Searches for light dark matter through dijets and long-lived particles at the LHC

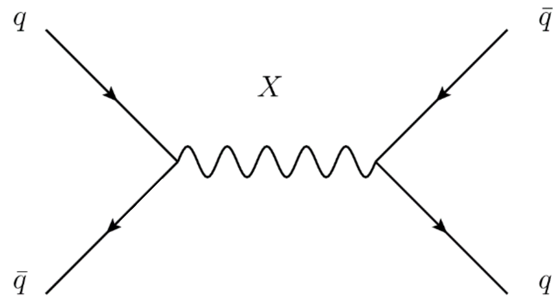
Rachel Rosten – University of Washington

On behalf of the ATLAS and CMS Collaborations

12 September 2016

Dark Matter and Dijets

- Rather than searching for E_T^{miss} as evidence of the creation of DM, take DM mediator coupling to quarks and look for resonances in the dijet mass spectrum



- Dijet searches already a standard of collider-based experiments, but probing low masses is a challenge

Triggers and Dijet Resonances

- ATLAS and CMS use a two-stage trigger to record events
  - Level 1: Hardware based
  - High level trigger: Software based
- Triggers select events to record and reject the vast majority (1.5 *MB*/25 ***ns*** → < 1 *GB*/*s*)
- Light resonances produce low p_T jets
  - These jets have very high trigger rates
  - High trigger rates are dealt with by *prescaling* (recording only a fraction of qualifying events)
- Searches for resonance must work around this limitation

Light dijet resonance with ISR photon

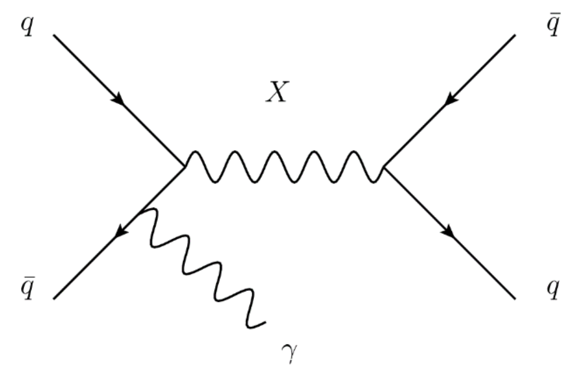
- Z' recoiling off ISR photon (or jet) and decaying to quarks
- Trigger on ISR photon with p_T > 140 GeV
- Identify pair of p_T > 25 GeV jets
  - $|y^*| < 0.8$ to exclude non resonant jet pairs (QCD processes contribute mainly at high y*)

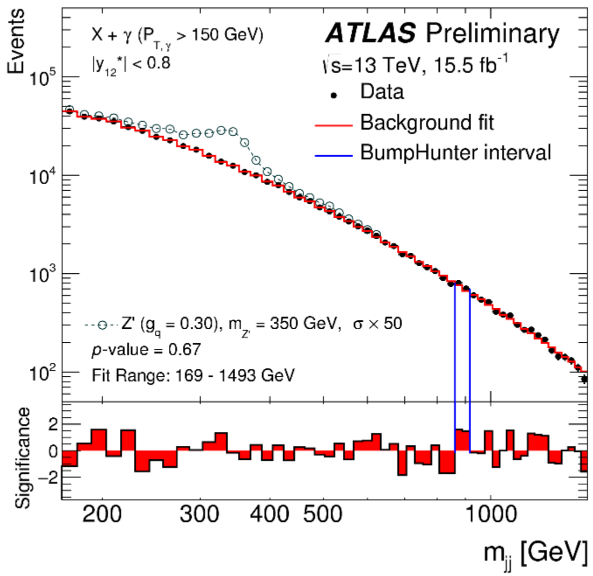
$$y^* \equiv \frac{y_1 - y_2}{2}$$

- Data-driven background estimate via parametric fit to the reconstructed dijet mass

$$f(z) = p_1(1-z)^{p_2} z^{p_3 + p_4 \ln z}$$

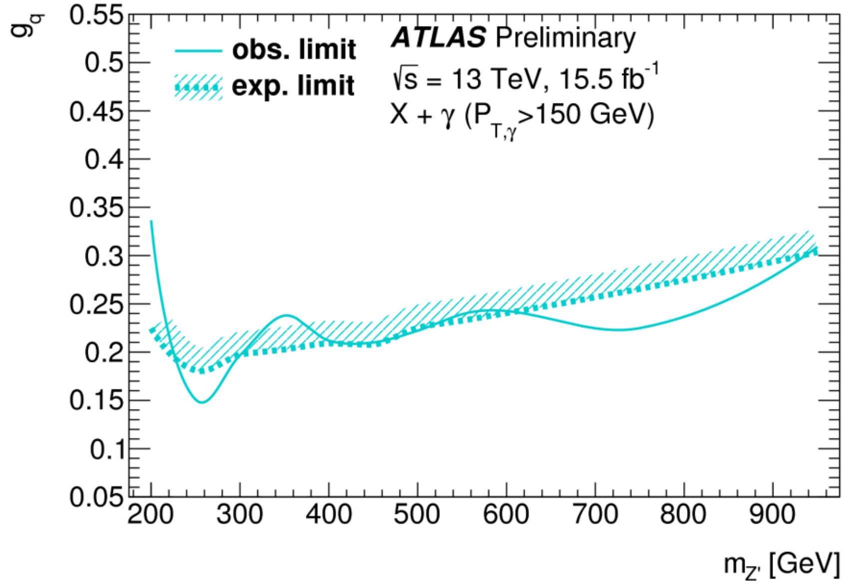
$$z = \frac{m_{jj}}{\sqrt{s}}$$

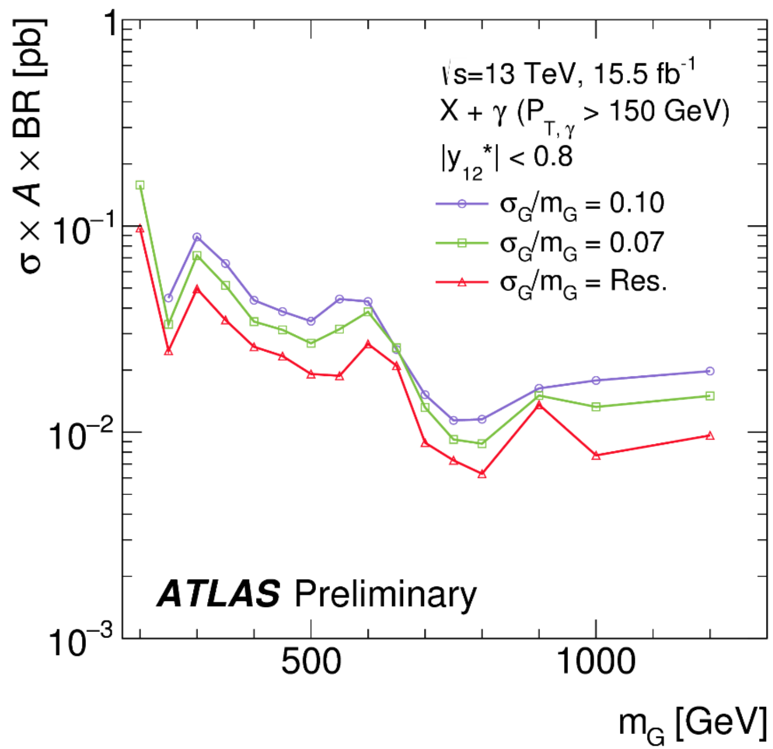




Light dijet resonance with ISR photon

- Determine limits by interpolating between limits derived at discrete points on $m_{Z'}$-g_q plane
- Limits set both on coupling and the Z' mass

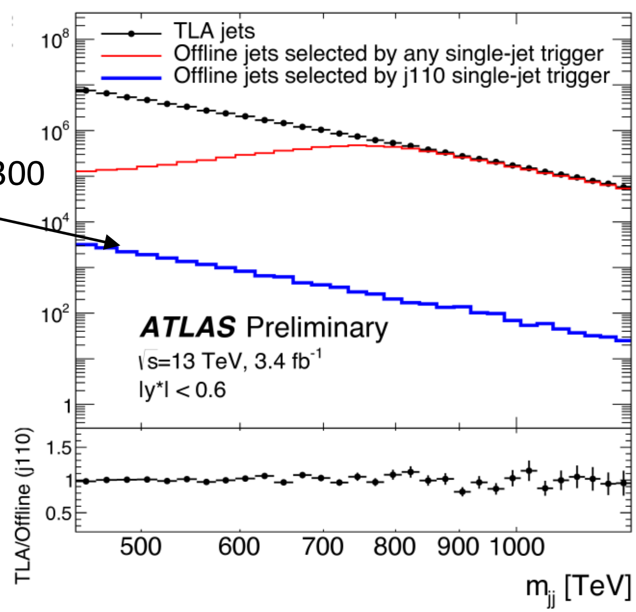


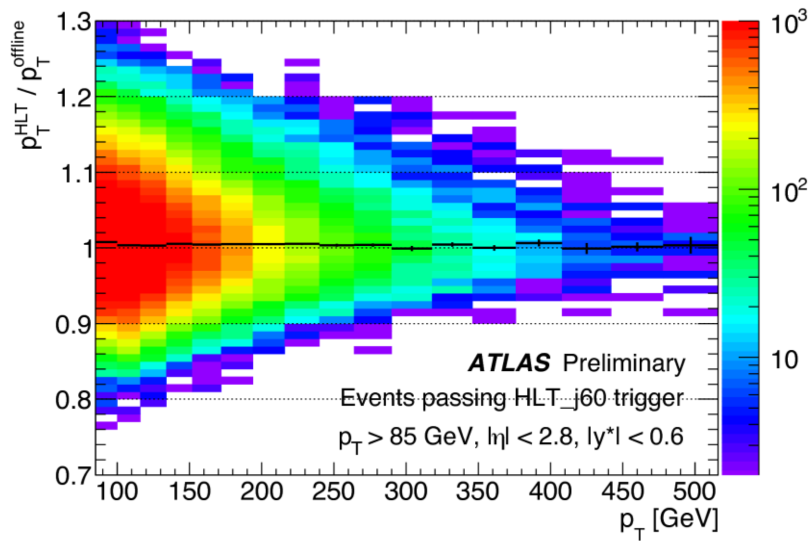


Trigger level dijet resonance analysis

- Trigger directly on lower-energy jets and record only a portion of the event
  - Use L1 trigger to identify candidate events
  - Record jet four-momentum and some jet substructure information, but little other event information
- Required dedicated jet calibration for partially built events
- Background calculated with fit to dijet mass spectrum

Average prescale: 2300

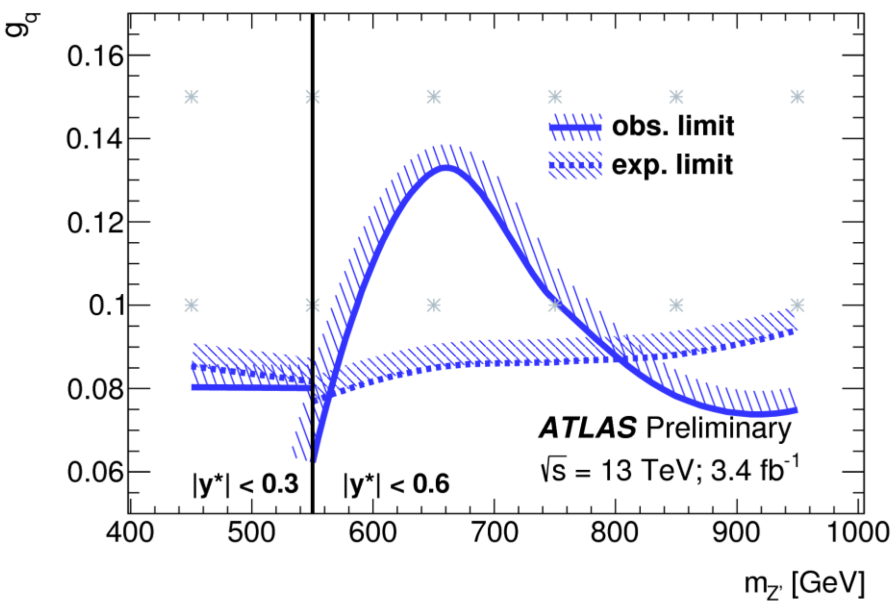


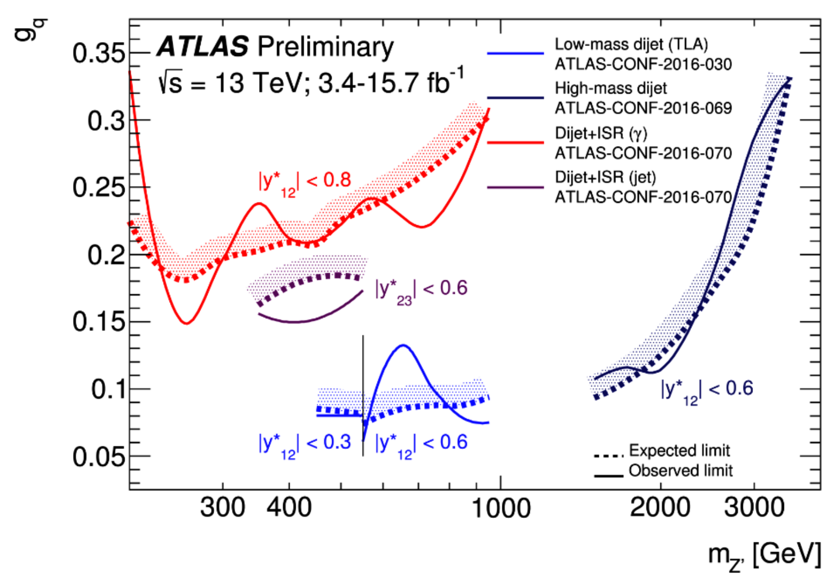


Trigger level dijet resonance analysis

- Analysis in two signal regions:
  - $|y^*| < 0.3$ & $|y^*| < 0.6$
  - In both cases leading-jet p_T > 185 GeV for full L1 efficiency
- Calculate limits at several points in the g_q-m_{jj} plane

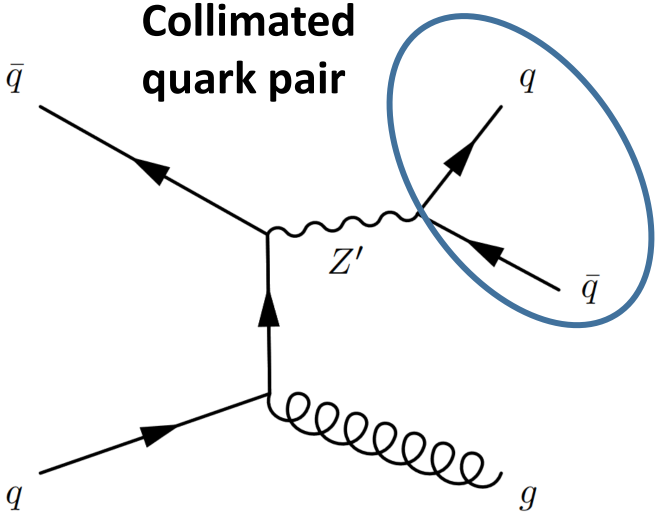
m





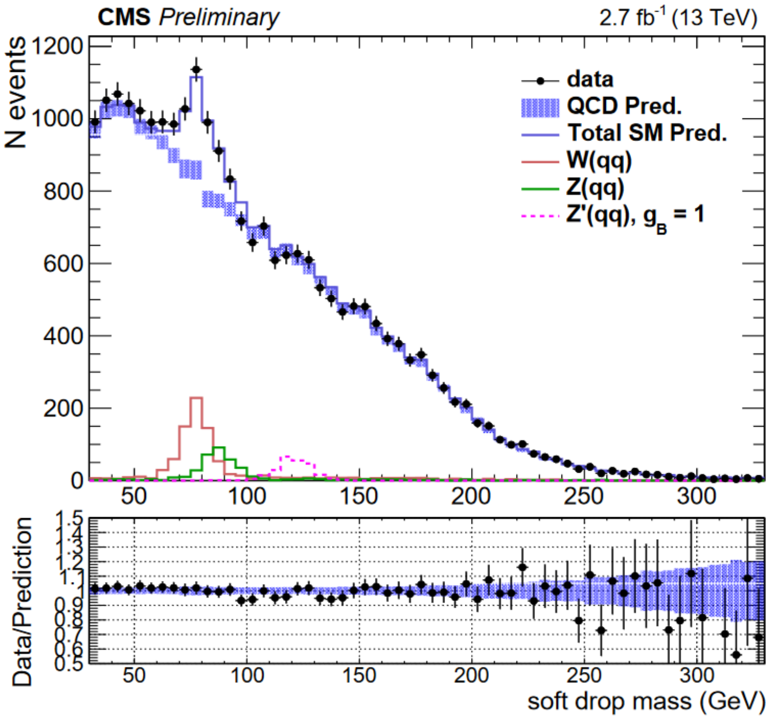
Very boosted light dijet resonance

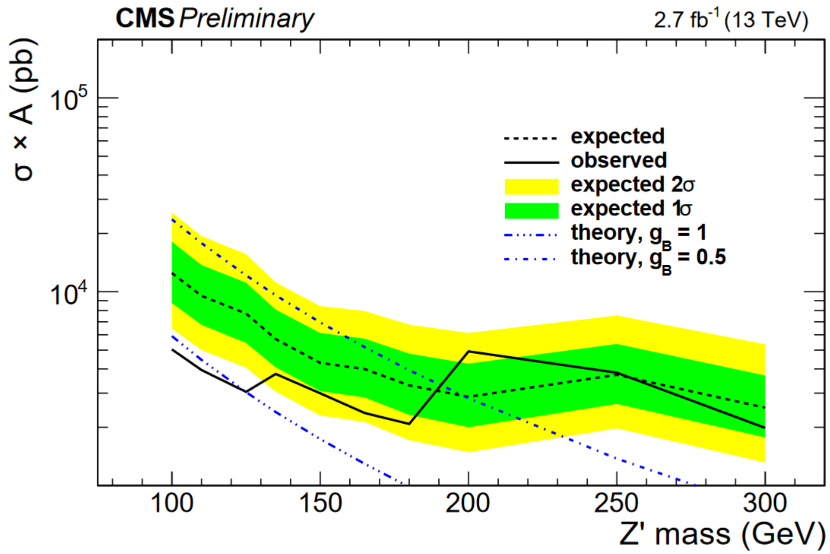
- Z' recoiling off ISR jet and decaying to quarks
  - Quark pair reconstructed as a single jet
- Trigger on H_T or (relatively high) p_T of jet
- Z' initiated jet as leading jet (mass $m_{Z'}$) with 2-prong substructure
- Background calculated using data-driven QCD scaling sideband method



Very boosted light dijet resonance

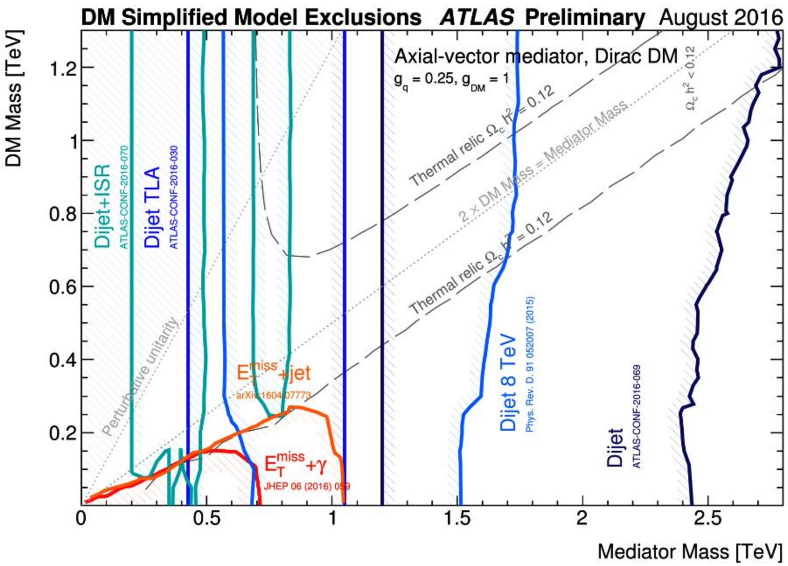
- Set limits for with 100 GeV < $m_{Z'}$ < 300 GeV
- First limits below 140 GeV and highest sensitivity up to 300 GeV

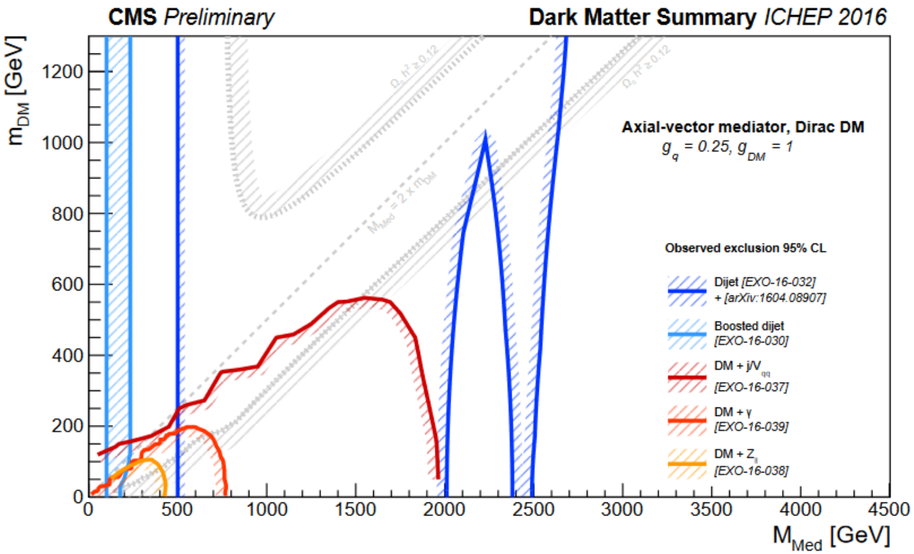




Combined Excluded Regions

- E_T^{miss} + X and dijet searches complement one another, exploiting as much of the mass range provided by the collisions as possible
- Both experiments working to expand "as possible" to lower masses





Dark Matter in LLP Searches

- "Long-lived" = decays within or outside of detector volume
- Long-lived particles (LLPs) appear in a variety of models and can gain their long lifetimes via a variety of mechanisms
  - Nearly conserved quantities, small couplings, phase-space suppression
- Many LLP producing models include DM candidates
  - Produced in association with the LLP, mediate interactions, result from a charged LLP decay
- LLP signatures tend to be unusual and require dedicated searches
  - May be E_T^{miss} triggered, but focus in on the LLP

Example LLP Signatures

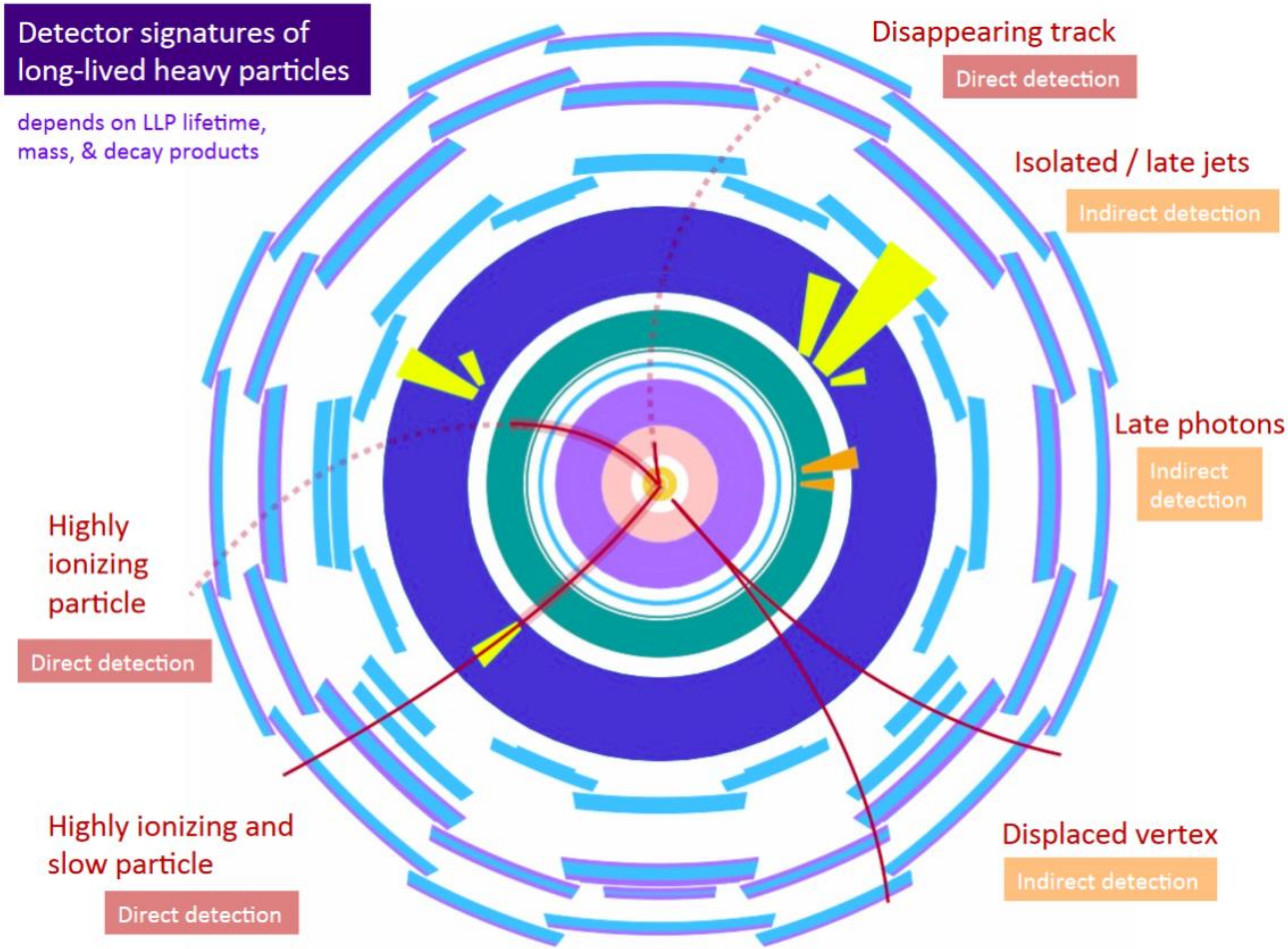


Figure credit: Laura Jeanty

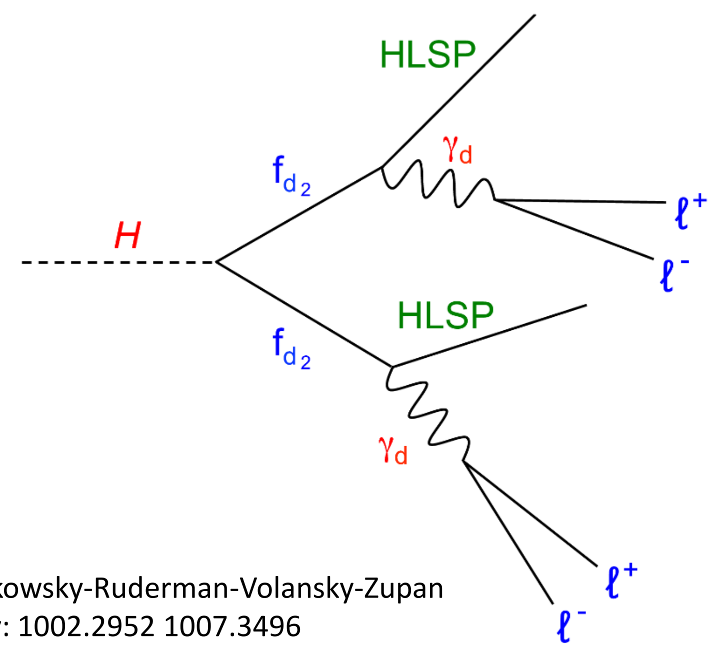
ATLAS-CONF-2016-042

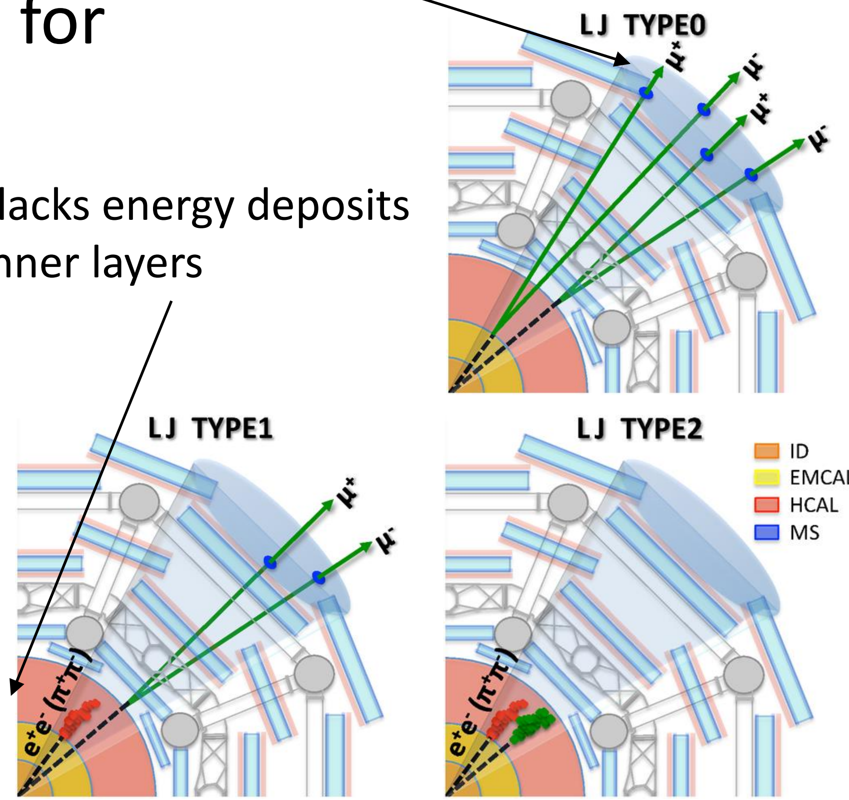
Displaced Lepton Jets

- Search for collimated pairs of leptons (lepton jets) as in FRVZ* models
- Uses specialized triggers for displaced objects

Decay products all within a $\Delta R < 0.5$ cone

Jet lacks energy deposits in inner layers





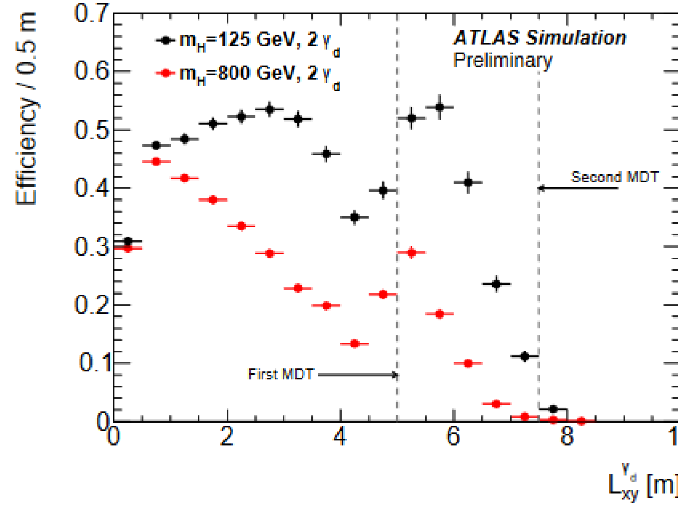
*Falkowsky-Ruderman-Volansky-Zupan
arXiv: 1002.2952 1007.3496

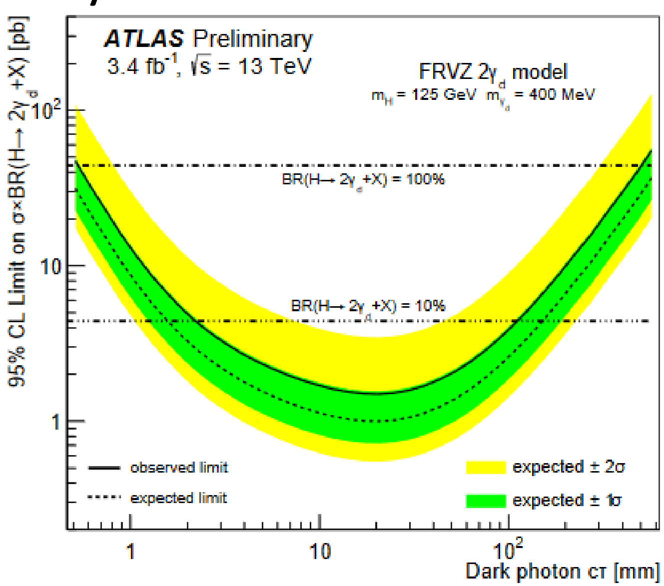
ATLAS-CONF-2016-042

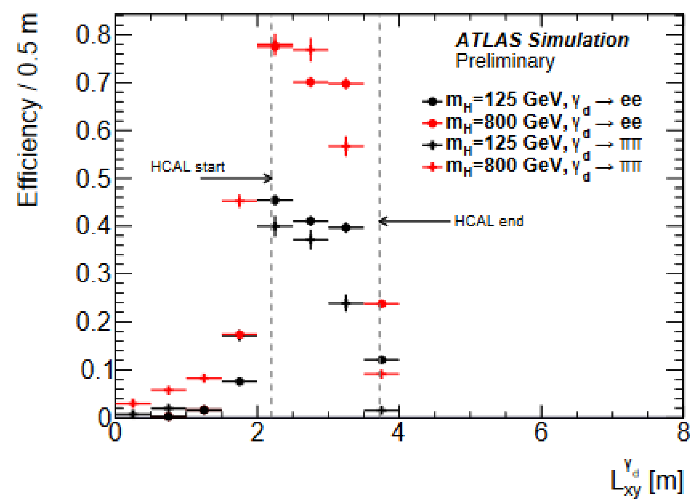
ATLAS EXPERIMENT

Displaced Lepton Jets

- Selection efficiency depends on γ_d decay position
- Background estimated via ABCD method using
  - $|\Delta\phi|$ between the two lepton jets
  - Sum of all ID track p_T within ΔR cone of the LJs (for p_T > 500 MeV)
- Limits set for both 2 γ_d and 4 γ_d decays







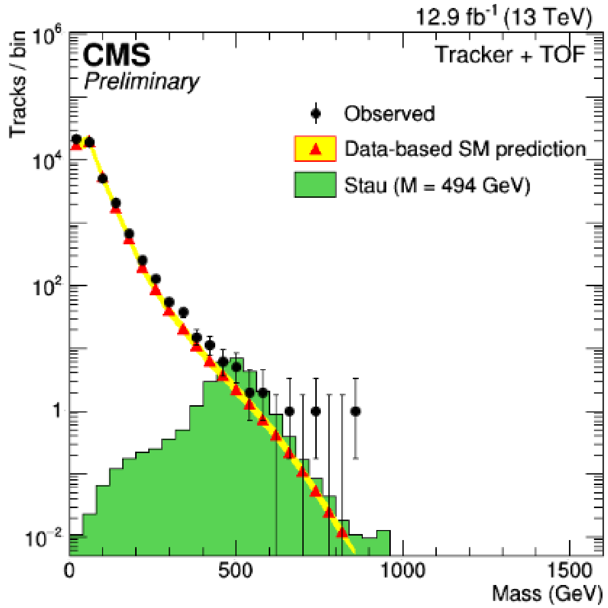
Heavy Stable Charged Particles

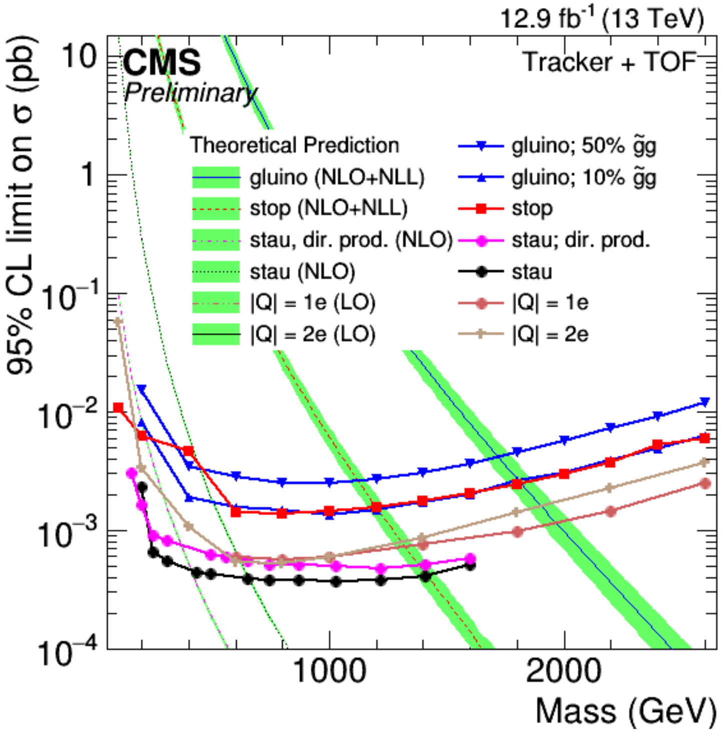
- Heavy Stable Charged Particles (HSCP) are low β particles which may have non-integer charge
  - Discovery would suggest non-WIMP DM, such as gravitinos, resulting from HSCP decay to LSP + x
- Low β → long time-of-flight to outer systems
- Highly ionizing → large $\frac{dE}{dx}$
- Searches frequently focus on R-hadrons (hadronized gluinos or squarks) which may change sign or become neutral as they propagate

EXO-16-036-pas

Heavy Stable Charged Particles Search

- Search for singly and multiply charged heavy stable charged particles (both R-hadrons and lepton-like HSCPs)
- Trigger on E_T^{miss} or a high-p_T "muon", two types of tracks
  - Inner tracker only
  - Inner tracker + muon system

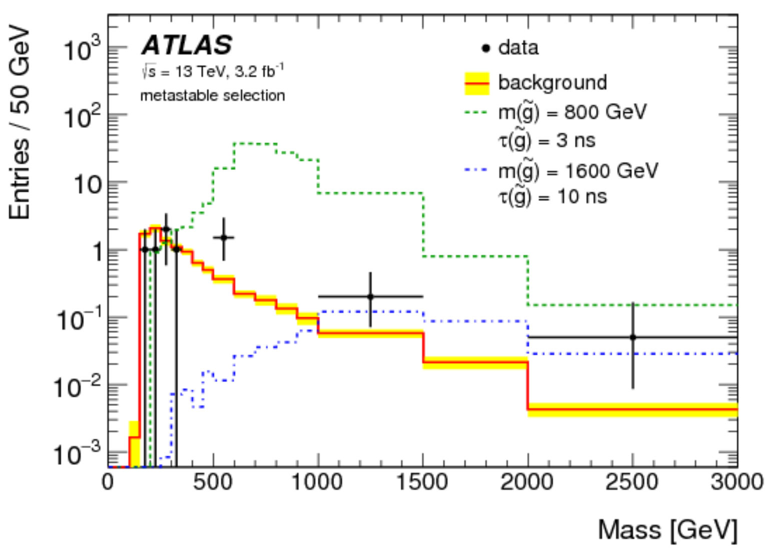


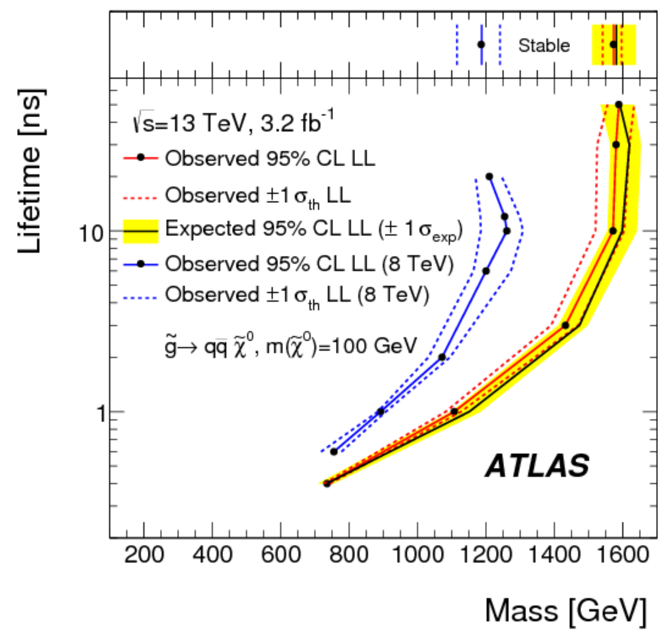


Phys. Rev. D 93, 112015 (2016)

Metastable heavy charged particles

- Search for R-hadrons with lifetimes from O(1ns)-O(10ns), i.e. decays within the volume of the detector
- Trigger with 70 GeV E_T^{miss} trigger
  - 65% efficiency at 50 ns , 95% efficient at 0.4 ns lifetimes
  - Estimate background via templates developed in control regions





Complementary ATLAS stable R-hadron search: Phys. Lett. B Vol. 760, 647-665

Conclusions

- Collider experiments provide means of searching for DM other than missing energy
- Challenges posed by trigger rates drive innovation in dijet resonance studies
- LLP searches often not explicitly DM searches but frequently feature DM candidates
- Unusual signatures open to reinterpretation in variety of models

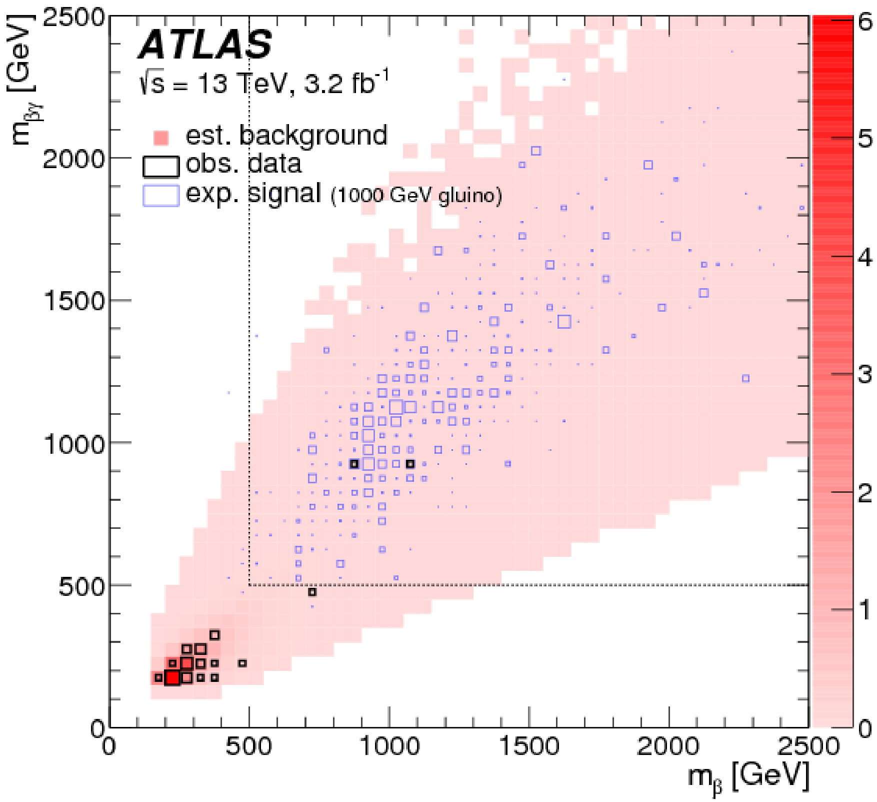
Searches active and ongoing on the LHC!

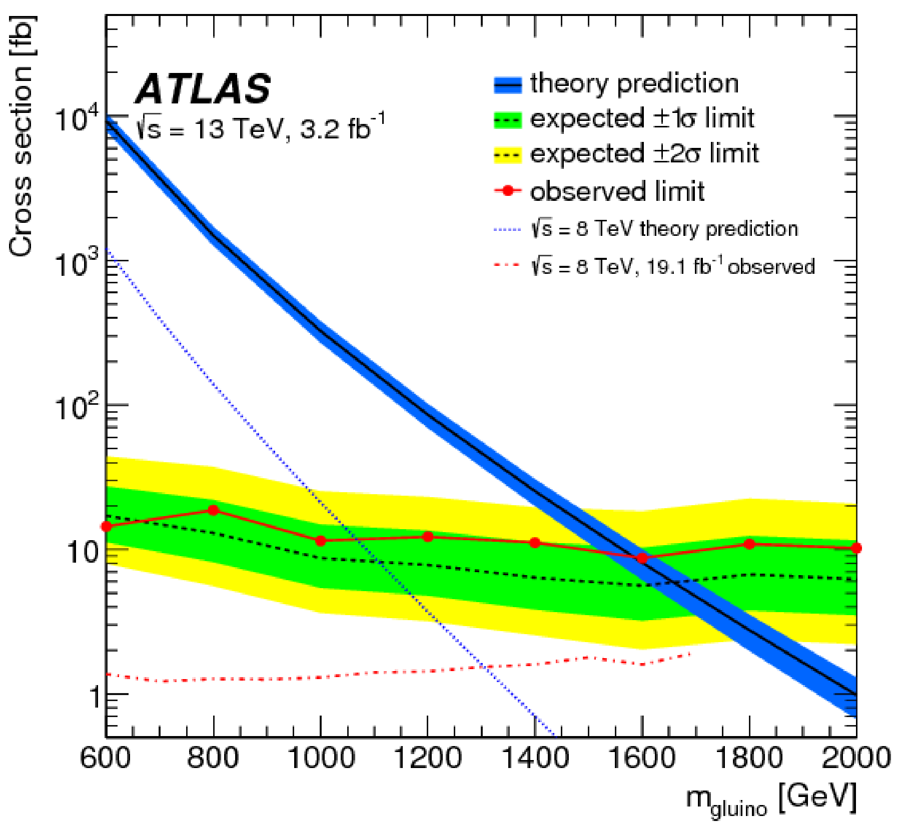
Backup

Physics Letters B (2016), pp. 647-665

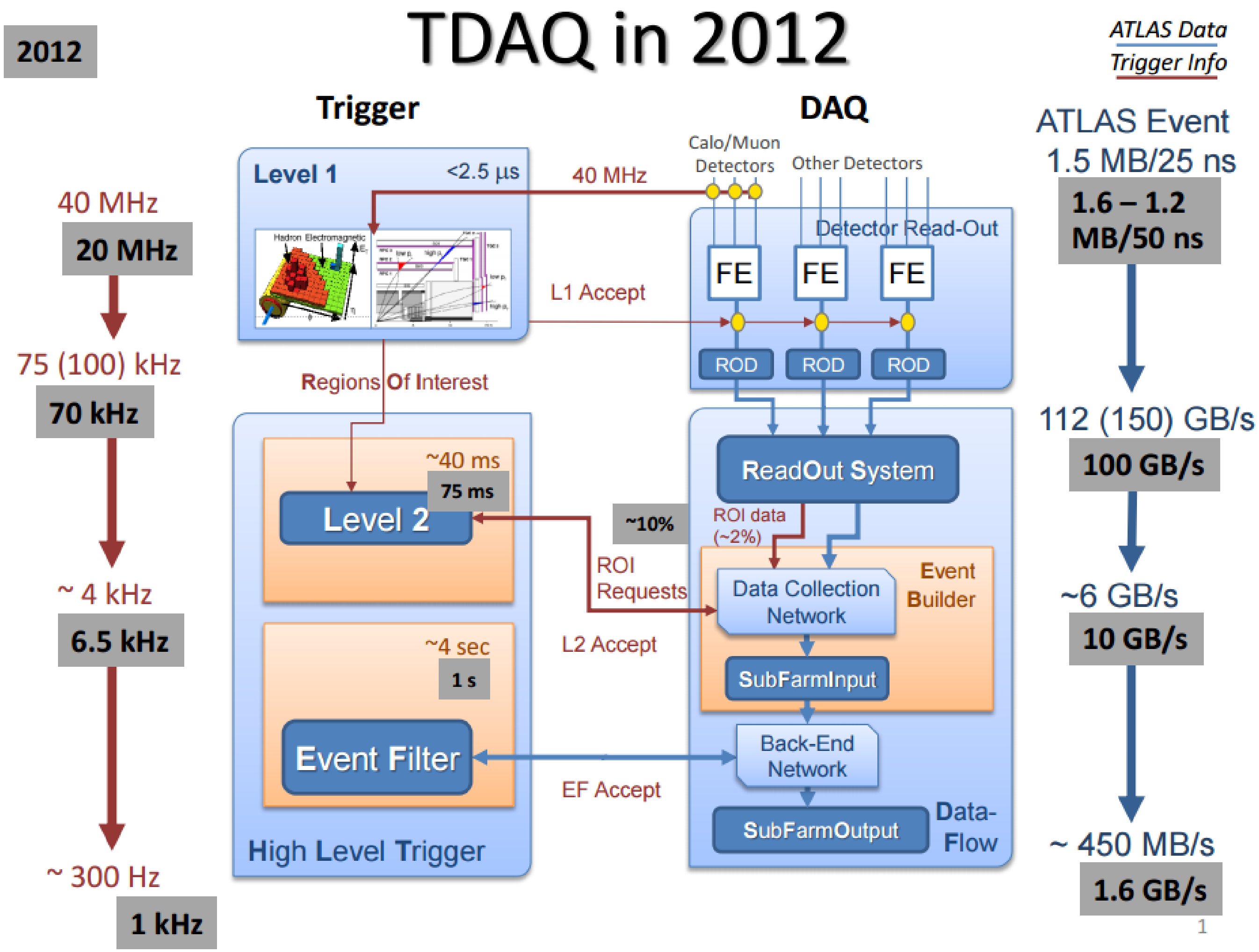
Heavy Long Lived Charged Hadrons

- Similar to previous search, with time-of-flight to the calorimeter used to aid in identification of particles
- Cut on the β–$\beta\gamma$ plane to isolate signal region

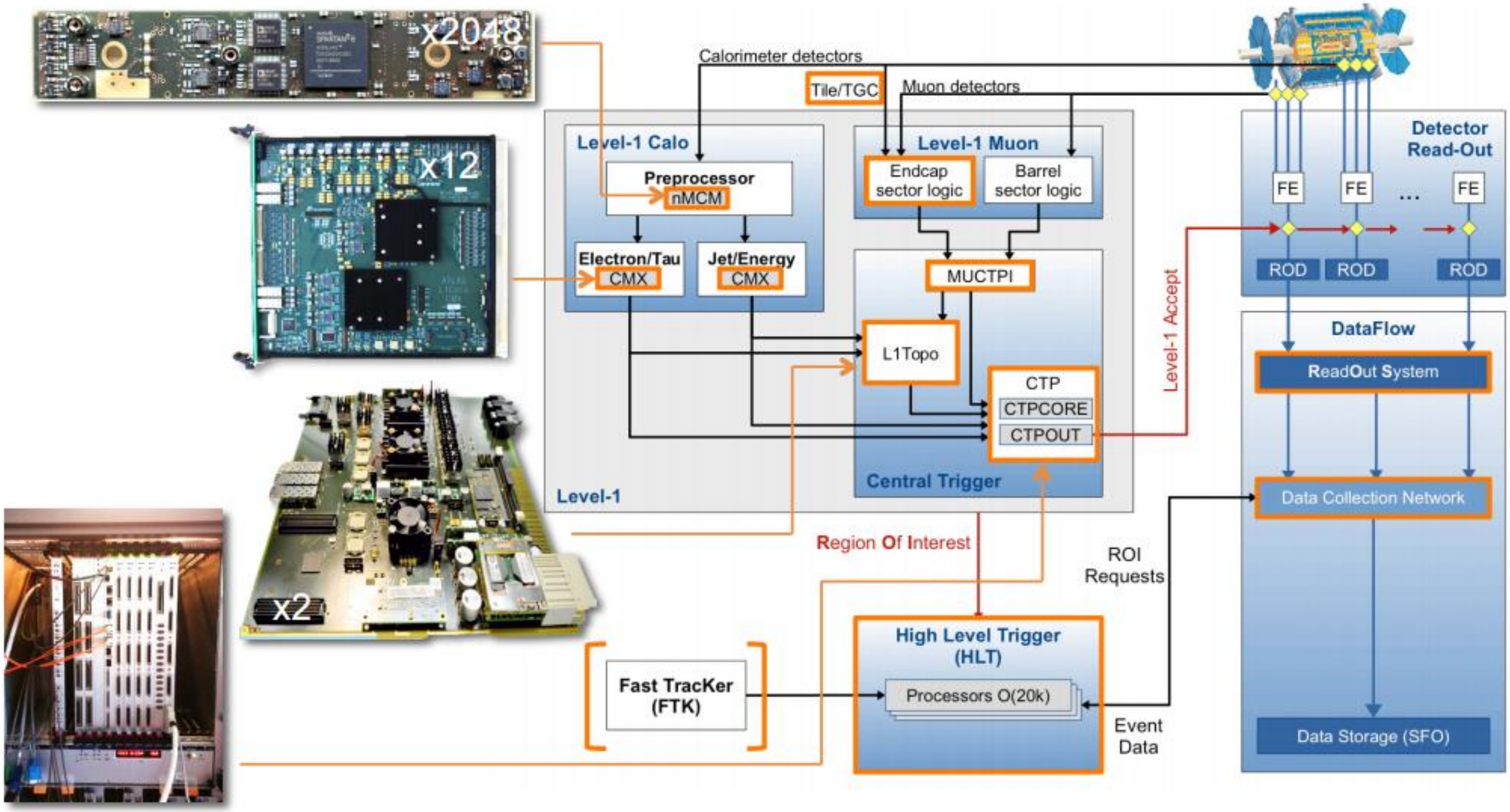




ATLAS Trigger System 2012



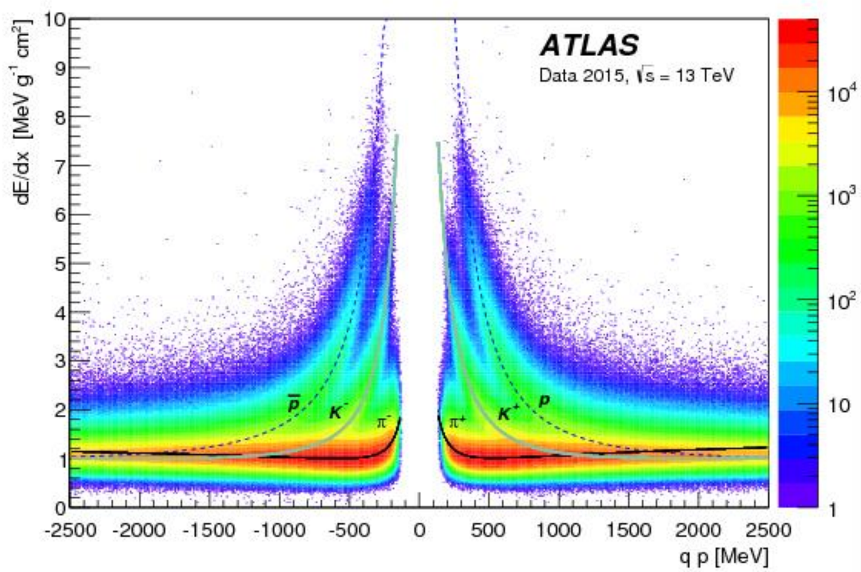
ATLAS Trigger System 2015



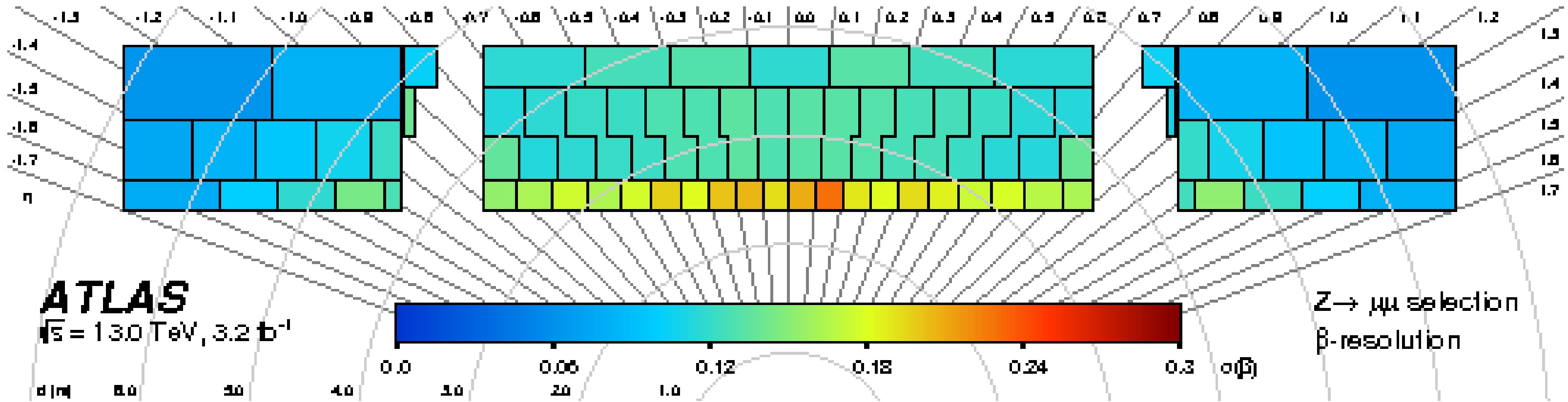
LJ LLP Triggers

- Narrow-Scan:
  - New in 2015
  - Requires single L1 muon item (most triggers require several)
  - Scan in narrow cone (using only part of detector info) around first muon to find a second muon with no matching ID track
- Tri-muon MS-only:
  - Require three L1 muon RoIs in a narrow cone and reconstruct three muons with no associated ID tracks or jets
- CalRatio:
  - Require a L1 TAU item (narrow than a L1 jet item, appropriate for a displaced decay)
  - Require a reconstructed jet to lack large EM energy deposits and associated ID tracks

HSCP mass and lifetime



- Ionization energy loss and momentum measurements are combined to determine masses
- ToF measurement to calorimetry identify slow moving particles

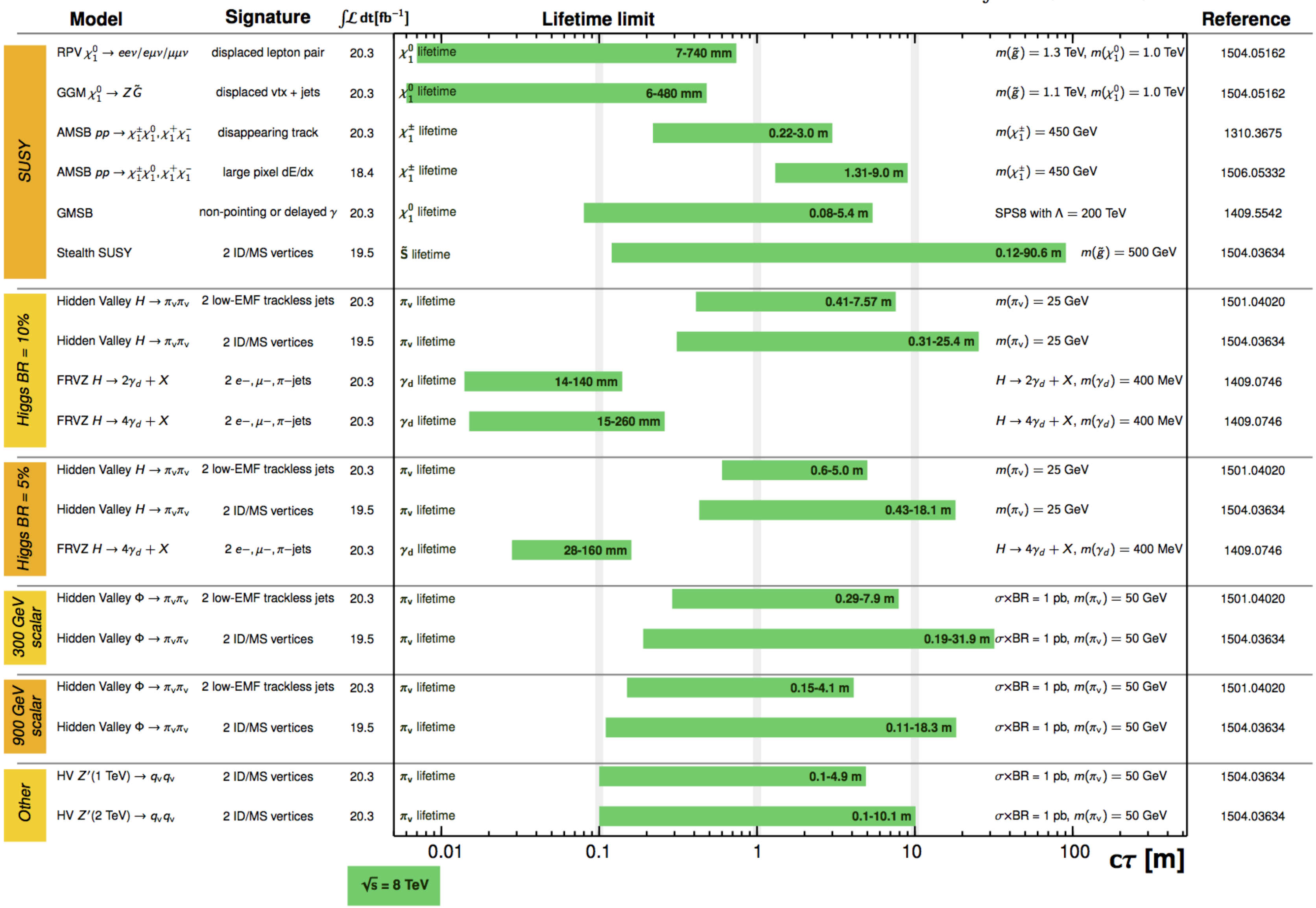


ATLAS Long-lived Particle Searches* - 95% CL Exclusion

Status: July 2015

ATLAS Preliminary

$\int \mathcal{L} dt = (18.4 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8$ TeV



*Only a selection of the available lifetime limits on new states is shown.

ATLAS Exotics Searches* - 95% CL Exclusion

Status: August 2016

ATLAS Preliminary

$\int \mathcal{L}\,dt = (3.2 - 20.3)$ fb^{-1} $\sqrt{s}$ = 8, 13 TeV

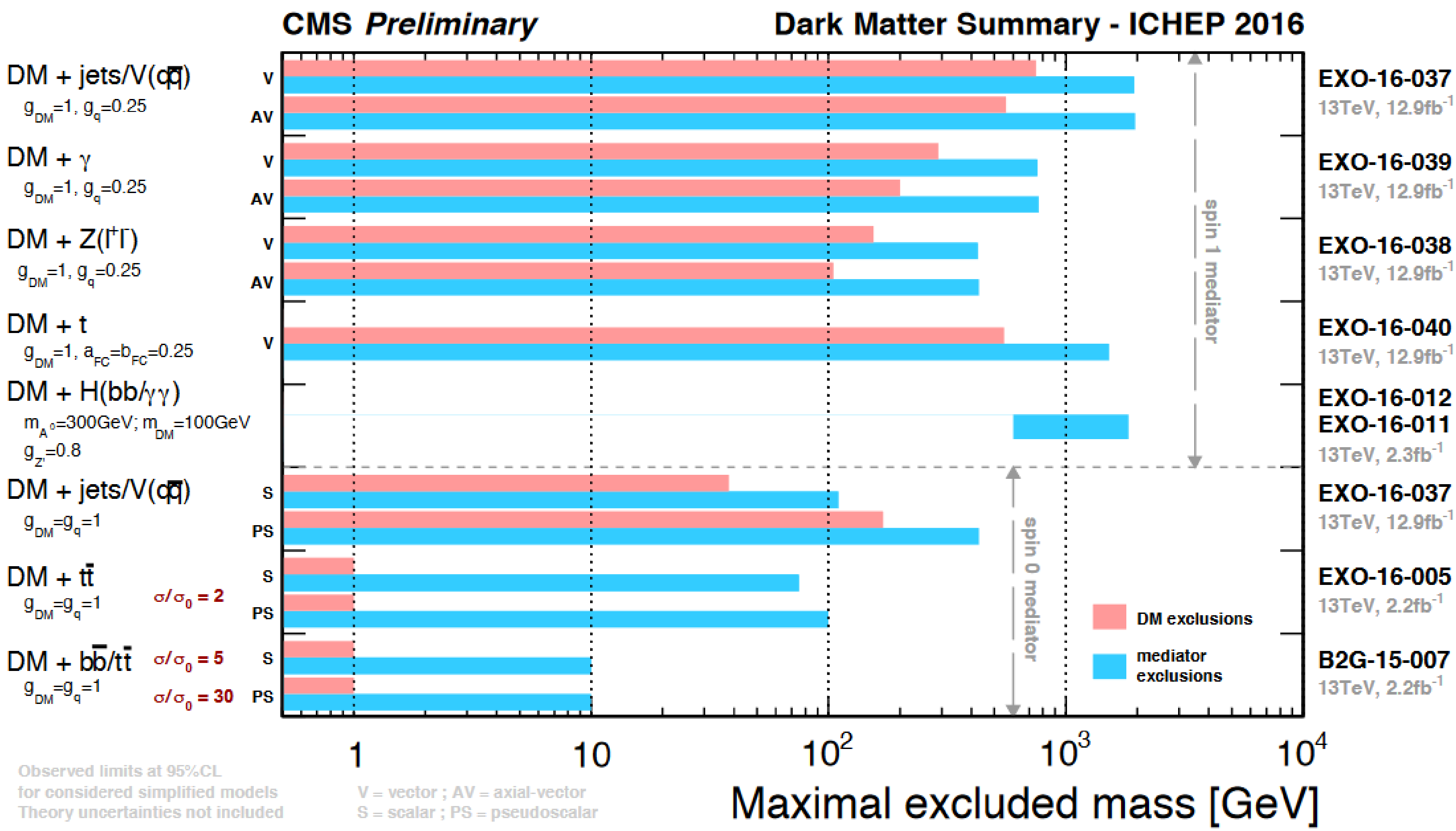
	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	3.2	M_D 6.58 TeV	$n = 2$	1604.07773
	ADD non-resonant $\ell\ell$	2 e,μ	–	–	20.3	M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH $\to \ell q$	1 e,μ	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	15.7	M_{th} 8.7 TeV	$n = 6$	ATLAS-CONF-2016-069
	ADD BH high $\sum p_T$	≥ 1 e,μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \ell\ell$	2 e,μ	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	3.2	G_{KK} mass 3.2 TeV	$k/\overline{M}_{Pl} = 0.1$	1606.03833
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e,μ	1 J	Yes	13.2	G_{KK} mass 1.24 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2016-062
	Bulk RS $G_{KK} \to HH \to bbbb$	–	4 b	–	13.3	G_{KK} mass 360-860 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2016-049
	Bulk RS $g_{KK} \to tt$	1 e,μ	≥ 1 b, ≥ 1J/2j	Yes	20.3	g_{KK} mass 2.2 TeV	BR = 0.925	1505.07018
	2UED / RPP	1 e,μ	≥ 2 b, ≥ 4 j	Yes	3.2	KK mass 1.46 TeV	Tier (1,1), BR($A^{(1,1)} \to tt$) = 1	ATLAS-CONF-2016-013
Gauge bosons	SSM $Z' \to \ell\ell$	2 e,μ	–	–	13.3	Z' mass 4.05 TeV		ATLAS-CONF-2016-045
	SSM $Z' \to \tau\tau$	2 τ	–	–	19.5	Z' mass 2.02 TeV		1502.07177
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	Z' mass 1.5 TeV		1603.08791
	SSM $W' \to \ell\nu$	1 e,μ	–	Yes	13.3	W' mass 4.74 TeV		ATLAS-CONF-2016-061
	HVT $W' \to WZ \to qq\nu\nu$ model A	0 e,μ	1 J	Yes	13.2	W' mass 2.4 TeV	$g_V = 1$	ATLAS-CONF-2016-082
	HVT $W' \to WZ \to qqqq$ model B	–	2 J	–	15.5	W' mass 3.0 TeV	$g_V = 3$	ATLAS-CONF-2016-055
	HVT $V' \to WH/ZH$ model B	multi-channel			3.2	V' mass 2.31 TeV	$g_V = 3$	1607.05621
	LRSM $W'_R \to tb$	1 e,μ	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	0 e,μ	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	15.7	Λ 19.9 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2016-069
	CI $\ell\ell qq$	2 e,μ	–	–	3.2	Λ 25.2 TeV	$\eta_{LL} = -1$	1607.03669
	CI $uutt$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	20.3	Λ 4.9 TeV	$\lvert C_{RR}\rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e,μ	≥ 1 j	Yes	3.2	m_A 1.0 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 250$ GeV	1604.07773
	Axial-vector mediator (Dirac DM)	0 e,μ, 1 γ	1 j	Yes	3.2	m_A 710 GeV	g_q=0.25, g_χ=1.0, $m(\chi) < 150$ GeV	1604.01306
	$ZZ\chi\chi$ EFT (Dirac DM)	0 e,μ	1 J, ≤ 1 j	Yes	3.2	M_* 550 GeV	$m(\chi) < 150$ GeV	ATLAS-CONF-2015-080
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e,μ	≥1 b, ≥3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht + X$	1 e,μ	≥ 2 b, ≥ 3 j	Yes	20.3	T mass 855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY \to Wb + X$	1 e,μ	≥ 1 b, ≥ 3 j	Yes	20.3	Y mass 770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB \to Hb + X$	1 e,μ	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 735 GeV	isospin singlet	1505.04306
	VLQ $BB \to Zb + X$	2/≥3 e,μ	≥2/≥1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	1409.5500
	VLQ $QQ \to WqWq$	1 e,μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
	VLQ $T_{5/3}T_{5/3} \to WtWt$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	3.2	$T_{5/3}$ mass 990 GeV		ATLAS-CONF-2016-032
Excited fermions	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	3.2	q^* mass 4.4 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1512.05910
	Excited quark $q^* \to qg$	–	2 j	–	15.7	q^* mass 5.6 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2016-069
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	8.8	b^* mass 2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \to Wt$	1 or 2 e,μ	1 b, 2-0 j	Yes	20.3	b^* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	3 e,μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e,μ,τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LSTC $a_T \to W\gamma$	1 e,μ, 1 γ	–	Yes	20.3	a_T mass 960 GeV		1407.8150
	LRSM Majorana ν	2 e,μ	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to ee$	2 e (SS)	–	–	13.9	$H^{\pm\pm}$ mass 570 GeV	DY production, BR($H_L^{\pm\pm} \to ee$)=1	ATLAS-CONF-2016-051
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e,μ,τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, BR($H_L^{\pm\pm} \to \ell\tau$)=1	1411.2921
	Monotop (non-res prod)	1 e,μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1509.08059

$\sqrt{s}$ = 8 TeV $\sqrt{s}$ = 13 TeV

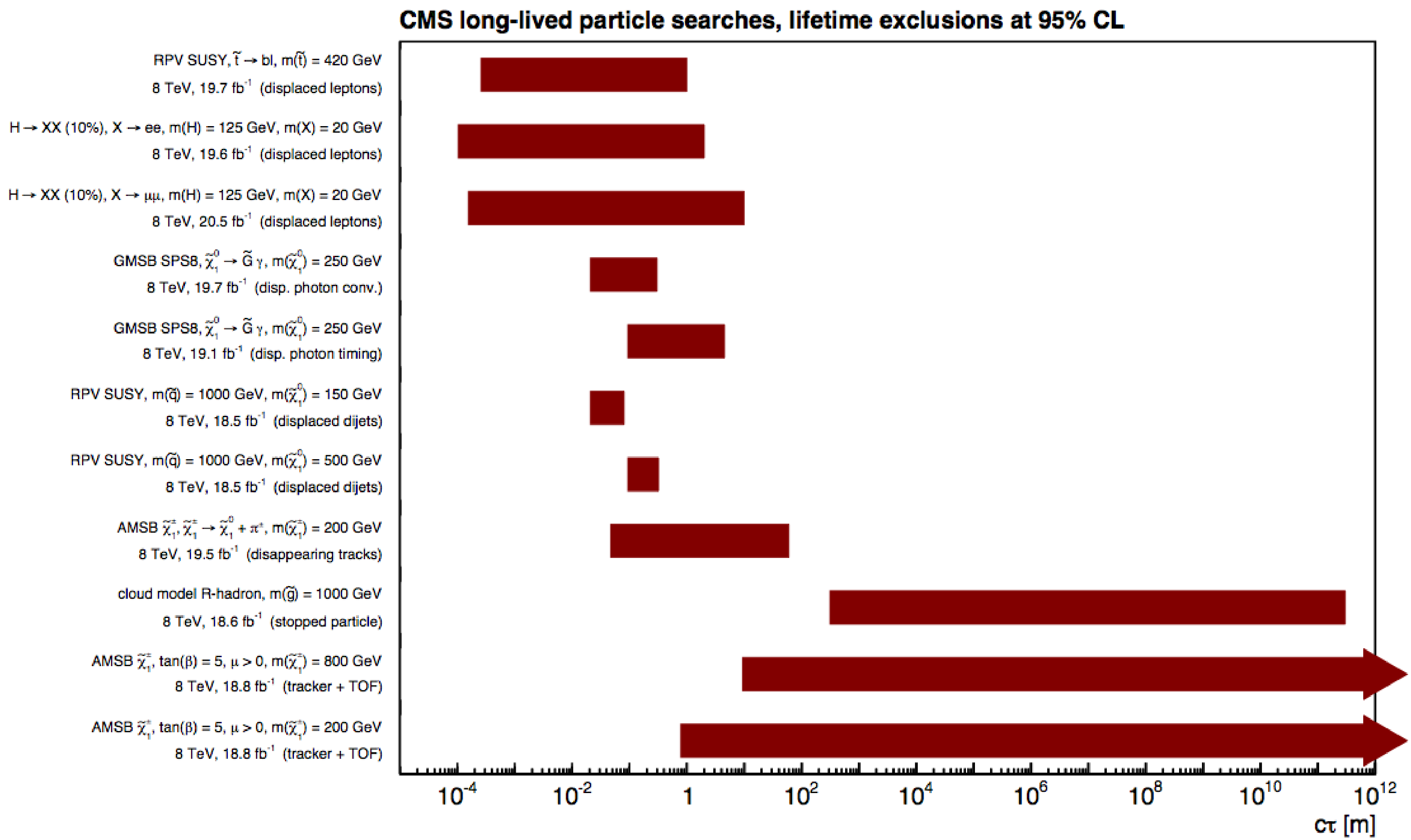
10^{-1} 1 10 **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

†Small-radius (large-radius) jets are denoted by the letter j (J).



CMS Preliminary
Dark Matter Summary - ICHEP 2016
DM + jets/V(qq̄)
g_{DM}=1, g_q=0.25
V
AV
DM + γ
g_{DM}=1, g_q=0.25
V
AV
DM + Z(l^+l^-)
g_{DM}=1, g_q=0.25
V
AV
DM + t
g_{DM}=1, a_{FC}=b_{FC}=0.25
V
DM + H(bb/γγ)
m_{A^0}=300GeV; m_{DM}=100GeV
$g_{Z'}$=0.8
DM + jets/V(qq̄)
g_{DM}=g_q=1
S
PS
DM + tt̄
g_{DM}=g_q=1
σ/σ_0 = 2
S
PS
DM + bb̄/tt̄
g_{DM}=g_q=1
σ/σ_0 = 5
σ/σ_0 = 30
S
PS
EXO-16-037
13TeV, 12.9fb^{-1}
EXO-16-039
13TeV, 12.9fb^{-1}
EXO-16-038
13TeV, 12.9fb^{-1}
EXO-16-040
13TeV, 12.9fb^{-1}
EXO-16-012
EXO-16-011
13TeV, 2.3fb^{-1}
EXO-16-037
13TeV, 12.9fb^{-1}
EXO-16-005
13TeV, 2.2fb^{-1}
B2G-15-007
13TeV, 2.2fb^{-1}
spin 1 mediator
spin 0 mediator
DM exclusions
mediator exclusions
1
10
10^2
10^3
10^4
Maximal excluded mass [GeV]
Observed limits at 95%CL
for considered simplified models
Theory uncertainties not included
V = vector ; AV = axial-vector
S = scalar ; PS = pseudoscalar


CMS long-lived particle searches, lifetime exclusions at 95% CL
RPV SUSY, t̃ → bl, m(t̃) = 420 GeV
8 TeV, 19.7 fb⁻¹ (displaced leptons)
H → XX (10%), X → ee, m(H) = 125 GeV, m(X) = 20 GeV
8 TeV, 19.6 fb⁻¹ (displaced leptons)
H → XX (10%), X → μμ, m(H) = 125 GeV, m(X) = 20 GeV
8 TeV, 20.5 fb⁻¹ (displaced leptons)
GMSB SPS8, χ̃⁰₁ → G̃ γ, m(χ̃⁰₁) = 250 GeV
8 TeV, 19.7 fb⁻¹ (disp. photon conv.)
GMSB SPS8, χ̃⁰₁ → G̃ γ, m(χ̃⁰₁) = 250 GeV
8 TeV, 19.1 fb⁻¹ (disp. photon timing)
RPV SUSY, m(q̃) = 1000 GeV, m(χ̃⁰₁) = 150 GeV
8 TeV, 18.5 fb⁻¹ (displaced dijets)
RPV SUSY, m(q̃) = 1000 GeV, m(χ̃⁰₁) = 500 GeV
8 TeV, 18.5 fb⁻¹ (displaced dijets)
AMSB χ̃±₁, χ̃±₁ → χ̃⁰₁ + π±, m(χ̃±₁) = 200 GeV
8 TeV, 19.5 fb⁻¹ (disappearing tracks)
cloud model R-hadron, m(g̃) = 1000 GeV
8 TeV, 18.6 fb⁻¹ (stopped particle)
AMSB χ̃±₁, tan(β) = 5, μ > 0, m(χ̃±₁) = 800 GeV
8 TeV, 18.8 fb⁻¹ (tracker + TOF)
AMSB χ̃±₁, tan(β) = 5, μ > 0, m(χ̃±₁) = 200 GeV
8 TeV, 18.8 fb⁻¹ (tracker + TOF)
10⁻⁴
10⁻²
1
10²
10⁴
10⁶
10⁸
10¹⁰
10¹²
cτ [m]