

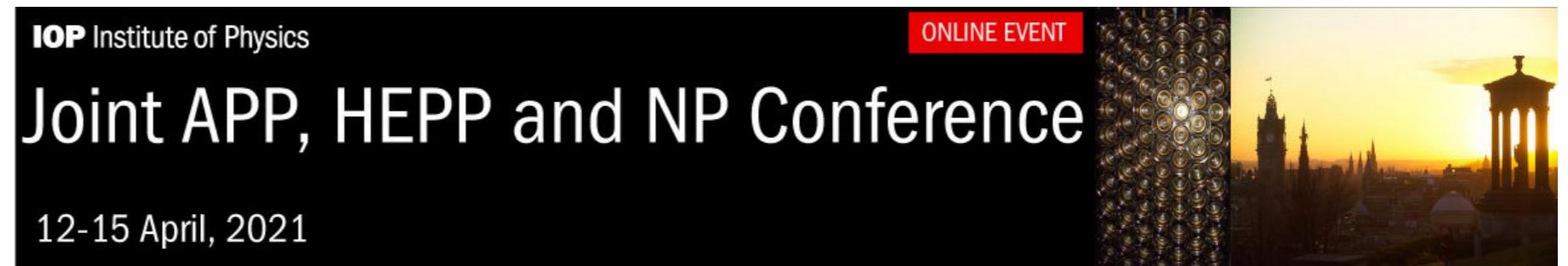


IOP Institute of Physics

Joint APP, HEPP and NP Conference

12-15 April, 2021

ONLINE EVENT

A black rectangular banner for the conference. At the top left is the IOP logo. In the top right corner is a red rectangular button with the white text "ONLINE EVENT". The main title "Joint APP, HEPP and NP Conference" is centered in large white font. Below it is the date "12-15 April, 2021". To the right of the text is a vertical column of small circular icons, likely representing particle detectors. The background of the banner shows a silhouette of a city skyline against a sunset sky.

Searches for BSM physics at the LHC

Yanyan Gao (University of Edinburgh)

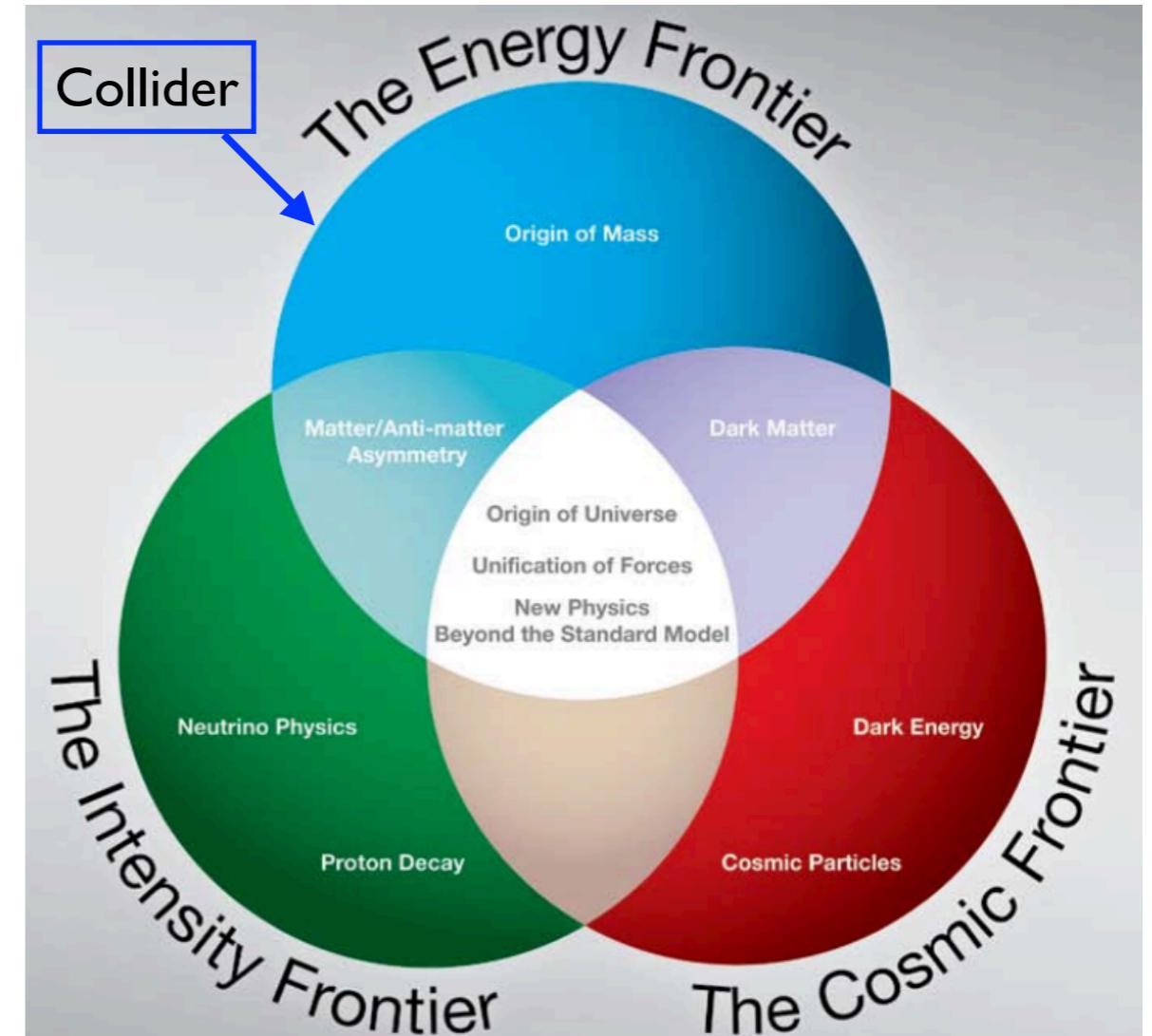
12-April-2021

IOP Joint APP, HEPP and NP Conference 2021



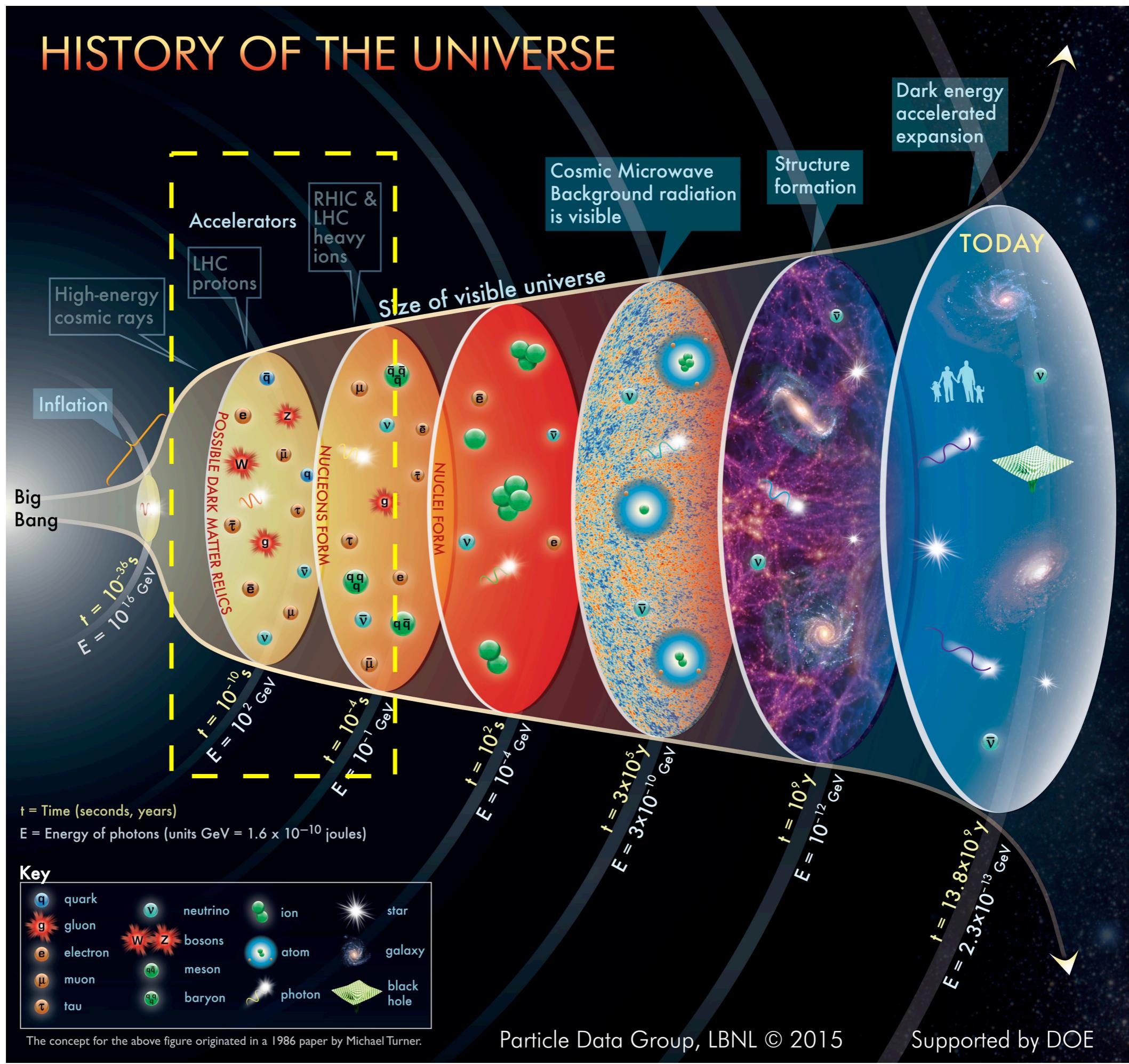
Setting the theme - BSM searches

- Dark matter and dark energy
- Abundance of matter over anti-matter
- Neutrino masses and origin
- Origin of EW symmetry breaking
- A more “natural” solution to the hierarchy problem
- Strong CP problem



“There is no experiment nor facility, proposed or conceivable, in the lab or in space, accelerator or non-accelerator driven, which can guarantee discoveries beyond the SM, and answers to the big questions of the field” (M.Mangano, 98th ECFA, November 2015)

HISTORY OF THE UNIVERSE

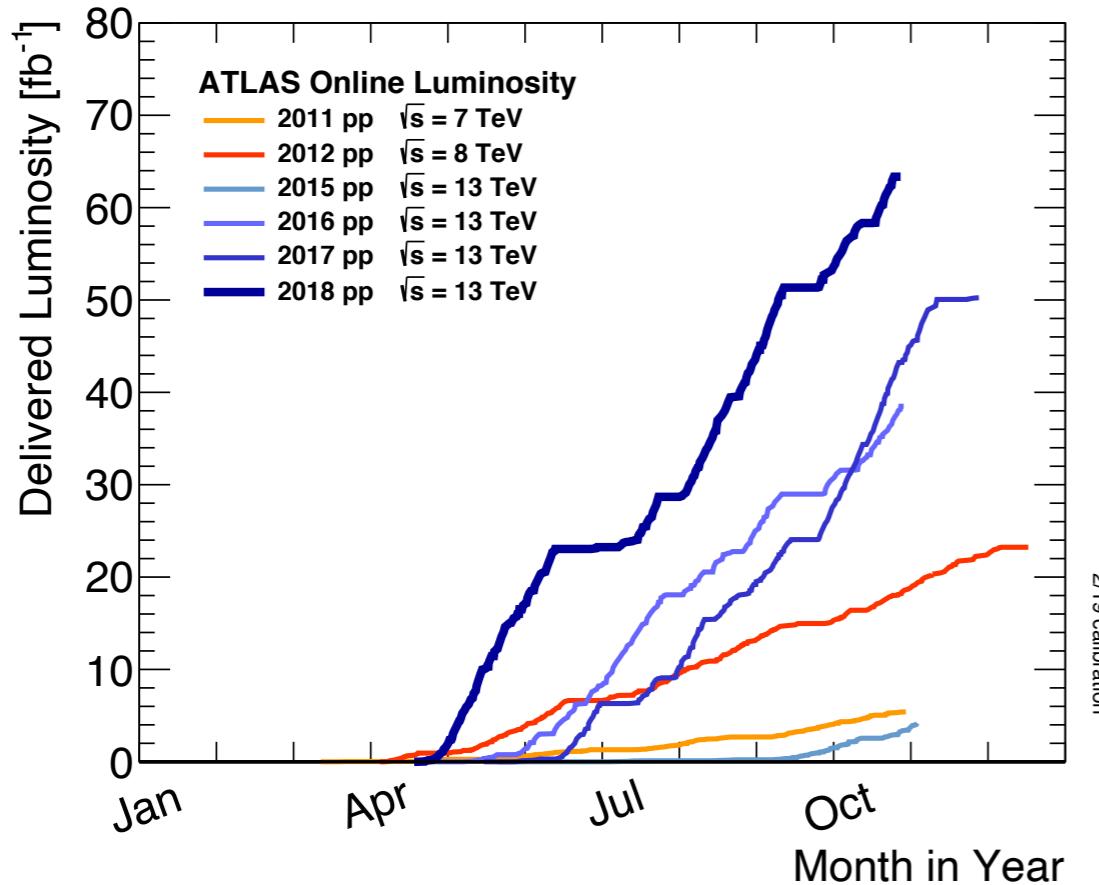


Setting the theme - BSM searches at the LHC

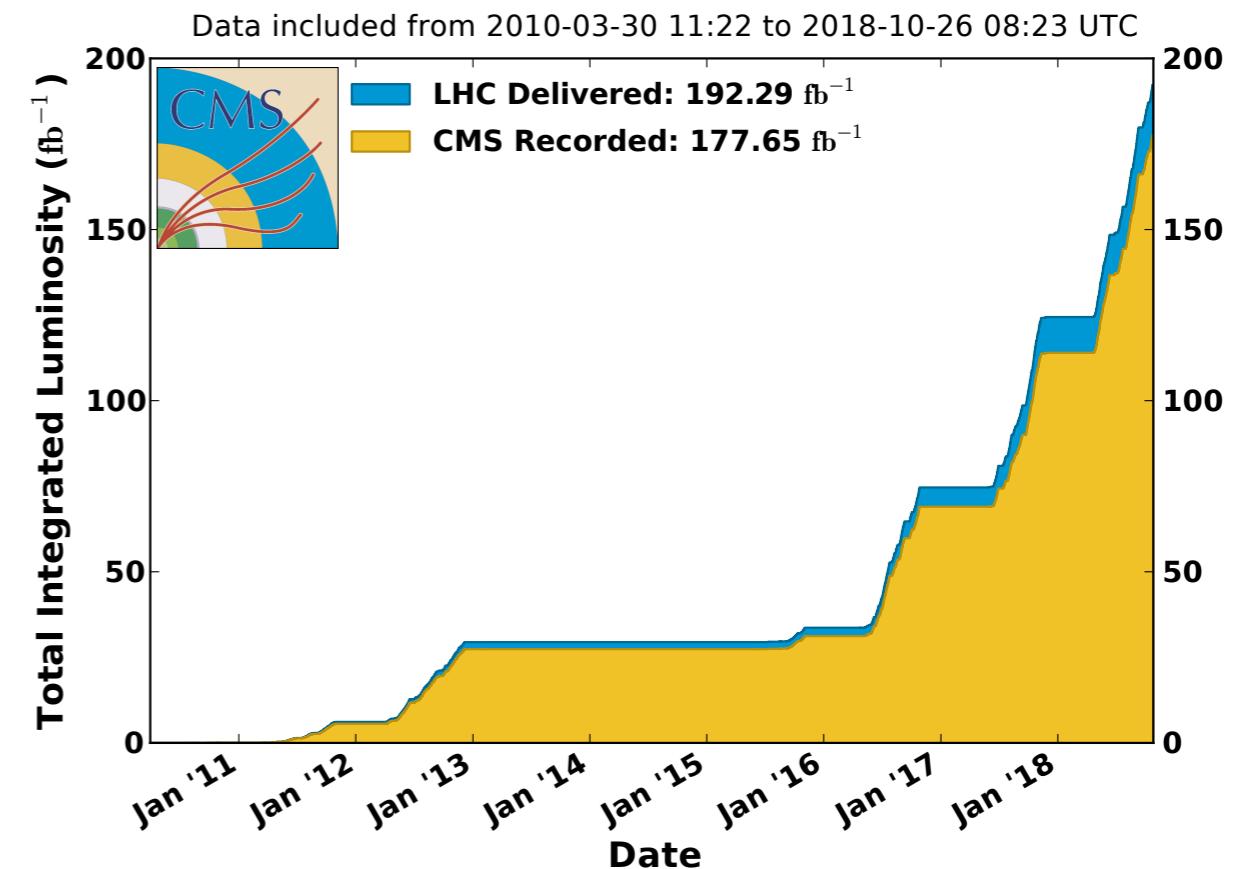
- There is an overwhelmingly large collection of BSM models to choose from
 - Non exhausted list: SUSY, extra dimensions, vector-like quarks, lepto-quarks...
 - Also: simplified models, minimal models, and EFT
 - Gauge invariance, UV-completion, existing experimental results provide the best guidance
 - The constraint can be very loose: many caveats and work-around
- LHC searches are signature-driven as a first principle
 - Search for **excesses in number of events** in a plethora of kinematic regions and for resonances from new particles, exploring the highest mass range possible → main focus of this talk
 - Perform **precision measurements** of SM parameters to search for deviations → not covered
- Challenges in interpreting LHC search results
 - There are numerous results with similar final states → not trivial to correlate or compare
 - Many searches take advantage of machine learning algorithms → non-trivial to interpret
 - ⇒ Present, and preserve, physics object efficiency/resolutions, and particle-level results

Run I+2 pp collision data

[Link to ATLAS Lumi public plot](#)



CMS Integrated Luminosity, pp, $\sqrt{s} = 7, 8, 13$ TeV



- Many key analyses are based on full Run I+Run-2 data

ATLAS/CMS: 140 fb⁻¹ at $\sqrt{s} = 13$ TeV

- Expect more results: many analyses are still analysing this legendary dataset

Highlight of the search results

- General remarks on the LHC DM searches, embedded in many BSM searches
- Highlight of recent searches results in
 - High mass/pT regions
 - SUSY
 - Long-lived particles (LLP)
- Areas not covered
 - BSM searches in dedicated quark-flavour sector → Eva Gersabeck's talk earlier
 - Dark sector scenarios → Phil Ilten's talk next
 - BSM searches using Higgs boson → Kristin Lohwasser's talk tomorrow
- For detailed information, especially the “how”, tune in the relevant parallel sessions
 - Also follow these experimental public webpages for complete list of results

[ATLAS public results](#)

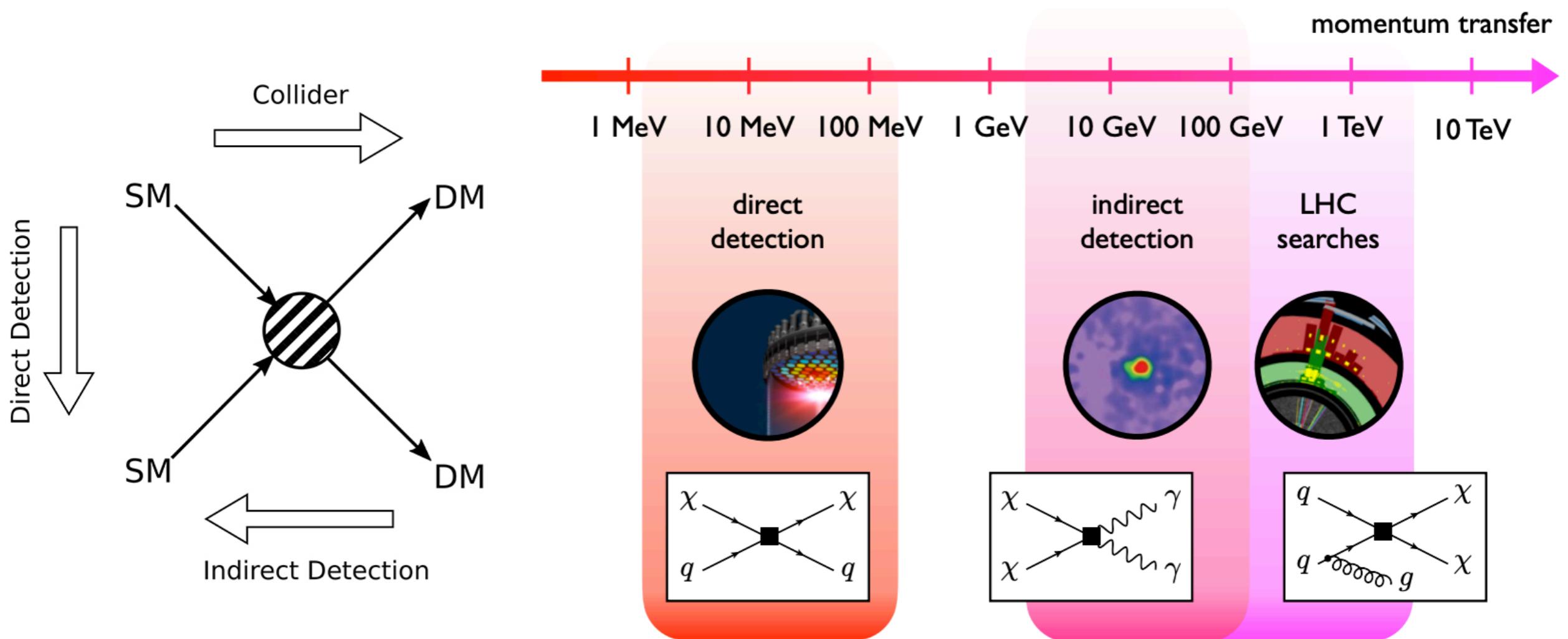
[CMS public results](#)

General remark on DM searches

- Dark matter represents one of the clear guidance for BSM physics
- Embedded in many BSM models, e.g. R-parity conserving SUSY, dark sector...
- LHC searches have gone much beyond the traditional MET+X regions

LHC Dark Matter Working Group: joint ATLAS/CMS/theory forum

Recommend: benchmark signal models, LHC DM results presentation and comparison with non-collider frontiers



DM searches - models and signatures*

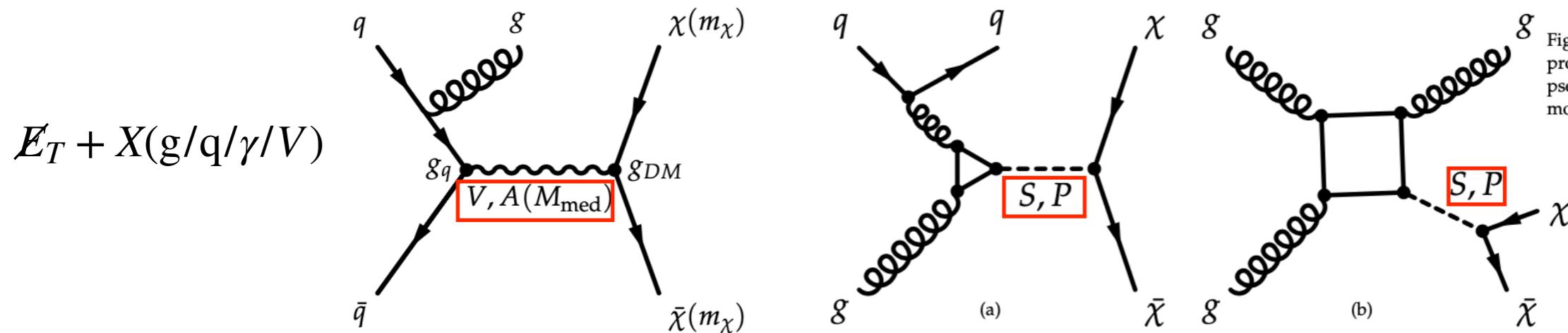
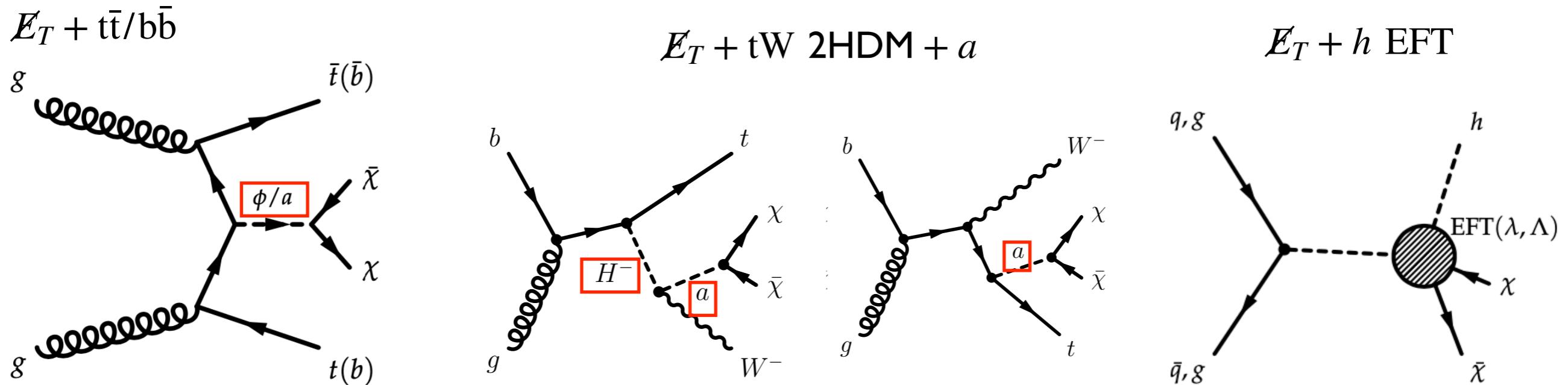


Figure 2.14: One-loop diagrams of processes exchanging a scalar (S) or pseudoscalar (P) mediator, leading to a mono-jet signature.



Can search for these BSM particles (mediators) in visible decays as well!

In many cases, the visible decay dominate the sensitivity

* non-exclusive list, much more at arXiv:1507.00966 (LHCdmWG)

High pT/mass region

A summary of search results - mass scale (non-SUSY)

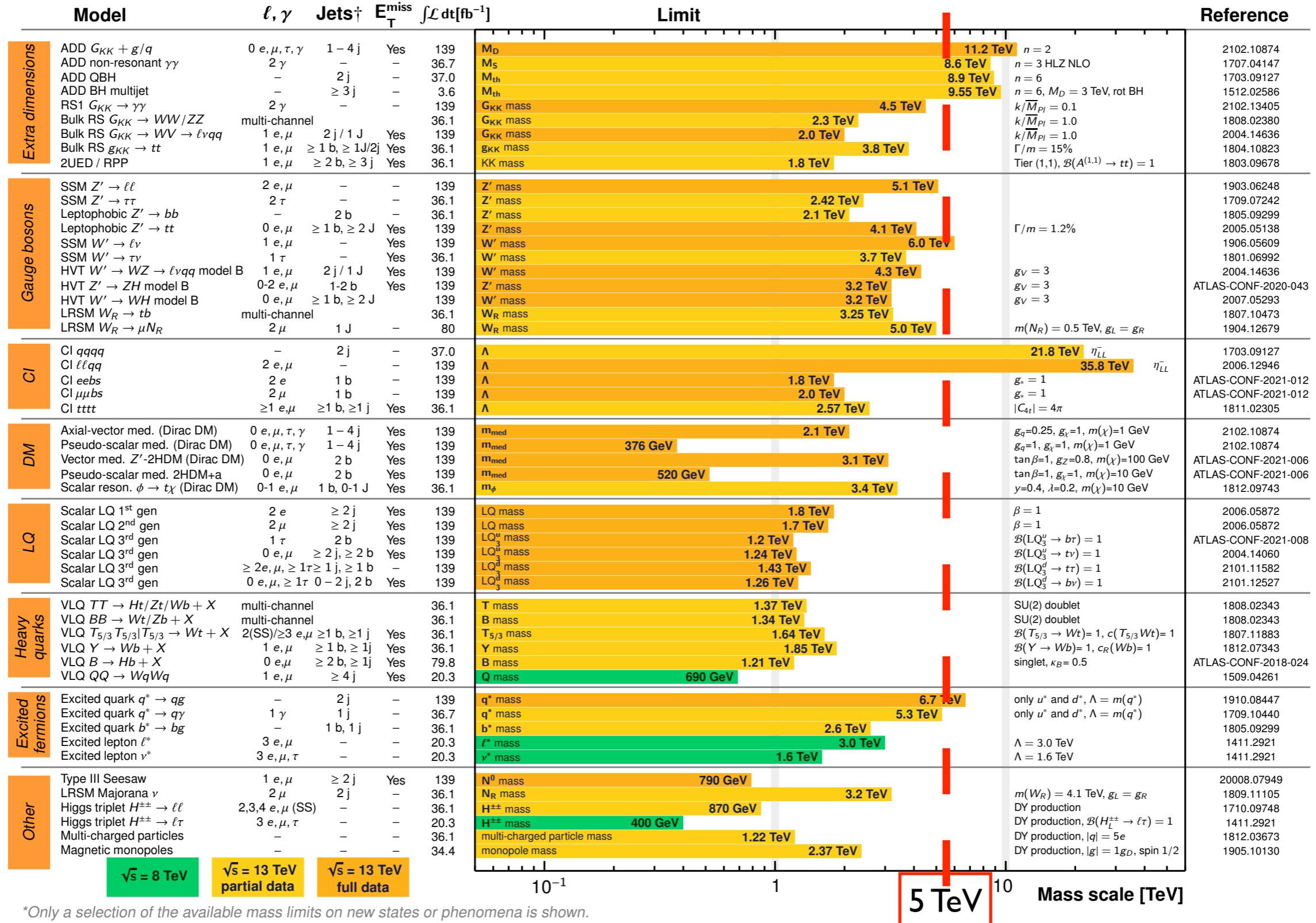
ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: March 2021

ATLAS Preliminary

$\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$

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

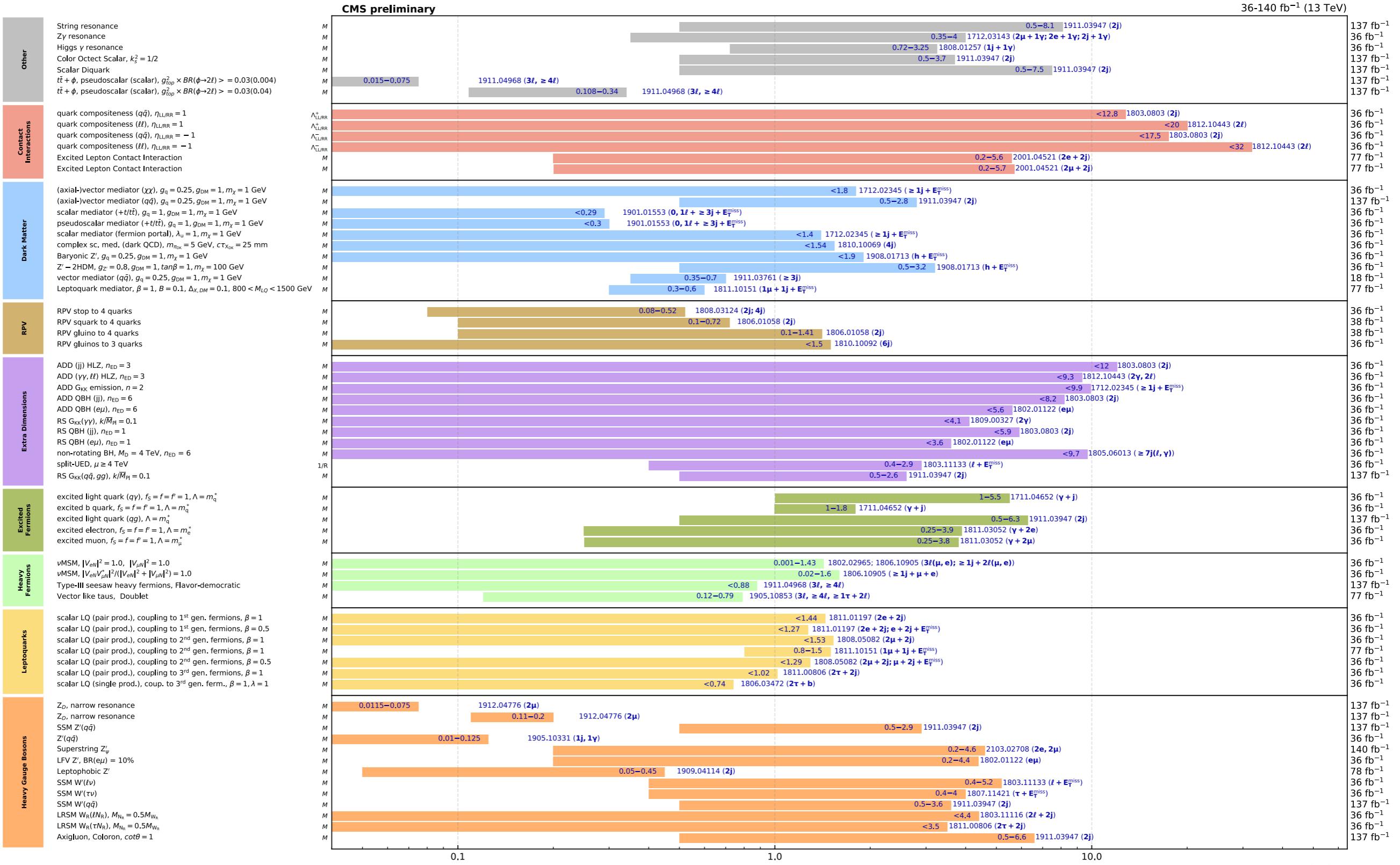


*Only a selection of the available mass limits on new states or phenomena is shown.

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

A summary of search results - mass scale (non-SUSY)

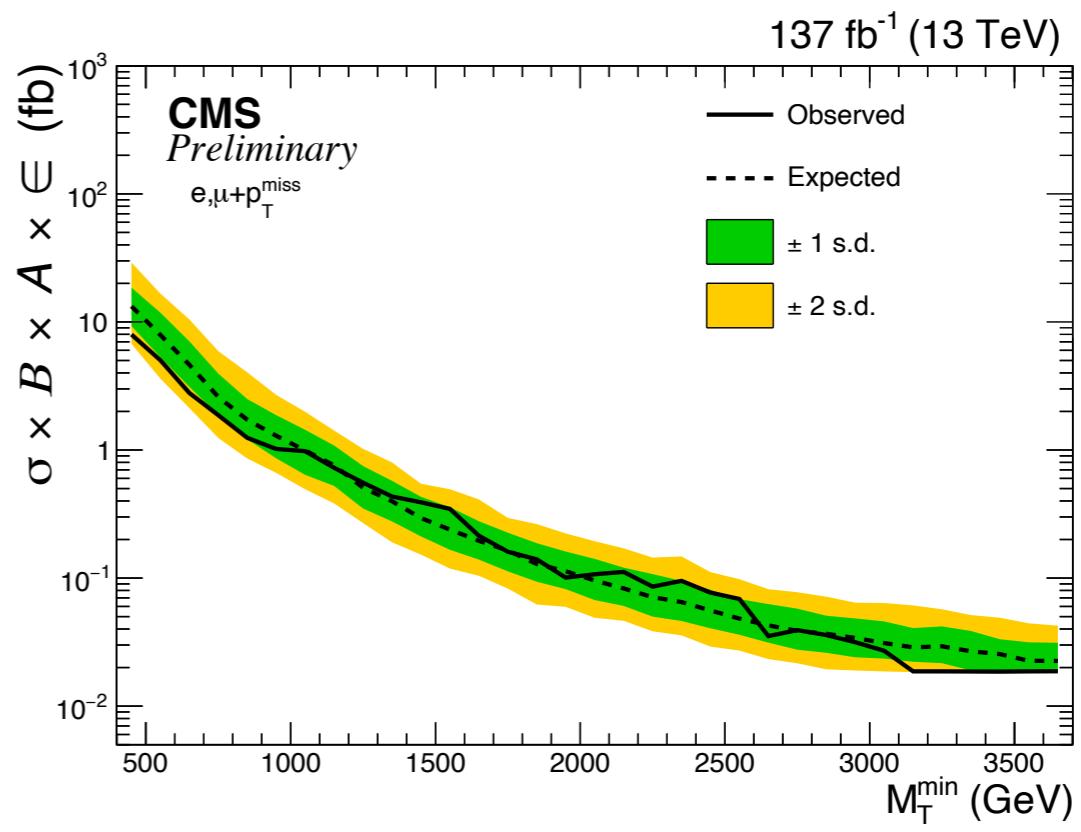
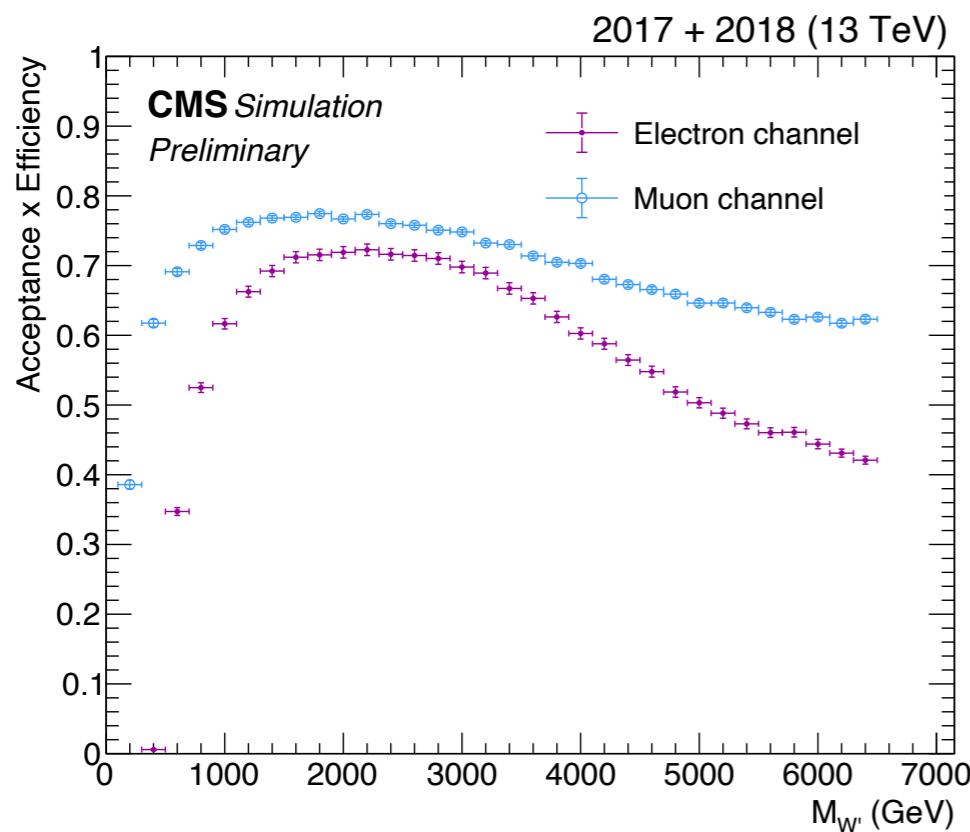
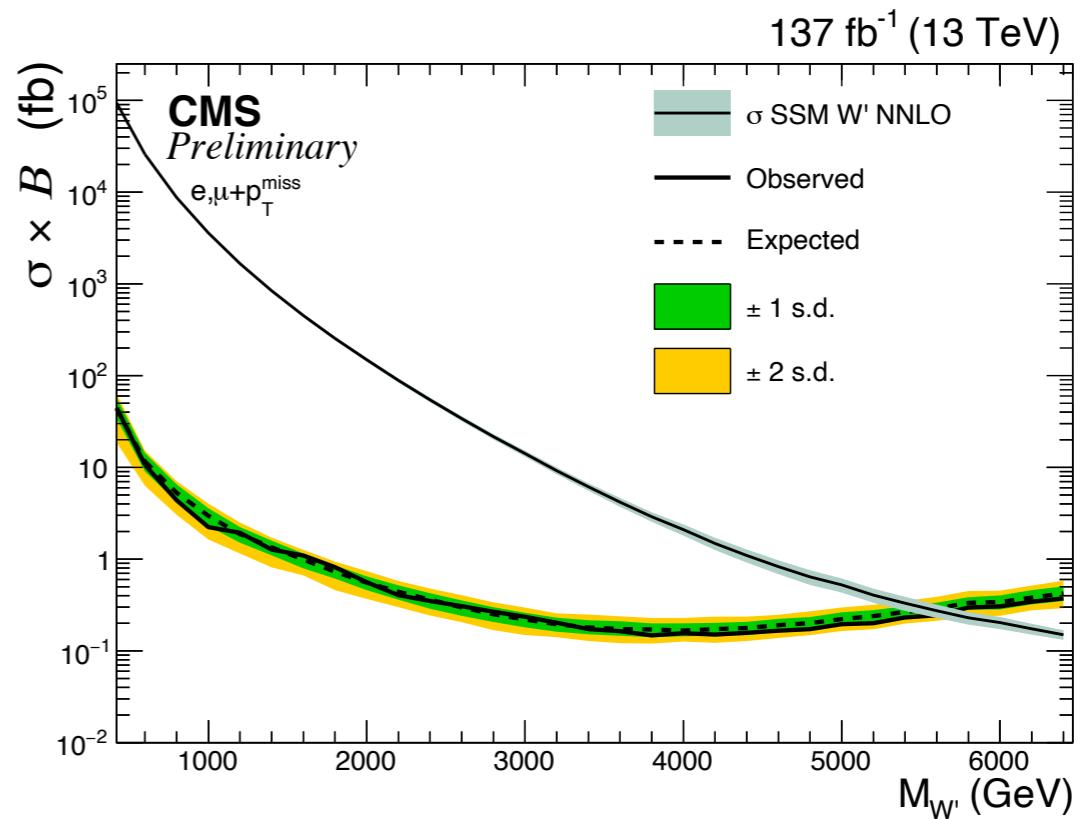
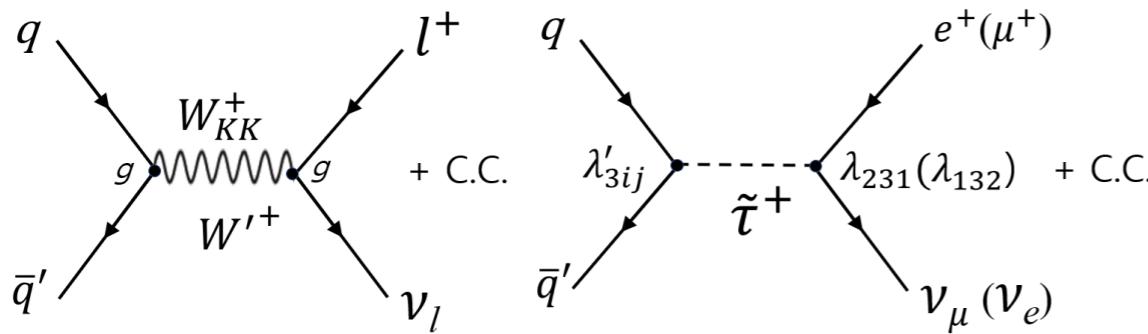
Overview of CMS EXO results



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

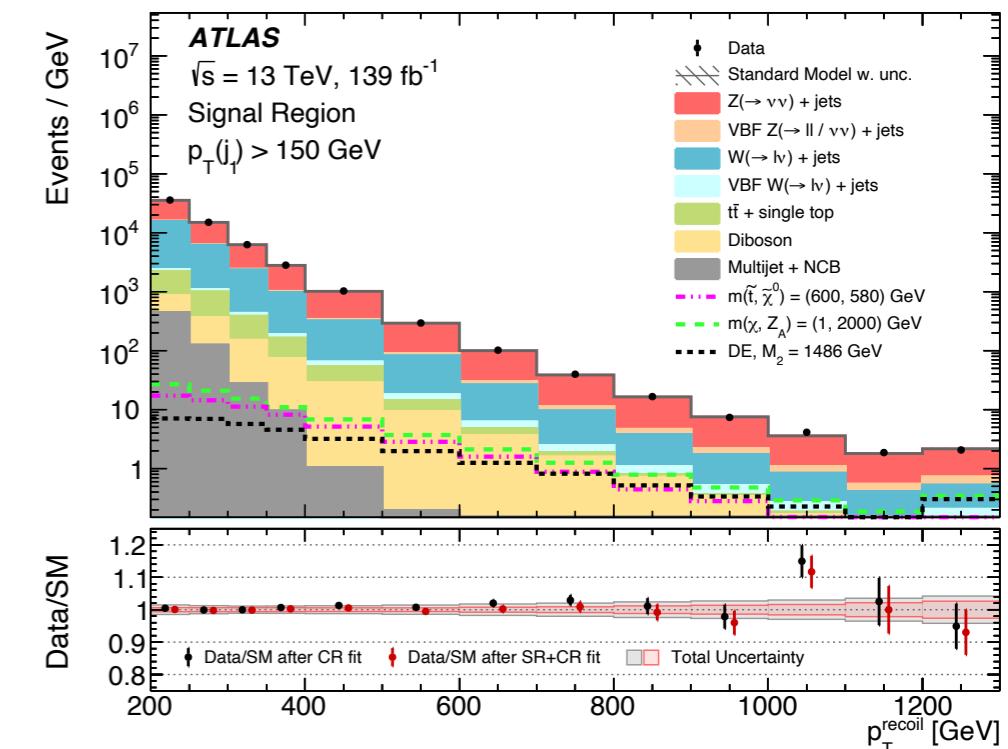
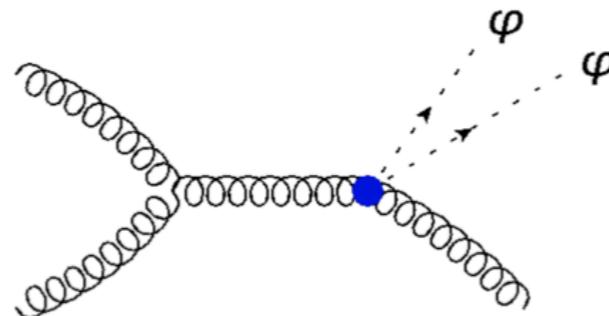
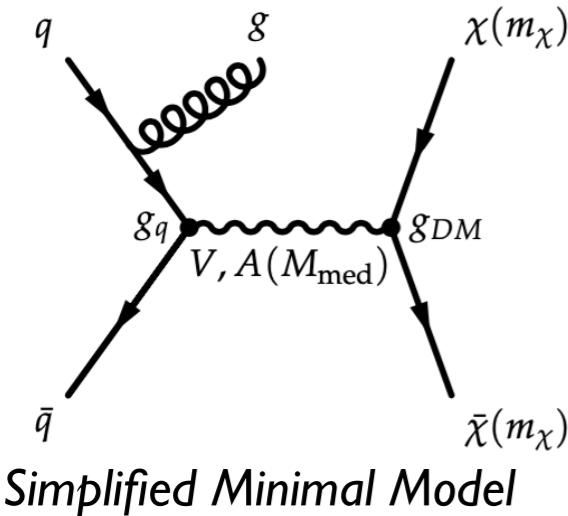
Moriond 2021

Single lepton + E_T

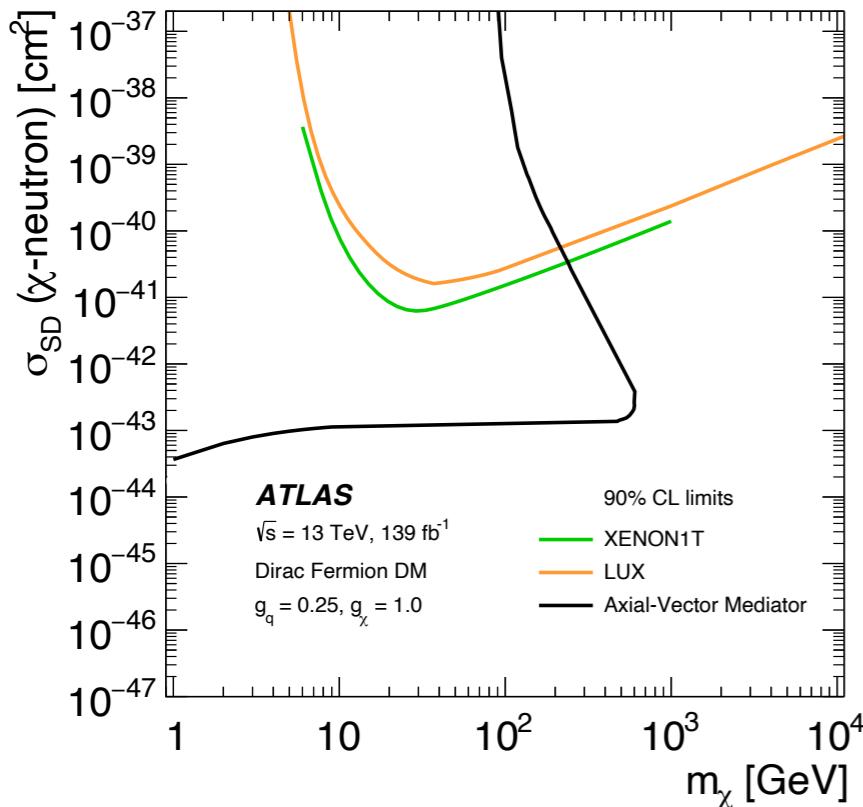


Mono-jet + E_T

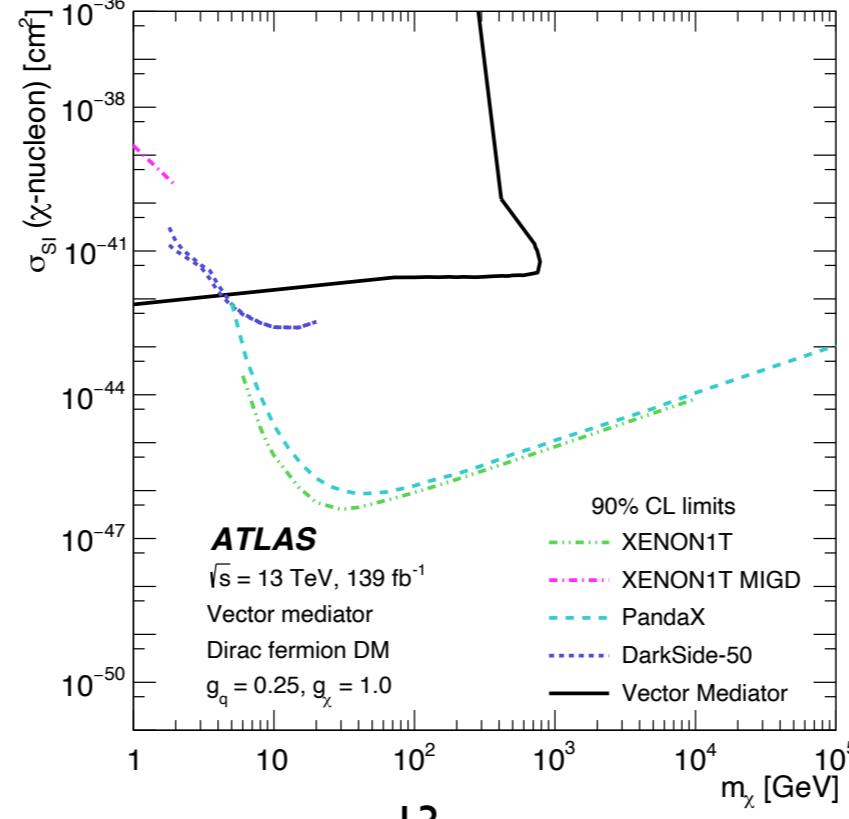
- Flagship high-pT DM search for invisible particles



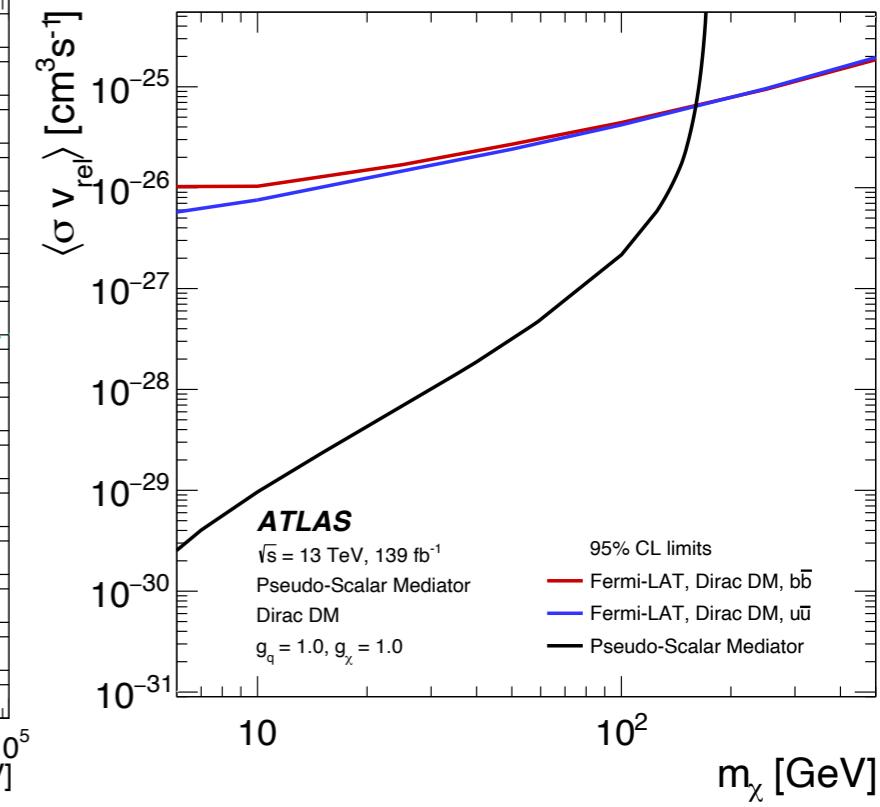
spin-dependent
Axial-Vector mediator



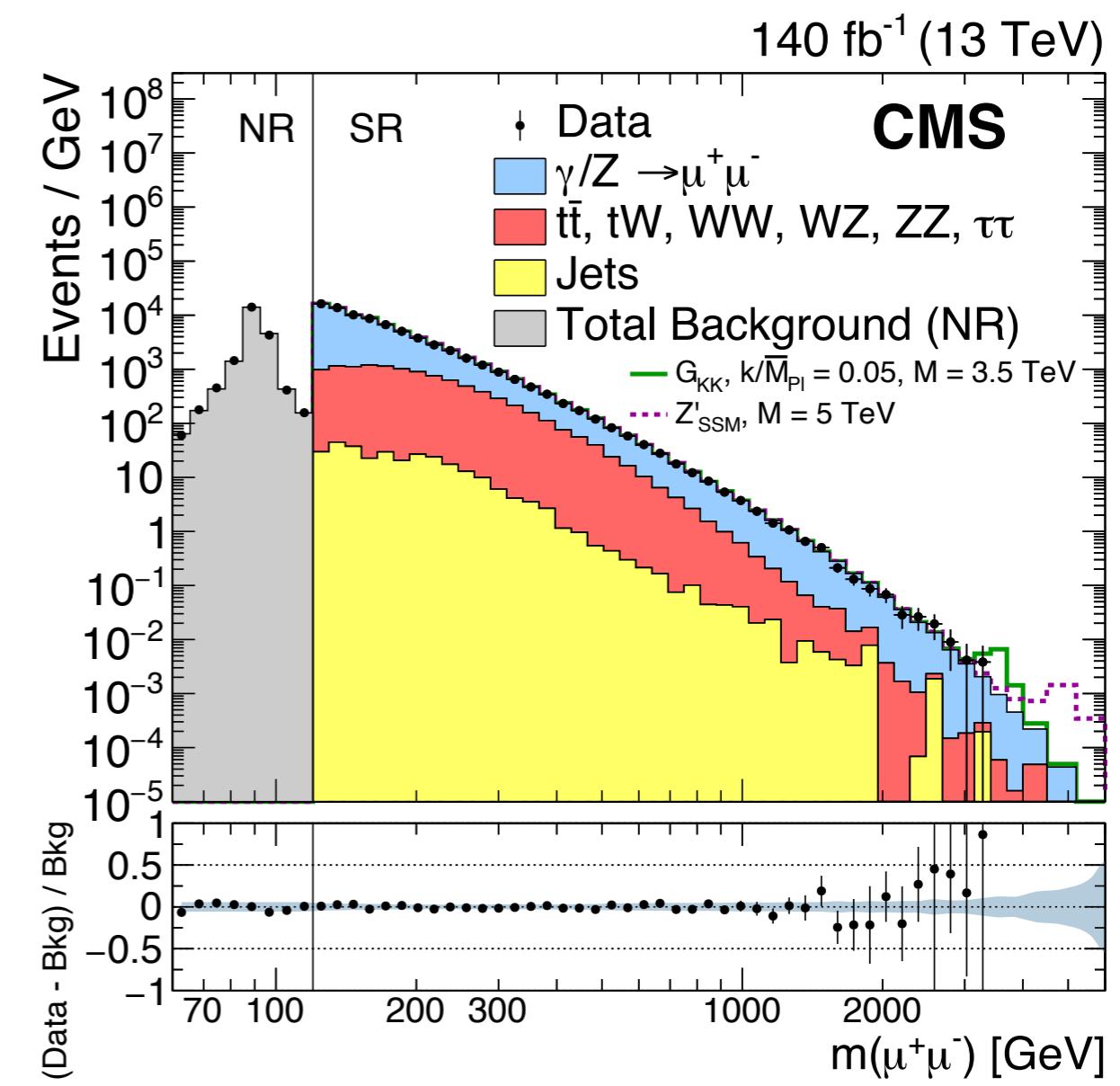
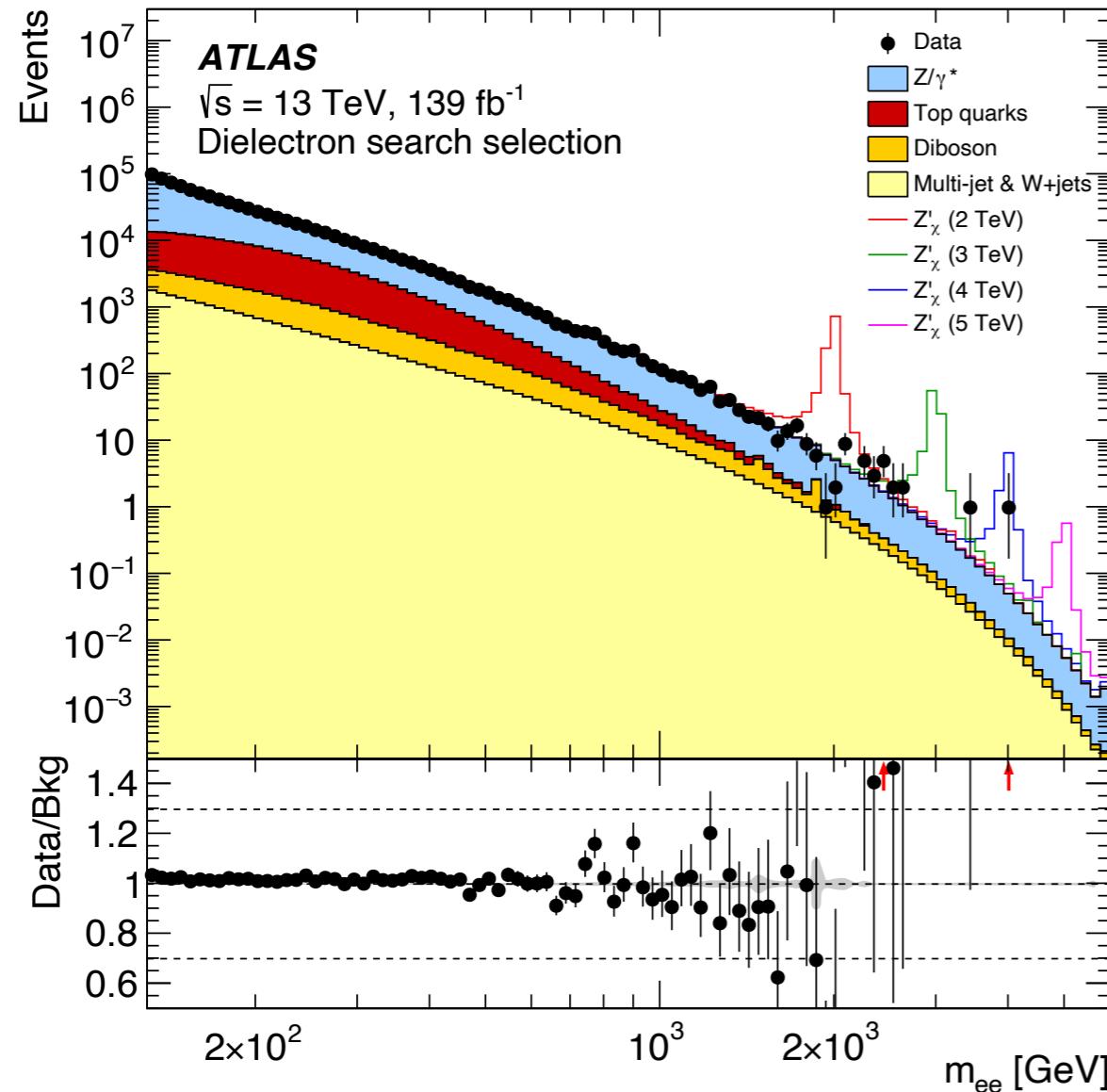
spin-independent
Vector mediator



pseudoscalar mediator



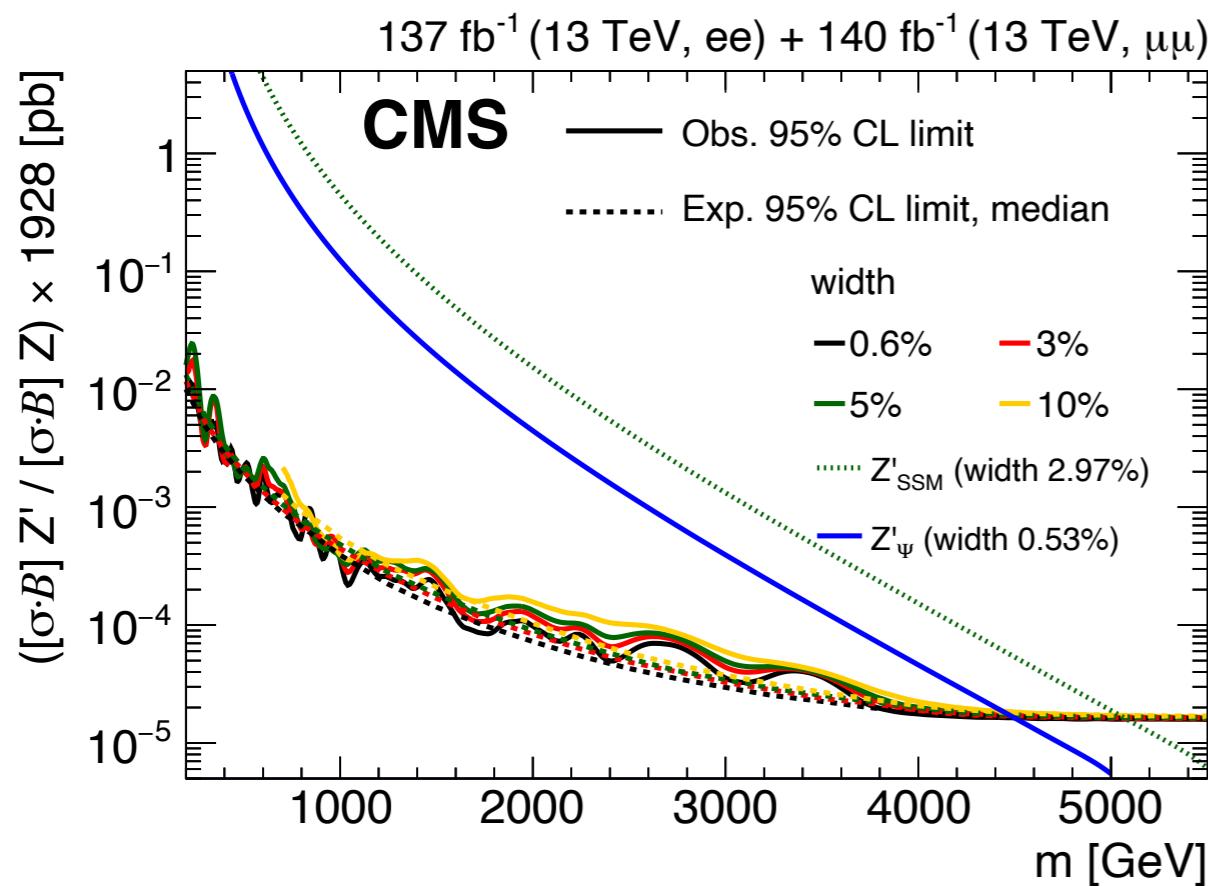
Di-lepton searches



Phys. Lett. B 796 (2019) 68

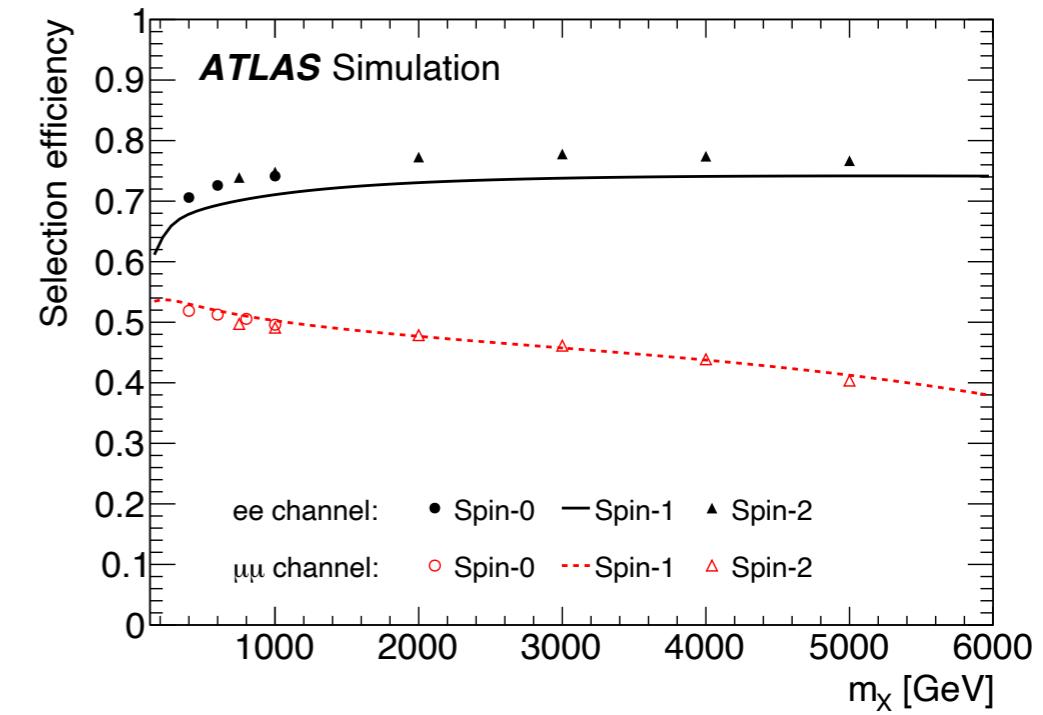
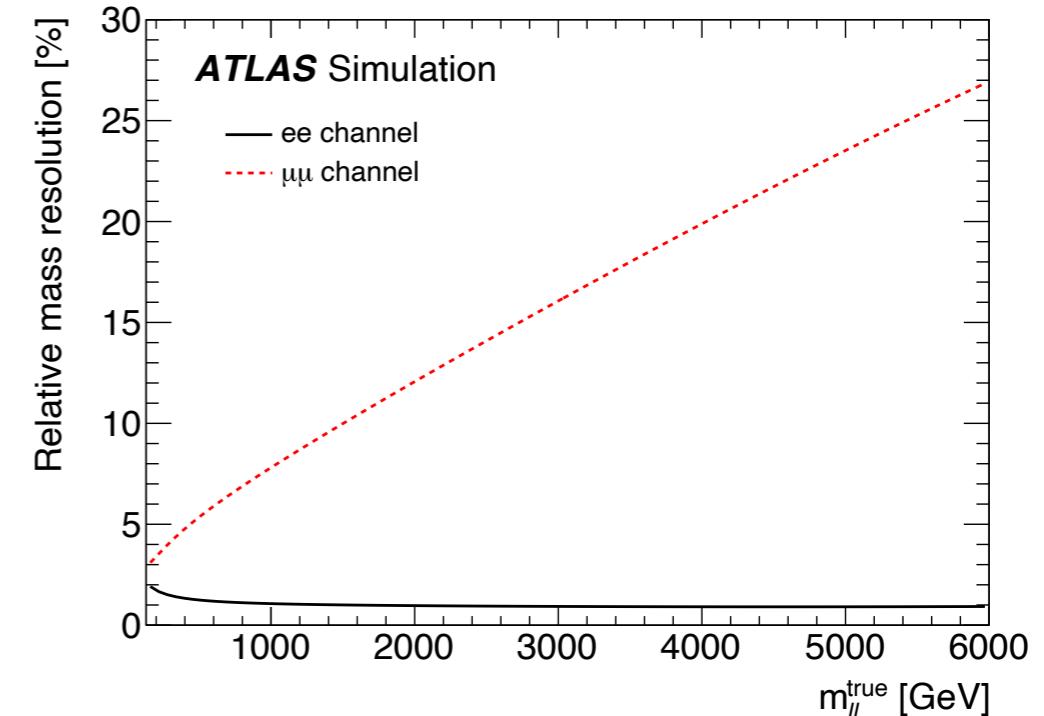
[2103.02708](https://arxiv.org/abs/2103.02708)

Interpretation of search results

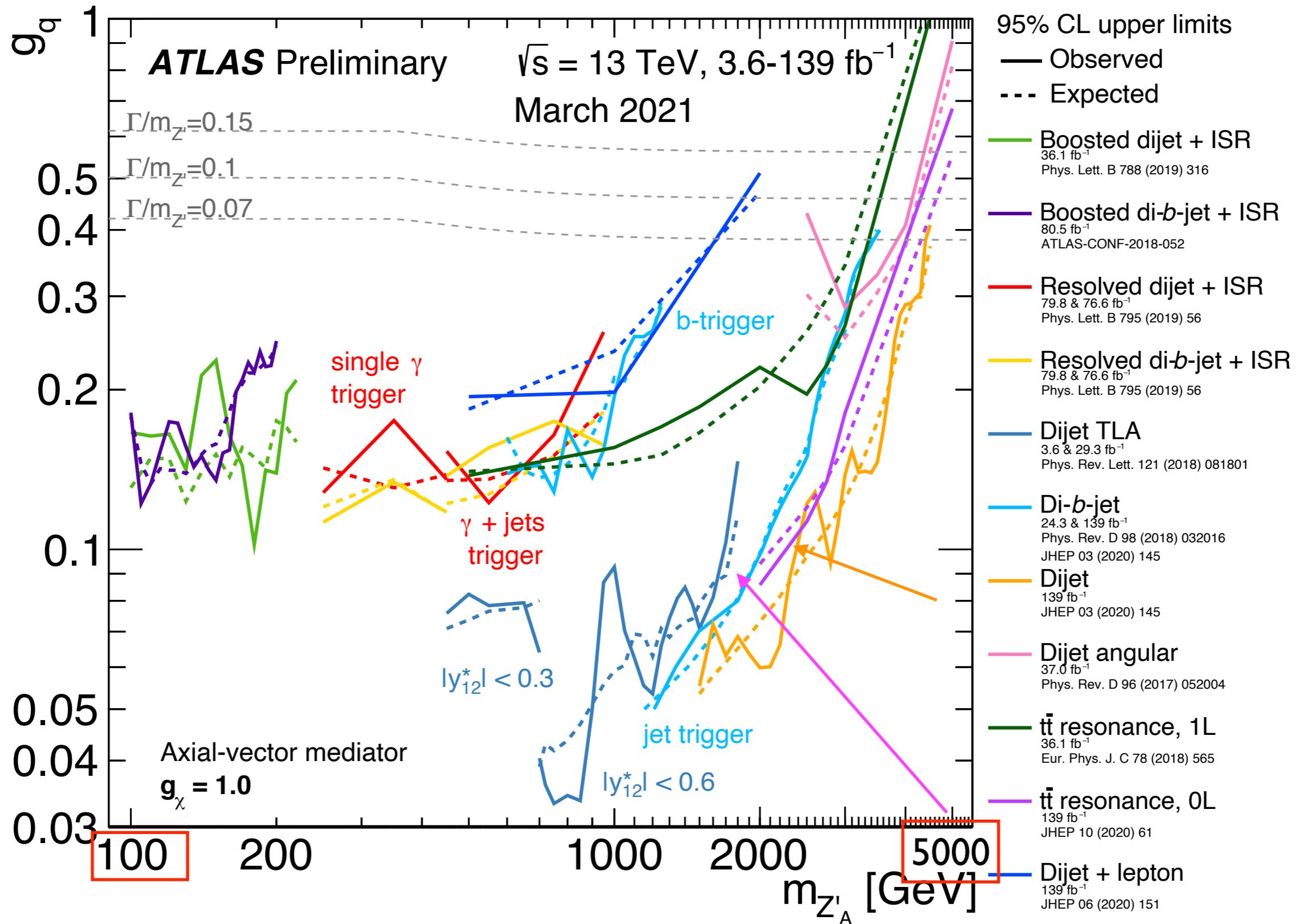


ATLAS

Model	Lower limits on $m_{Z'}$ [TeV]					
	ee		$\mu\mu$		$\ell\ell$	
	obs	exp	obs	exp	obs	exp
Z'_{ψ}	4.1	4.3	4.0	4.0	4.5	4.5
Z'_{χ}	4.6	4.6	4.2	4.2	4.8	4.8
Z'_{SSM}	4.9	4.9	4.5	4.5	5.1	5.1



Di-“jet” summary $X \rightarrow q\bar{q}/qg/gg/b\bar{b}/t\bar{t}$

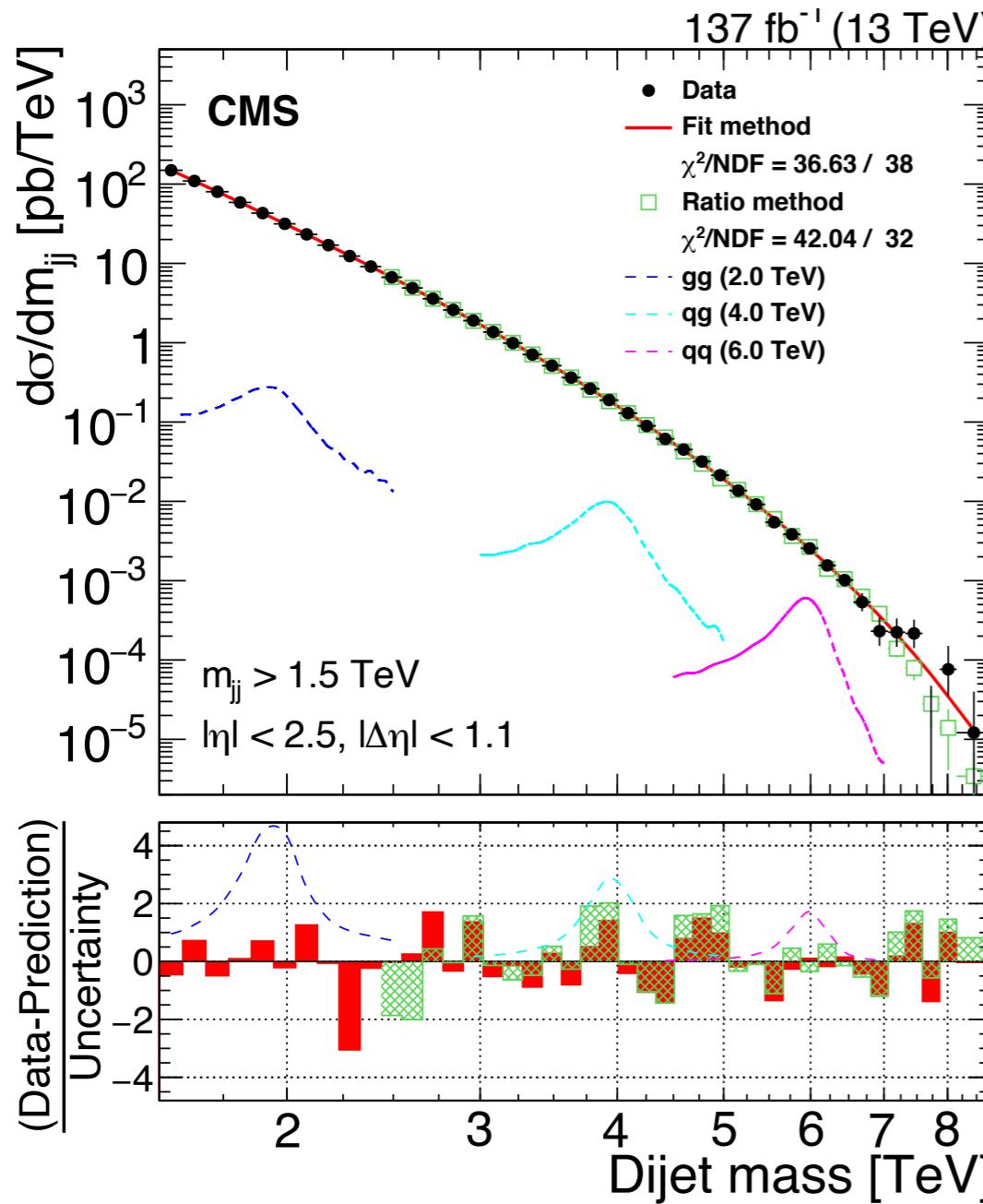


Creative trigger strategy is a must → See Elena Villhauer's talk
on how ATLAS can keep improving L1-jet trigger in Run-3

ATL-PHYS-PUB-2021-006

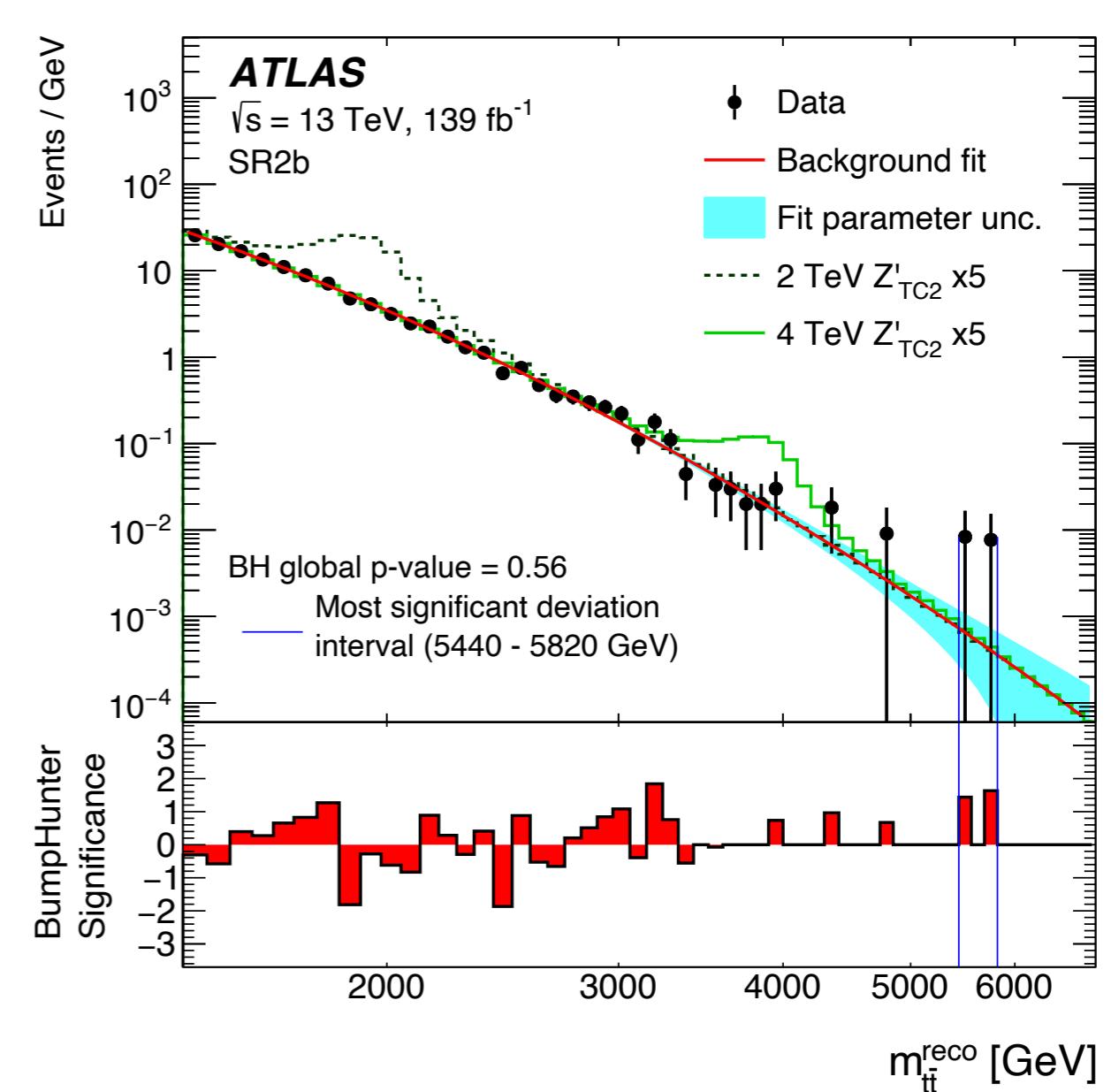
Two examples of di-“jet” searches

$pp \rightarrow X \rightarrow q\bar{q}/gg/qg$



JHEP 05 (2020) 033

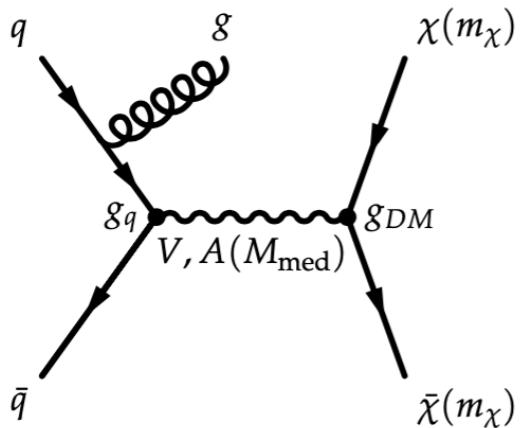
$pp \rightarrow X \rightarrow t\bar{t}(\text{all} - \text{had})$



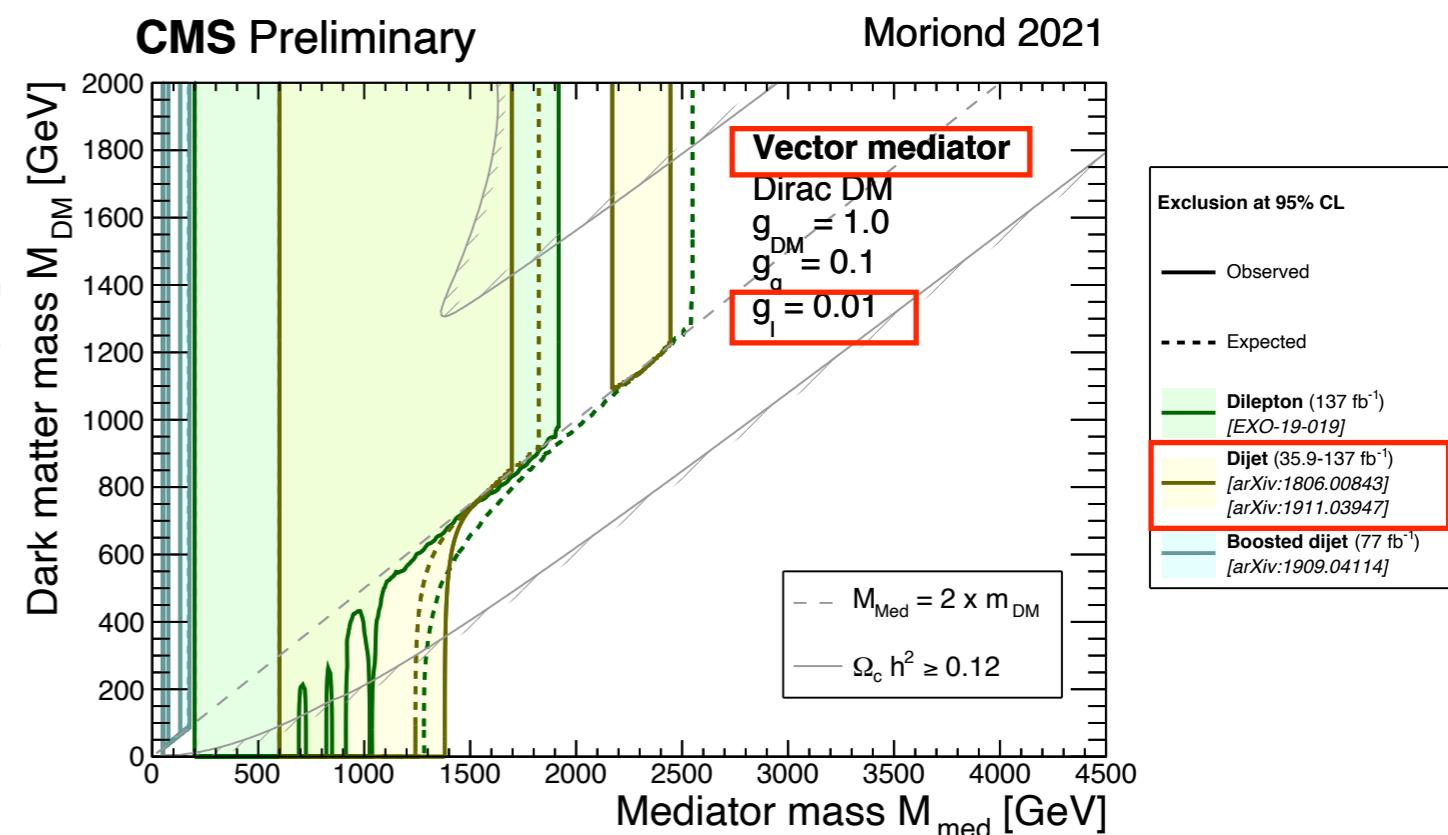
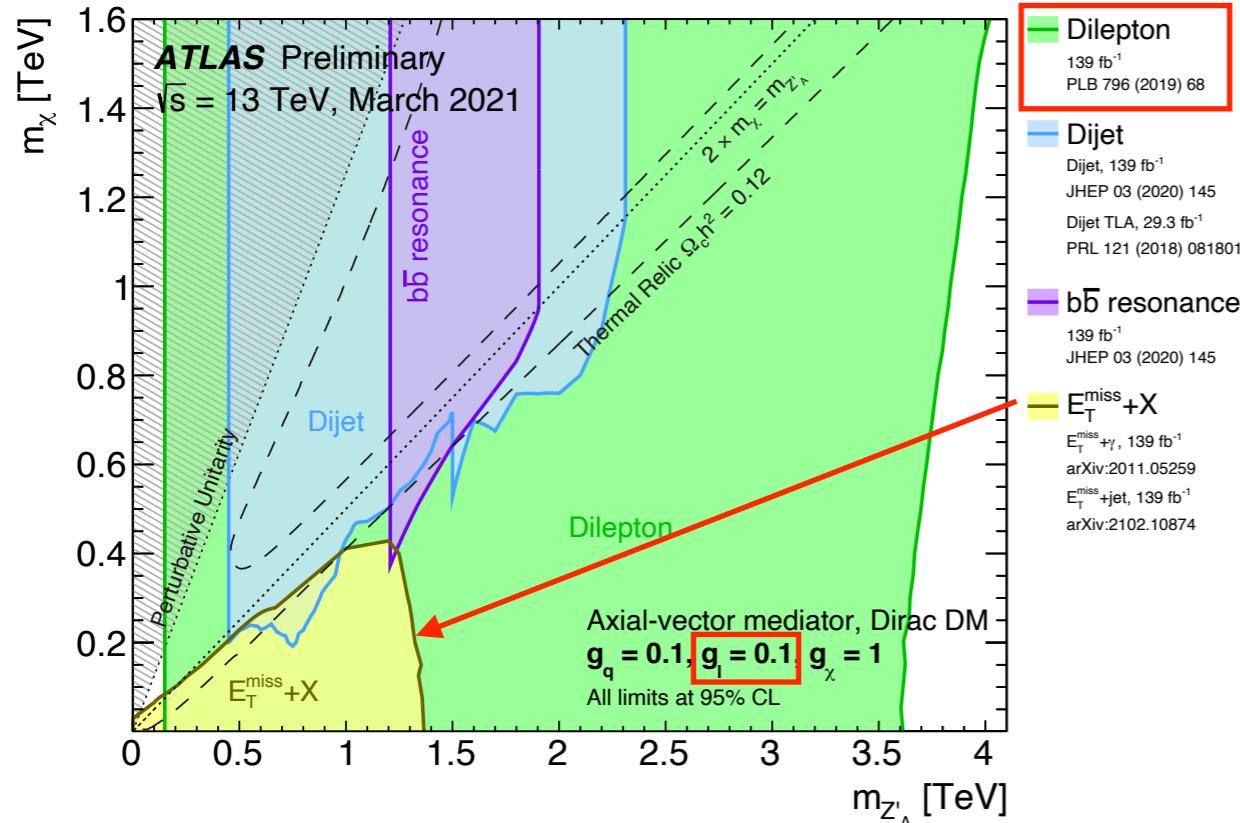
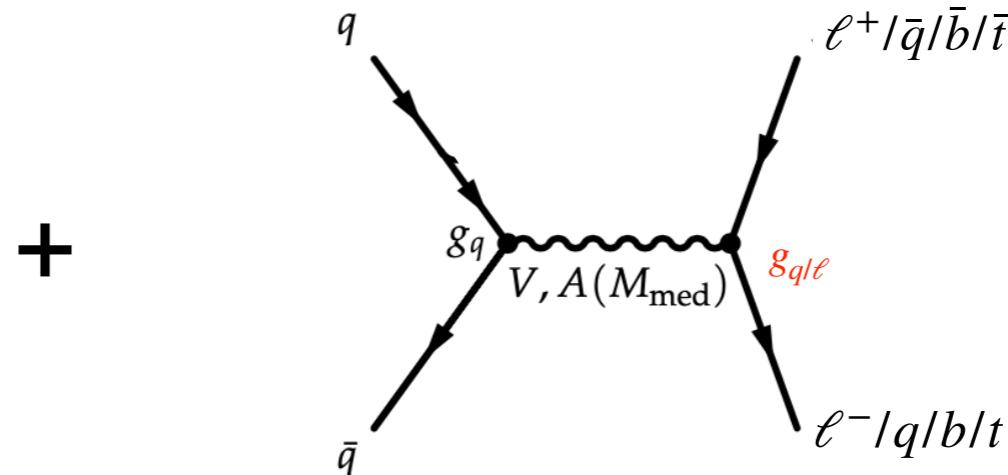
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Dilepton and Dijet implications on DM searches

$E_T + X$



no intrinsic E_T : dilepton/dijet

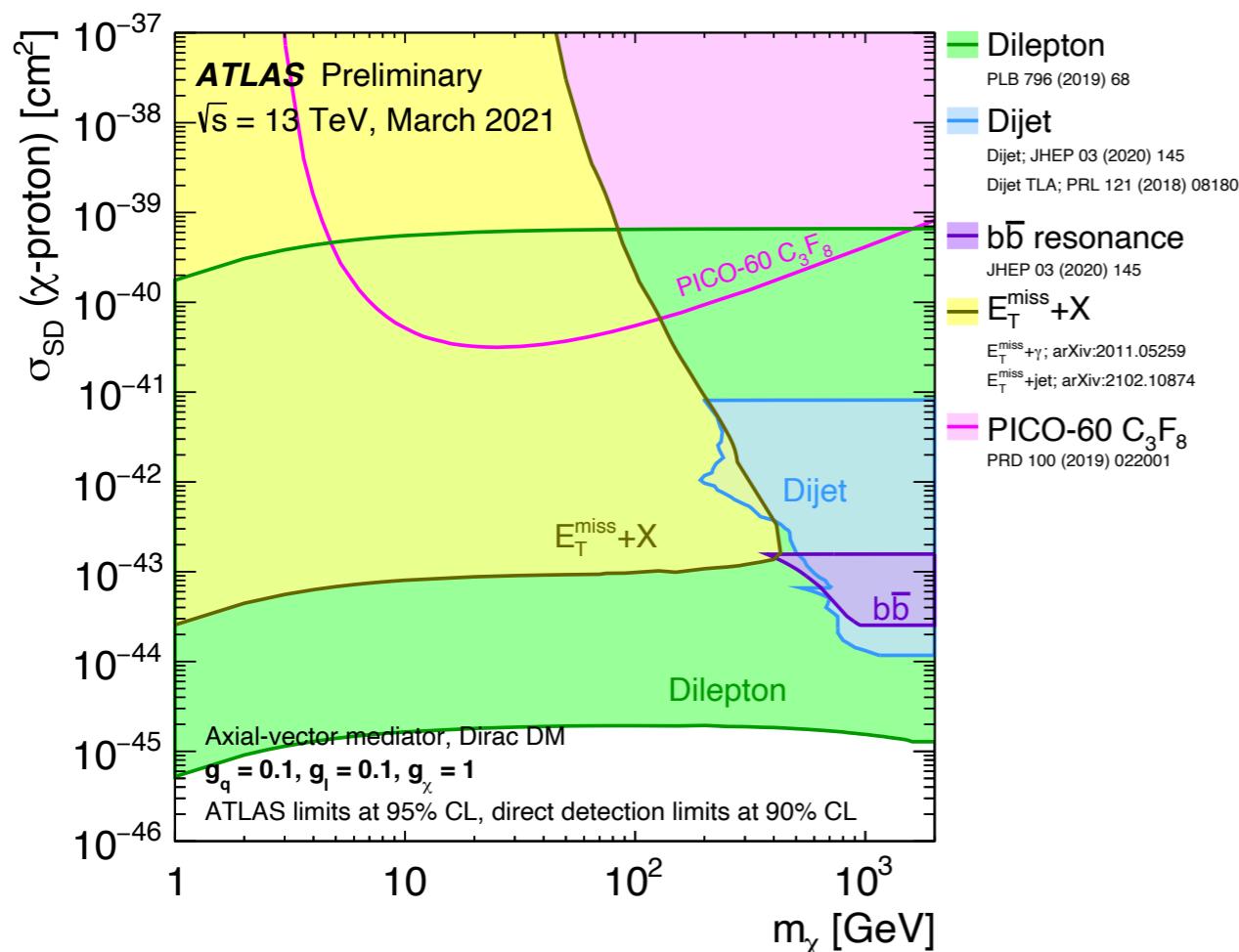


ATL-PHYS-PUB-2021-006

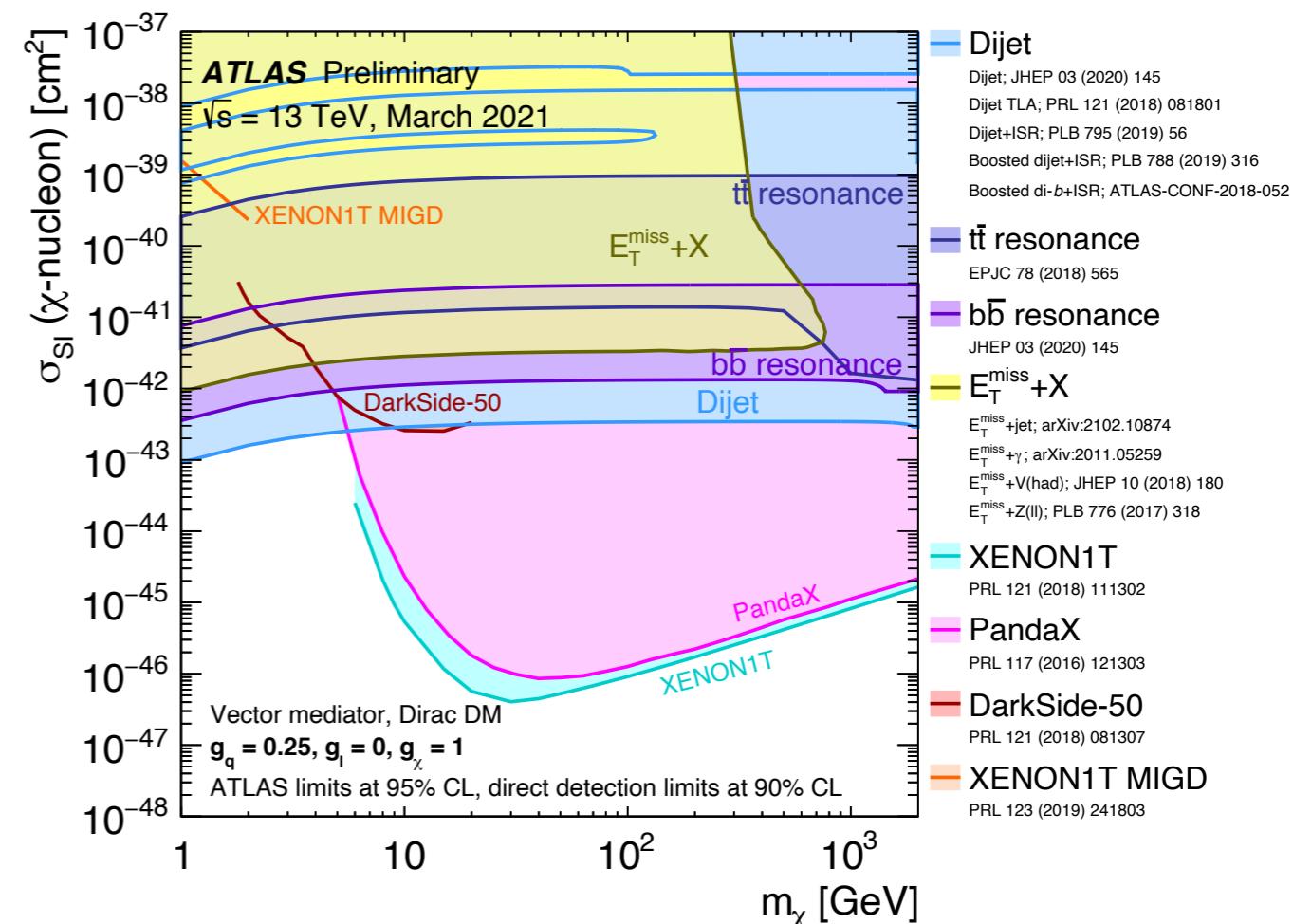
CMS EXO Summary

LHC DM searches vs non-Collider approaches

Spin-dependent
Universal fermion coupling

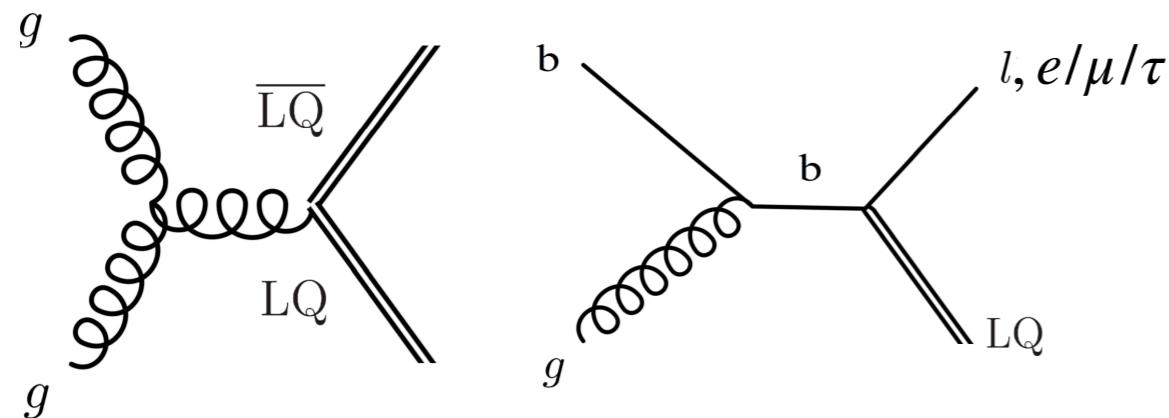


Spin-independent
Lepotonphobic couplings

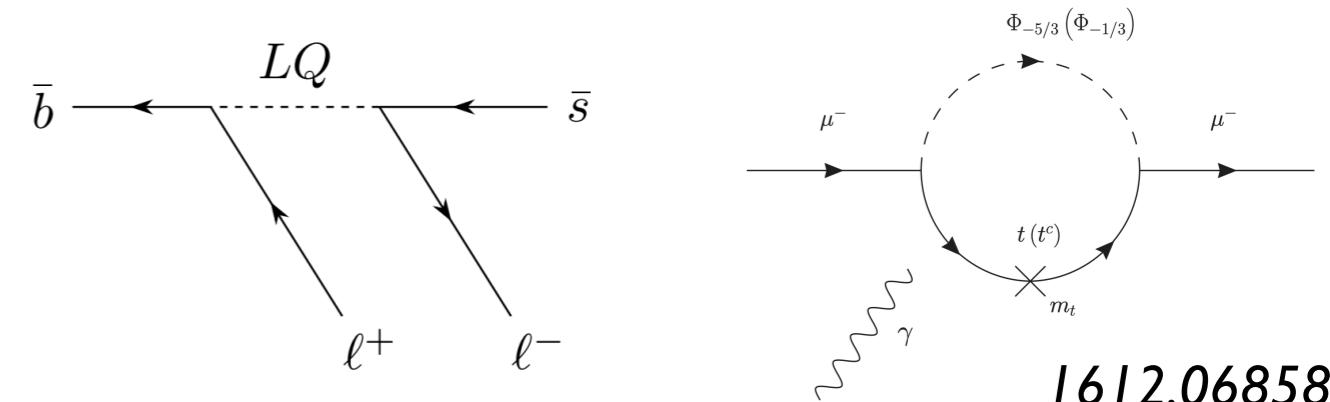


Lepto-quark searches

Productions at the LHC



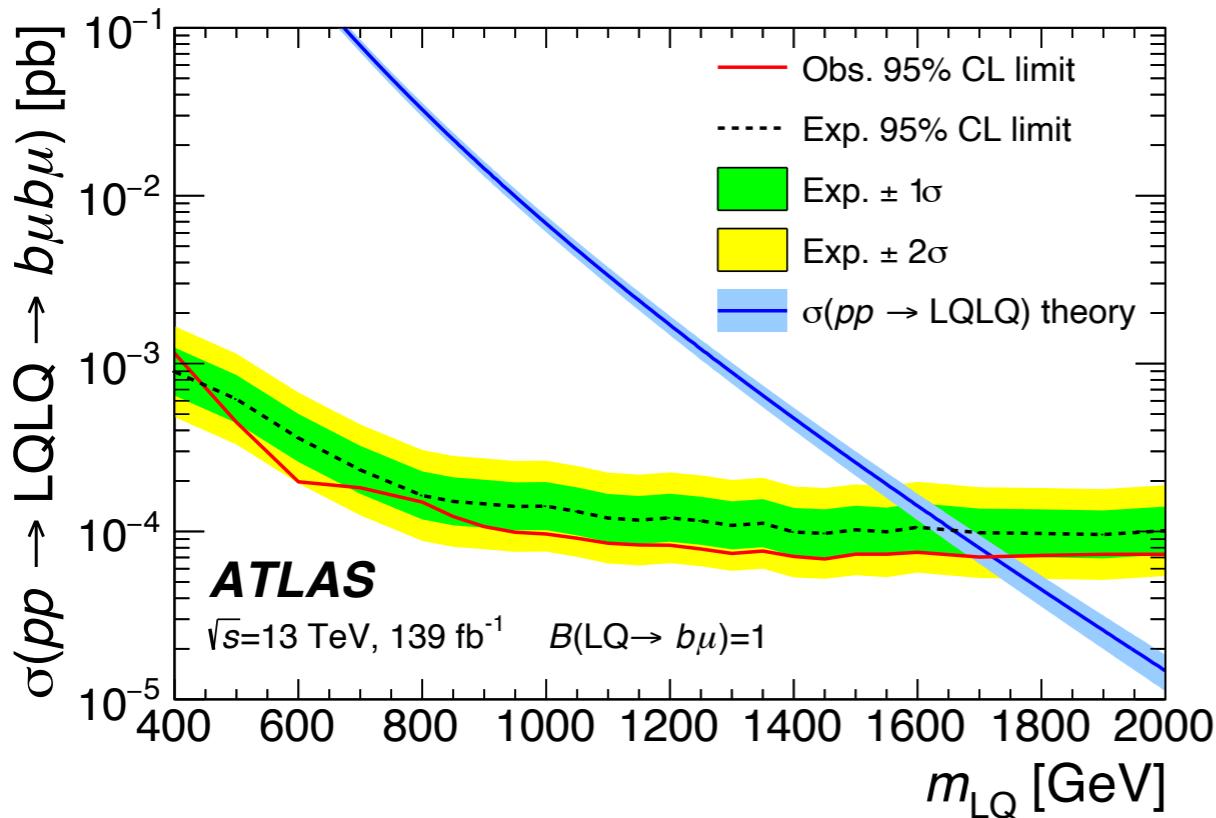
Potential contributions to anomalies



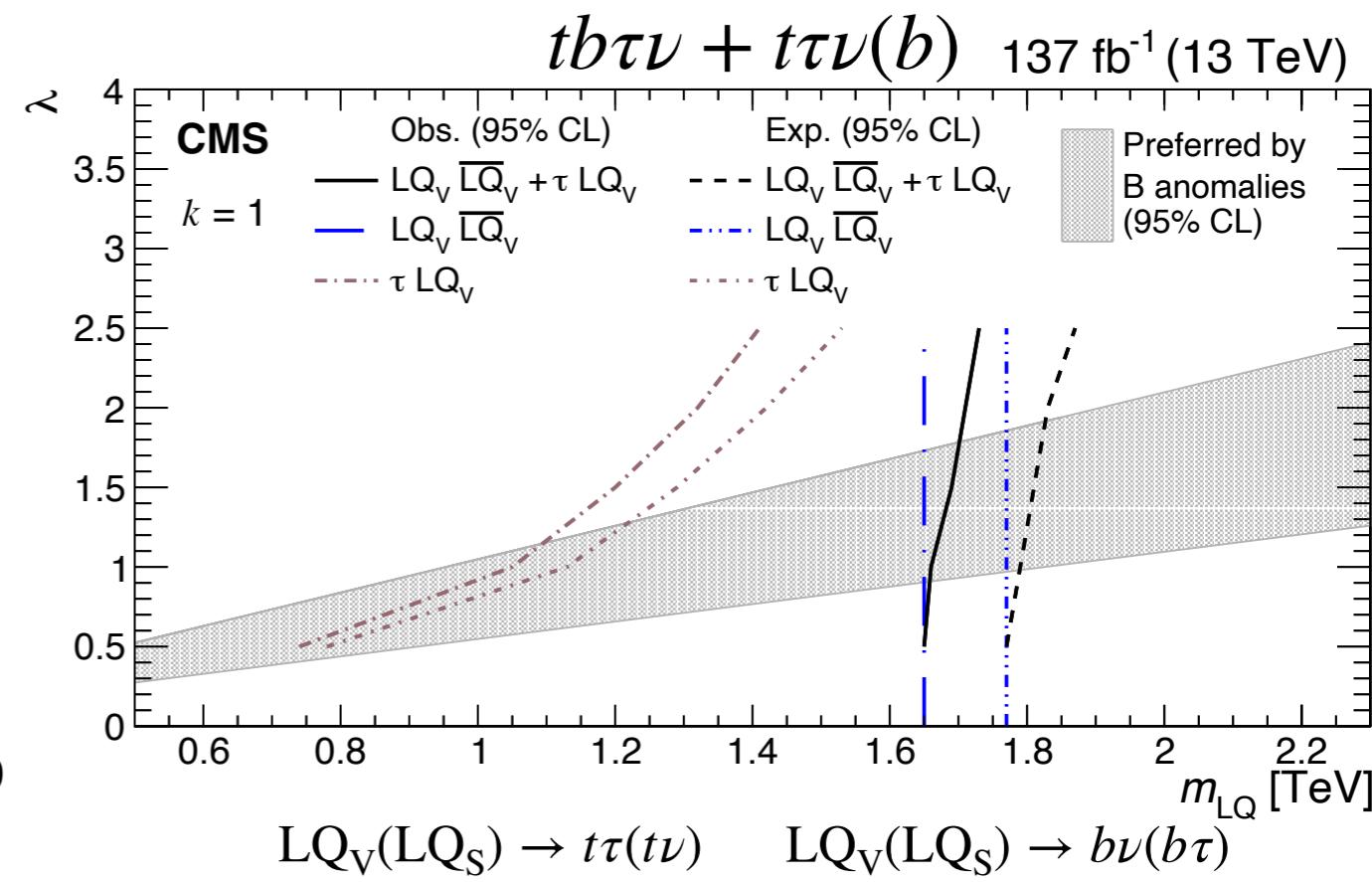
1612.06858

Two latest results focusing on third-generation fermion LQ

$$\mathcal{B}(\text{LQ}_S \rightarrow b\mu) = 100\%$$

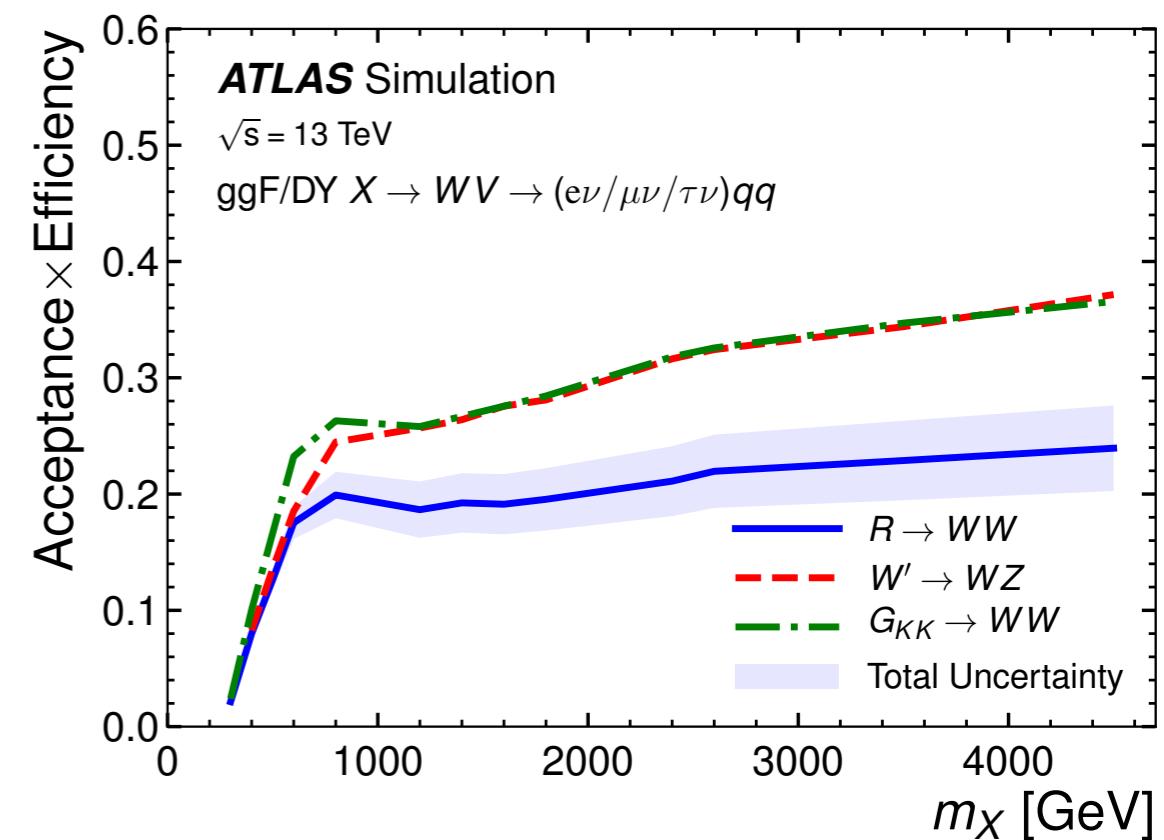
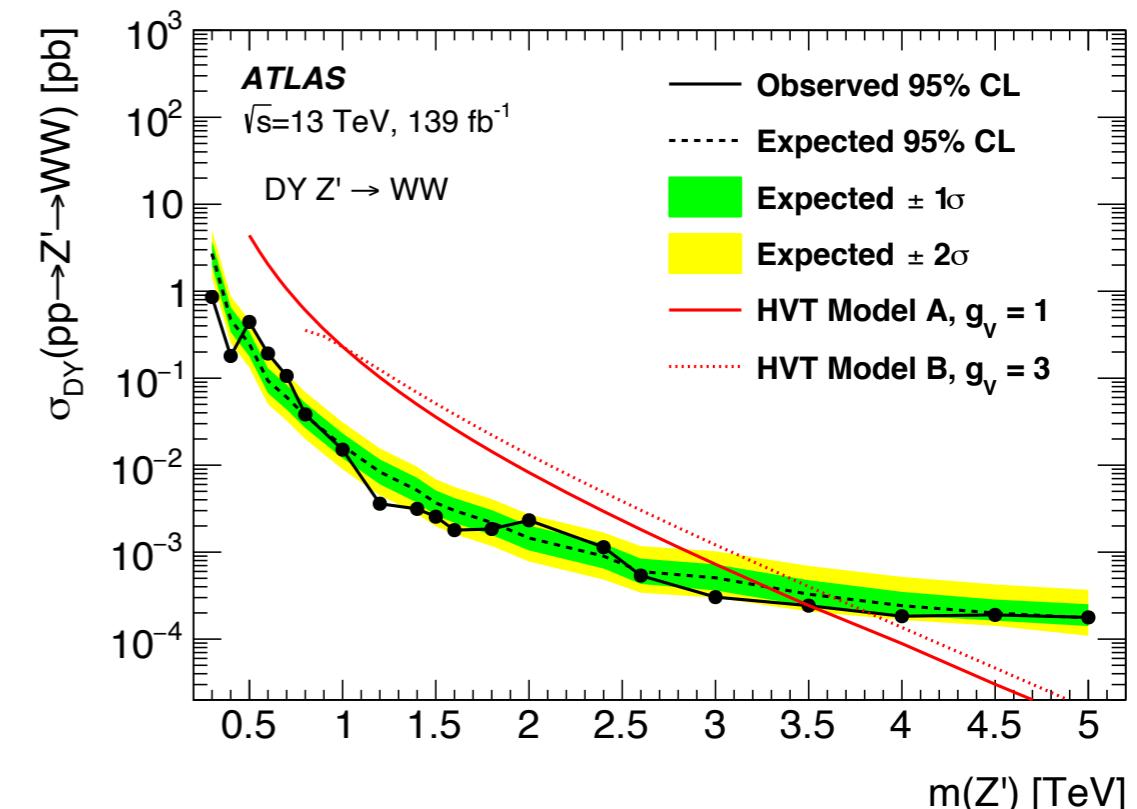
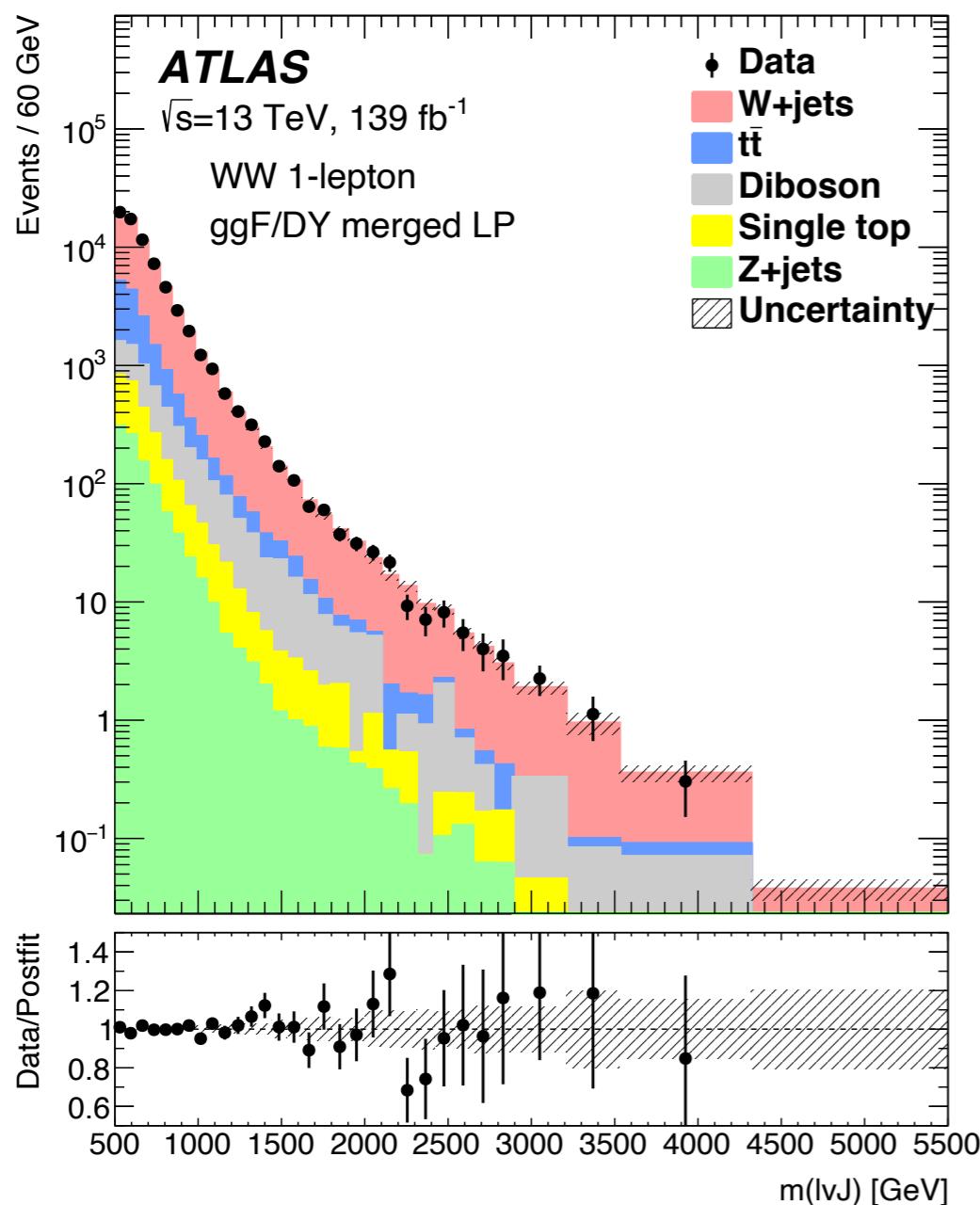
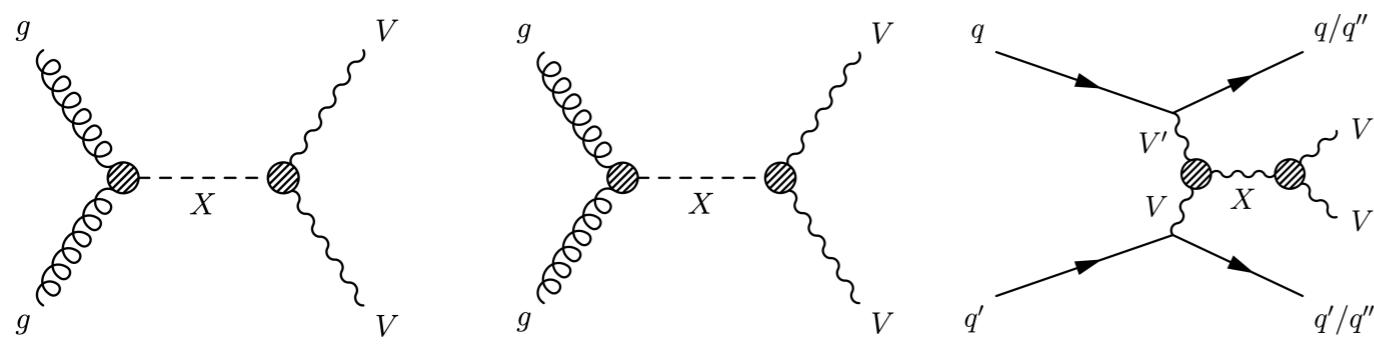


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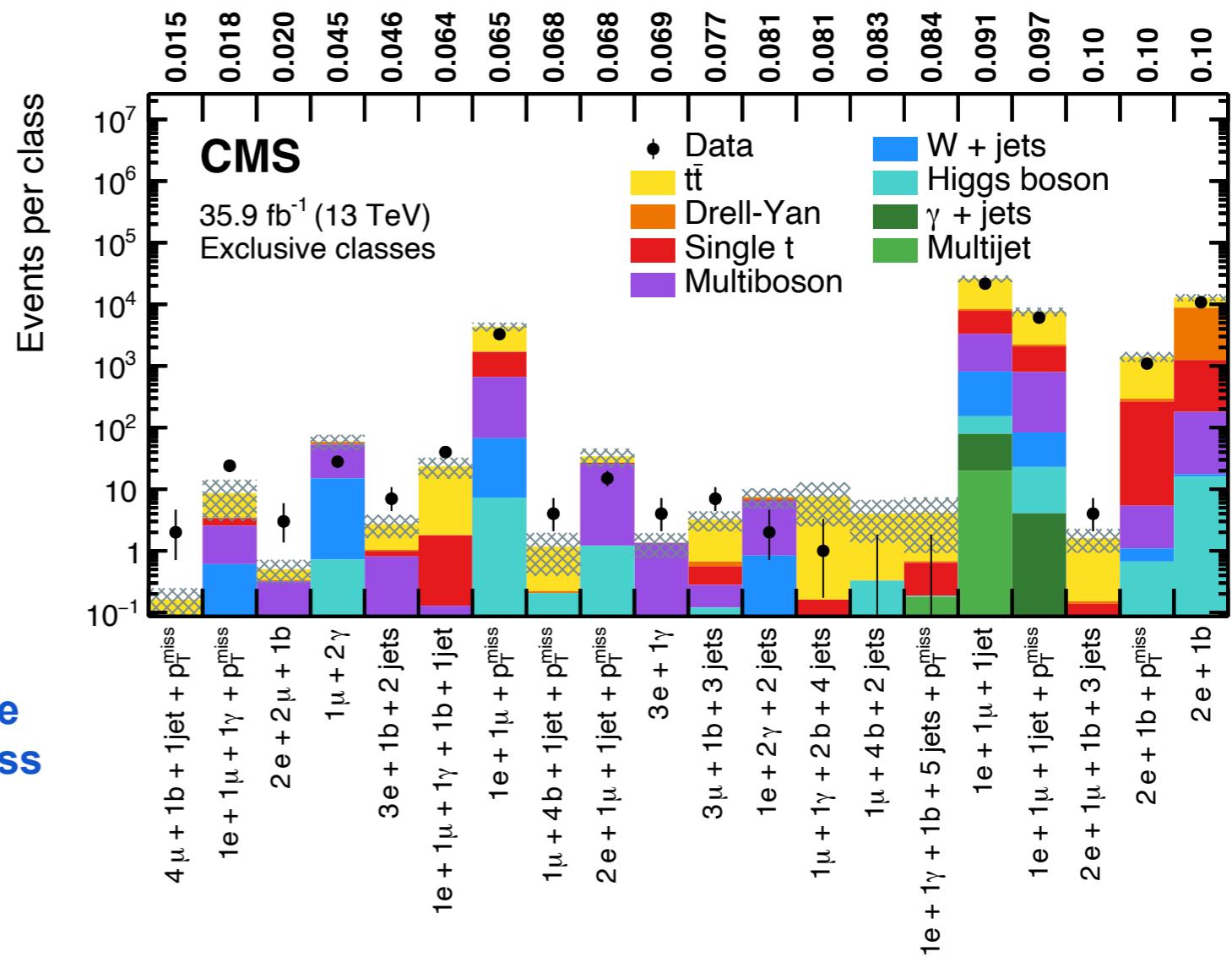
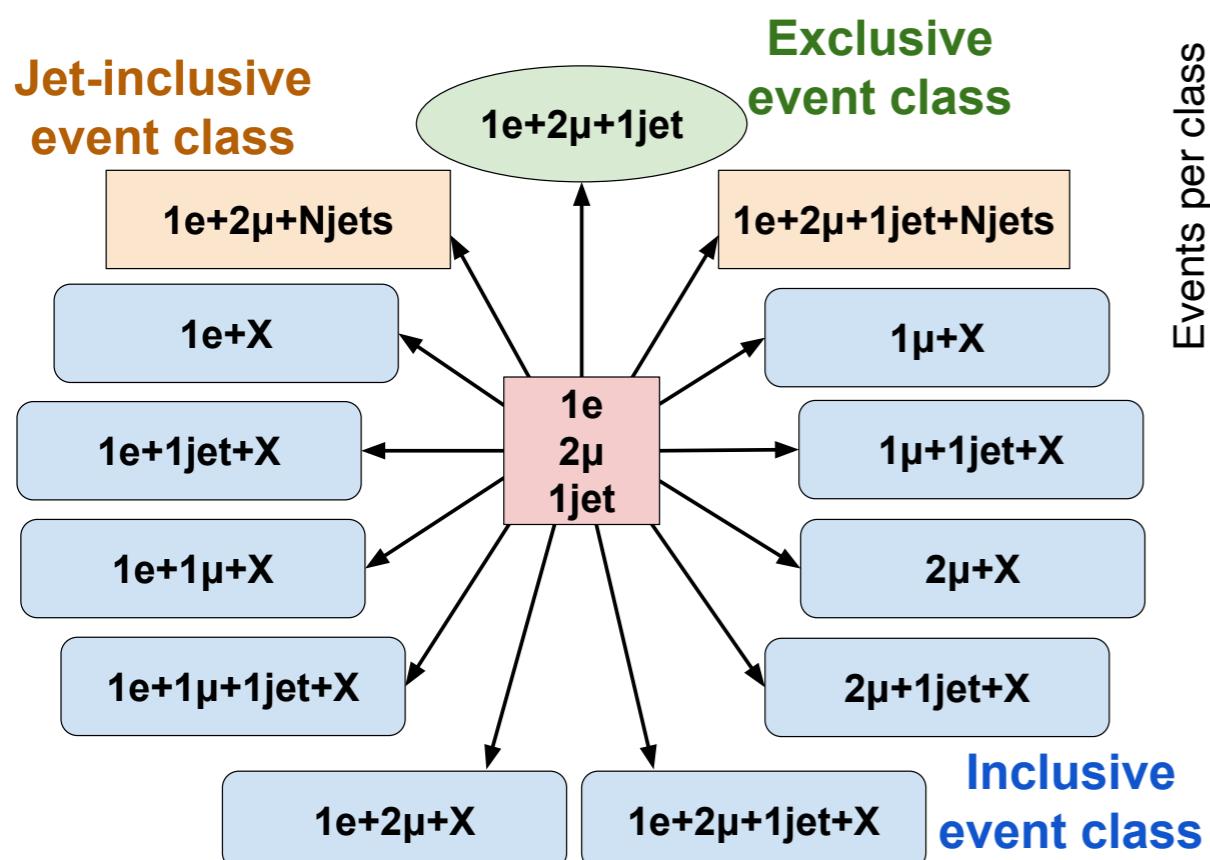
2012.04178

Diboson searches



Model Unspecific Search in CMS (MUSiC)

Input: several hundred final states and multiple kinematic distributions



2010.02984

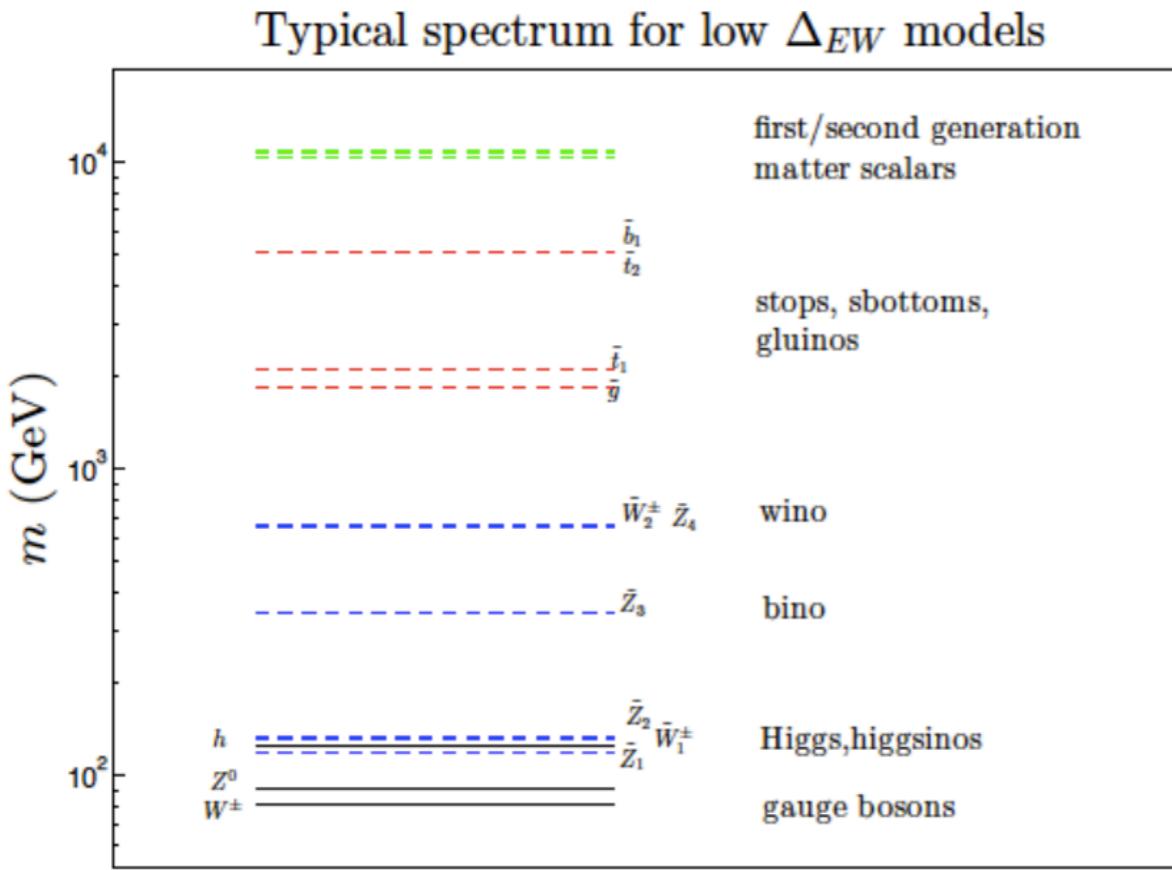
Supersymmetry

General remark on SUSY searches

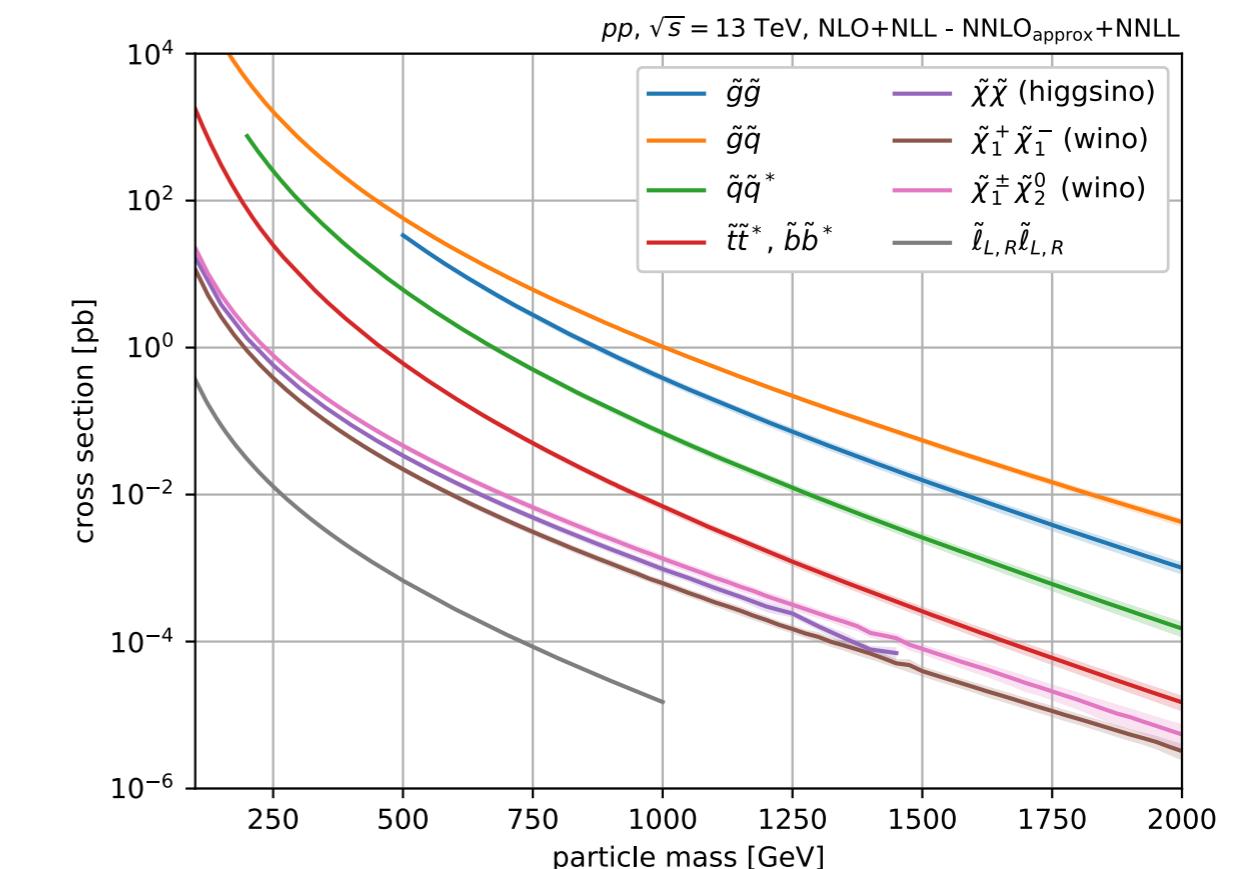
- One of the long-term favourite of both theorists and experimentalists
 - Elegant solution to hierarchy problem, stabilising the Higgs boson mass
 - DM candidates in R-parity violation scenarios
 - Gauge coupling unifications
- No SUSY particles seen yet at the LHC \Rightarrow a blow to the much hoped favoured “natural” region
 - SUSY breaking varies \rightarrow wide range of predictions on signal parameters at EWK
 - There is no rigours definition of naturalness \Rightarrow **SUSY searches continue, and more creatively!**

M. Carena, SUSY 2014

If $M_{\text{SUSY}} \sim M_{\text{weak}}$	\longrightarrow	Natural SUSY
If $M_{\text{SUSY}} \ll M_{\text{GUT}}$	\longrightarrow	big hierarchy problem solved



H. Baer, FNAL HL/HE-LHC workshop



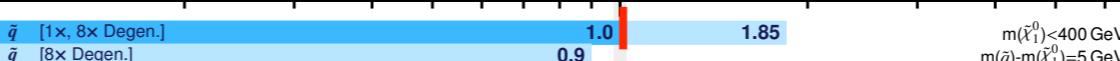
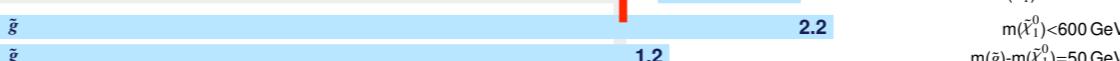
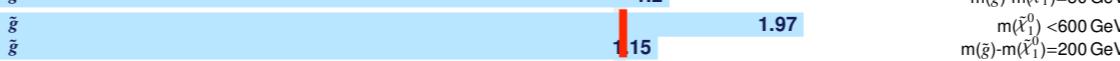
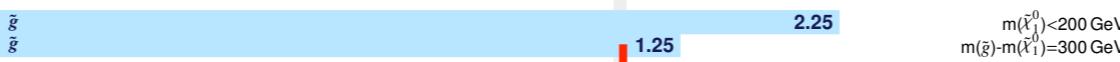
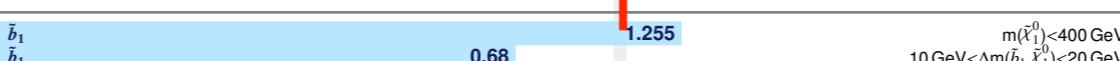
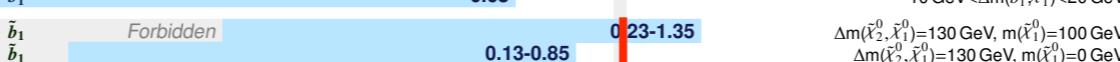
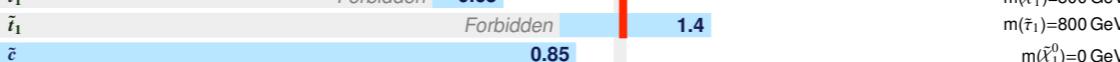
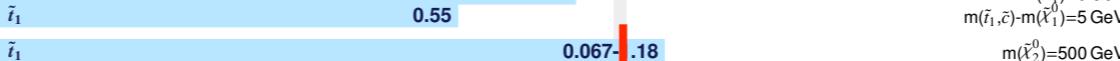
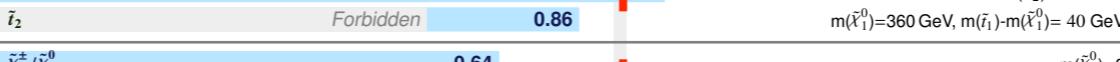
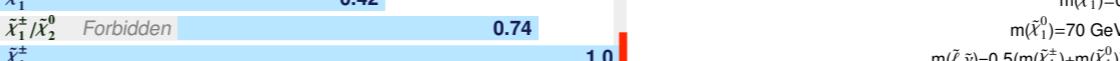
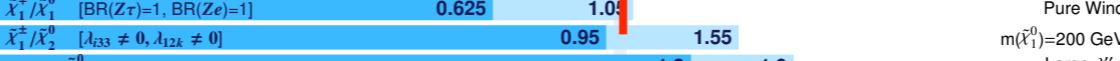
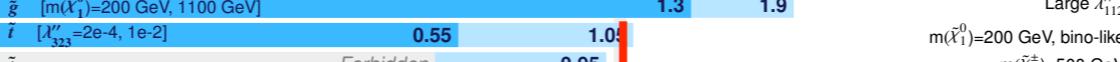
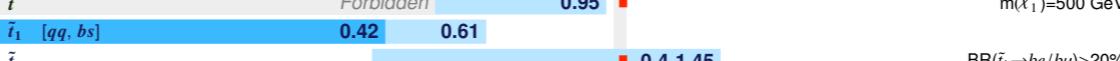
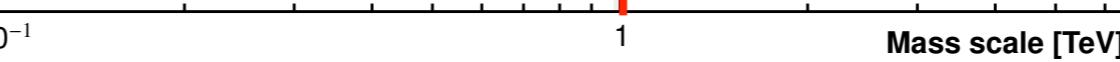
A snapshot of search summary

ATLAS SUSY Searches* - 95% CL Lower Limits

March 2021

ATLAS Preliminary

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

Model	Signature	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\rightarrow q\tilde{\chi}_1^0$ mono-jet	0 e,μ E_T^{miss} 1-3 jets E_T^{miss} 139 36.1		$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ $m(\tilde{q})-m(\tilde{\chi}_1^0)=5 \text{ GeV}$
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow q\tilde{q}\tilde{\chi}_1^0$	0 e,μ 2-6 jets E_T^{miss} 139		$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 1000 \text{ GeV}$
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow q\tilde{q}W\tilde{\chi}_1^0$	1 e,μ 2-6 jets 139		$m(\tilde{\chi}_1^0) < 600 \text{ GeV}$
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}$	$ee, \mu\mu$ 2 jets E_T^{miss} 36.1		$m(\tilde{g})-m(\tilde{\chi}_1^0)=50 \text{ GeV}$
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow qqWZ\tilde{\chi}$	0 e,μ SS e,μ 7-11 jets 6 jets E_T^{miss} 139		$m(\tilde{\chi}_1^0) < 600 \text{ GeV}$ $m(\tilde{g})-m(\tilde{\chi}_1^0)=200 \text{ GeV}$
3 rd gen. squarks direct production	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow t\tilde{t}\tilde{\chi}_1^0$	0-1 e,μ SS e,μ 3 b 6 jets E_T^{miss} 79.8 139		$m(\tilde{\chi}_1^0) < 200 \text{ GeV}$ $m(\tilde{g})-m(\tilde{\chi}_1^0)=300 \text{ GeV}$
	$\tilde{b}_1\tilde{b}_1$	0 e,μ 2 b E_T^{miss} 139		$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ $10 \text{ GeV} < \Delta m(\tilde{b}_1, \tilde{\chi}_1^0) < 20 \text{ GeV}$
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\rightarrow b\tilde{\chi}_2^0 \rightarrow bh$	0 e,μ 2 τ 2 b E_T^{miss} 139		$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)=130 \text{ GeV}, m(\tilde{\chi}_1^0)=100 \text{ GeV}$ $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)=130 \text{ GeV}, m(\tilde{\chi}_1^0)=0 \text{ GeV}$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow t\tilde{\chi}_1^0$	0-1 e,μ $\geq 1 \text{ jet}$ E_T^{miss} 139		$m(\tilde{\chi}_1^0)=1 \text{ GeV}$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow Wb\tilde{\chi}_1^0$	1 e,μ 3 jets/1 b E_T^{miss} 139		$m(\tilde{\chi}_1^0)=500 \text{ GeV}$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow \tilde{\tau}_1 b\nu, \tilde{\tau}_1\rightarrow \tau G$	1-2 τ 2 jets/1 b E_T^{miss} 139		$m(\tilde{\tau}_1)=800 \text{ GeV}$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c}\rightarrow \tilde{c}\tilde{\chi}_1^0$	0 e,μ 2 c mono-jet E_T^{miss} 36.1 139		$m(\tilde{\chi}_1^0)=0 \text{ GeV}$ $m(\tilde{t}_1, \tilde{c})-m(\tilde{\chi}_1^0)=5 \text{ GeV}$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow t\tilde{\chi}_2^0, \tilde{\chi}_2^0\rightarrow Z/h\tilde{\chi}_1^0$	1-2 e,μ 1-4 b E_T^{miss} 139		$m(\tilde{\chi}_1^0)=500 \text{ GeV}$
EW direct	$\tilde{t}_1\tilde{t}_2, \tilde{t}_2\rightarrow \tilde{t}_1 + Z$	3 e,μ 1 b E_T^{miss} 139		$m(\tilde{\chi}_1^0)=360 \text{ GeV}, m(\tilde{t}_1)-m(\tilde{\chi}_1^0)=40 \text{ GeV}$
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \text{ via } WZ$	3 e,μ $ee, \mu\mu$ $\geq 1 \text{ jet}$ E_T^{miss} 139		$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)=5 \text{ GeV}$
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^\mp \text{ via } WW$	2 e,μ E_T^{miss} 139		$m(\tilde{\chi}_1^0)=0$
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \text{ via } Wh$	0-1 e,μ 2 b/2 γ E_T^{miss} 139		$m(\tilde{\chi}_1^0)=70 \text{ GeV}$
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^\mp \text{ via } \tilde{\ell}_L/\tilde{\nu}$	2 e,μ E_T^{miss} 139		$m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^+)+m(\tilde{\chi}_1^-))$
	$\tilde{\tau}_1, \tilde{\tau}_1\rightarrow \tau\tilde{\chi}_1^0$	2 τ E_T^{miss} 139		$m(\tilde{\tau}_1)=0$
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\rightarrow \ell\tilde{\chi}_1^0$	2 e,μ 0 jets E_T^{miss} 139		$m(\tilde{\ell})-m(\tilde{\chi}_1^0)=10 \text{ GeV}$
Long-lived particles	$H\tilde{H}, H\rightarrow h\tilde{G}/Z\tilde{G}$	0 e,μ 4 e,μ $\geq 3 b$ 0 jets E_T^{miss} 36.1 139		$BR(\tilde{\chi}_1^0 \rightarrow h\tilde{G})=1$ $BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G})=1$
	Direct $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk 1 jet E_T^{miss} 139		Pure Wino
	Stable \tilde{g} R-hadro	Multiple E_T^{miss} 36.1		Pure higgsino
	Metastable \tilde{g} R-hadro	Multiple E_T^{miss} 36.1		$m(\tilde{\chi}_1^0)=100 \text{ GeV}$
	$\tilde{\ell}, \tilde{\ell}\rightarrow \ell\tilde{\chi}_1^0$	Displ. lep E_T^{miss} 139		$\tau(\tilde{\ell})=0.1 \text{ ns}$
RPV	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp, \tilde{\chi}_1^\pm\rightarrow Z\ell\rightarrow \ell\ell\ell$	3 e,μ E_T^{miss} 139		Pure Wino
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp, \tilde{\chi}_1^\pm\rightarrow WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ 0 jets E_T^{miss} 139		$m(\tilde{\chi}_1^0)=200 \text{ GeV}$
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0\rightarrow q\tilde{q}$	4-5 large- R jets E_T^{miss} 36.1		Large λ'_{12}
	$\tilde{\tau}, \tilde{\tau}\rightarrow \tau\tilde{\chi}_1^0, \tilde{\chi}_1^0\rightarrow tb\bar{s}$	Multiple E_T^{miss} 36.1		$m(\tilde{\chi}_1^0)=200 \text{ GeV}, \text{bino-like}$
	$\tilde{\tau}, \tilde{\tau}\rightarrow b\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm\rightarrow tb\bar{s}$	$\geq 4b$ E_T^{miss} 139		$m(\tilde{\chi}_1^0)=500 \text{ GeV}$
	$\tilde{\tau}_1, \tilde{\tau}_1\rightarrow tb\bar{s}$	2 jets + 2 b E_T^{miss} 36.7		$BR(\tilde{\tau}_1\rightarrow be/b\mu)>20\%$
	$\tilde{\tau}_1, \tilde{\tau}_1\rightarrow ql$	2 e,μ 1 μ DV E_T^{miss} 36.1 136		$BR(\tilde{\tau}_1\rightarrow q\mu)=100\%, \cos\theta_l=1$
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0, \tilde{\chi}_1^0\rightarrow tb\bar{s}, \tilde{\chi}_1^0\rightarrow bbs$	1-2 e,μ E_T^{miss} $\geq 6 \text{ jets}$ 139		Pure higgsino

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

10⁻¹ 1 Mass scale [TeV]

A snapshot of search summary

ATLAS SUSY Searches* - 95% CL Lower Limits

March 2021

ATLAS Preliminary

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

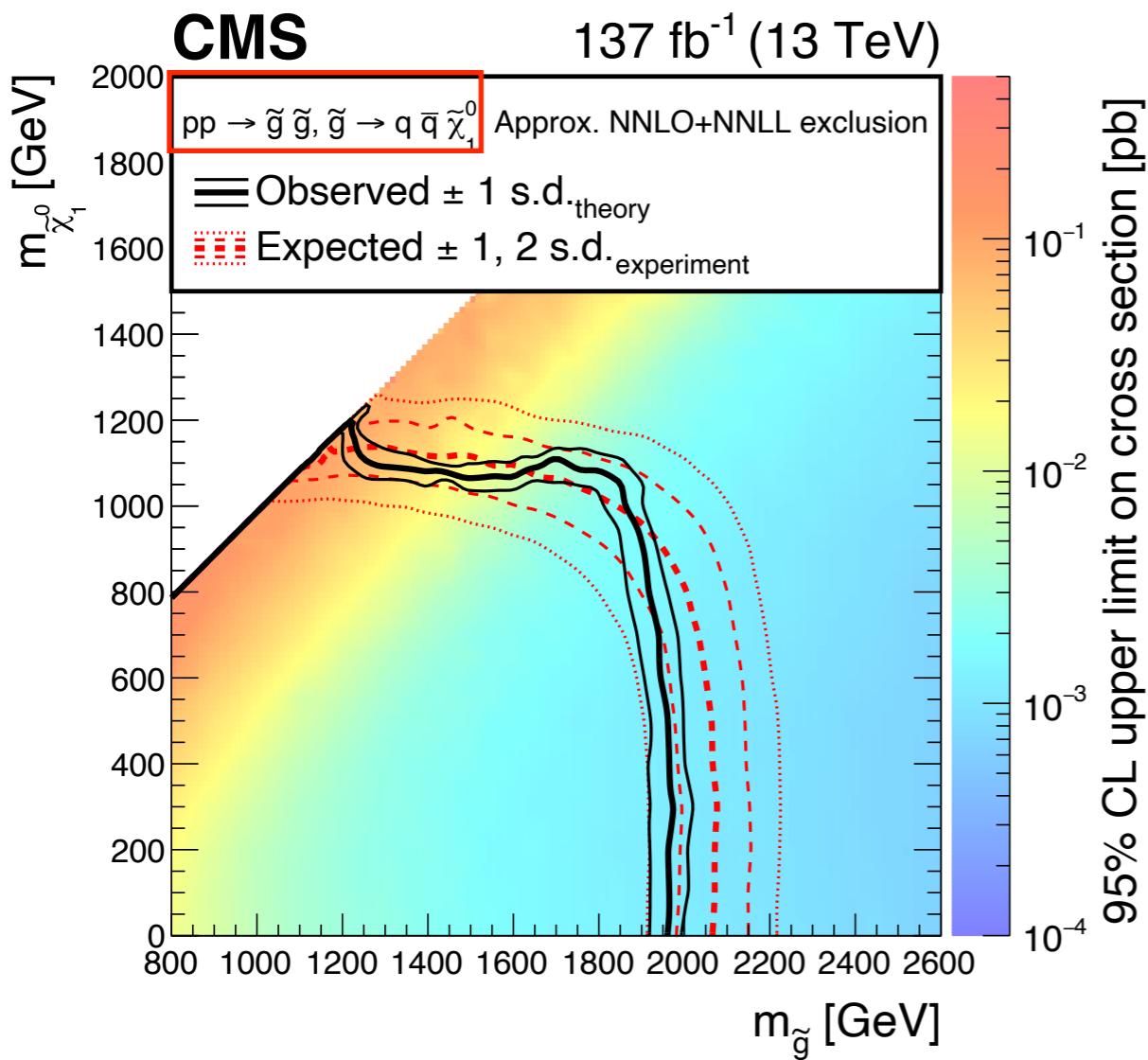
Model	Signature	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit				Reference	
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\rightarrow q\tilde{\chi}_1^0$ mono-jet	0 e, μ E_T^{miss} 1-3 jets E_T^{miss} 139 36.1	$\tilde{q} [1x, 8x \text{ Degen.}]$ $\tilde{q} [8x \text{ Degen.}]$	1.0 0.9	1.85		$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ $m(\tilde{q}) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}$	2010.14293 2102.10874
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow q\tilde{q}\tilde{\chi}_1^0$	0 e, μ E_T^{miss} 2-6 jets E_T^{miss} 139	$\tilde{g} [8x \text{ Degen.}]$	Forbidden	2.3 1.15-1.95	2.2	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 1000 \text{ GeV}$	2010.14293 2010.14293
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow q\tilde{q}W\tilde{\chi}_1^0$	1 e, μ E_T^{miss} 2-6 jets 139	$\tilde{g} [8x \text{ Degen.}]$		1.2		$m(\tilde{\chi}_1^0) < 600 \text{ GeV}$	2101.01629
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_1^0$	$ee, \mu\mu$ E_T^{miss} 2 jets 36.1	$\tilde{g} [8x \text{ Degen.}]$		1.2		$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 50 \text{ GeV}$	1805.11381
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	0 e, μ E_T^{miss} SS e, μ 7-11 jets 6 jets 139	$\tilde{g} [8x \text{ Degen.}]$		1.97 1.15		$m(\tilde{\chi}_1^0) < 600 \text{ GeV}$ $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 200 \text{ GeV}$	2008.06032 1909.08457
Inclusive Searches	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ SS e, μ 3 b 6 jets E_T^{miss} 79.8 139	$\tilde{g} [8x \text{ Degen.}]$		2.25 1.25		$m(\tilde{\chi}_1^0) < 200 \text{ GeV}$ $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300 \text{ GeV}$	ATLAS-CONF-2018-041 1909.08457
	$\tilde{b}_1\tilde{b}_1$	0 e, μ E_T^{miss} 2 b 139	\tilde{b}_1 \tilde{b}_1	0.68	1.255		$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ $10 \text{ GeV} < \Delta m(\tilde{b}_1, \tilde{\chi}_1^0) < 20 \text{ GeV}$	2101.12527 2101.12527
3rd gen. squarks direct production	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow t\tilde{\chi}_1^0$	0 e, μ E_T^{miss} 139	\tilde{t}_1					1908.03122 ATLAS-CONF-2020-031
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow Wb\tilde{\chi}_1^0$							2004.14060, 2012.03799
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow \tilde{t}_1 bv, \tilde{t}_1\rightarrow \tau\tilde{G}$							2012.03799 ATLAS-CONF-2021-008
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow c\tilde{\chi}_1^0 / \tilde{c}\bar{c}, \tilde{c}\rightarrow c\tilde{\chi}_1^0$							1805.01649 2102.10874
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow t\tilde{\chi}_2^0, \tilde{t}_2\rightarrow Z/h\tilde{\chi}_1^0$ $\tilde{t}_2\tilde{t}_2, \tilde{t}_2\rightarrow \tilde{t}_1 + Z$							2006.05880 2006.05880
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^\mp$ via WZ							ATLAS-CONF-2020-015 1911.12606
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via WW							1908.08215
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^\mp$ via Wh							2004.10894, 1909.09226
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via $\tilde{\ell}\tilde{\nu}$							1908.08215 1911.06660
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau}\rightarrow \tau\tilde{\chi}_1^0$							1908.08215 1911.12606
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\rightarrow \ell\tilde{\chi}_1^0$							
Long-lived particles	$\tilde{H}\tilde{H}, \tilde{H}\rightarrow h\tilde{G}/Z\tilde{G}$	0 e, μ 4 e, μ E_T^{miss} 0 jets 36.1 139	\tilde{H} H	0.13-0.23 0.55	0.29-0.88		$\text{BR}(\tilde{\chi}_1^0 \rightarrow h\tilde{G})=1$ $\text{BR}(\tilde{\chi}_1^0 \rightarrow Z\tilde{G})=1$	1806.04030 2103.11684
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	E_T^{miss} 139	$\tilde{\chi}_1^\pm$ $\tilde{\chi}_1^\pm$	0.21	0.66	Pure Wino Pure higgsino
RPV	Stable \tilde{g} R-hadron		Multiple	E_T^{miss} 36.1	\tilde{g}		2.0	
	Metastable \tilde{g} R-hadron, $\tilde{g}\rightarrow q\tilde{q}\tilde{\chi}_1^0$ $\tilde{t}\tilde{t}, \tilde{t}\rightarrow \ell\tilde{G}$	Multiple	E_T^{miss} 36.1	$\tilde{g} [\tau(\tilde{g}) = 10 \text{ ns}, 0.2 \text{ ns}]$		2.05 0.7	2.4	$m(\tilde{\chi}_1^0) = 100 \text{ GeV}$ $\tau(\tilde{t}) = 0.1 \text{ ns}$ $\tau(\tilde{\ell}) = 0.1 \text{ ns}$
	Displ. lep			E_T^{miss} 139	$\tilde{e}, \tilde{\mu}$ $\tilde{\tau}$	0.34		
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_1^0, \tilde{\chi}_1^\pm\rightarrow Z\ell\rightarrow \ell\ell\ell$	3 e, μ 4 e, μ E_T^{miss} 0 jets 139			0.625	1.05		Pure Wino
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^\mp/\tilde{\chi}_2^0, \tilde{\chi}_1^\pm\rightarrow WW/Z\ell\ell\ell\ell\nu\nu$				0.95	1.55		$m(\tilde{\chi}_1^0) = 200 \text{ GeV}$
RPV	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0\rightarrow qqq$	4 e, μ 4-5 large- R jets		$\tilde{g} [m(\tilde{\chi}_1^0) = 200 \text{ GeV}, 1100 \text{ GeV}]$		1.3	1.9	Large λ'_{112}
	$\tilde{t}\tilde{t}, \tilde{t}\rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0\rightarrow tbs$	Multiple	E_T^{miss} 36.1	$\tilde{t} [J''_{323} = 2e-4, 1e-2]$	0.55	1.05		ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}, \tilde{t}\rightarrow b\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm\rightarrow bbs$	$\geq 4b$	E_T^{miss} 139					2010.01015
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow bs$	2 jets + 2 b	E_T^{miss} 36.7	$\tilde{t}_1 [qq, bs]$	0.42 0.61	0.95		1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow ql$	2 e, μ 1 μ DV	E_T^{miss} 36.1 136	$\tilde{t}_1 [1e-10 < \lambda'_{234} < 1e-8, 3e-10 < \lambda'_{234} < 3e-9]$	0.4-1.45 1.0 1.6		$\text{BR}(\tilde{t}_1 \rightarrow be/b\mu) > 20\%$ $\text{BR}(\tilde{t}_1 \rightarrow q\mu) = 100\%, \cos\theta_t = 1$	1710.05544 2003.11956
	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0/\tilde{\chi}_1^0, \tilde{\chi}_1^0\rightarrow tbs, \tilde{\chi}_1^+ \rightarrow bbs$	1-2 e, μ ≥ 6 jets	E_T^{miss} 139	$\tilde{\chi}_1^0$	0.2-0.32			Pure higgsino
								ATLAS-CONF-2021-007

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

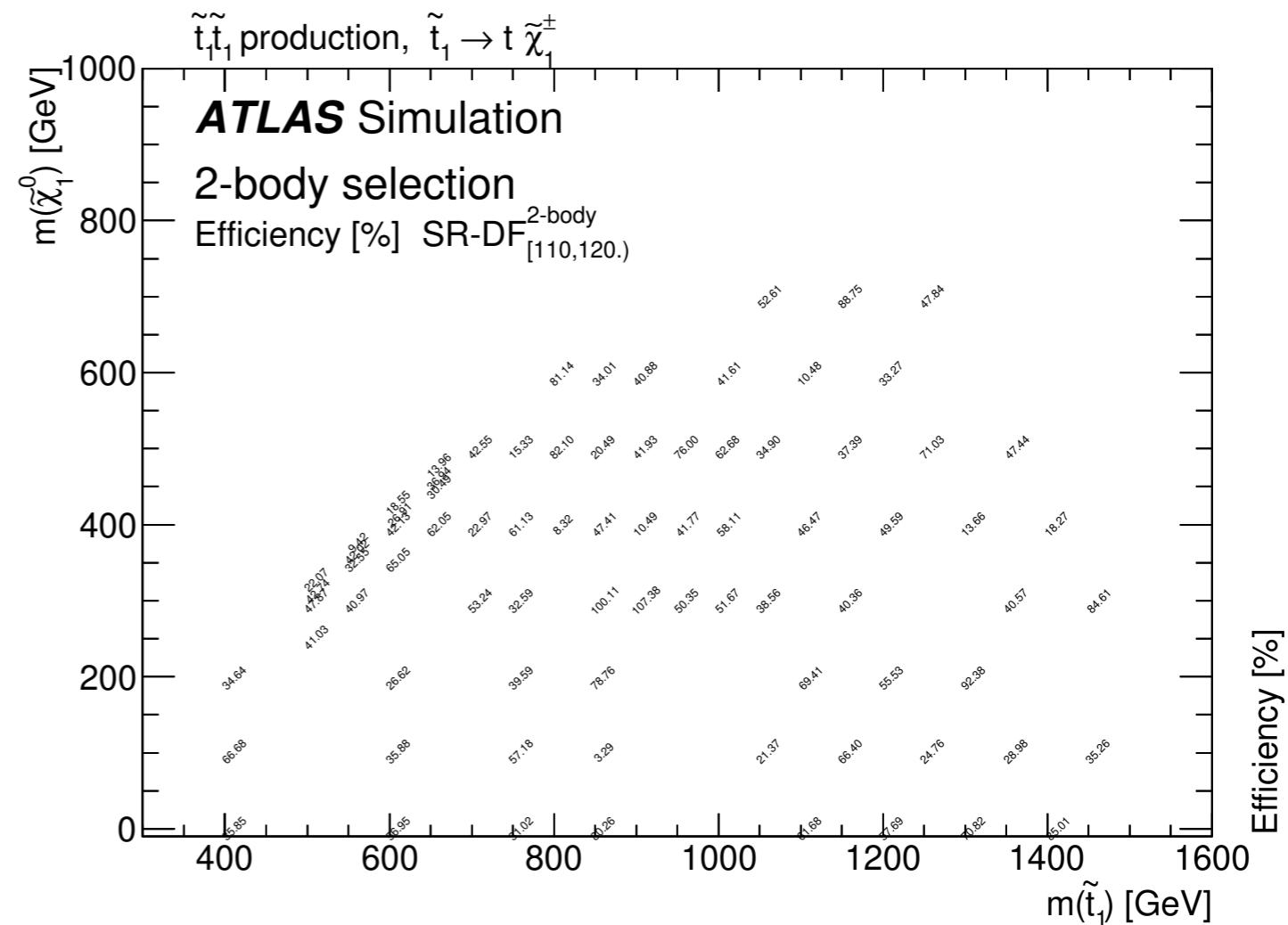
10⁻¹ 1 Mass scale [TeV]

General remarks on SUSY results

- Typical result: exclusion limits as functions of two masses
 - Strong assumptions on the remaining signal parameters
 - Extra information, e.g. efficiencies in signal regions, are provided to allow for re-interpretation
- Interpretations in many different signal models, even beyond SUSY

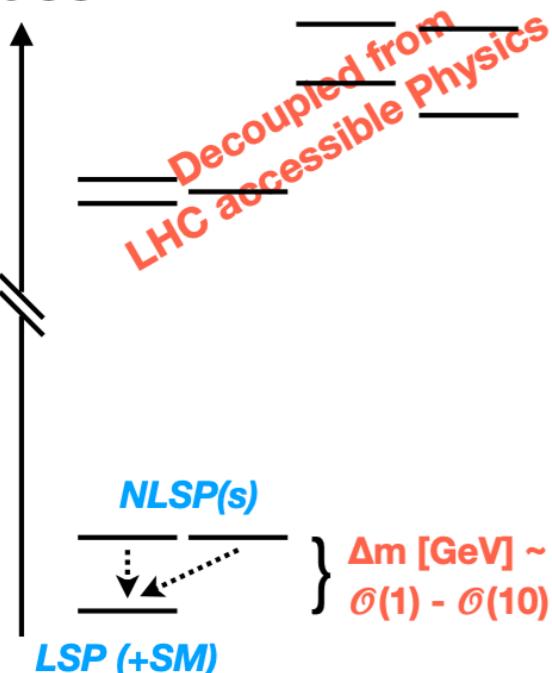


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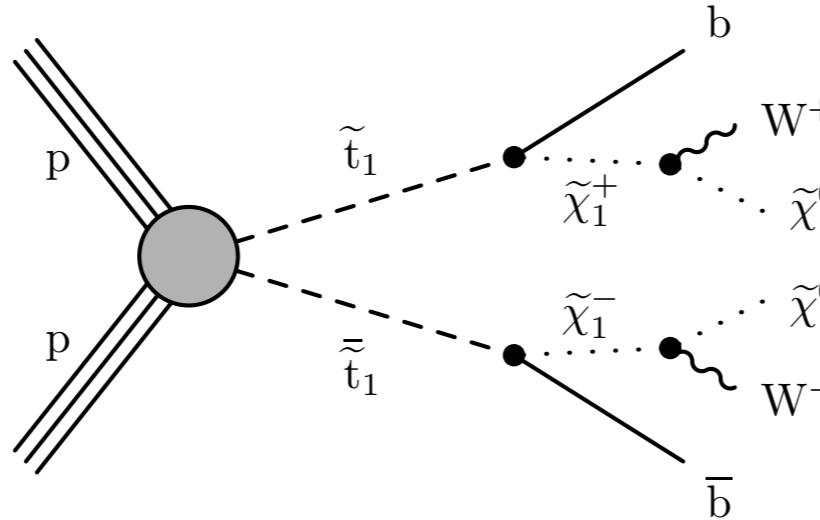
Compressed Region - \tilde{t} in the top corridor

Mass

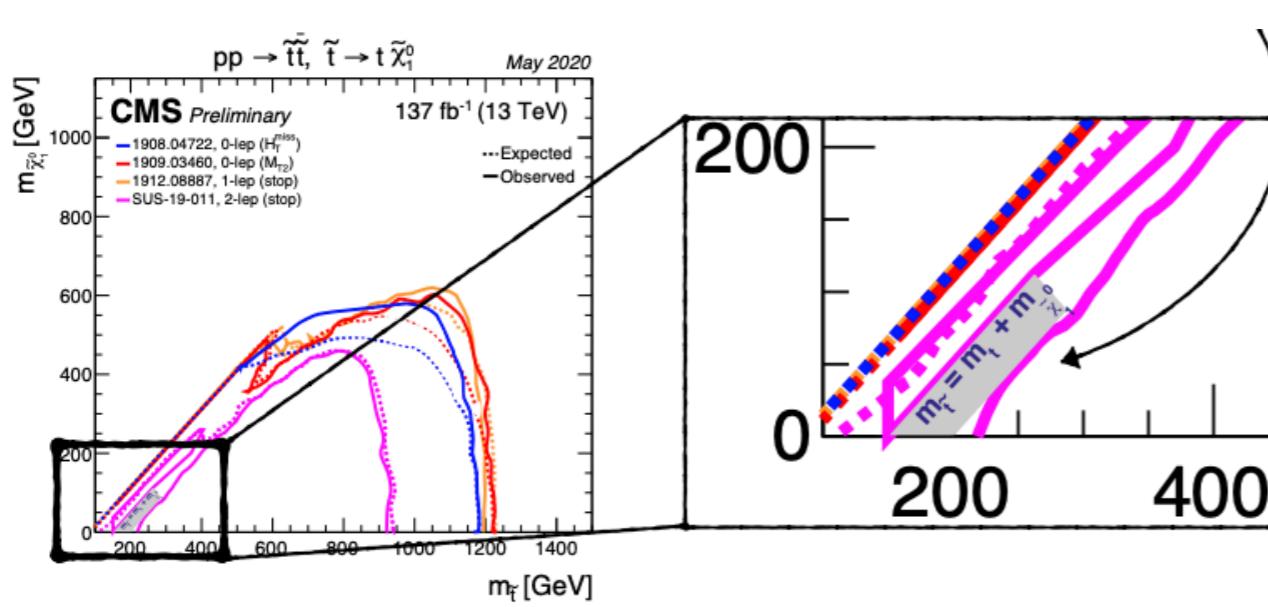


top corridor region

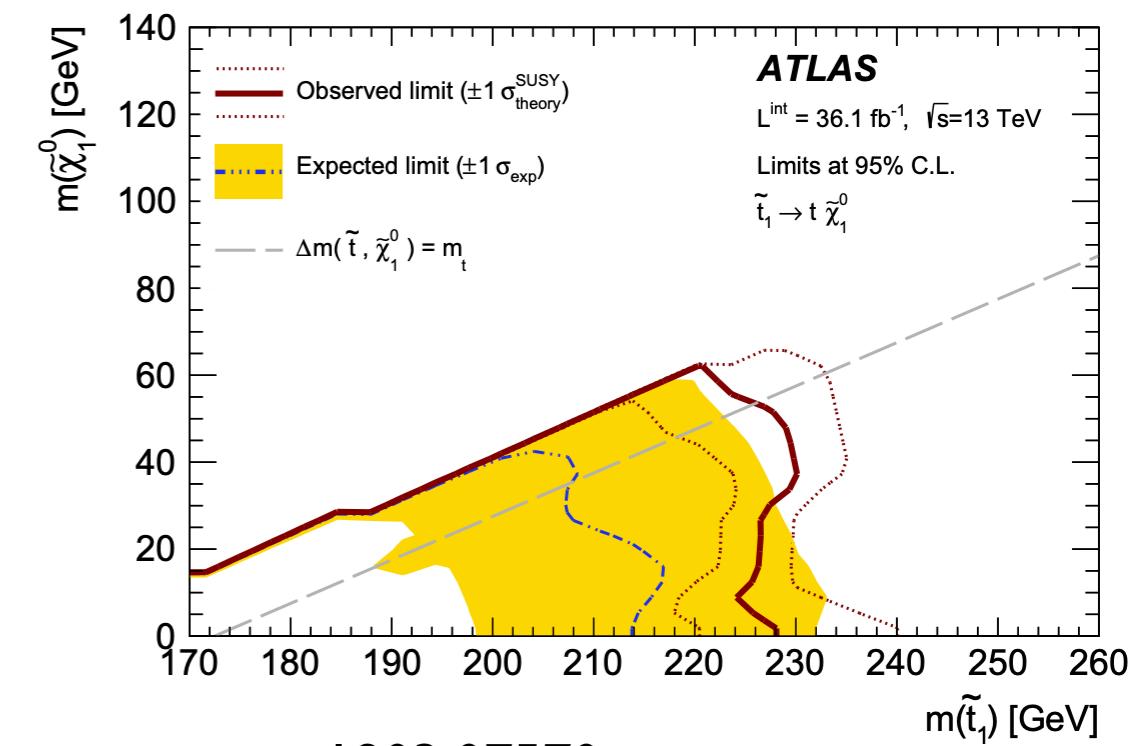
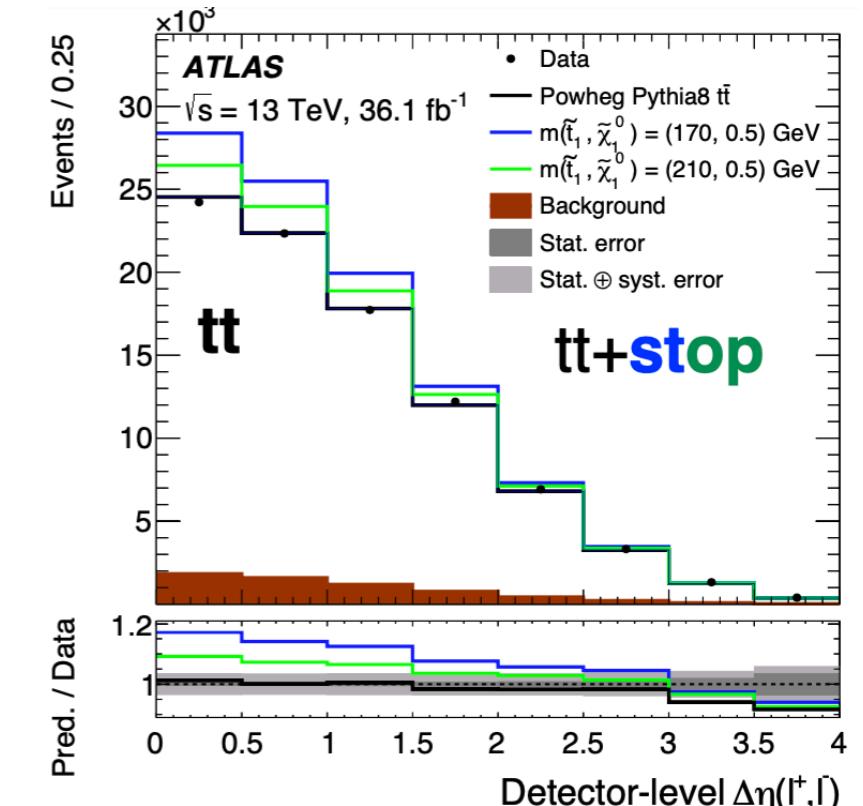
$$m(\tilde{t}) - m(t) \sim m(\tilde{\chi}_1^0)$$



very little p_T^{miss}
signal resembles to $t\bar{t}$ background

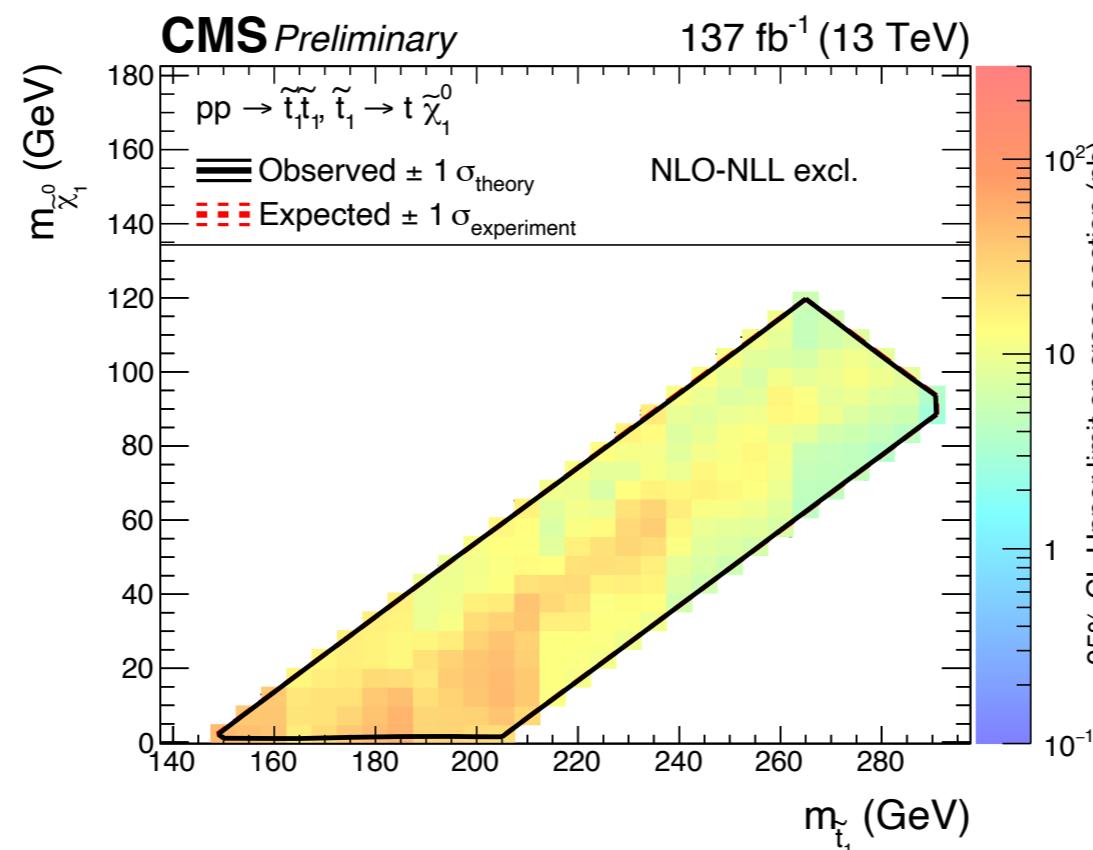
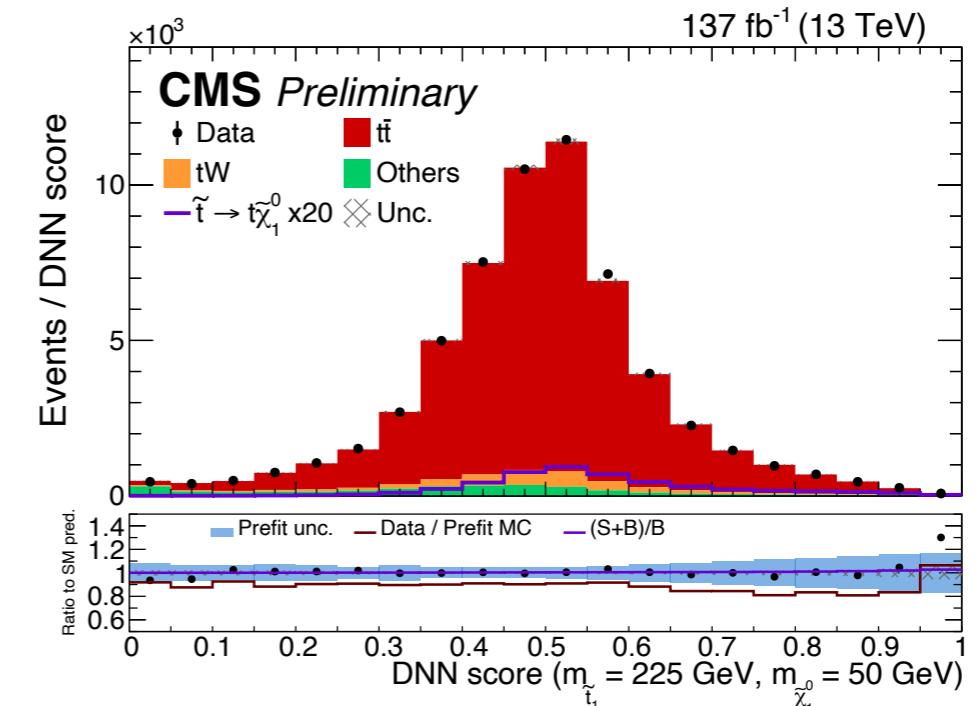
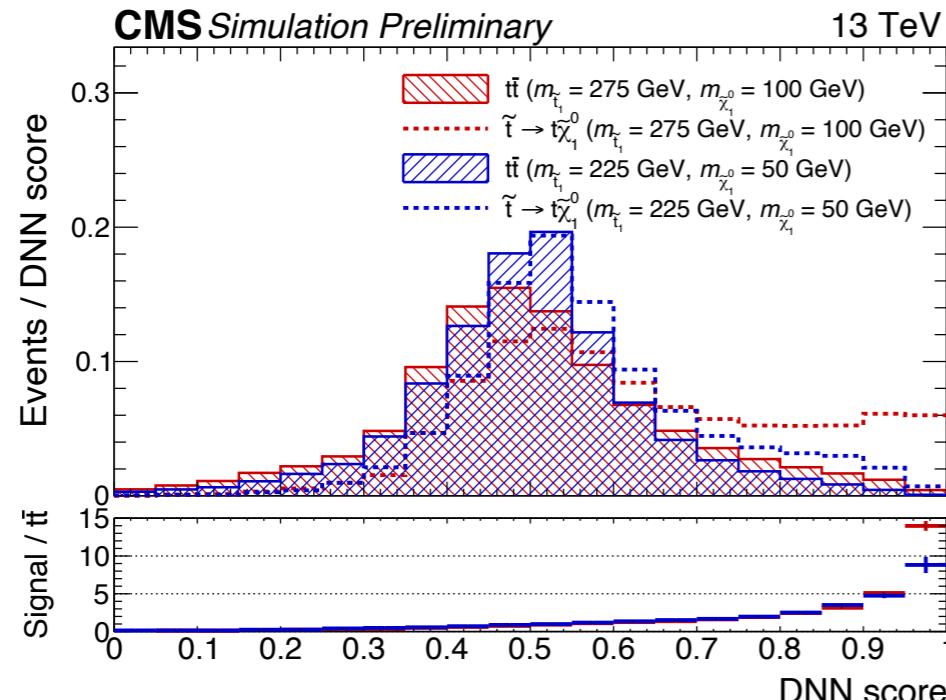


ATLAS explores top quark spin correlations



\tilde{t} in the compressed “top corridor”

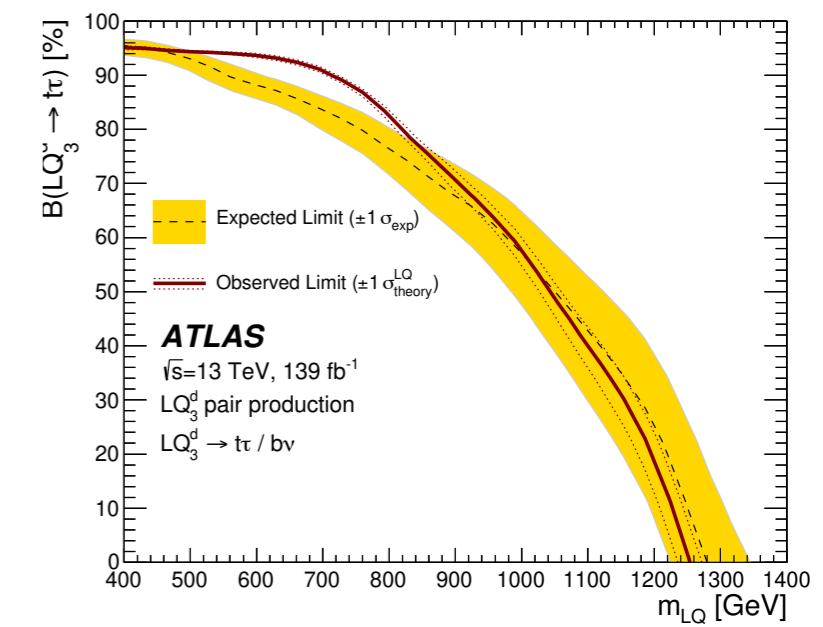
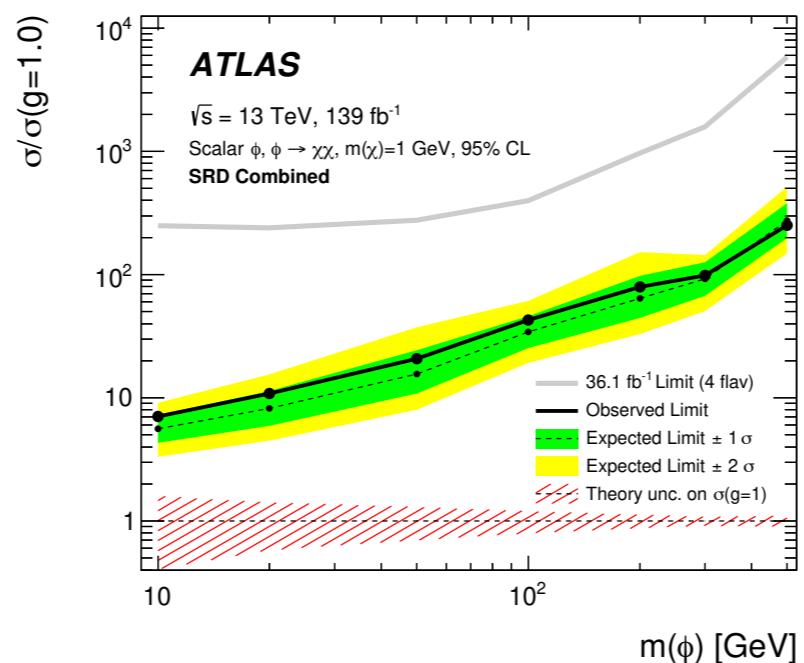
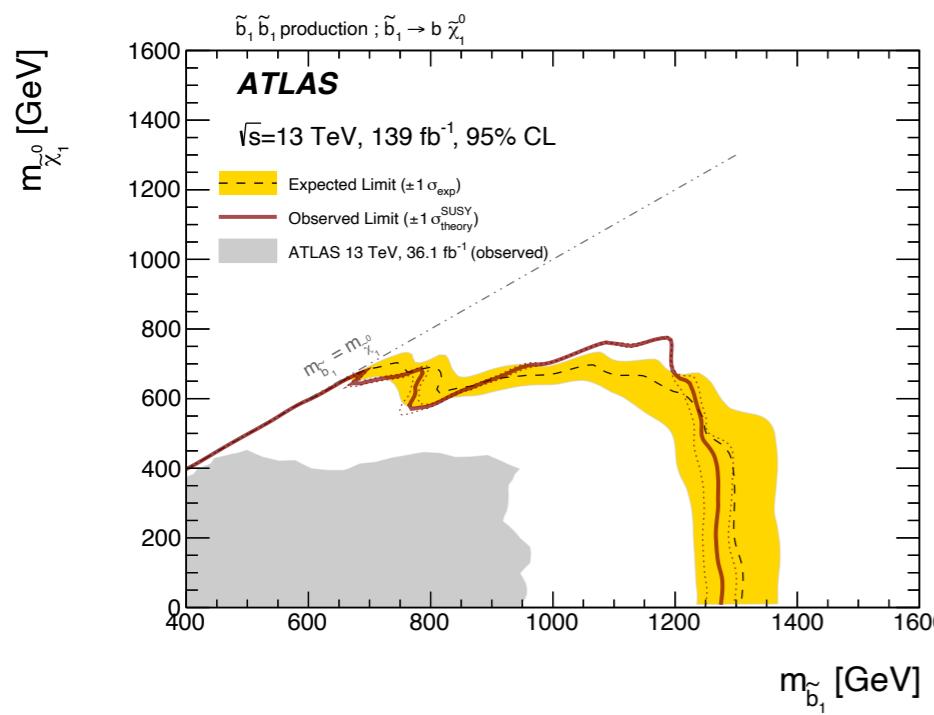
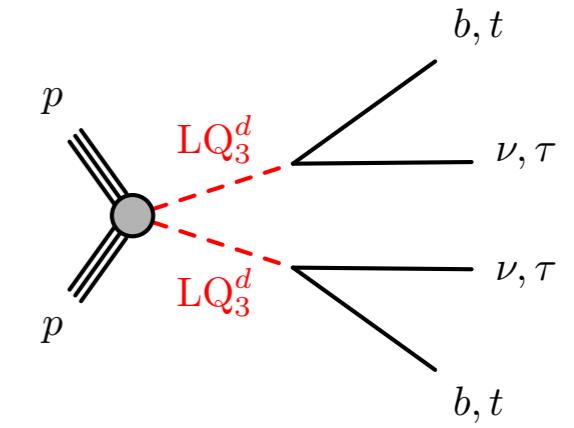
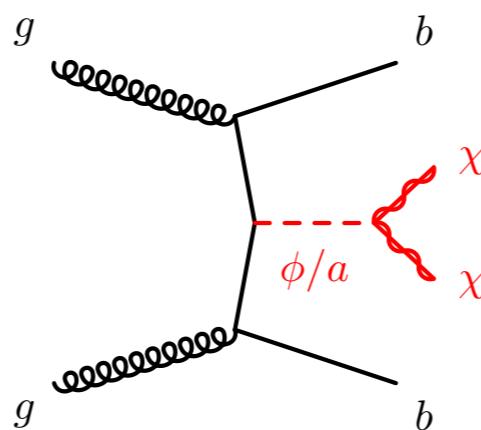
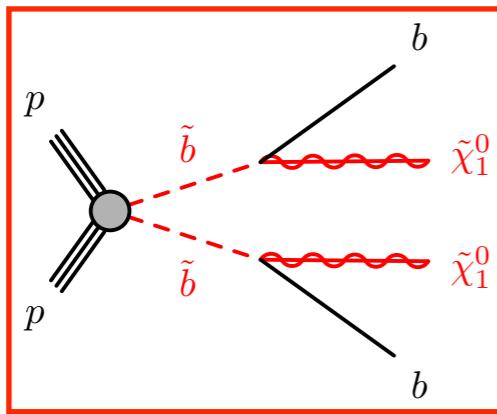
- Multivariate analysis: 11 input variables 7 hidden layer DNN



Entire corridor excluded for
the first time in CMS

$|m_{\tilde{t}_1} - m_t - m_{\tilde{\chi}_1^0}| < 30 \text{ GeV}$
 $m_{\tilde{\chi}_1^0} < 120 \text{ GeV}$

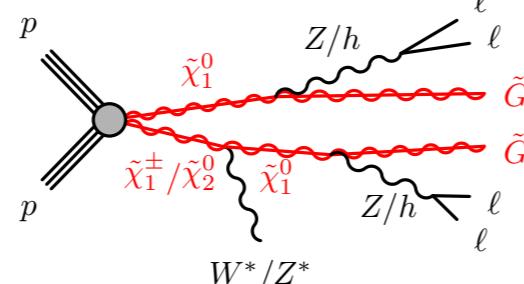
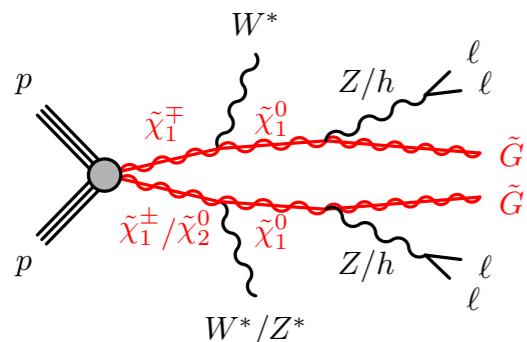
$b\bar{b} + E_T$



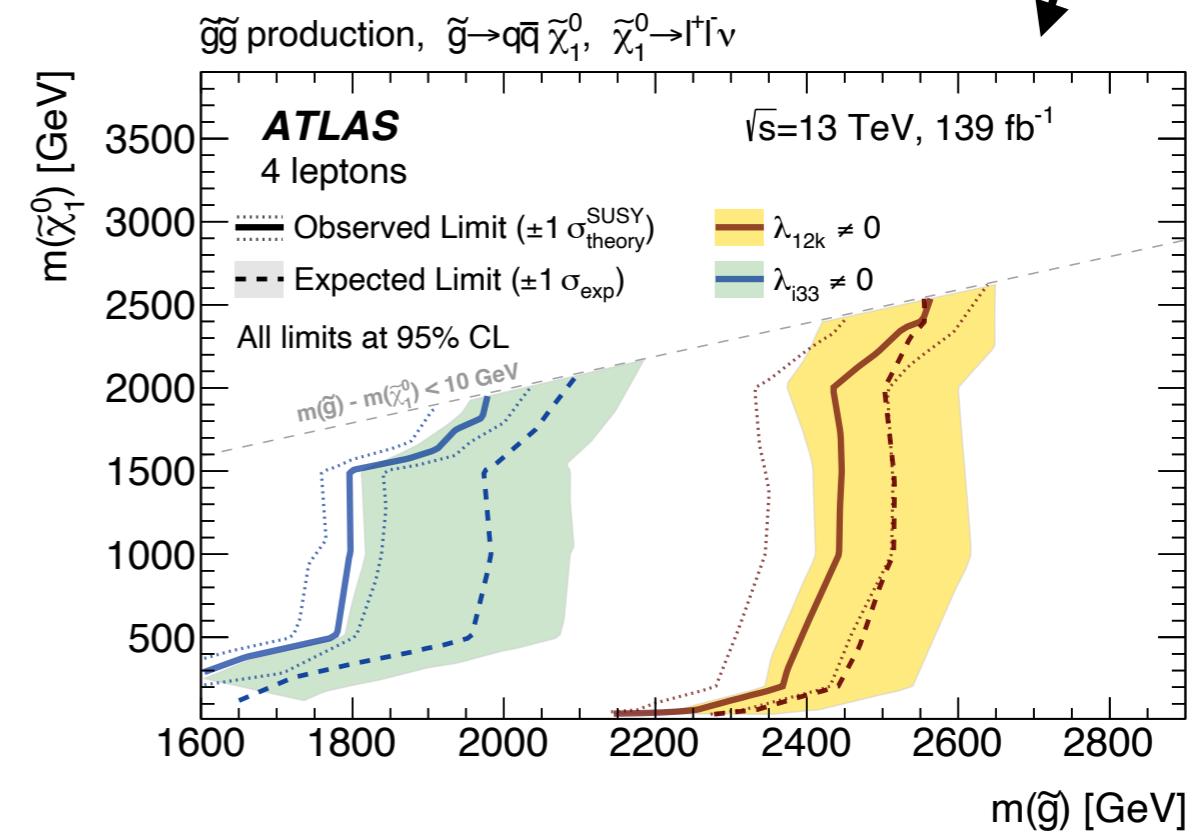
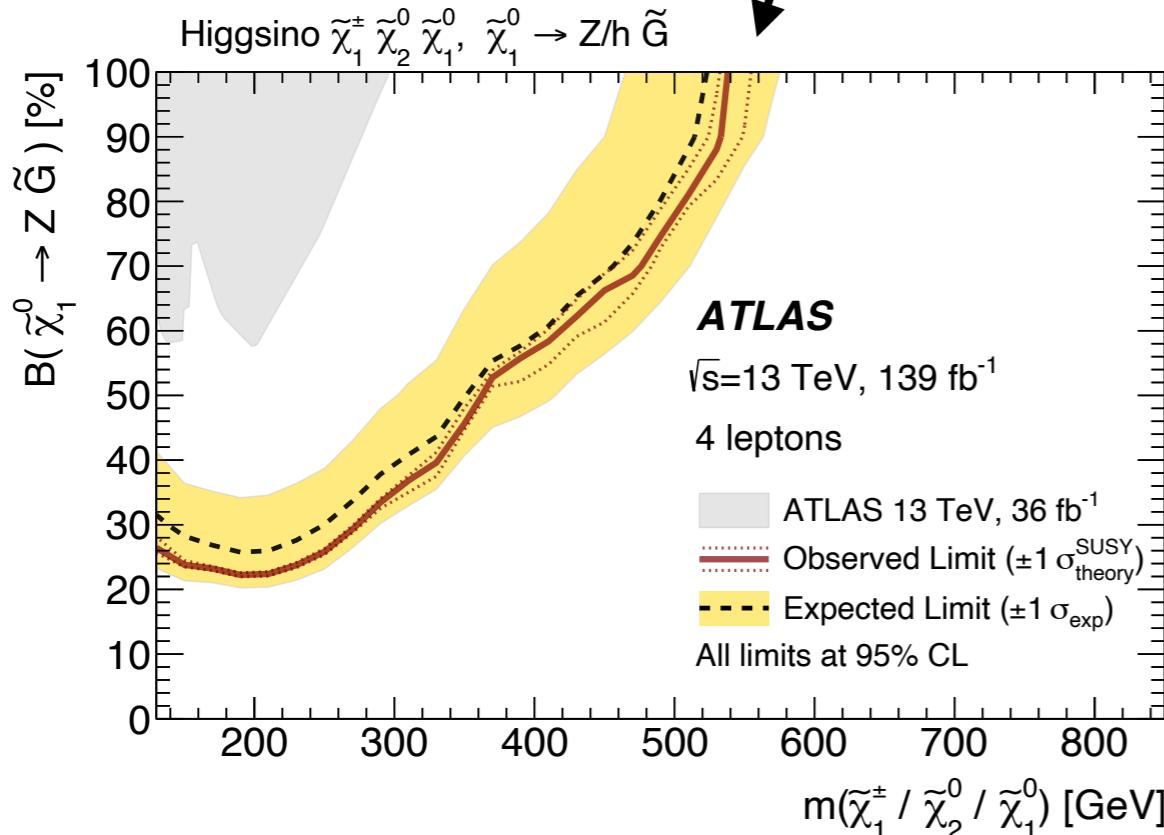
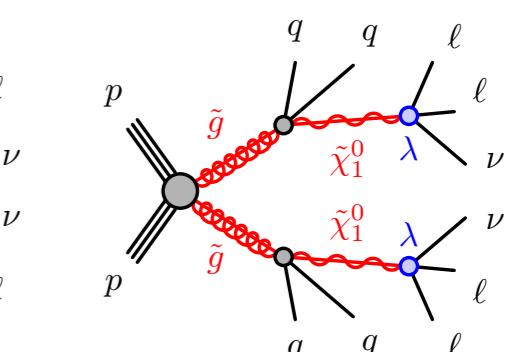
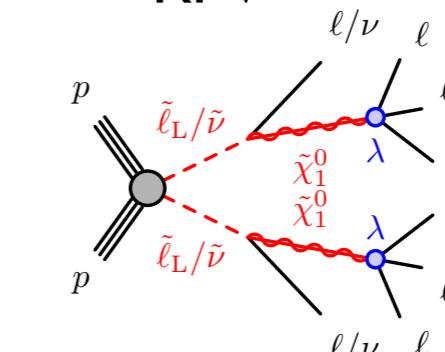
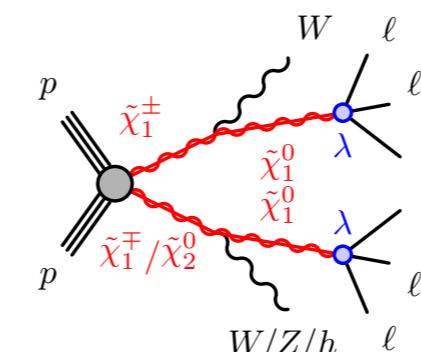
Tackling rare final states $4\ell + E_T$

RPC

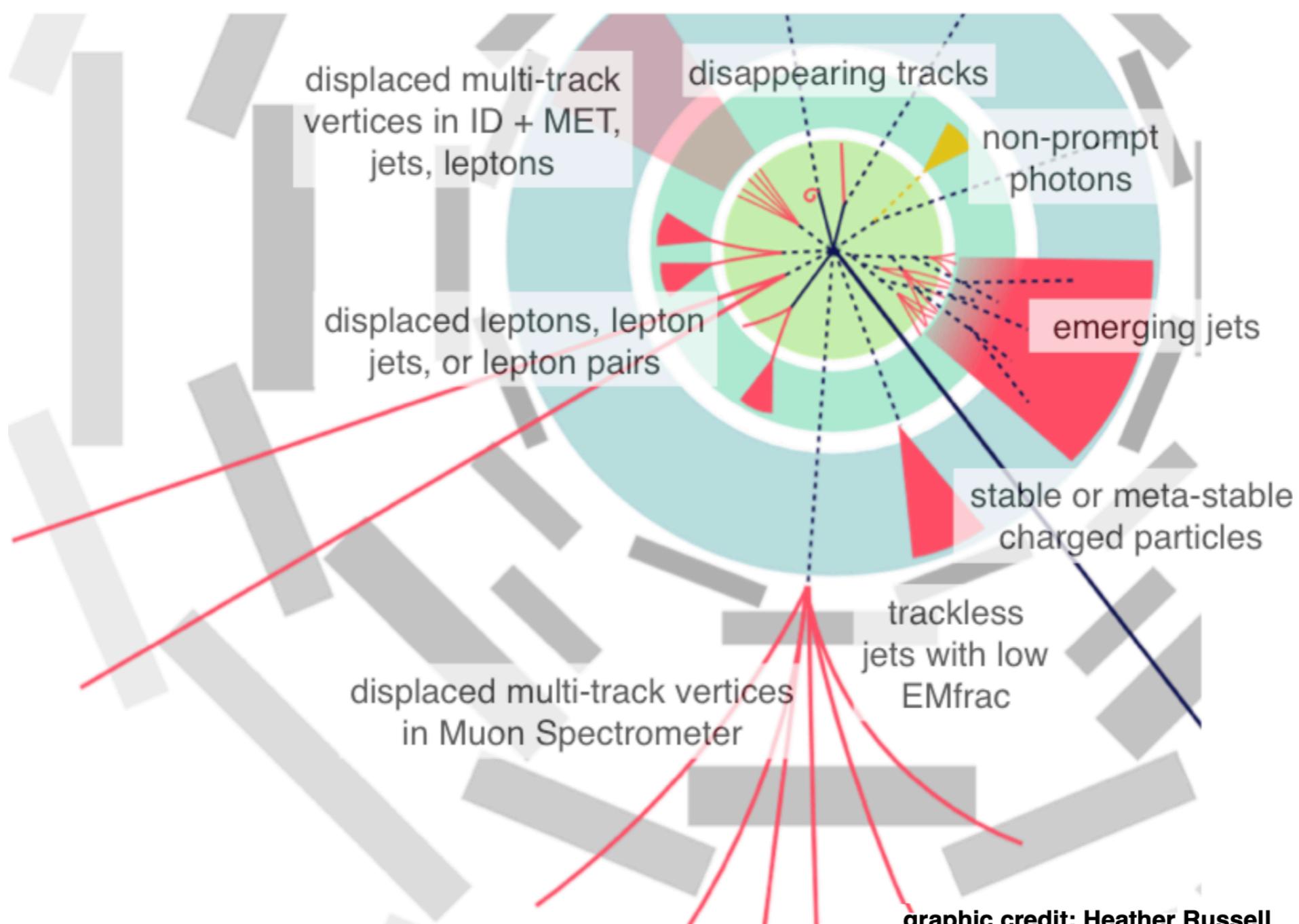
Gauge mediated susy



RPV



Long-lived particles



A summary of search results - $c\tau$

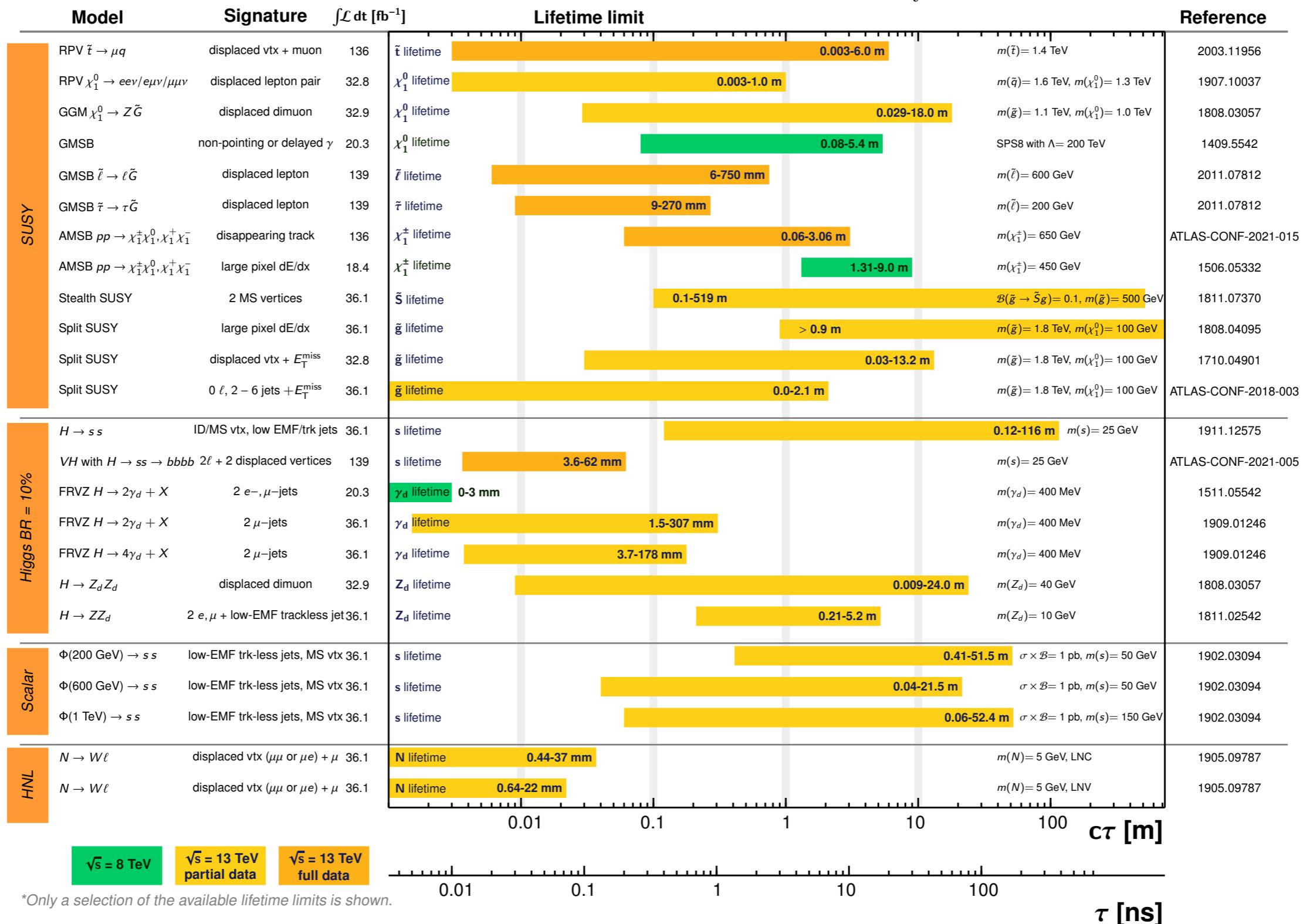
ATLAS Long-lived Particle Searches* - 95% CL Exclusion

Status: March 2021

ATLAS Preliminary

$\int \mathcal{L} dt = (18.4 - 139) \text{ fb}^{-1}$

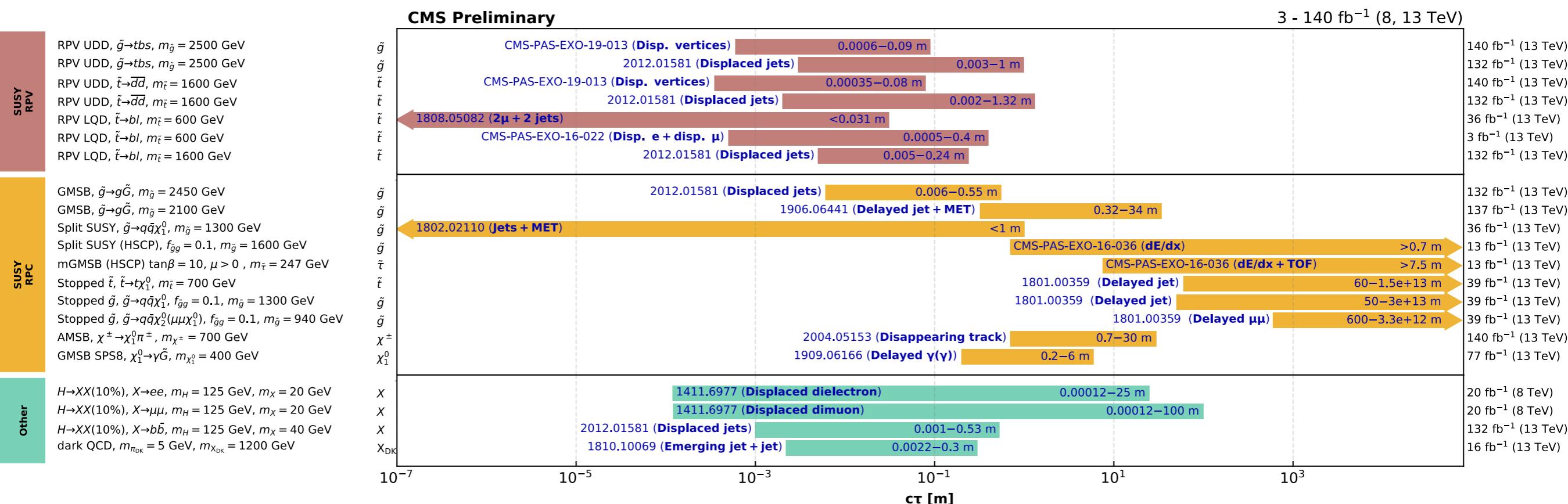
$\sqrt{s} = 8, 13 \text{ TeV}$



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

A summary of search results - $c\tau$

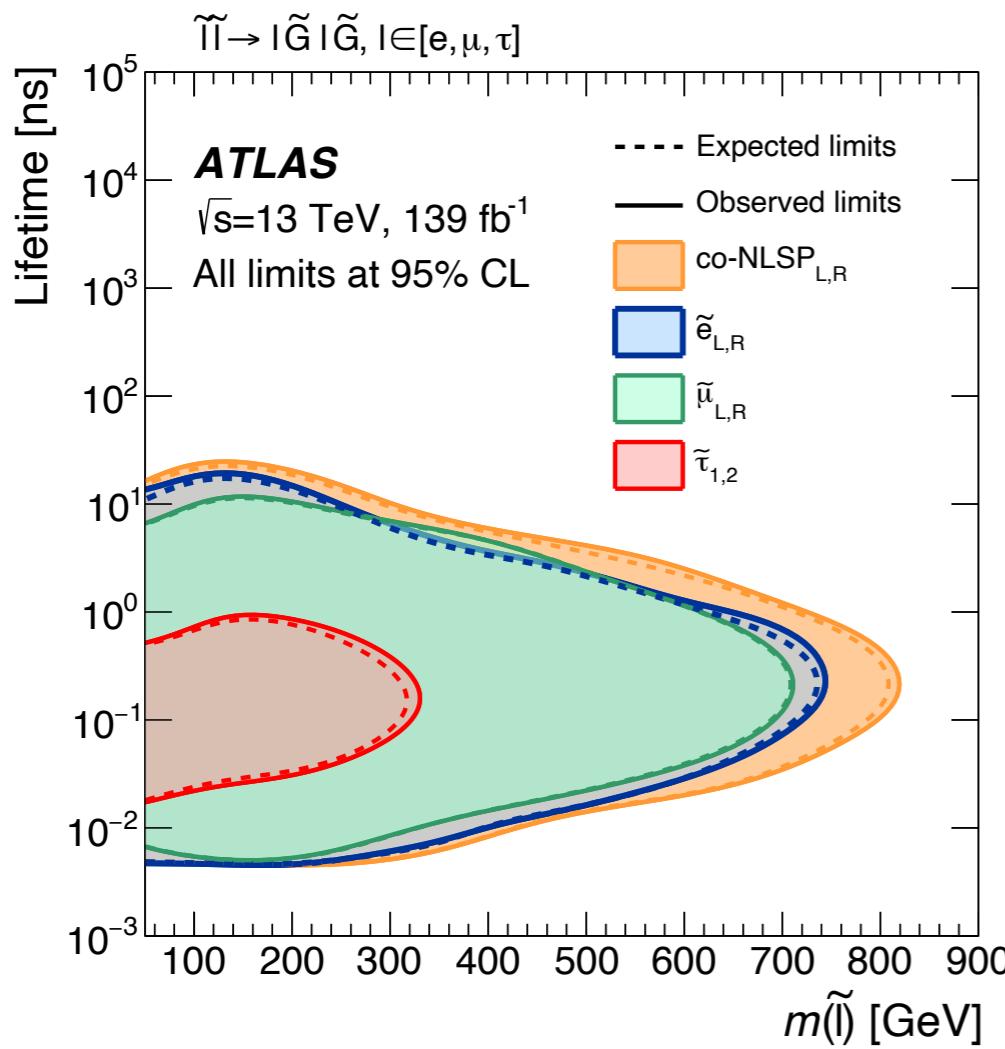
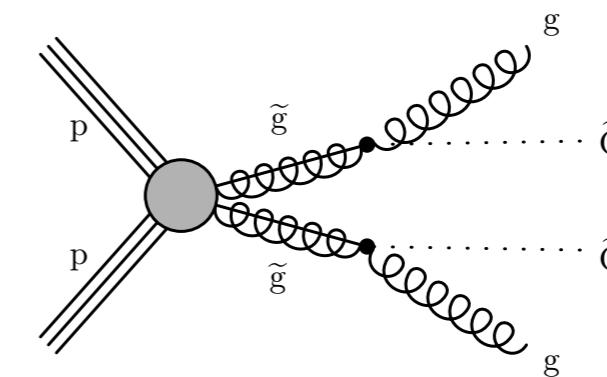
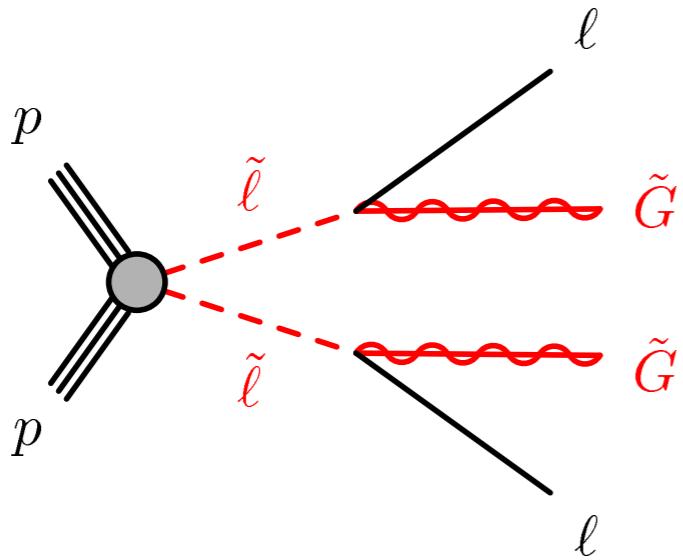
Overview of CMS long-lived particle searches



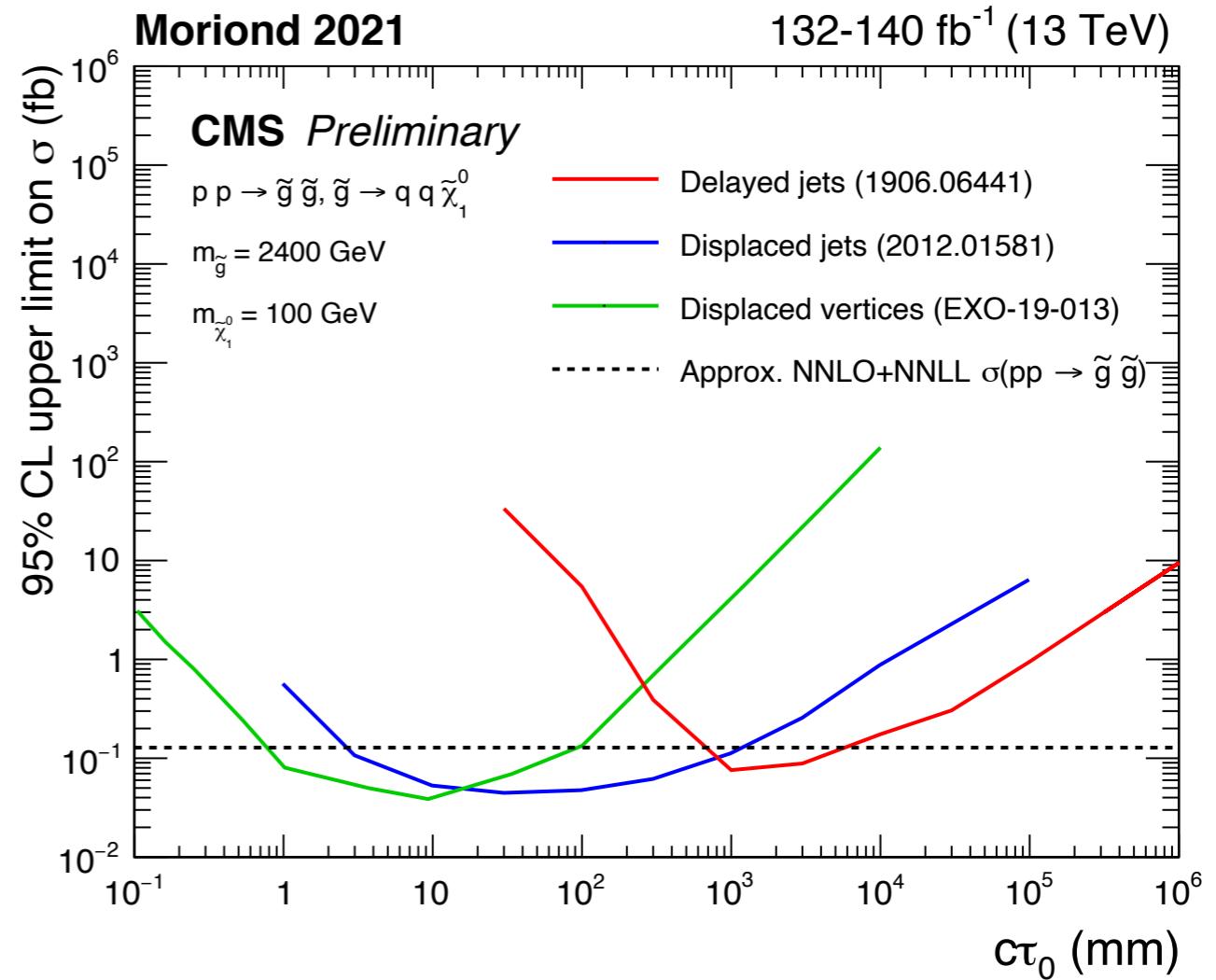
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

Moriond 2021

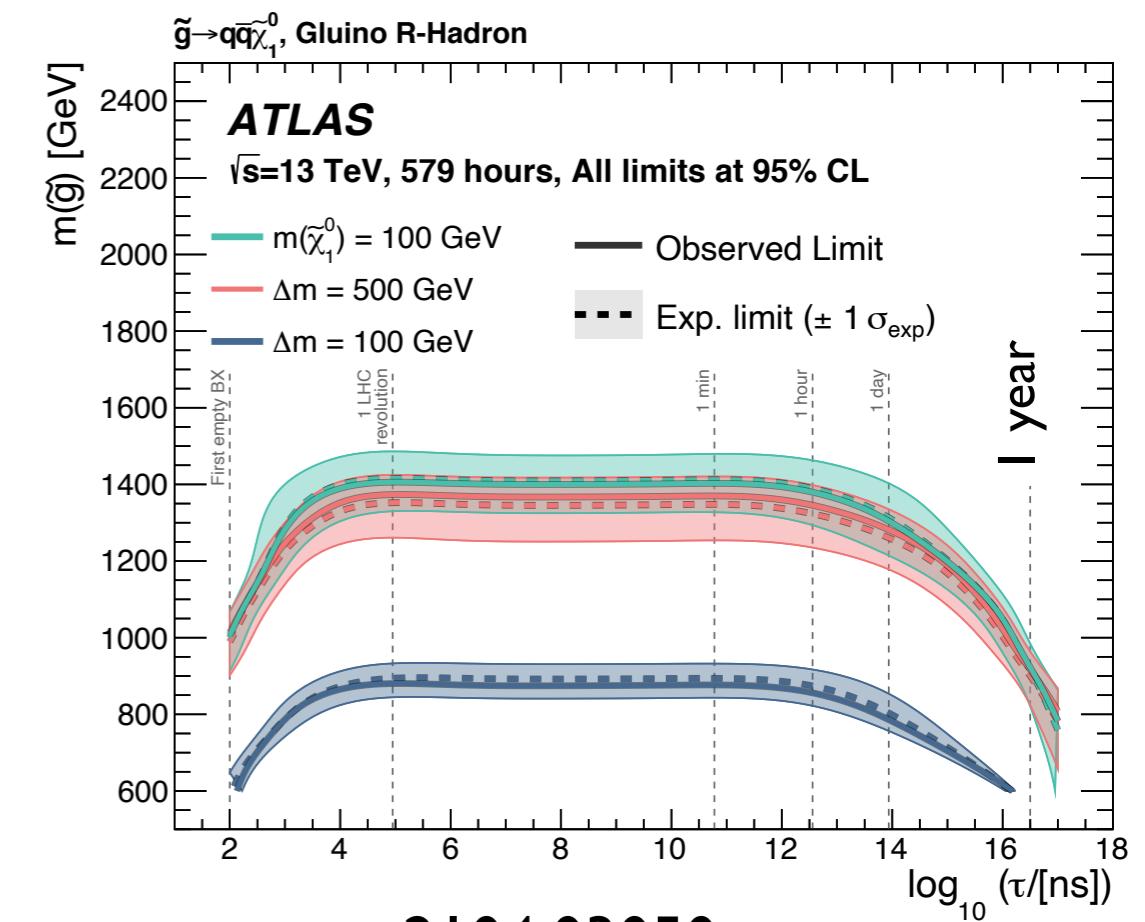
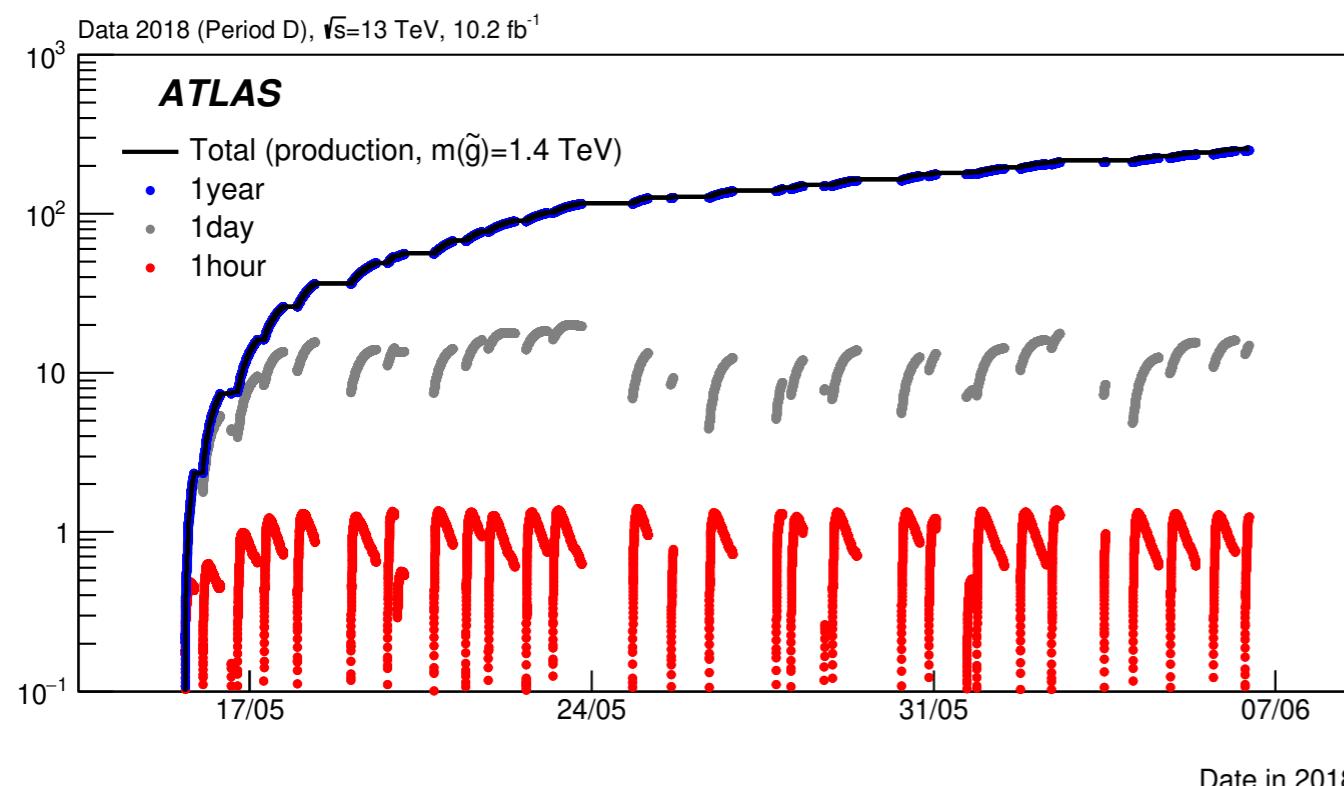
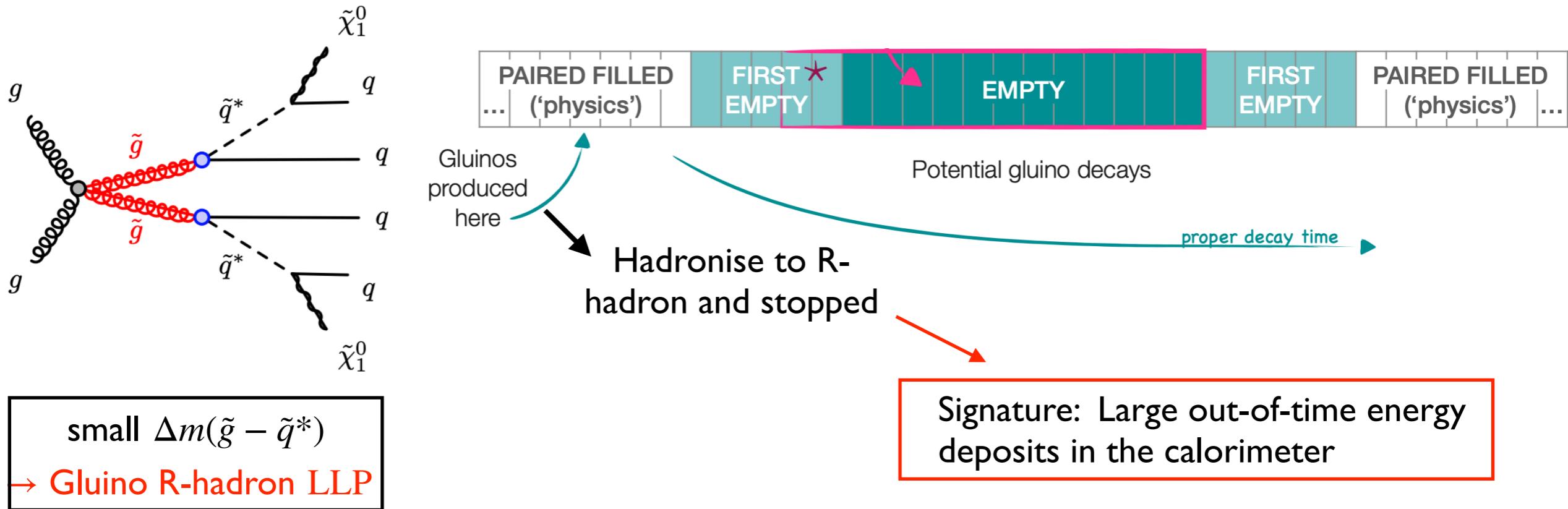
Displaced signatures in high pT/mass region



2011.07812

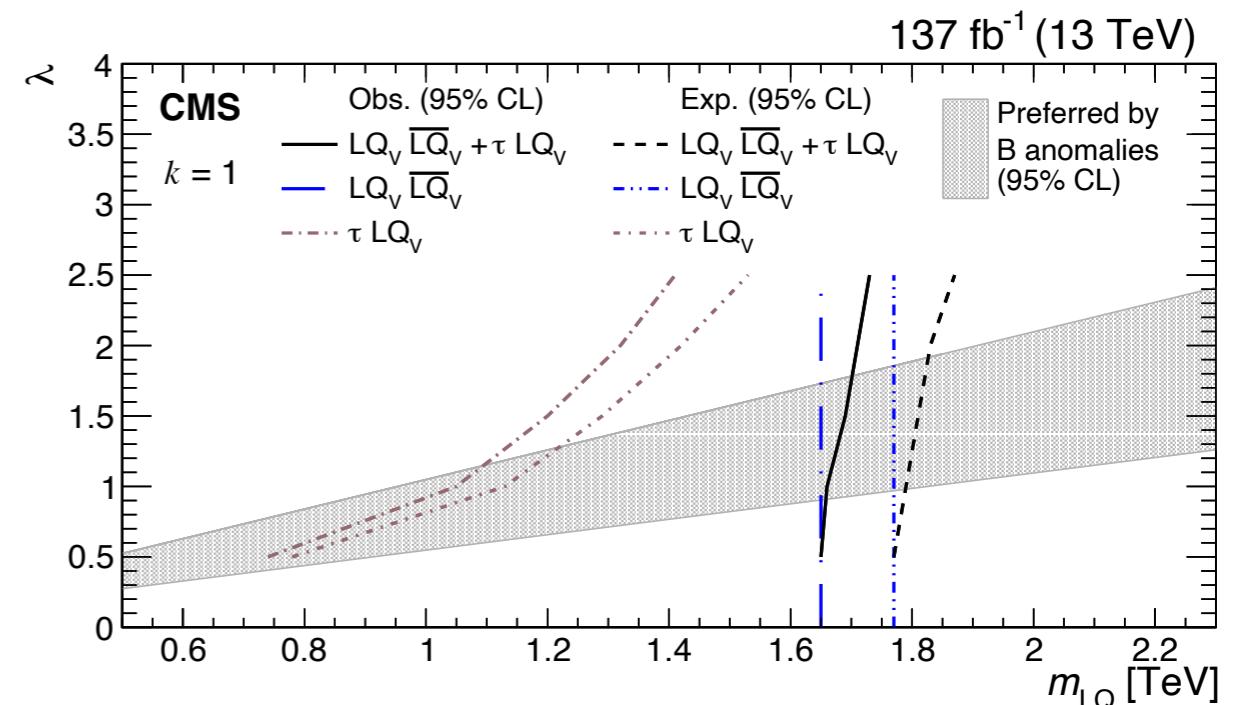
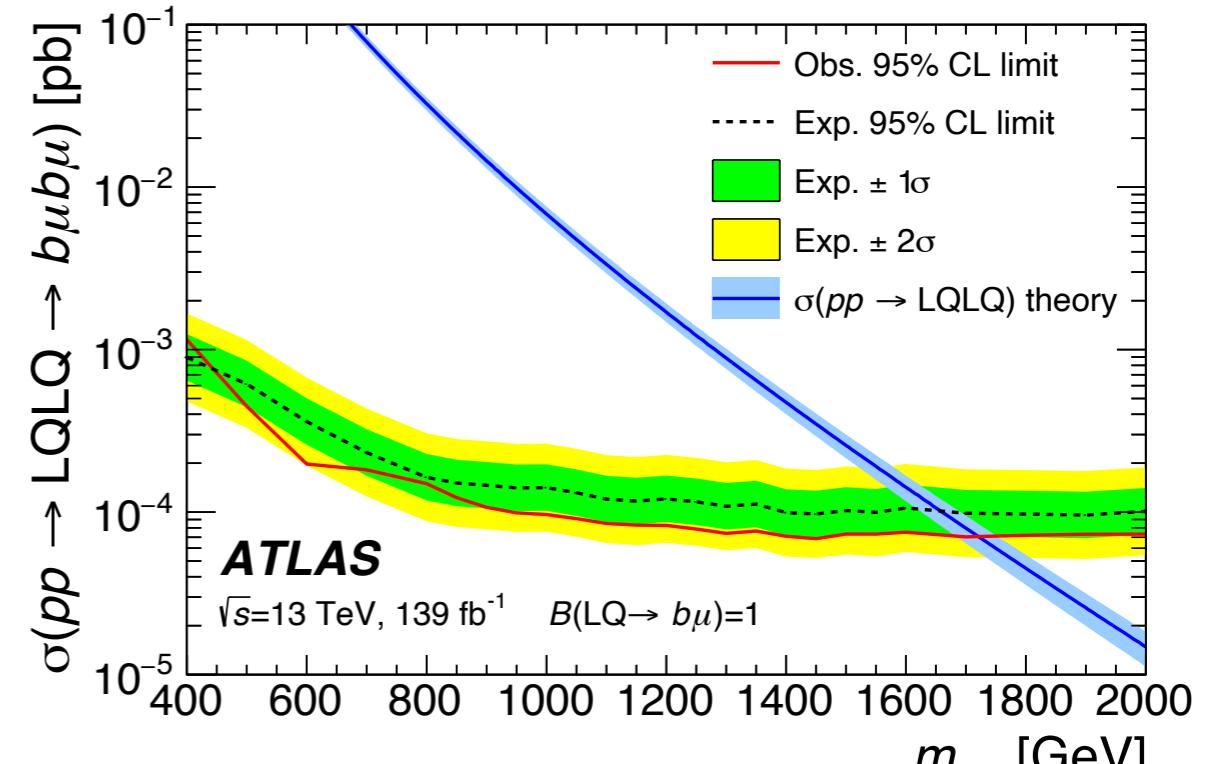


Stopped LLP in bunch crossings with no collision

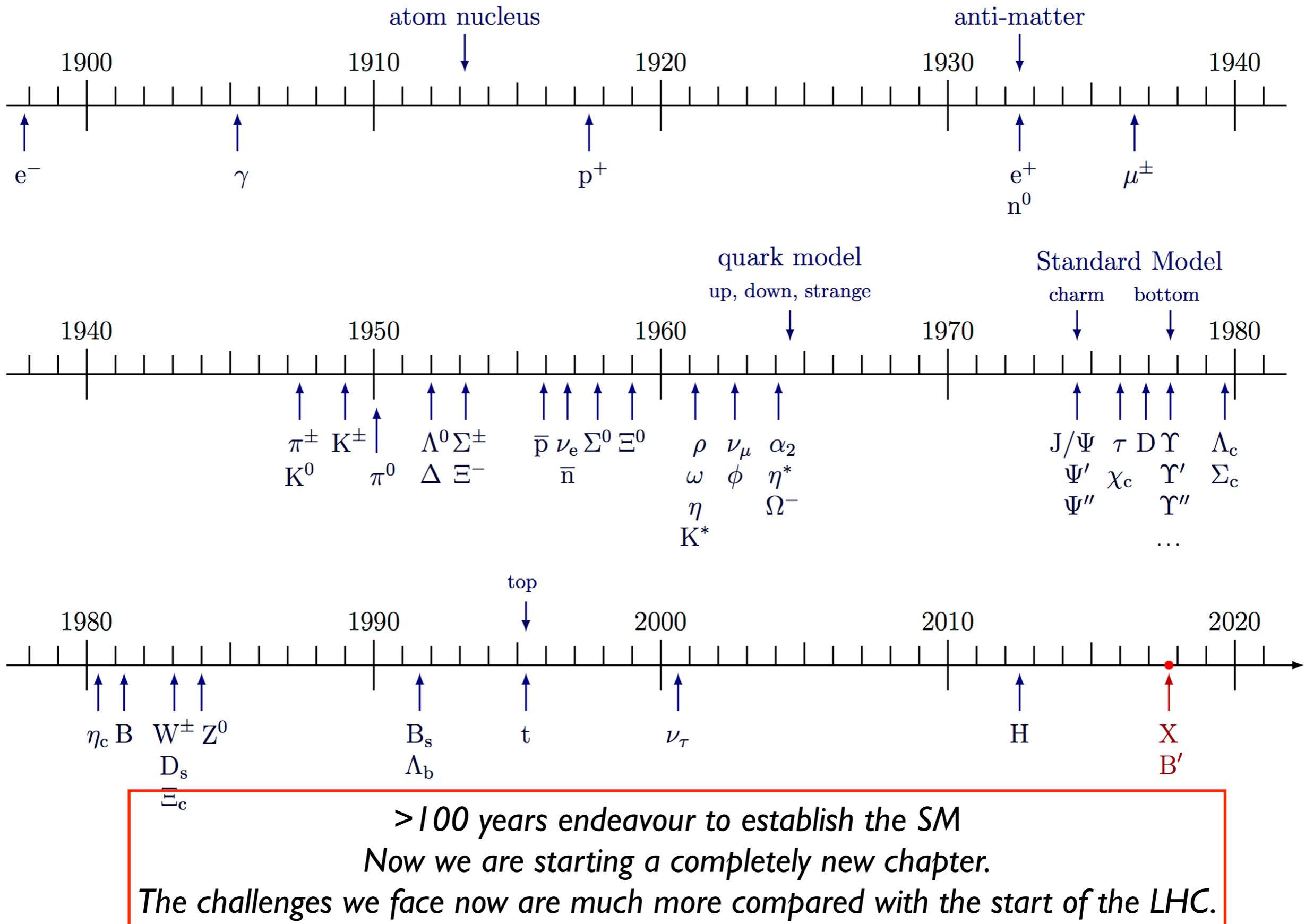


Summary

- A vast programme of BSM physics searches has been carried out based on the successful LHC Run 1+2 data-taking
- ATLAS and CMS explored a huge chunk of the phase-space at multi- TeV scale
 - More efforts are now devoted to challenging kinematic regions and theoretical phase-space
 - Closing up the gaps!
 - Presenting and preserving this legendary dataset are also becoming mainstream
- Several intriguing anomalies in the flavour sector, led by the LHCb experiment, may just be what we need to go behind the SM
 - Muons appear to be “acting up” in several places, and will surely shake/shape the LHC BSM physics programme
- This is really just the beginning ...

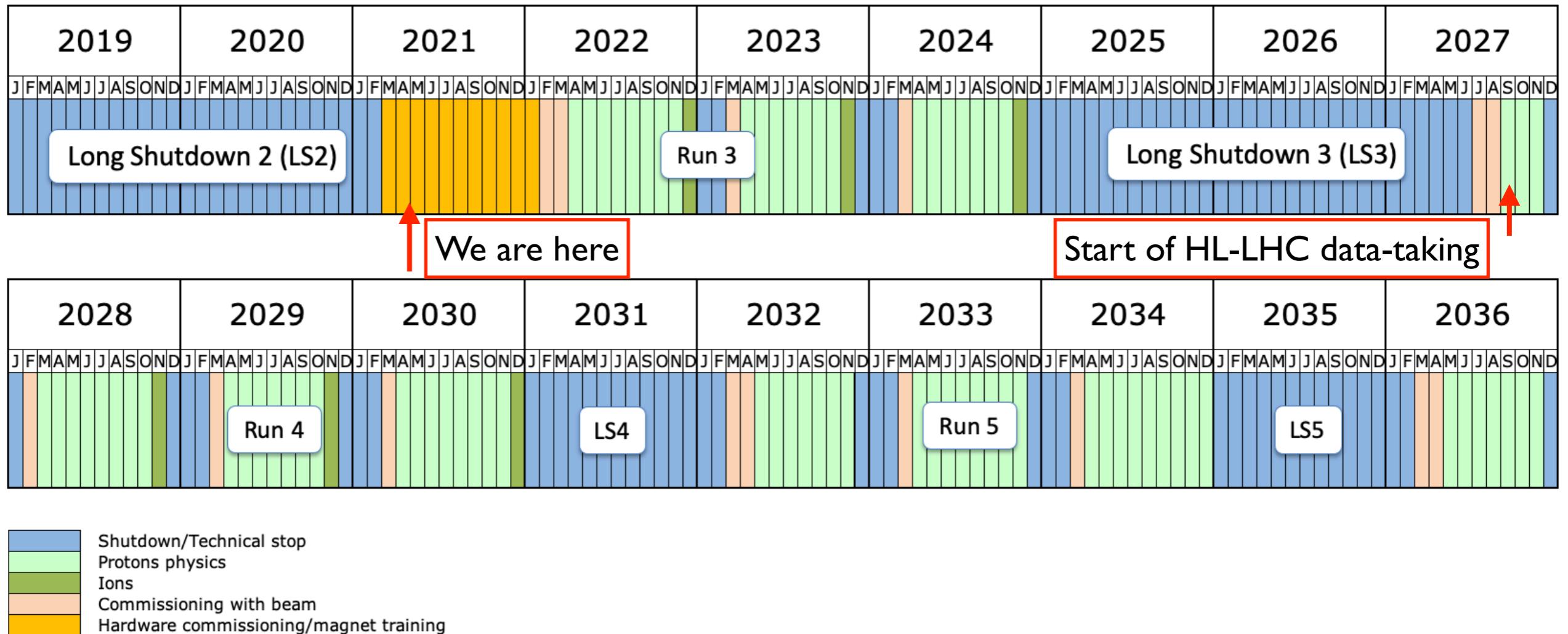


A historical perspective

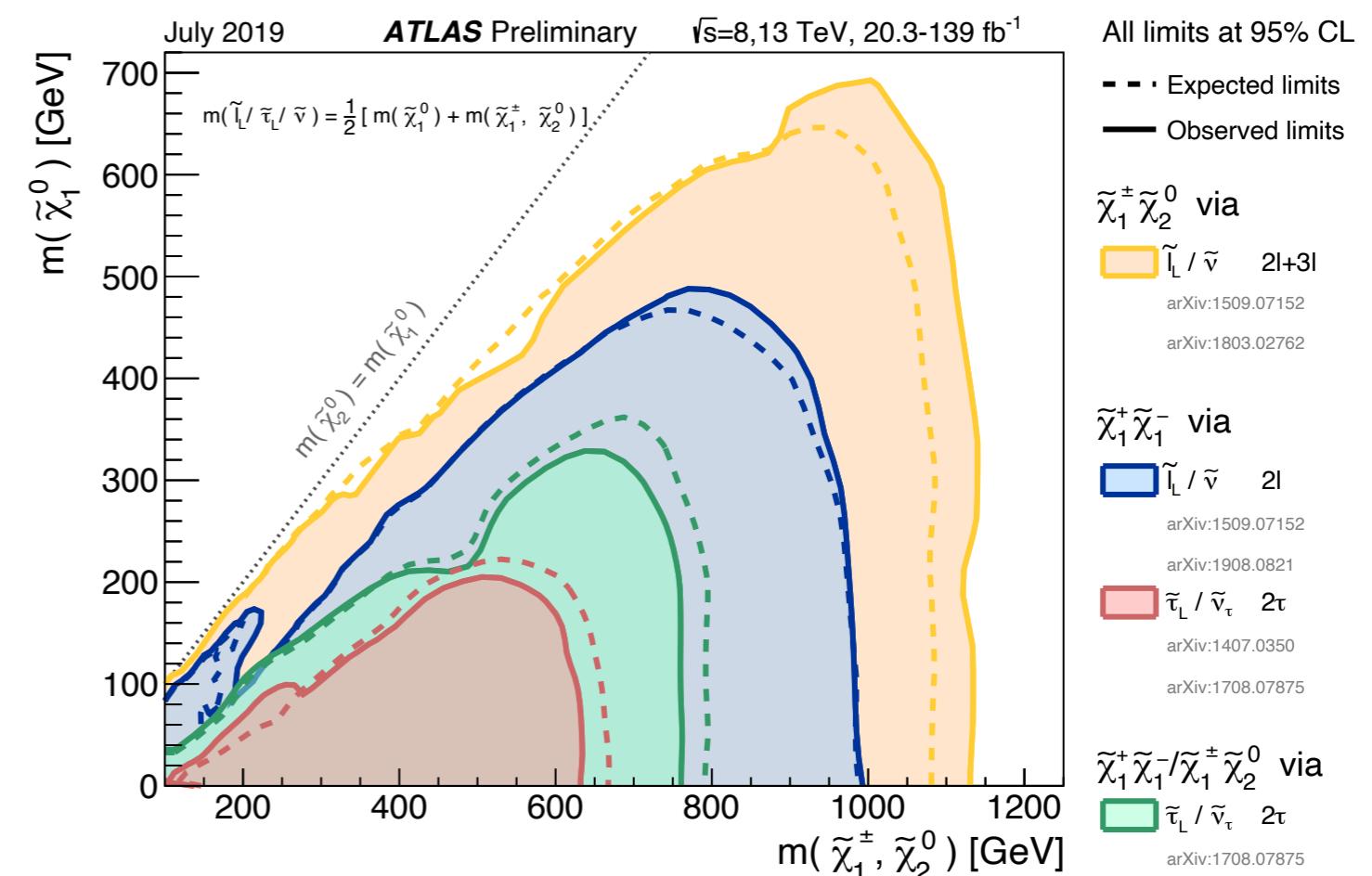
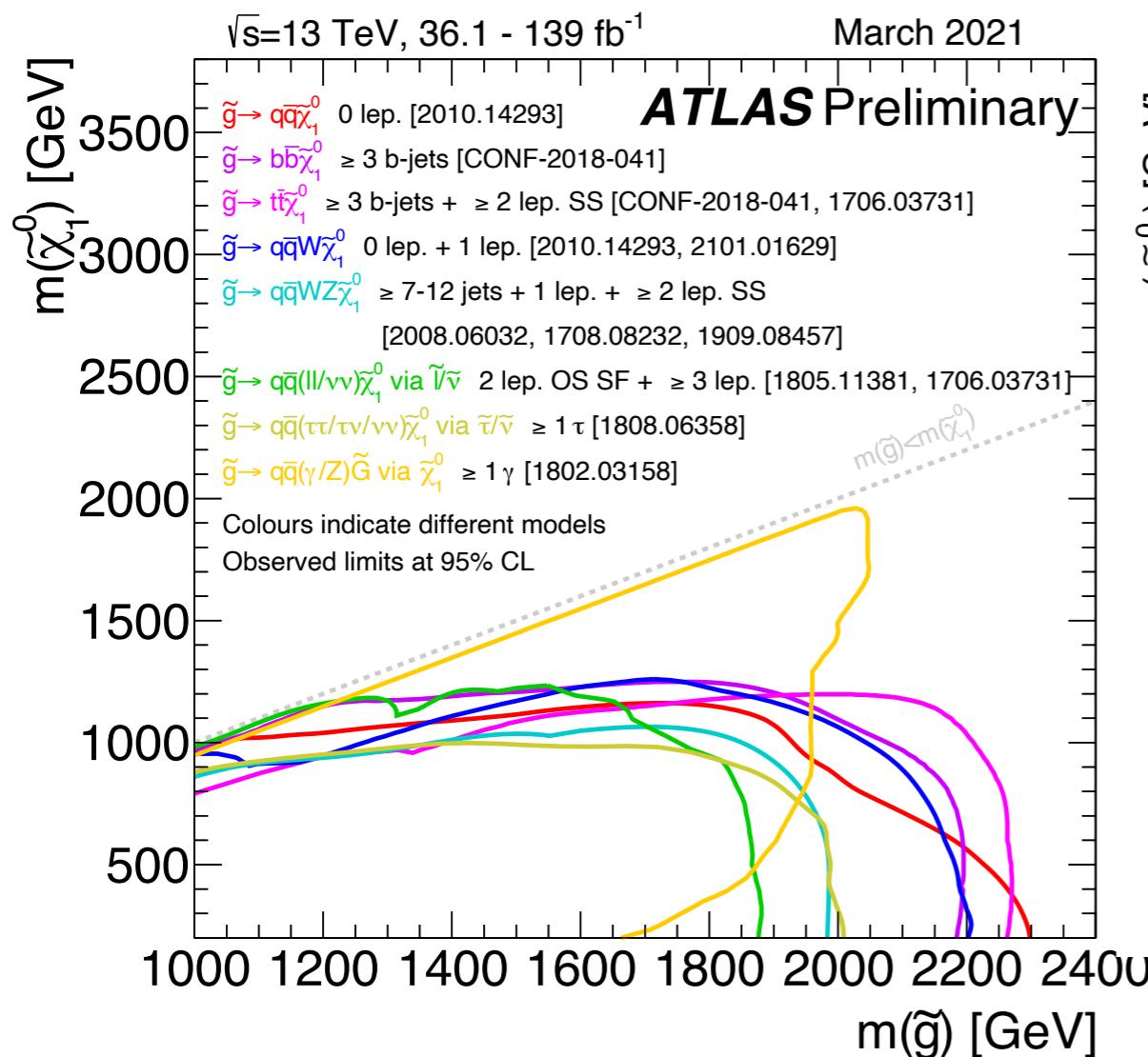


Backup slides

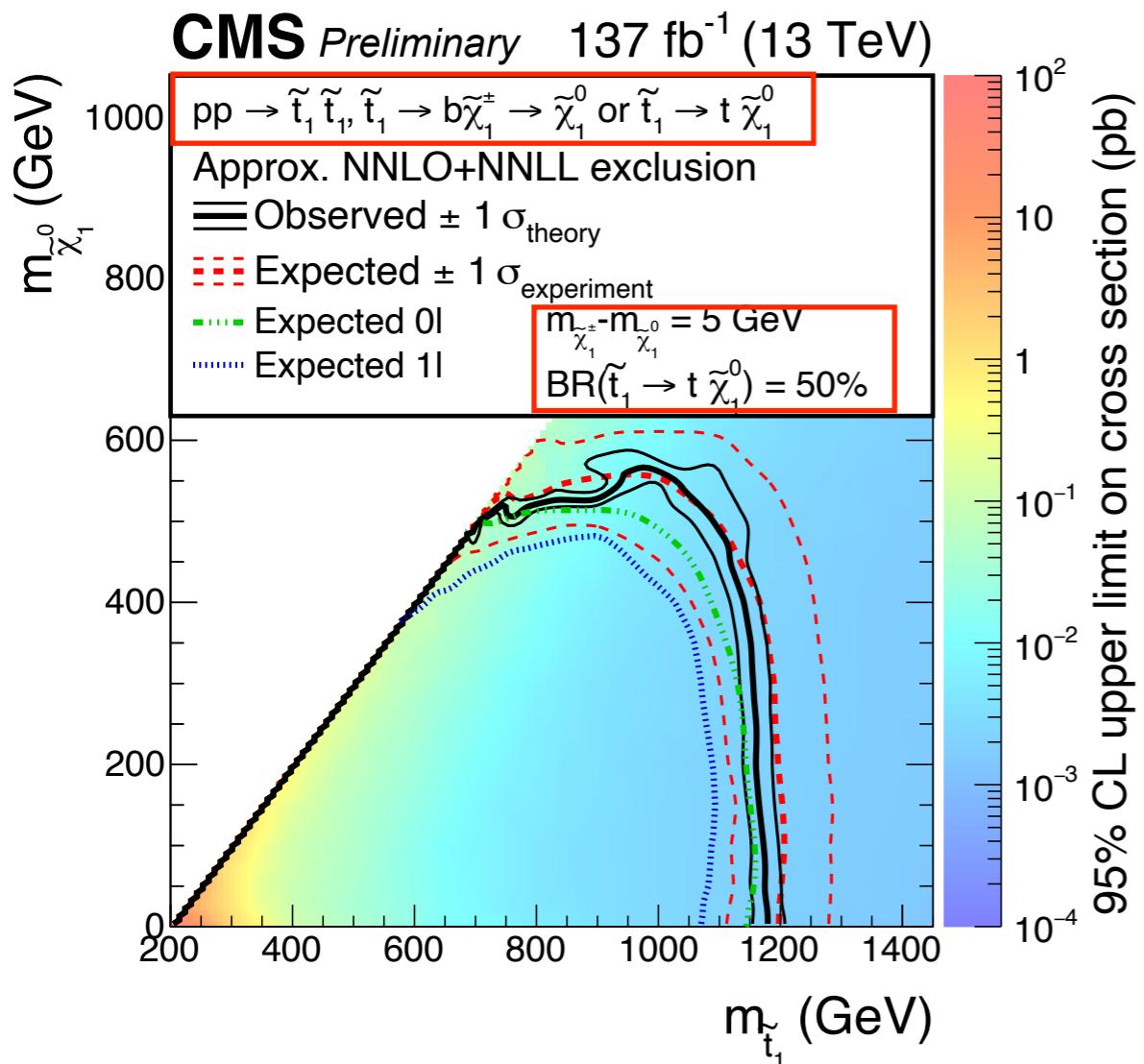
LHC schedule



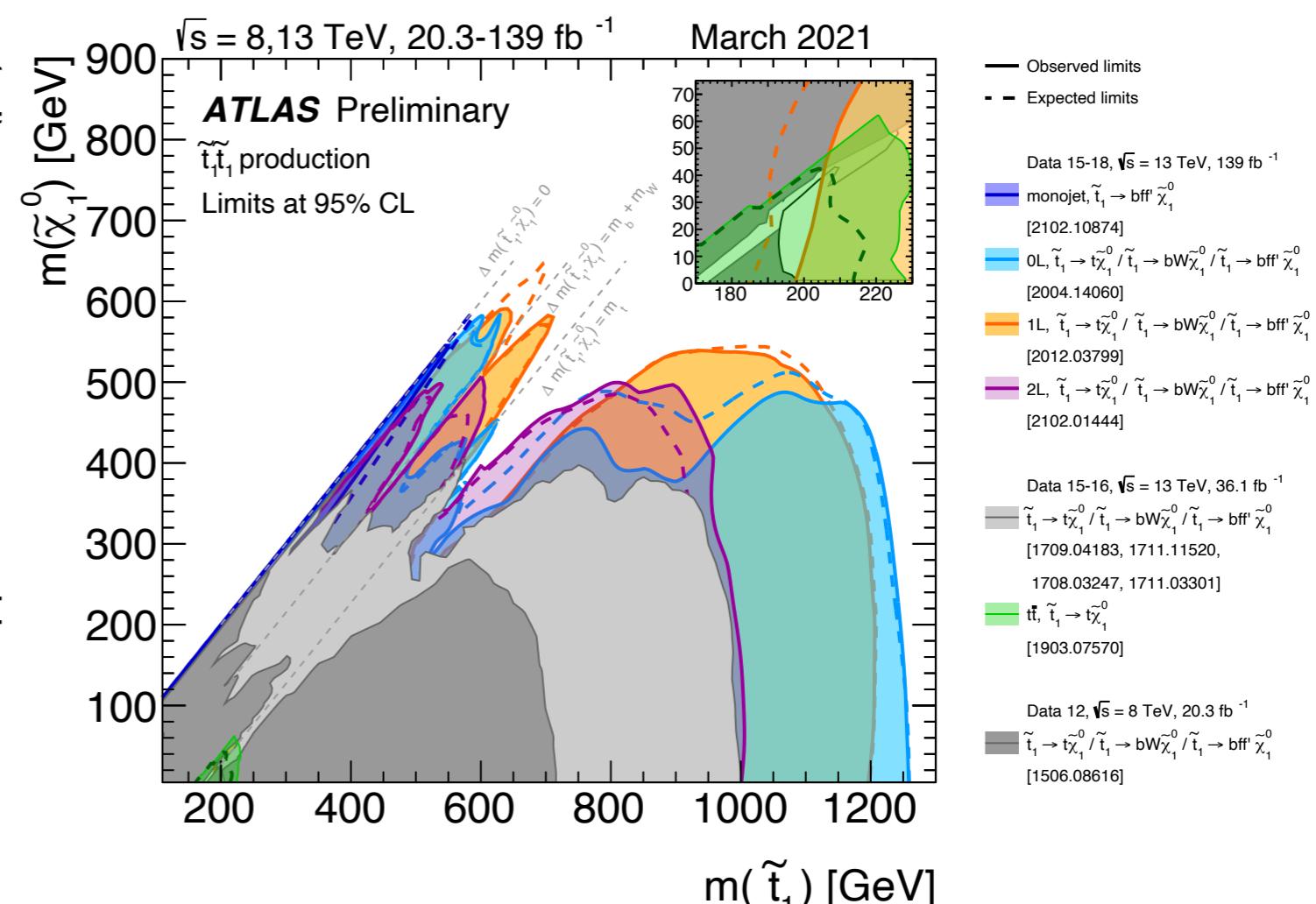
ATLAS SUSY summary results



Third-generation $\tilde{t}\tilde{t}$



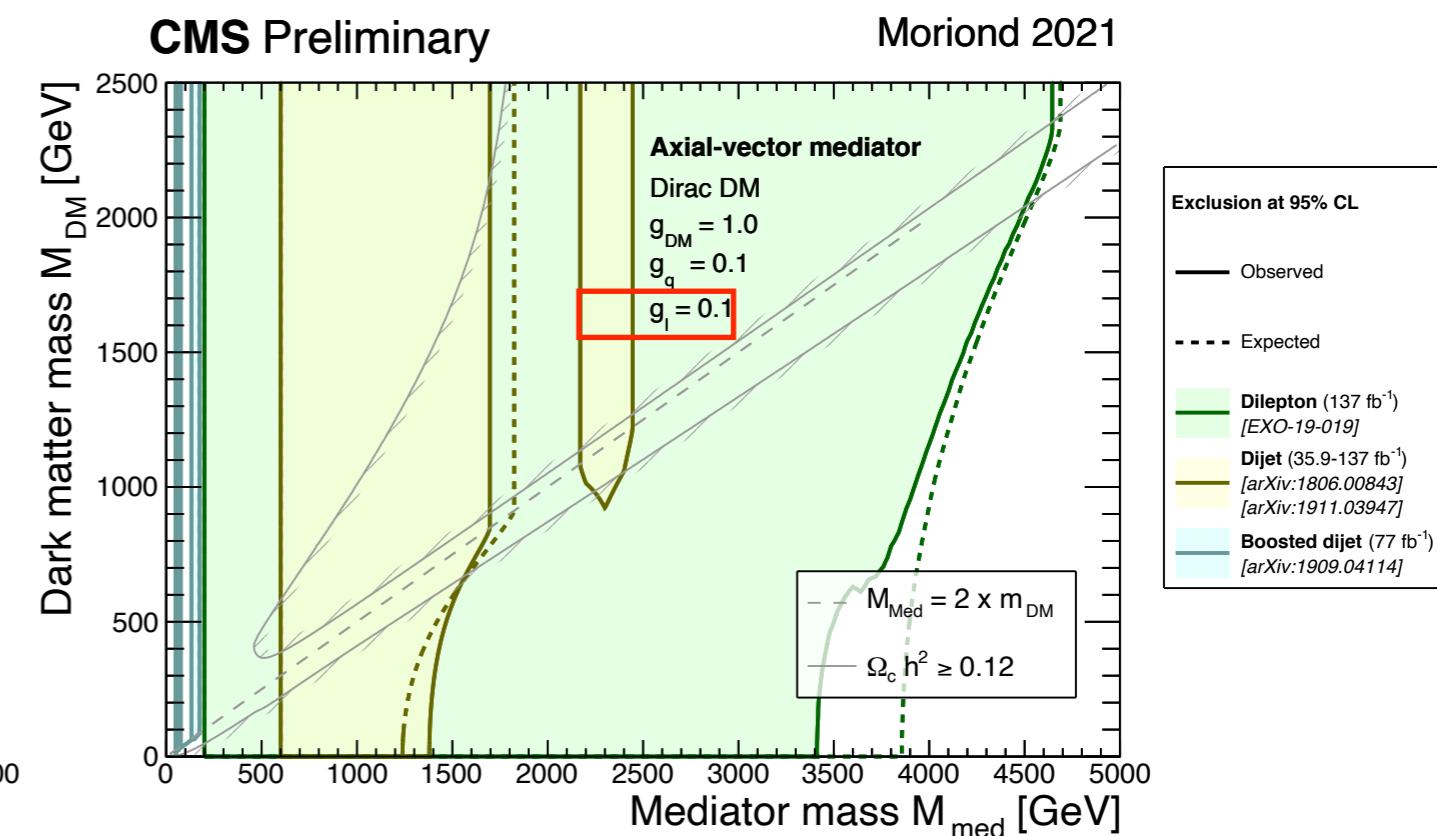
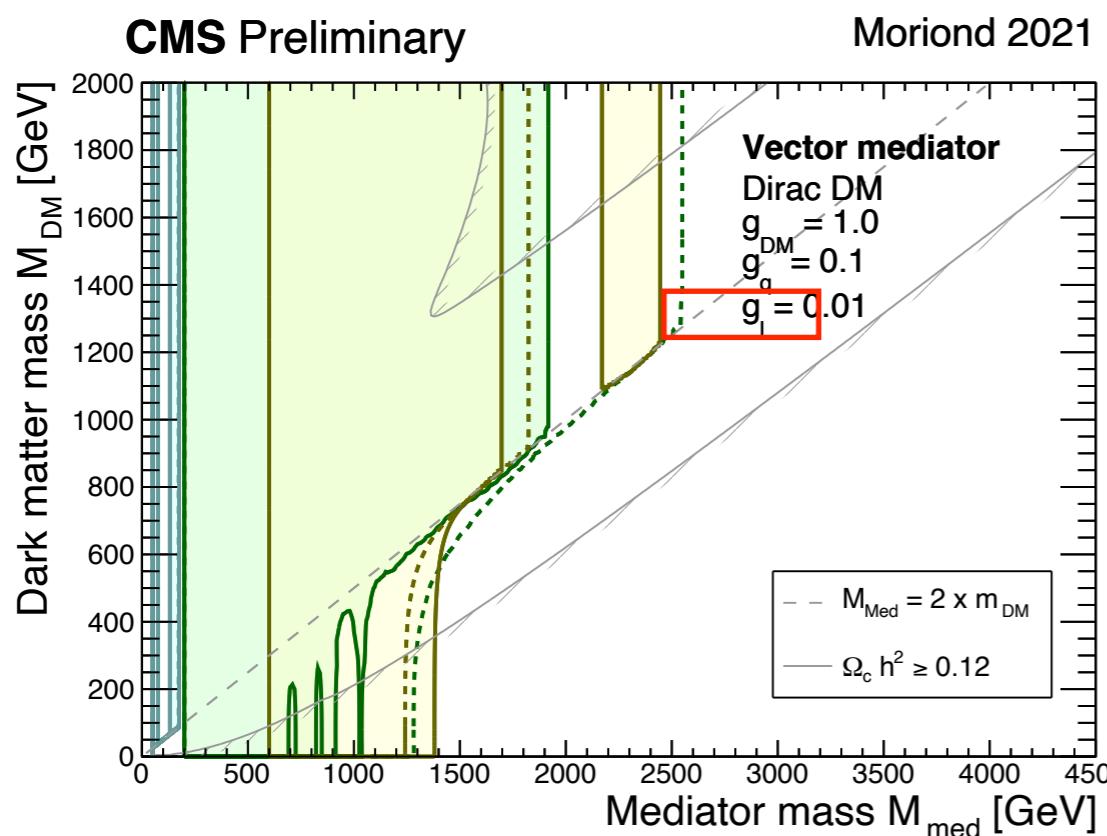
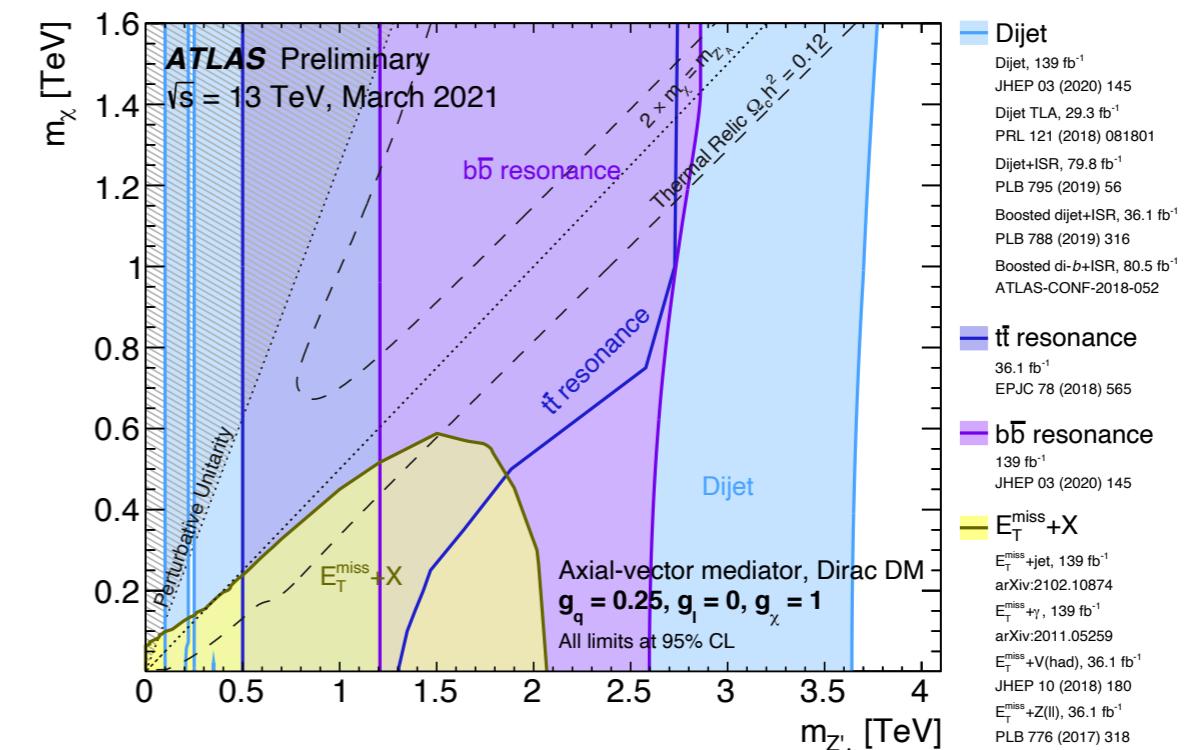
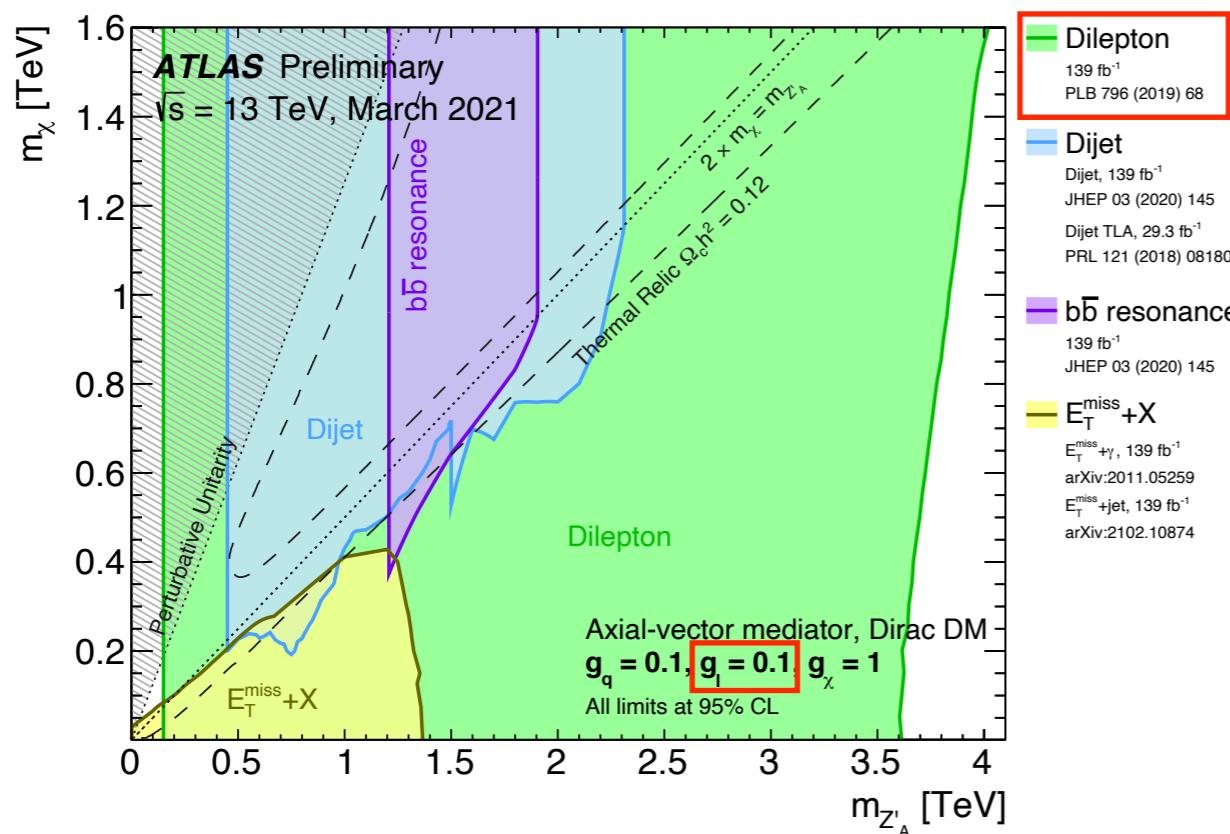
[CMS-PAS-SUS-20-002](#)



[ATL-PHYS-PUB-2020-020](#)

Dilepton and Dijet implications on DM mediators

ATL-PHYS-PUB-2021-006

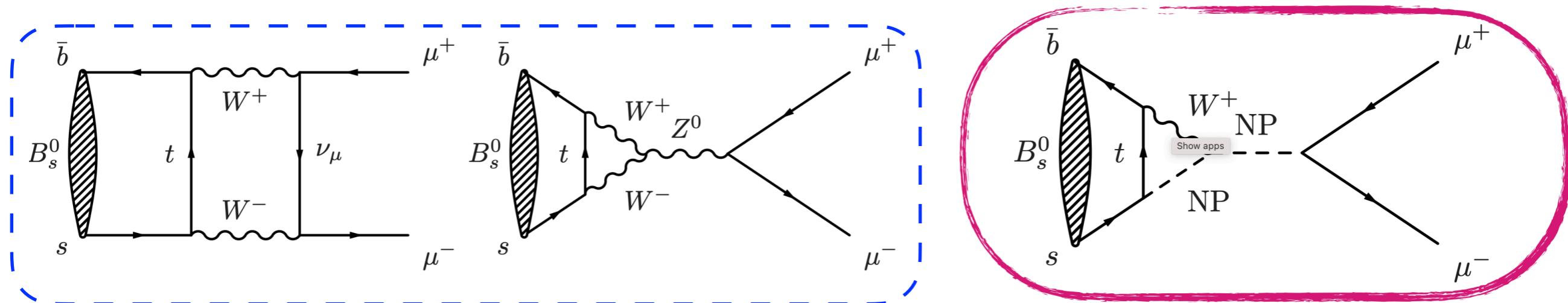


BSM searches in b -decays

Dedicated quark-flavour results in Eva Gersabeck's talk earlier

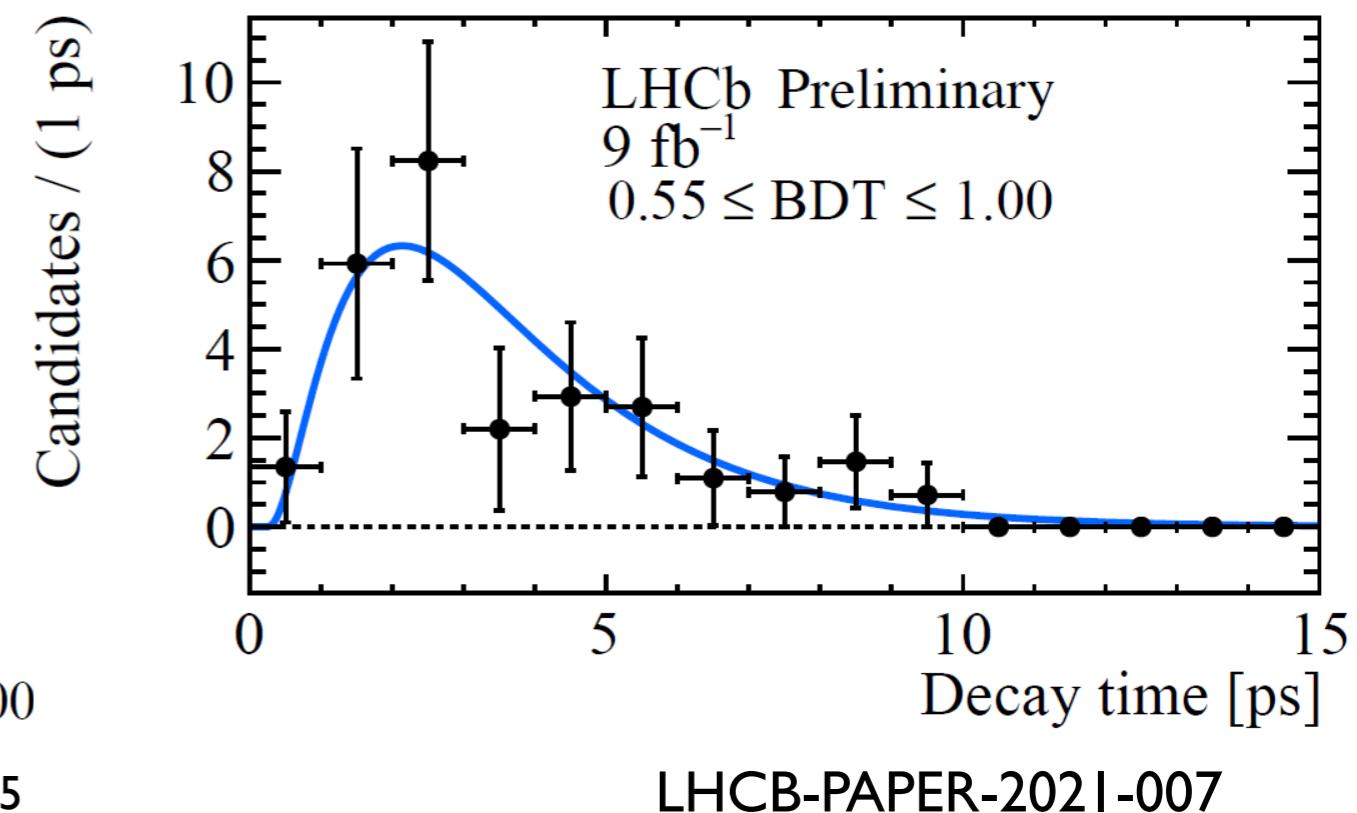
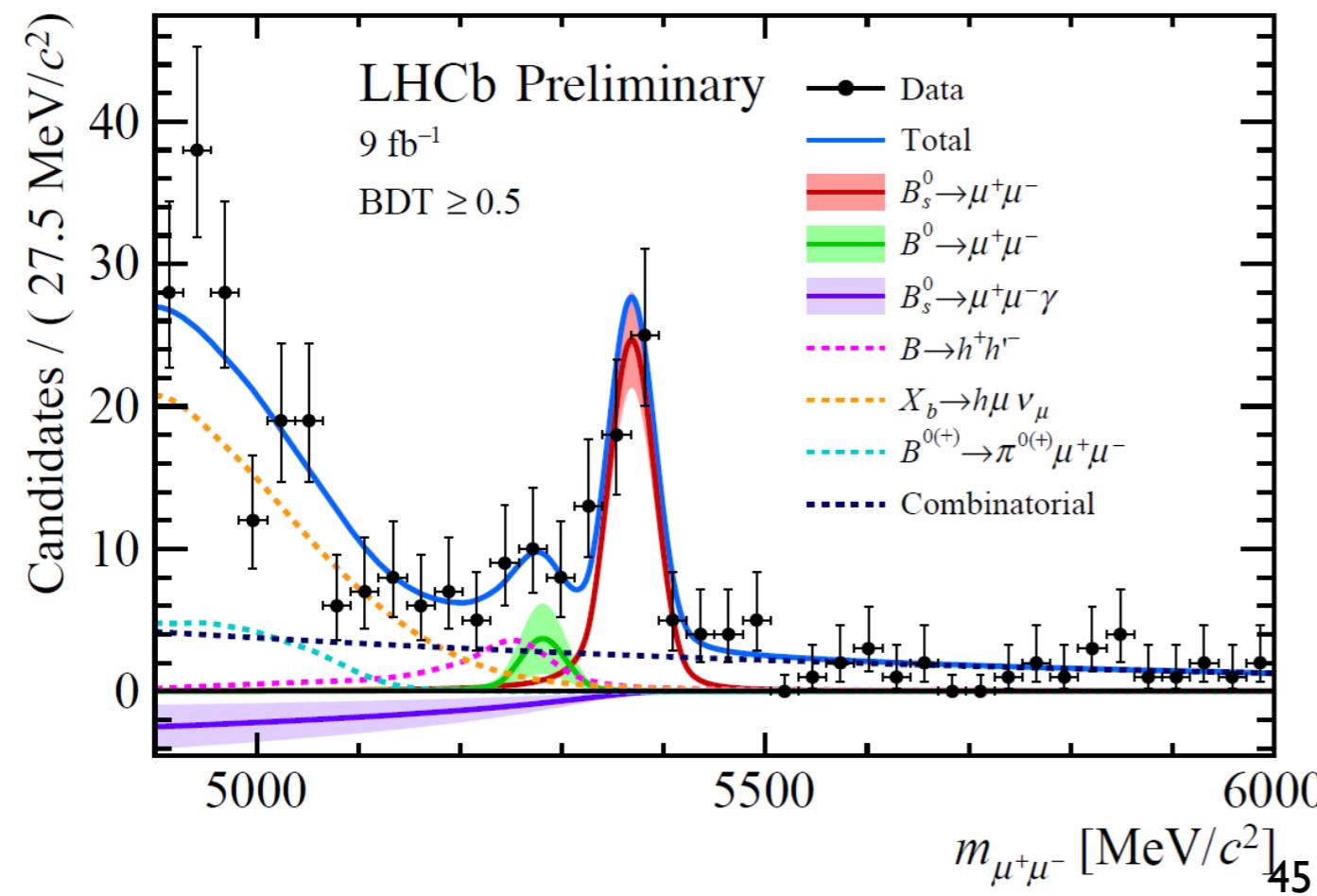
$B_s \rightarrow \mu^+ \mu^-$

- Very rare and experimentally clean final states, particularly sensitive to NP

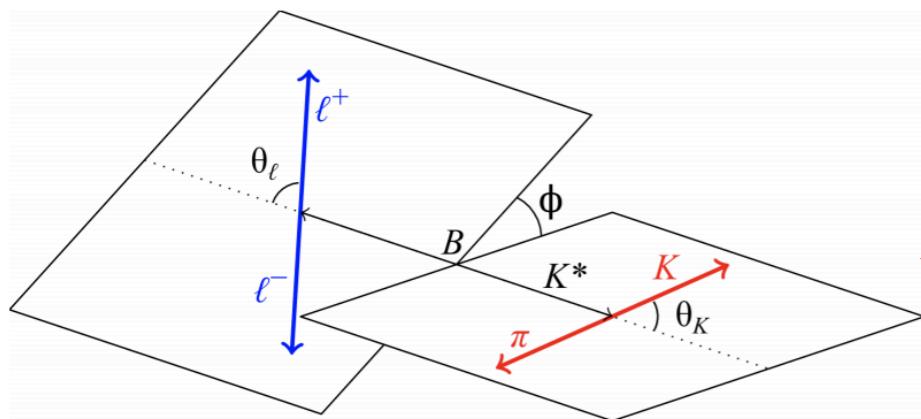


$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)_{\text{SM}} = 3.66 \pm 0.14 \times 10^{-9}$$

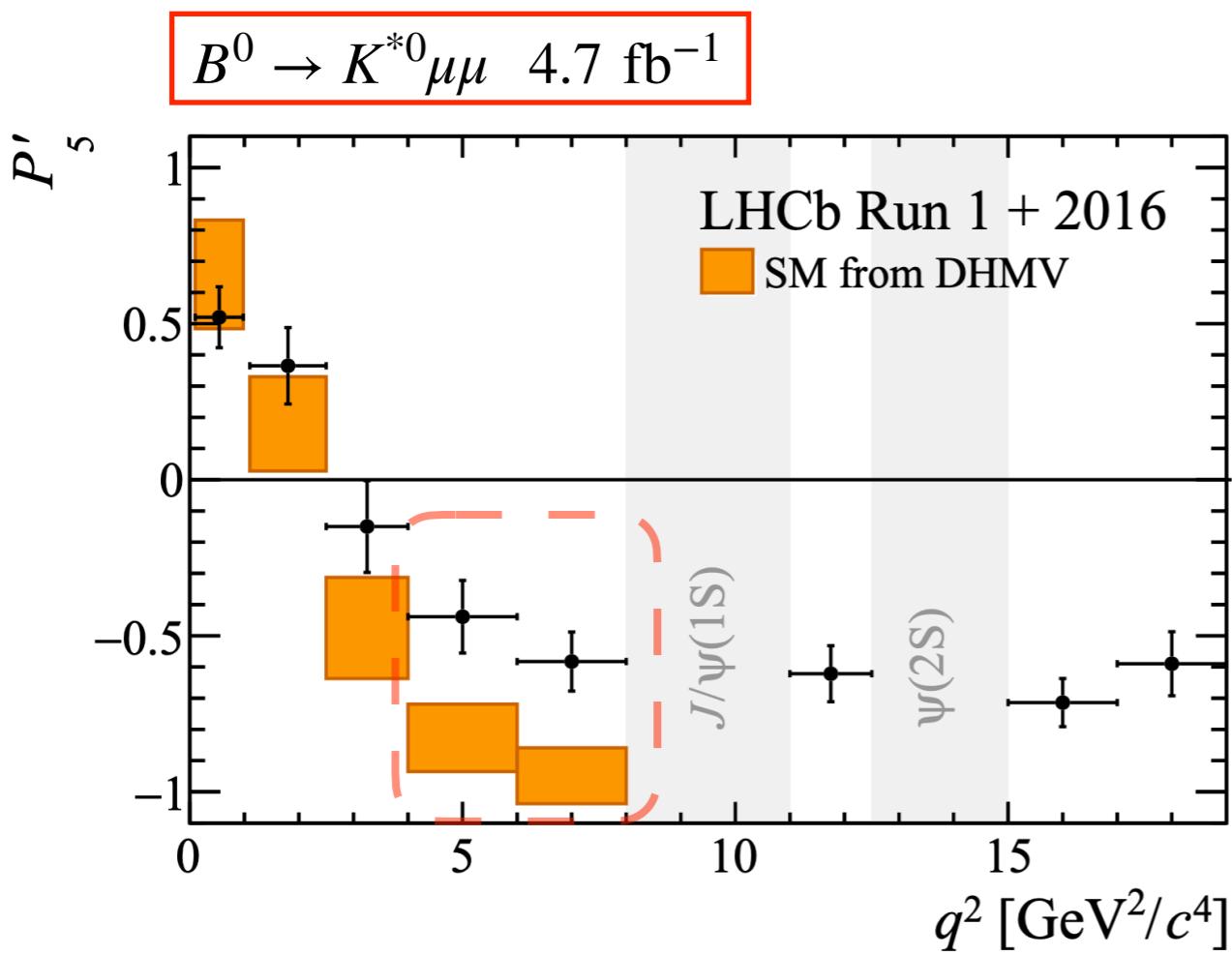
$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9} \quad (10.8\sigma)$$



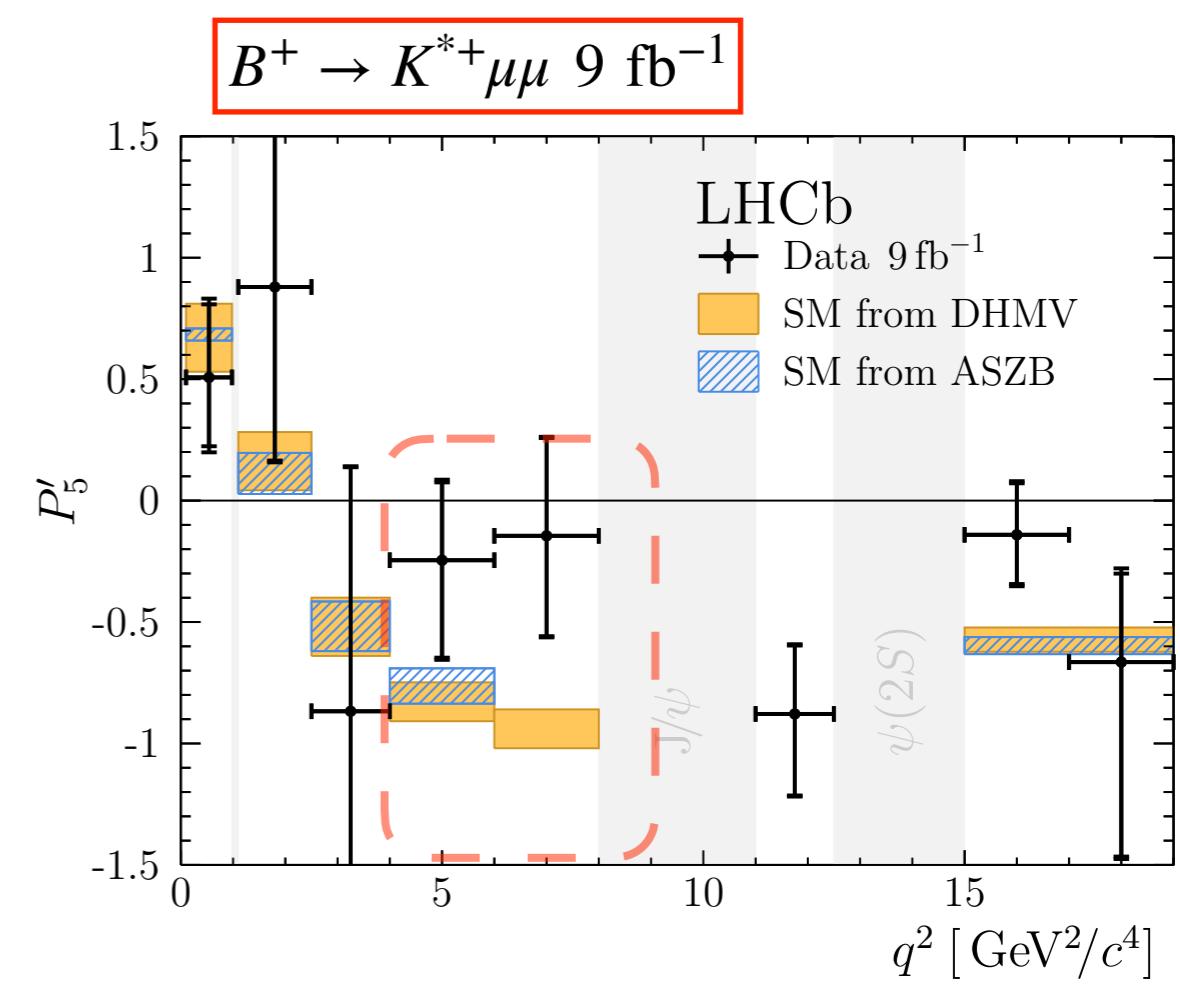
Angular anomaly in $B \rightarrow K^* \mu^+ \mu^- (P'_5)$



$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \left. \frac{d^4(\Gamma + \bar{\Gamma})}{dq^2 d\vec{\Omega}} \right|_P = \frac{9}{32\pi} \left[\begin{aligned} & \frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \\ & + \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_l \\ & - F_L \cos^2 \theta_K \cos 2\theta_l + S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi \\ & + S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_K \sin \theta_l \cos \phi \\ & + \frac{4}{3}A_{FB} \sin^2 \theta_K \cos \theta_l + S_7 \sin 2\theta_K \sin \theta_l \sin \phi \\ & + S_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \end{aligned} \right]$$



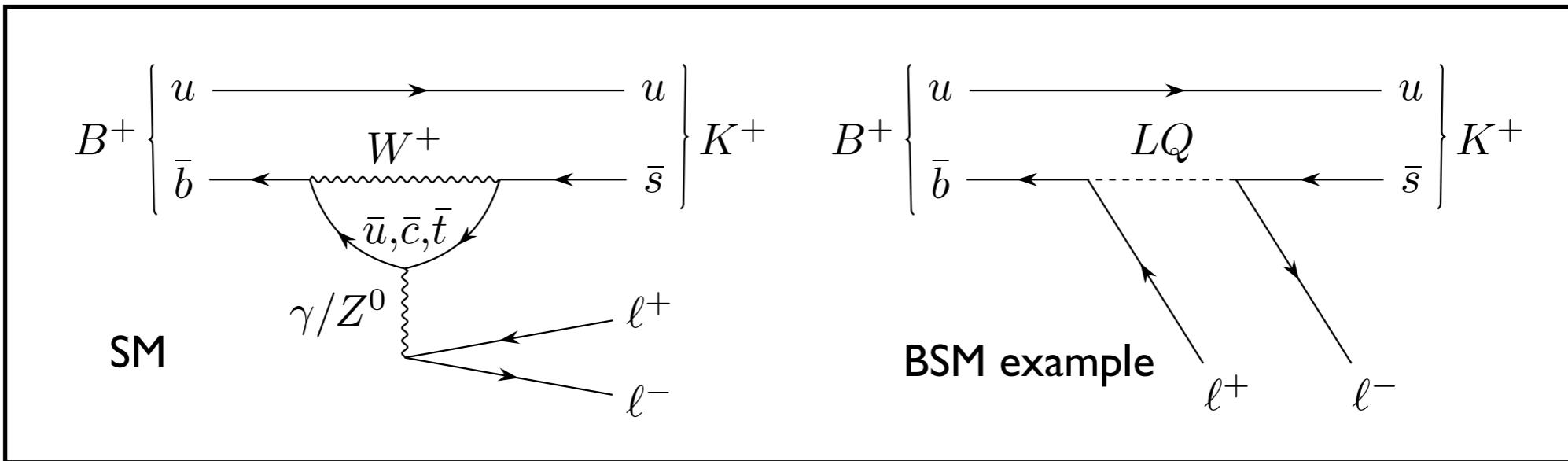
Phys. Rev. Lett. 125, 011802



2012.13241

Test of lepton flavour universality R_K

- Many experiments are testing LFU \rightarrow 2 dedicated sessions in Parallel Stream 2
- In particular LHCb has revealed a range of anomalies known as $R_K, R_{K^*}, R_{D^*}^{\tau,\ell}$

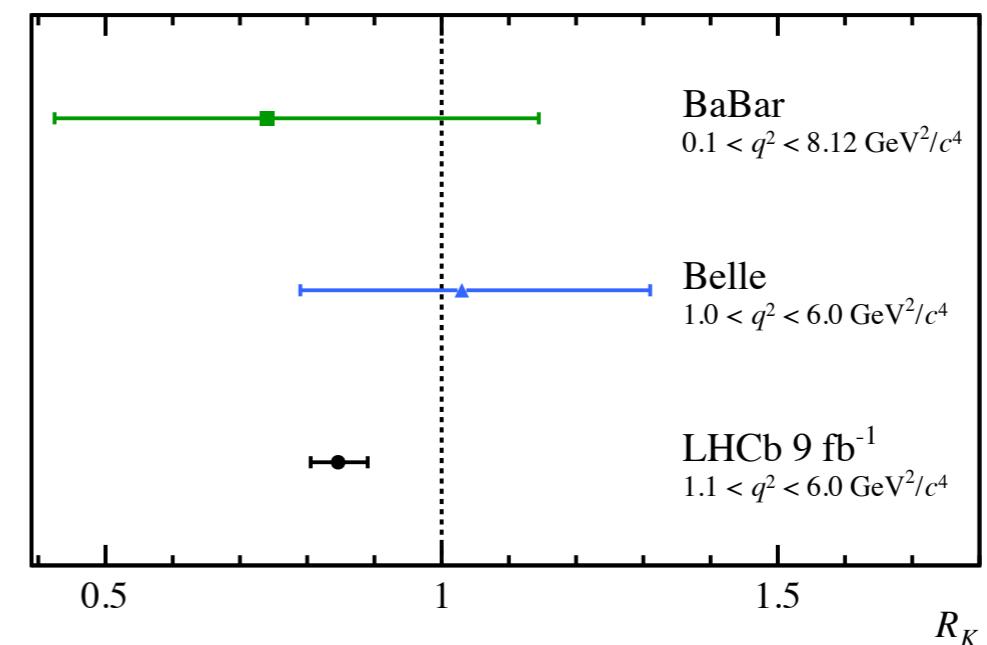
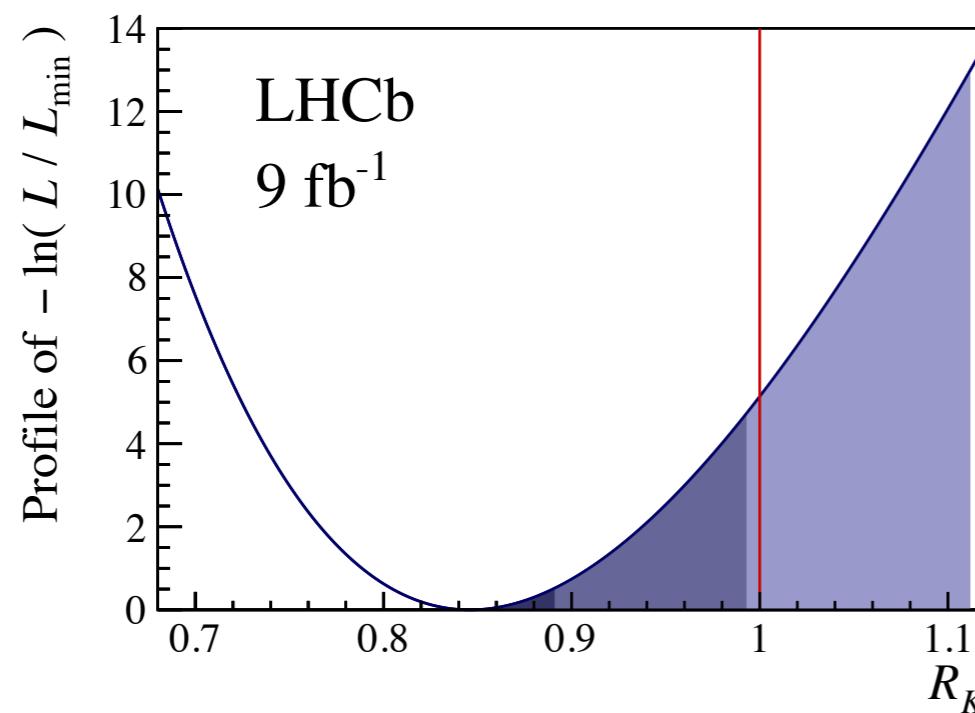
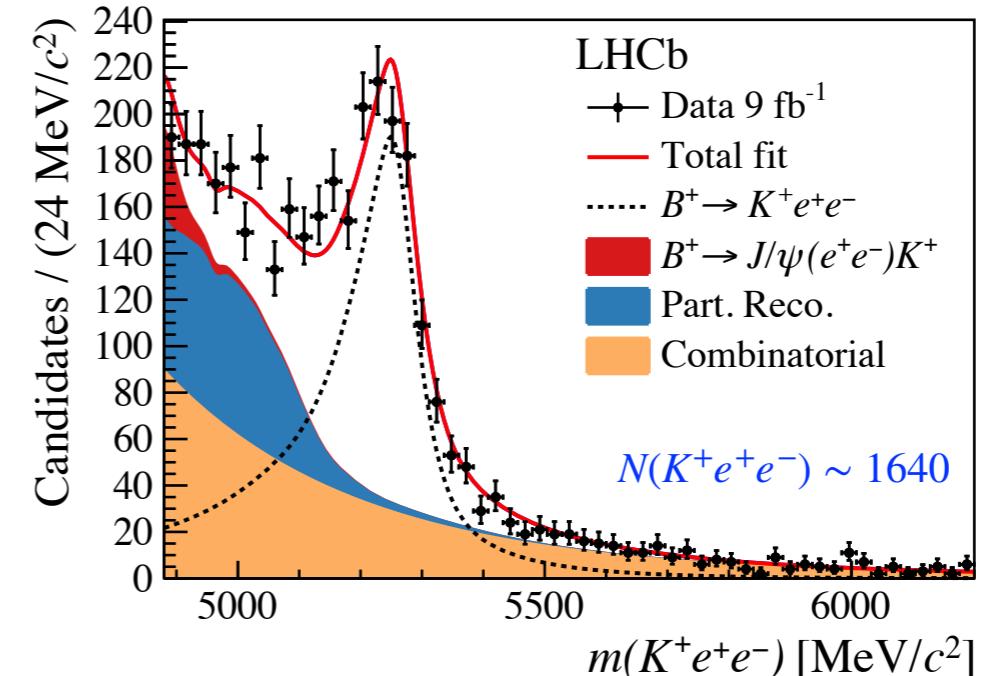
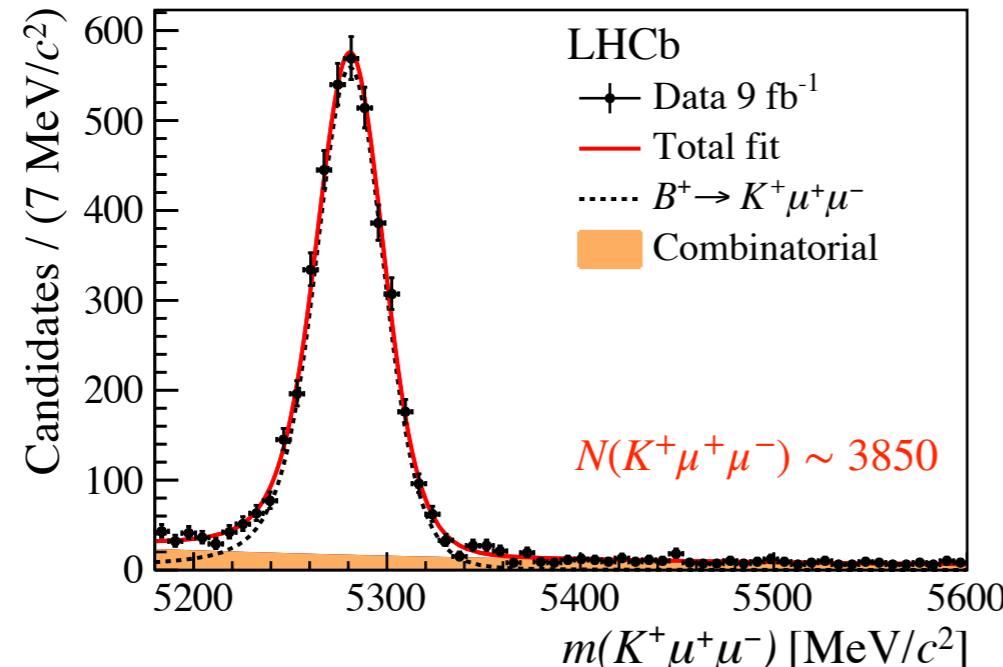


$$R_K = \frac{\int_{1.1 \text{ GeV}^2}^{6.0 \text{ GeV}^2} \frac{d\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{dq^2} dq^2}{\int_{1.1 \text{ GeV}^2}^{6.0 \text{ GeV}^2} \frac{d\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)}{dq^2} dq^2}$$

Double-ratio approach \rightarrow cancel out most systematic uncertainties

$$R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ J/\psi(\mu^+ \mu^-))} \Big/ \frac{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)}{\mathcal{B}(B^+ \rightarrow K^+ J/\psi(e^+ e^-))} = \frac{N_{\mu^+ \mu^-}^{\text{rare}} \varepsilon_{\mu^+ \mu^-}^{J/\psi}}{N_{\mu^+ \mu^-}^{J/\psi} \varepsilon_{\mu^+ \mu^-}^{\text{rare}}} \times \frac{N_{e^+ e^-}^{J/\psi} \varepsilon_{e^+ e^-}^{\text{rare}}}{N_{e^+ e^-}^{\text{rare}} \varepsilon_{e^+ e^-}^{J/\psi}}$$

Test of lepton flavour universality in $B^+ \rightarrow K^+ \ell^+ \ell^-$



- What does this mean for BSM searches?
 - Dedicated resonance searches (e.g. LQ, Z' at ATLAS CMS)
 - Global fit EFT Lagrangian for $b \rightarrow sll$: $\mathcal{L}_{\text{eff}} \propto \frac{4G_F}{\sqrt{2}} \sum_k \mathcal{C}_k(\mu) \mathcal{O}_k(\mu)$

J. Kriewald, Moriond 2021

Input to the global fit on $b \rightarrow s\ell\ell$

Results: V_1 leptoquark & non-unitary mixing from VL leptons

~ 350 Observables taken into account:

Lepton Flavour Violation: $(\mu - e)$ -conversion, $\ell \rightarrow \ell' \gamma$, $\ell \rightarrow \ell' \ell' \ell'$, $\tau \rightarrow (\rho, \phi) \ell$,
 $B_{d,s} \rightarrow \ell^\pm \ell' \mp$, $K_L \rightarrow \mu^\pm e^\mp$, $B \rightarrow (K, K^*, \pi) \ell^\pm \ell' \mp$, $K \rightarrow \pi \ell^\pm \ell' \mp$, ($B \rightarrow K \nu \bar{\nu}$, $K \rightarrow \pi \nu \bar{\nu}$)

EW Precision Observables: g_V^ℓ , g_A^ℓ , Γ_Z^ℓ , $Z \rightarrow \ell \ell^{(\prime)}$

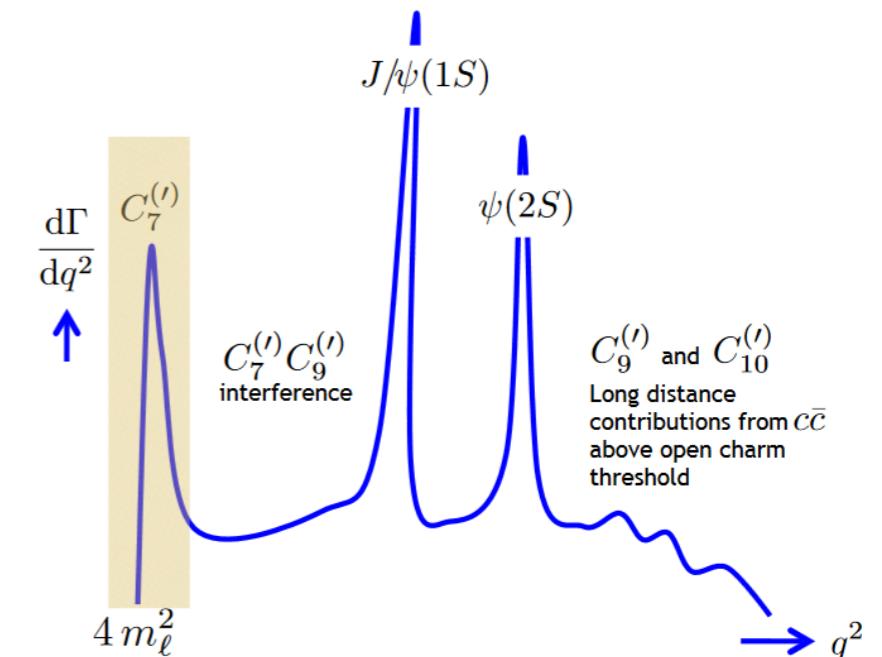
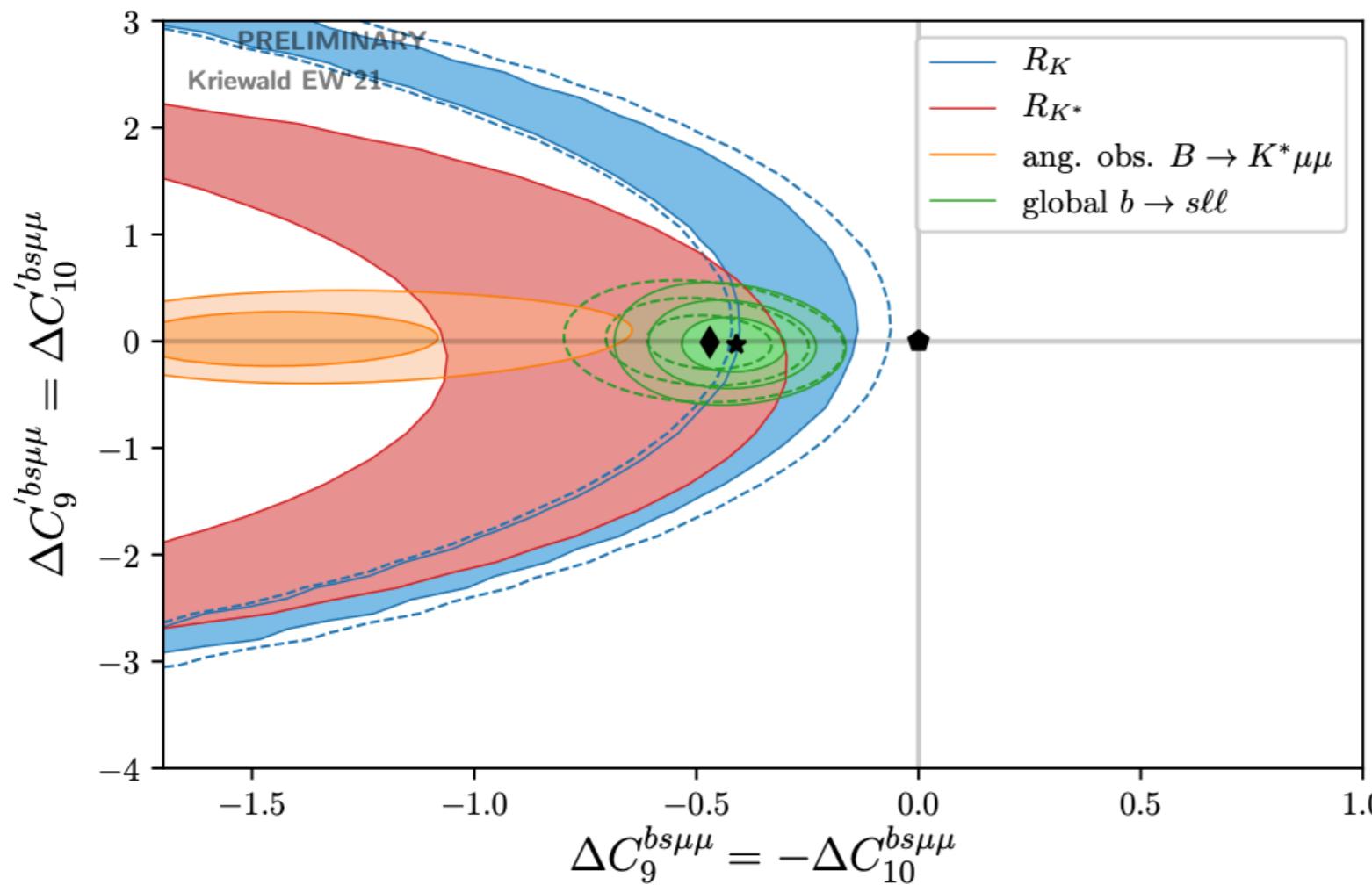
Semi-leptonic decays: $B_{d,s} \rightarrow \mu \mu$, $B_s \rightarrow \phi \mu \mu$, $B \rightarrow K^{(*)} \mu \mu$, $B \rightarrow K^{(*)} ee$, $B \rightarrow D^{(*)} \tau \nu$,
 $D_{(s)} \rightarrow \ell \nu$, $D \rightarrow \pi \ell \nu$, $D \rightarrow K \ell \nu$, $K \rightarrow \ell \nu$, $\tau \rightarrow (K, \pi) \nu$, $B \rightarrow \ell \nu$, $B \rightarrow \pi \ell \nu$

LFU Violation: $R_{K^{(*)}}$, $R_{D^{(*)}}$, angular observables and asymmetries in $b \rightarrow s\ell\ell$ à la P'_5

Direct searches (colliders): $m_{V_1} \gtrsim 1.5$ TeV

Global EFT fit for $b \rightarrow s\ell\ell$

EFT Lagrangian for $b \rightarrow s\ell\ell$: $\mathcal{L}_{\text{eff}} \propto \frac{4G_F}{\sqrt{2}} \sum_k C_{\mathbf{k}}(\mu) \mathcal{O}_{\mathbf{k}}(\mu)$



- - -: old data
- ◇: SM
- ◊: former best fit (B.F.)
- ★: new B.F.