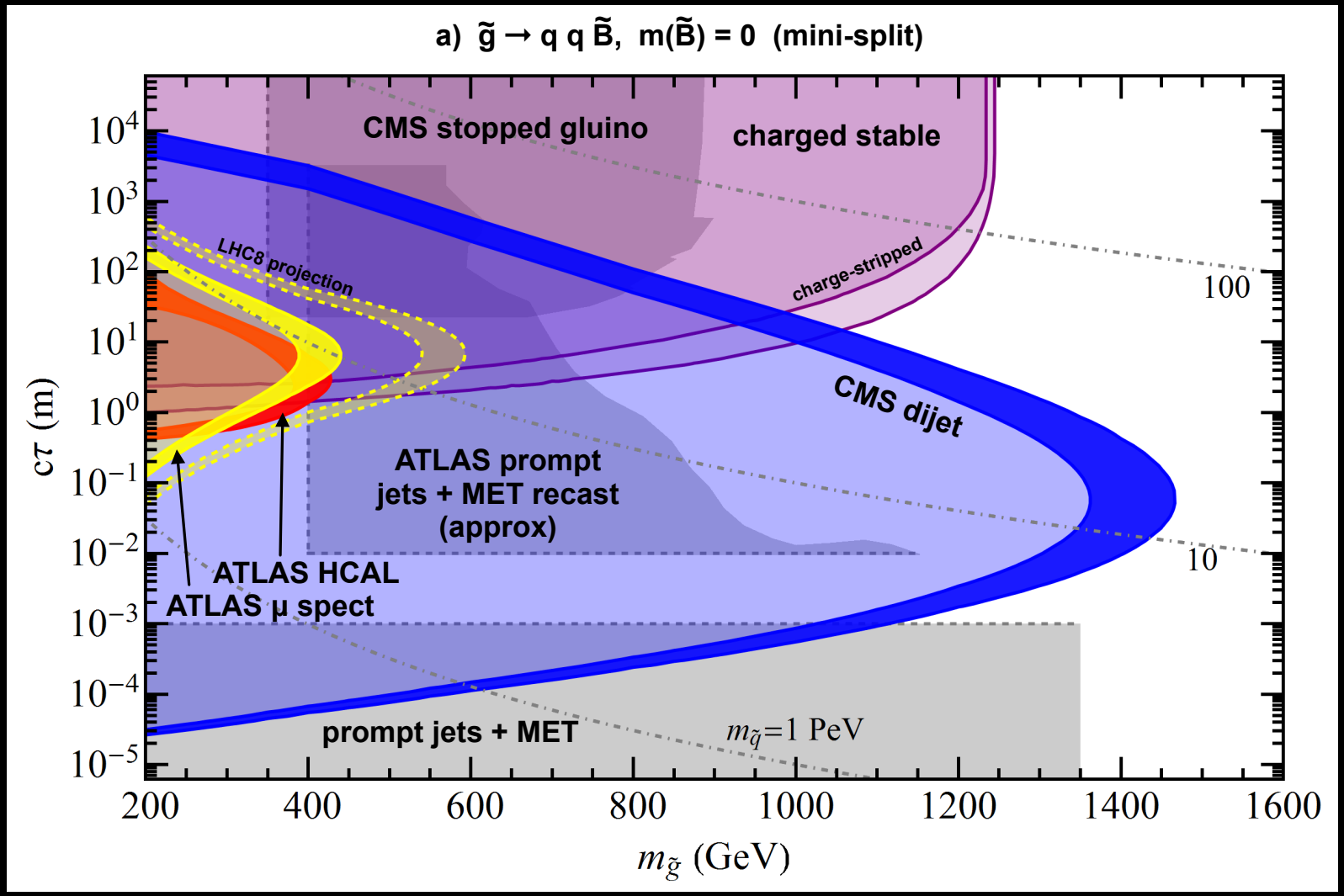
GMSB Higgsino → H + Gravitino



GMSB Stop → Top(*) + Gravitino



Mini-Split Gluino → 2j + LSP



* m(LSP) = 0

Some Lessons

- Coverage is generally extremely good with “no” extra work
  - recast displaced searches 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, displaced dijets usually wins
- Weak points are 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
- CMS dijets is (surprisingly) great, but room for more targeted hadronic searches
  - these are already coming online

Recaster's Wishlist (Partial)

- More varied test models
  - higher 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)
  - interference from nearby hits
  - fate of "exploding tracks"?
- Some "standard" detector emulation codes like PGS/Delphes?
  - 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?

Conclusions

- Stop→top compression line will finally begin to be uncovered in Run 2
  - discovery (exclusion) sensitivity 200-400 GeV (<550 GeV) @ 300 fb^{-1}, perhaps up to ~600 GeV (800 GeV) for HL-LHC
  - healthy S/B
  - near-stealth region seems attainable
  - different approaches give comparable sensitivity, almost certainly can further improve with more finessed analyses
- Lots of interesting displaced models, and lots of broadly powerful searches (and quickly growing), but traditionally painful to connect these via recasting
  - requires much inspired guesswork, usually little to calibrate on
  - the situation is certainly improving (more varied models tested, more model-independent analyses based on hard object triggers)
  - if something is found in Run 2, we'd like to have tools to help understand what it is!!