Searches for long-lived particles at the LHC

Closing the gaps in BSM signature coverage

Nishita Desai

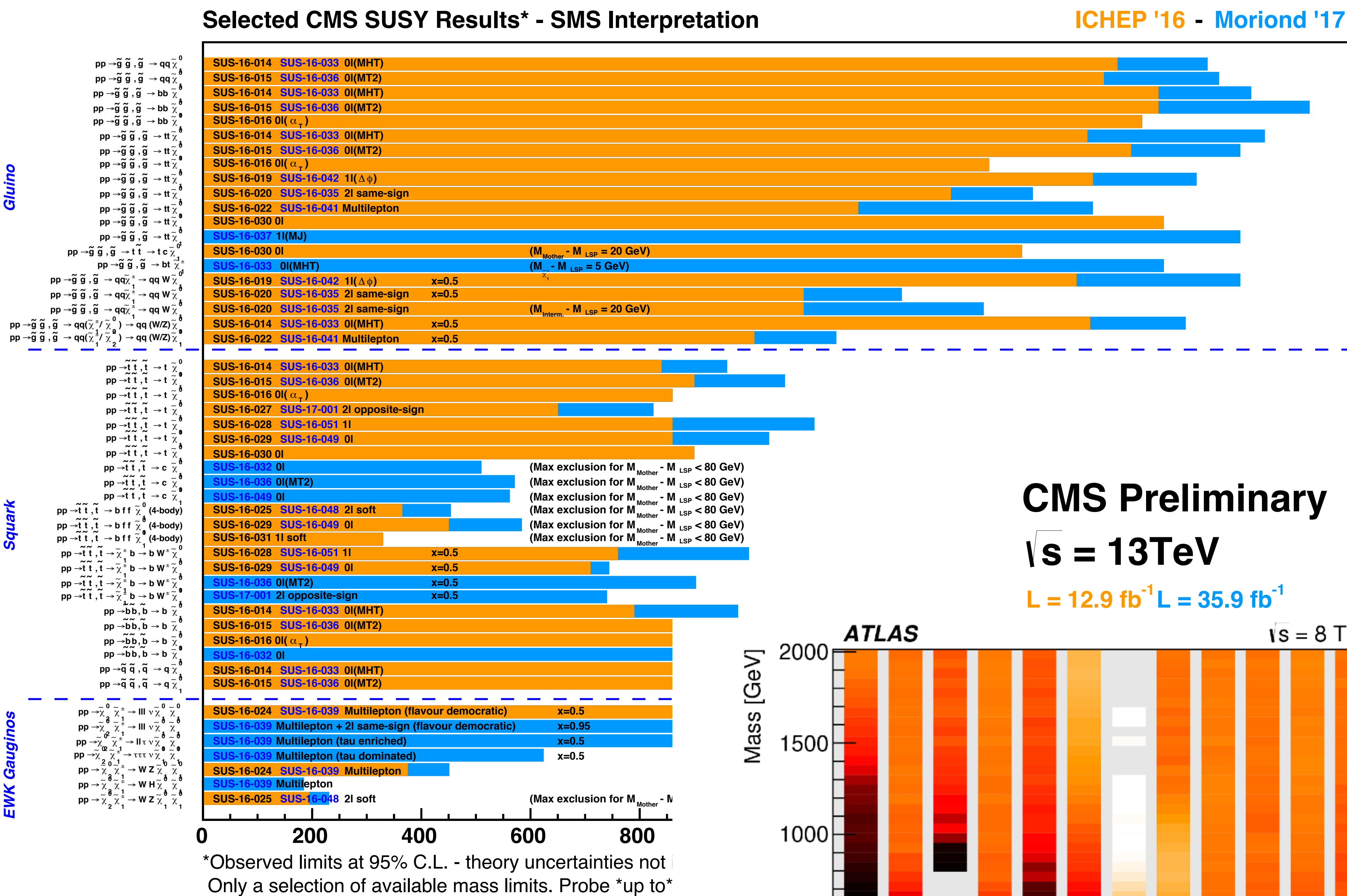
LUPM, Montpellier

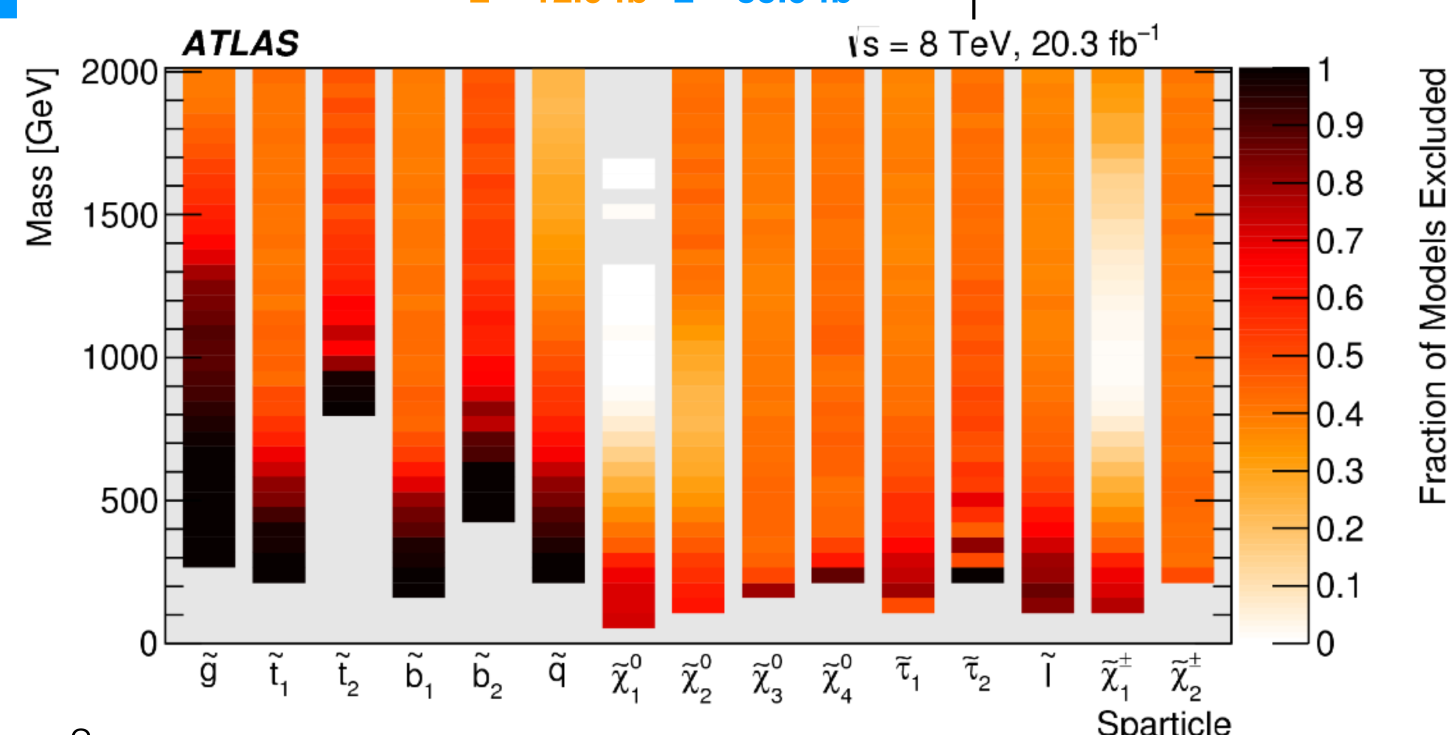
Based on: arXiv:1804.02357, 1803.10379, 1606.03099 and 1404.5061

With: B. Allanach, M. Badziak, G. Cottin, A. Bharucha, F. Brümmer, J. Ellis, C. Hugonie, F. Luo, J. Marrouche, R. Ziegler

22 May 2018; PLANCK 2018

Coverage of prompt signatures





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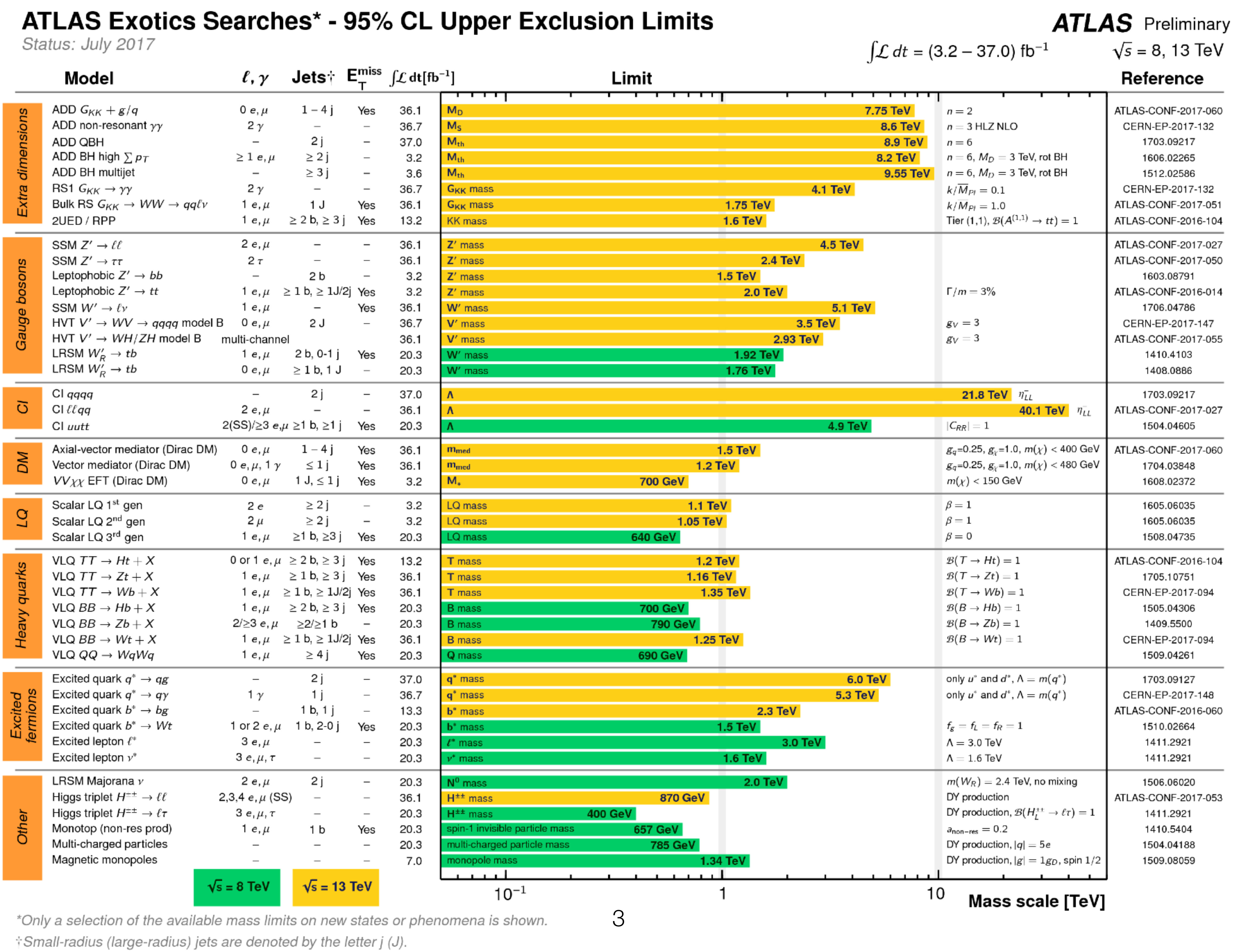
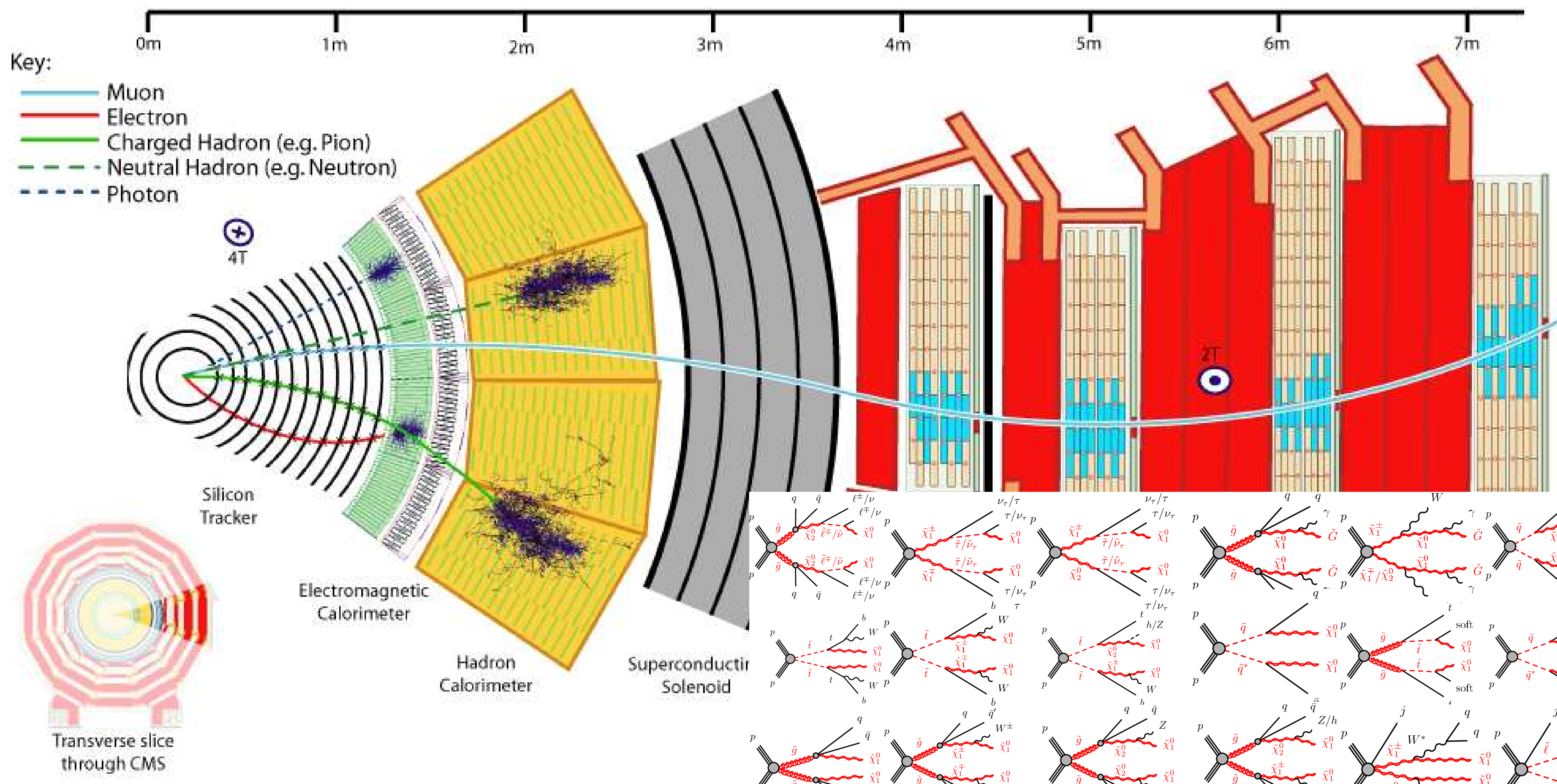
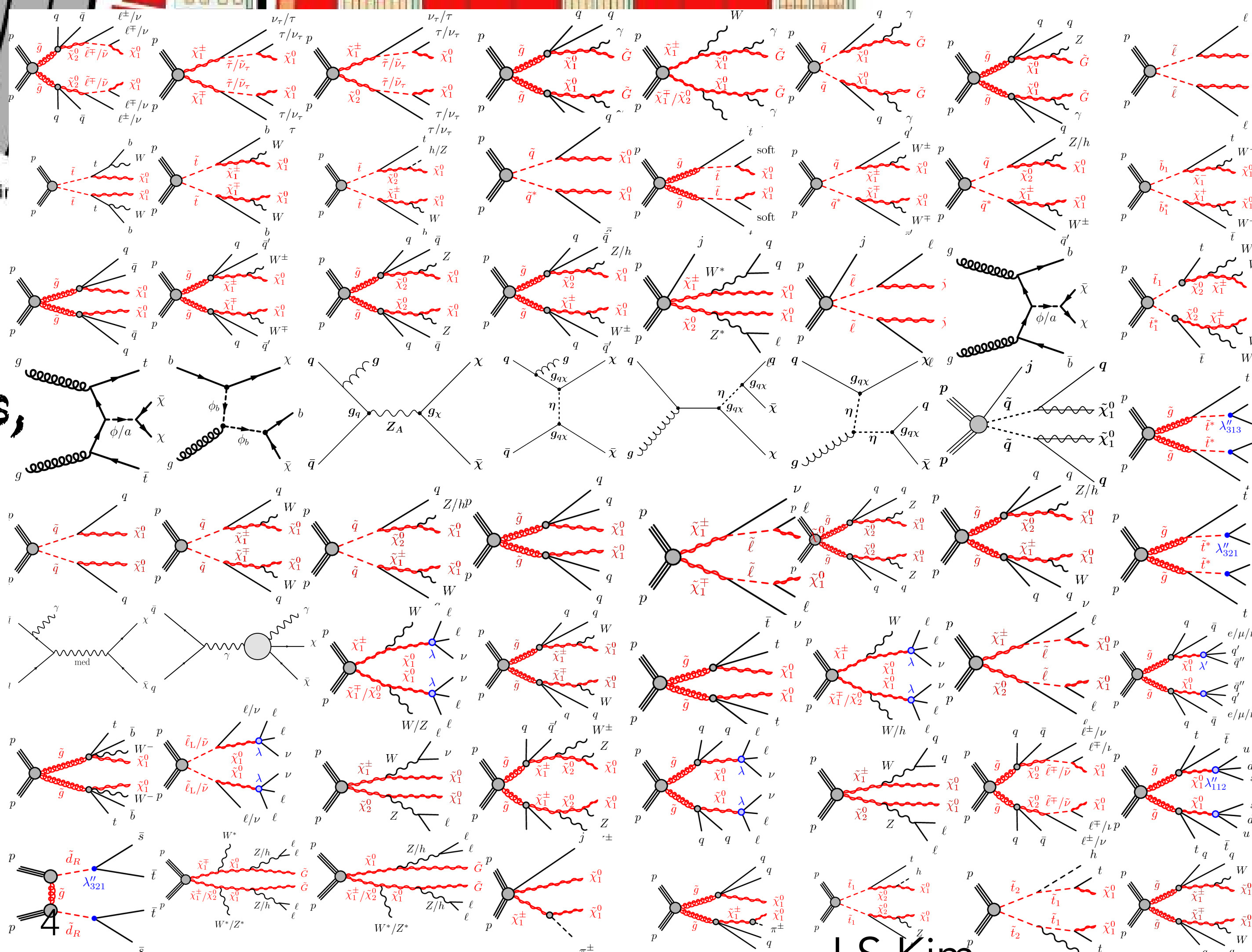


Prompt objects

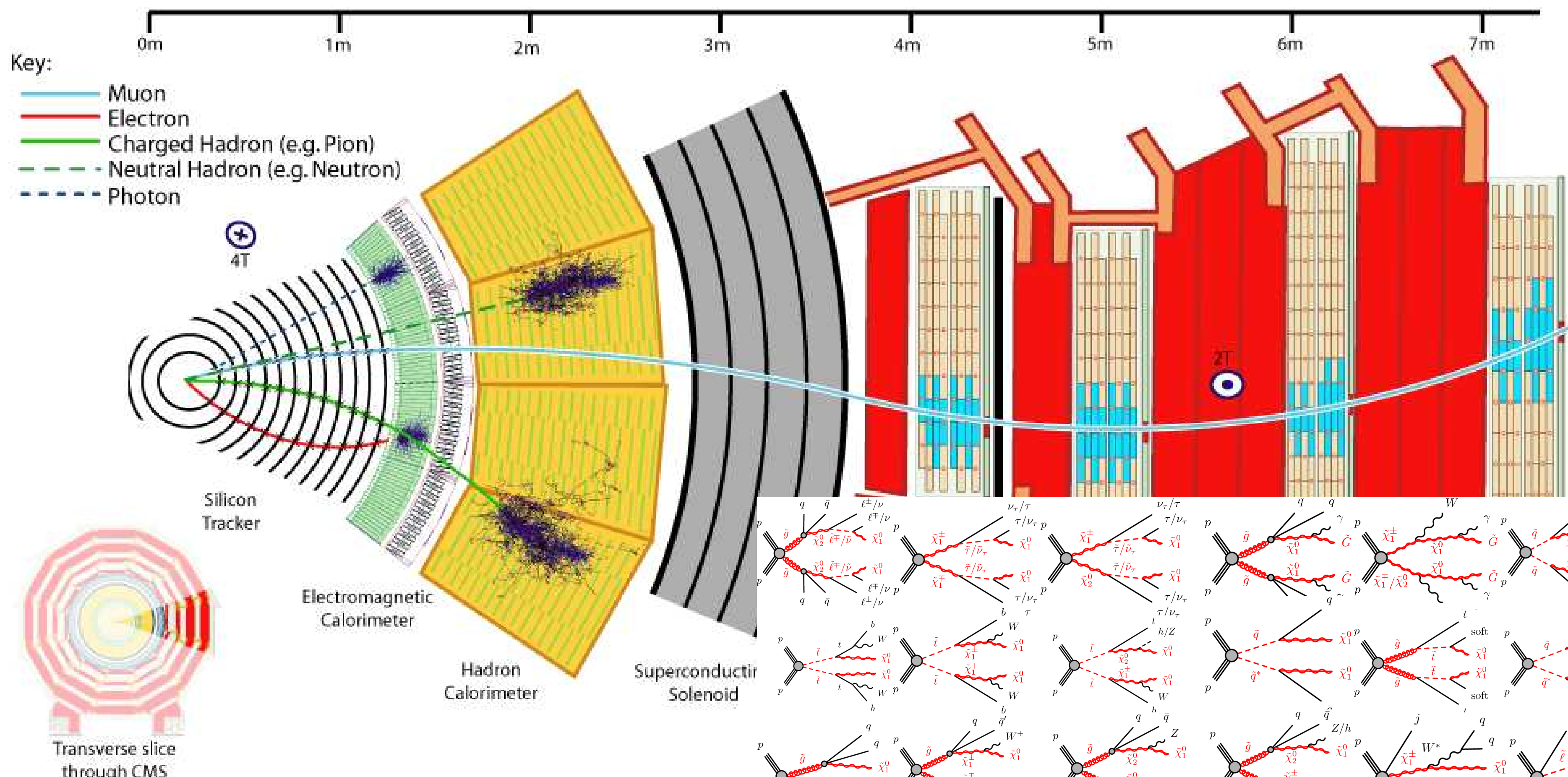


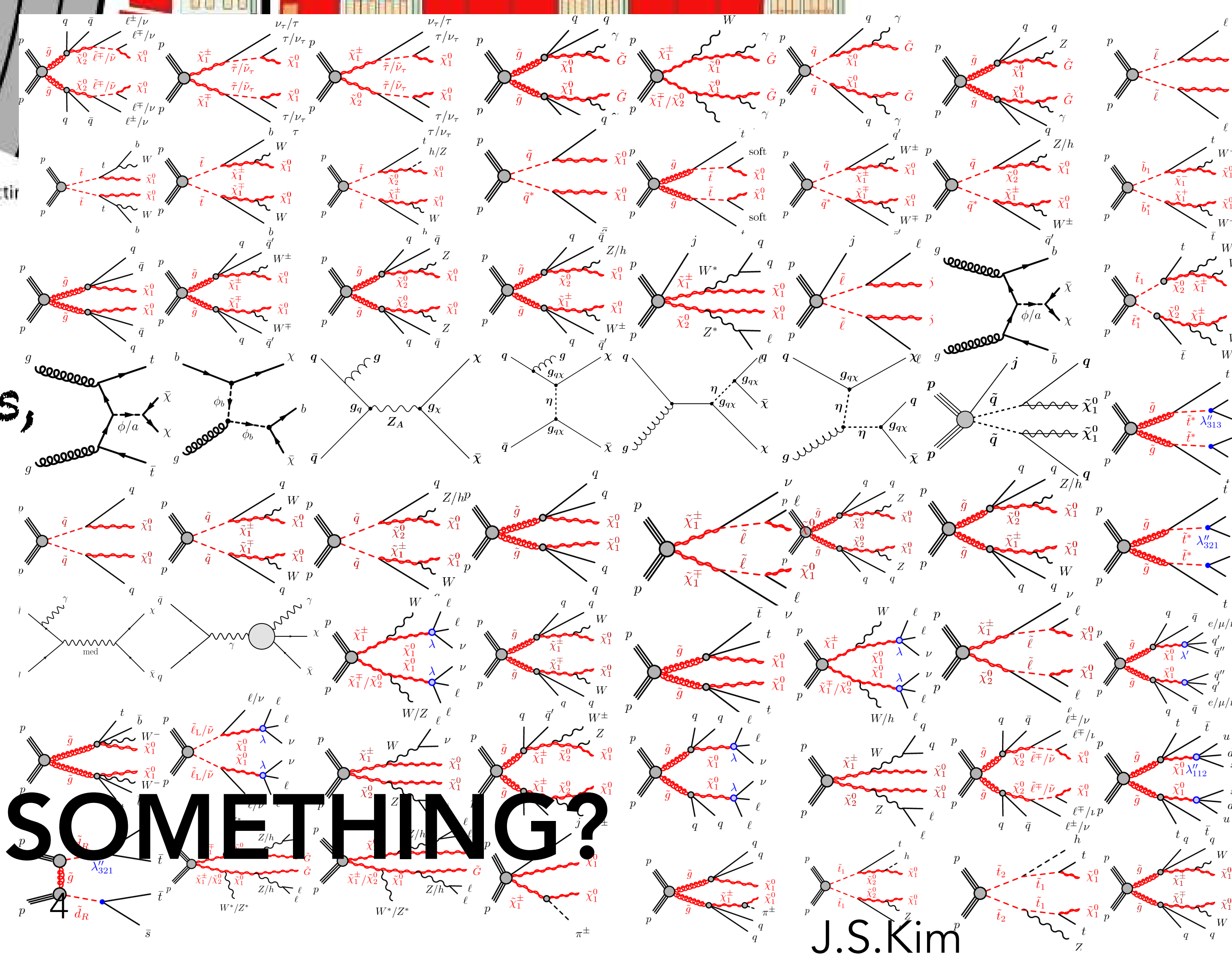


Most searches use Electrons, Muons, Photons, Jets (+HF tagging) from the collision vertex + Missing Energy

J.S.Kim

Prompt objects





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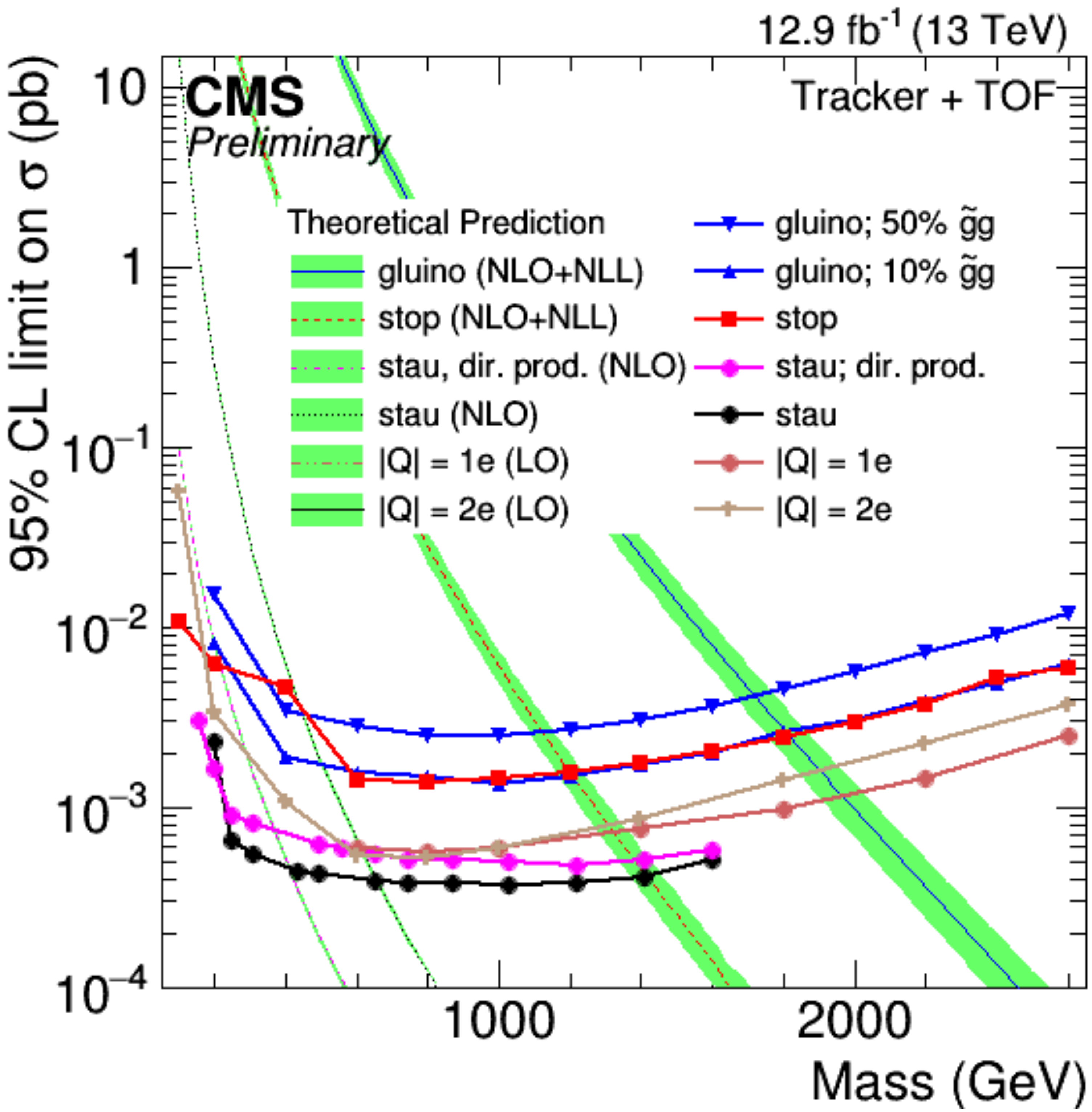
ARE WE MISSING SOMETHING?

J.S.Kim

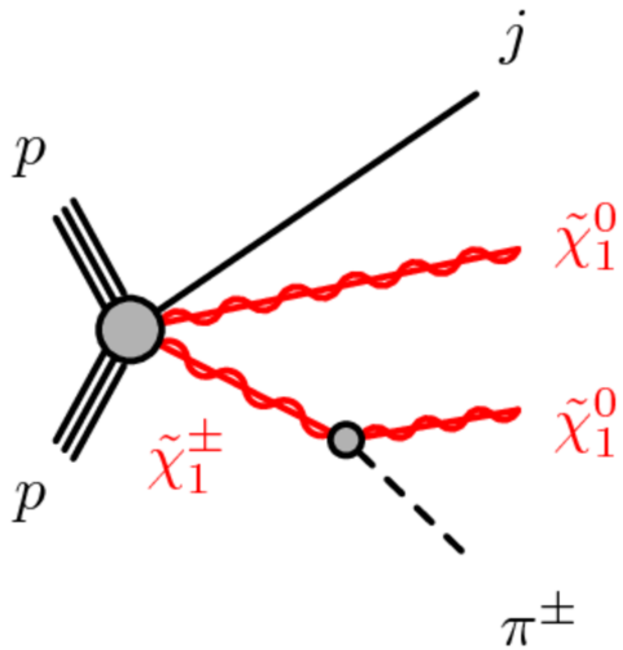
Models predicting long lived particles

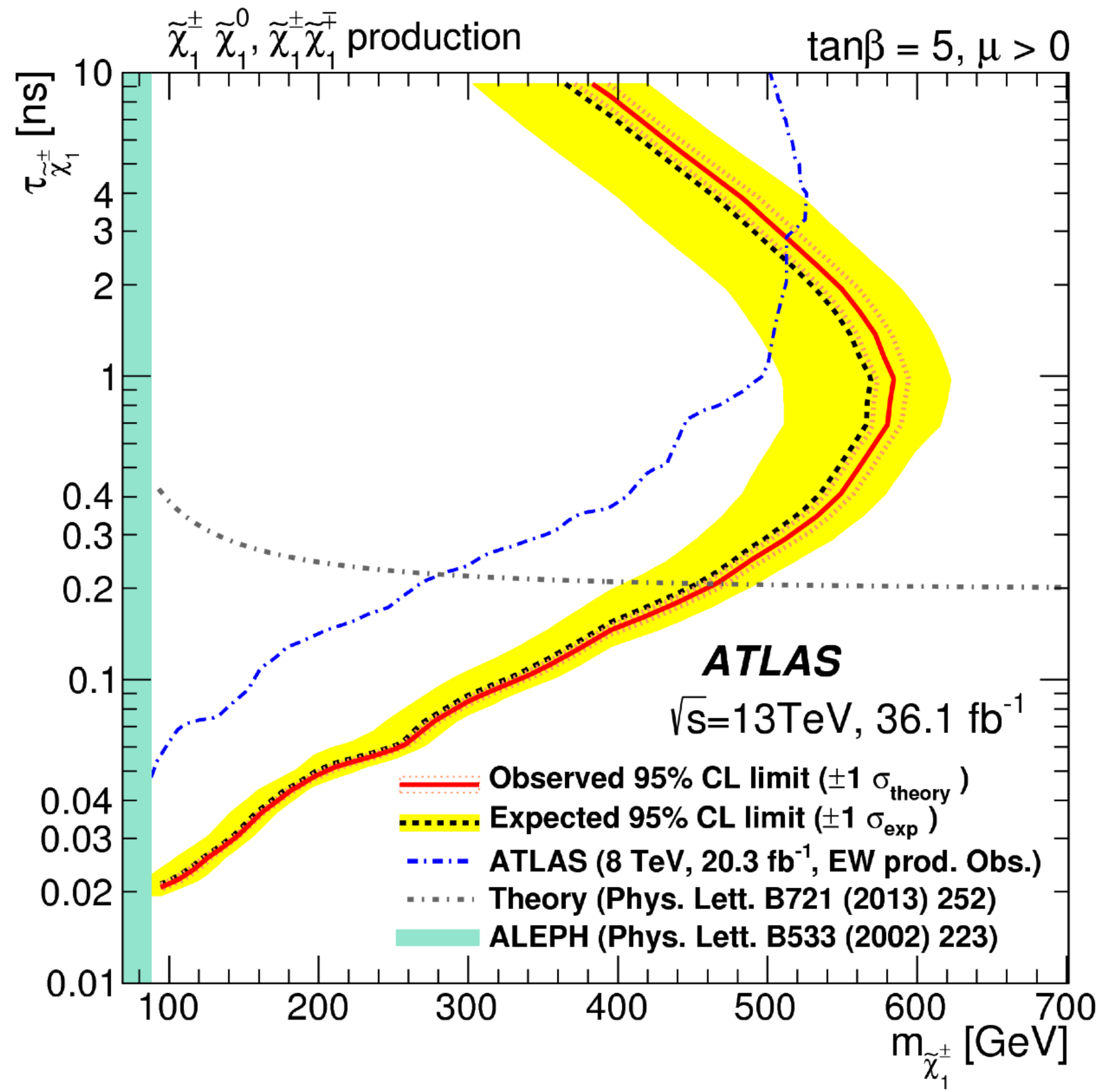
Dark Matter	SUSY (i.e. Winos, Higgsinos) Coannihilation with scalars Dark Photon Higgs Portal Freeze-in
Naturalness	Hidden valleys GMSB SUSY RPV SUSY
Neutrino Masses Flavour Anomalies	Sterile Neutrinos L-R models (Z′ & W′s) …

Charged track searches



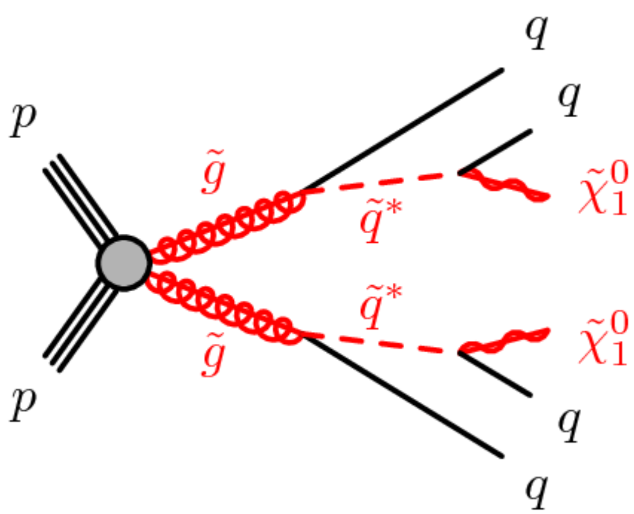
Disappearing track searches

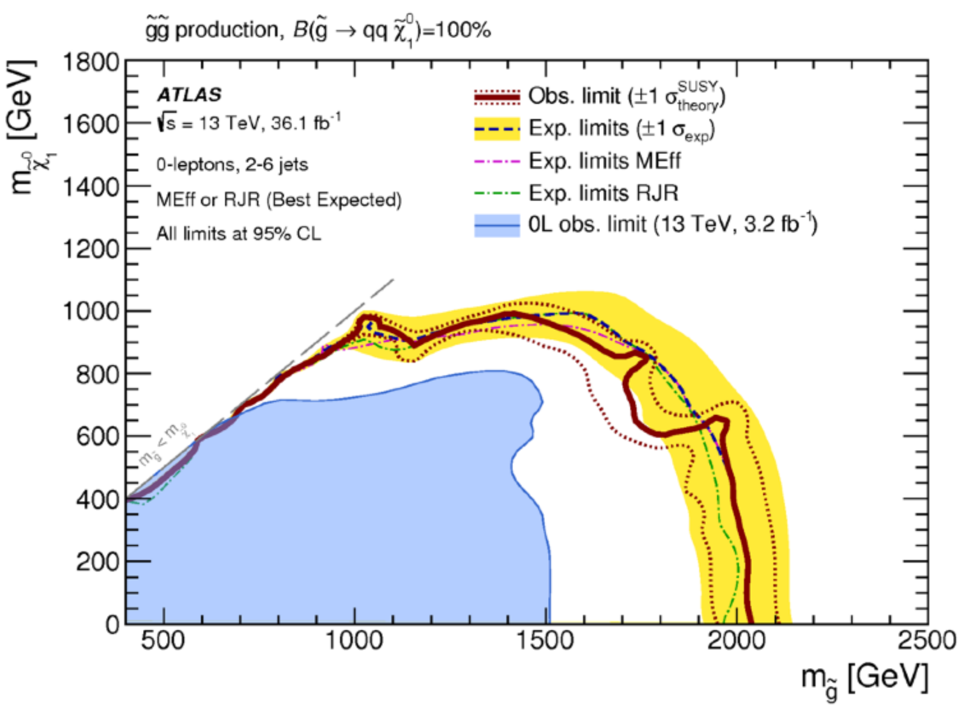


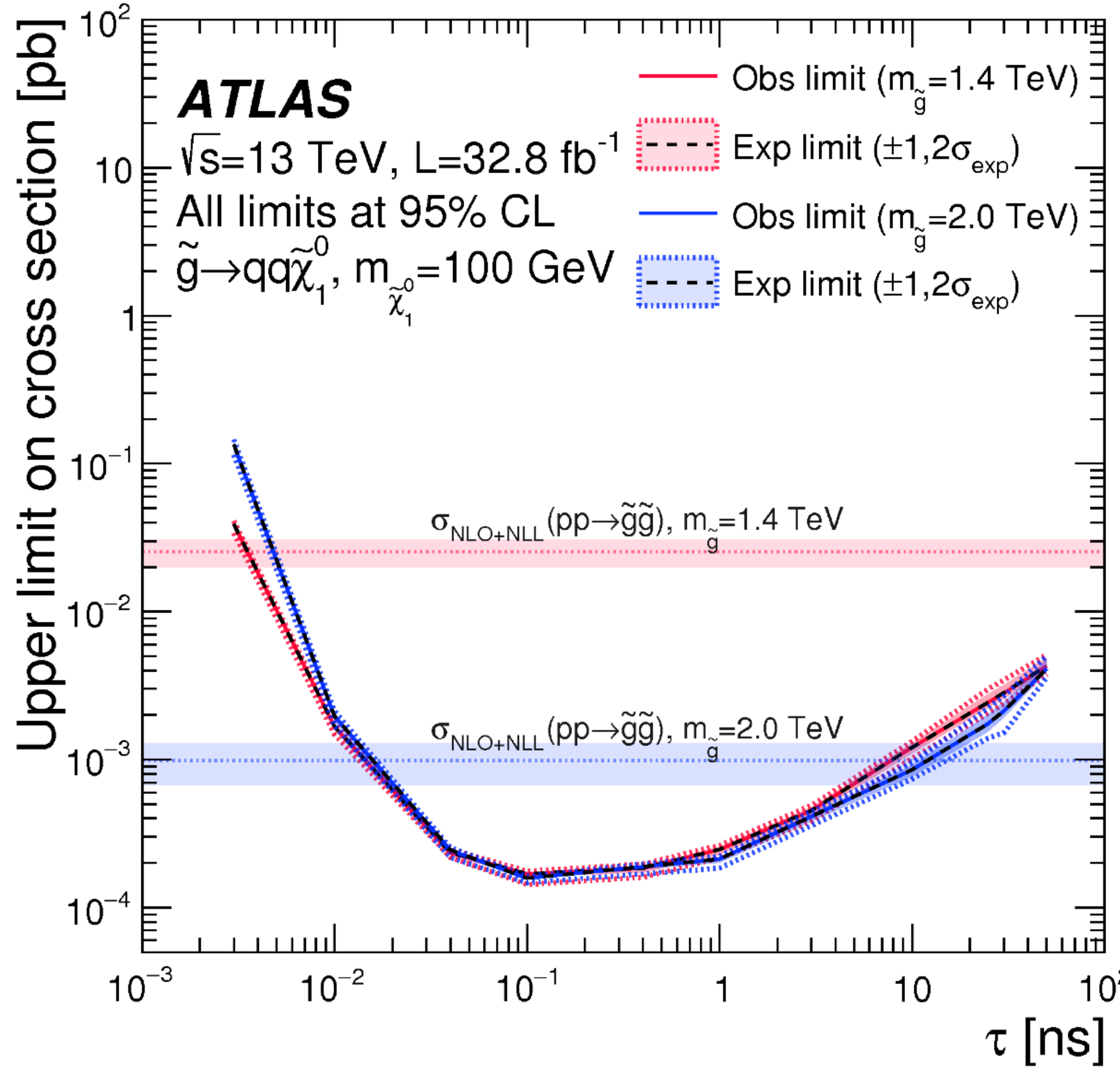


arXiv:1712.02118

Displaced Vertices

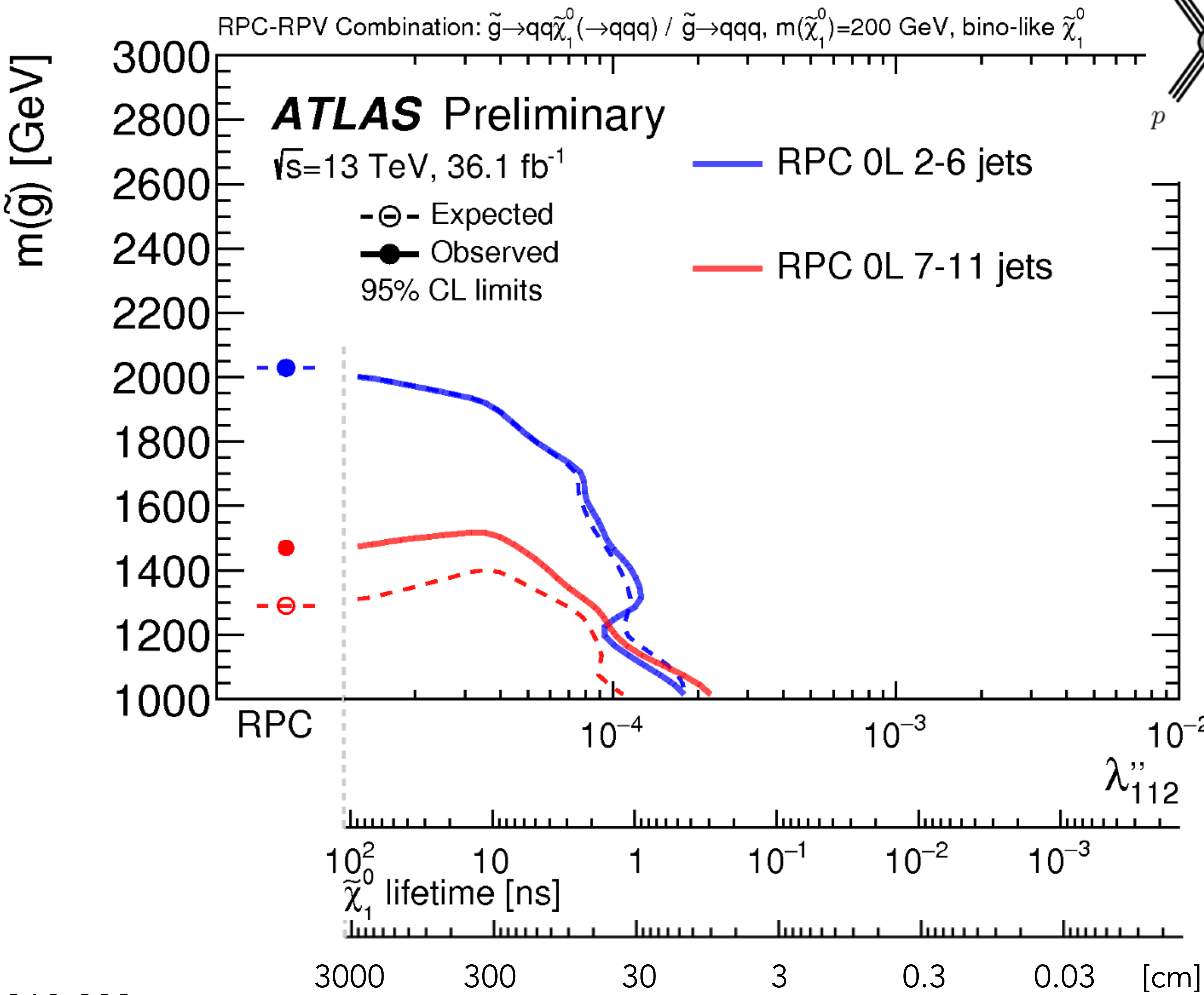


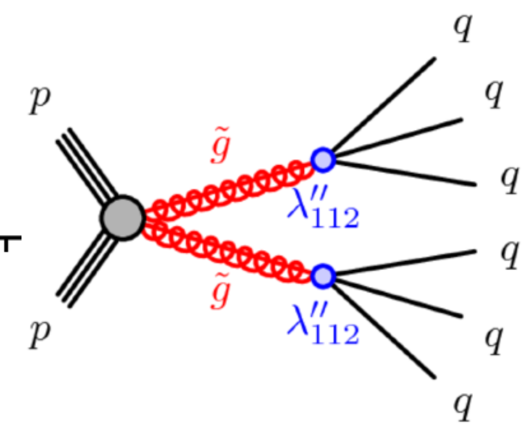




arXiv:1710.04901

Traditional searches fail for LLPs





ATLAS-CONF-2018-003

“Unexpected” cuts may restrict what we choose to see

ATLAS-CONF-2018-003

Looking at the simplest jets + MET search:

Selection GeV	RPC	$\tau = 100$ ns	$\tau = 10$ ns	$\tau = 1$ ns	$\tau = 0.1$ ns	$\tau = 0.01$ ns
DxAOD skimming	94.0	82.0	86.0	75.0	77.0	78.0
Jet/$E_{\mathrm{T}}^{\mathrm{miss}}$ cleaning	98.9	93.9	76.7	96.0	100.0	100.0
Cosmic muon cut	98.9	98.7	97.0	93.1	77.9	78.2
Lepton veto	58.7	53.9	54.7	47.8	43.3	39.3
$N_{\mathrm{jets}} \geq 4$	98.1	97.6	97.1	100.0	100.0	100.0
$\mathbf{p}_{\mathrm{T}}^{\mathrm{miss,track}} > 30$ GeV	71.7	75.0	85.3	90.6	88.5	87.5
$N_{b-\mathrm{jet}} \geq 1$	92.1	90.0	93.1	89.7	100.0	100.0
$E_{\mathrm{T}}^{\mathrm{miss}} > 250$ GeV	60.0	59.3	44.4	15.4	12.6	10.5
$\left\lvert\Delta\phi\left(\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss,track}}\right)\right\rvert < 1/3\pi$	95.2	93.8	91.7	72.5	72.4	63.6
$\left\lvert\Delta\phi\left(\mathrm{jet}^{0,1,2}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}\right)\right\rvert > 0.4$	95.0	93.3	85.5	65.5	71.4	71.4
$m_{\mathrm{jet},R=1.2}^{0} > 120$ GeV	73.7	78.6	75.5	78.9	86.7	90.0

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Already approx. 50% loss before MET cuts

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Already approx. 50% loss before MET cuts

Important to map all possible signatures to avoid the same mistakes!

Next-to-minimal DM

Dark Matter makes up ~20% of our universe; an EW scale particle seems to be a good fit

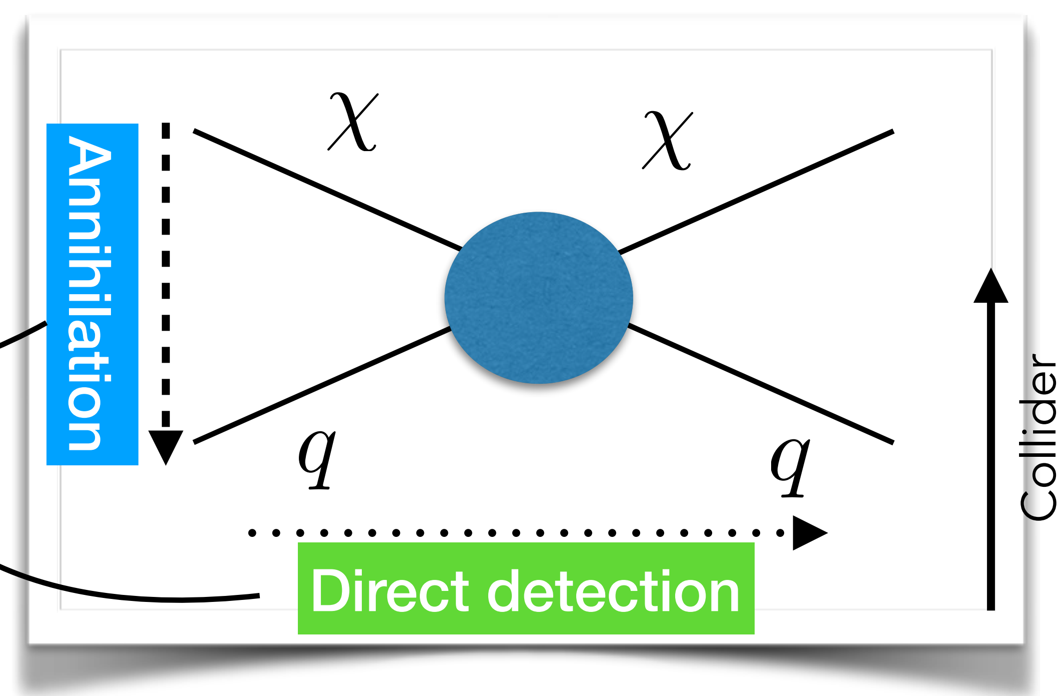
$$\Omega h^2 \sim 0.1 \Rightarrow \langle \sigma v \rangle \sim 1 \text{ pb} \cdot c$$

$$\Rightarrow m_\chi \sim O(10^2 - 10^3) \text{ GeV}; g \sim g_{\text{EW}}$$

What are minimal EW possibilities?

Cirelli et al; arXiv:hep-ph/0512090

- SU(2) doublet fermion (a.k.a. Higgsino) ⇒ ~ 1.2 TeV
- SU(2) triplet fermion (a.k.a Wino) ⇒ 2.7 TeV
- SU(2) 5-plet fermion (MDM) ⇒ ~10 TeV
- SU(2) 7-plet scalar (MDM) ⇒ ~10 TeV



100 TeV collider?

What about next-to-minimal scenarios?

- One SU(2) x U(1) singlet χ + one SU(2) N-plet ψ
- $\mathbb{Z}_2$ stabilises the lightest state

$$\mathcal{L}_{\rm DM} = i\,\psi^\dagger\overline{\sigma}^\mu D_\mu\psi + i\,\chi^\dagger\overline{\sigma}^\mu\partial_\mu\chi - \left(\frac{1}{2}M\psi\psi + \frac{1}{2}m\chi\chi + \text{ h.c.}\right) + \mathcal{L}_{\rm quartic} + \mathcal{L}_{\rm mix}$$

$$\mathcal{L}_{\rm quartic} = \frac{1}{2}\frac{\kappa}{\Lambda}\phi^\dagger\phi\chi\chi + \frac{1}{2}\frac{\kappa'}{\Lambda}\phi^\dagger\phi\psi^A\psi^A$$

Strong limits from DD

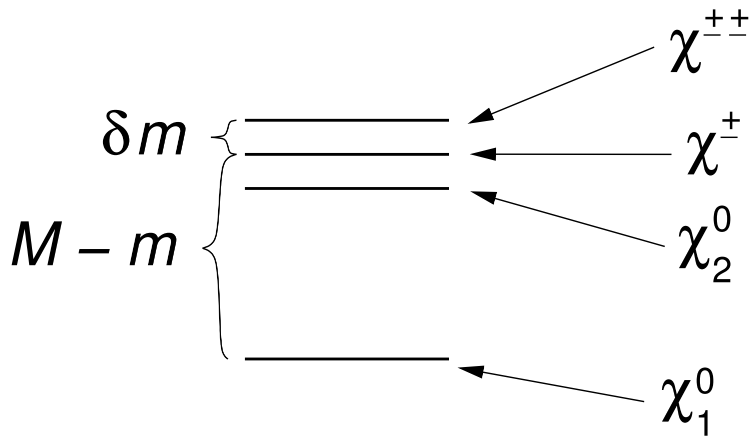
N=3

$$\mathcal{L}_{\rm mix} = \frac{\lambda}{\Lambda}\phi^\dagger\tau^a\phi\;\psi^a\chi + \text{ h.c.} \quad \longrightarrow \quad \theta \approx \frac{\sqrt{2}\lambda v^2}{\Lambda(M-m)}$$

N=5

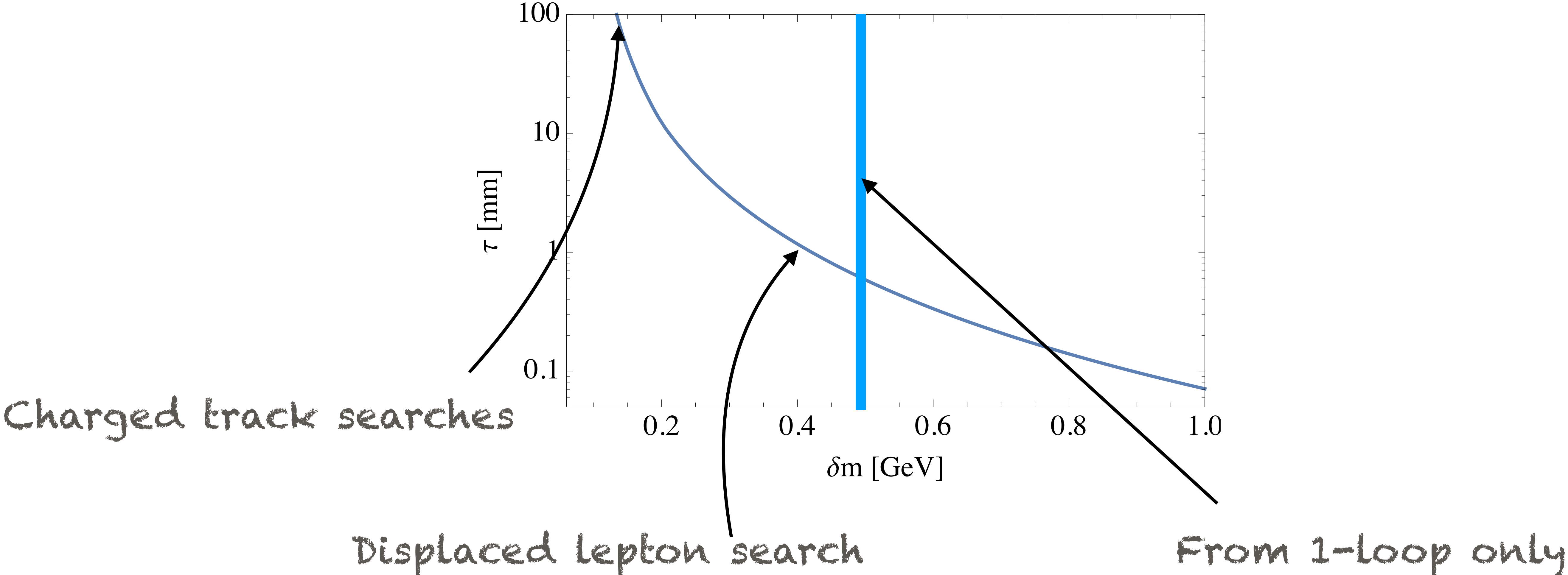
$$\mathcal{L}_{\rm mix} = \frac{\lambda}{\Lambda^3}\;C^{j\ell}_{A\,ik}\;\phi^{\dagger i}\phi_j\phi^{\dagger k}\phi_\ell\psi^A\chi + \text{ h.c.} \quad \longrightarrow \quad \theta \approx \sqrt{\frac{2}{3}}\frac{\lambda v^4}{\Lambda^3(M-m)}\,.$$

Collider searches: Quintuplet model

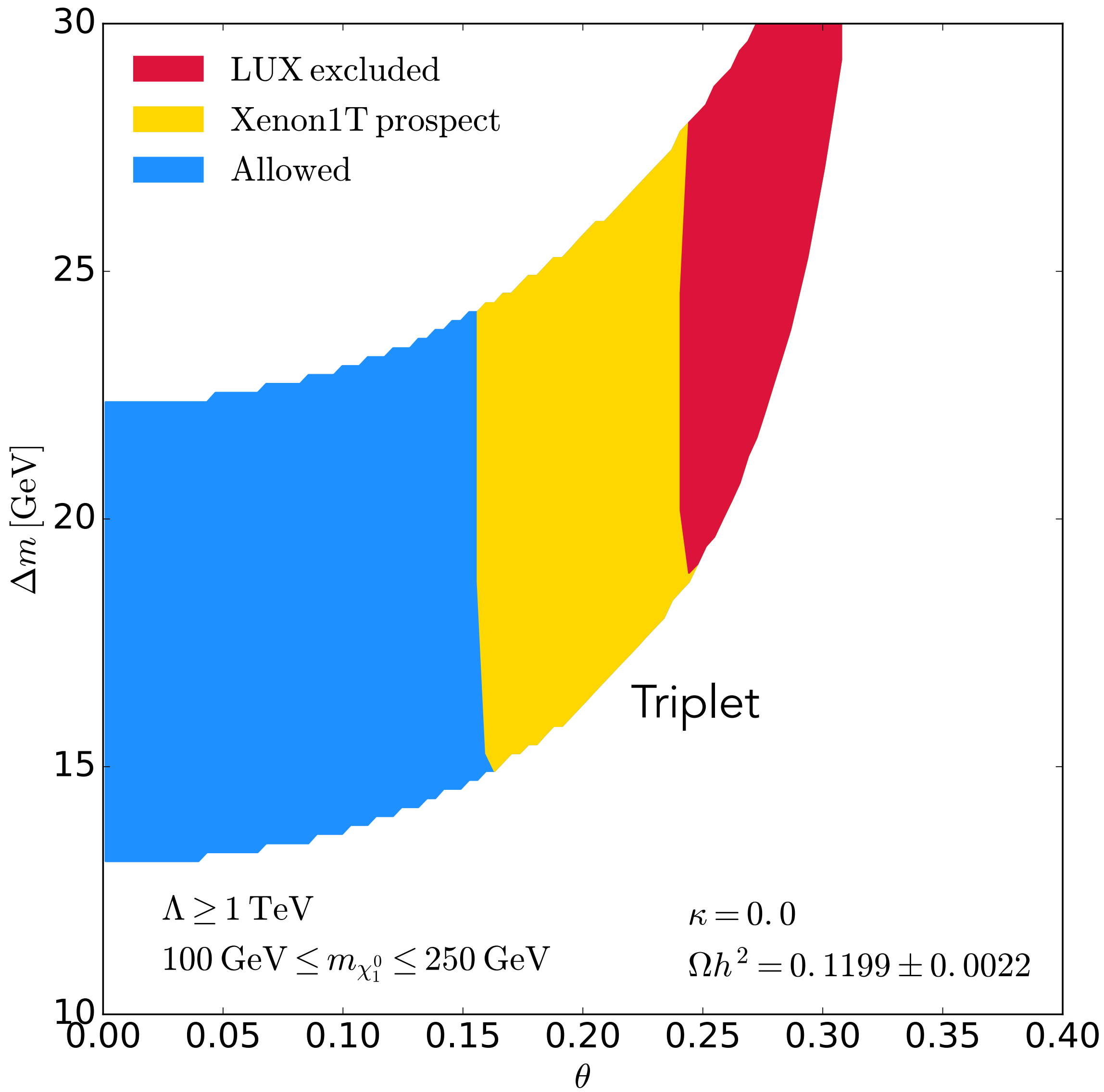


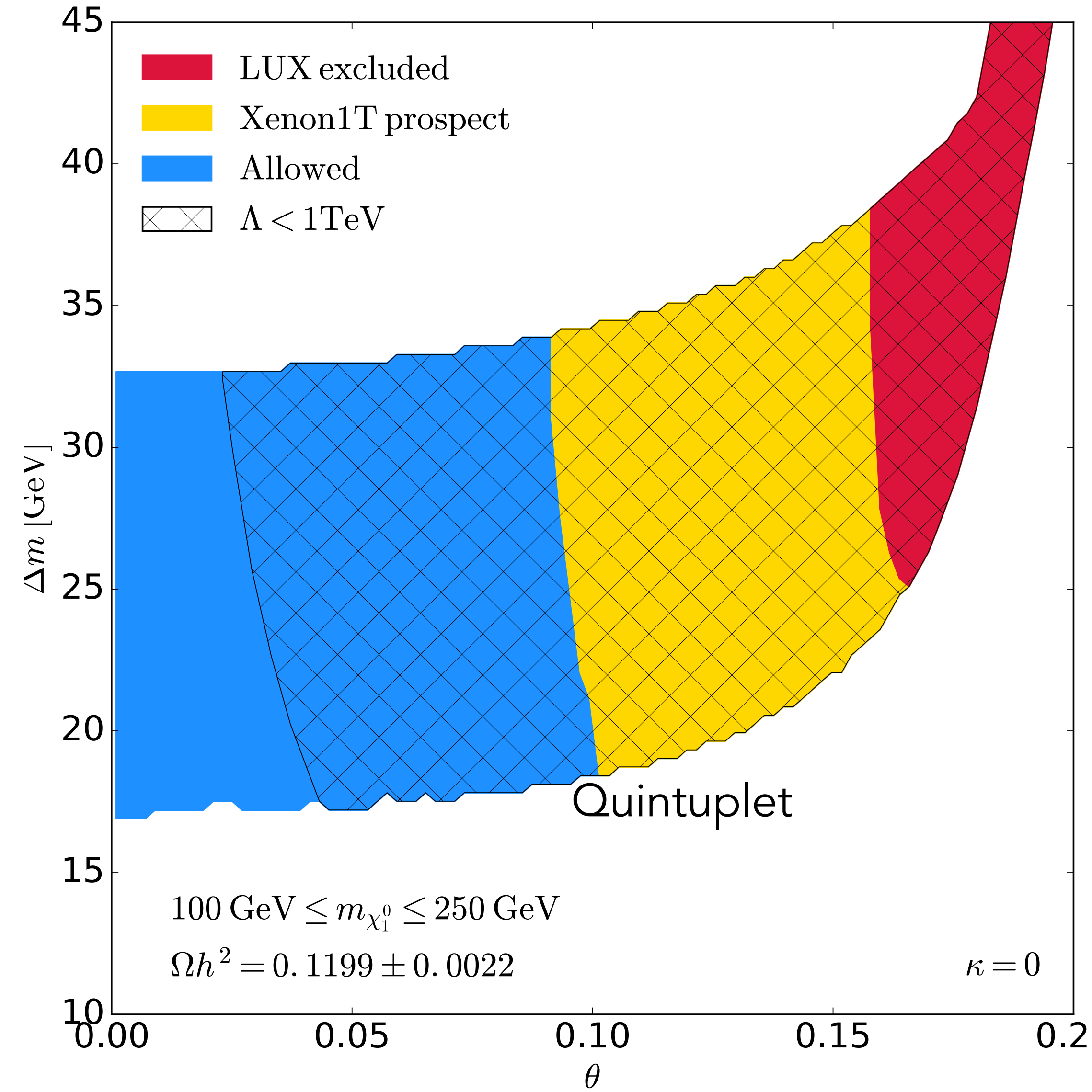
$$\chi^{++} \to \chi^{+}\pi^{+}$$
$$\chi^{+} \to \chi_1^0 W^* \to \ell\nu\chi_1^0$$
$$\chi_2^0 \to \chi_1^0 h^* \to b\bar{b}\chi_1^0$$

Large lifetime for the doubly charged partner



Direct Detection constraints

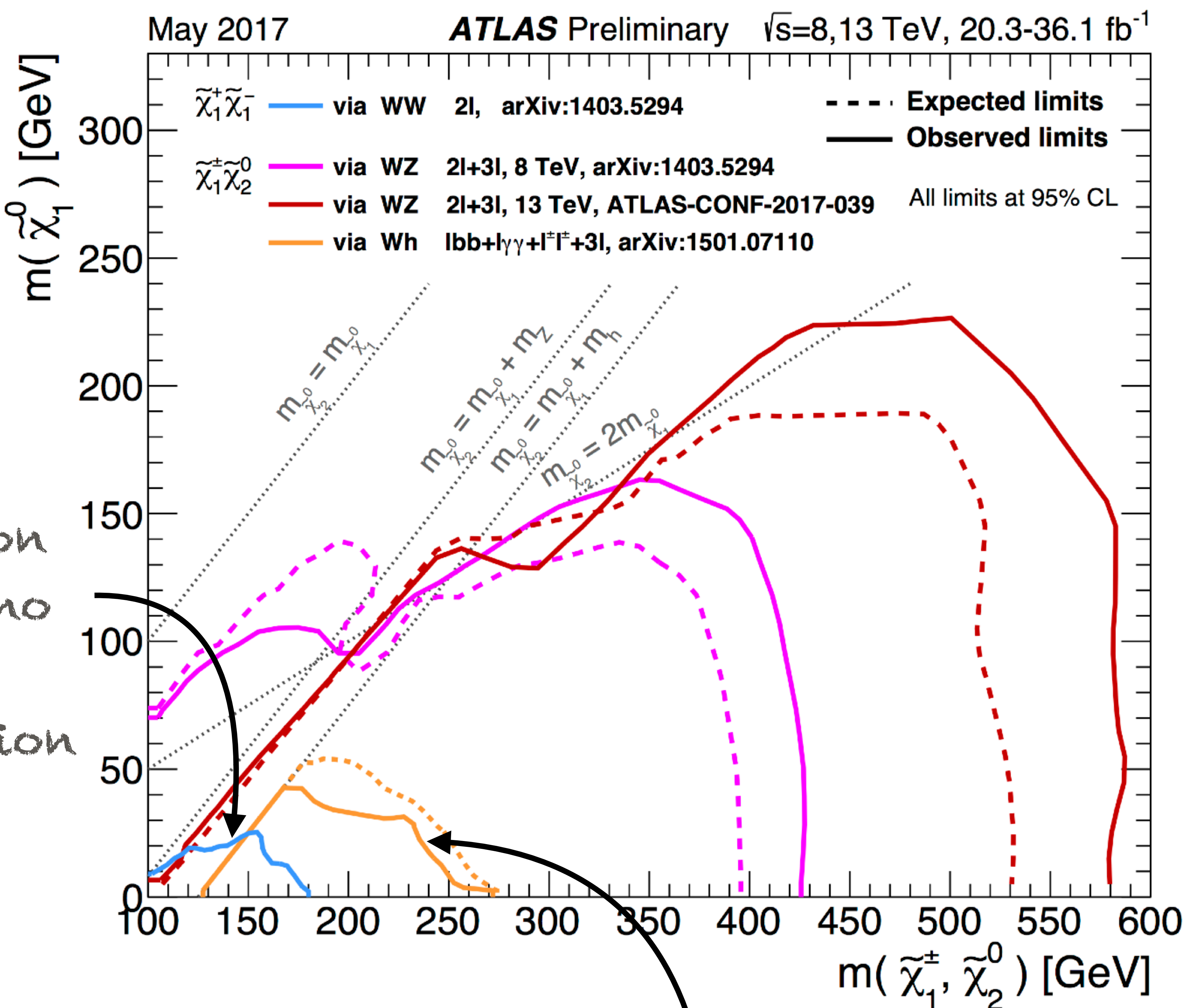




- Look at parameters that gives right relic density
- Low mixing angle gives low DD cross section; however, not a problem at the LHC because production is primarily Drell-Yan!

Brümmer et al; arXiv:1703.00370
Brümmer, Bharucha, Desai; arXiv:1804.02357

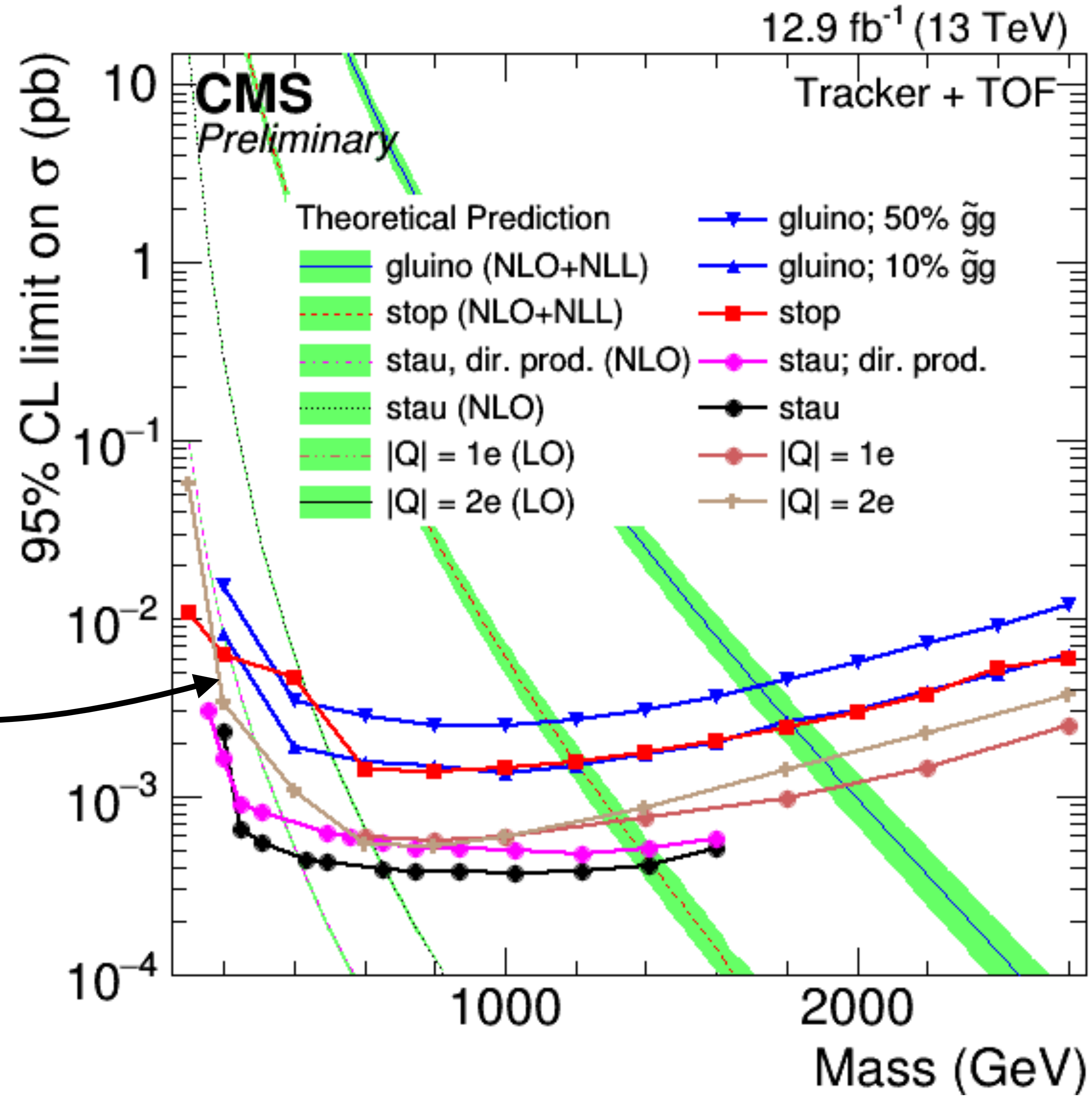
Prompt search limits: SUSY searches



Limit on Chargino pair production

LHC limit on WH final state; not stronger than displaced leptons

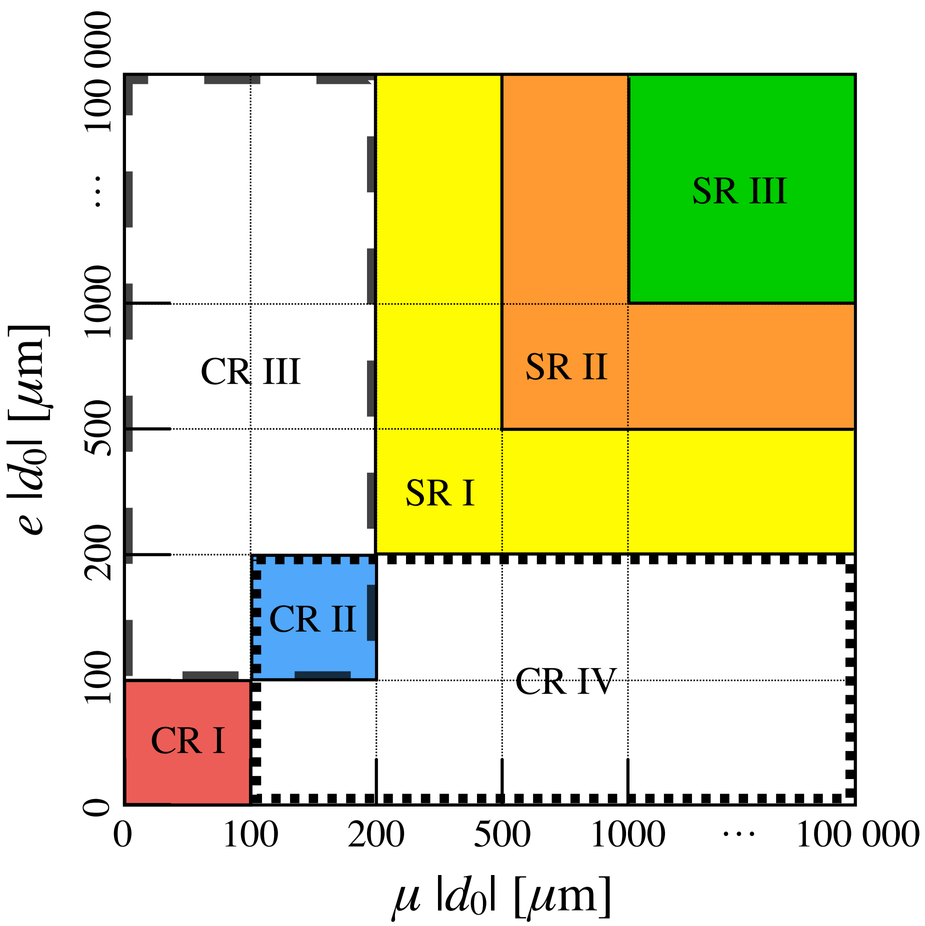
Other limits: charged track searches



Doubly charged

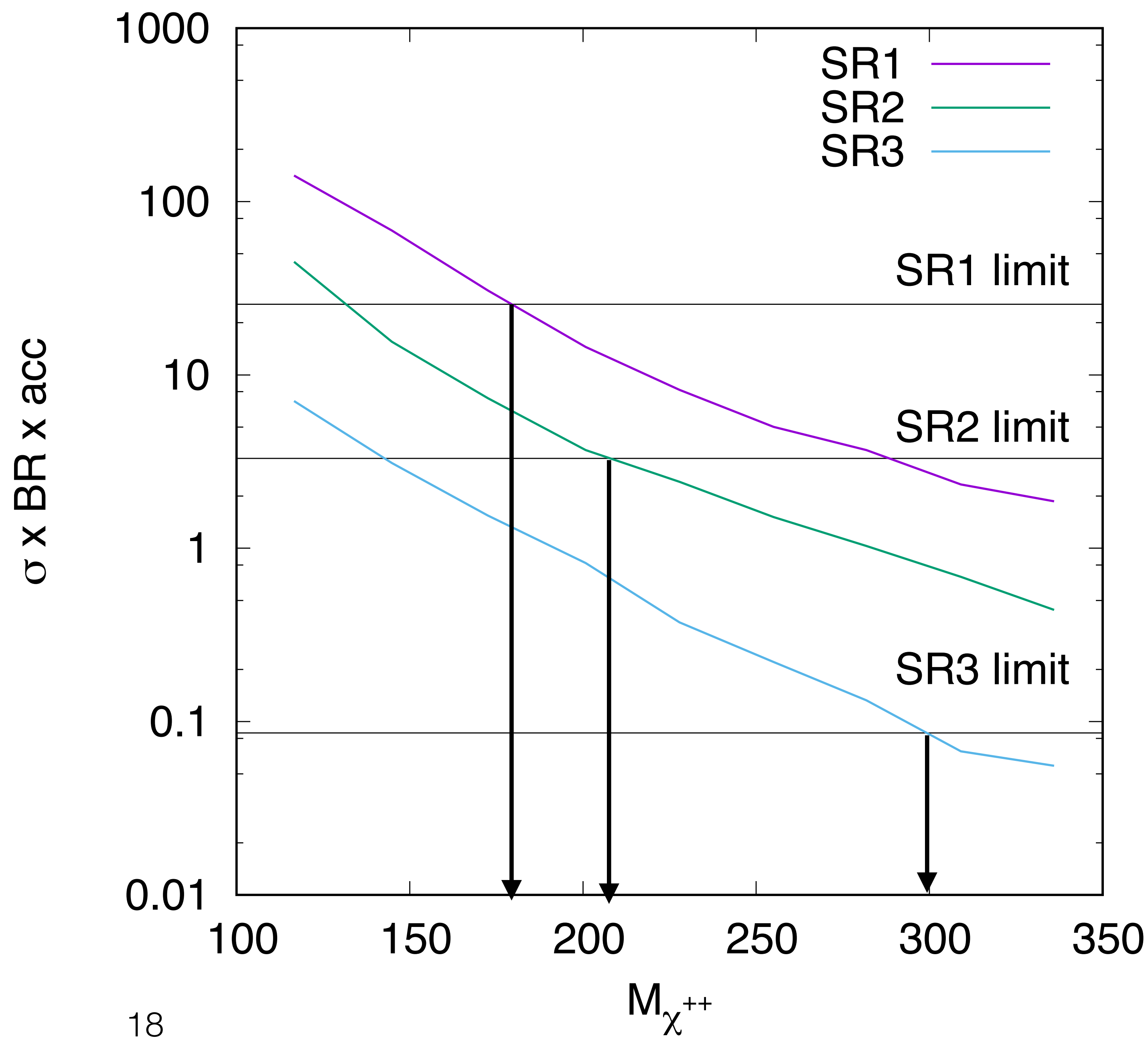
Rule out long-lived region i.e. when mass difference is smaller than pion mass

The CMS displaced lepton search



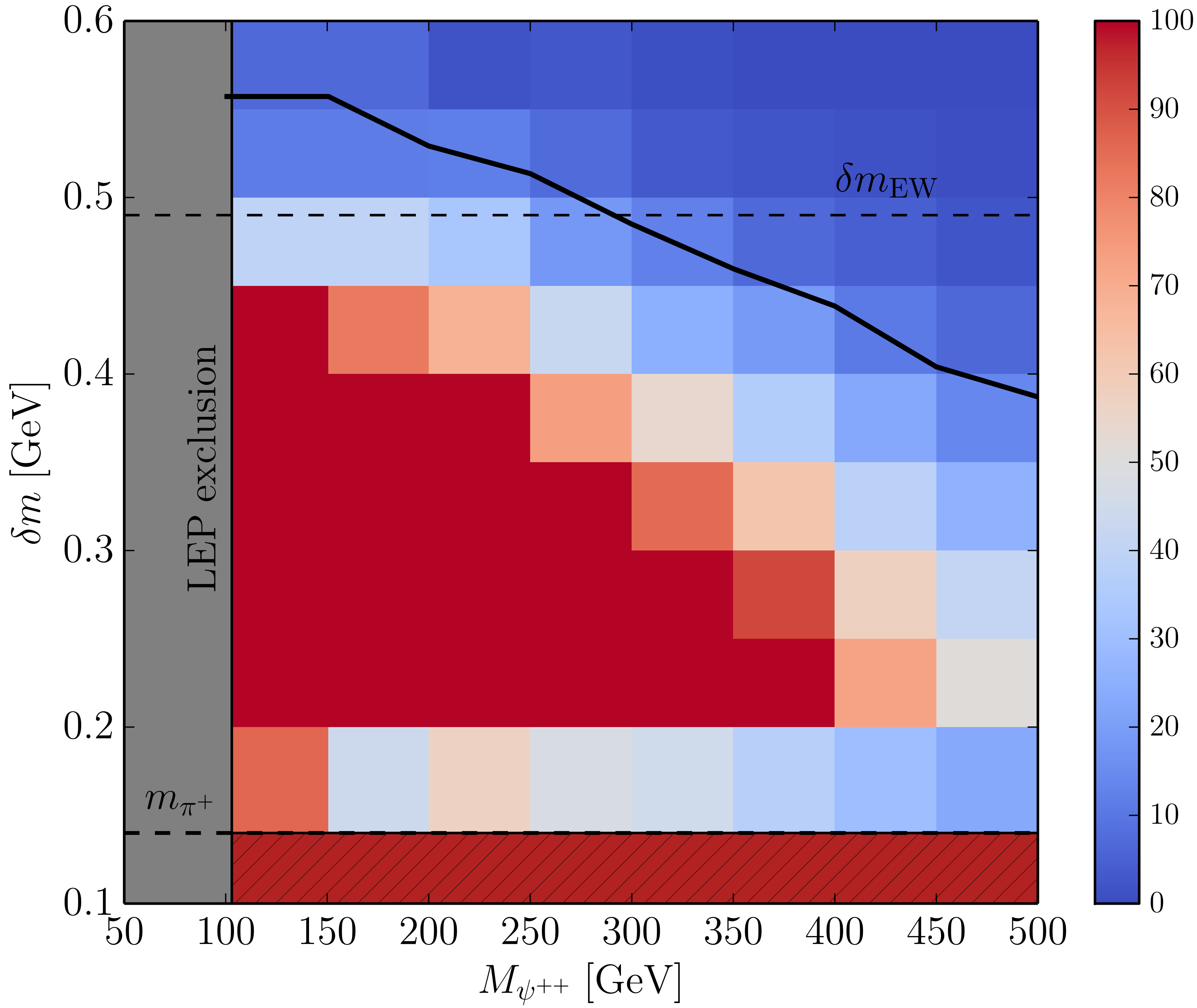
Validation

Lifetime	1 mm	10 mm	100 mm
SR1	34.4 (30 ± 5)	28.3 (35 ± 7)	4.83 (4 ± 1)
SR2	8.76 (6.5 ± 1)	24.6 (30 ± 5)	5.73 (5 ± 1)
SR3	1.69 (1.3 ± 0.3)	53.6 (51 ± 10)	24.6 (26 ± 5)



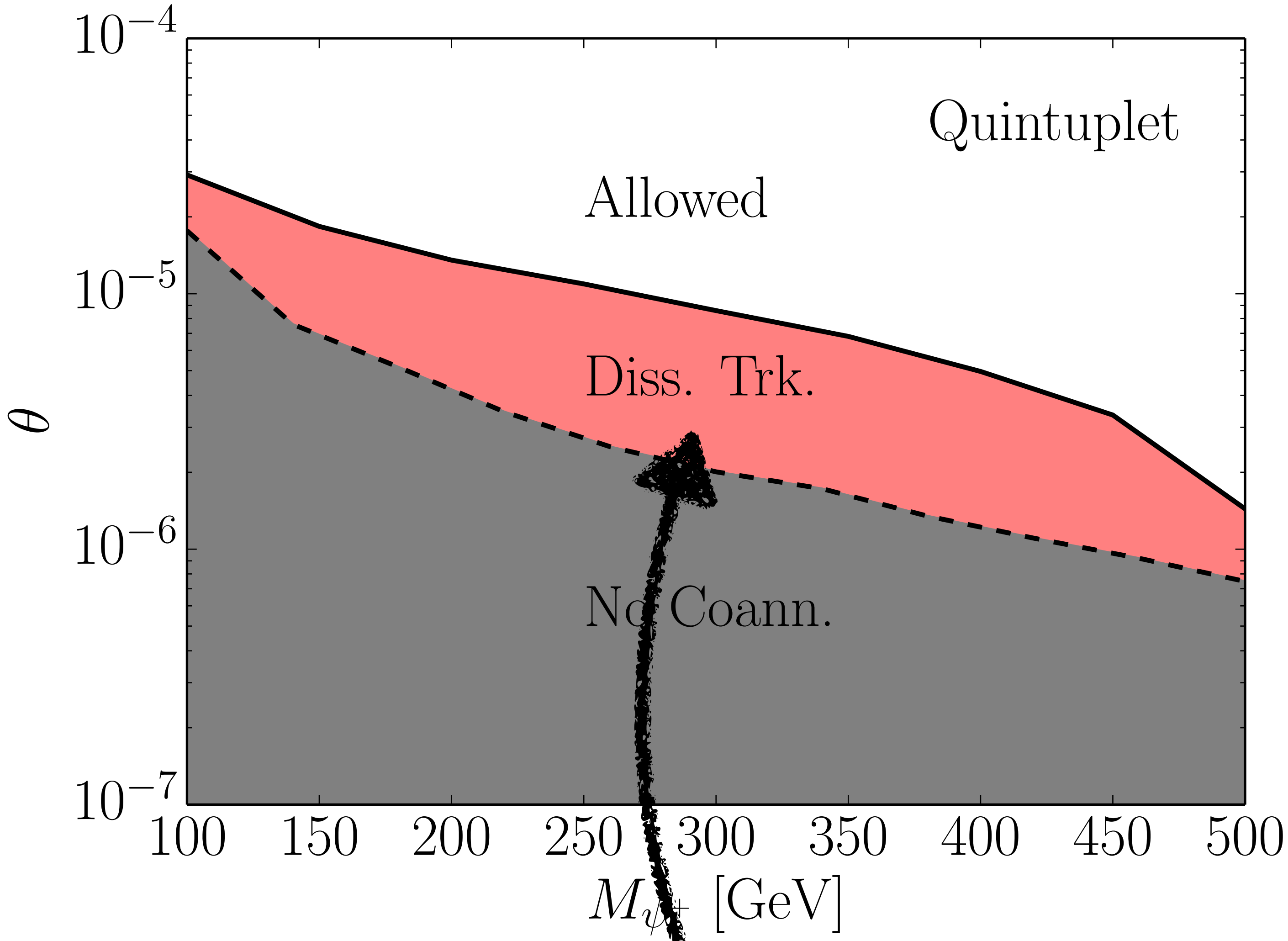
arXiv:1409.4789

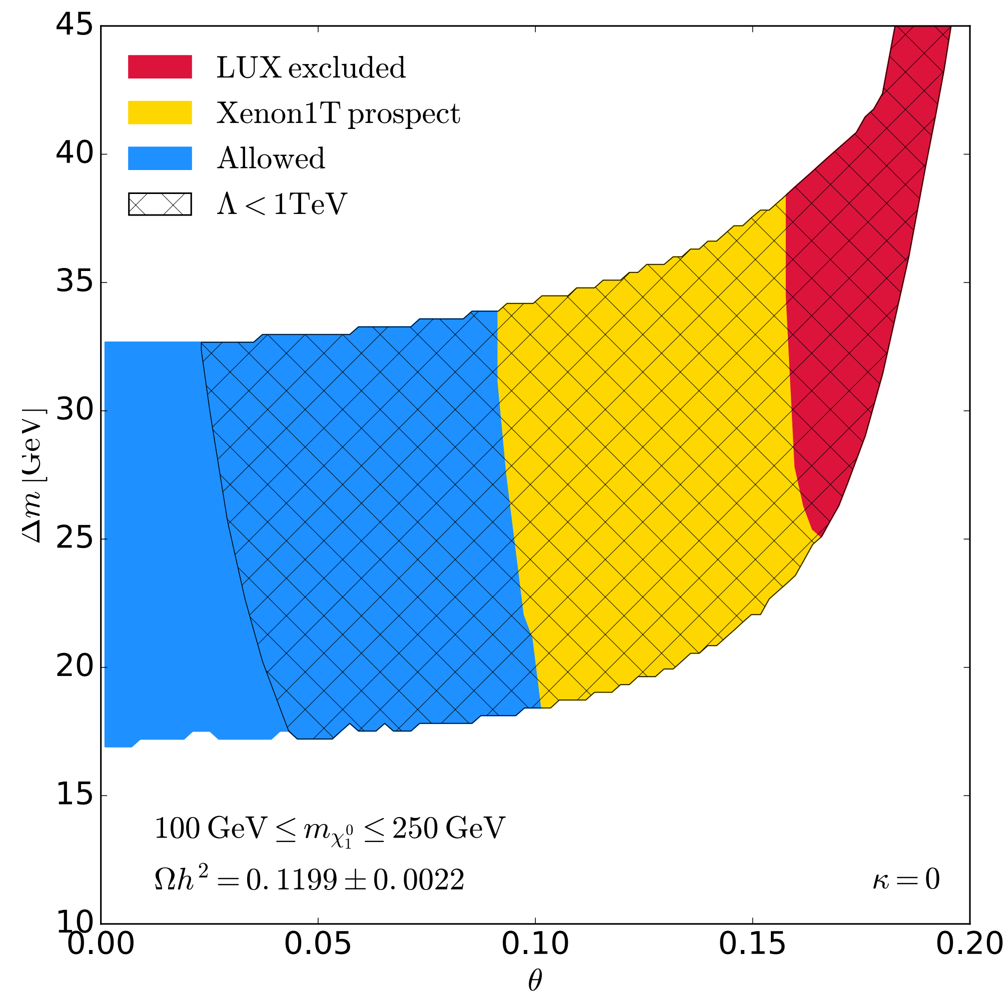
Combination of displaced lepton and charged tracks



Brümmer, Bharucha, Desai; arXiv:1804.02357

Limits on mixing angle

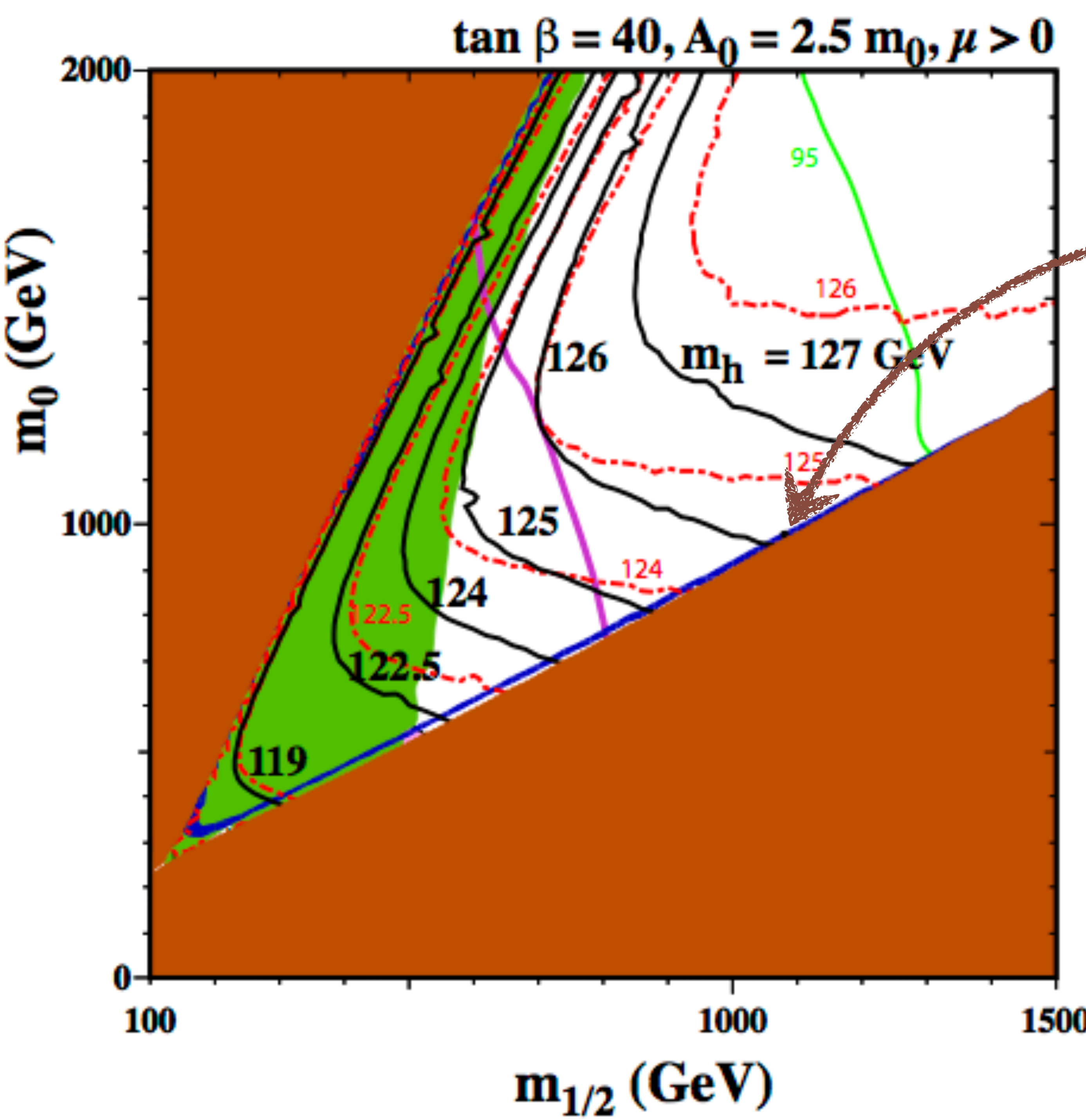




Provides a complementary lower limit on mixing

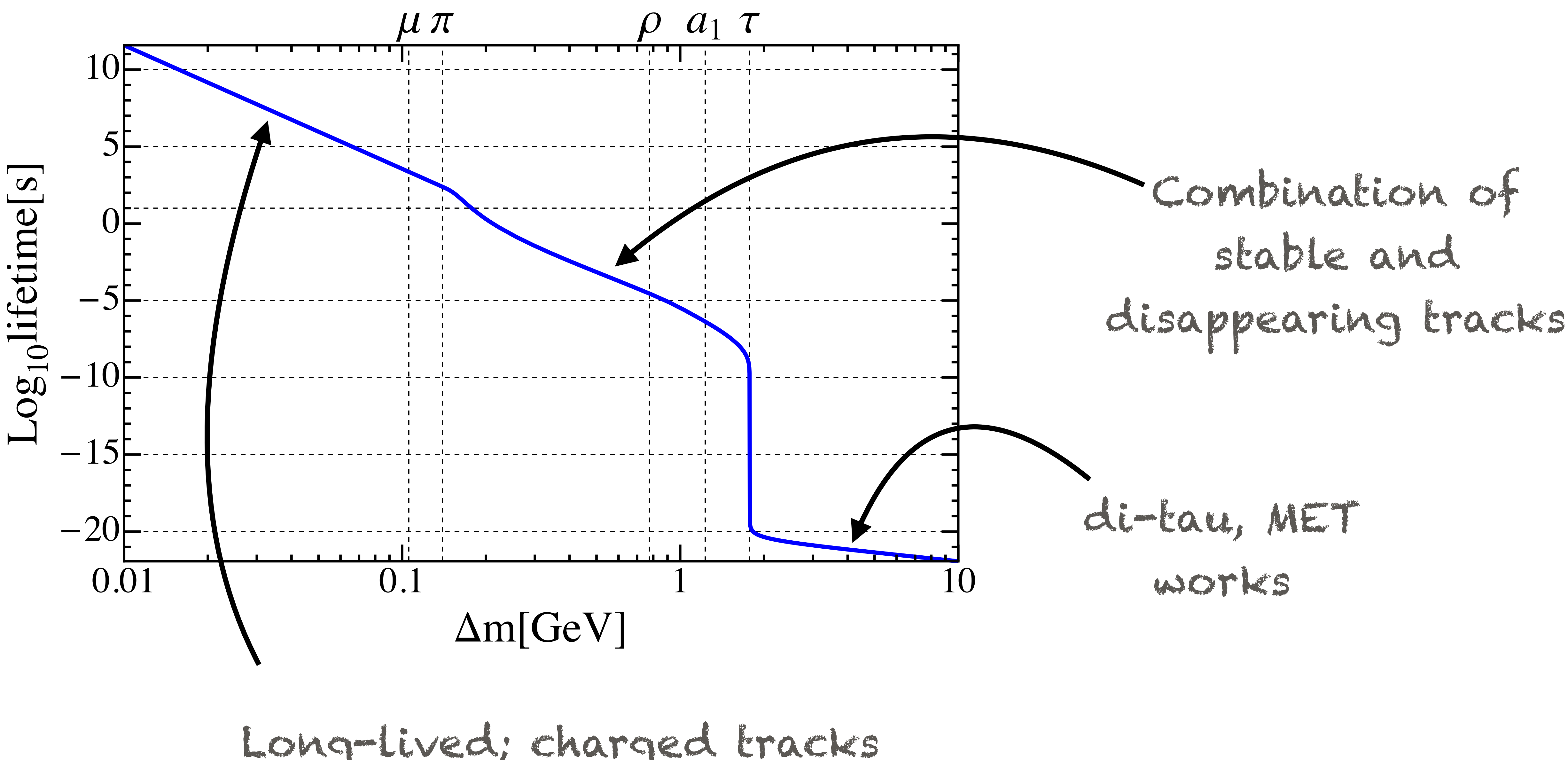
Stau Co-annihilation

Stau Co-annihilation strip



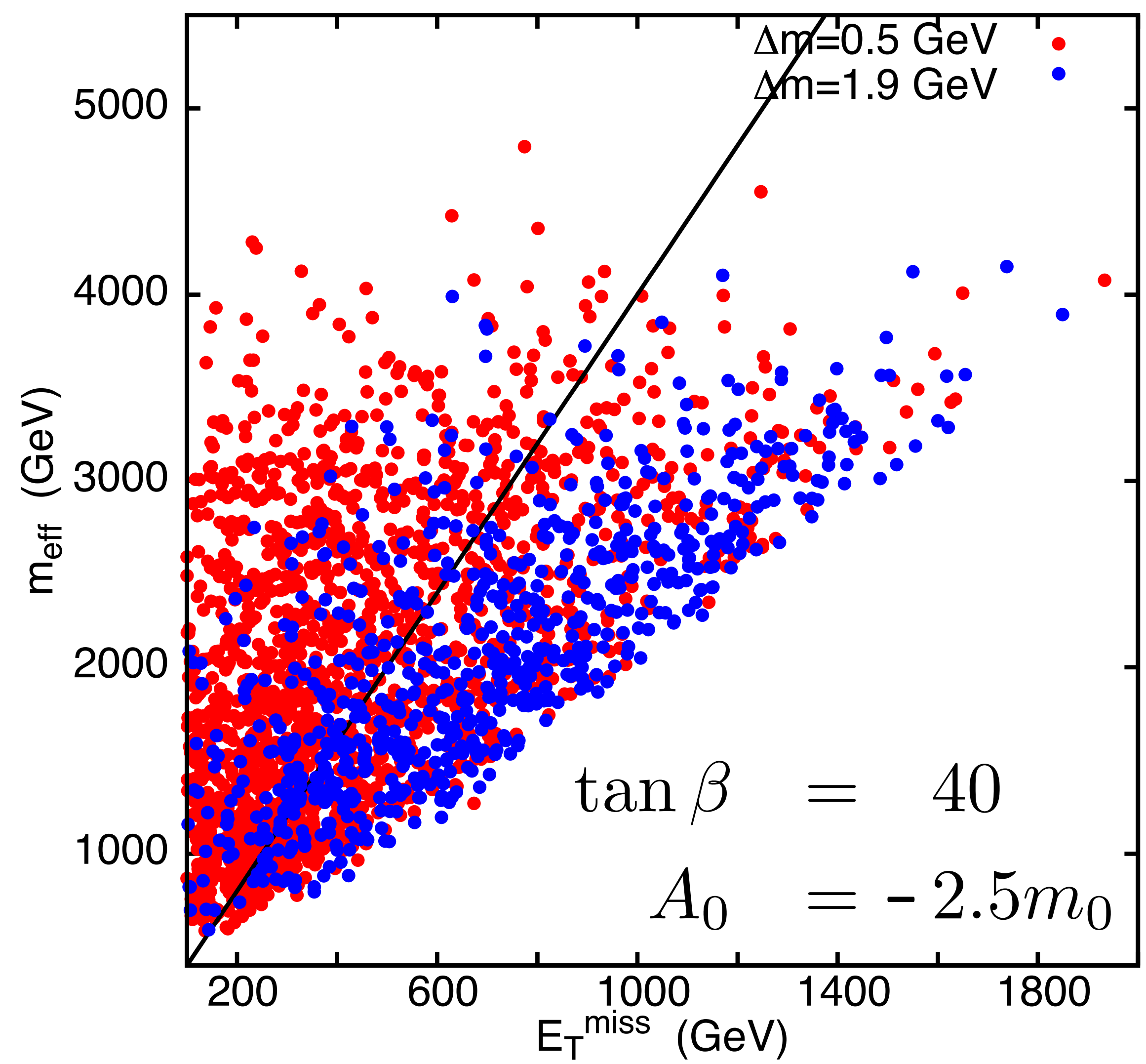
Compressed stau and neutralino

Lifetime of the stau

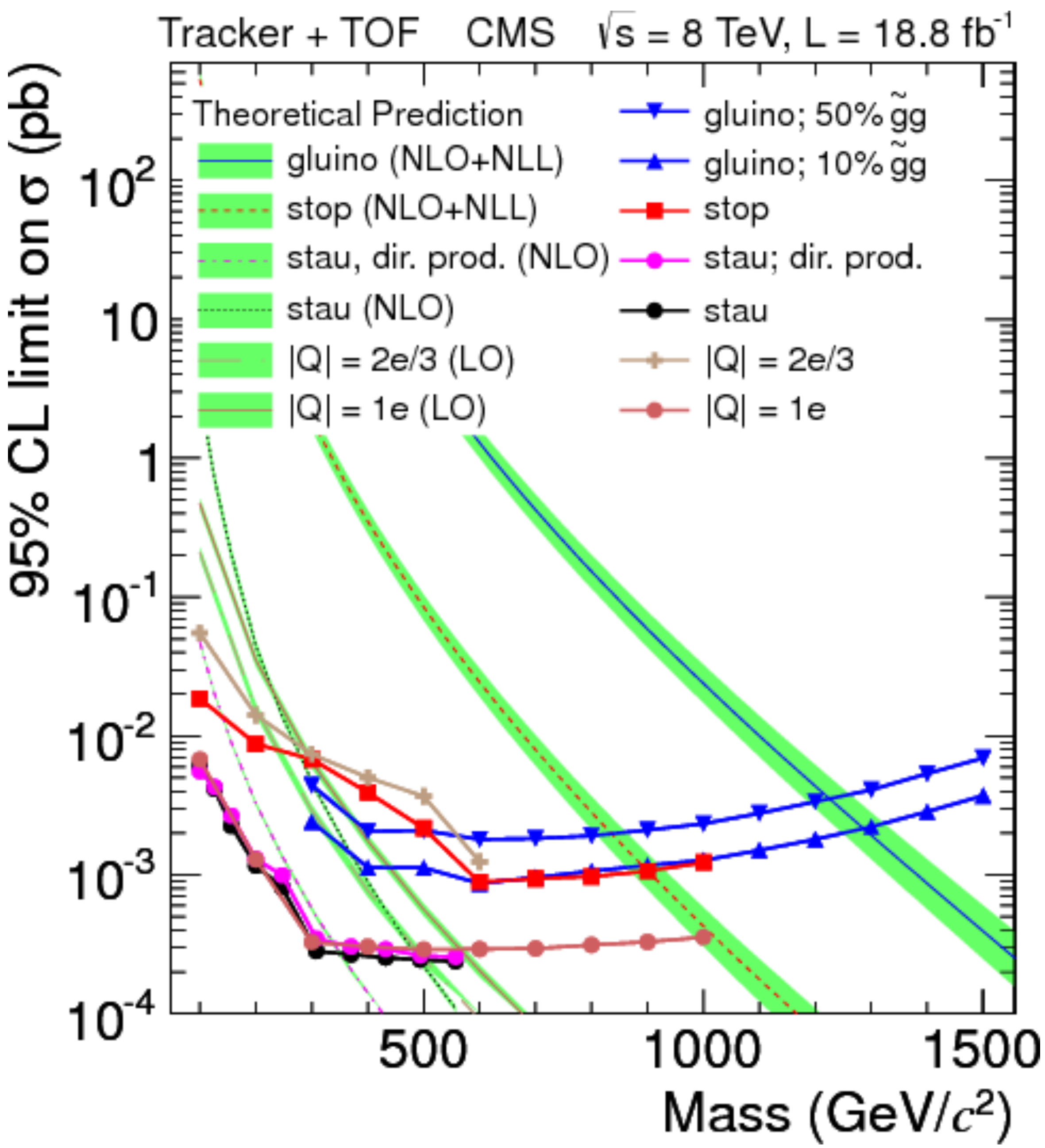


Not enough missing energy!

Requirement	Signal Region	
	2jW	**3j**
$E_{\mathrm{T}}^{\mathrm{miss}}$[GeV] $>$	160	
$p_{\mathrm{T}}(j_1)$ [GeV] $>$	130	
$p_{\mathrm{T}}(j_2)$ [GeV] $>$	60	
$p_{\mathrm{T}}(j_3)$ [GeV] $>$		60
$p_{\mathrm{T}}(j_4)$ [GeV] $>$		
$\Delta\phi(\mathrm{jet}_{1,2,(3)}, \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}})_{\mathrm{min}} >$	0.4	
$\Delta\phi(\mathrm{jet}_{i>3}, \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}})_{\mathrm{min}} >$		
W candidates	$2(W \to j)$	–
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ [GeV$^{1/2}$] $>$		
$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}(N_{\mathrm{j}}) >$	0.25	0.3
$m_{\mathrm{eff}}(\mathrm{incl.})$ [GeV] $>$	1800	2200

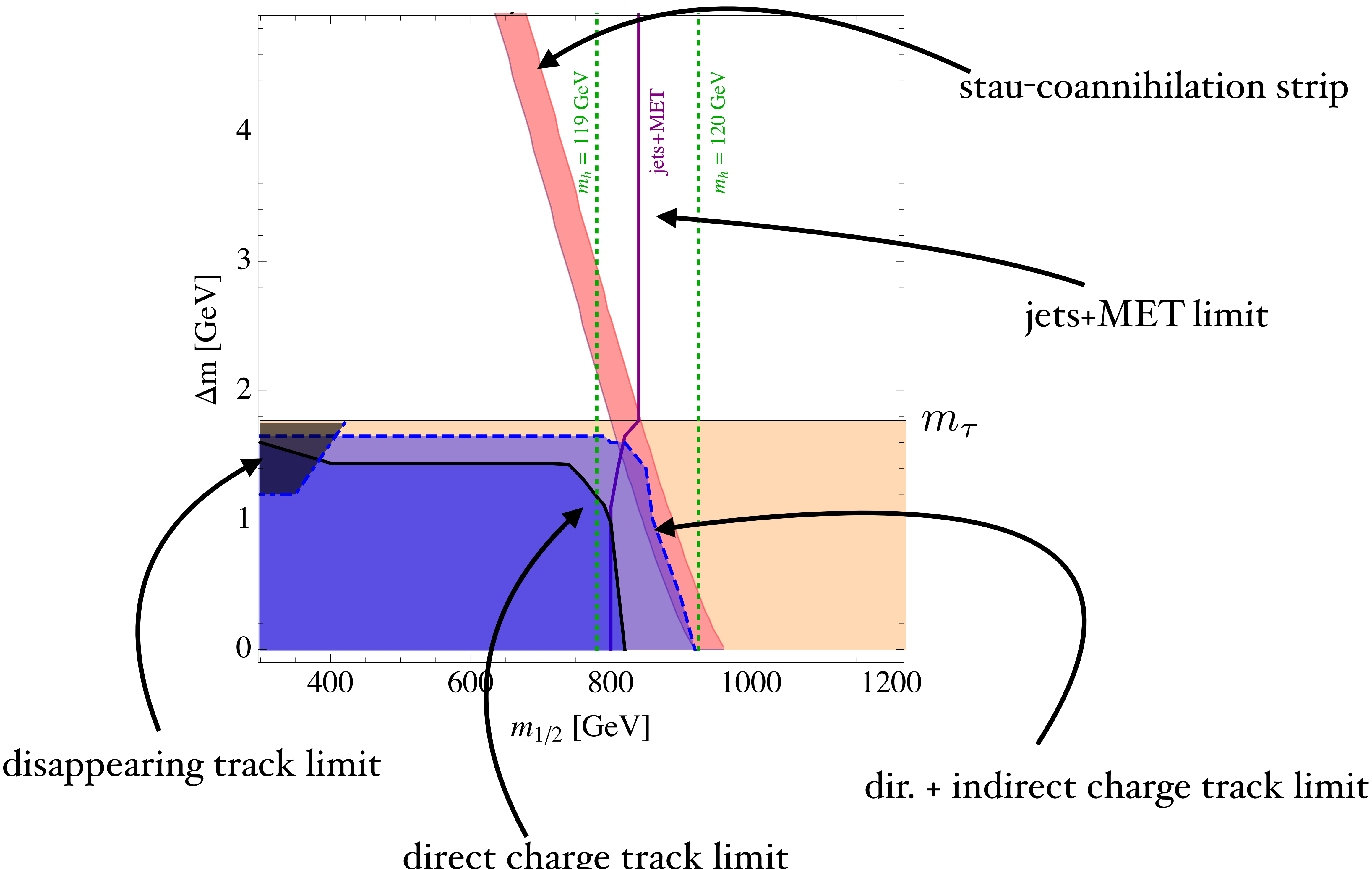


Long-lived charged tracks

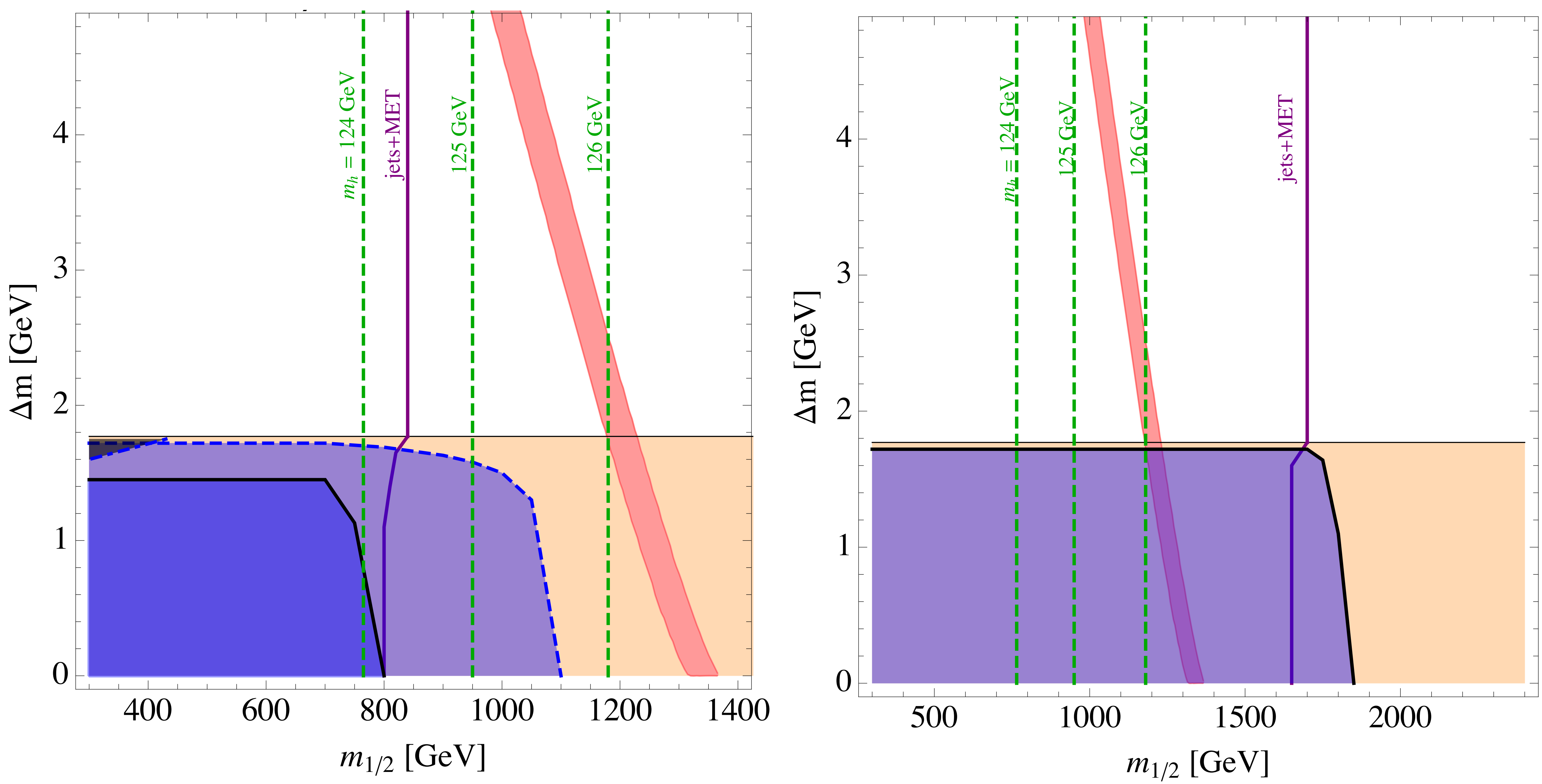


- Charged particle searches are specialised to take time of flight into account
- Fraction of staus that are stable on the detector scale decreases with increasing mass difference
- Run I limit on fully stable staus is ~550 GeV; since not all our staus exit the detector, we get a limit ~300 GeV.

combining multiple searches



CMSSM Stau co-annihilation is (probably) dead



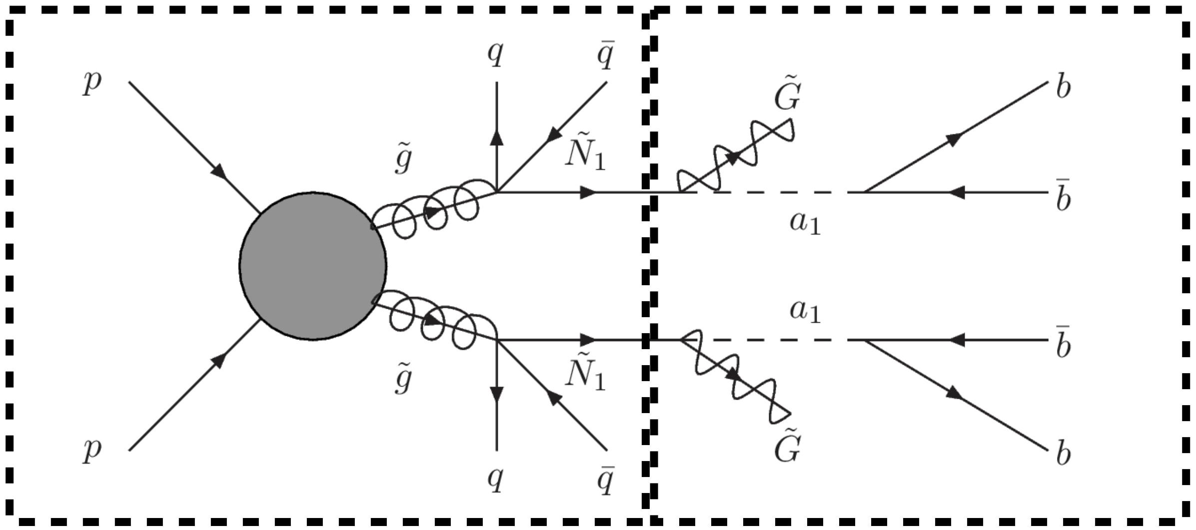
Coannihilation region not fully probed at 8 TeV; **we await 13 TeV data results in this Winter** to discover (or exclude!) the final part of the co-annihilation strip

Filling the gaps in DM searches

DM + s-channel mediator	Dilepton, dijet, mono-jet, displaced vertices
DM + t-channel mediator	"squark" & "slepton" searches, (disappearing) charged tracks, displaced leptons
SU(2) n-plets	jets+MET, di-lepton+MET searches, mono-jet, mono-photon, (disappearing) charged tracks, displaced leptons
ALPs	Di-gamma, non-pointing photons
Sterile Neutrinos, Heavy Neutral leptons	leptons+MET, Z/higgs+MET displaced vertices, displaced leptons

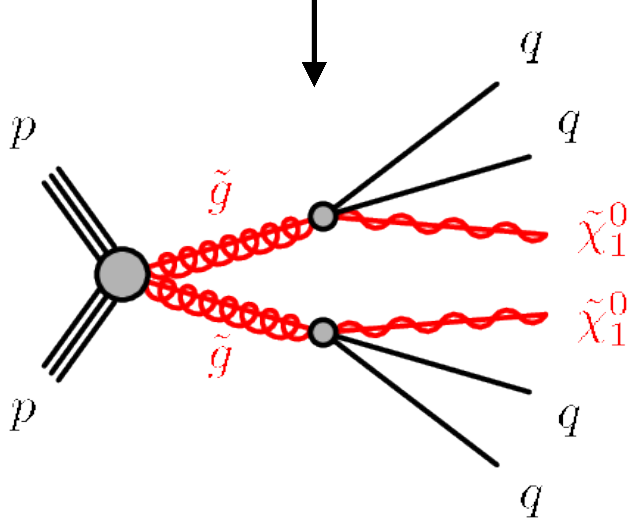
Displaced Vertices in NMSSM

NMSSM: Long Lived Neutral Particles



Same as standard SUSY

New decay



- Supersymmetry with extra singlino & gauge mediation

  Predicts 125 GeV higgs mass

  Doesn't violate low-scale observables

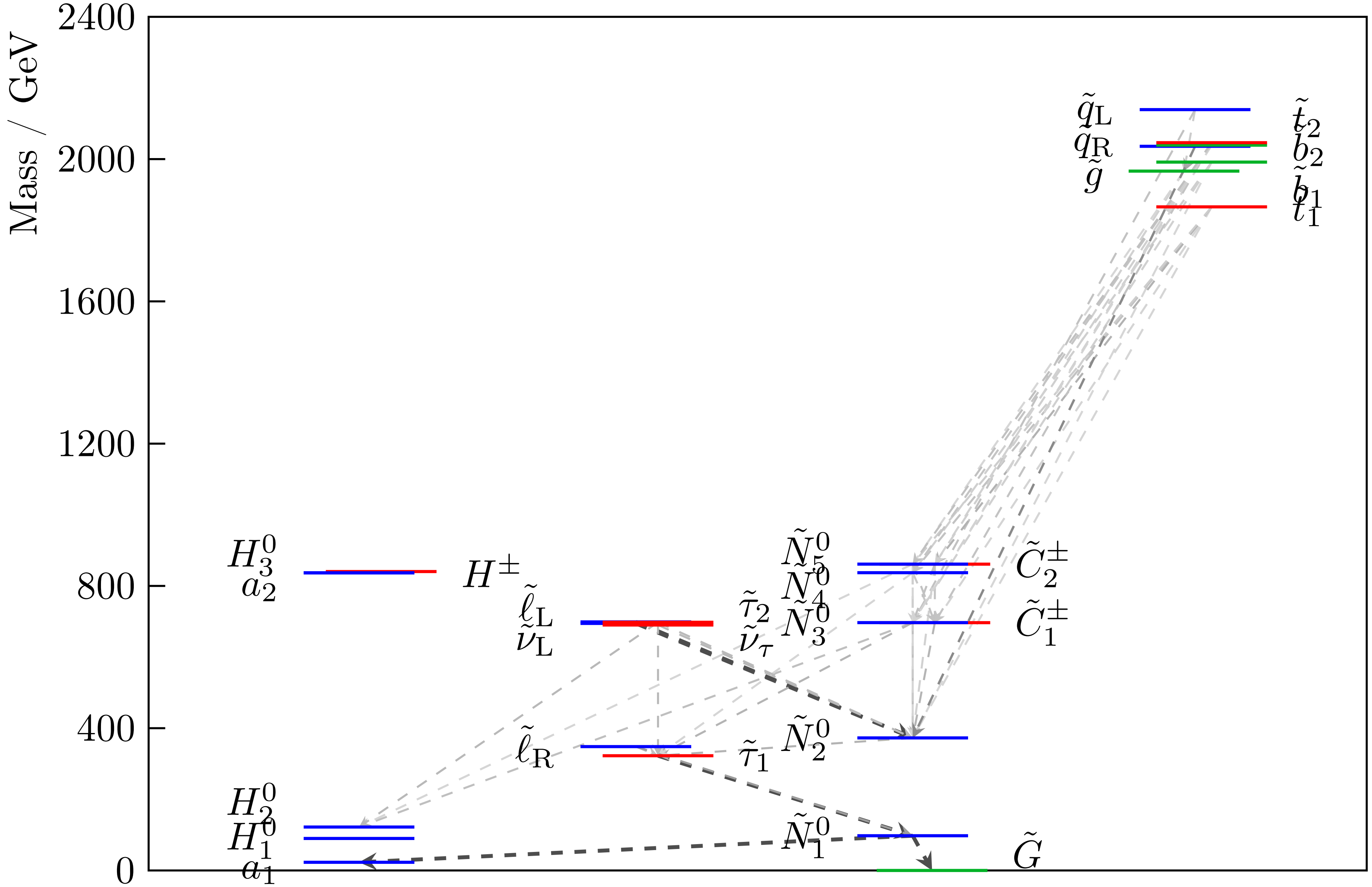
  Predicts high masses of strongly charged SUSY partners

- Predicts a pseudo-scalar boson of mass ~ 30 GeV; all chains end in producing this boson
- This boson has a lifetime ~ 1 mm (due to boost, decays after traveling ~100 mm in the detector)

Questions:

1. **Can ordinary SUSY searches find this scenario?**
2. **What are the effects of the extra pseudo scalar**

Spectrum of model



$m_{H_1^0}$	$m_{H_2^0}$	m_{a_1}	$m_{\tilde{N}_1}$	$m_{\tilde{N}_2}$	$m_{\tilde{e}_1}$	$m_{\tilde{\tau}_1}$	$m_{\tilde{g}}$	$m_{\tilde{u}_R}$	$m_{\tilde{b}_1}$	$m_{\tilde{t}_1}$	$m_{\tilde{G}}$
90	122.1	23	97.6	373	348	323	1966	2045	1992	1866	5×10^{-8}

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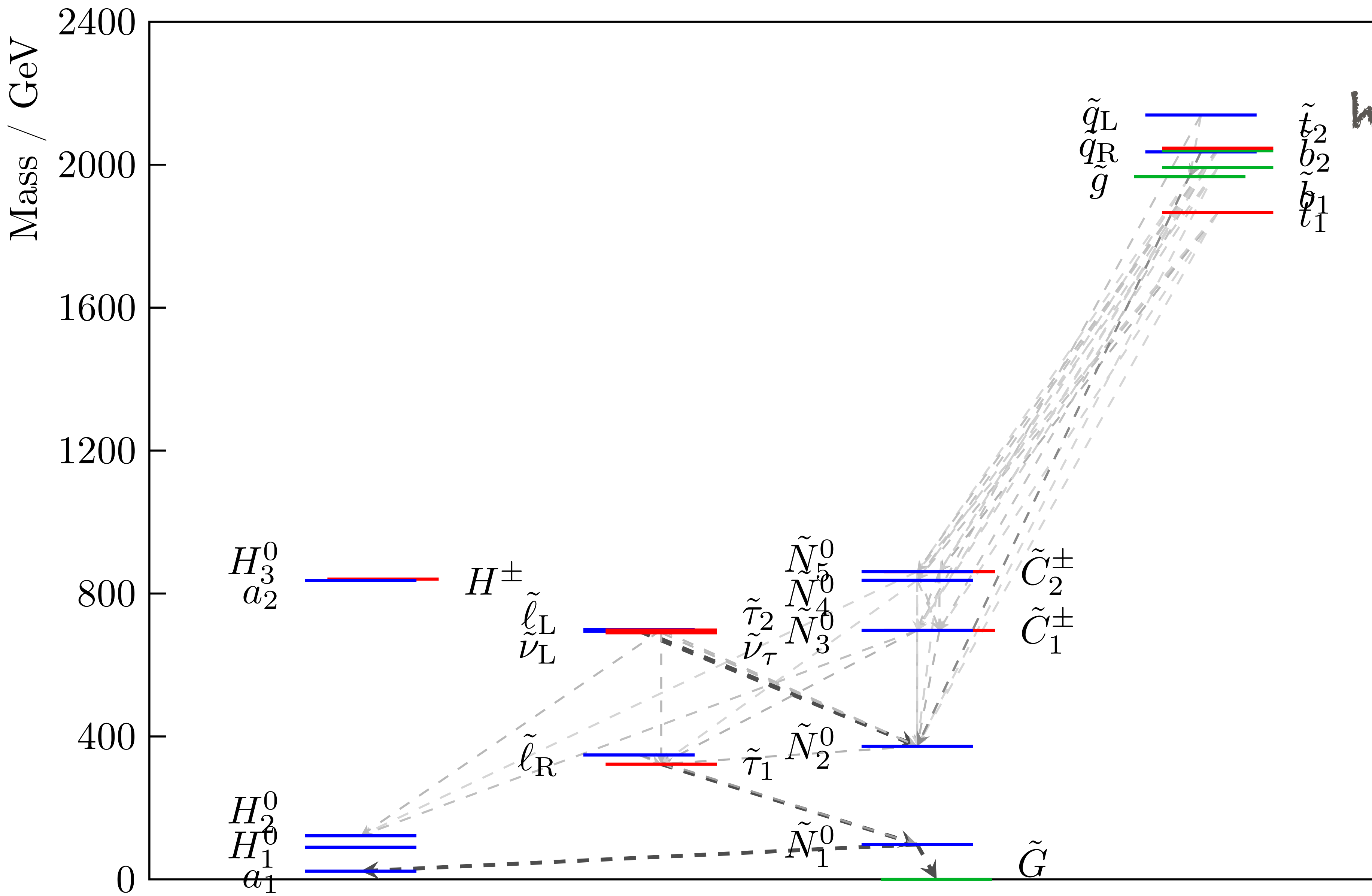

Naturally predicts heavy strong sector to get the right higgs mass

$m_{H_1^0}$	$m_{H_2^0}$	m_{a_1}	$m_{\tilde{N}_1}$	$m_{\tilde{N}_2}$	$m_{\tilde{e}_1}$	$m_{\tilde{\tau}_1}$	$m_{\tilde{g}}$	$m_{\tilde{u}_R}$	$m_{\tilde{b}_1}$	$m_{\tilde{t}_1}$	$m_{\tilde{G}}$
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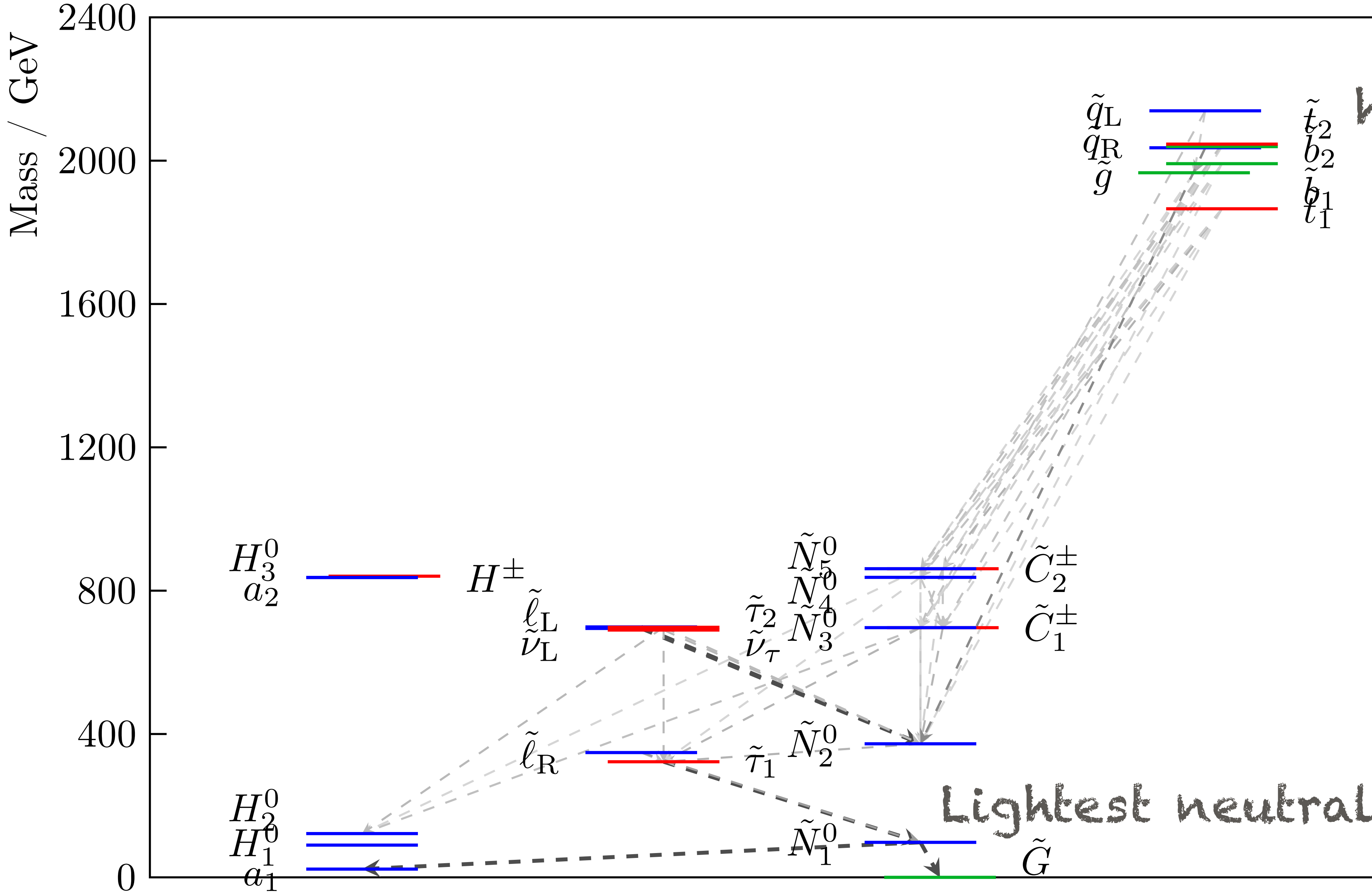
Spectrum of model



Naturally predicts heavy strong sector to get the right higgs mass

Lightest neutralino not stable

$m_{H_1^0}$	$m_{H_2^0}$	m_{a_1}	$m_{\tilde{N}_1}$	$m_{\tilde{N}_2}$	$m_{\tilde{e}_1}$	$m_{\tilde{\tau}_1}$	$m_{\tilde{g}}$	$m_{\tilde{u}_R}$	$m_{\tilde{b}_1}$	$m_{\tilde{t}_1}$	$m_{\tilde{G}}$
90	122.1	23	97.6	373	348	323	1966	2045	1992	1866	5×10^{-8}

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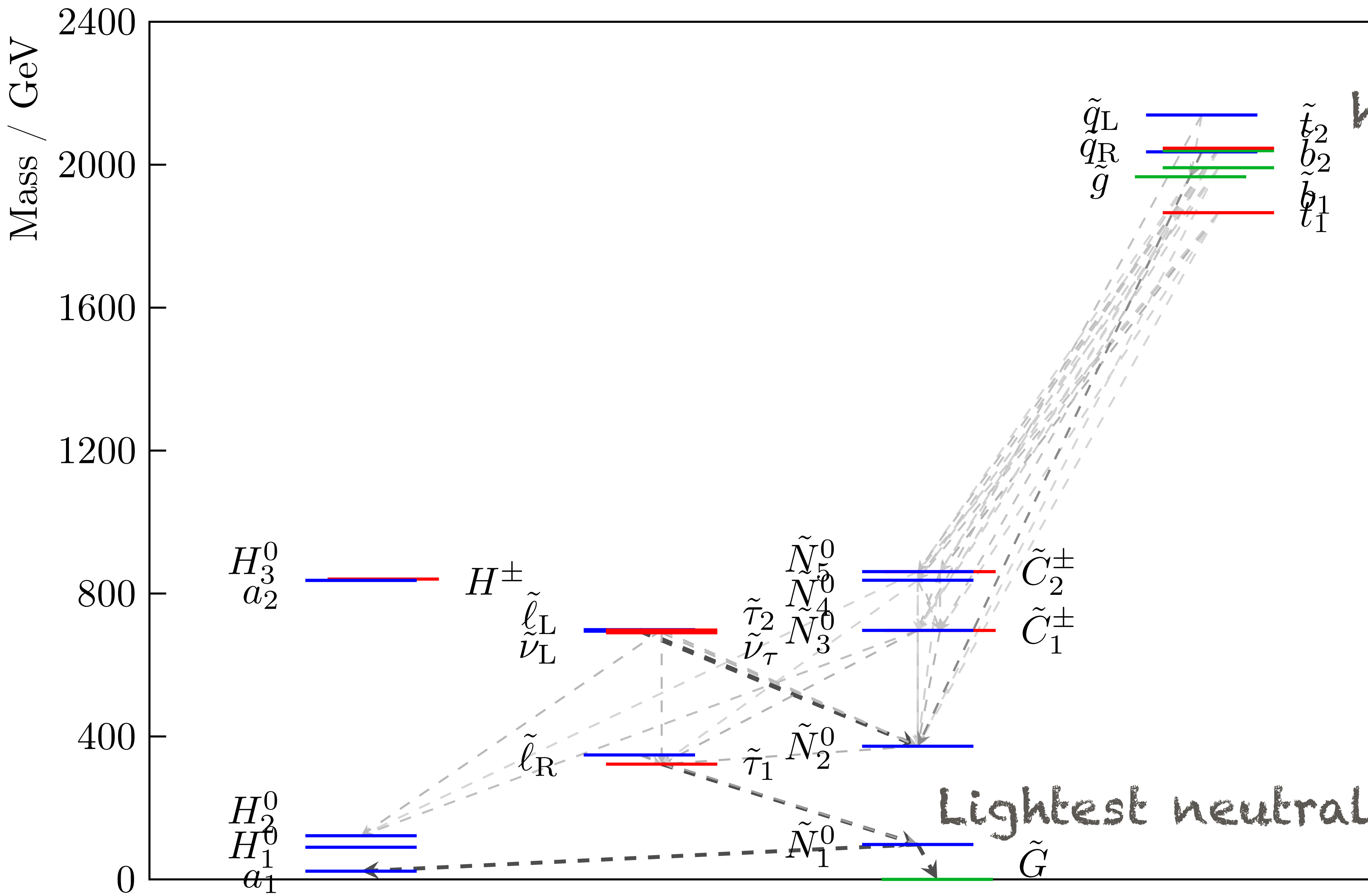

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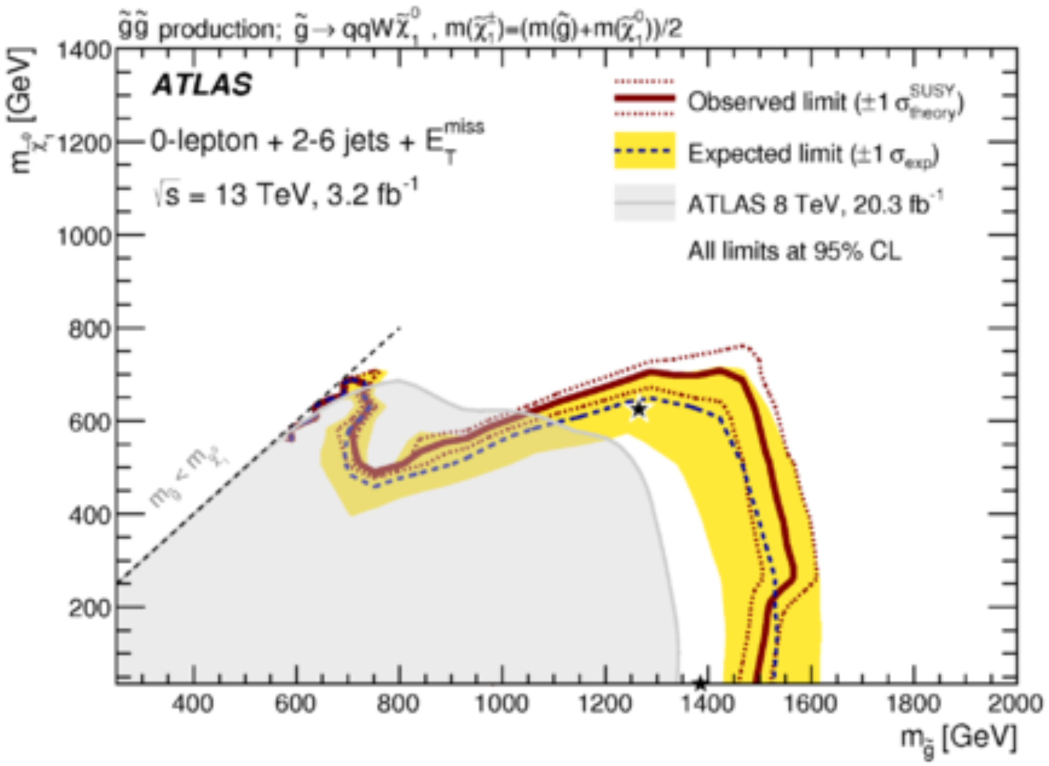
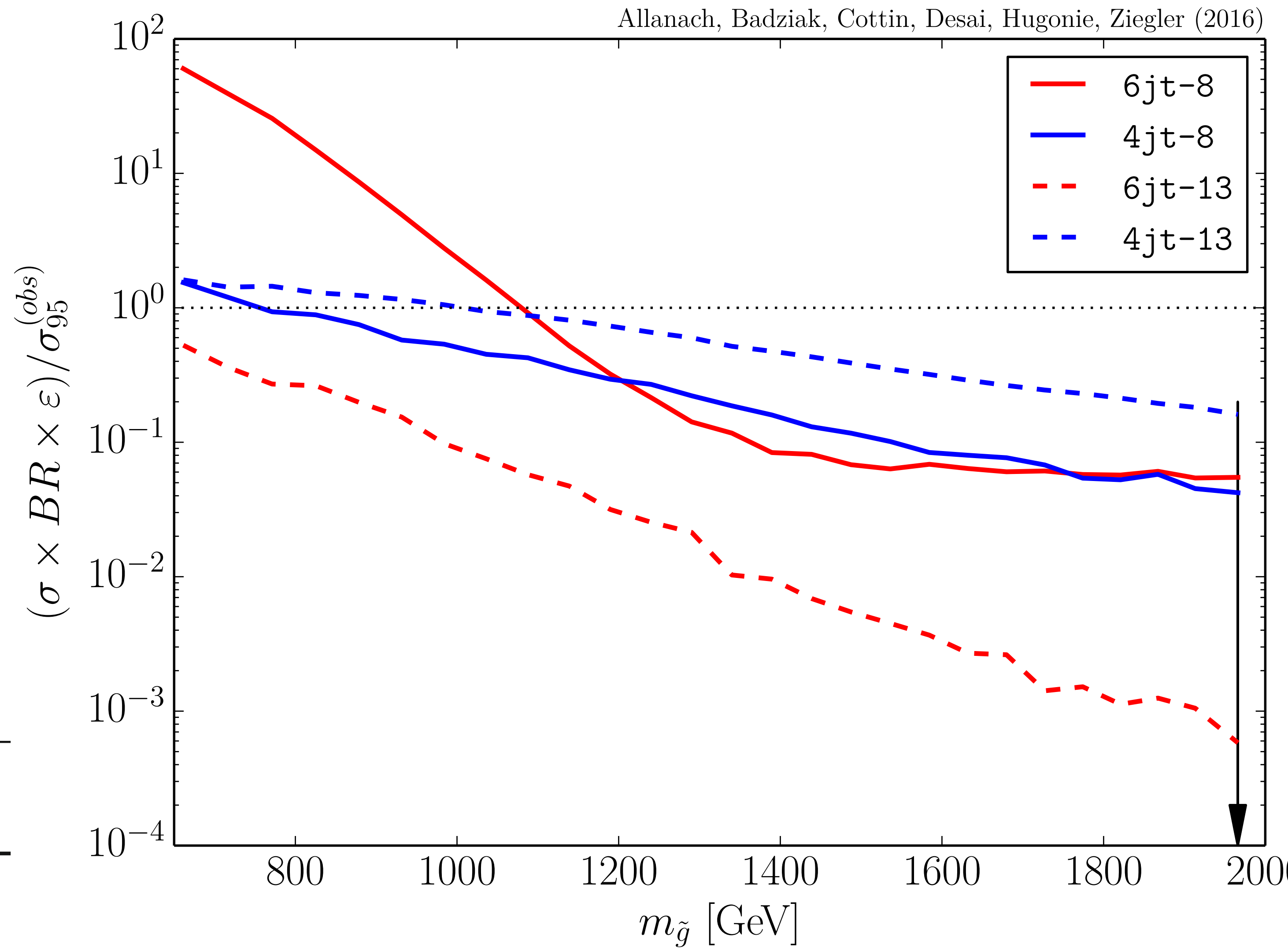
$m_{H_1^0}$	$m_{H_2^0}$	m_{a_1}	$m_{\tilde N_1}$	$m_{\tilde N_2}$	$m_{\tilde e_1}$	$m_{\tilde\tau_1}$	$m_{\tilde g}$	$m_{\tilde u_R}$	$m_{\tilde b_1}$	$m_{\tilde t_1}$	$m_{\tilde G}$
90	122.1	23	97.6	373	348	323	1966	2045	1992	1866	5×10^{-8}

a_1 decays mainly to bb, decay is long lived!

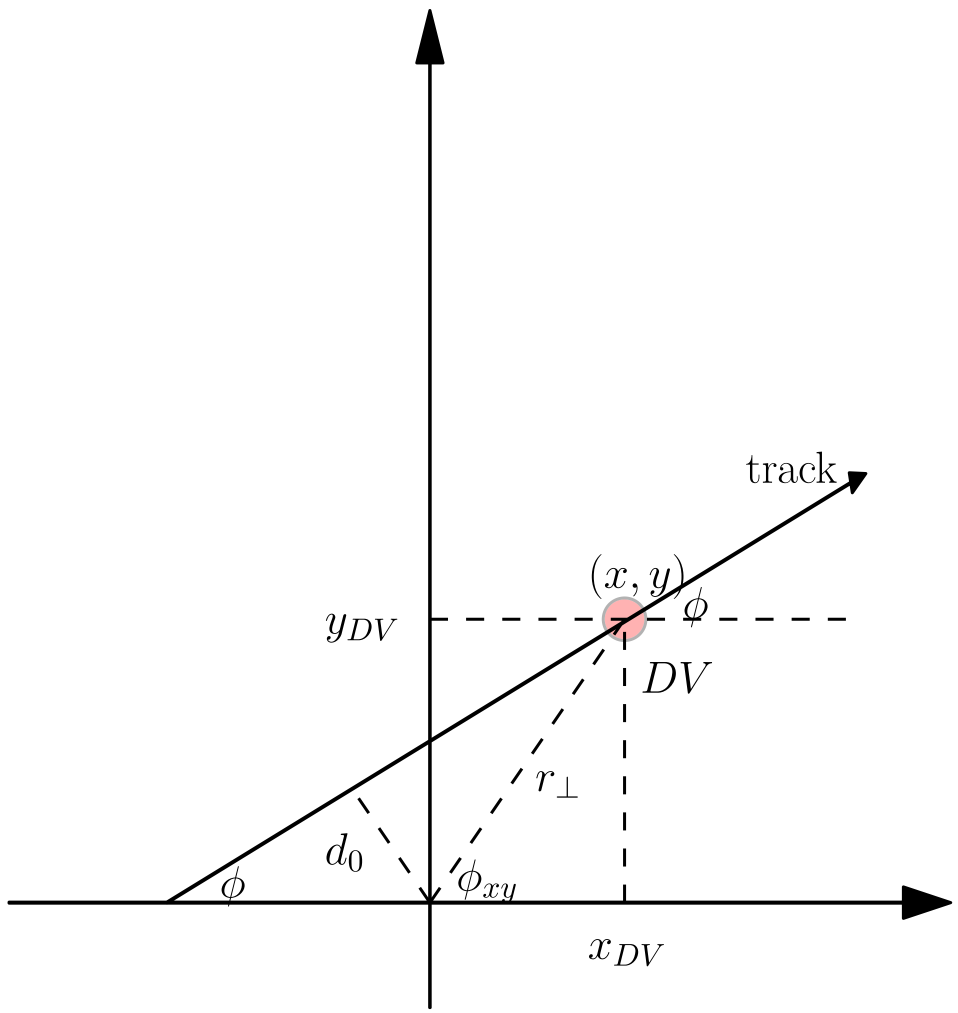
Recasting SUSY jets+MET search





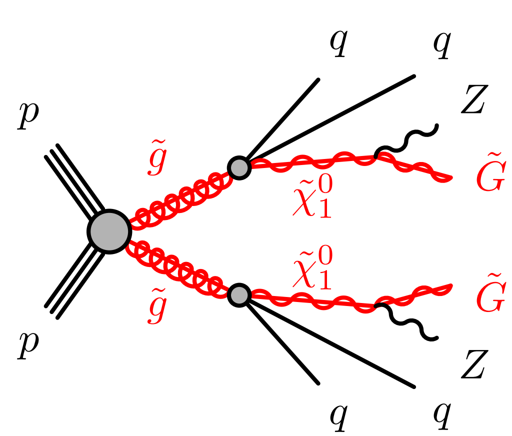
$\sqrt{s}$	8 TeV		13 TeV	
Signal region	4jt-8	6jt-8	4jt-13	6jt-13
p_T^{miss}/GeV >	160	160	200	200
$p_T(j_1)$/GeV >	130	130	200	200
$p_T(j_2)$/GeV >	60	60	100	100
$p_T(j_3)$/GeV >	60	60	100	100
$p_T(j_4)$/GeV >	60	60	100	100
$p_T(j_5)$/GeV >	–	60	–	50
$p_T(j_6)$/GeV >	–	60	–	50
$\Delta\phi(\text{jet}_{1,2,3}, \mathbf{p}_T^{miss})_{min}$ >	0.4			
$\Delta\phi(\text{jet}_{j>3}, \mathbf{p}_T^{miss})_{min}$ >	0.2			
$p_T^{miss}/m_{eff}(N_j)$ >	0.25		0.2	
m_{eff}(incl.)/GeV >	2200	1500	2200	2000
σ_{95}^{obs} (fb)	0.15	0.32	2.7	1.6

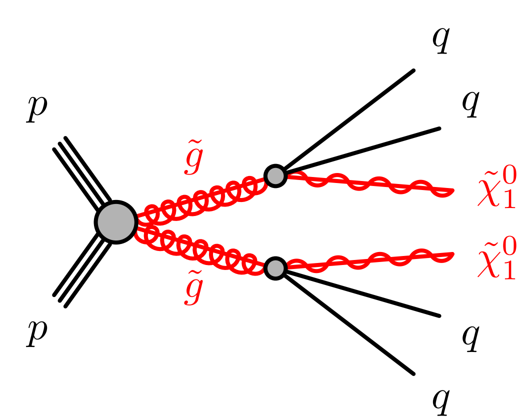
The displaced vertex search



DV jets	4 or 5 or 6 jets with $|\eta| < 2.8$ and $p_T > 90, 65, 55$ GeV, each
DV reconstruction	DV made from tracks with $p_T > 1$ GeV, $|\eta| < 2.5$ and $|d_0| > 2$ mm, satisfying a tracking efficiency Vertices within 1 mm are merged
DV fiducial	DV within 4 mm $< r_{\mathrm{DV}} <$ 300 mm and $|z_{\mathrm{DV}}| <$ 300 mm
DV material	No DV in regions near beampipe or within pixel layers: Discard tracks with $r_{\mathrm{DV}}/\mathrm{mm} \in \{[25, 38], [45, 60], [85, 95], [120, 130]\}$
N_{trk}	DV track multiplicity ≥ 5
m_{DV}	DV mass > 10 GeV

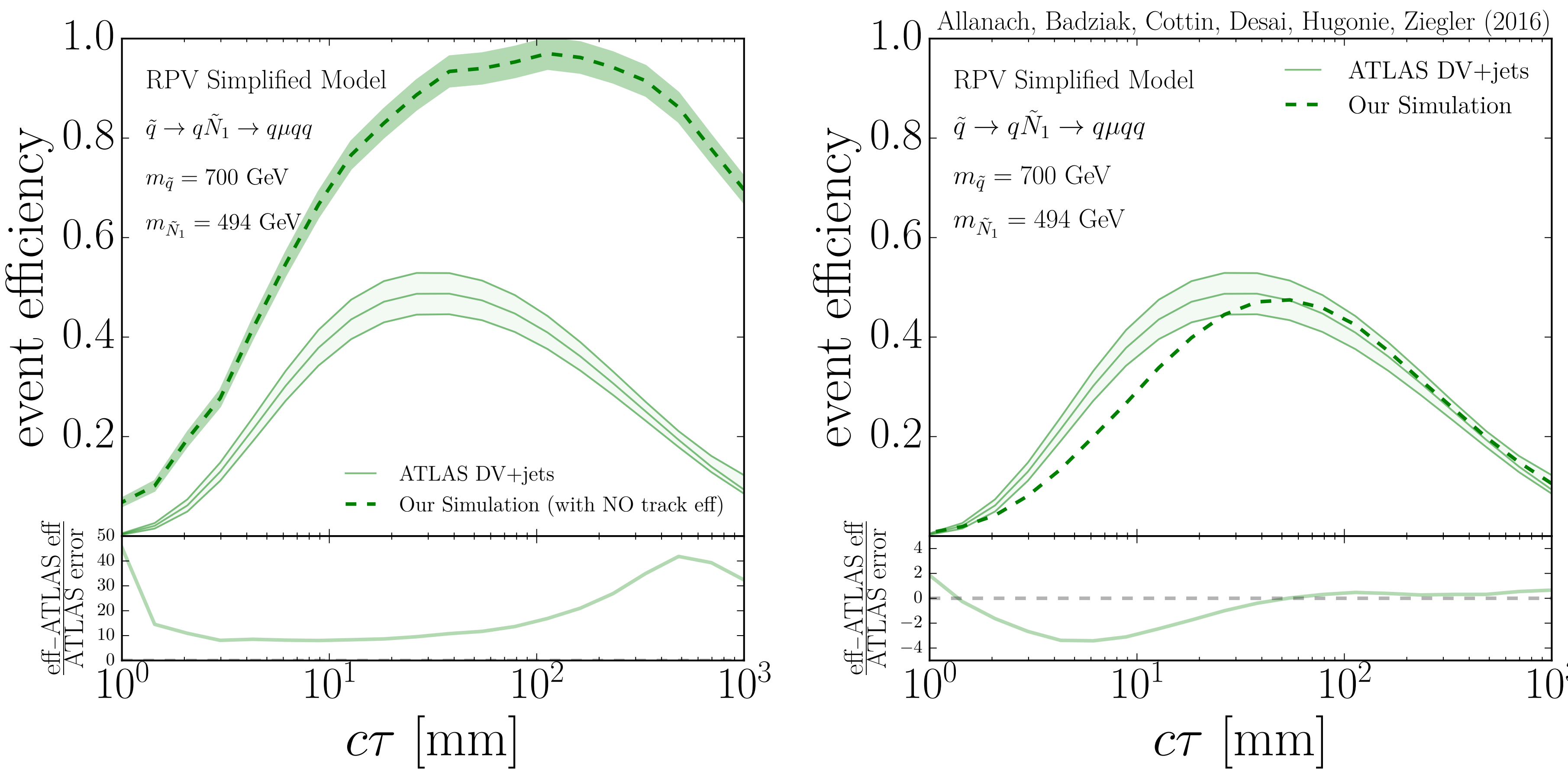
Gauge Mediated benchmarks





RPV benchmark

Finding the track efficiency

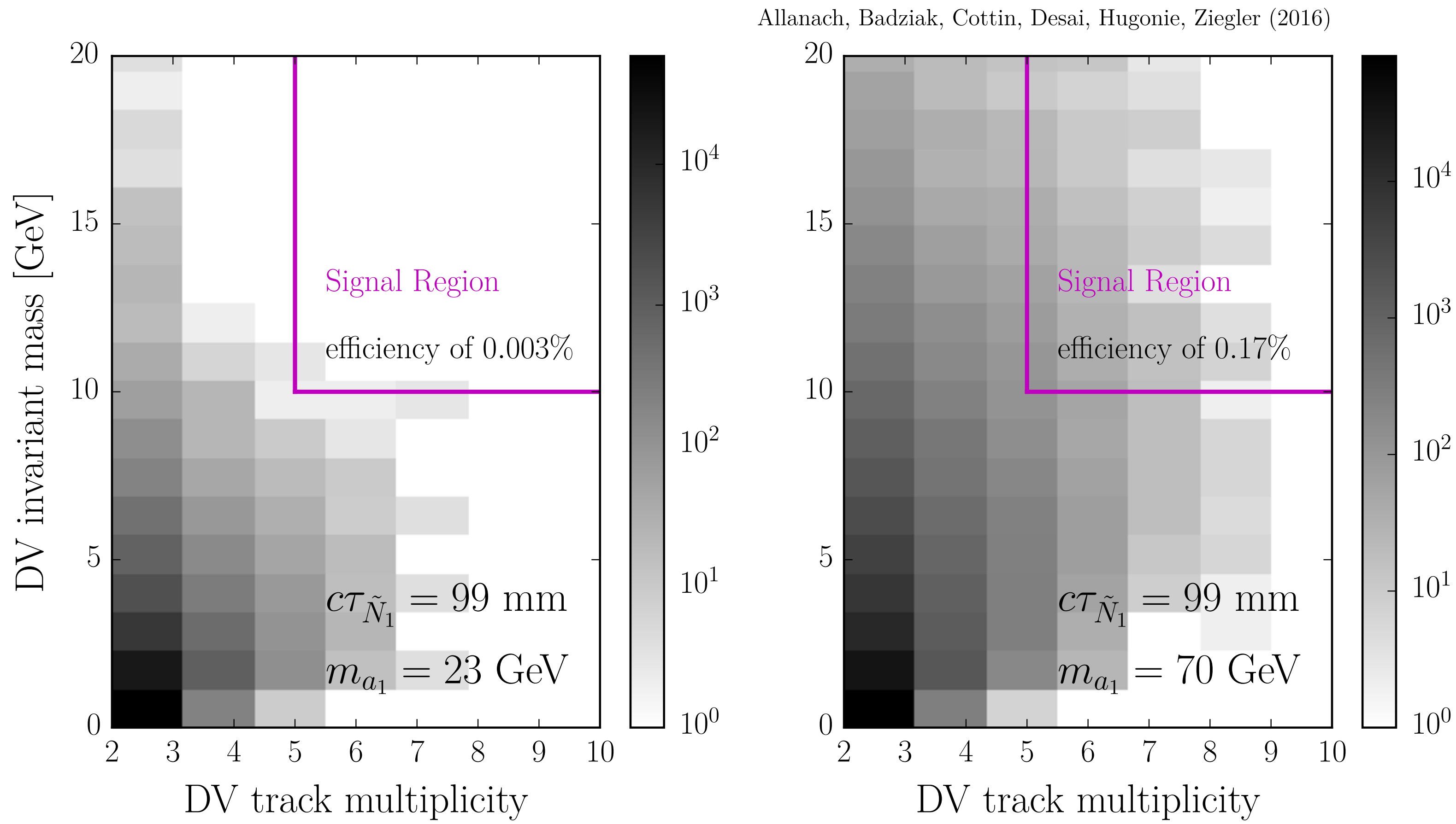


Tracking efficiency determined by fitting parameters of an empirical function

$$\begin{aligned}\varepsilon_{\rm trk} &= 0.5 \times (1 - \exp(-p_T/[4.0\ \text{GeV}])) \\ &\times \exp(-z/[270\ \text{mm}]) \\ &\times \max(-0.0022 \times r_\perp/[1\ \text{mm}] + 0.8, 0)\end{aligned}$$

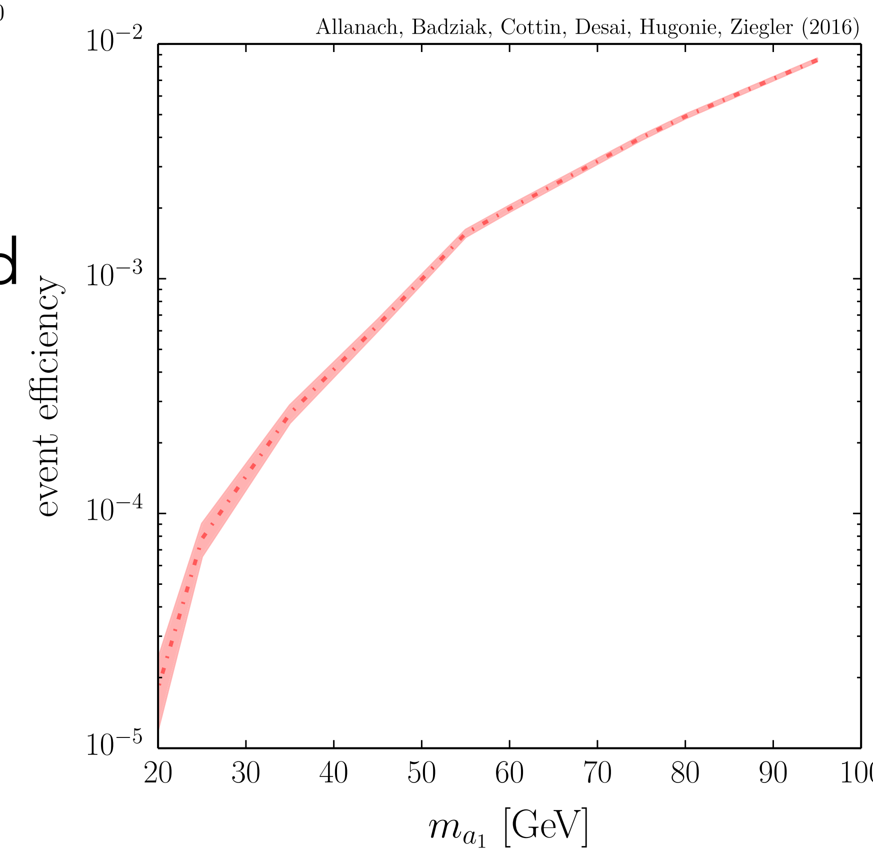
Remove low p_T
Dependence on z of DV
Dependence on radial distance of DV

Dependence on DV mass and N_{trk}

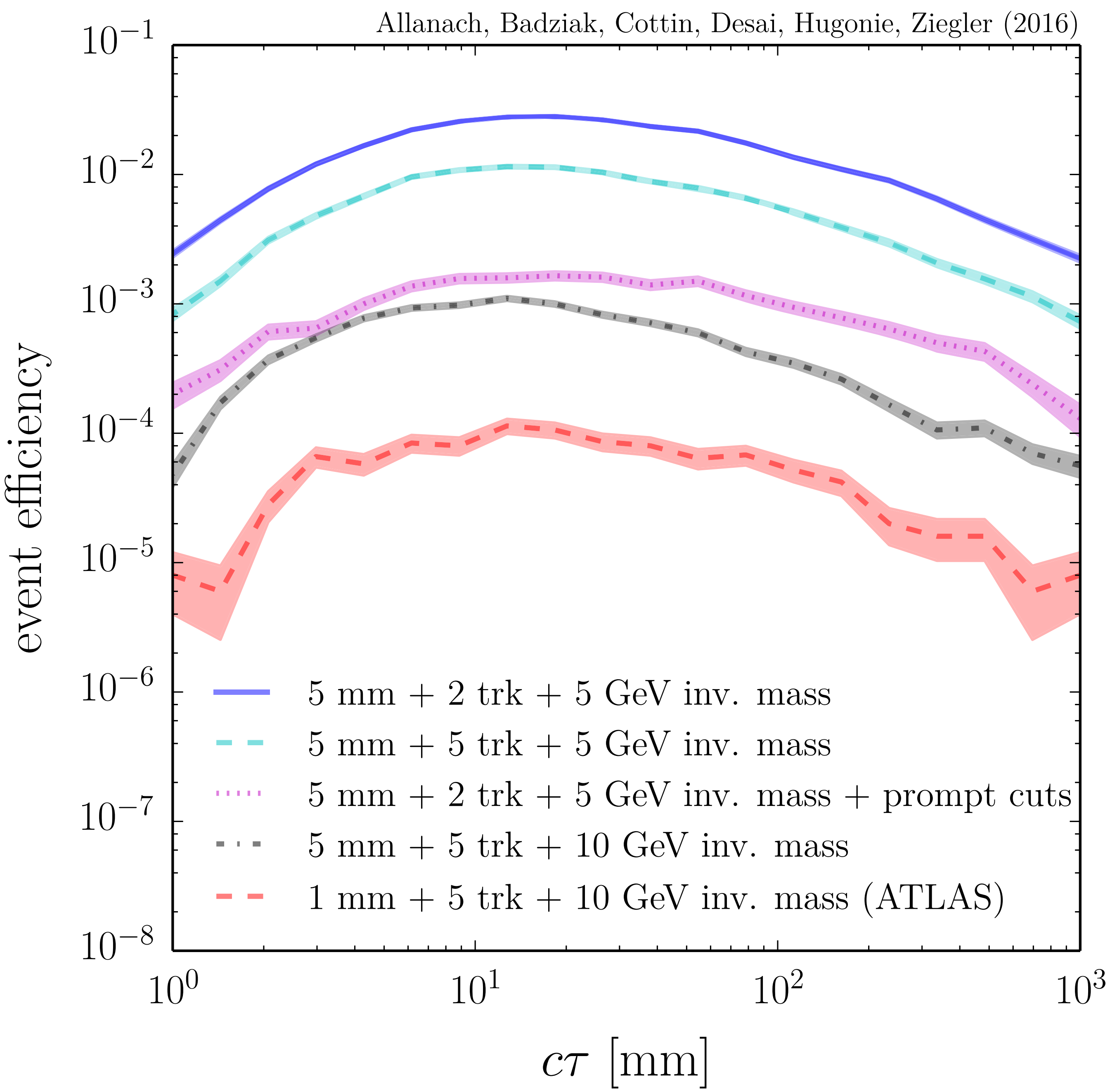


Our model fails to satisfy the DV cuts because of long lived B-mesons in the final state.

- B-mesons themselves give displaced vertices (not enough tracks < 1mm)
- Small momentum transfer. This improves with heavier a_1.

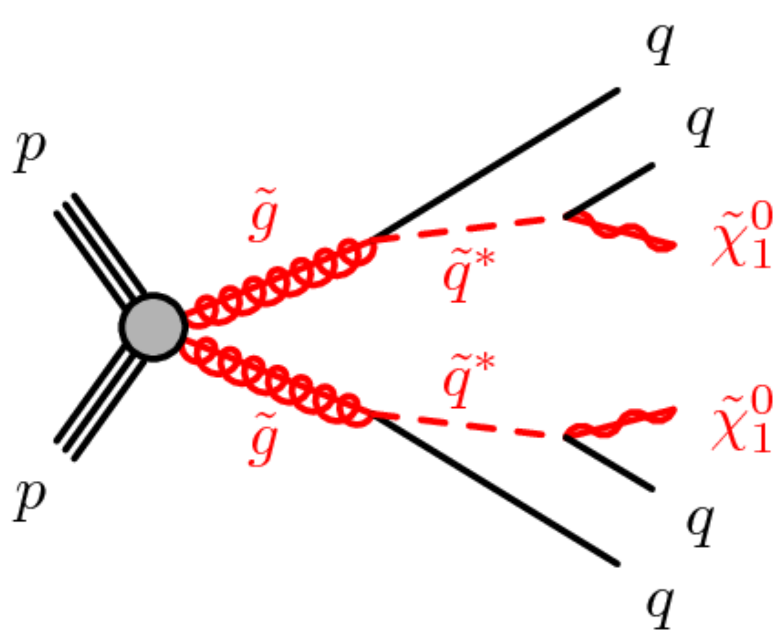


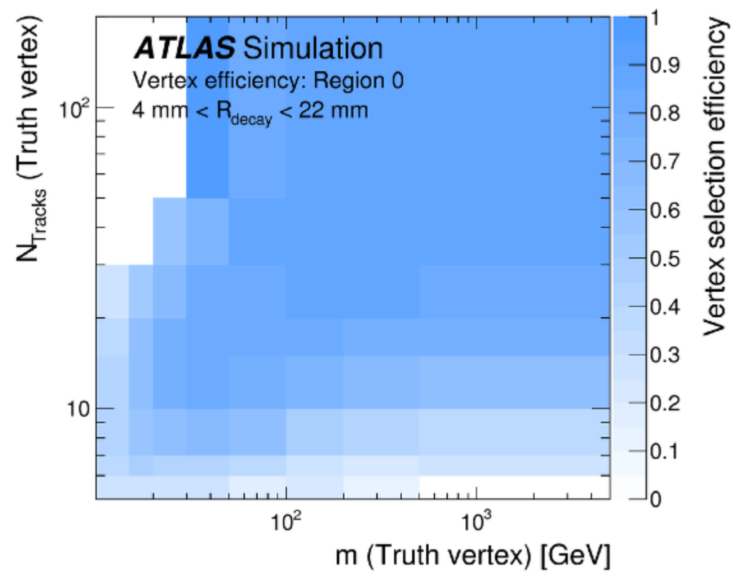
Modifying the displaced vertex criteria

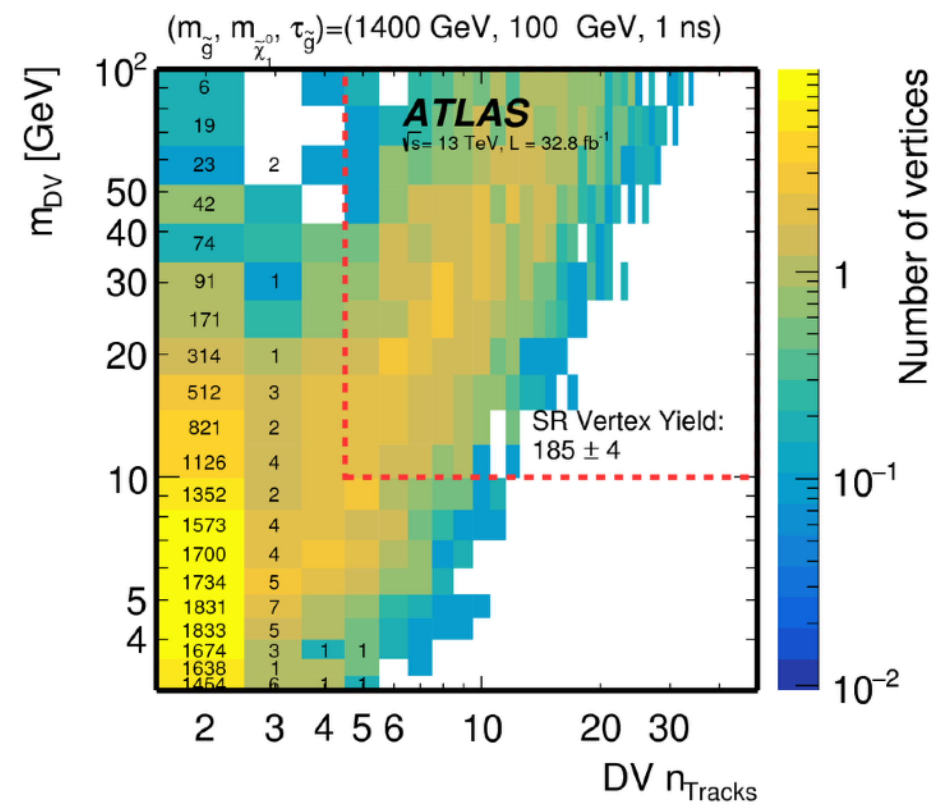


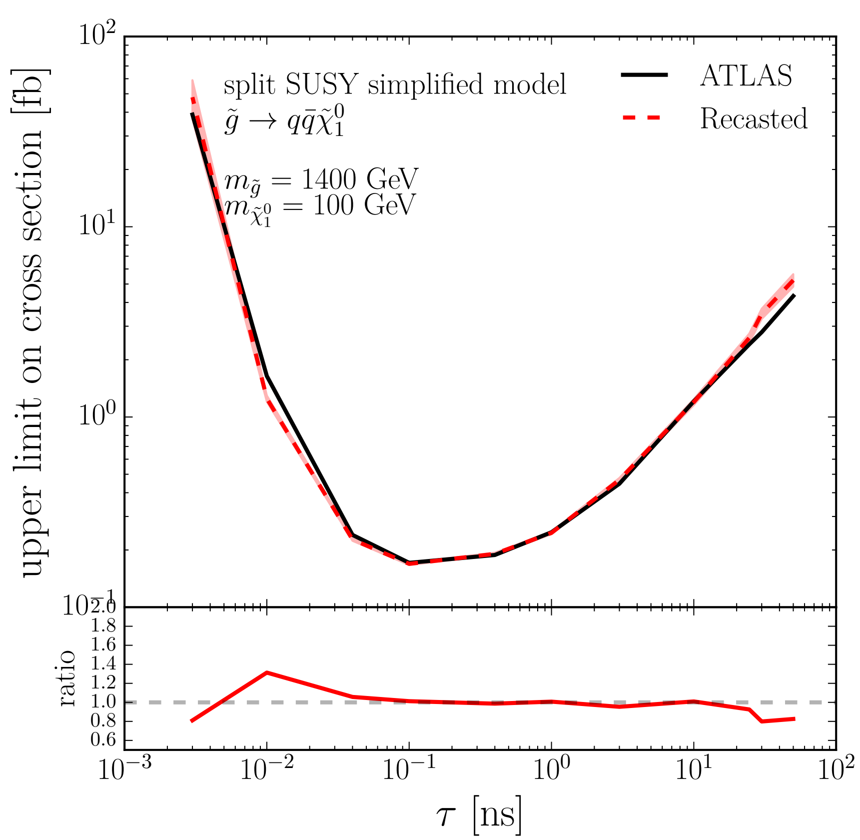
- It is possible to significantly improve efficiency by relaxing cuts
- Not easy to estimate background for these changes
- Our solution: combine prompt cuts + DV cuts & use prompt background estimate as a conservative upper limit
- Reach can be 1.9 TeV with 100/fb
- Much better sensitivity possible with better estimate of background

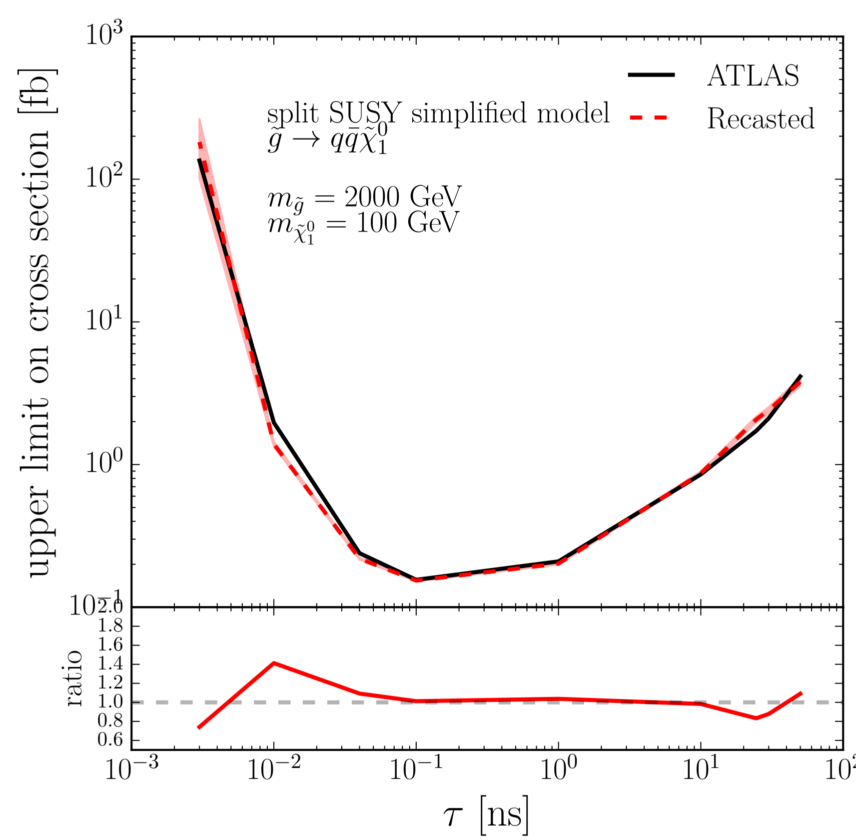
Updated DV analysis







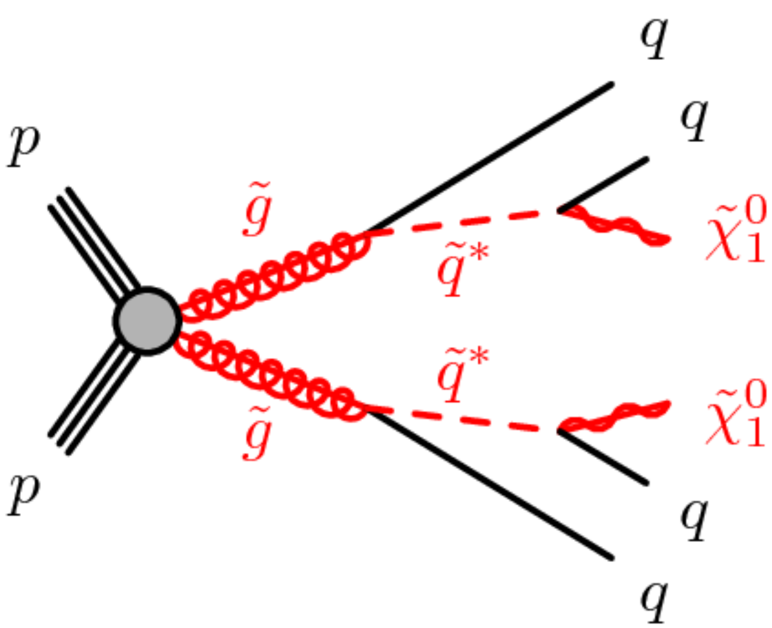


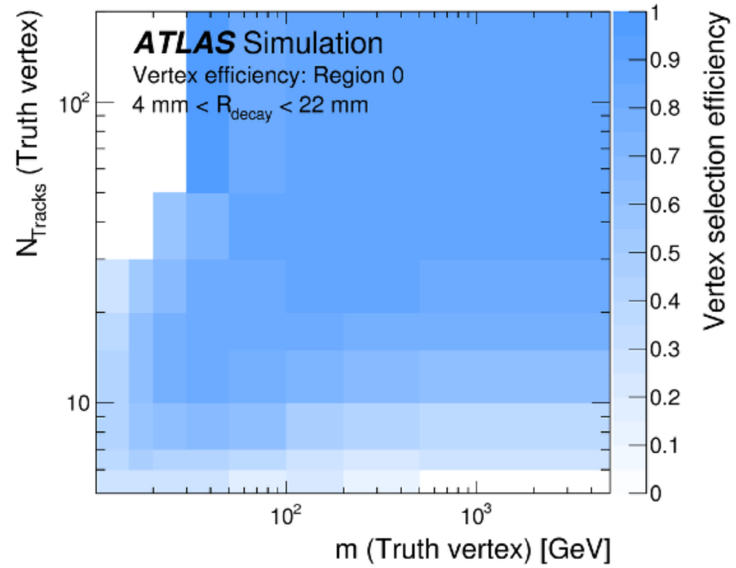


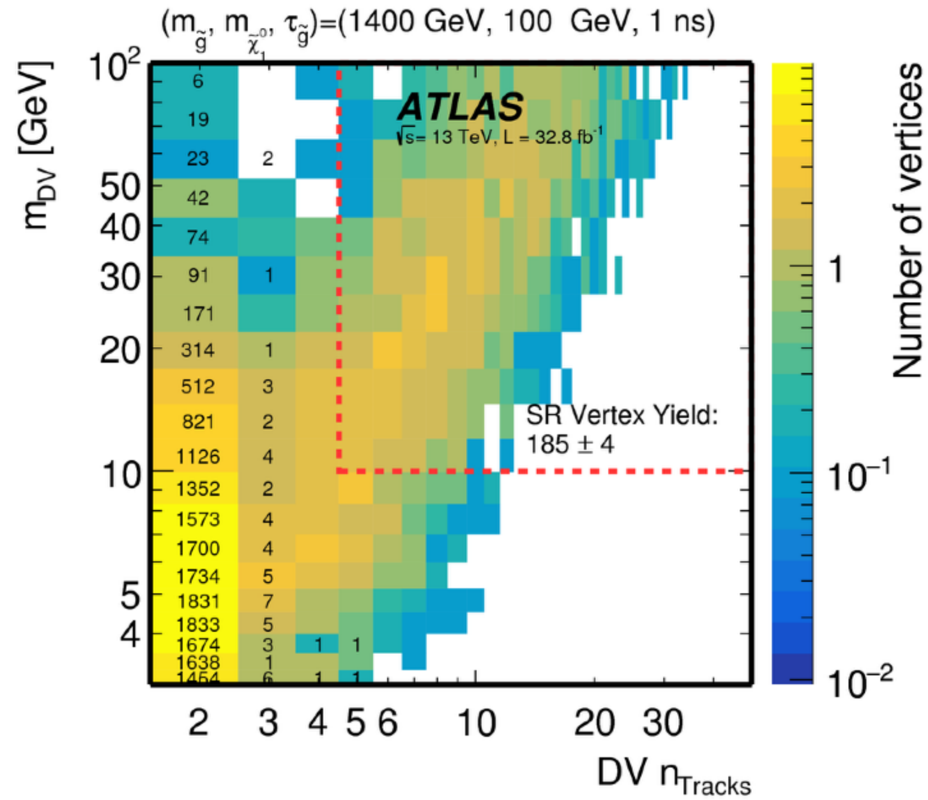
ATLAS, arXiv:1710.04901

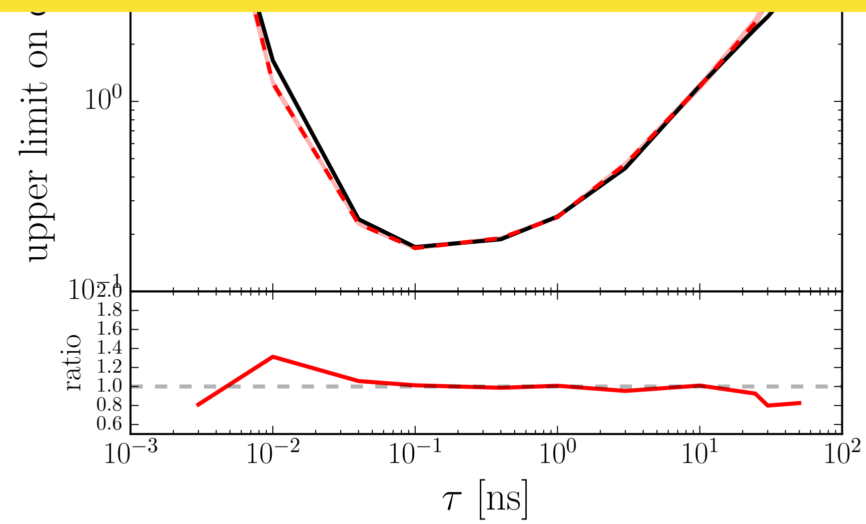
Cottin, Desai, Heisig & Lessa; arXiv:1803.10379

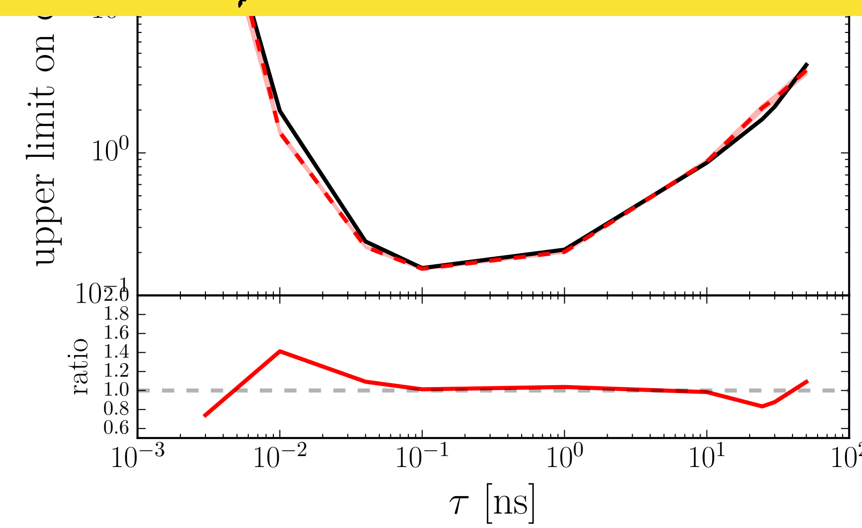
Updated DV analysis











Communication with experimentalists leads to better data transfer!

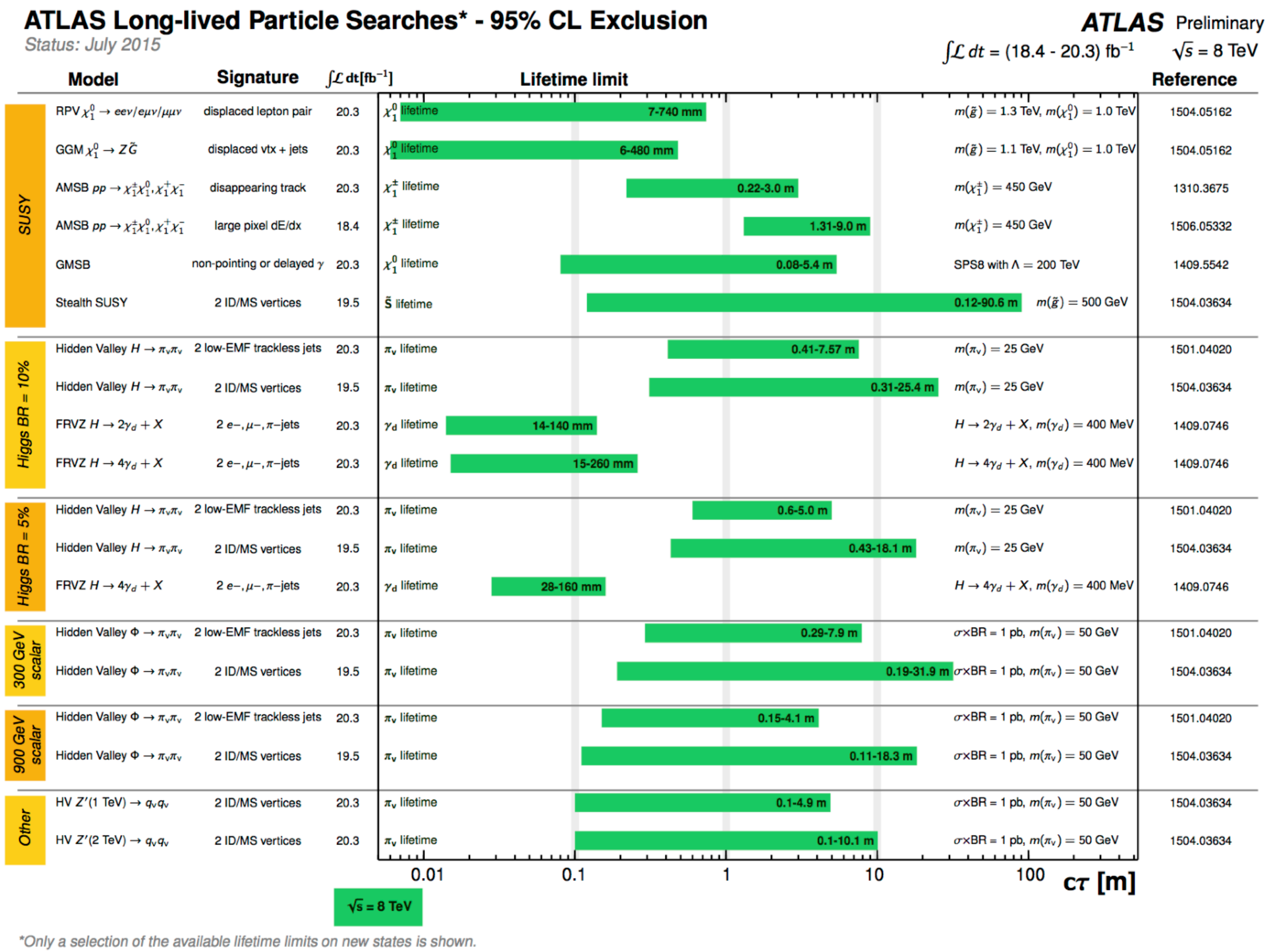
ATLAS, arXiv:1710.04901

Cottin, Desai, Heisig & Lessa; arXiv:1803.10379

Summary

- Long-lived particles predicted by many theories as a natural consequence
- LLP searches often have nearly **zero background** and can provide a clean signature
- Co-annihilation partners in DM models are long-lived in certain parameter space and can provide the first indications of signal
- Light long-lived scalars decay to b-quarks or taus and escape current displaced vertex searches. Need to improve selection criteria.
- Overall: traditional searches ignore objects not originating from primary vertex; If we have a new theory with LLPs, **it won't be possible to go back and look for LLPs in LHC data if we don't know what data to store**.

Some LLP limits



ARE WE MISSING SOMETHING?