LHC-TI meeting @ SLAC

Long-Lived Superparticles with Hadronic Decays at the LHC

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Talk based on work with B. Tweedie, 1503.05923, JHEP06(2015)042

also covers some of my ongoing study

Feb.11th 2017

MOTIVATION

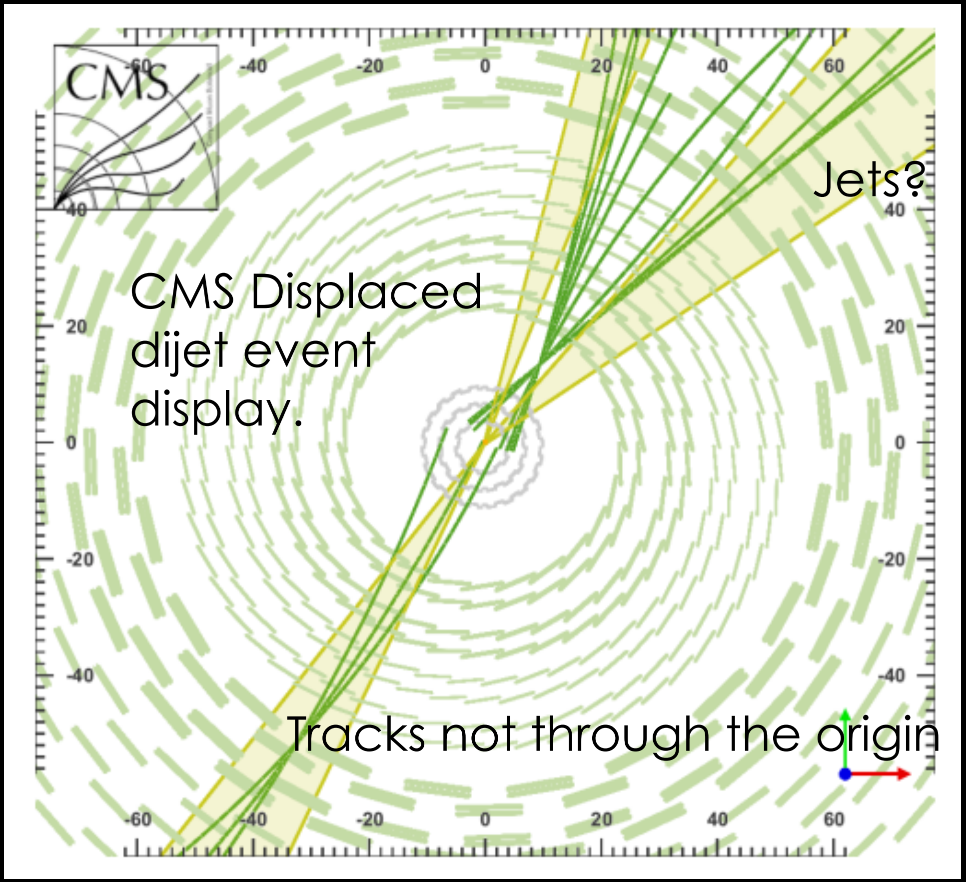
LHC-running well

No strong evidence for new physics yet

BSM physics may hide behind some non-conventional signatures

We need to think about ways to make the best use of this large multi-purpose/all-purpose high energy experiment

THINKING OUTSIDE THE BEAMPIPE



Most LHC signatures are prompt—particles decay at the beampiple Most of our collider signature tools are developed under this assumption, including our jet definitions, MET definitions, particle flow algorithms, etc.

However, there are another series of well-motivated signatures not captured in normal searches—displaced decays.

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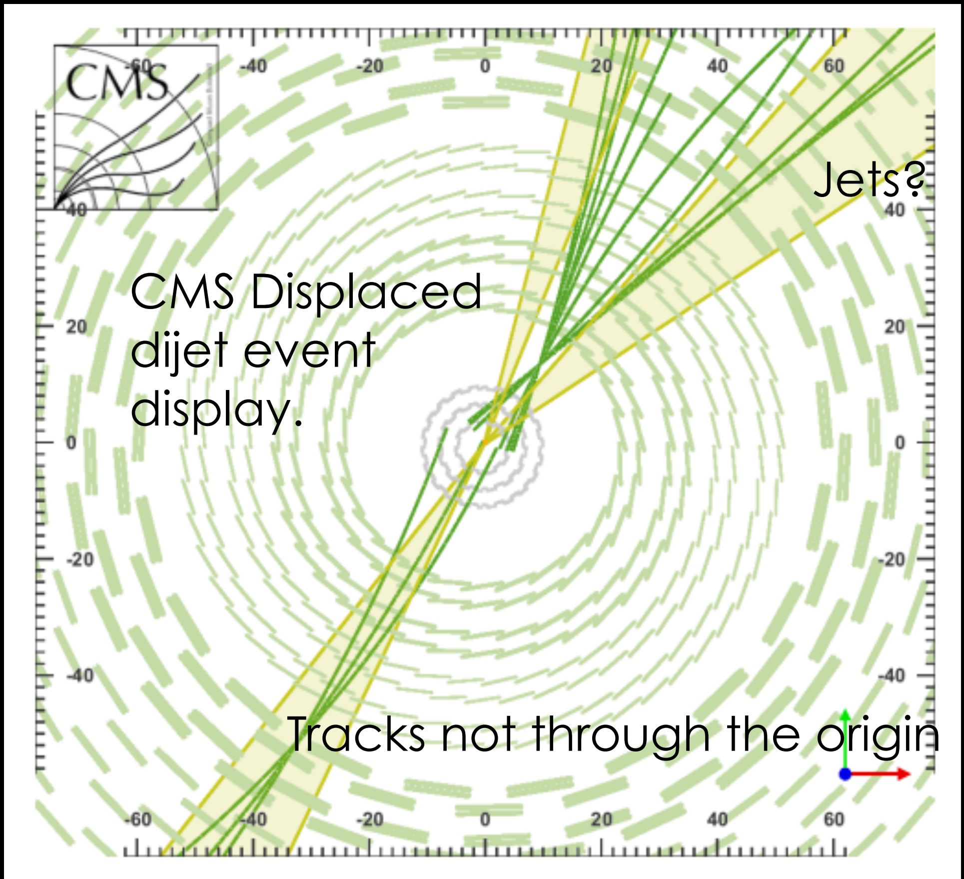

Detector not designed for displaced signatures.
Need to re-configure the trigger, events reconstruction etc to capture these signatures.

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However, there are another series of well-motivated signatures not captured in normal searches—displaced decays.

Displaced decay are particles with lifetime long enough to travel a certain distance within/though the detector before decaying.

Many public 7/8 TeV searches (and two at 13 TeV)

	Final state targeted	7 TeV	8 TeV	13 TeV
1	displaced e-e/μ-μ pairs	1211.2472	1411.6977	
2	displaced μ-μ pairs in muon system		2005761	
3	displaced e-μ events		1409.4789	2205146
4	displaced μ-μ pairs (dark photons)		1506.00424	
5	displaced photons using ECAL timing	1212.1838	2063495	
6	displaced photons using conversions	1207.0627	2019862	
7	displaced vertices		2160356	
8	displaced dijets		1411.6530	
9	short, highly ionizing disappearing tracks		thesis	
10	disappearing tracks		1411.6006	
11	kinked tracks		thesis	
12	fractionally charged particles	1210.2311	1305.0491	
13	heavy stable charged particles (HSCP)	1205.0272	1305.0491	2114818 (2015) 2205281 (2016)
14	stopped particles	1207.0106	1501.05603	
15	out of time muons		thesis	

Other than HSCP, analyses are relatively "immature"

Still working through "lowest-hanging fruit"

Small analysis groups - teams can evaporate easily

Many 13 results in the pipeline - updates and new searches!

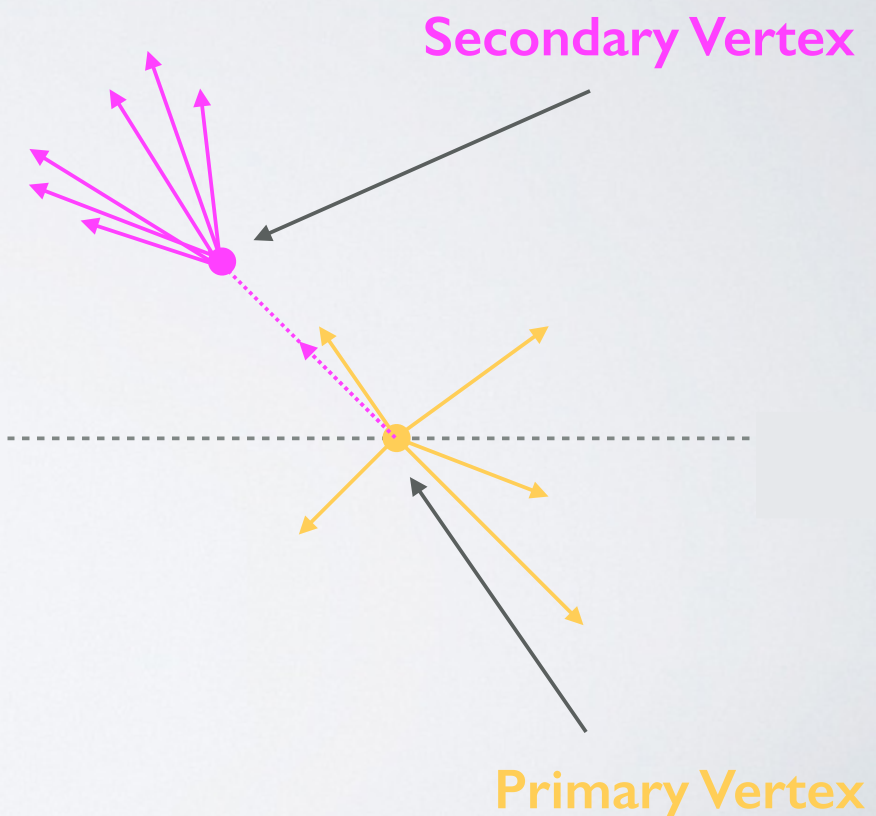
Roughly 3% of CMS papers

HOW DO THE SEARCH LOOK LIKE

Example of displaced dijet search at CMS

DISPLACED VERTEX

- Search for a vertex in the tracker that is not aligned with beam axis



slides from Eric Kuflik's talk at Higgs Exotic Decays meeting 2016

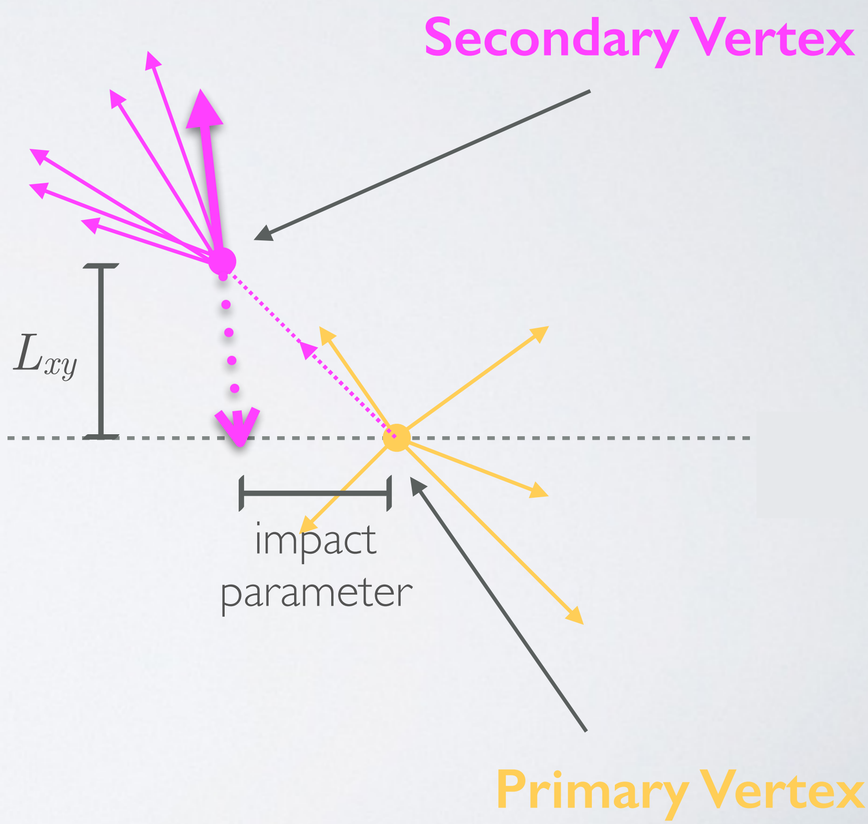
DISPLACED VERTEX

- Search for a vertex in the tracker that is not aligned with beam axis
  - Sensitive to

    $L_{xy} \sim 50$ cm

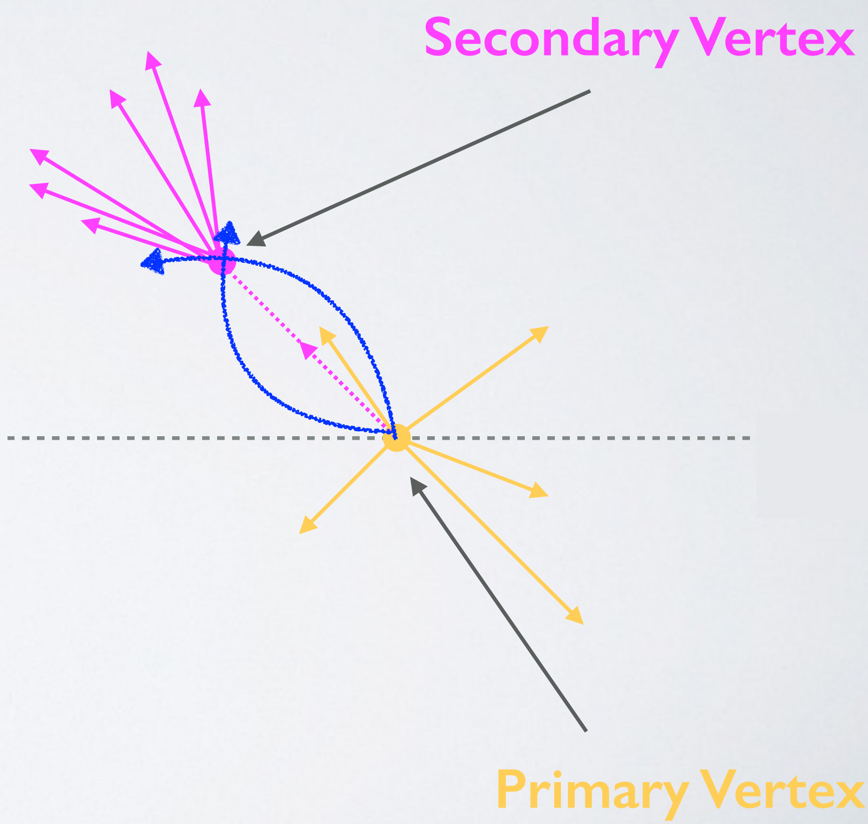
    IP ~ 0.5 mm to 30 cm
  - No Level 1 triggers

    Triggers require other hard objects



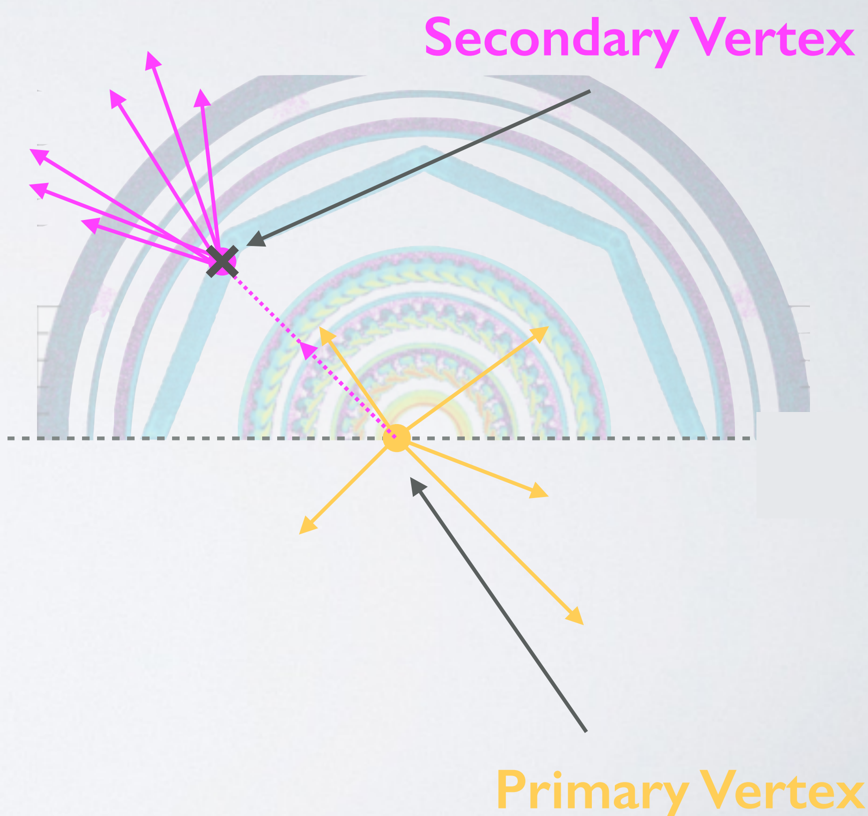
DISPLACED VERTEX

- Search for a vertex in the tracker that is not aligned with beam axis
- Backgrounds:
  - Crossing tracks



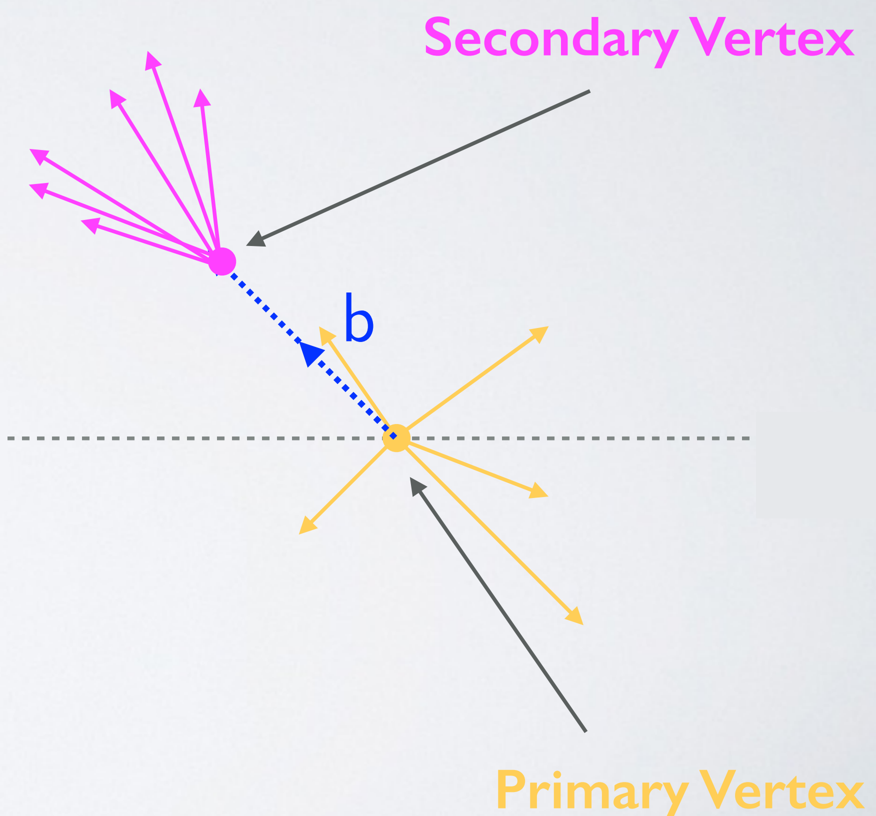
DISPLACED VERTEX

- Search for a vertex in the tracker that is not aligned with beam axis
- Backgrounds:
  - Crossing tracks
  - Interactions with detector material



DISPLACED VERTEX

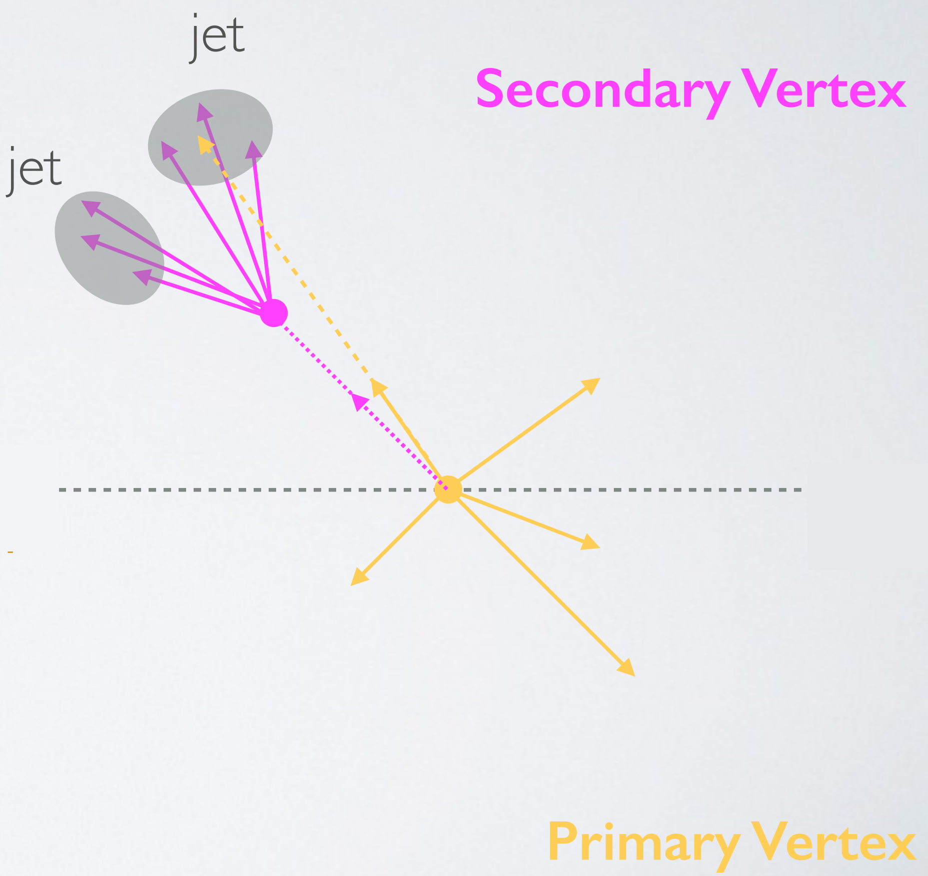
- Search for a vertex in the tracker that is not aligned with beam axis
- Backgrounds:
  - Crossing tracks
  - Interactions with detector material
  - b-jets ($c\tau \sim 0.5$ mm)



CMS DISPLACED DIJET

Search for long-lived neutral particles decaying to quark-antiquark pairs in proton-proton collisions at sqrt(s) = 8 TeV

- Search for 2 displaced jets with $p_T > 60$ GeV (Leptons also counted as jets)
- Important cuts
  - $H_T > 350$ GeV (trigger)
  - $m_{DV} > 4$ GeV
  - $N_{tracks} > 4, 5$
  - At most one prompt (IP <0.5 mm) track per jet
  - Dijet consistent with DV



SUSY and Displacement

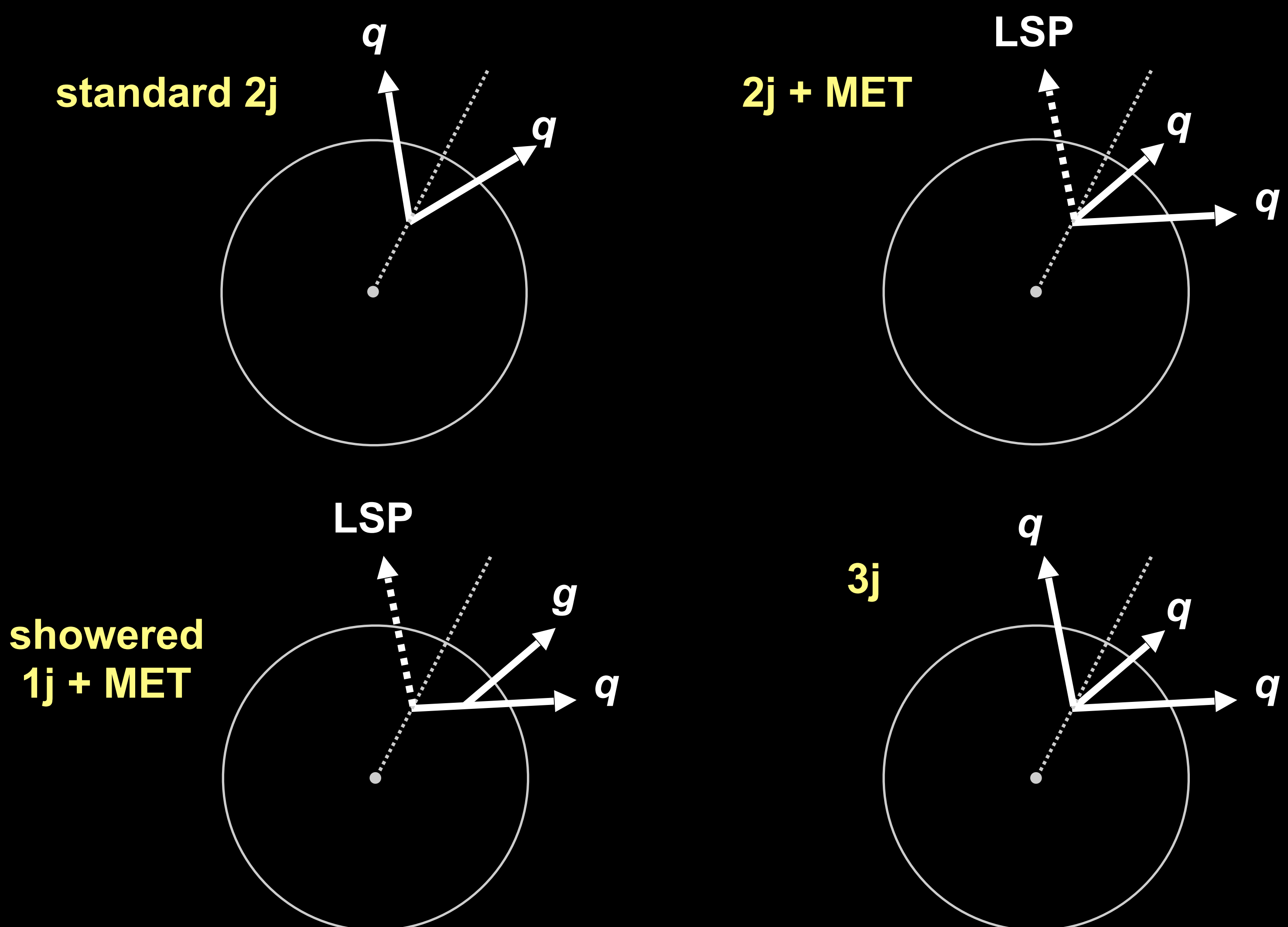
- R-Parity Violation $c\tau_{\mathrm{RPV}} \sim 0.1\mathrm{mm} \left(\frac{100\ \mathrm{GeV}}{\tilde{m}}\right) \left(\frac{10^{-6}}{\lambda}\right)^2$
  - final-stage decay controlled by B/L-violating couplings, favored small by precision tests & cosmology (displaced when RPV Yukawas < O(10^{-7}))
- Gauge mediation $c\tau_{\mathrm{GMSB}} \sim 0.1\mathrm{mm} \left(\frac{100\ \mathrm{GeV}}{\tilde{m}}\right)^5 \left(\frac{\sqrt{F}}{100\ \mathrm{TeV}}\right)^4$
  - final-stage decay controlled by Goldstino coupling (displaced when sqrt(F) > O(100 TeV))
- Mini-split spectrum $c\tau \approx 10^{-5}\ \mathrm{m} \left(\frac{m_{\tilde{q}}}{\mathrm{PeV}}\right)^4 \left(\frac{\mathrm{TeV}}{m_{\tilde{g}}}\right)^5$
  - 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)

Loose Organizing Principles for Our First-Pass Survey

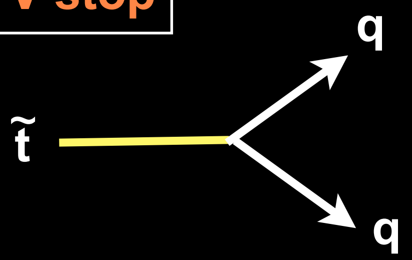
- Hadronic final states
  - can be difficult when decays are prompt
  - explicit displaced limits are limited (esp BRPV)
  - colored sparticles have big cross sections
- Naturalness
  - lightest sparticle tends to be stop or Higgsinos
  - gluino also can’t be too heavy
- Simplified spectra
  - only one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

A EXAMPLE OF DISPLACED DIJET

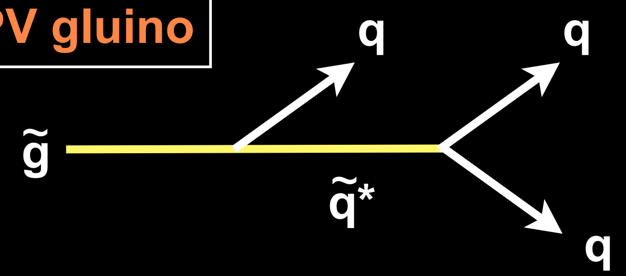


Some of the Models We Studied

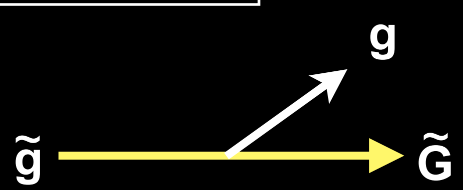
BRPV stop



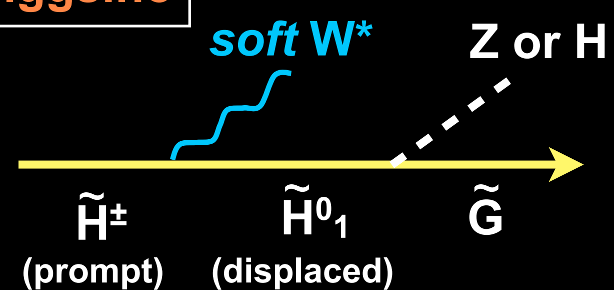
BRPV gluino



GMSB gluino

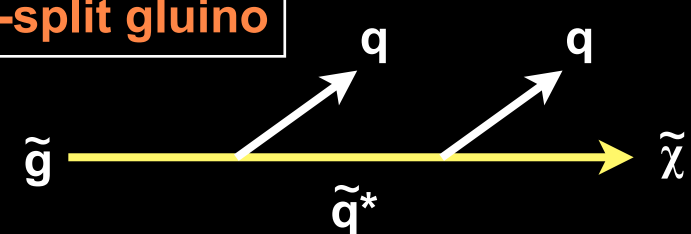


GMSB Higgsino



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)**

OVERVIEW OF OUR STUDY

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- CMS displaced dijets (tracker)
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* 7 TeV, 2 fb^{-1}

** All via direct pair-production

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Hadronic R-parity violation

- $\tilde{t} \to \bar{d}_i \bar{d}_j$ via baryonic RPV including $\tilde{t} \to \bar{b}\bar{b}$
- $\tilde{g} \to u_i d_j d_k$ via baryonic RPV
- $\tilde{H} \to u_i d_j d_k$ (+soft) via baryonic RPV

gauge mediation

- $\tilde{q} \to q\, \tilde{G}$ in GMSB
- $\tilde{g} \to g\, \tilde{G}$ in GMSB
- $\tilde{t} \to t^{(*)}\, \tilde{G}$ in GMSB
- $\tilde{H} \to h/Z\, \tilde{G}$ (+soft) in GMSB

mini-split

- $\tilde{g} \to q\bar{q}\tilde{B}$ in mini-split SUSY

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Our selection of signals covers a large range of displace decay topologies, including 1j+MET, 2j+MET, 3j+MET, 2j, 3j, as well as heavy flavors, making it easy for theorists to estimate exclusions for their own models in concern.

* 7 TeV, 2 fb^{-1}

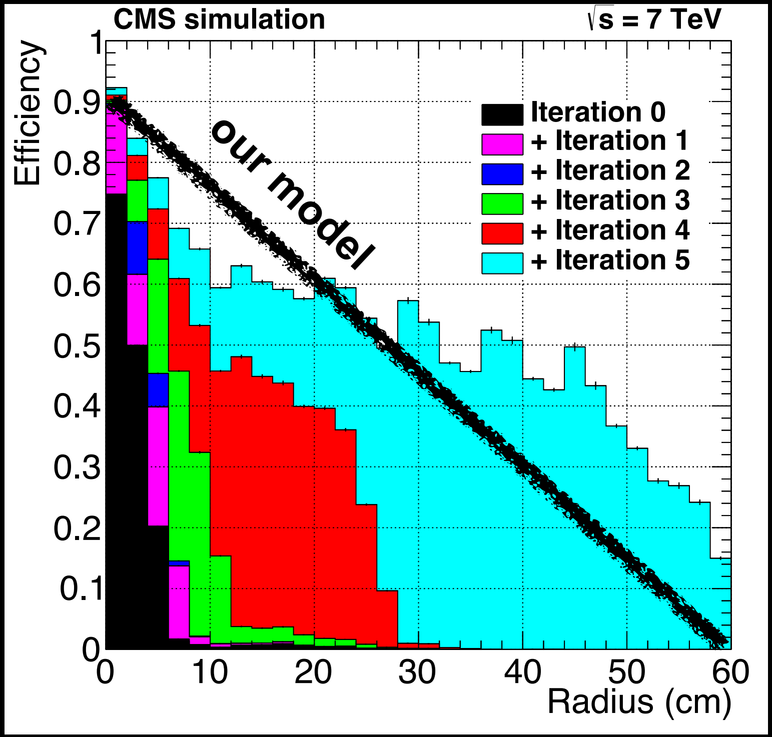
** All via direct pair-production

DETECTOR SIMULATION AND RECASTING

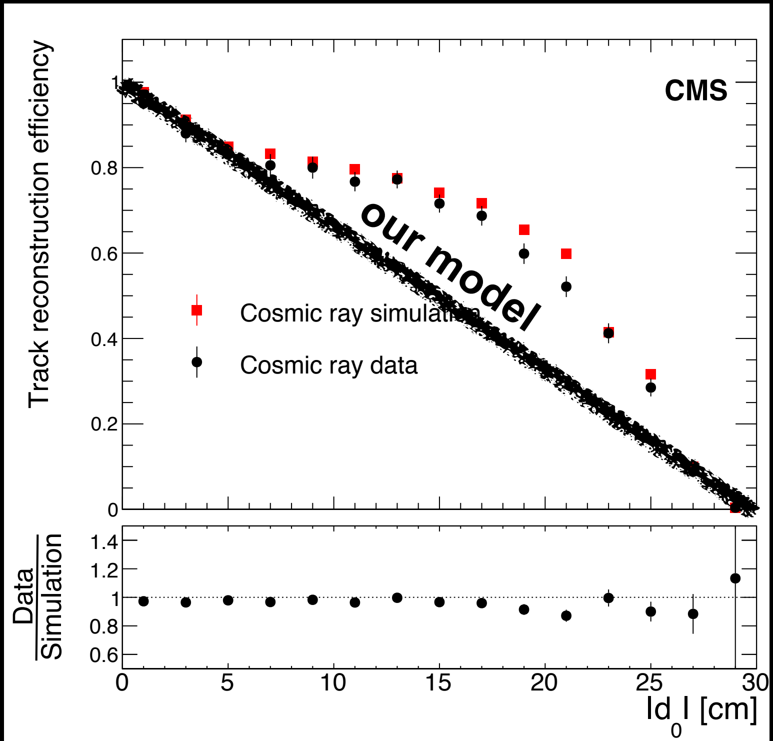
Detector Simulation Methodology

- 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"



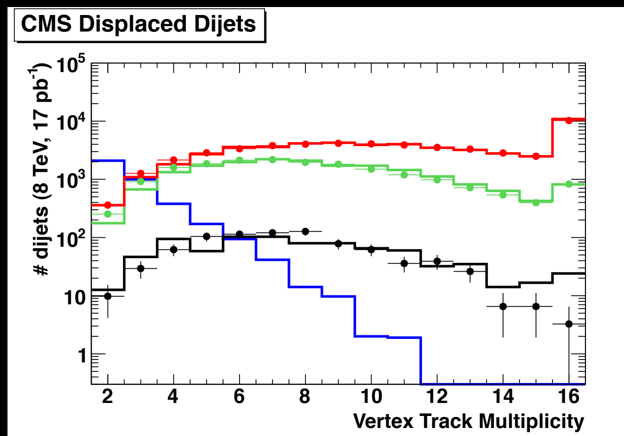
1405.6569

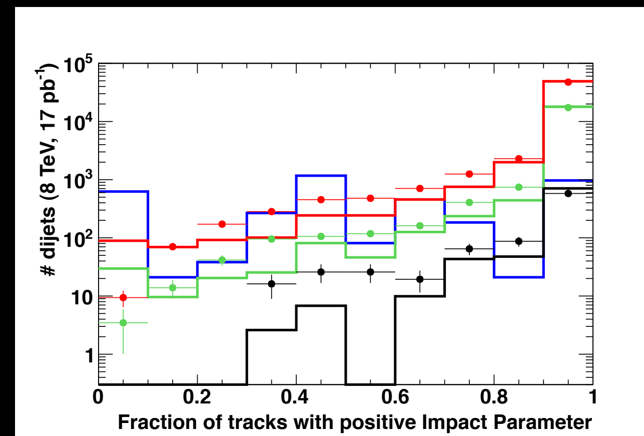


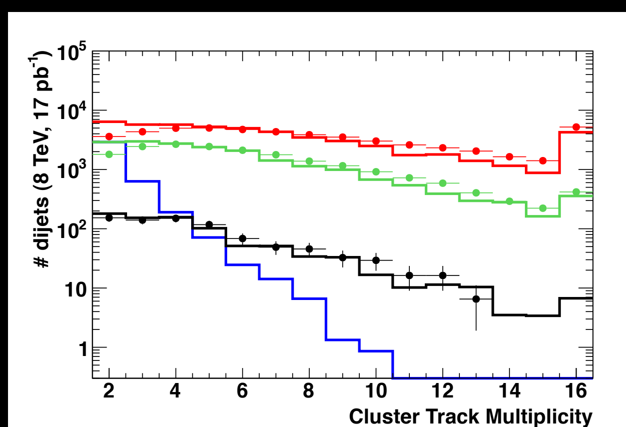
1411.6977

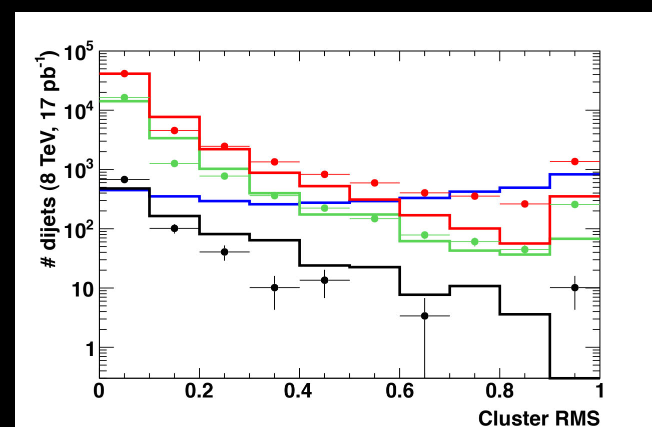
- linearly-falling inefficiency vs Lz (to 55 cm)

CMS Dijets Validation









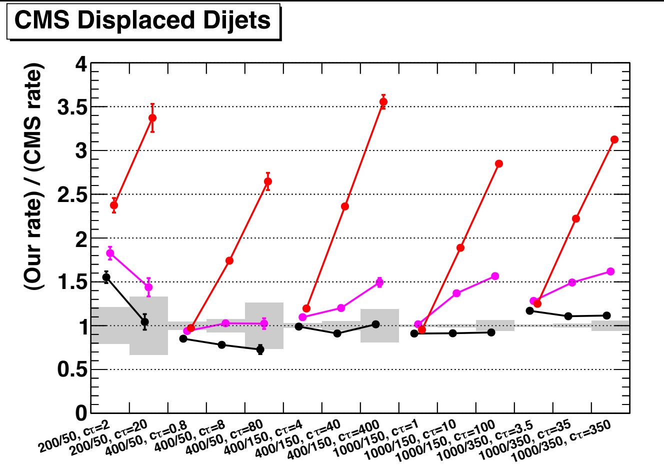
H(1000) → X(350) X(350), cτ = 35 cm

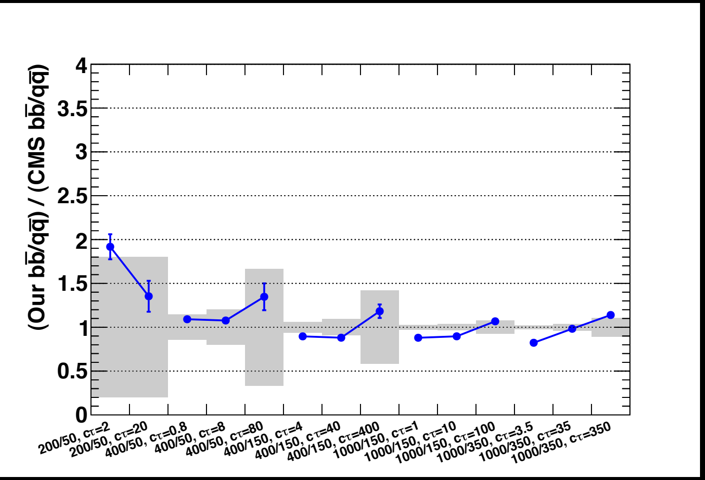
H(400) → X(150) X(150), cτ = 40 cm

H(200) → X(50) X(50), cτ = 20 cm

QCD background

Dijets Validation





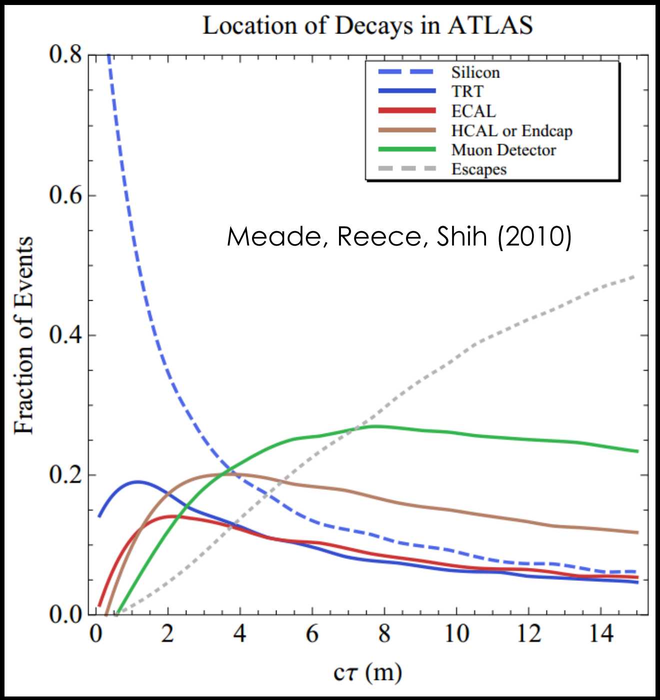
Perfect tracking & vertexing

Imperfect tracking, perfect vertexing

Imperfect tracking & vertexing

X → bb / X → qq

A TYPICAL EFFICIENCY MAP



Depend on lifetime, how is the particle being produced (How Lorentz factor distributes), the decay distributes shape differently at different layers of the detector.

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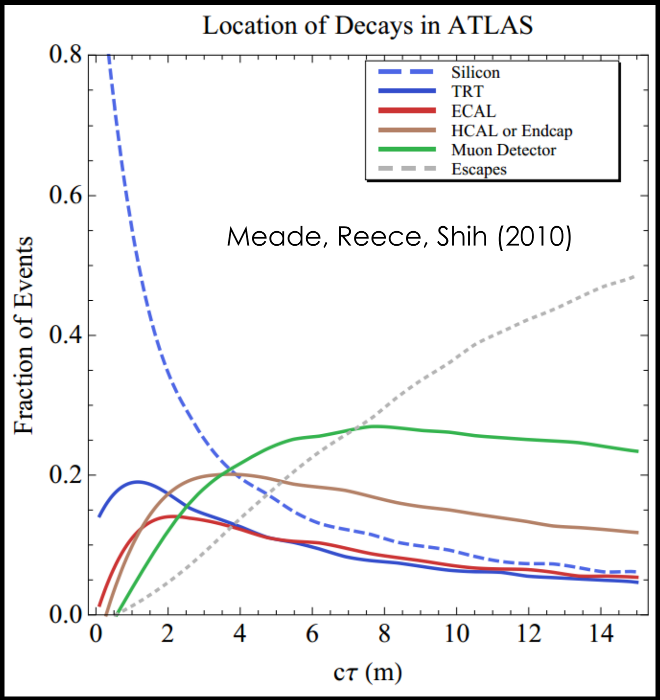

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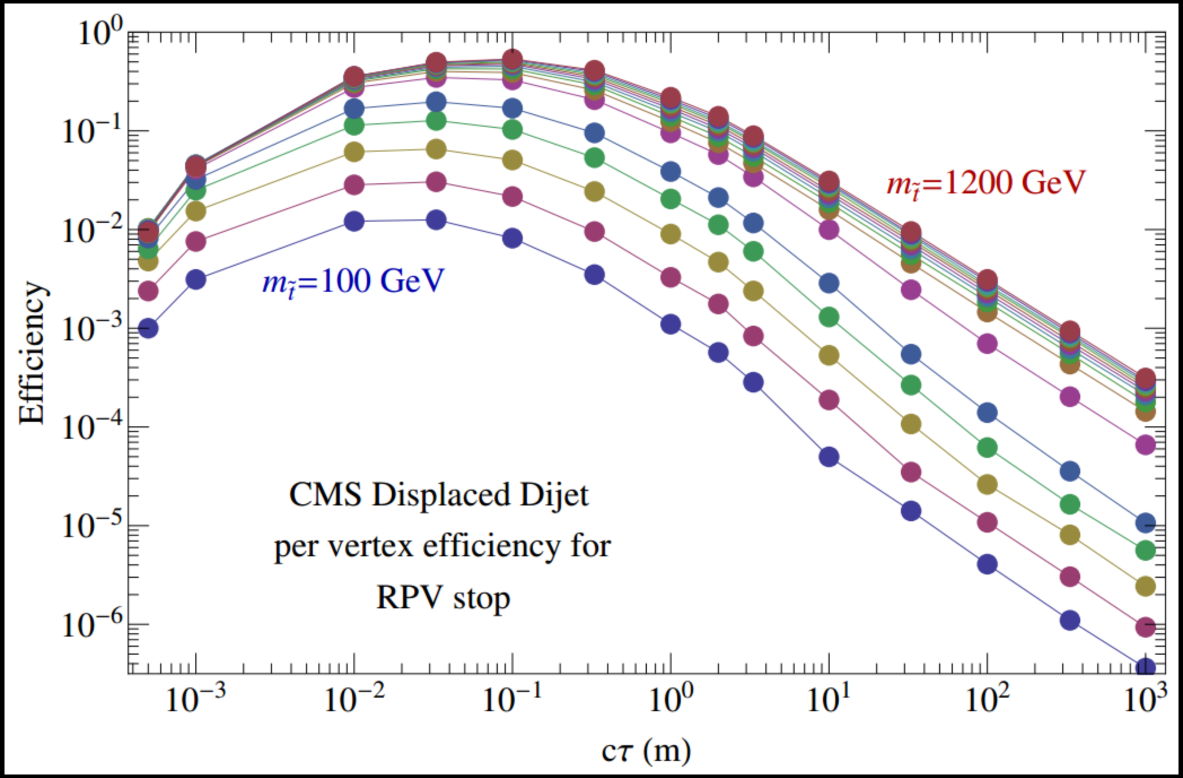


Efficiency map for RPV stop decays into light jet pairs in the CMS displaced dijet analysis.

- Lines at increase of 100 GeV
- Low mass suffers more for cuts on jet energy
- High mass approaches constant efficiency shape
- Low efficiency at low lifetime (cut to remove SM)
- (Shift in peak due to Lorentz Factor)

RESULTS ON GMSB SUSY

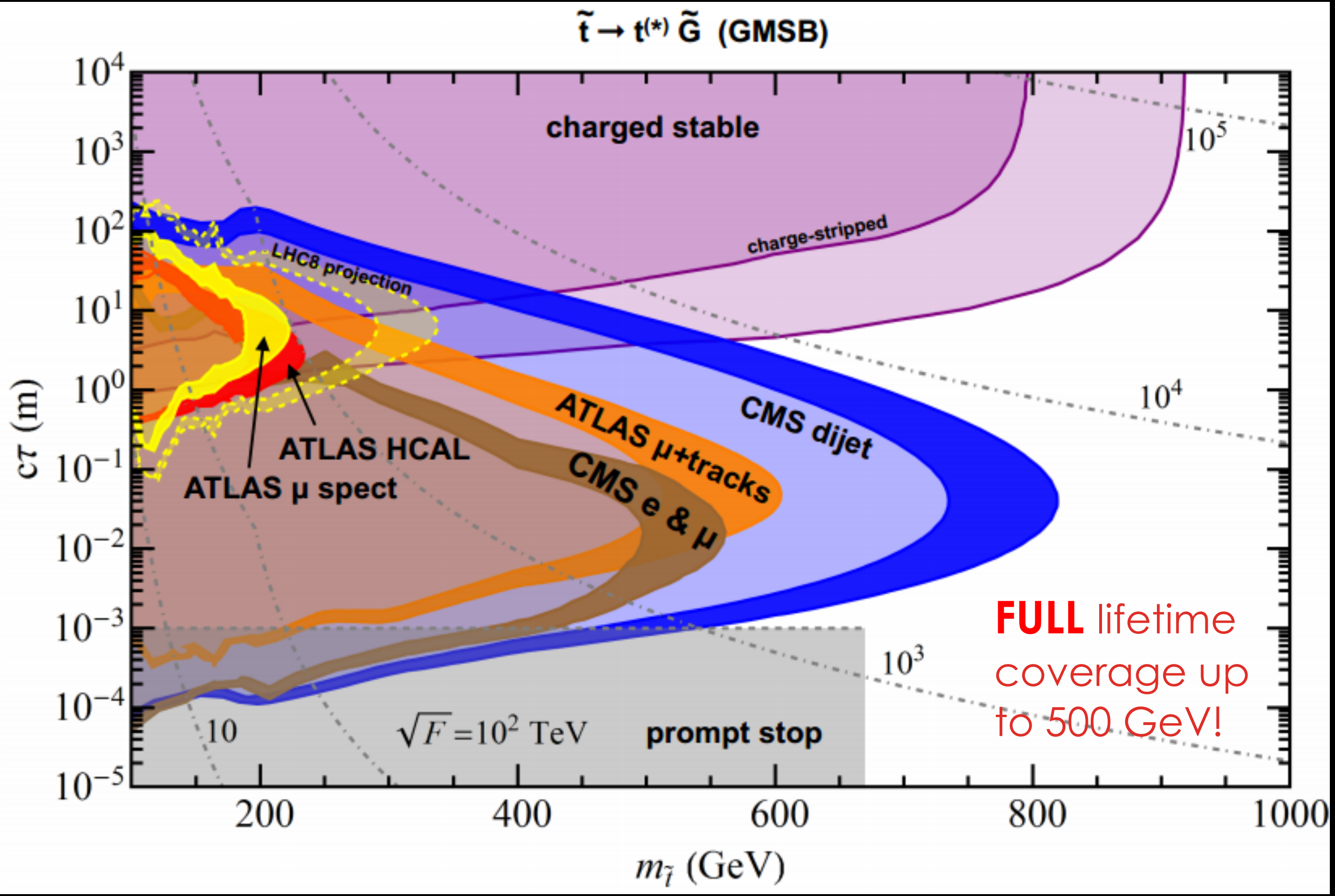
GMSB STOP

With detailed simulation and our own modeling of the displacement, after carefully calibrating with existing searches, we can derive the limits from many search of our simplified models.

GMSB STOP

GMSB Stop → Top$^{(*)}$ + Gravitino

- Displaced searches (dijet, μ+tracks, $e + \mu$, HCAL, μ spectrometer) covers mid-lifetime Heavy charges
- stable particle searches (pink; CHAMP) covers long lifetime
- Prompt (gray) covers short lifetime



FULL lifetime coverage up to 500 GeV!

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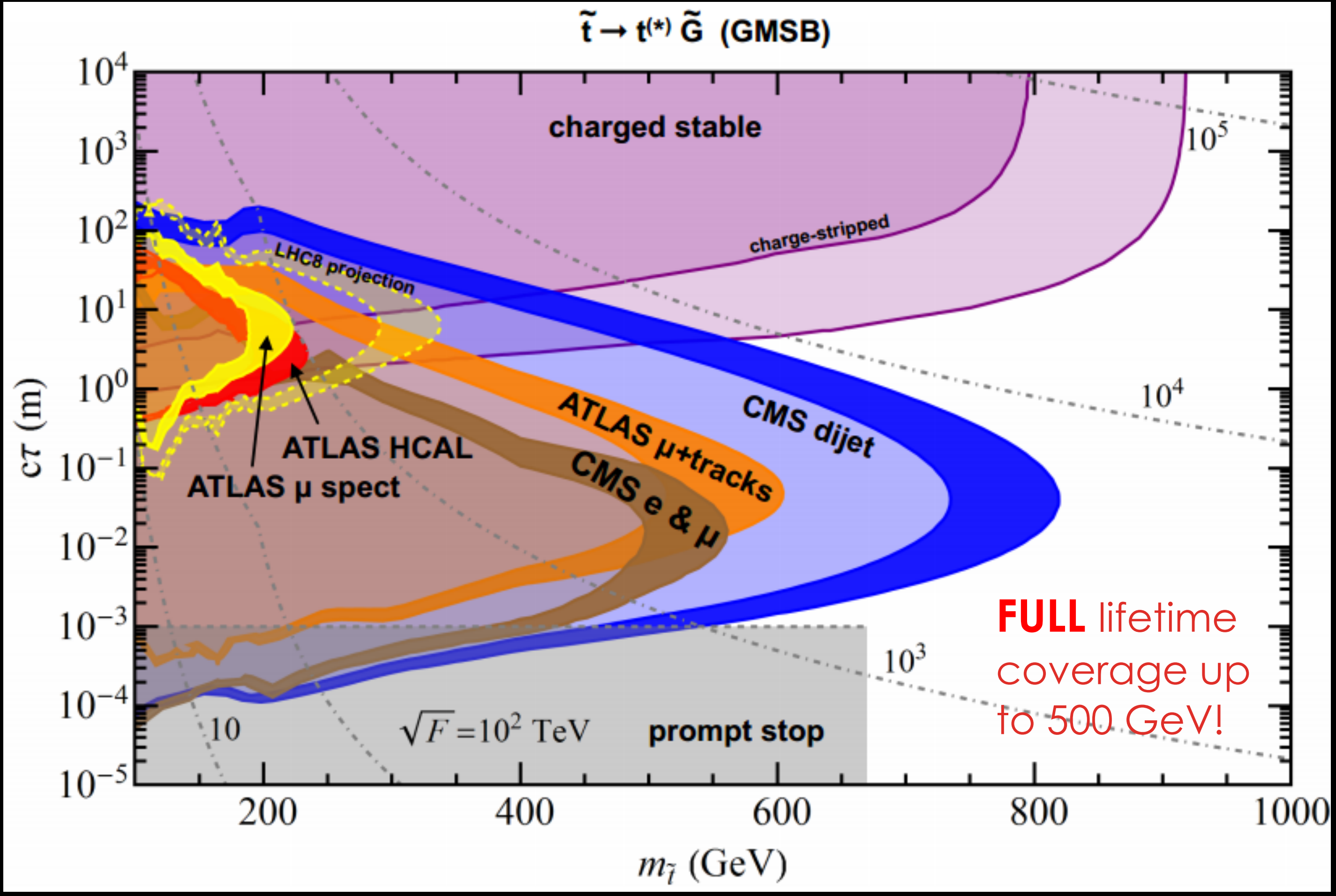

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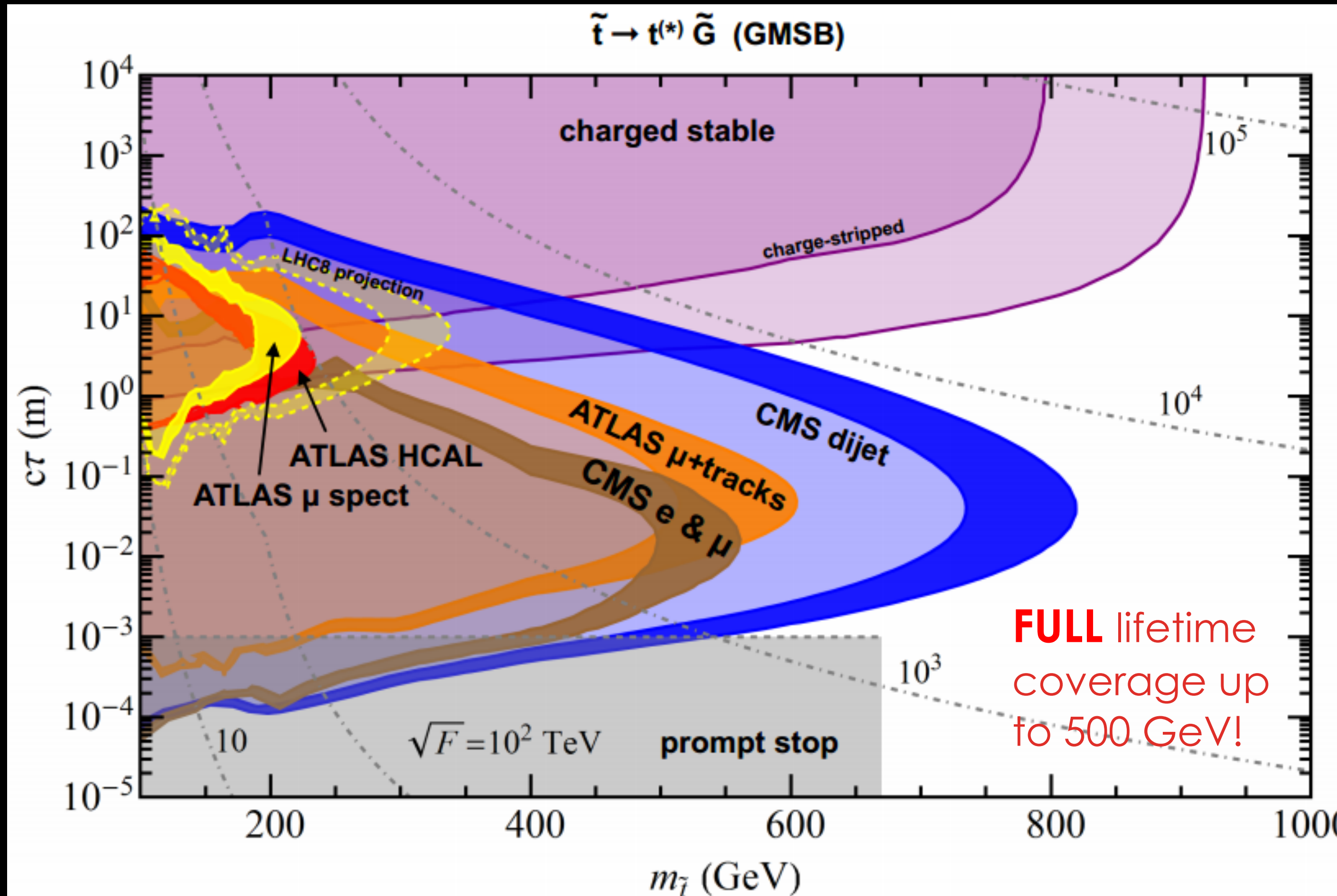

Dijet search has very good sensitivity reach, lepton plus tracks searches also sensitive to leptonic top- and b-decays. HCAL and muon spectrometer searches sensitive to higher lifetimes but so far suffers large efficiency cost. Optimization may provide additional information, e.g., heavy neutral displaced particles.

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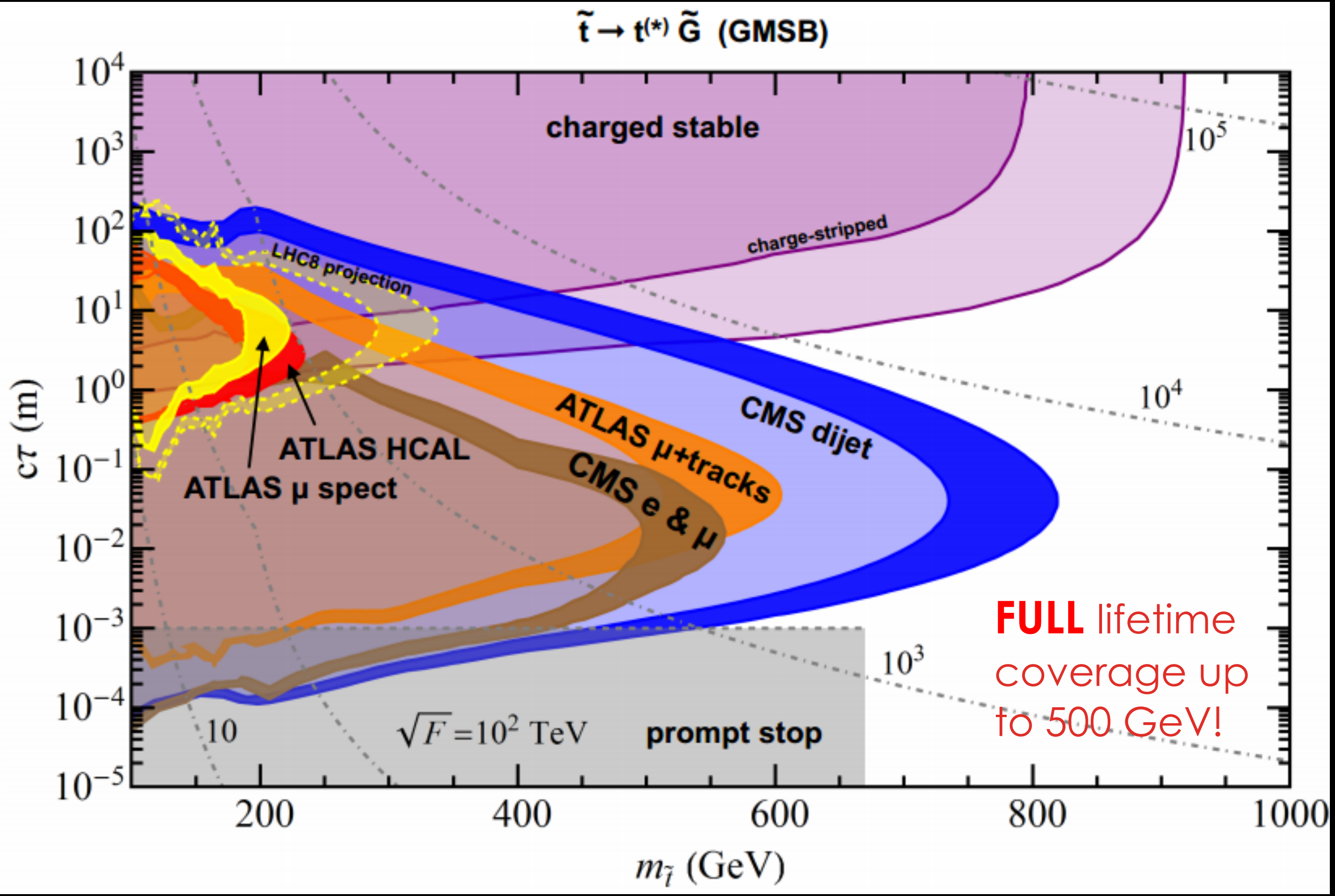

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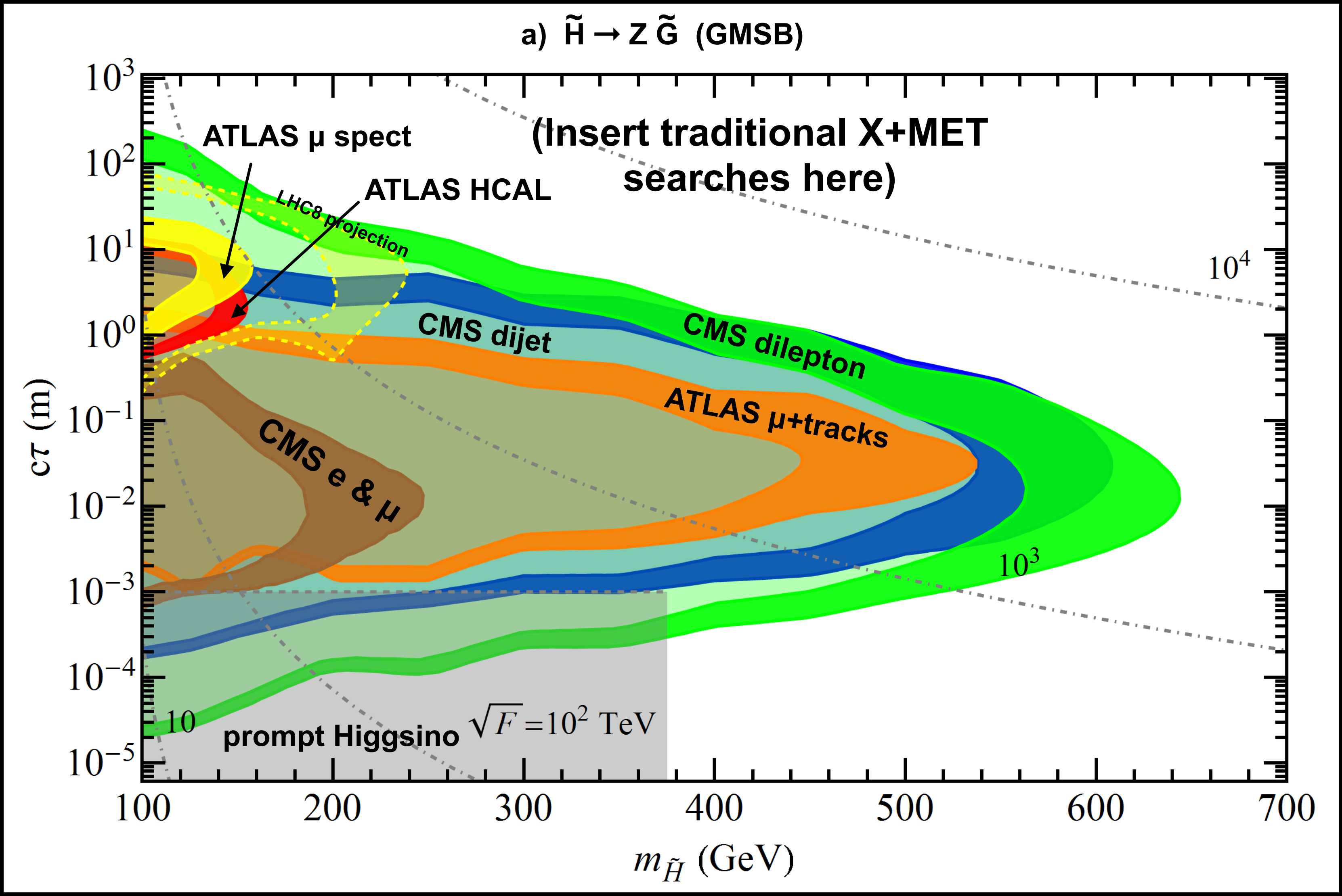
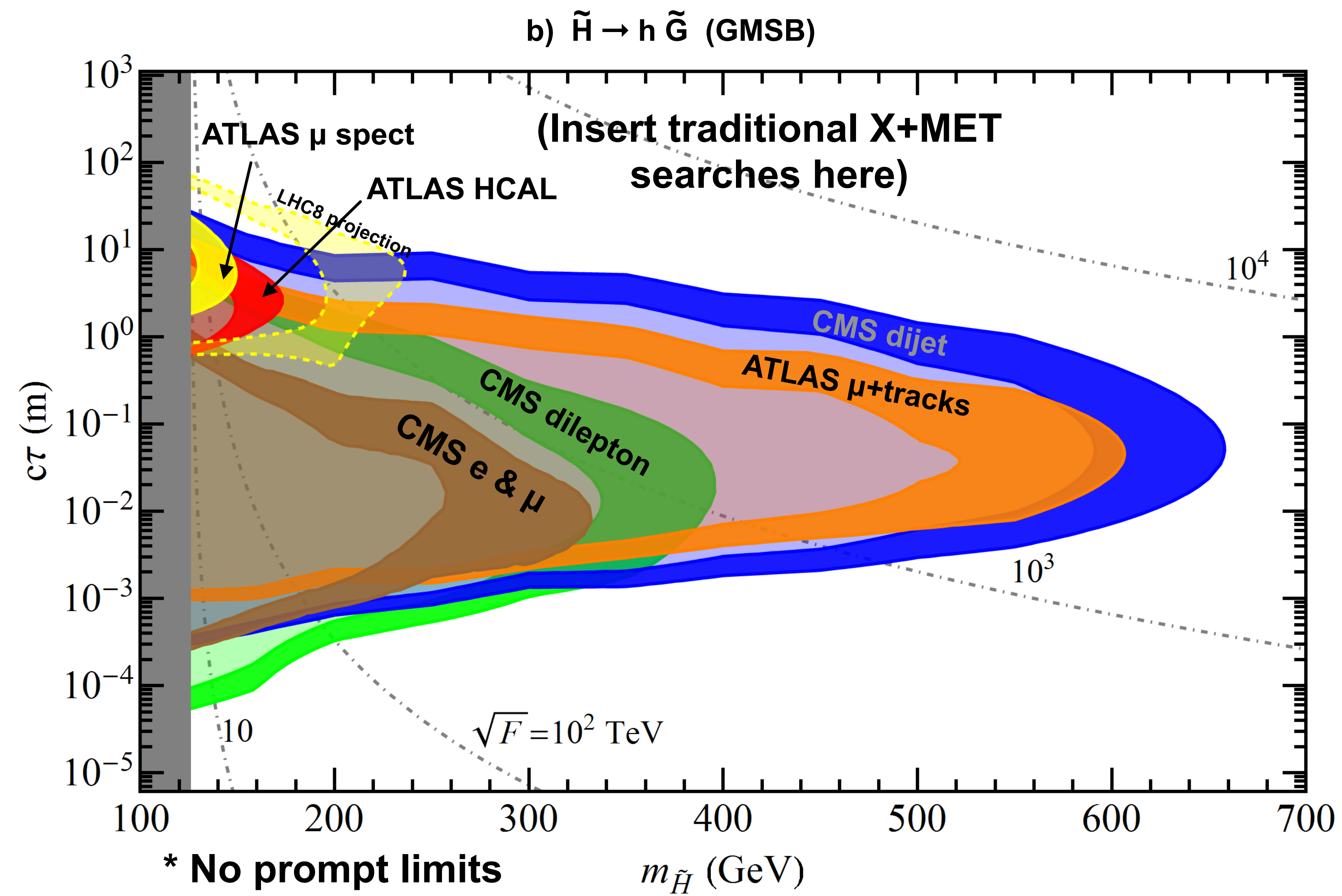
GMSB Higgsino → Z + Gravitino



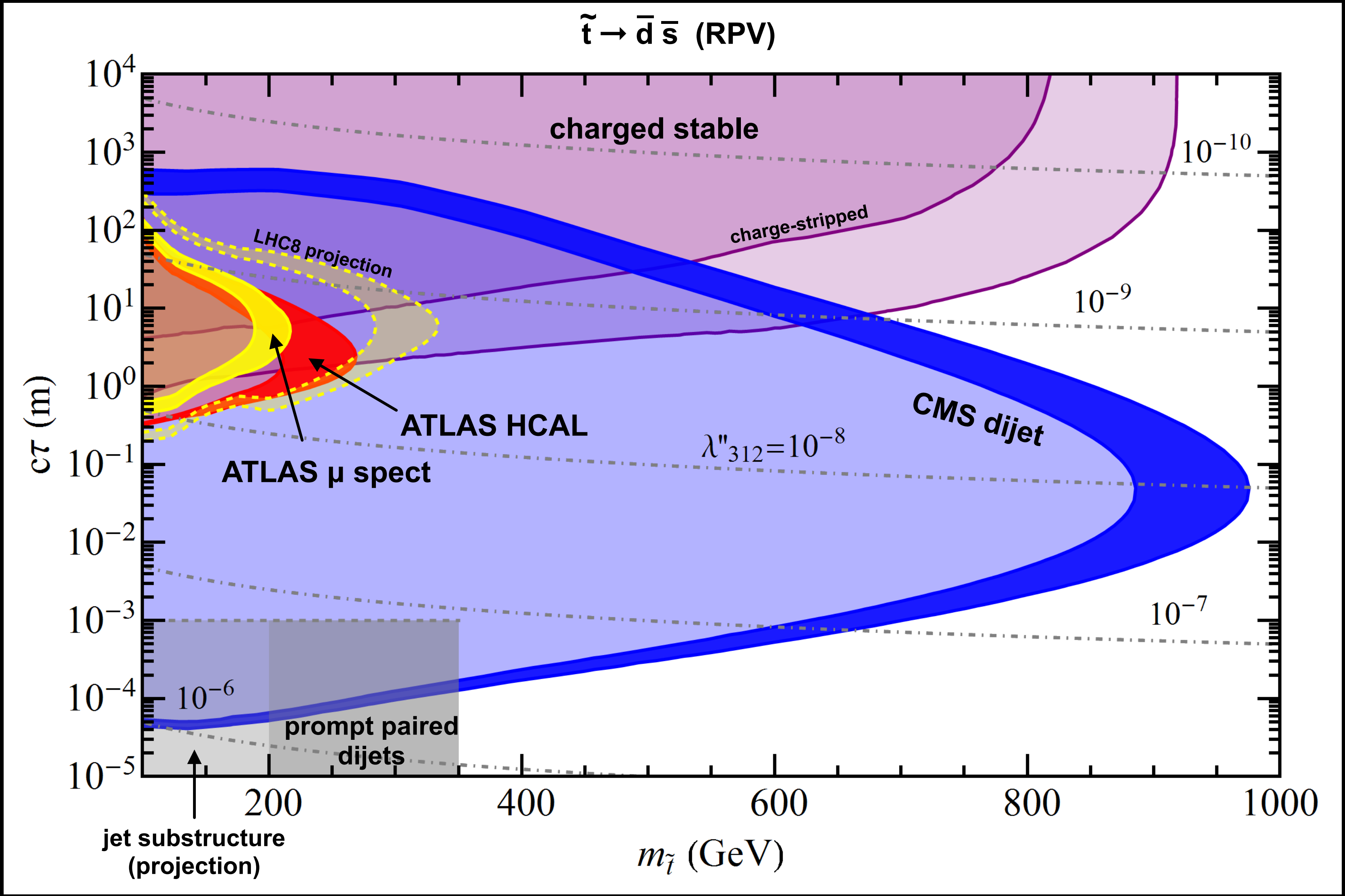
GMSB Higgsino → H + Gravitino



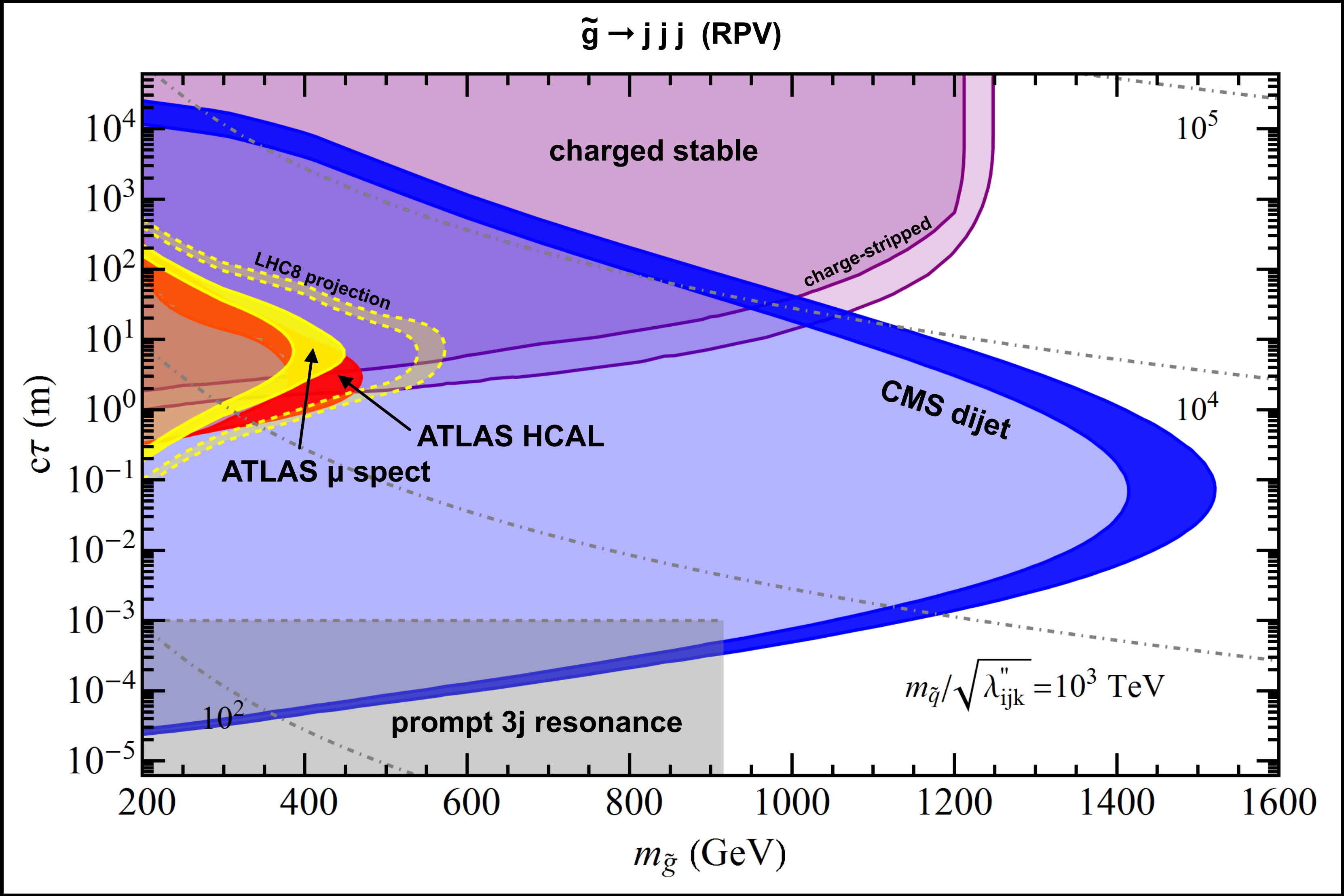
* No prompt limits

RESULTS ON RPV SUSY

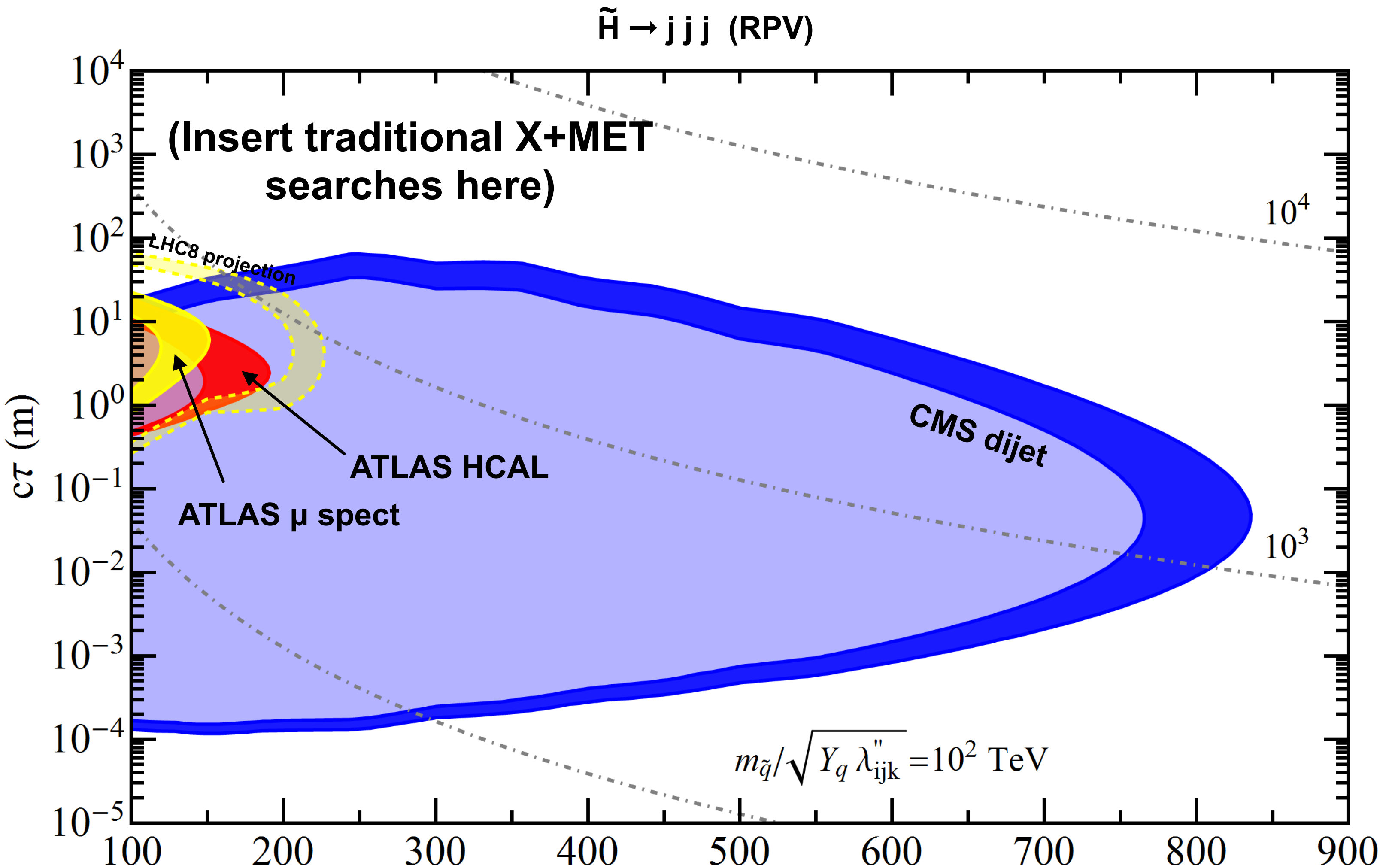
RPV Stop → 2q (Light Flavors)



RPV Gluino → 3q (Light Flavors)



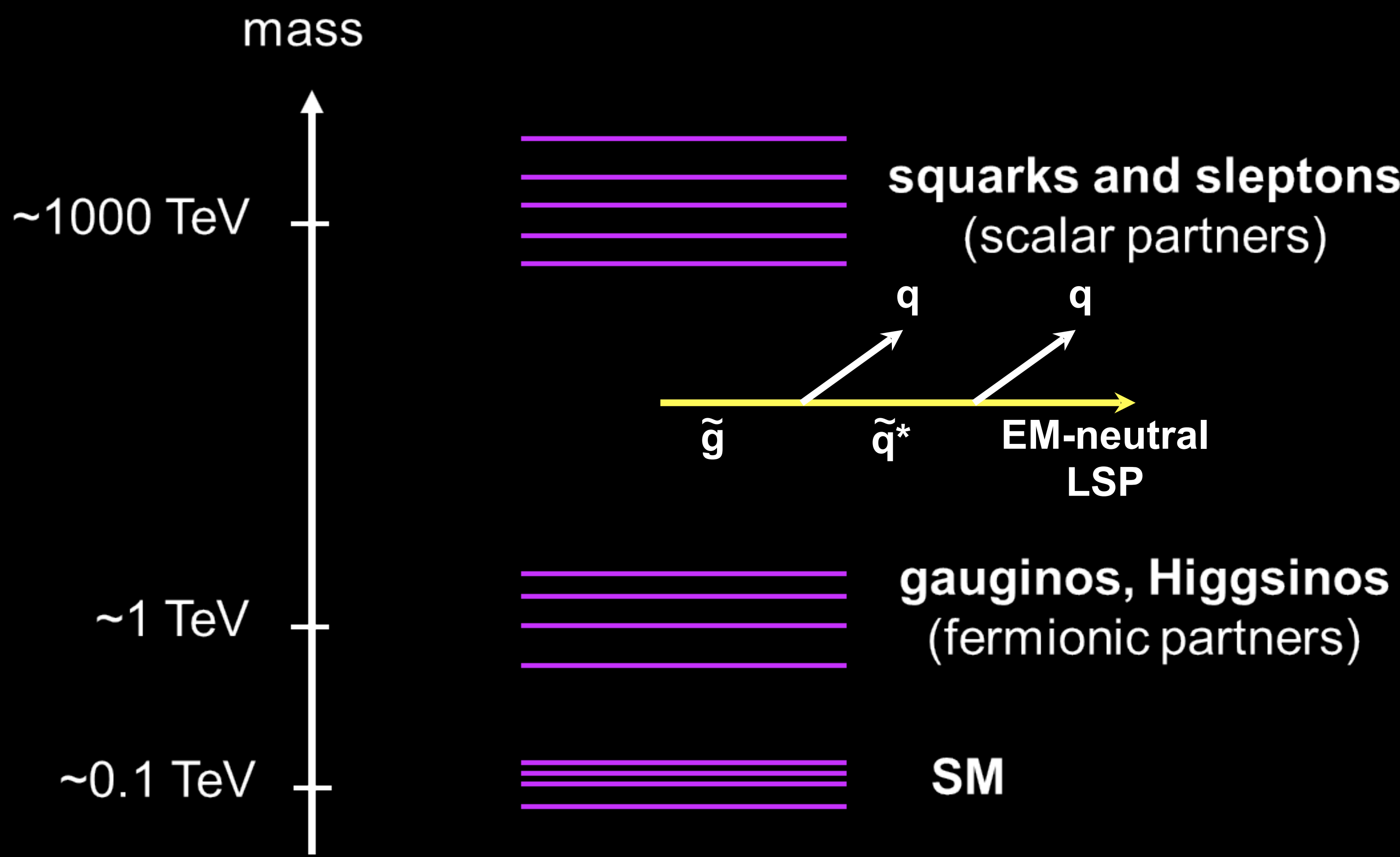
RPV Higgsino → 3q (Light Flavors)



* No prompt limits

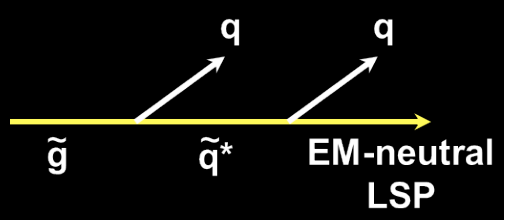
RESULTS ON MINI-SPLIT SUSY

MINI-SPLIT GLUINO → 2J + LSP



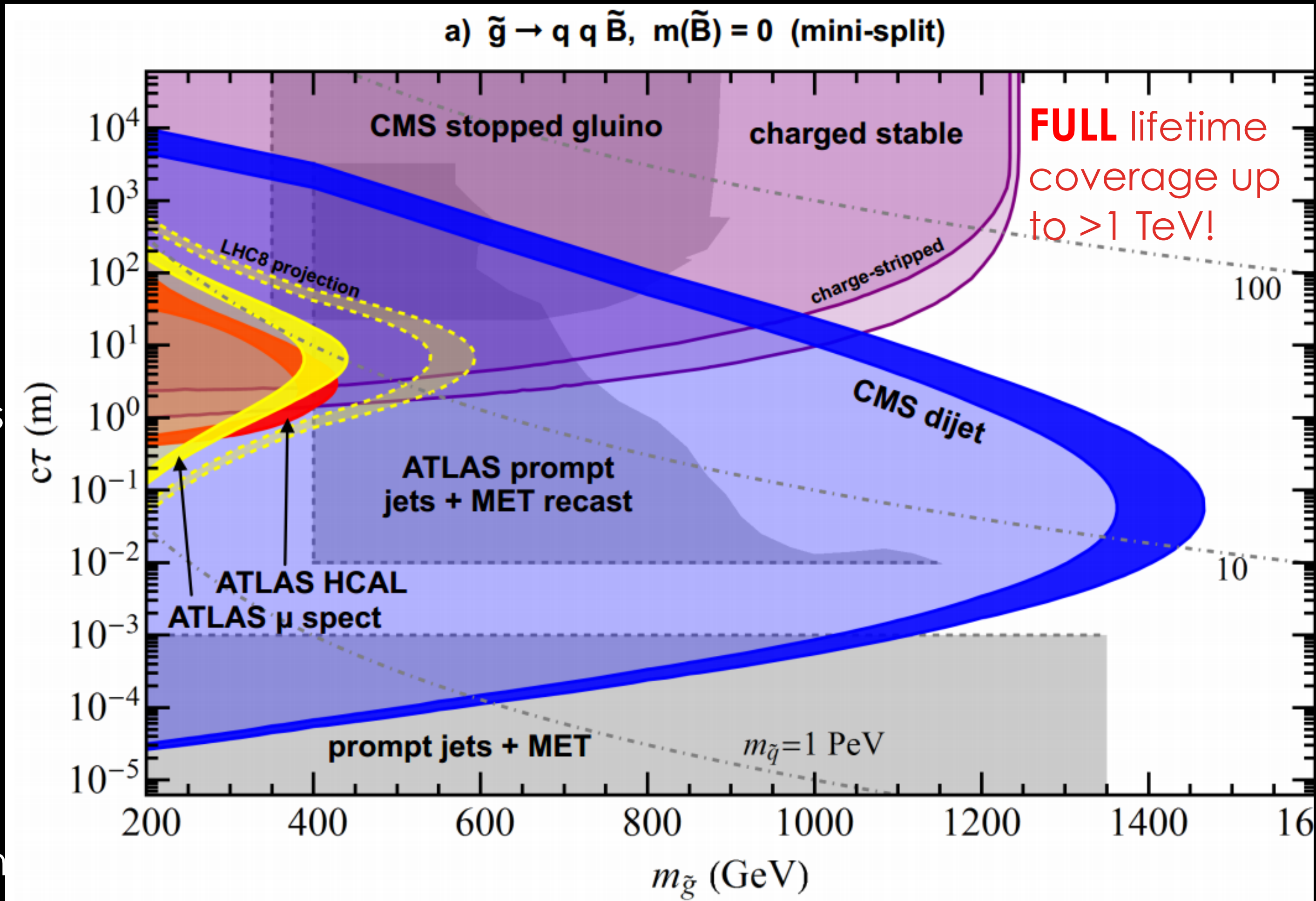
Arkani-Hamed & Dimopoulos (2004)
Arvanitaki, Craig, Dimopoulos, Villadoro (2012)
Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawksi (2012)

MINI-SPLIT GLUINO → 2J + LSP



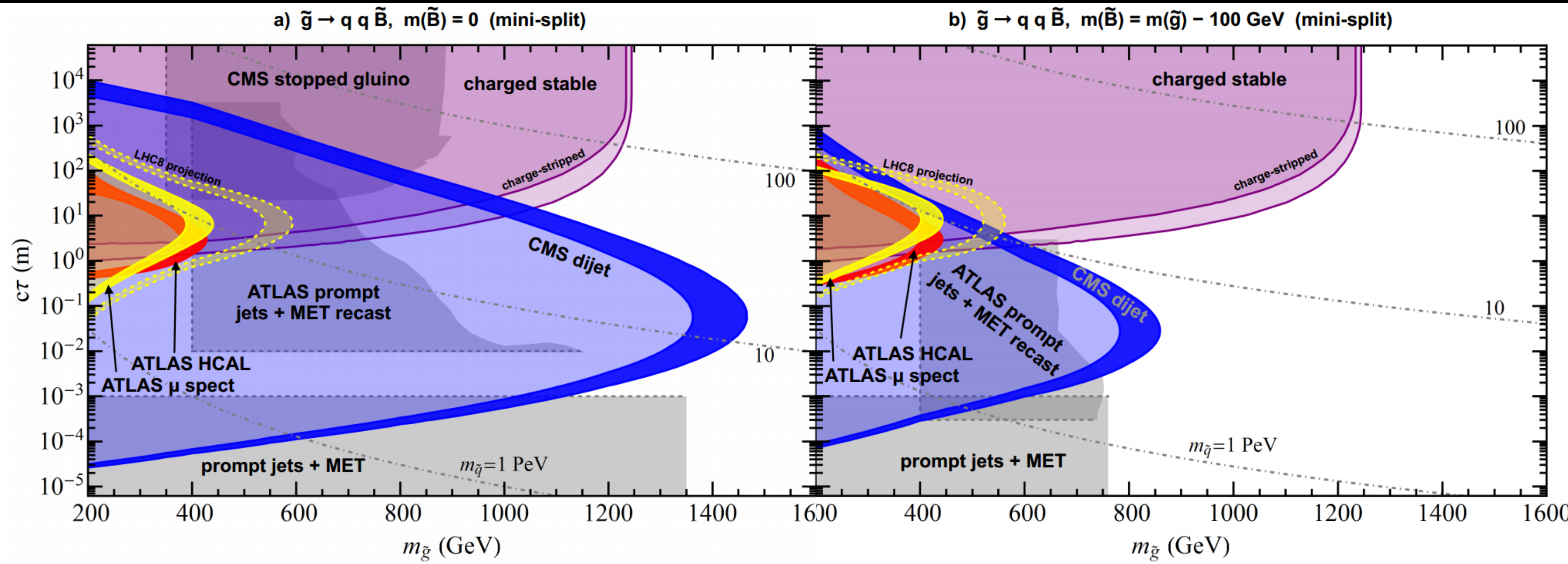
$$c\tau \propto m^4_{squark}/m^5_{gluino}$$

- The dijet in the final boosts the efficiencies for displaced dijet searches.
- The prompt jets+MET searches also covers a range of lifetime in the low mass, as fractions of long-lived particles decay promptly (boundary in dashed lines indicates possible extrapolation.



This figure shows one extreme case with large mass splitting between the LSP and NLSP. How about a bit compressed?

MINI-SPLIT GLUINO → 2J + LSP



In case of compressed spectra (right panel)

- Most searches rely on visible SM particles greatly reduced due to energy cuts (necessary to cut away SM backgrounds from non-prompt decay and cosmic rays, etc)
- Heavily charged stable particle search remains the same as no decays are required.
- Different displaced search channels are more complementary, more important.

SUMMARY AND OUTLOOK

Summary

- Major classes of well-motivated SUSY models exhibit displaced decays
  - RPV, GMSB, mini-split
  - broad range of possible particle spectra and decay topologies
  - only a handful covered by explicit searches
- Existing displaced decay searches can be extremely powerful
  - "weird looking" $\Rightarrow$ tiny backgrounds
  - non-SUSY searches cover lots of SUSY model space
- Understanding the full LHC potential requires careful recastings for many models
  - map ranges/overlaps in coverage
  - identify gaps/ambiguities/opportunities
  - we have made some first steps in this direction

New studies

Triggers + (soft) DV Matrix?
(Any traditional trigger, mono-jet, MET, multijet, VBF, multi lepton, etc times
long-lived signatures, displaced leptons, tracks, vertices, disappearing tracks, etc.)

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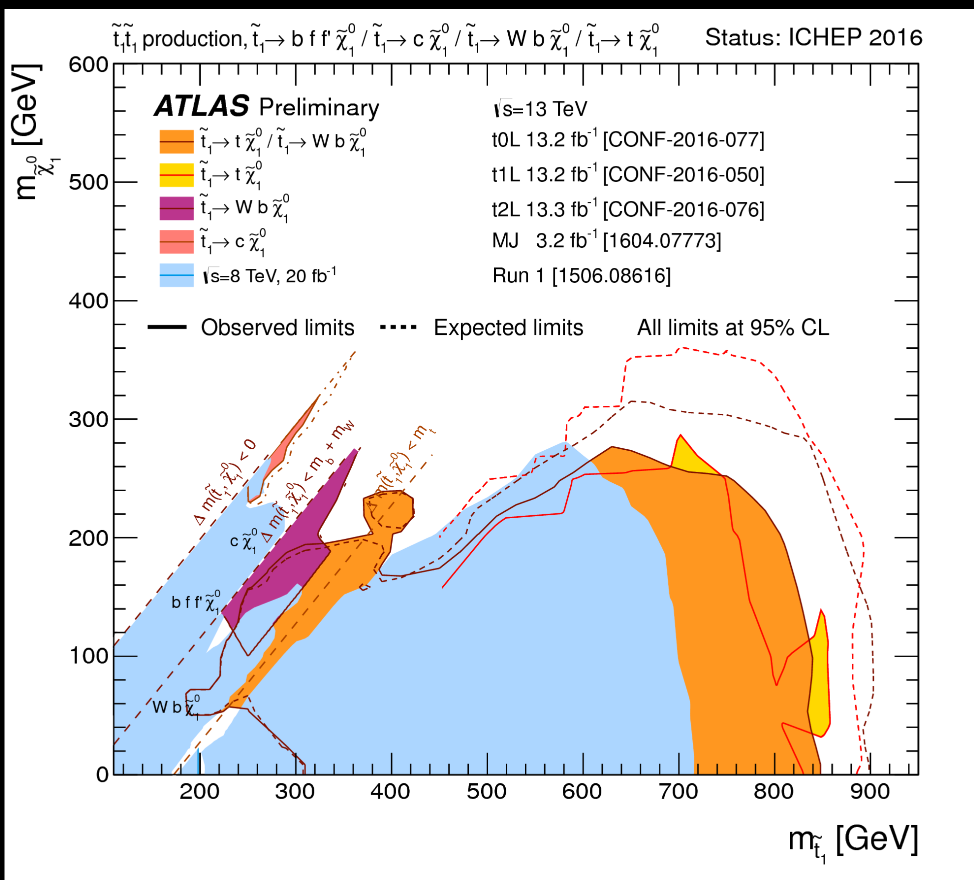

$$\Gamma_{\tilde{t}} \approx \frac{2\alpha_{\rm em} G_F^2 (\Delta m)^8}{315\pi^4 \cos^2\theta_W m_t^2 m_{\tilde{t}}} = (1.64\ {\rm mm})^{-1} \left(\frac{\Delta m}{20\ {\rm GeV}}\right)^8 \left(\frac{600\ {\rm GeV}}{m_{\tilde{t}}}\right.$$

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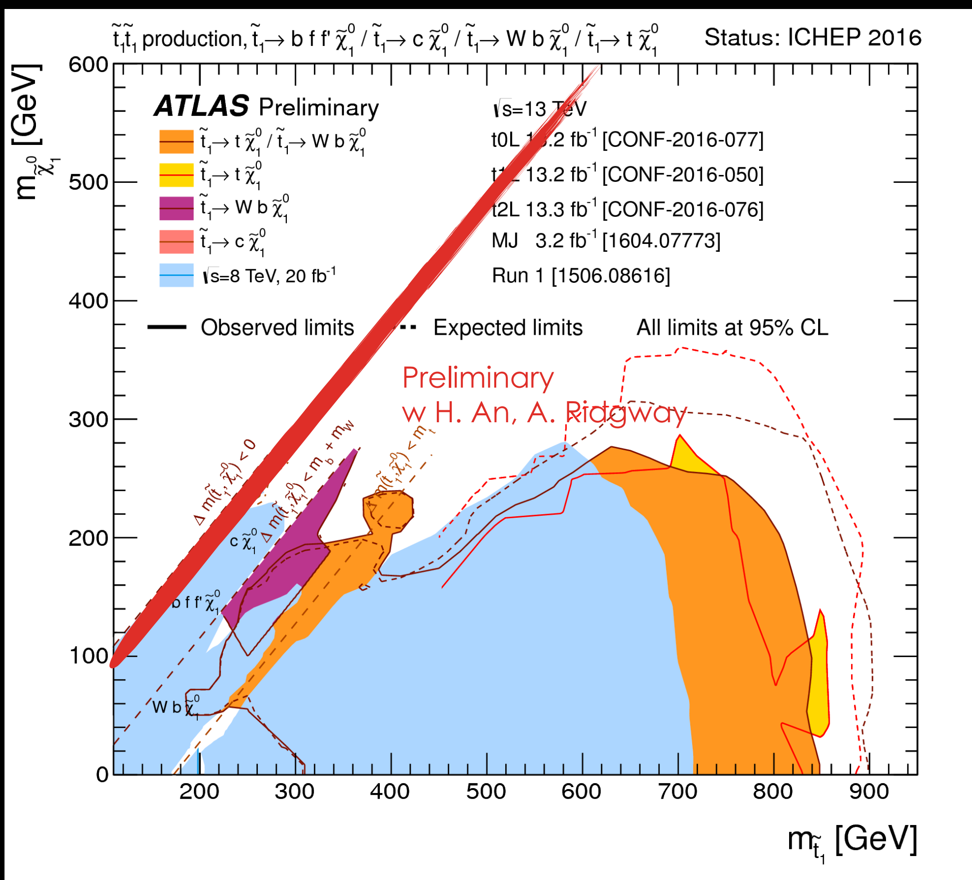

1. Requiring two displaced vertices
2. Each contains at least 4 tracks with PT > 1 GeV and transverse IP > 0.5.
3. The distance between the 2 vertices larger than 5 mm
4. Exclude the region within 1 mm surround the beam pipe.
5. MET > 200 GeV

Achieve impressive limit already with old data.

$$\Gamma_{\tilde{t}} \approx \frac{2\alpha_{\rm em} G_F^2 (\Delta m)^8}{315\pi^4 \cos^2\theta_W m_t^2 m_{\tilde{t}}} = (1.64\ \text{mm})^{-1} \left(\frac{\Delta m}{20\ \text{GeV}}\right)^8 \left(\frac{600\ \text{GeV}}{m_{\tilde{t}}}\right.$$

Final Remark

Displaced decays is becoming a more and more active field

- (Inelastic) Dark Matter
- (Twin Higgs) **Higgs decays** to long-lived particles (gluballs)
- Dark sector strong dynamics (Dark QCD, quirk)

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- Designing/implementing/considering explicit Displaced triggers (both ATLAS and CMS)
- Upgrading modules also useful for displaced decays (high granularity tracking, precision (ps) timing)
- Proposing new experiment for displaced decays (SHiP experiment, MATHUSLA, milliQan, etc.)
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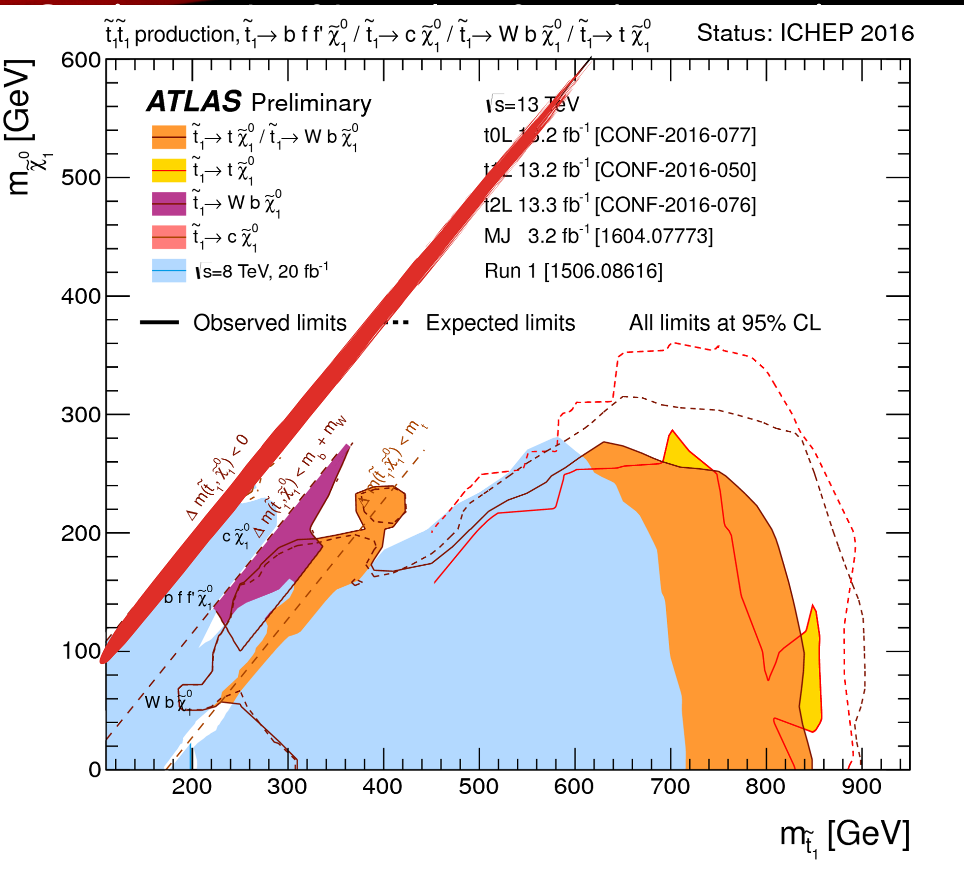

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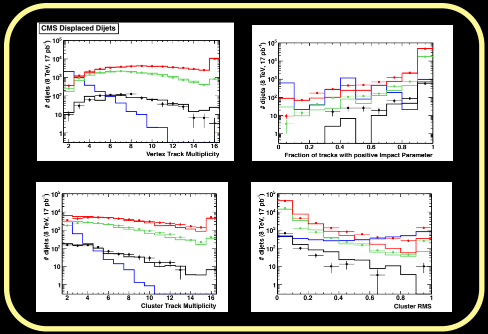
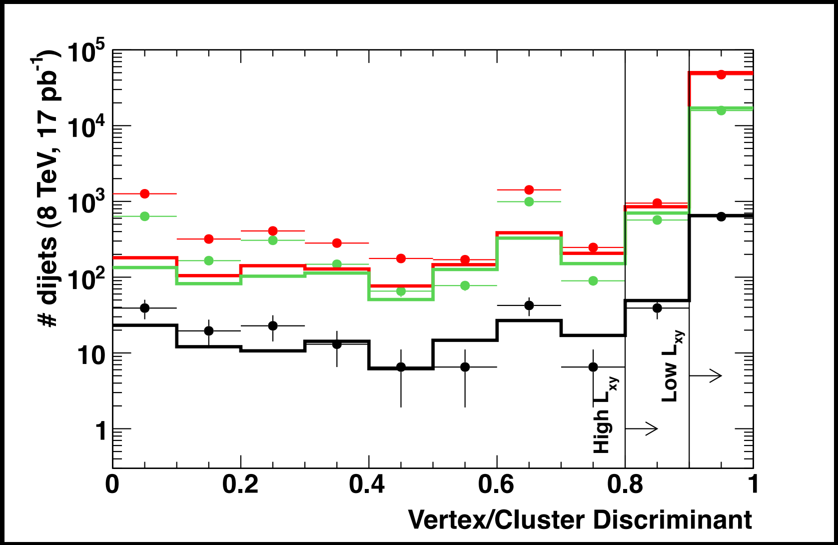
Backup

CMS Dijets Validation





(Dominated by multiplicity variables)

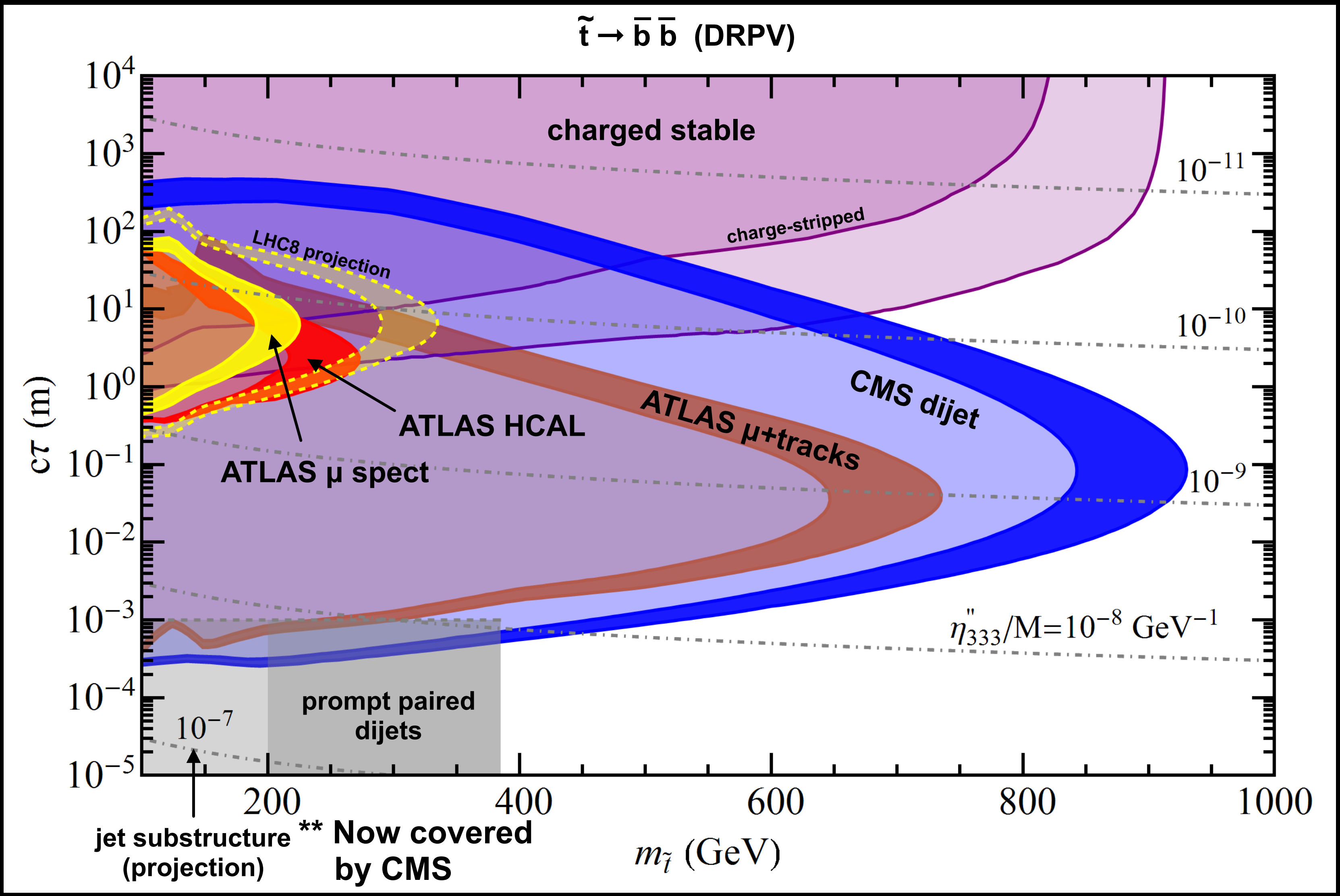
H(1000) → X(350) X(350), cτ = 35 cm

H(400) → X(150) X(150), cτ = 40 cm

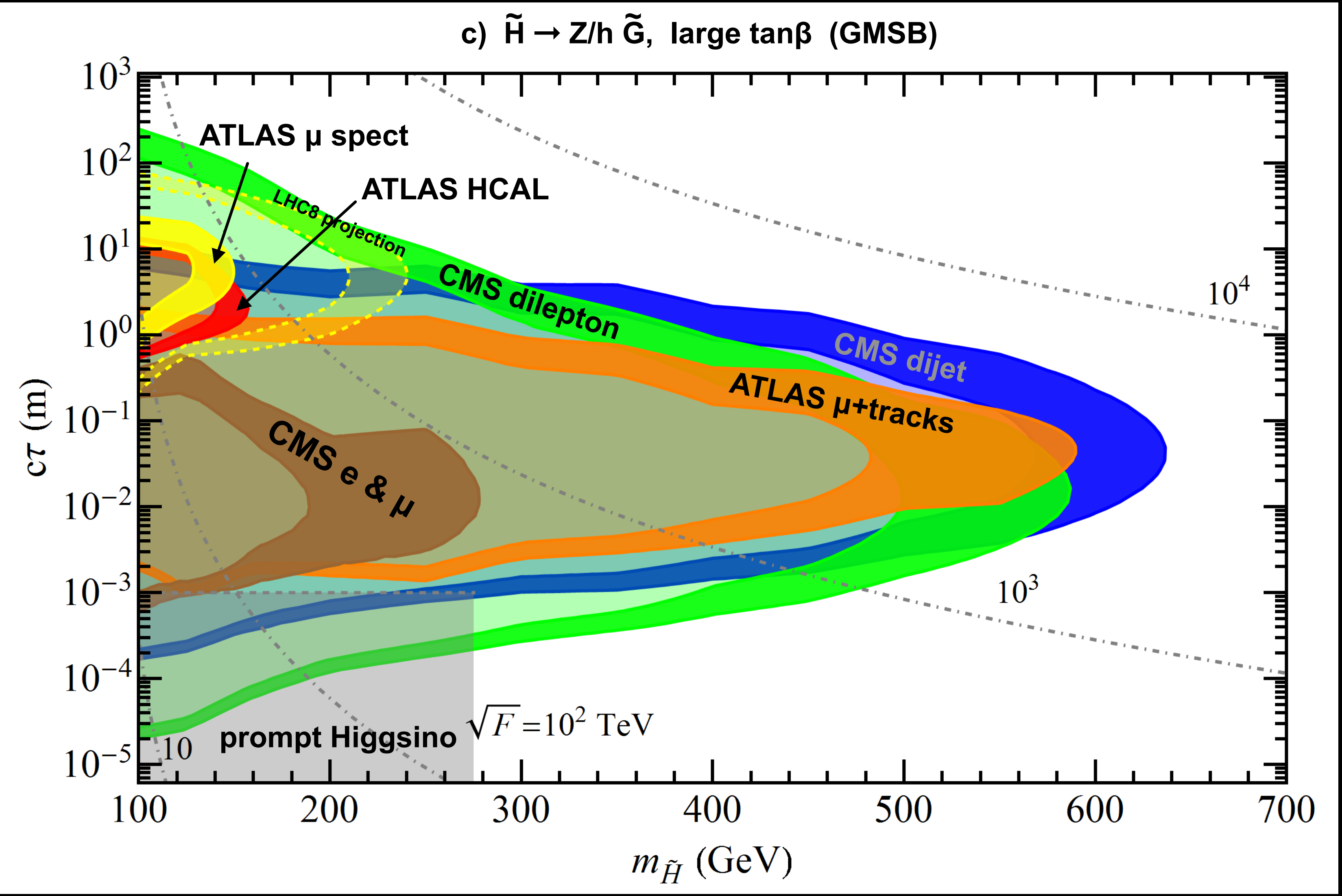
H(200) → X(50) X(50), cτ = 20 cm

QCD background

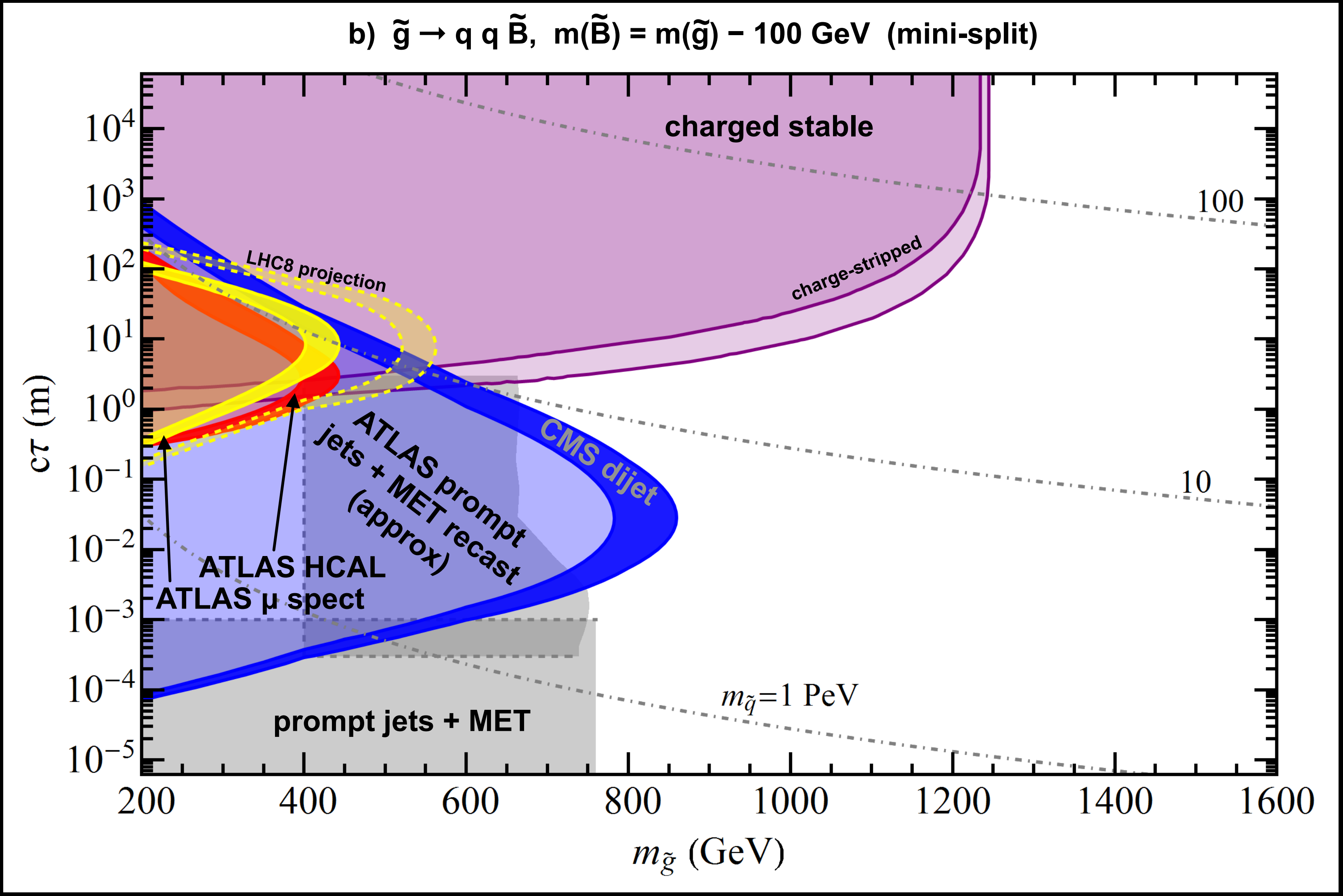
dRPV Stop → 2b


$\tilde{t} \rightarrow \bar{b}\,\bar{b}$ (DRPV)
charged stable
charge-stripped
LHC8 projection
ATLAS HCAL
ATLAS μ spect
ATLAS μ+tracks
CMS dijet
prompt paired dijets
10^{-11}
10^{-10}
10^{-9}
$\eta''_{333}/M=10^{-8}$ GeV^{-1}
10^{-7}
$c\tau$ (m)
$m_{\tilde{t}}$ (GeV)
200
400
600
800
1000
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
jet substructure (projection)
** Now covered by CMS

GMSB Higgsino → Z/h + Gravitino
Large tanβ Limit



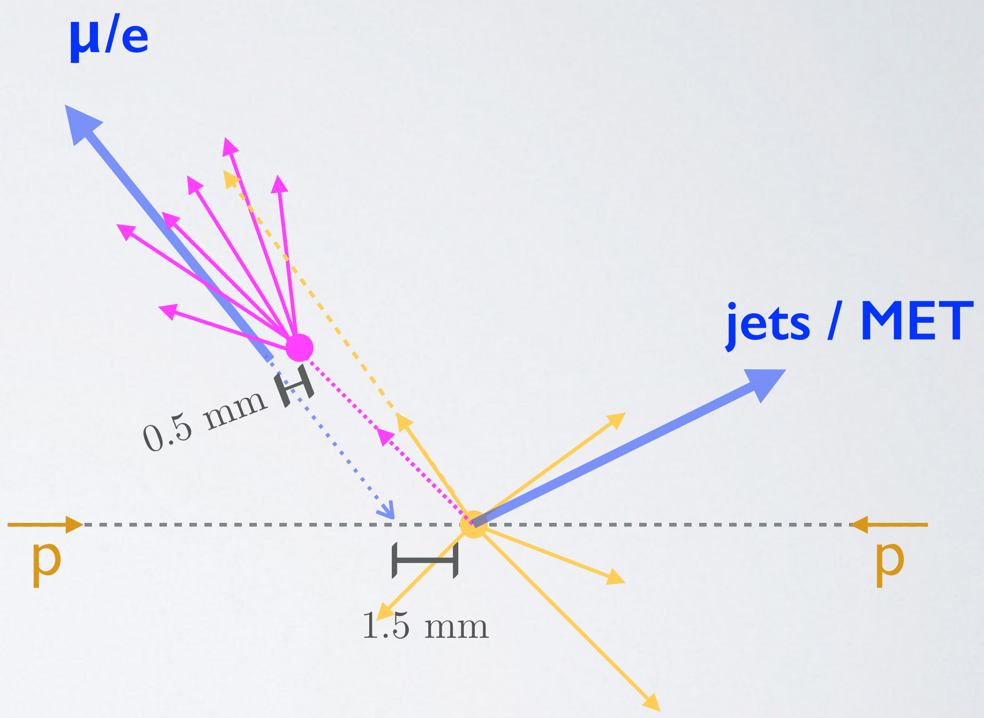
Mini-Split Gluino → 2j + LSP



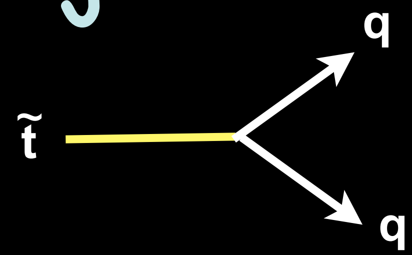
ATLAS DV + *muon/e/jets/MET*

Search for massive, long-lived particles using multitrack displaced vertices or displaced lepton pairs in pp collisions at sqrt(s) = 8 TeV with the ATLAS detector

- Search for displaced vertex with
  - $N_{tracks} > 5$
  - $m_{DV} > 10$ GeV
- Trigger/cut on associated object
  - muon, $p_T > 55$ GeV
  - electron, $p_T > 125$ GeV
  - MET > 180 GeV
  - Jets 4, 5 or 6, $p_T > 65, 60, 55$ GeV

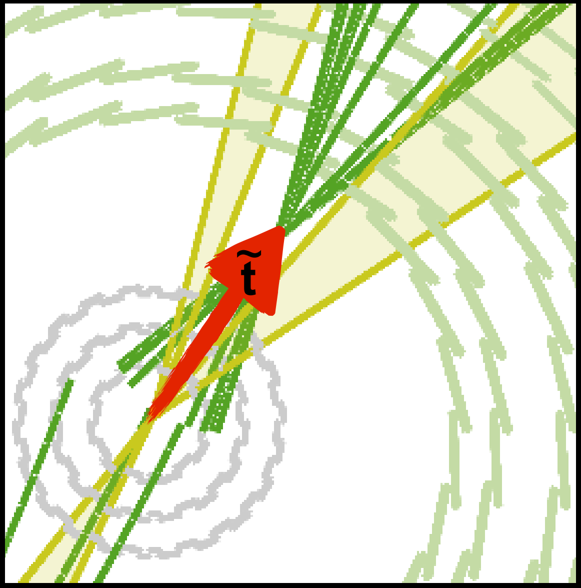


An Example: $\not{B}$RPV Stop from H -> aa -> Displaced Dijets



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

RUN II - TRIGGERS

- New CMS dijet trigger. But new 4 x larger impact parameter than Run I
- For most lifetimes, use prompt triggers
- *Depends on backgrounds

Trigger	Trigger Requirement
Displaced jet	$H_T > 175$ GeV or three jets with $p_T^{j_{1,2,3}} > (92, 76, 64)$ GeV, $\lvert\eta_{j_{1,2,3}}\rvert < (5.2, 5.2, 2.6)$ with $\lvert\eta_{j_1}\rvert$ or $\lvert\eta_{j_2}\rvert < 2.6$, and two of the three jets satisfying $m_{jj} > 500$ GeV, and $\Delta\eta > 3.0$. A displaced jet satisfying $p_T > 40$ GeV, at most 1 prompt track (2D IP $<$ 2.0 mm) [a], and at least 2 displaced tracks.
Inclusive VBF	Two jets with $\lvert\eta_{j_1,j_2}\rvert > 2$, $\eta_{j_1} \cdot \eta_{j_2} < 0$, $\lvert\eta_{j_1} - \eta_{j_2}\rvert > 3.6$ and $m_{j_1,j_2} > 1000$ GeV.
VBF, h $\to b\bar{b}$	Three jets with $p_T^{j_{1,2,3}} > (112, 80, 56)$ GeV and $\lvert\eta_{j_{1,2,3}}\rvert < (5.2, 5.2, 2.6)$ and at least one of the two first jets with $\lvert\eta_{j_1}\rvert$ or $\lvert\eta_{j_2}\rvert <$ 2.6.
Isolated Lepton	One lepton with $p_T > 25$ GeV, $\lvert\eta\rvert < 2.4$, and 3D IP $<$ 1 mm. Isolation requires the summed p_T of all tracks with $p_T > 1$ and within $\Delta R < 0.2$ of the lepton is less than 10% of the lepton p_T.
Trackless jets	A jet with $p_T > 40$ GeV and $\lvert\eta\rvert < 2.5$ matched with a muon with $p_T > 10$ GeV within $\Delta R = 0.4$. No tracks with $p_T > 0.8$ GeV in the ID within a $\Delta\phi \times \Delta\eta$ region of 0.2×0.2.

TRIGGER EFFICIENCIES

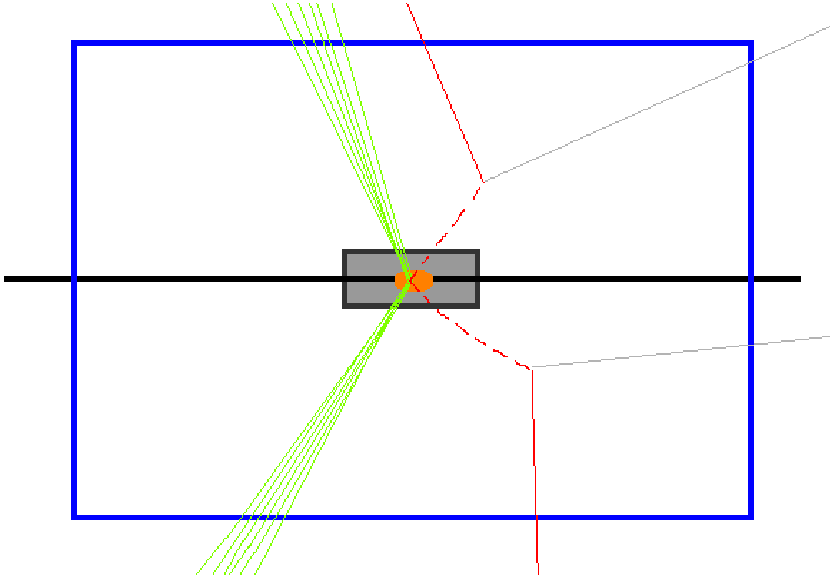
Trigger	m_{π_v} (GeV)	$c\tau = 1$ mm				$c\tau = 10$ mm				$c\tau = 100$ mm			
		ϵ_{ggF}	ϵ_{VBF}	ϵ_{VH}	ϵ_{Total}	ϵ_{ggF}	ϵ_{VBF}	ϵ_{VH}	ϵ_{Total}	ϵ_{ggF}	ϵ_{VBF}	ϵ_{VH}	ϵ_{Total}
Displaced jet	10	0.03%	1.3%	1.1%	**0.2%**	1.0 %	30.0%	25.1%	**3.9%**	1.0%	42.0%	34.7%	**5.1%**
	25	0.01%	0.8%	0.7%	**0.09%**	0.7%	20.4%	16.9%	**2.7%**	1.5%	45.3%	37.3%	**5.9%**
	40	0.02%	1.0 %	0.9%	**0.1%**	0.6%	19.7%	16.4%	**2.5%**	1.4%	44.6%	36.3%	**5.7%**
Inclusive VBF	10	1.9%	15.5%	0.8%	**2.8%**	1.8%	15.5%	0.7%	**2.8%**	1.6%	15.1%	0.6%	**2.6%**
	25	1.7%	15.3%	0.7%	**2.7%**	1.7%	15.3%	0.7%	**2.7%**	1.6%	15.2%	0.6%	**2.6%**
	40	1.6%	15.2%	0.7%	**2.6%**	1.6%	15.2%	0.7%	**2.6%**	1.6%	15.2%	0.6%	**2.6%**
VBF, $h \to b\bar{b}$	10	5.8%	20.3%	13.1%	**7.2%**	5.8%	20.2%	13.0%	**7.2%**	3.5%	13.3%	8.1%	**4.4%**
	25	4.6%	16.6%	10.9%	**5.8%**	4.7%	16.7%	10.9%	**5.9%**	4.2%	15.2%	9.7%	**5.3%**
	40	4.0%	14.2%	9.2%	**5.0%**	4.0%	14.2%	9.2%	**5.0%**	3.8%	13.9%	8.9%	**4.8%**
Isolated Lepton	10	3.6%	3.7%	14.7%	**4.1%**	1.0%	1.0%	12.5%	**1.5%**	0.1%	0.2%	11.8%	**0.6%**
	25	1.0%	1.5%	13.0%	**1.6%**	0.3%	0.4%	11.9%	**0.8%**	0.05%	0.07%	11.7%	**0.6%**
	40	1.0%	1.4%	12.6%	**1.6%**	0.3%	0.4%	11.9%	**0.8%**	0.05%	0.07%	11.6%	**0.6%**
Trackless jet	10	0.02%	0.04%	0.04%	**0.02%**	0.8%	1.5%	1.3%	**0.9%**	2.0%	2.4%	2.2%	**2.0%**
	25	0.02%	0.04%	0.06%	**0.02%**	0.5%	1.0%	0.8%	**0.6%**	3.6%	5.9%	5.0%	**3.8%**
	40	0.01%	0.02%	0.03%	**0.01%**	0.1%	0.2%	0.2%	**0.1%**	2.1%	4.1%	3.3%	**2.3%**

LEPTONIC DECAYS

Displaced Leptons in Prompt Searches

Prompt lepton-based searches:

- Quality criteria drop displaced electrons
- Displaced muons veto events (cosmics)
- Vetoes range from 50 μm–1 mm



Prompt jets+$\not{E}_T$ searches:

- Veto events with leptons
- Definition not always transparent

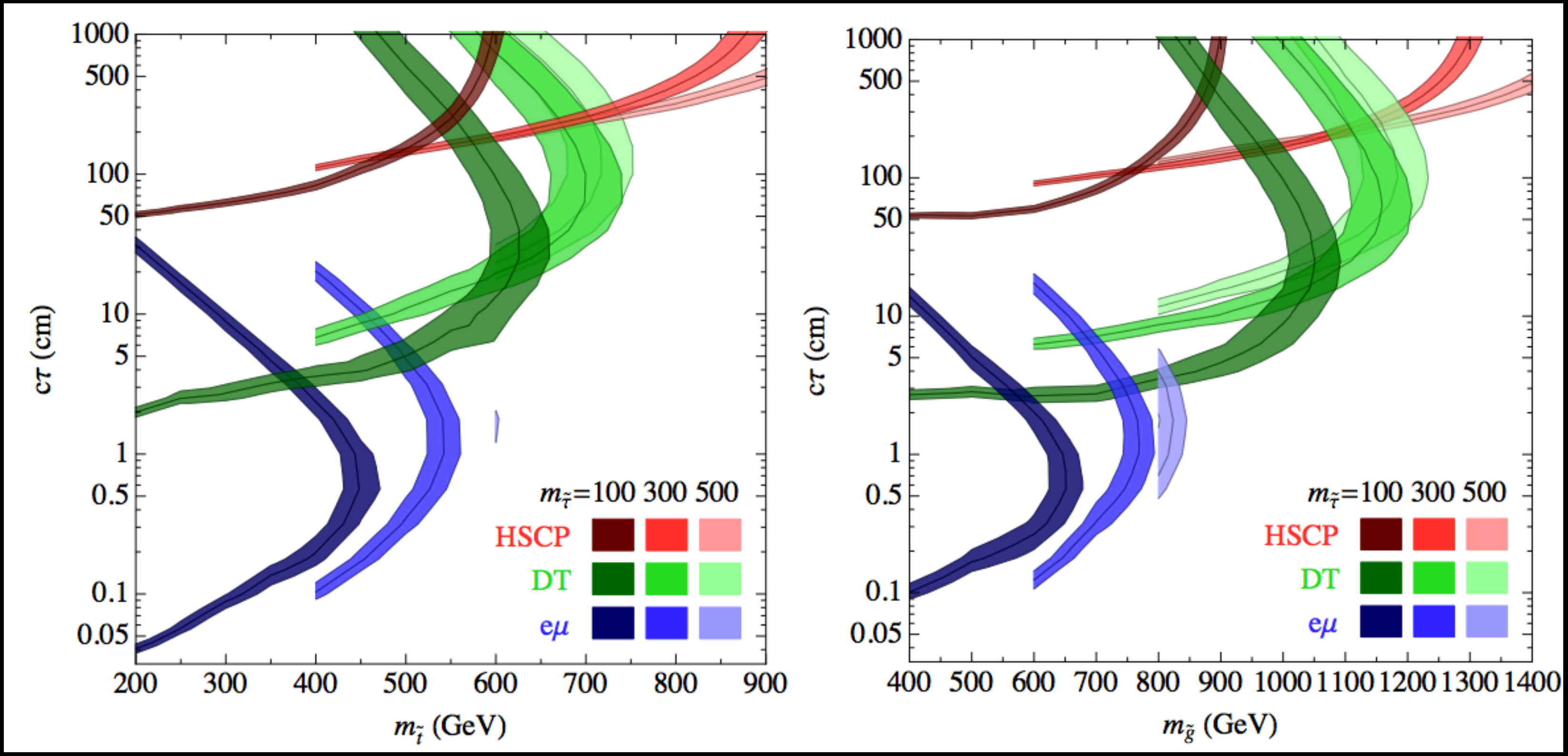
Very dangerous region!

$$pp \to \tilde{\ell}^+\tilde{\ell}^- + X \to \{\text{displaced muons}\} + X$$

lives in a prompt search blind spot!

Displaced electrons and taus $\Rightarrow$ reduced efficiency

DISPLACED LEPTONS



J. Evans, J. Shelton, arXiv:1601.01326

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**)

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 $c\tau$ ~ m and $c\tau$ ~ 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