Exotics Searches at Colliders

Sinéad Farrington
University of Edinburgh

Exotics Searches at Colliders

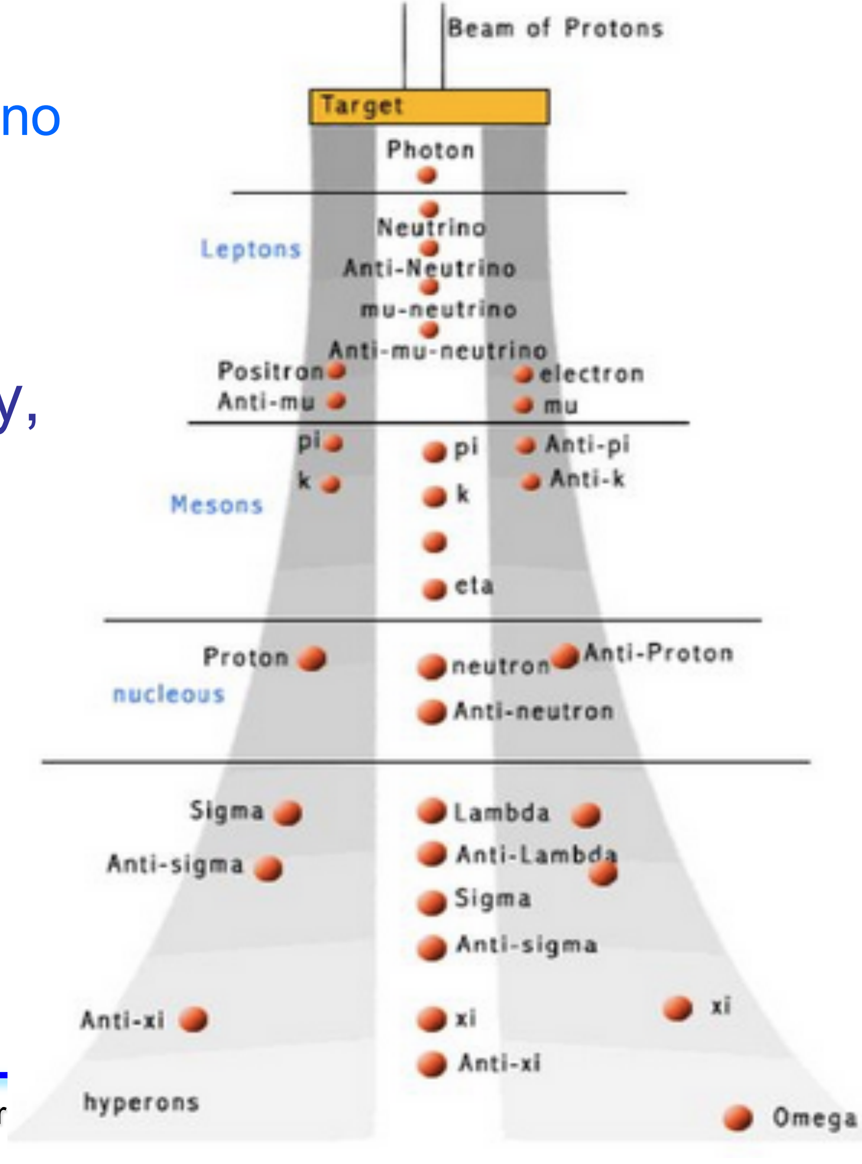
Why and How?

Sinéad Farrington
University of Edinburgh

When did Exotics Searches begin?

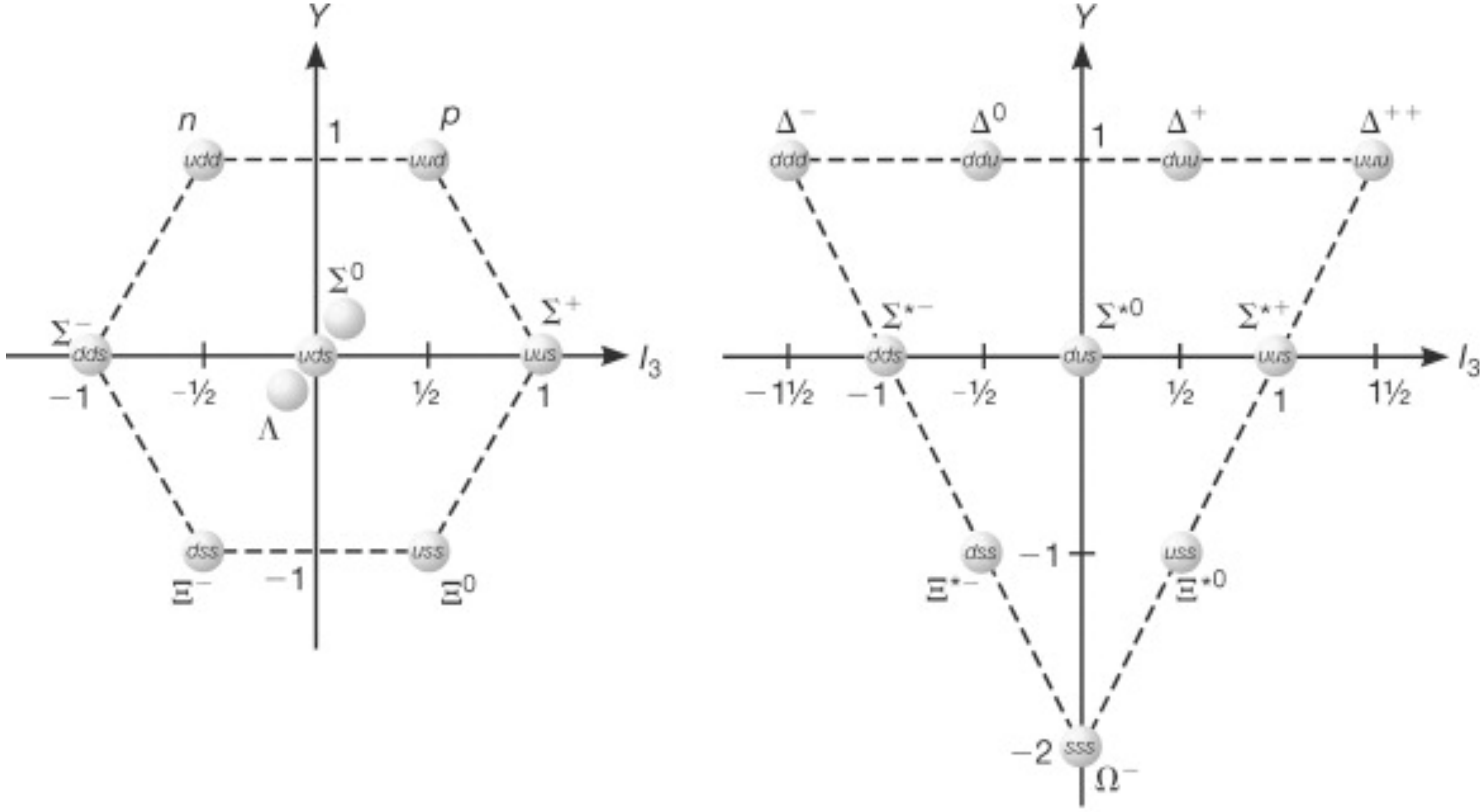
When did Exotics Searches begin?

- Everything was an exotics search for a while
- Back to the beginning:
  - Electron, muon discovery, neutrino
- Then a several-decades-long phase of search and discovery, up to ~late 1960s



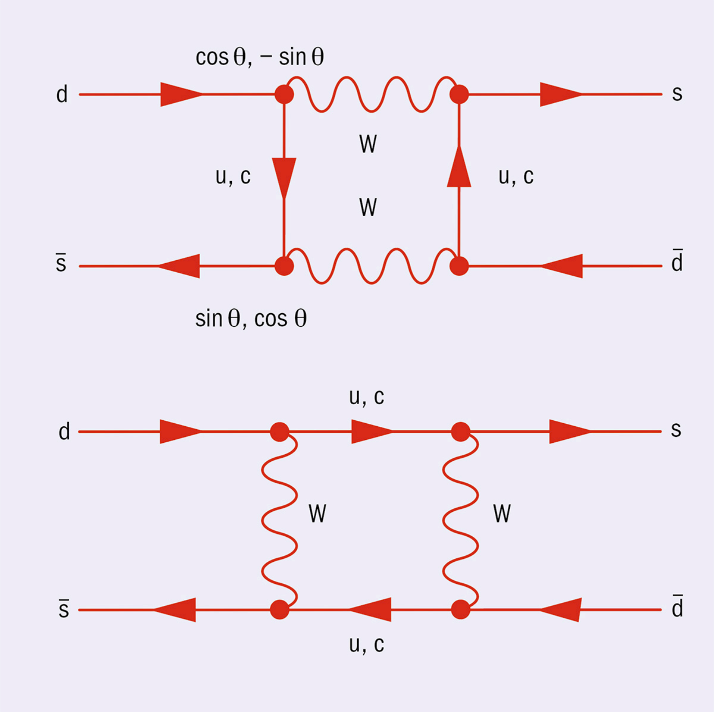
The Quark Model (1964)

- Alongside search and discovery ran efforts to organise the discovered particles into underlying patterns
  - Some false dawns, then the quark model representation
  - Based on 3 quarks (up, down, strange)



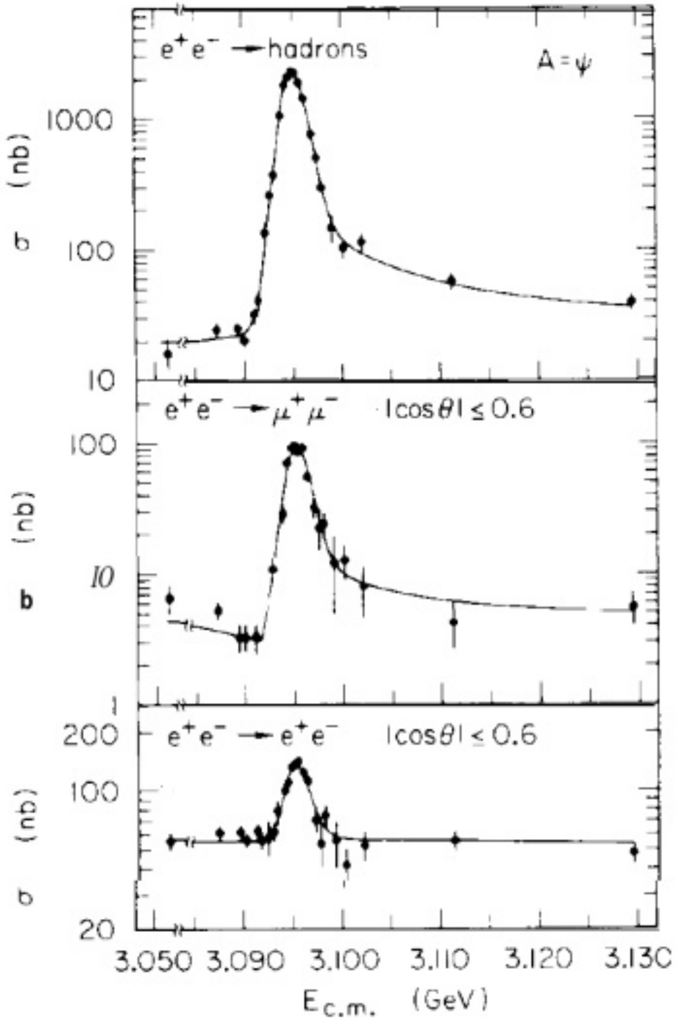
The GIM Mechanism (1970)

- (Glashow, Illiopoulos, Maiani)
- Questioned why there were no FCNC
  - Several false dawns also (23 predictions for R ratio!)
  - GIM mechanism suggested that the facts could be explained if a fourth quark existed (no experimental evidence at the time)



Time of Exploration and Surprises (1970s)

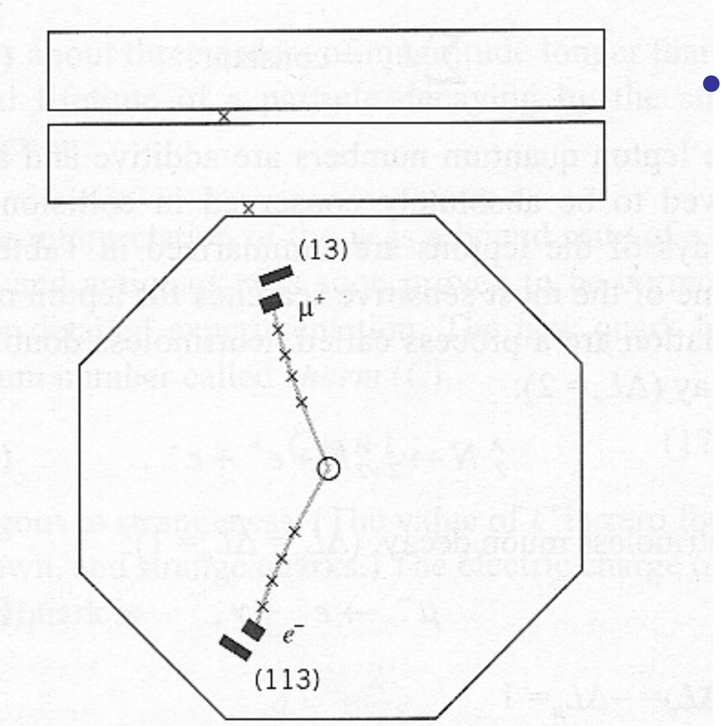
- J/ψ discovery (November revolution, 1974)
  - SPEAR (e+e- at SLAC), ASG (fixed target at Brookhaven)
  - Searching higher CoM energies in an open-minded way, scanning across energies, measuring R ratio



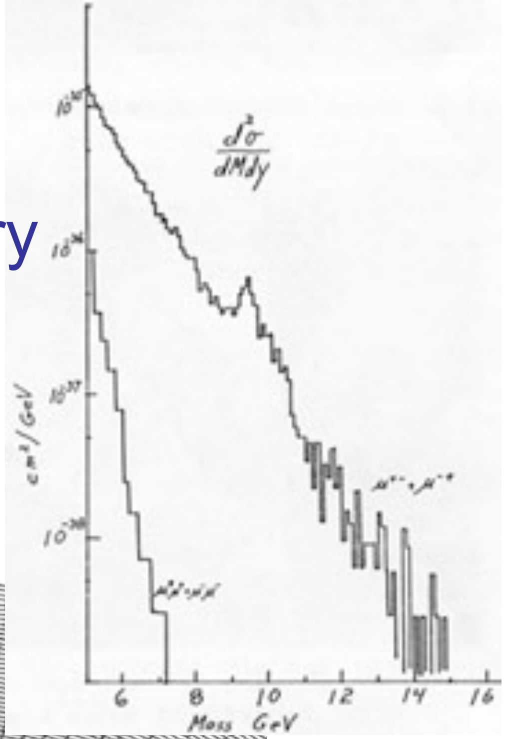
- Not immediately obvious what it was
  - Very narrow width implied lifetime 1000x longer than other known resonances
  - Decay to hadrons suppressed, leaves phase space to decay to leptons via EM
  - Spectroscopy (two weeks later found ψ')

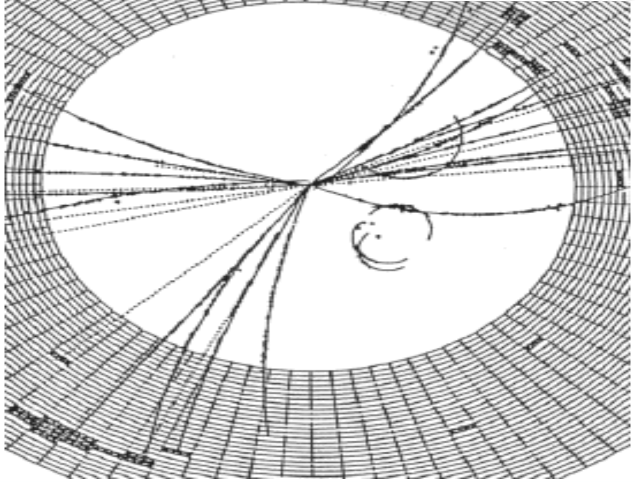
Building up the Standard Model

- Tau discovery (e+e-, 1975)



- b (Upsilon) discovery (Fermilab fixed target) 1977

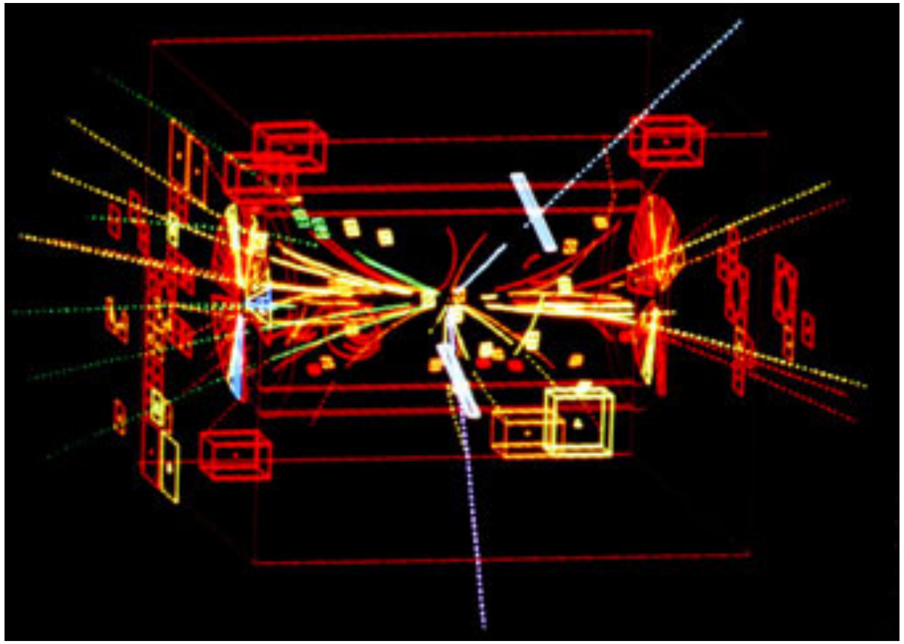




- Gluon (e+e-, PETRA) 1979

And then the bosons were found

- These were searches for particles needed to complete the Standard Model (but this was not known for sure!)
    - Not “exotics”?
    - (The Higgs boson was the last such case, 2012)



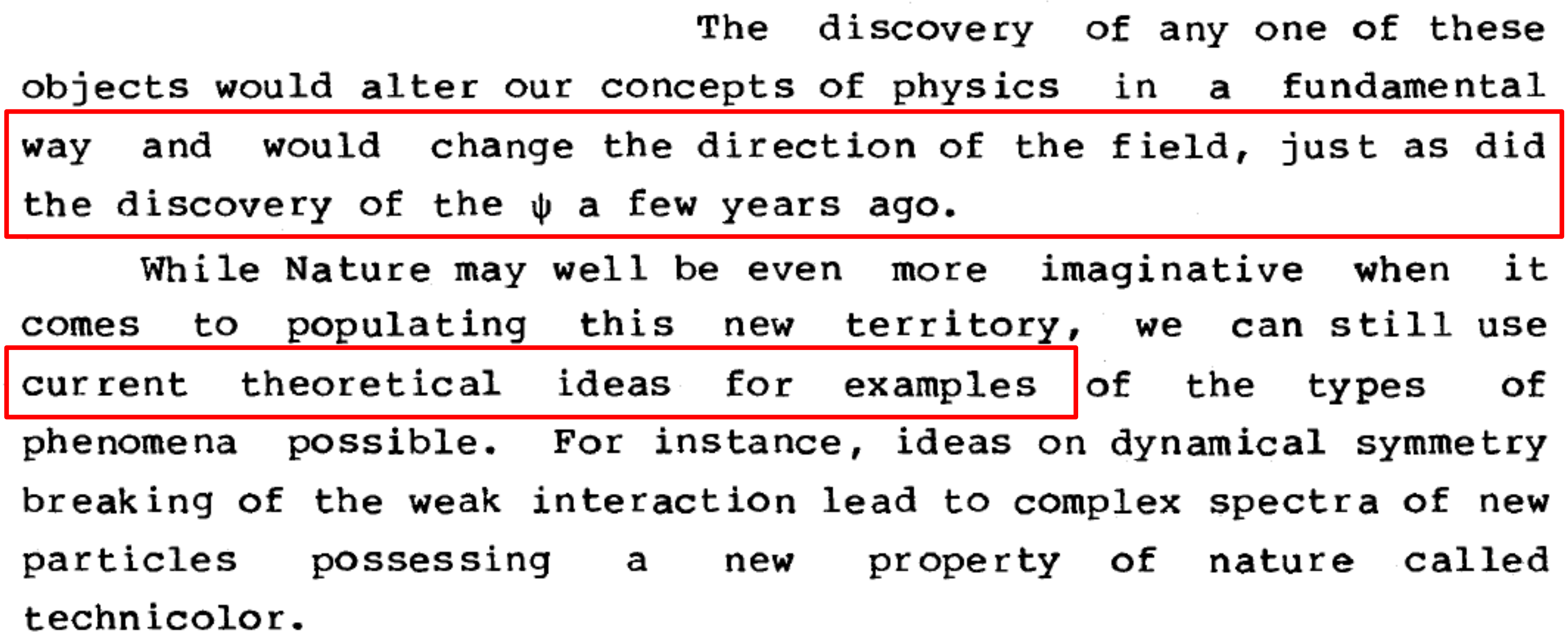
Z boson (ppbar,1983)

- SM particle content was then complete except for top quark (1995), tau neutrino (2000), Higgs (2012)

Exotics Searches post-1980

- LEP/SLC/Tevatron/LHC (as well as non-collider facilities) pursued an exotics program over the following decades

From CDF Proposal (1981):



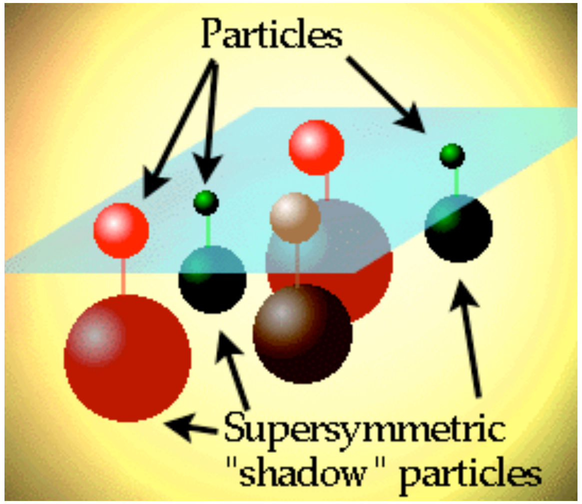
The discovery of any one of these objects would alter our concepts of physics in a fundamental way and would change the direction of the field, just as did the discovery of the ψ a few years ago.

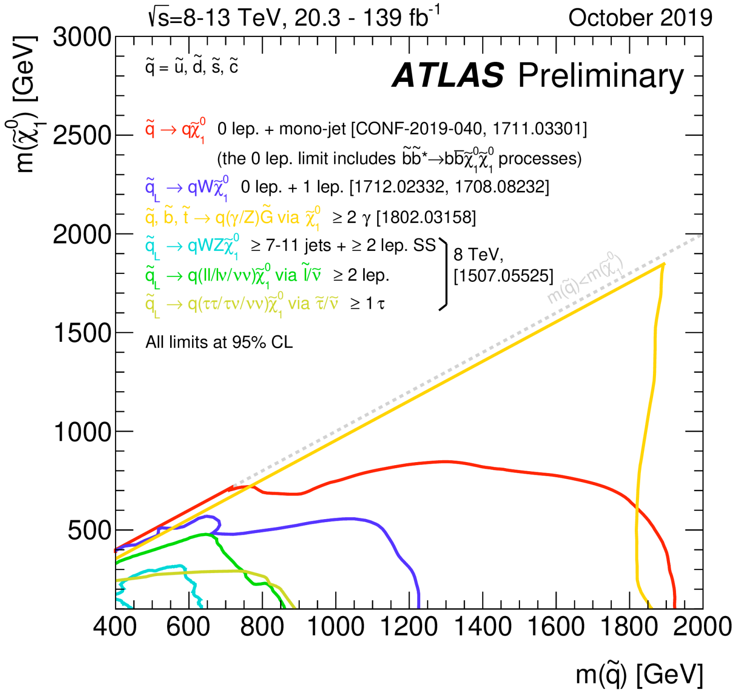
While Nature may well be even more imaginative when it comes to populating this new territory, we can still use current theoretical ideas for examples of the types of phenomena possible. For instance, ideas on dynamical symmetry breaking of the weak interaction lead to complex spectra of new particles possessing a new property of nature called technicolor.

- Centauros, lepton and quark substructure, heavy quasi-stable particles
- SUSY not mentioned explicitly (Dynamic Symmetry Breaking is)

Supersymmetry

- SUSY stabilises the Higgs mass
  - Solves fine tuning
  - Provides dark matter candidate (lightest supersymmetric particle)
- Searches tend to involve long decay-chain signatures, low momentum particles, large missing energy – multiple signatures
- A useful framework for setting limits, even if it does not yield discovery

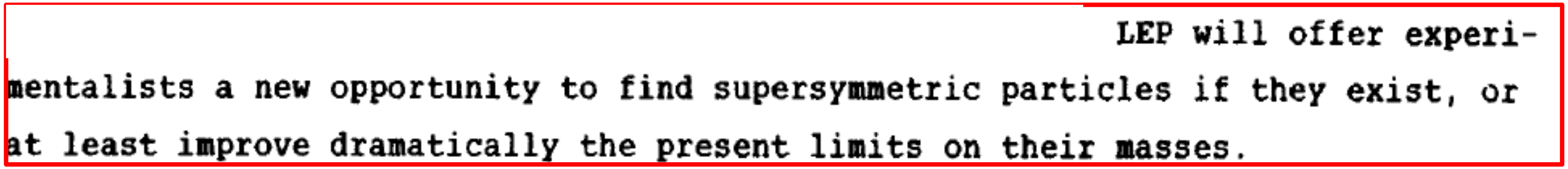




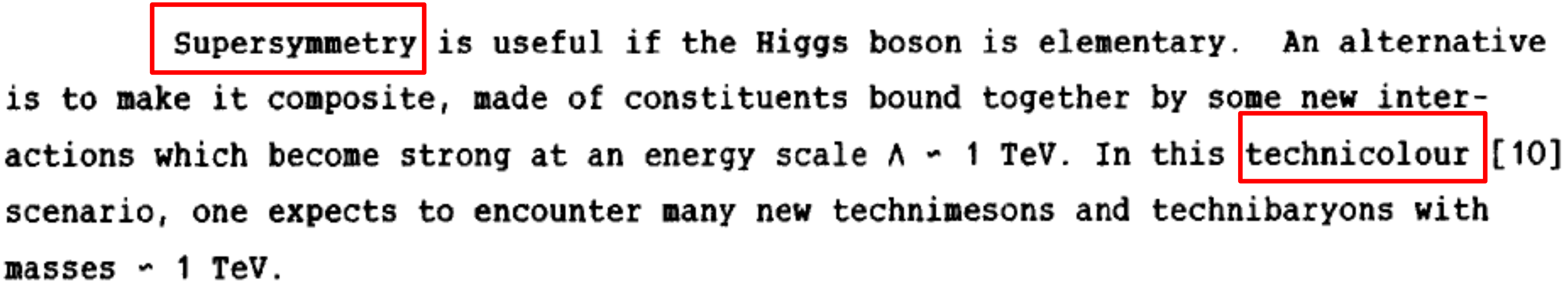
Exotics Searches post-1980

- LEP/SLC/Tevatron/LHC (as well as non-collider facilities) pursued an exotics program over the following decades

From “Physics at LEP” (1986)



LEP will offer experimentalists a new opportunity to find supersymmetric particles if they exist, or at least improve dramatically the present limits on their masses.



Supersymmetry is useful if the Higgs boson is elementary. An alternative is to make it composite, made of constituents bound together by some new interactions which become strong at an energy scale Λ ~ 1 TeV. In this technicolour [10] scenario, one expects to encounter many new technimesons and technibaryons with masses ~ 1 TeV.

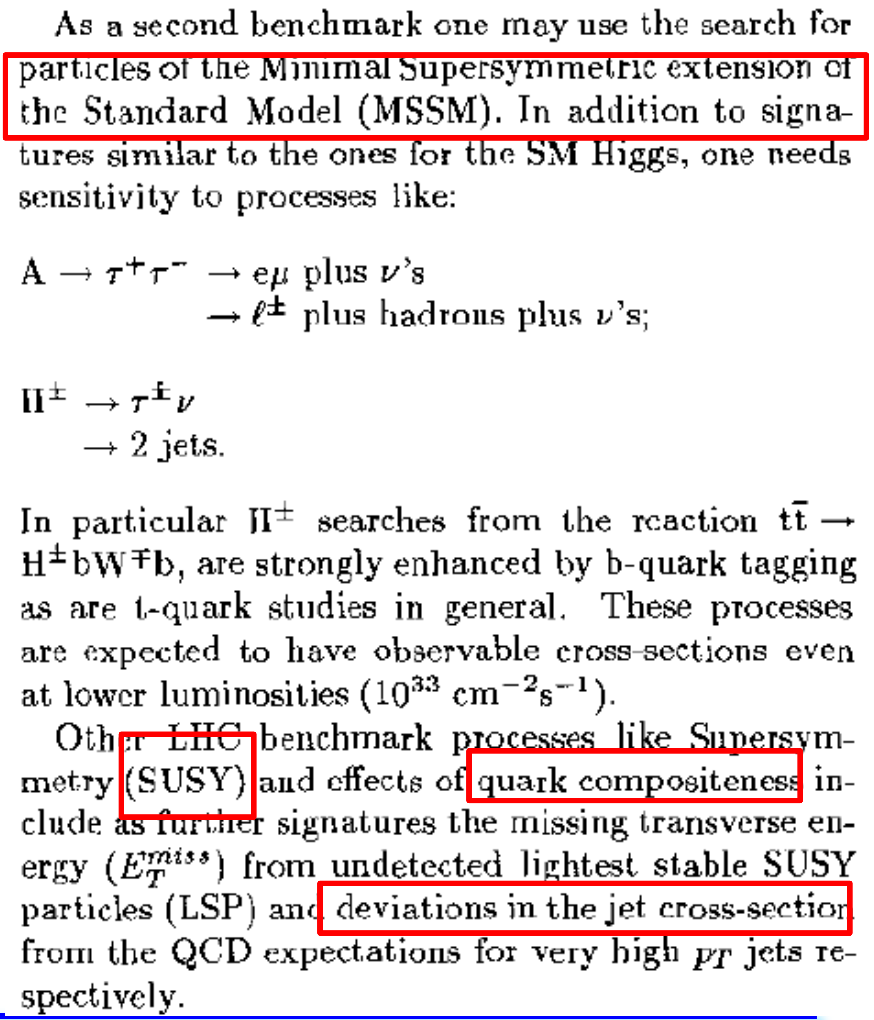
- Precision measurements, toponium, New heavy leptons/quarks, technicolour

Exotics Searches post-1980

- LEP/SLC/Tevatron/LHC (as well as non-collider facilities) pursued an exotics program over the following decades

From ATLAS

Letter of Intent (1992)



As a second benchmark one may use the search for particles of the Minimal Supersymmetric extension of the Standard Model (MSSM). In addition to signatures similar to the ones for the SM Higgs, one needs sensitivity to processes like:

$$A \to \tau^+\tau^- \to e\mu \text{ plus } \nu\text{'s}$$
$$\to \ell^\pm \text{ plus hadrons plus } \nu\text{'s};$$

$$H^\pm \to \tau^\pm \nu$$
$$\to 2 \text{ jets.}$$

In particular $H^\pm$ searches from the reaction $t\bar{t} \to H^\pm bW^\mp b$, are strongly enhanced by b-quark tagging as are t-quark studies in general. These processes are expected to have observable cross-sections even at lower luminosities (10^{33} cm^{-2}s^{-1}).

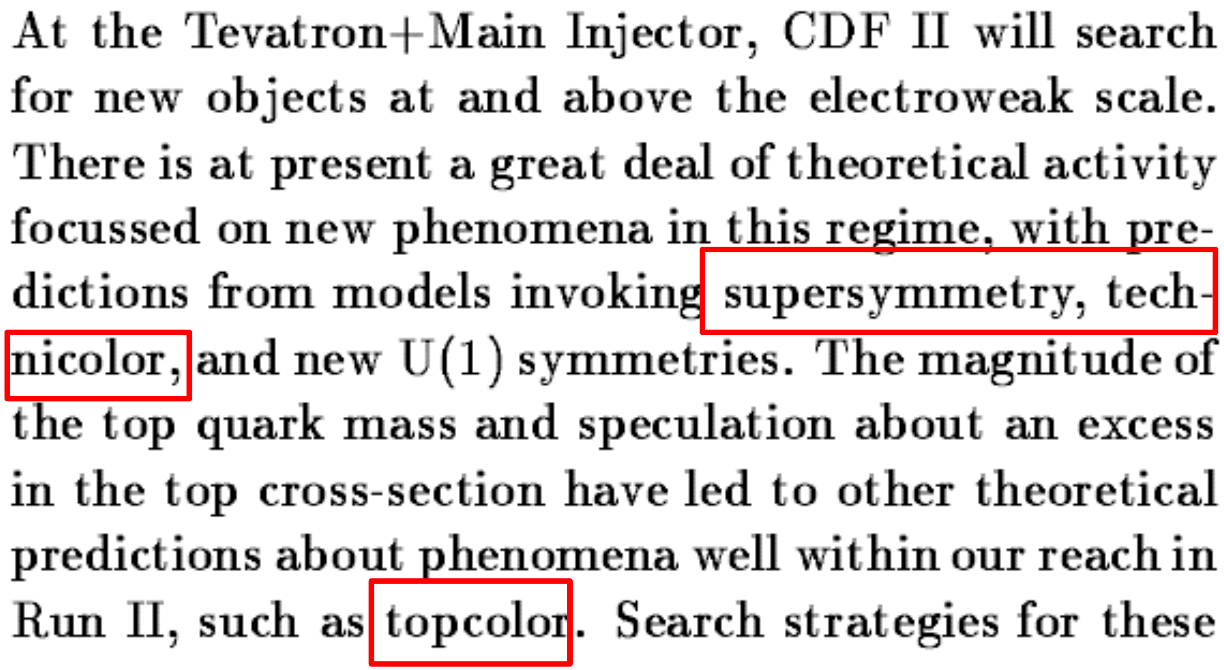
Other LHC benchmark processes like Supersymmetry (SUSY) and effects of quark compositeness include as further signatures the missing transverse energy (E_T^{miss}) from undetected lightest stable SUSY particles (LSP) and deviations in the jet cross-section from the QCD expectations for very high p_T jets respectively.

Exotics Searches post-1980

- LEP/SLC/Tevatron/LHC (as well as non-collider facilities) pursued an exotics program over the following decades

From CDF Run II

Technical Design Report (1996)



At the Tevatron+Main Injector, CDF II will search for new objects at and above the electroweak scale. There is at present a great deal of theoretical activity focussed on new phenomena in this regime, with predictions from models invoking supersymmetry, technicolor, and new U(1) symmetries. The magnitude of the top quark mass and speculation about an excess in the top cross-section have led to other theoretical predictions about phenomena well within our reach in Run II, such as topcolor. Search strategies for these

And now?

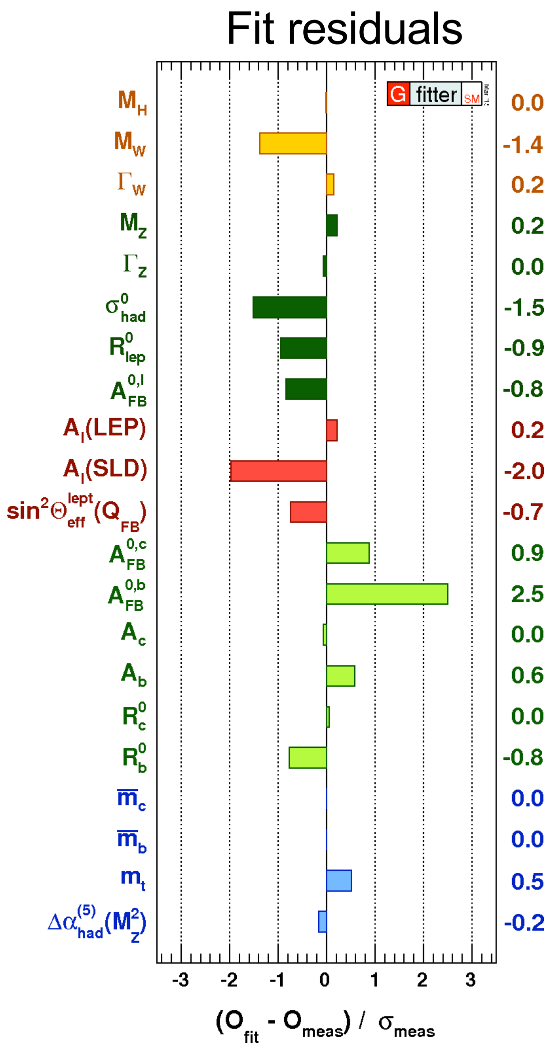
- What do we mean by exotics searches now - why do we think that there is still New Physics to find?
  - Can safely argue that pre-1980 was a time of great exploration but it turns out in retrospect to have all been building towards the same conclusion – the Standard Model

Standard Model Shortcomings

- Standard Model: best-tested theory
  - Describes the fundamental particles and the interactions among them

- *But...*
  - 26 free parameters (compelling?)
  - Higgs mass appears to be unnaturally fine-tuned
  - Not possible to unify with gravity
  - Dark Matter/Energy
  - Effective theory? (c.f. Classical mechanics ➔ Special Relativity)

- Candidate overarching theories imply 'New Physics'
  - New fundamental particles
  - New fundamental interactions among them



Exotics Searches

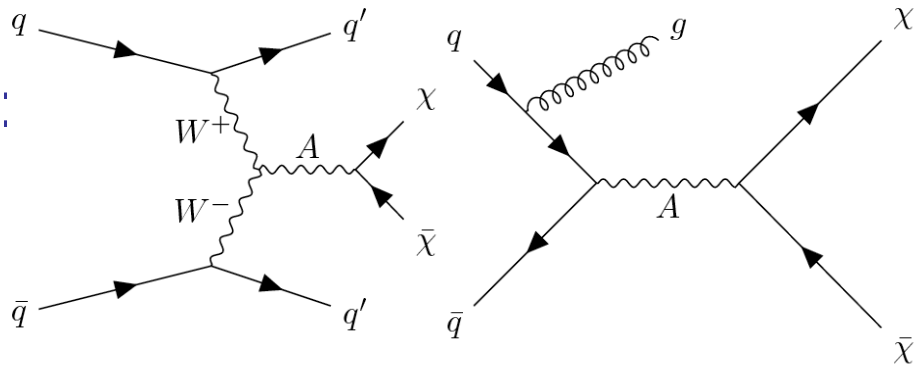
- Search for those new fundamental particles and interactions
  - Often those searches are ~targeted at specific candidate theories
  - The choice of candidate changes over time
    - Archaeology on the proposal documents illustrates an open-mindedness throughout the decades and an awareness of “theoretical biases”

- But much more than that: exploration as a goal in itself
  - A full exploitation of the LHC is open-mindedly to ask the question “what happens when hadrons collide”
  - Model-independence is a good goal
    - Signature-based searches

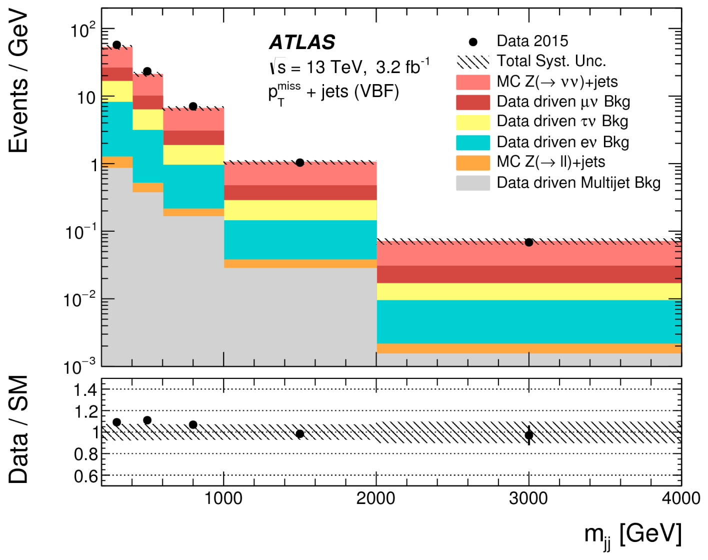
Model Independence

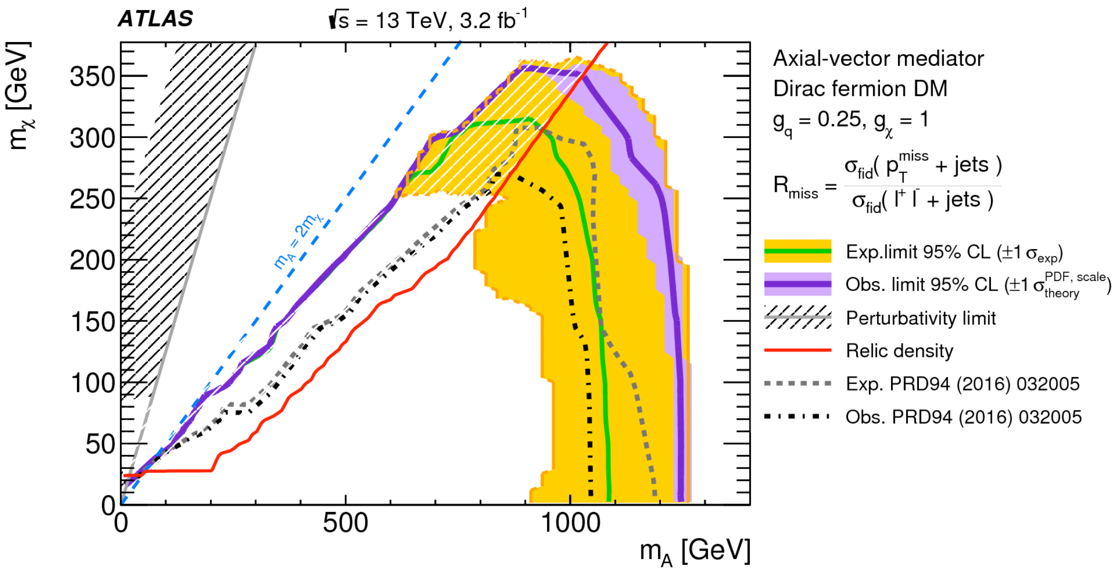
Eur. Phys. J. C 77 (2017) 765

- An example of good practice:
- Set up a search to be sensitive to e.g. WIMPs



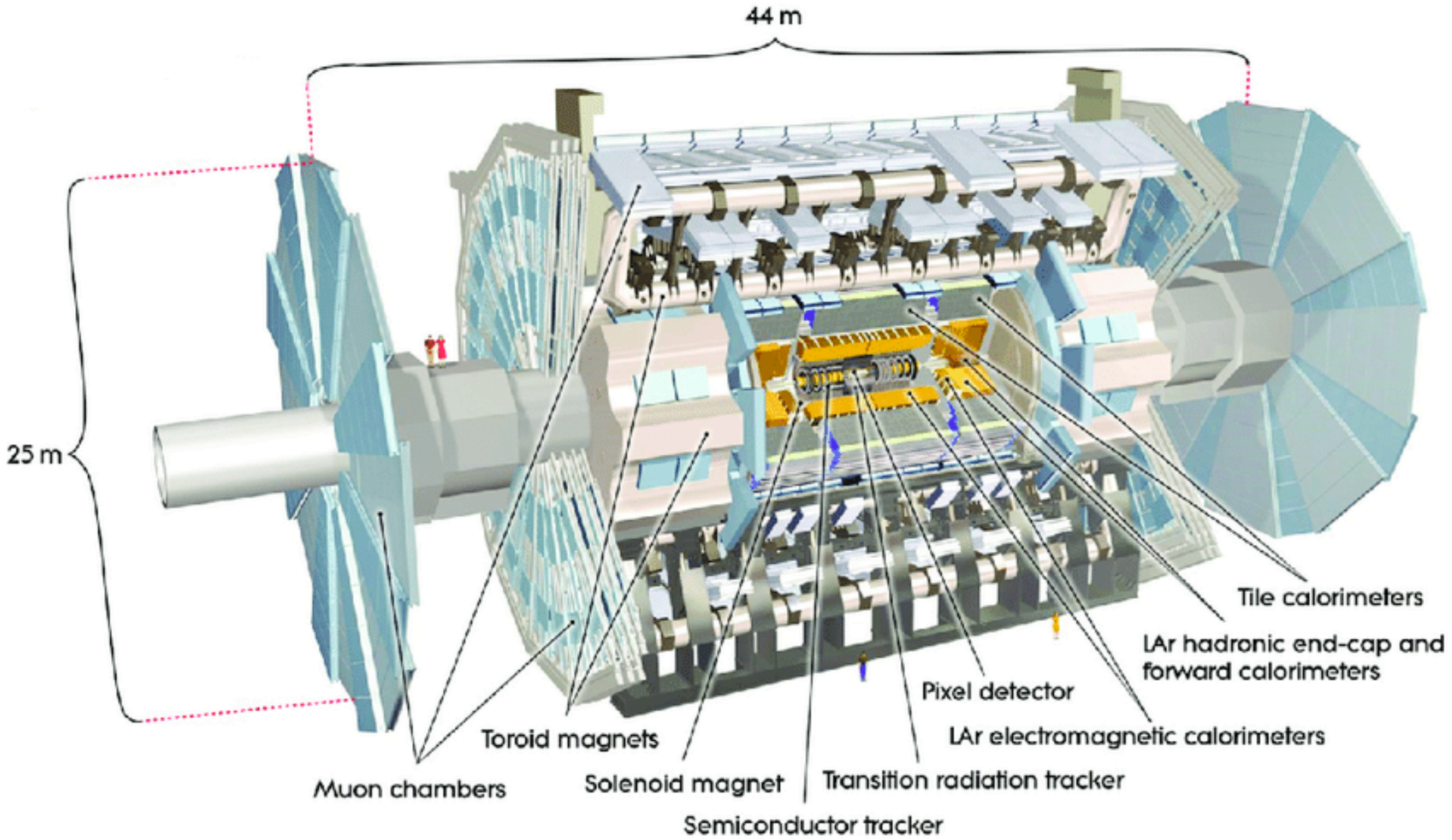
- Measure detector-corrected observables e.g. di-jet mass
  - These are re-interpretable
- Can still set limits in a model of choice as well:





How to search in practice?

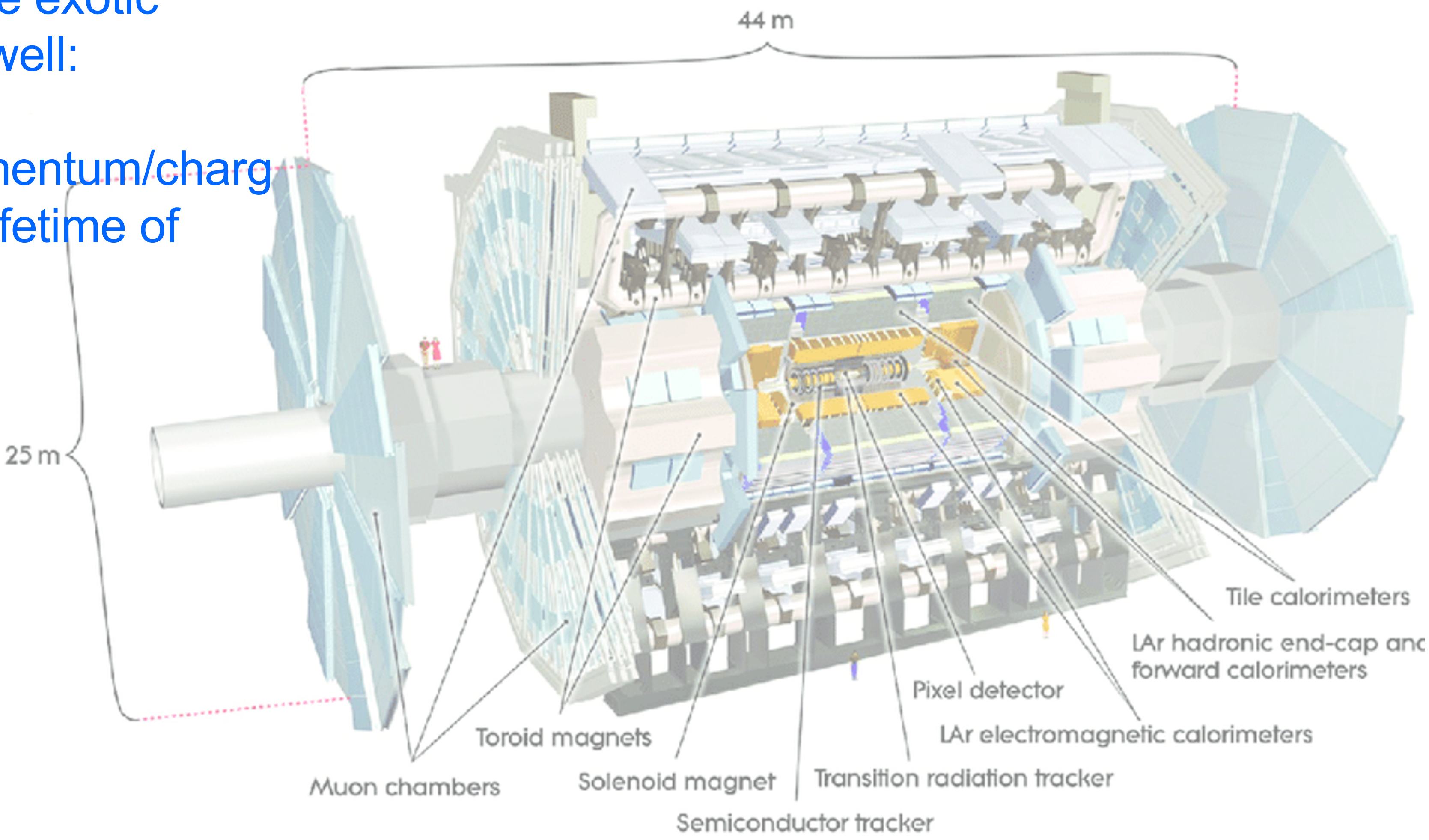
- Prerequisite: Design a detector with sensitivity



How to search in practice?

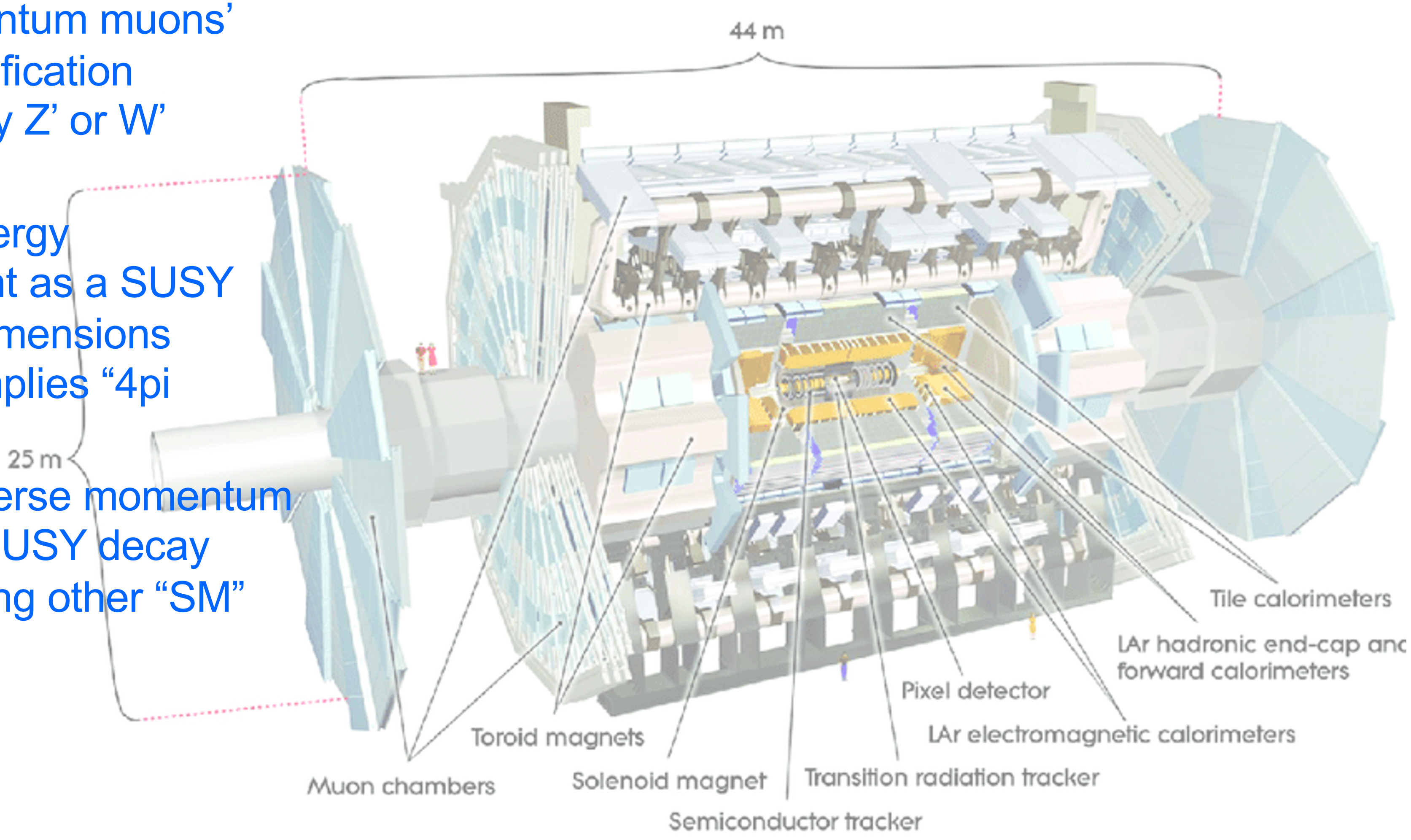
- ATLAS is a General Purpose Detector (GPD)

- Most of the generic goals serve exotic searches well: measuring mass/momentum/charge/energy/lifetime of particles



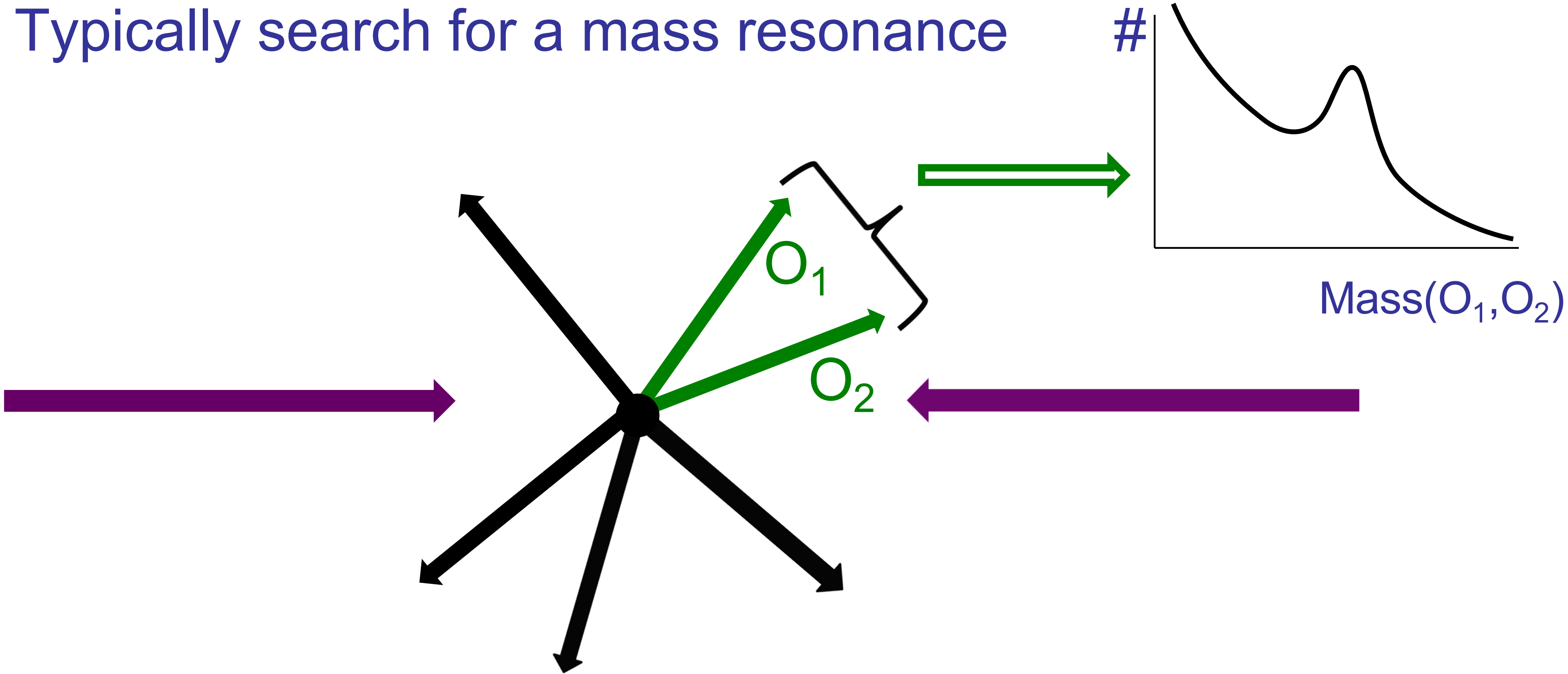
How to search in practice?

- Some notable special design criteria for exotics given some classes of models e.g.
  - high momentum muons' charge identification (motivated by Z' or W' search)
  - Missing energy measurement as a SUSY and Extra Dimensions signature (implies "4pi coverage")
  - Low transverse momentum triggers for SUSY decay chains (among other "SM" physics)



New Physics Search: Mass axis

- Typically search for a mass resonance

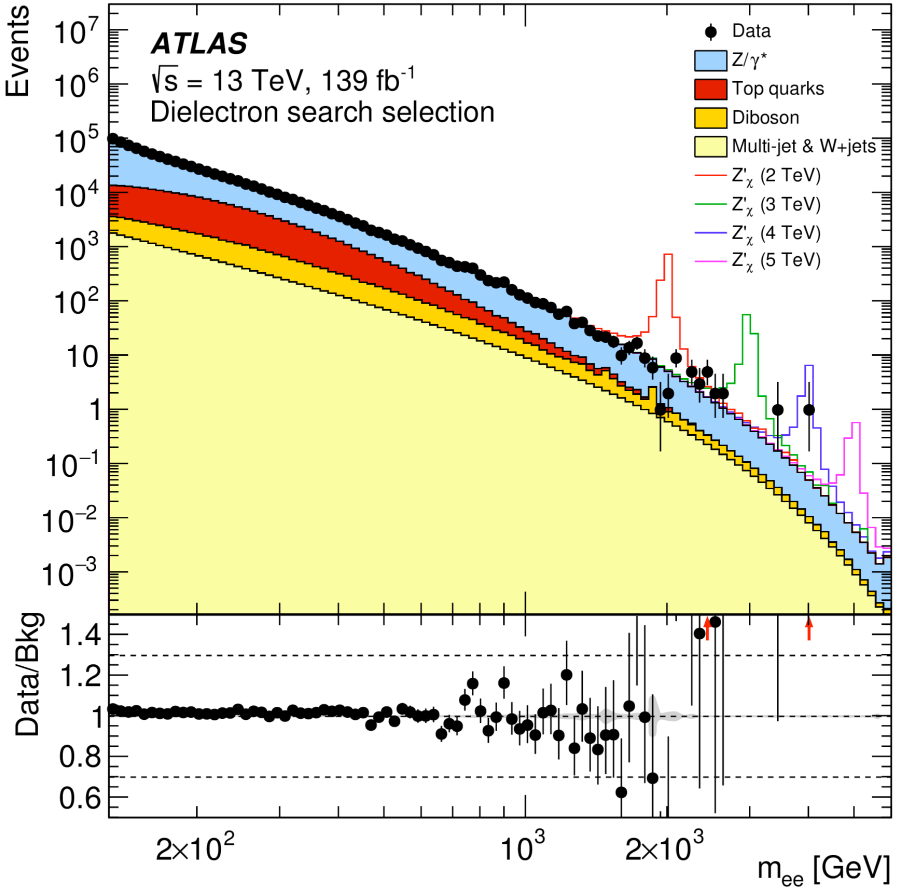


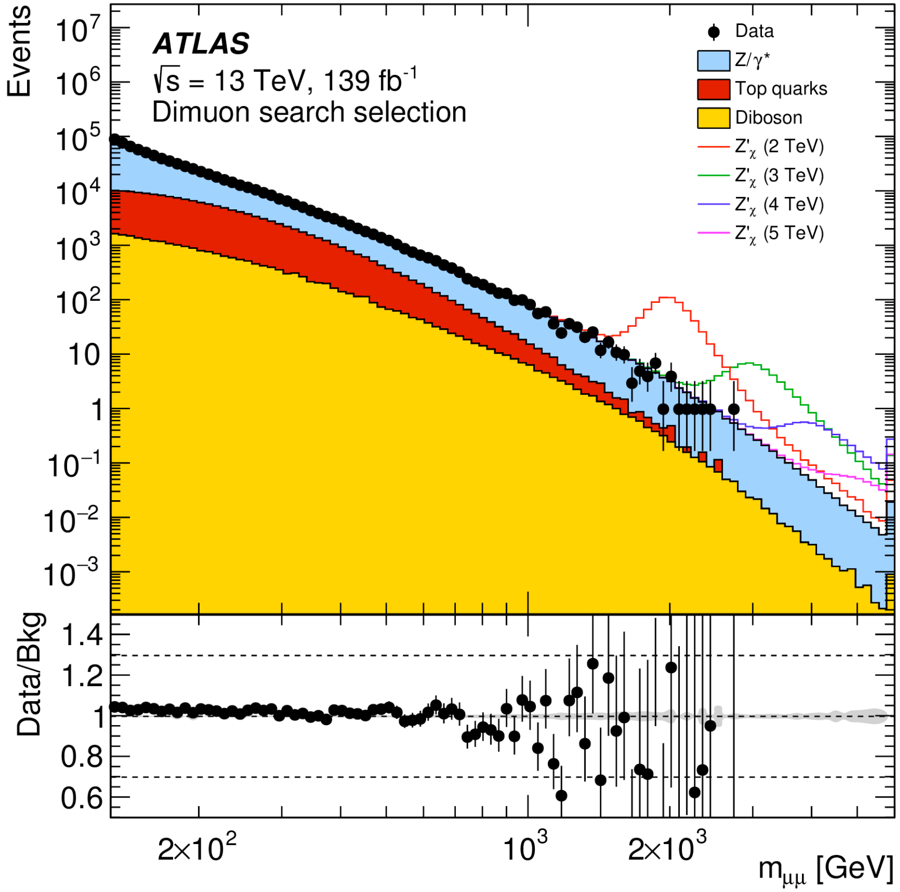
  - Higher energy ➔ Access higher mass states
  - Higher luminosity ➔ Access rarer production processes
- This has worked: ...J/ψ, ϒ, Z, Higgs, ...
  - But no evidence for resonances Beyond the Standard Model
    Ruled out phase-space: e.g. mass(Z’➔ $\tau^+\tau^-$) is > 2.4 TeV
  - This provides legacy constraints and there is a lot of discovery phase space still to explore.

Phys. Lett. B 796 (2019) 68

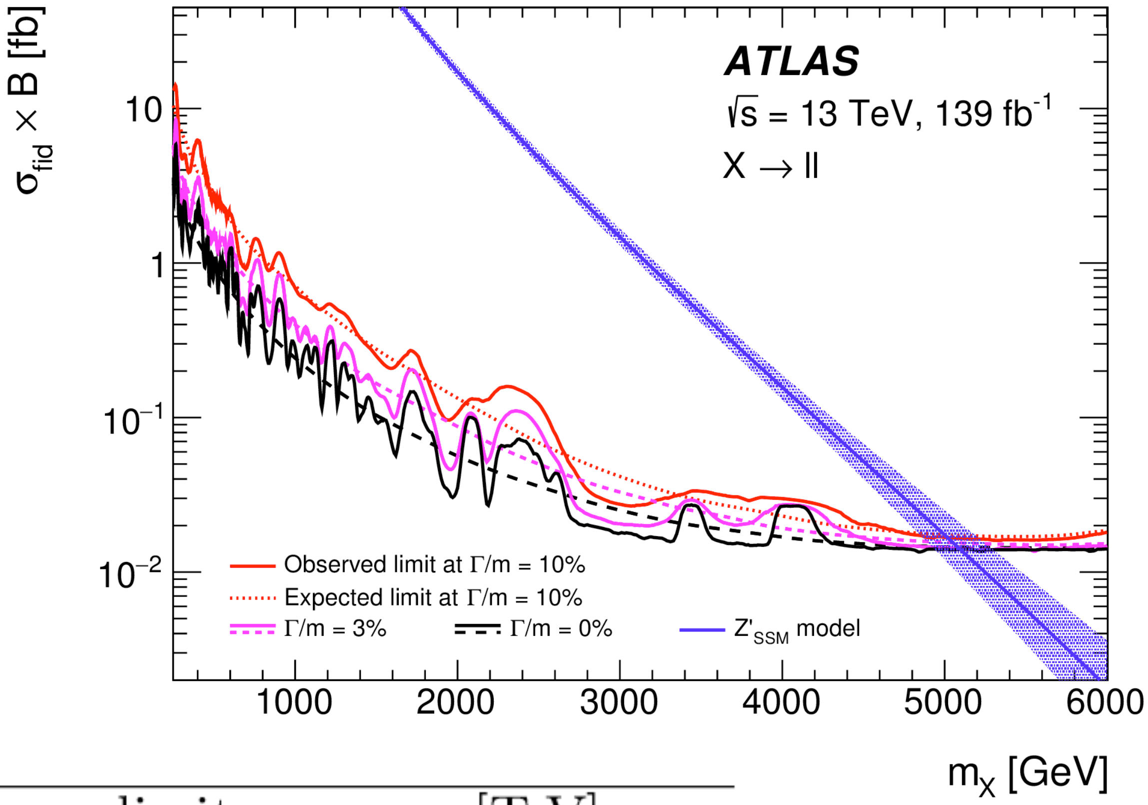
Z' searches

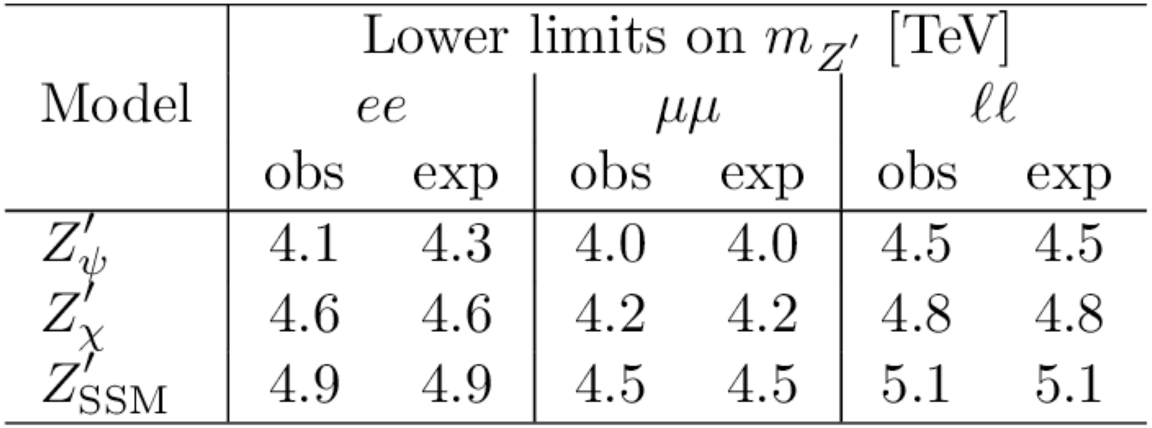
- Balance theory/experiment (signature) motivations
- For example, Z' search





Z’ searches

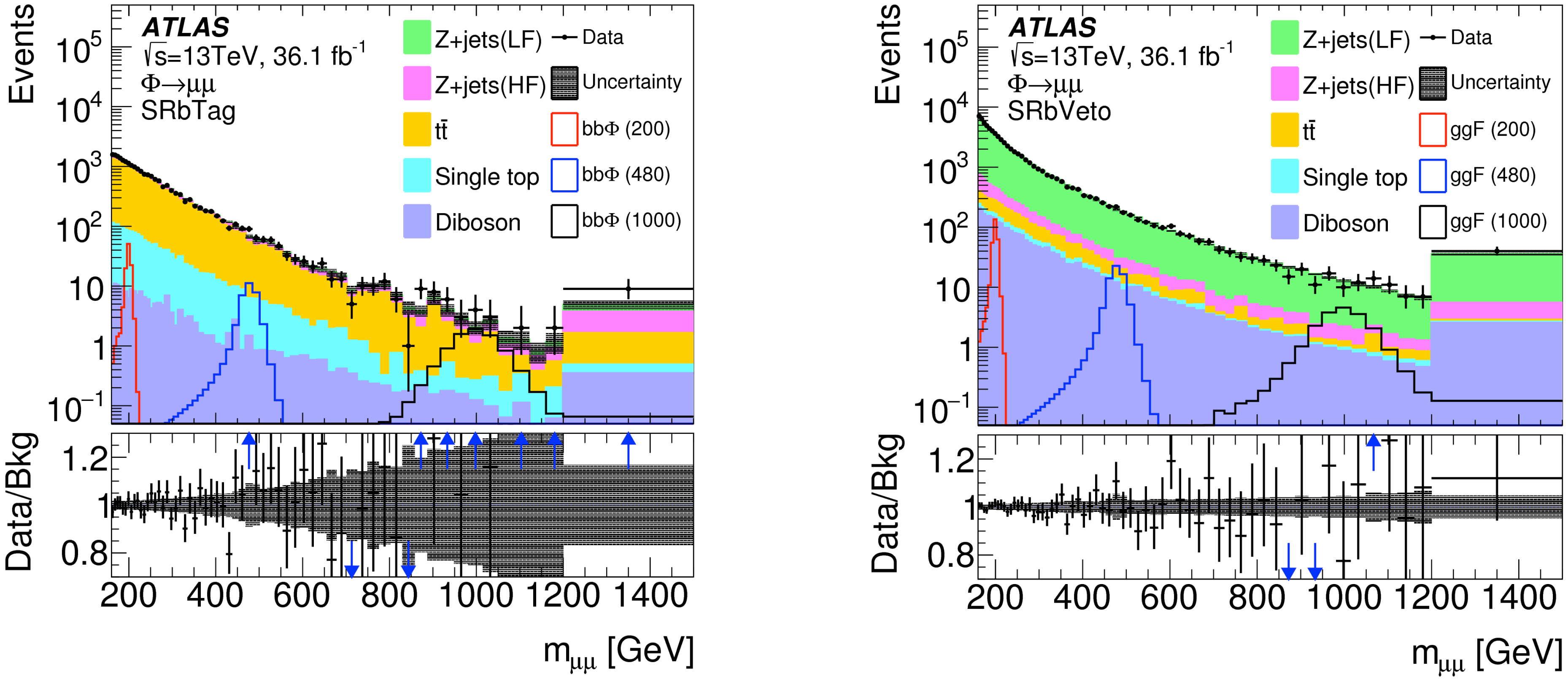




Model	Lower limits on $m_{Z'}$ [TeV]					
	ee		$\mu\mu$		$\ell\ell$	
	obs	exp	obs	exp	obs	exp
Z'_ψ	4.1	4.3	4.0	4.0	4.5	4.5
Z'_χ	4.6	4.6	4.2	4.2	4.8	4.8
Z'_{SSM}	4.9	4.9	4.5	4.5	5.1	5.1

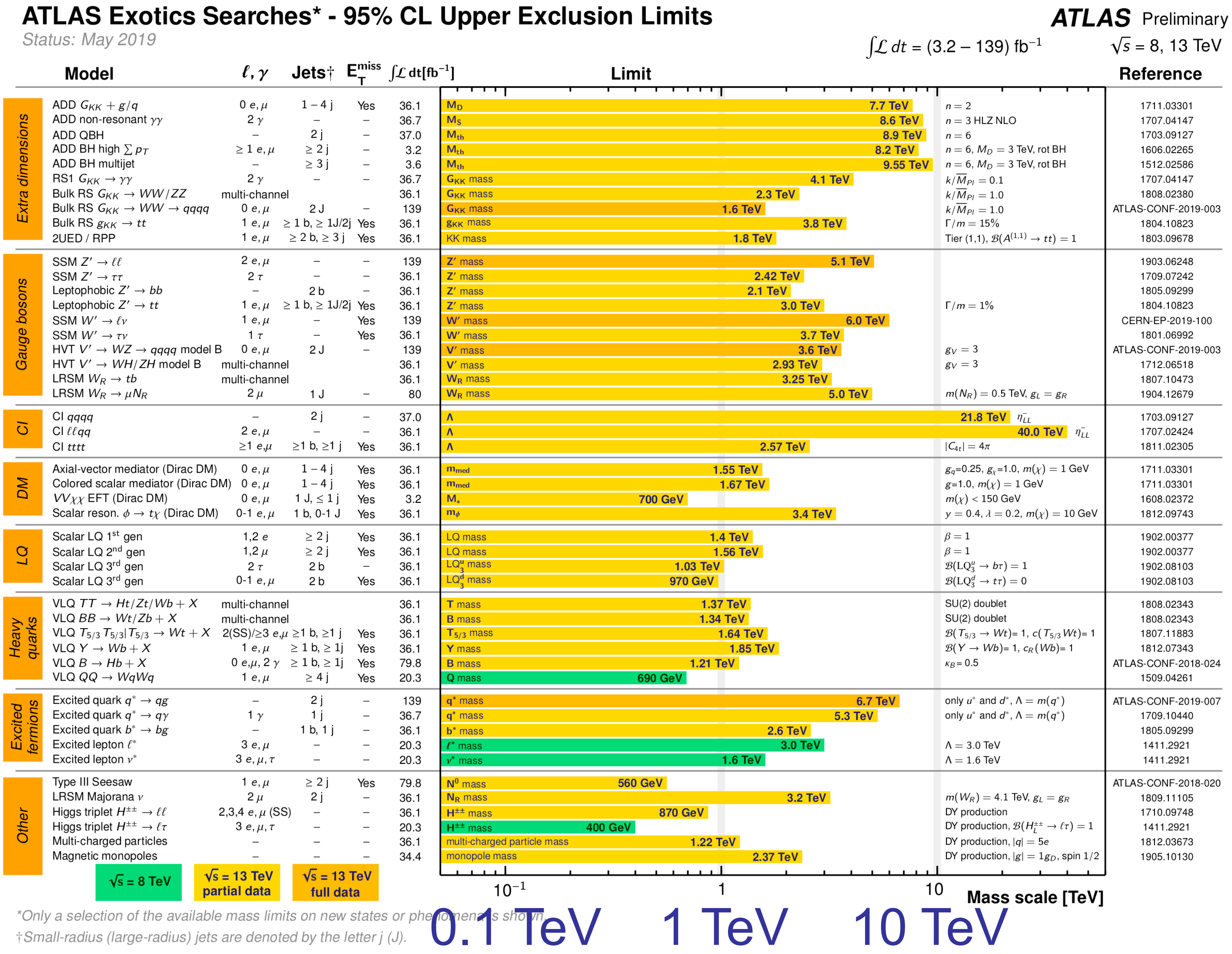
Go “exclusive”: Require a b-jet (or veto b)

- Data are subsets of the Z’ search: production with a b quark and production with explicitly no b-quark
  - Move to exclusive searches could reveal peaks where the inclusive distributions do not see them



JHEP 07 (2019) 117

ATLAS Exotics reach (so far)



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2019

ATLAS Preliminary

$\int\mathcal{L}\,dt = (3.2 - 139)\ \text{fb}^{-1}$ $\sqrt{s}$ = 8, 13 TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\text{fb}^{-1}]$	Limit			Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	M_D	7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S	8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th}	8.9 TeV	$n = 6$	1703.09127
	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 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass	4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass	2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WW \to qqqq$	0 e, μ	2 J	–	139	G_{KK} mass	1.6 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2019-003
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass	3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass	1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	Z' mass	5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass	2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass	2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	Z' mass	3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	139	W' mass	6.0 TeV		CERN-EP-2019-100
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass	3.7 TeV		1801.06992
	HVT $V' \to WZ \to qqqq$ model B	0 e, μ	2 J	–	139	V' mass	3.6 TeV	$g_V = 3$	ATLAS-CONF-2019-003
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass	2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W_R \to tb$	multi-channel			36.1	W_R mass	3.25 TeV		1807.10473
	LRSM $W_R \to \mu N_R$	2 μ	1 J	–	80	W_R mass	5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ	21.8 TeV η_{LL}^-		1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	Λ	40.0 TeV η_{LL}^-		1707.02424
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	Λ	2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med}	1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med}	1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_*	700 GeV	$m(\chi) < 150$ GeV	1608.02372
	Scalar reson. $\phi \to t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	m_ϕ	3.4 TeV	$y = 0.4$, $\lambda = 0.2$, $m(\chi) = 10$ GeV	1812.09743
LQ	Scalar LQ 1st gen	1,2 e	≥ 2 j	Yes	36.1	LQ mass	1.4 TeV	$\beta = 1$	1902.00377
	Scalar LQ 2nd gen	1,2 μ	≥ 2 j	Yes	36.1	LQ mass	1.56 TeV	$\beta = 1$	1902.00377
	Scalar LQ 3rd gen	2 τ	2 b	–	36.1	LQ_3^u mass	1.03 TeV	$\mathcal{B}(\text{LQ}_3^u \to b\tau) = 1$	1902.08103
	Scalar LQ 3rd gen	0-1 e, μ	2 b	Yes	36.1	LQ_3^d mass	970 GeV	$\mathcal{B}(\text{LQ}_3^d \to t\tau) = 0$	1902.08103
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass	1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass	1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\vert T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass	1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $Y \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	36.1	Y mass	1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb + X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	B mass	1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass	690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass	6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2019-007
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass	5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass	2.6 TeV		1805.09299
	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	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	N^0 mass	560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass	3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass	870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass	400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	multi-charged particle mass	1.22 TeV	DY production, $\lvert q\rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	monopole mass	2.37 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1905.10130

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

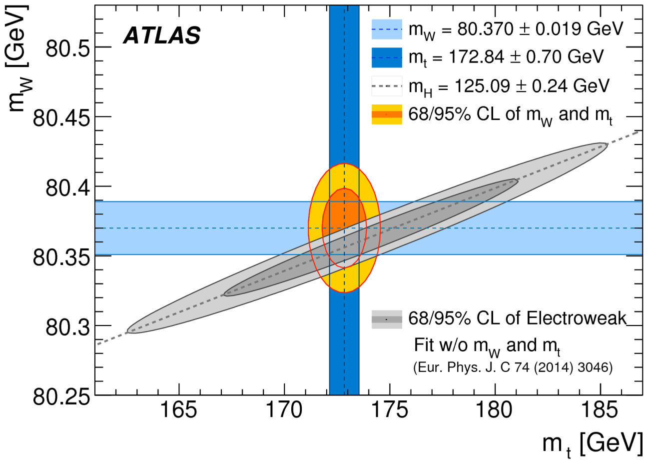
†Small-radius (large-radius) jets are denoted by the letter j (J).

0.1 TeV 1 TeV 10 TeV

S. Farrington, University of Edinburgh

Precision Measurements as a "search"

- Another way to search is to make precision measurements of already-discovered particles
  - This happened with W, Z, Higgs, b… you name it
  - e.g. W mass



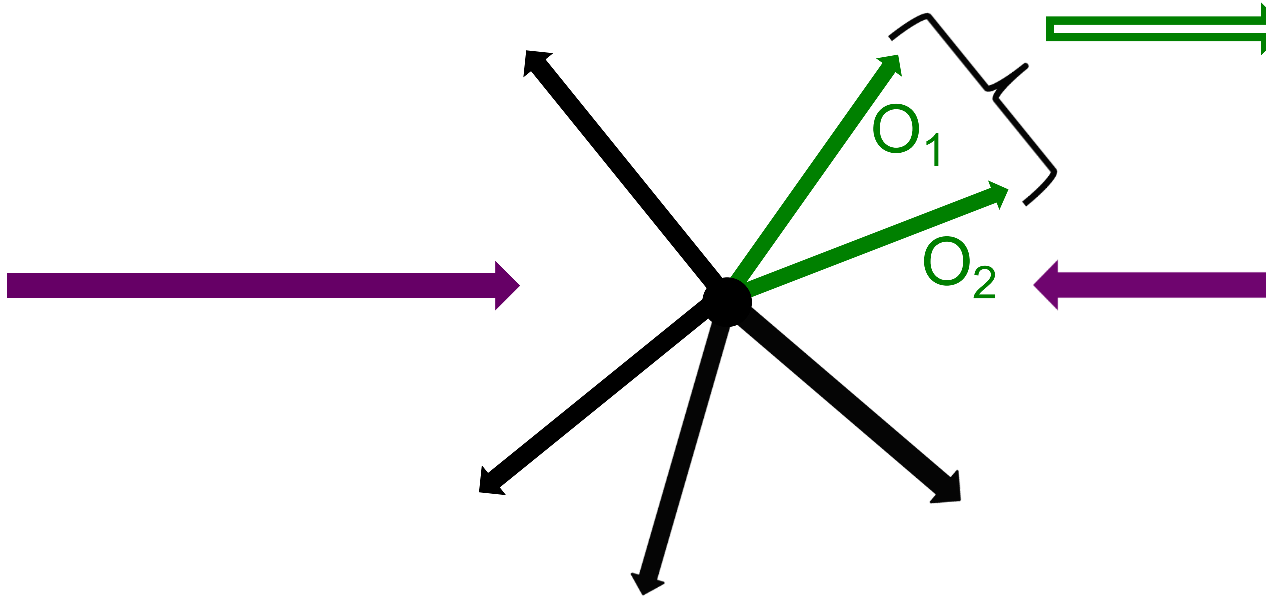
Eur. Phys. J. C 78 (2018) 110

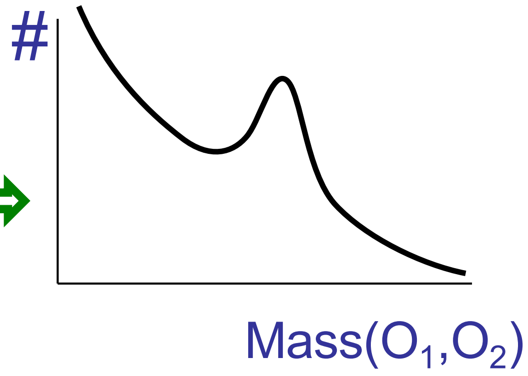
The Higgs

- The Higgs search was not assured to turn up a H(125)
- That search now yields searches
    - For rare decays of the H(125)
    - While the search for an extended Higgs sector continues
- Combined with a move towards precise and differential measurements tests the SM
        - Ample room for something to turn up, this is the only fundamental scalar we know of, explore it.

New Physics Search: Mass axis

- Typically search for a mass resonance

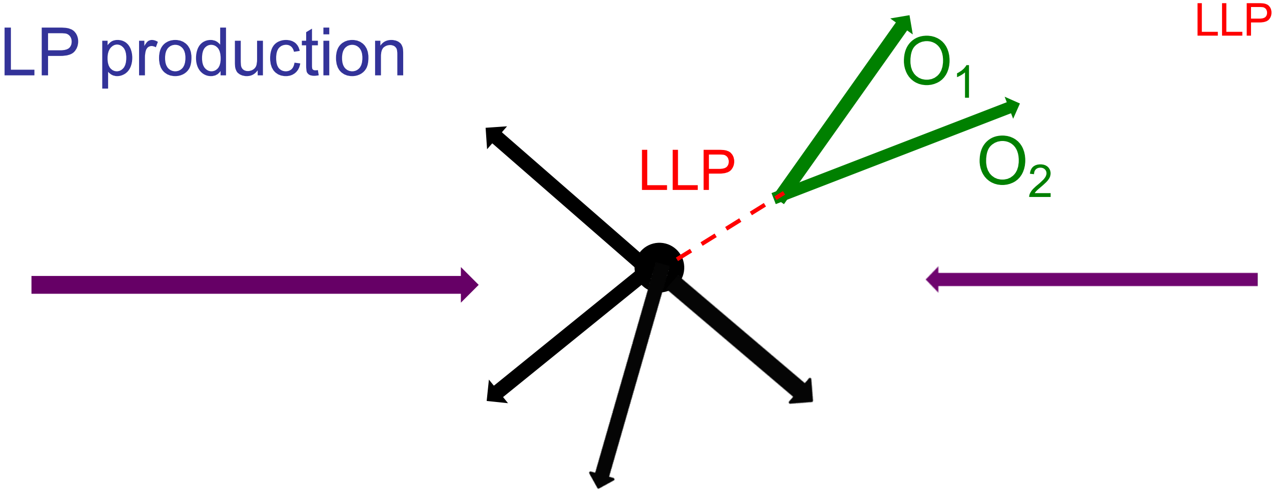




Alternative Axis: Lifetime

Single LLP production

LLP = Long Lived
Particle



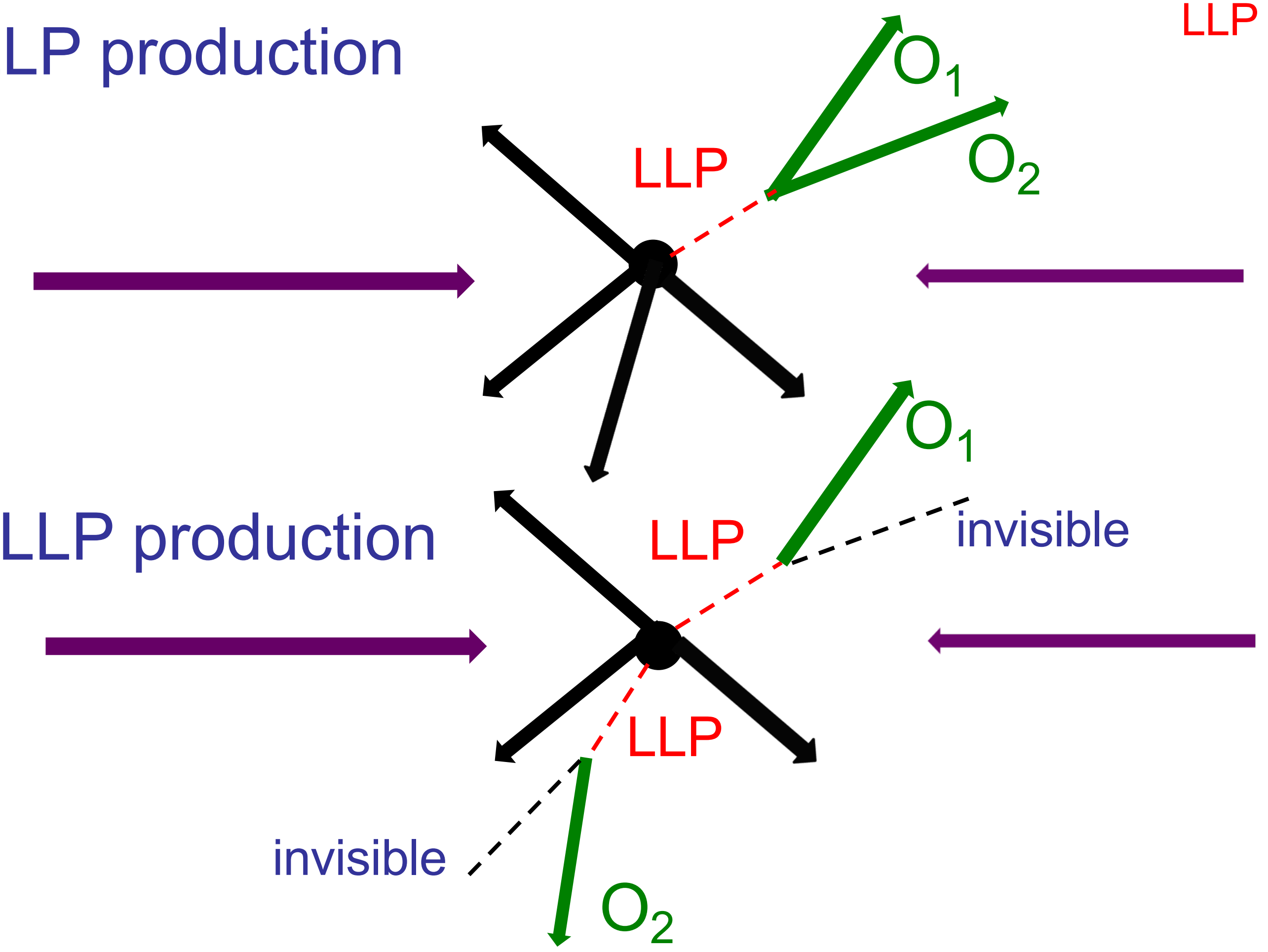
Alternative Axis: Lifetime

LLP = Long Lived Particle

Single LLP production

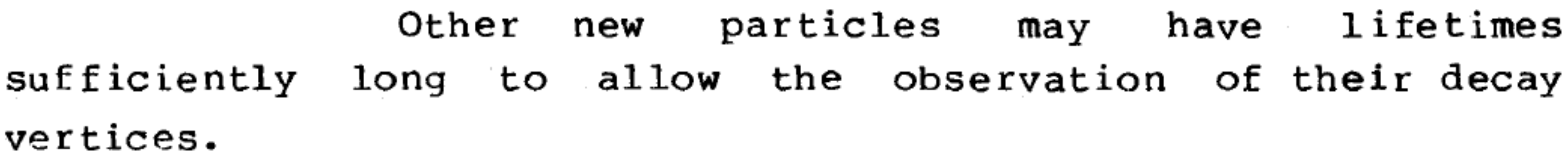
OR

Double LLP production



Why Long Lived Particles?

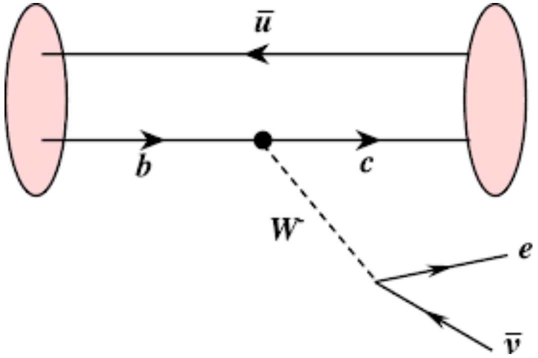
Foresight in CDF proposal in 1981:



Other new particles may have lifetimes sufficiently long to allow the observation of their decay vertices.

Why Long Lived Particles?

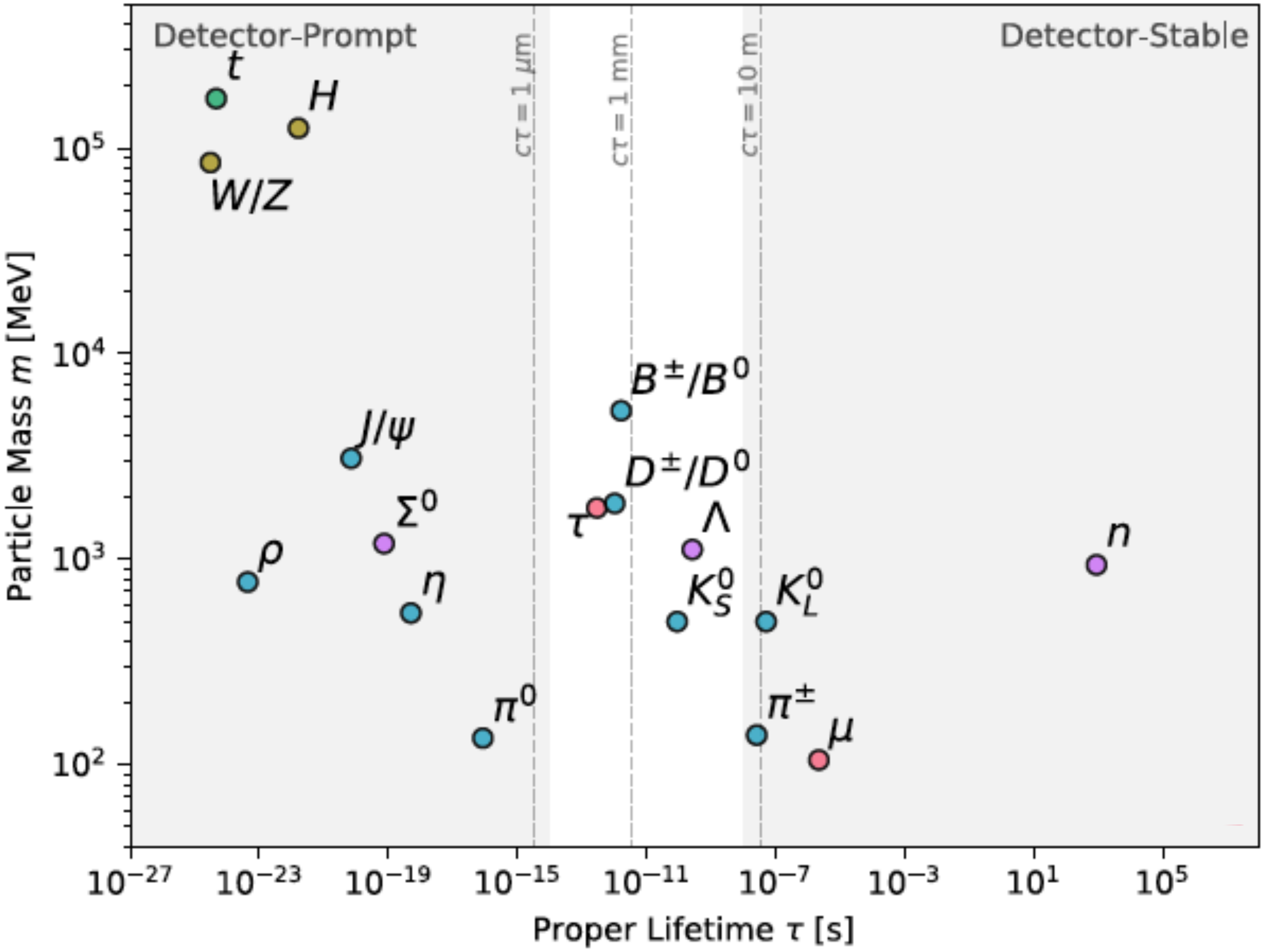
- Familiar case: b-hadrons
- Long-lived because
  - G_F is small (= W mass is large c.f. Q^2)
  - Off-diagonal CKM matrix elements are small



- New Physics could be long-lived for the same reasons:
  - Massive propagators, small couplings
  - Lack of phase space
  - Inability to decay by a faster route
- It makes sense to search for these at the LHC to explore the full range of new physics that we can be sensitive to
  - It is part of a full exploitation of the LHC, many theories as benchmarks

Standard Model Particle Lifetimes

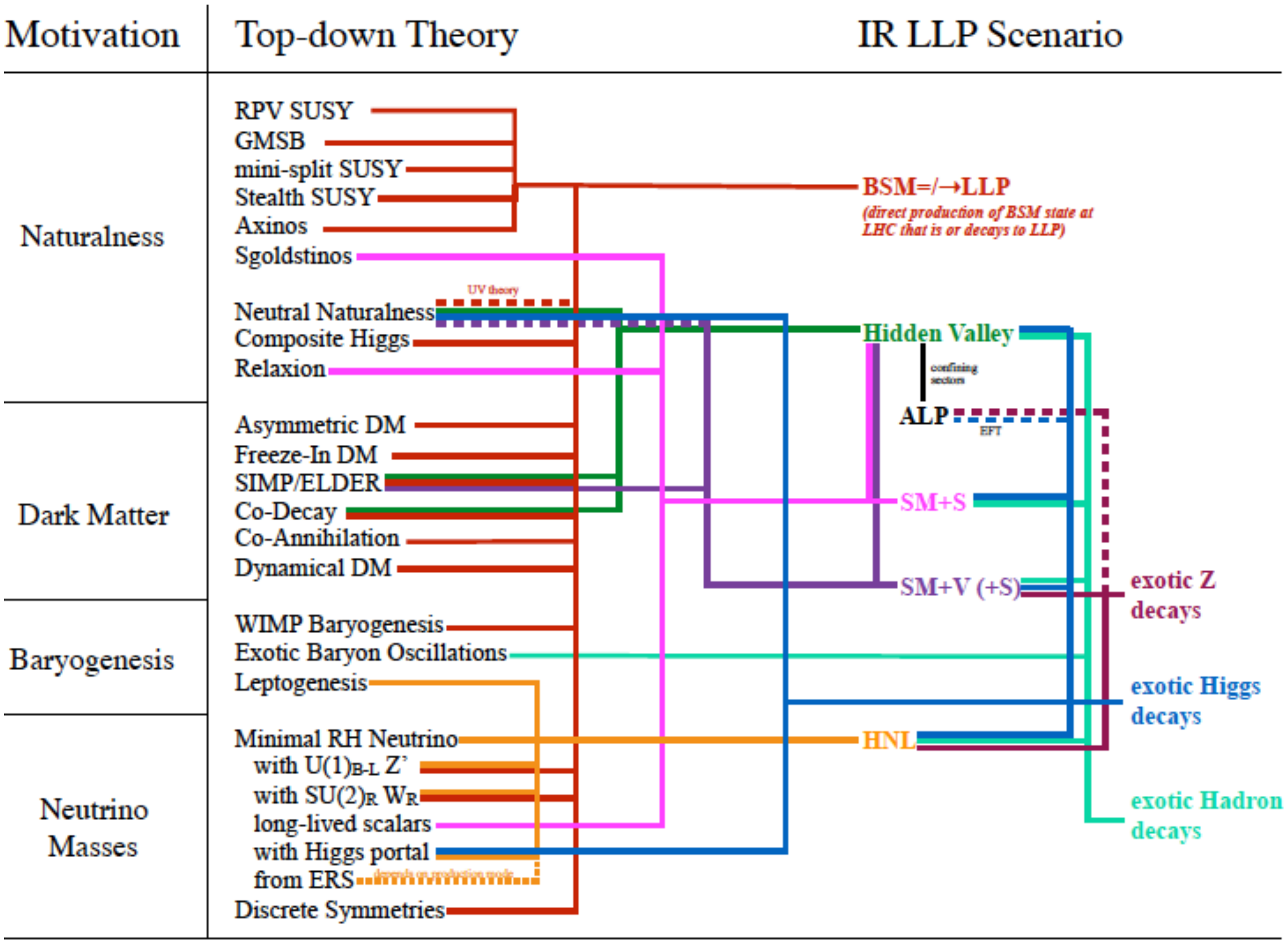
Prog.Part.Nucl.Phys. 106 (2019) 210-255



What else could be on this plane?

Theory Motivations

1806.07396



Simplified Models

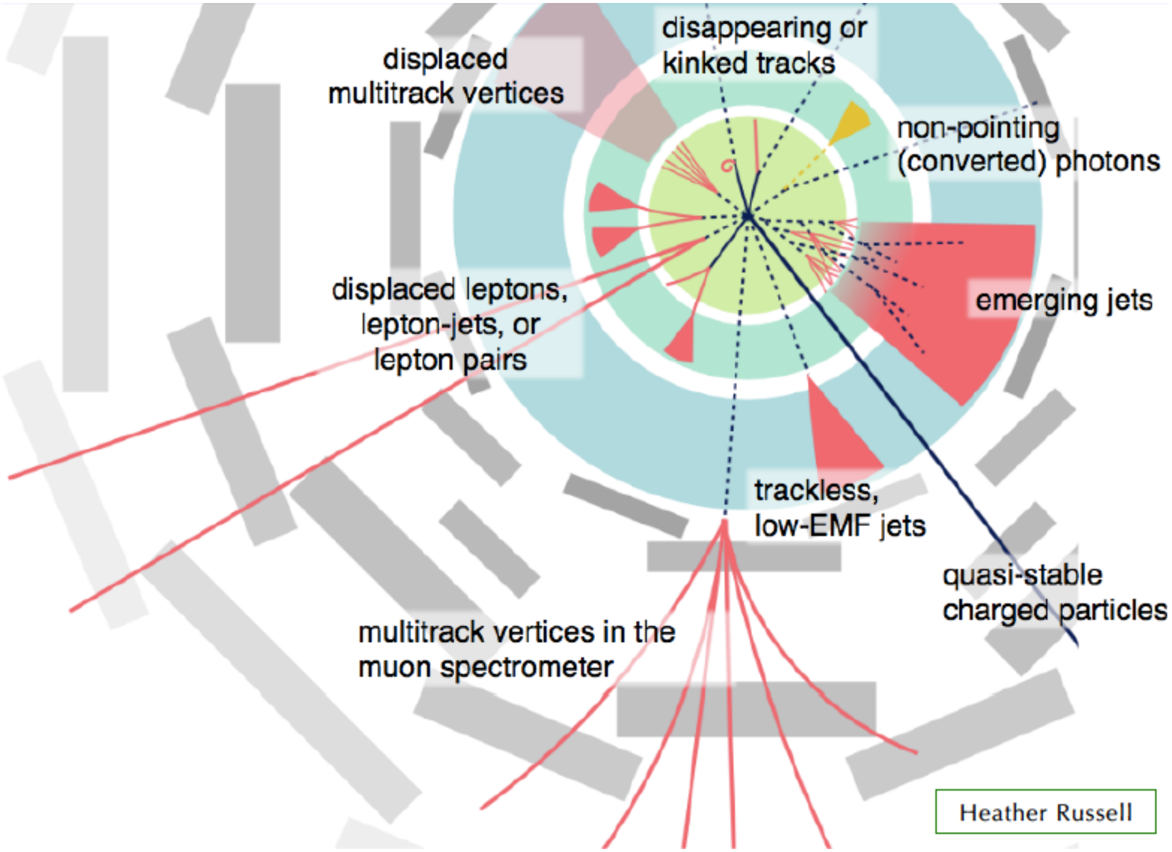
(The short answer is that many theories motivate LLPs, let's look at a few examples of how it has been realised so far.)

Experimental Considerations

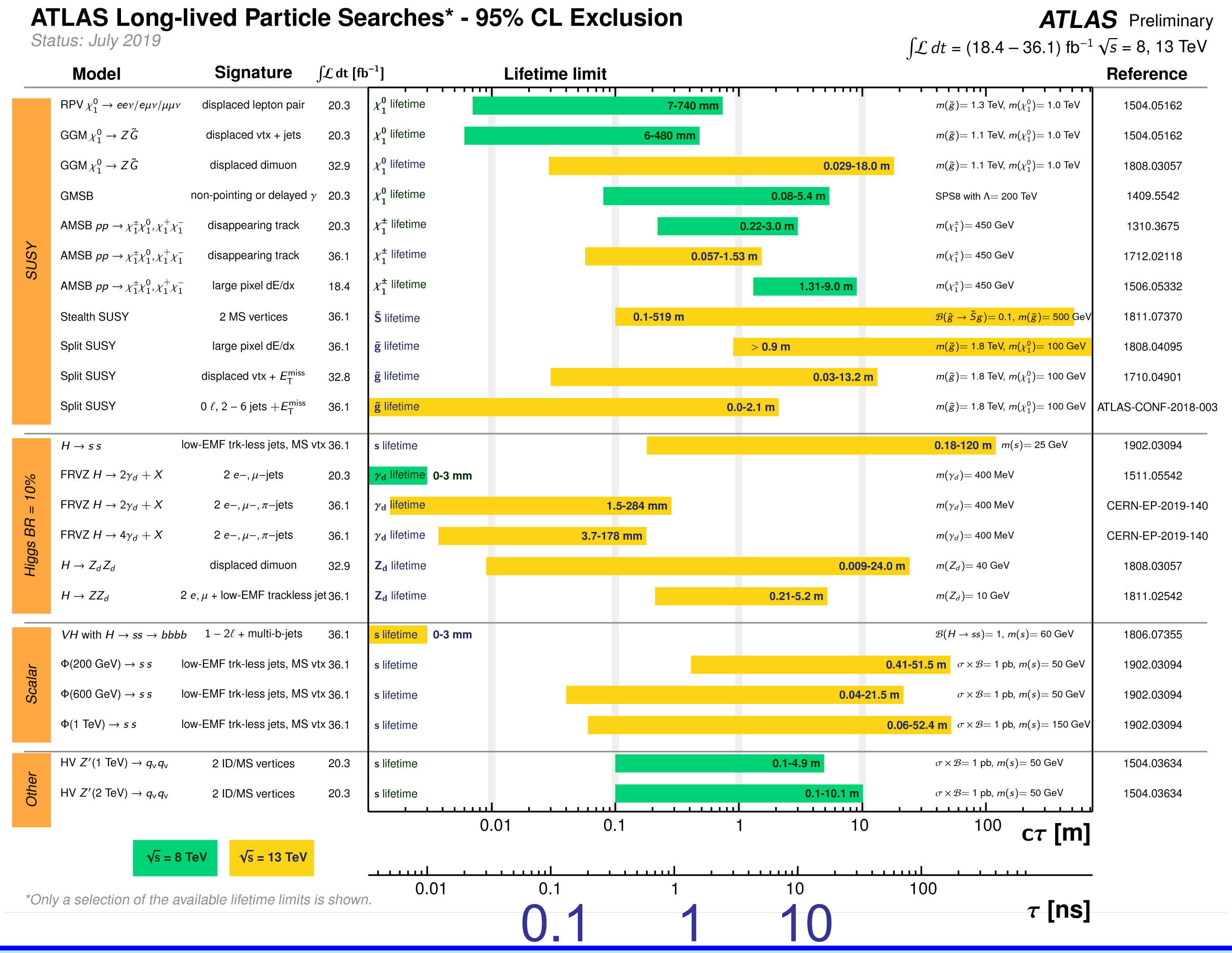
- The hardware and software of ATLAS and CMS were designed with broad goals in mind
  - But long lived particle sensitivity was not a major design criterion

How do we detect LLPs at the LHC

- Bespoke reconstruction algorithms layered on top of standard ones, dedicated triggers in some cases
  - Sensitivity comes from a patchwork of methods

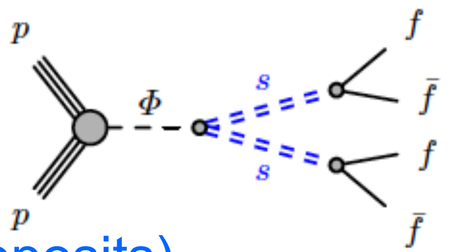


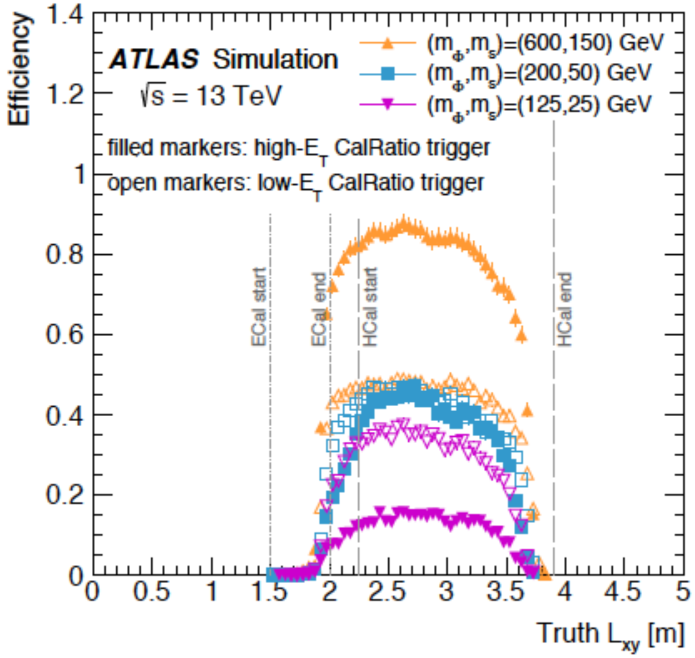
Current Coverage (ATLAS)



Displaced Jets (Low EM fraction)

- Look at decays that happen outside the EM calorimeter
- Search motivated by long-lived scalars
  - LLP decays in the hadronic calorimeter
    - No associated tracks
  - Specialised trigger (shape and location of calo deposits)
  - Backgrounds
    - Jets of neutral hadrons
    - Beam-induced backgrounds

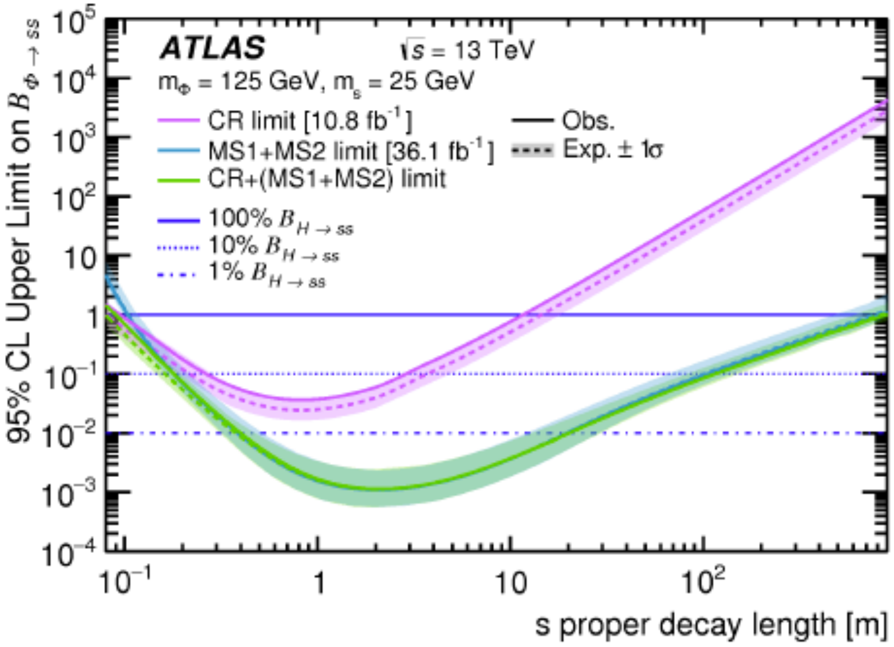




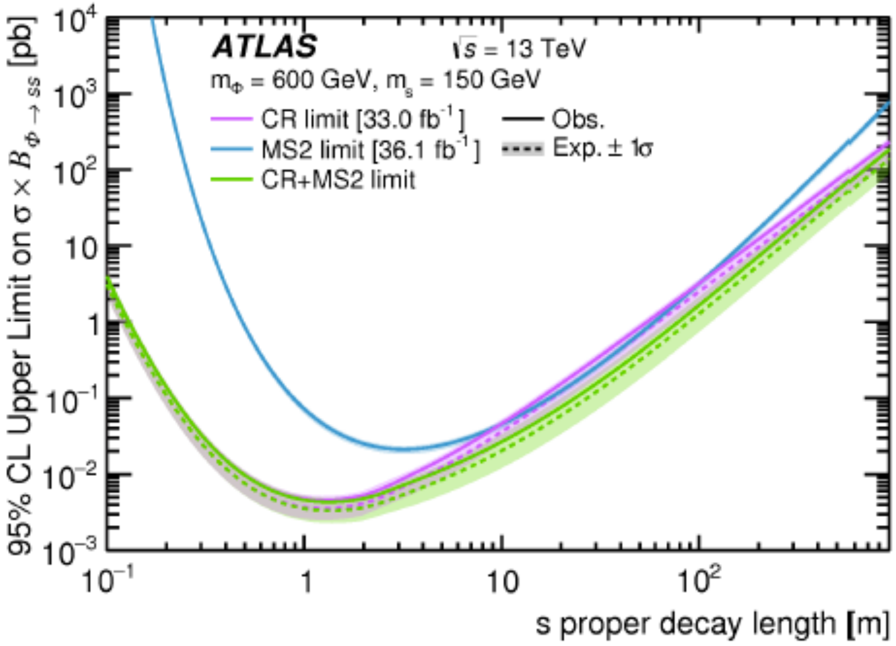
Eur. Phys. J. C 79 (2019) 481

Displaced Jets (Low EM Fraction)

Scalar mass 125 GeV

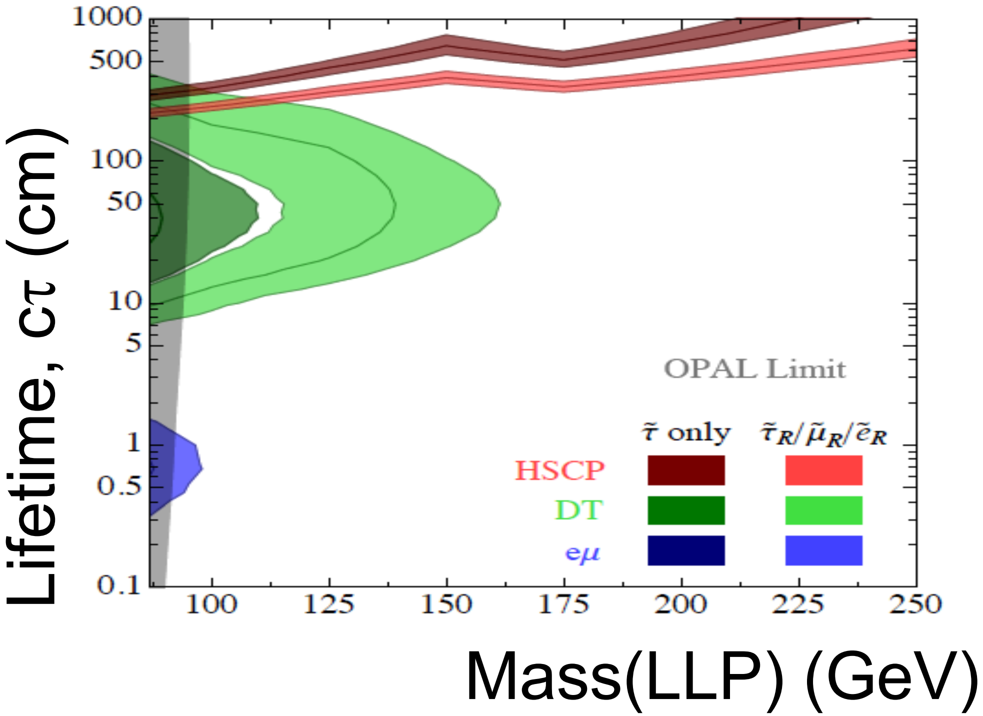


Scalar mass 600 GeV



Current Coverage for LLP to tau

- Current efforts leave huge unexplored phase space (plot a couple of years old but the picture has changed little for taus)



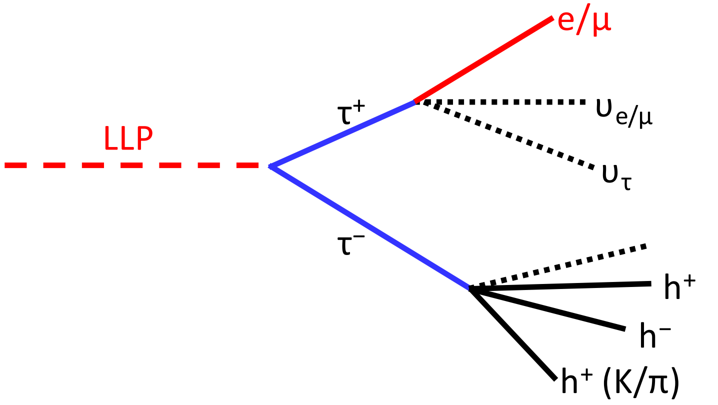
J. Evans & J. Shelton
JHEP 1604 (2016) 056

- Special motivations for LLP to tau decays – if new particles mix with Higgs, mass-dependent couplings arise
- ERC project on figuring out how we probe the rest of the phase space for taus (new hadronic tau ID, new triggers)

Tau ID

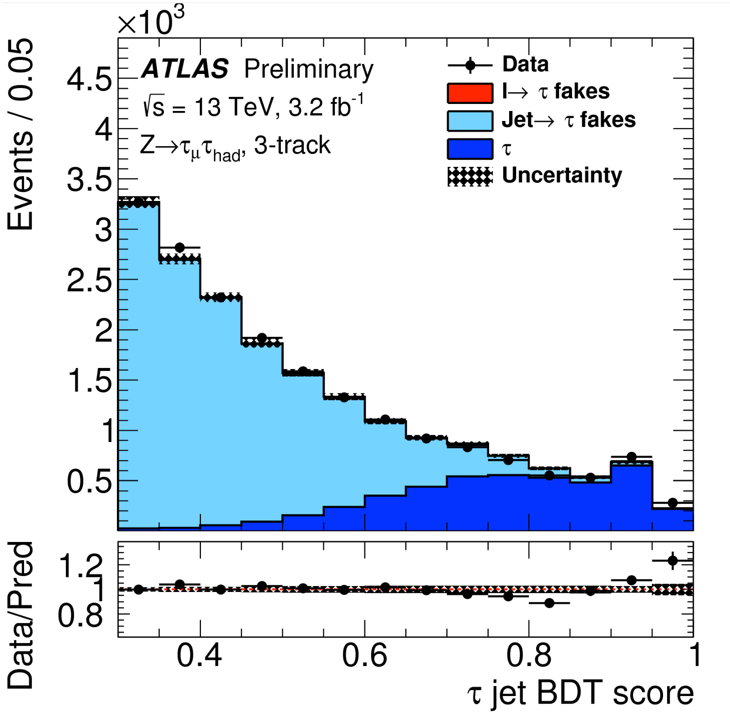
Tau hadronic decays

- BR(τ_h = 65%)



Tau ID

- Tau ID method
  (Boosted Decision Tree)
  - Currently trained on γ^* $\tau\tau$ decaying promptly



Same arguments for hadronic tau trigger

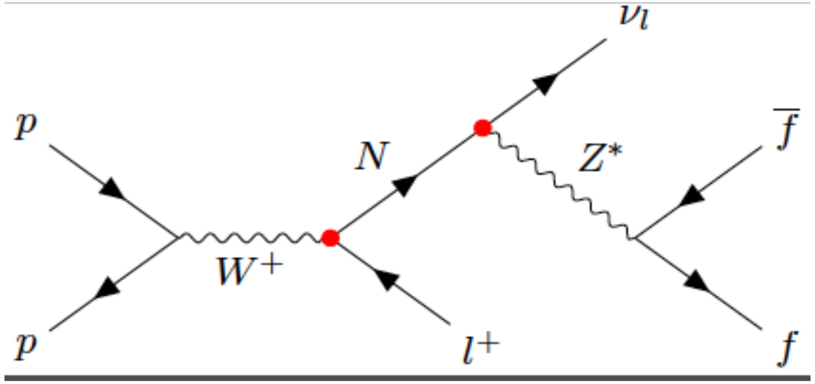
Workshop on LLP to 3rd generation

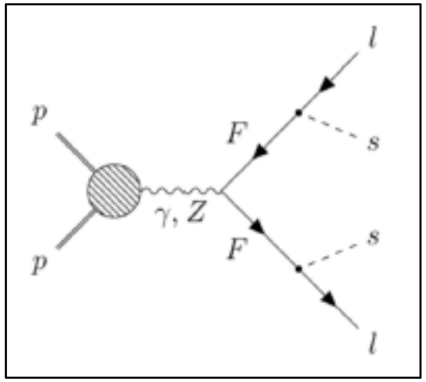
Aiming at a model independent search for LLP decaying to tau

Held a workshop at Higgs Centre for Theoretical Physics to identify benchmark theories to target:

https://indico.ph.ed.ac.uk/event/59/timetable/#20191120

Benchmarks include: Heavy neutral lepton, stau, FIMPs, Higgs to aa





Outlook

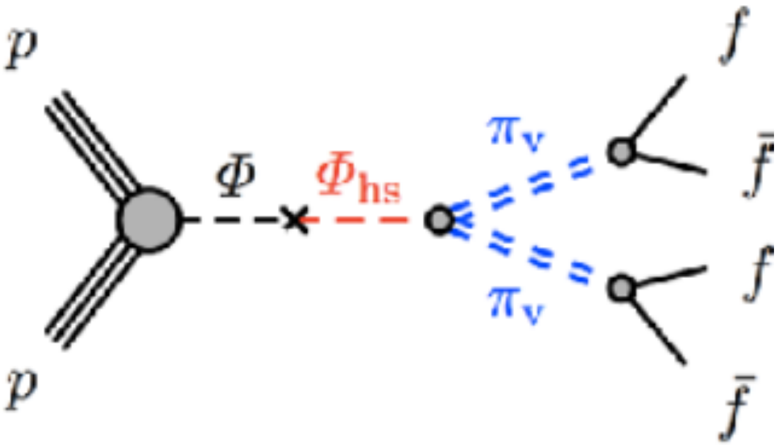
- Run 3 at the LHC and HL-LHC offer:
  - Possibly higher energy (13.5 TeV)
  - Higher luminosity, and luminosity levelling
  - New detector and software components
  - Allows smarter trigger decisions
    - Also an argument that as the doubling time lengthens, it is profitable to use the trigger bandwidth in novel ways
- Huge data rates combined with capacity to record and process them, provide us with an unprecedented opportunity to open up new phase-spaces
- With well-designed analyses, null searches are still valuable in constraining theories (and can be in perpetuity – factor out the detectors and be model-independent)
- History tells us to be prepared for surprises, and to be ready to find order in the chaos when surprises come along

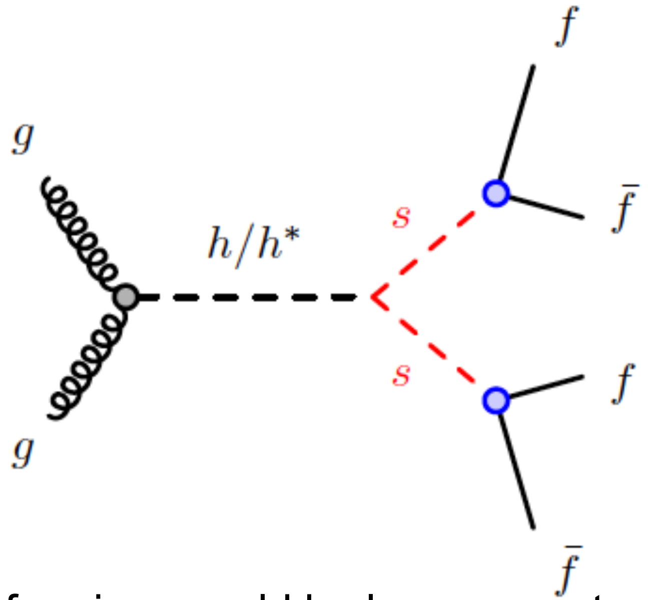
Extras

LLP Link to 125 GeV Higgs

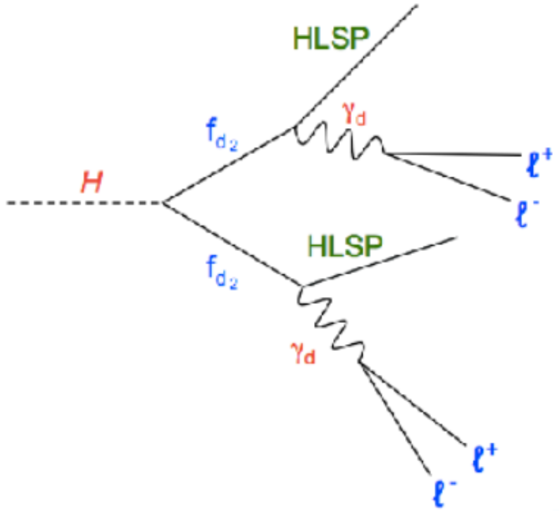
Phys.Lett. B651 (2007) 374(379); Phys.Lett. B661 (2008) 263(267)

- H(125) could mix with “dark sector Higgs”
- Or decay to long-lived scalars
- Or to dark fermions

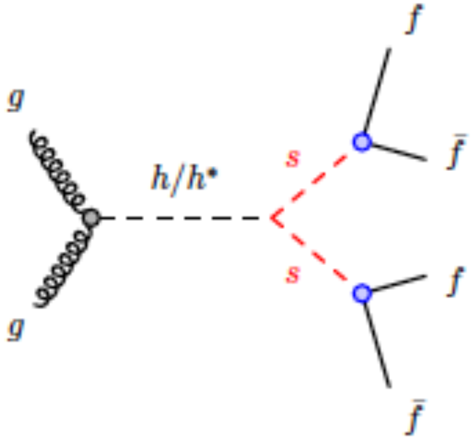


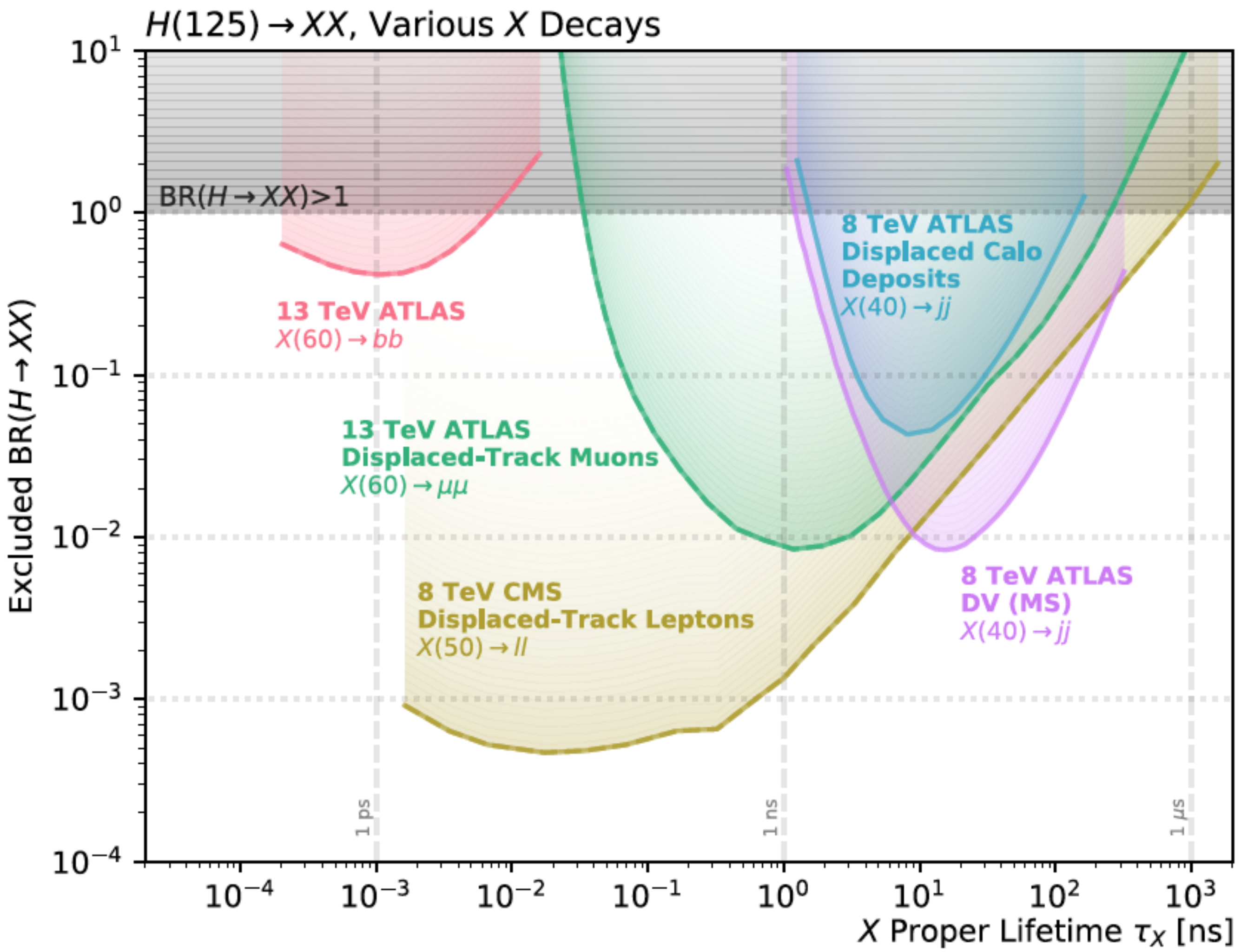


(the fermions could be low momentum and hard to trigger on.)



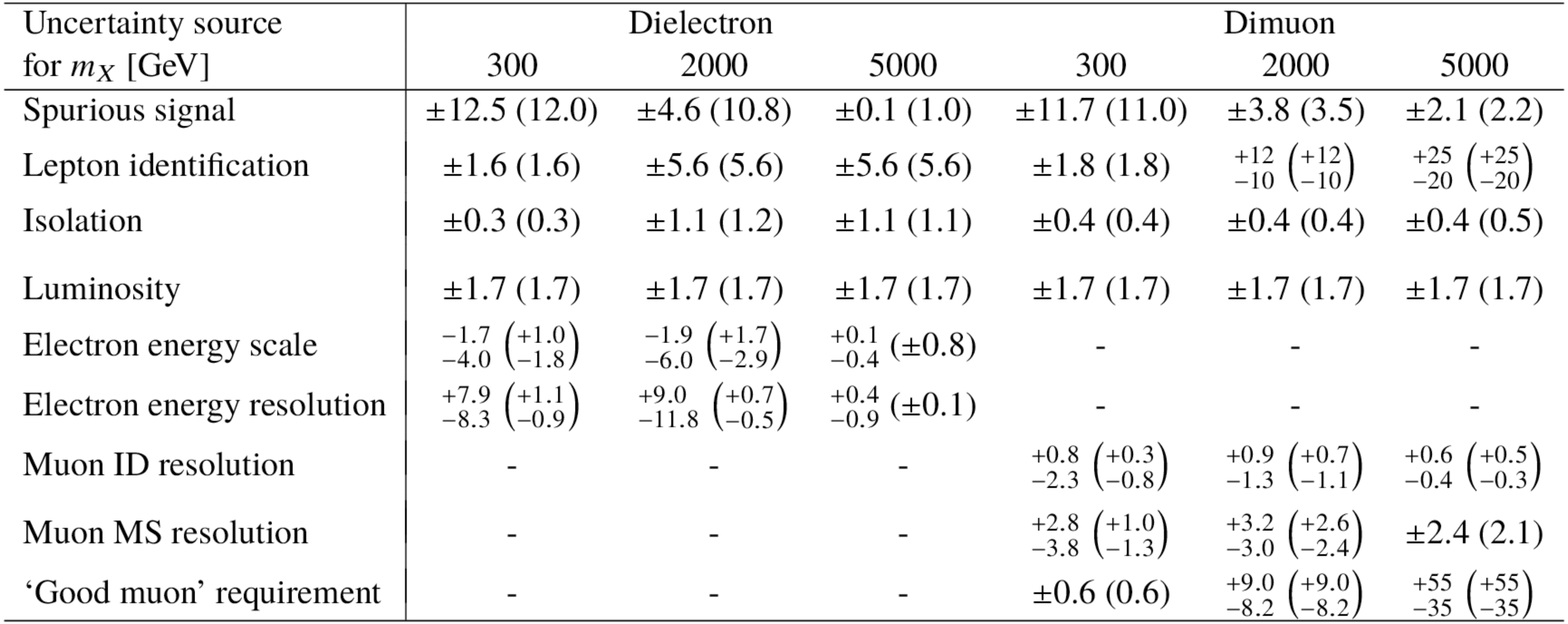
Current LHC Coverage: H to e/μ/j





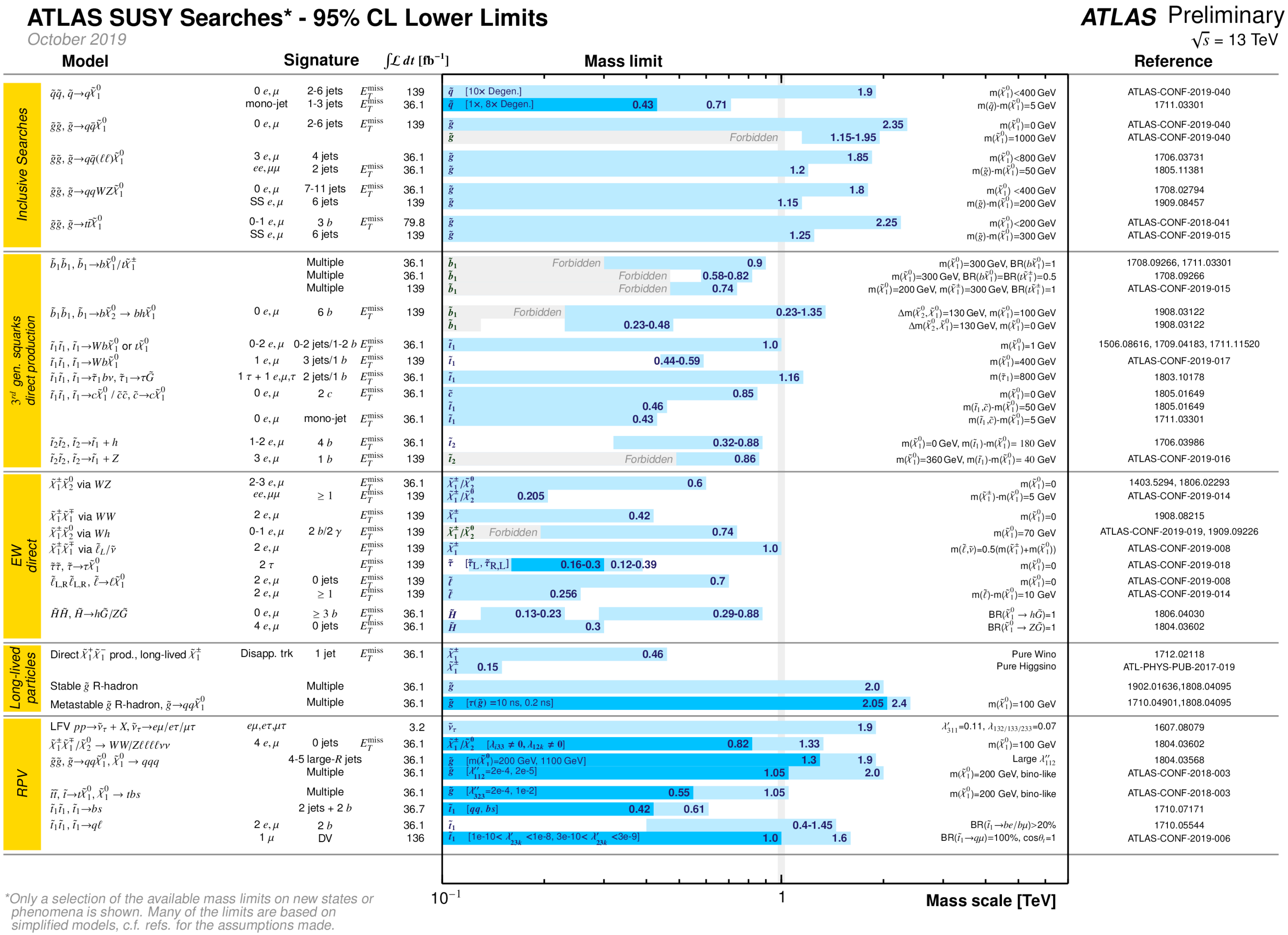
- Large areas of phase space are being ruled out at the LHC
- But small lifetimes are difficult for the LHC; large lifetimes capped by detector dimensions
- Work is ongoing to maximise the sensitivity across LHC experiments and beyond

Z’ searches



Uncertainty source for m_X [GeV]	Dielectron 300	Dielectron 2000	Dielectron 5000	Dimuon 300	Dimuon 2000	Dimuon 5000
Spurious signal	±12.5 (12.0)	±4.6 (10.8)	±0.1 (1.0)	±11.7 (11.0)	±3.8 (3.5)	±2.1 (2.2)
Lepton identification	±1.6 (1.6)	±5.6 (5.6)	±5.6 (5.6)	±1.8 (1.8)	$^{+12}_{-10}\left(^{+12}_{-10}\right)$	$^{+25}_{-20}\left(^{+25}_{-20}\right)$
Isolation	±0.3 (0.3)	±1.1 (1.2)	±1.1 (1.1)	±0.4 (0.4)	±0.4 (0.4)	±0.4 (0.5)
Luminosity	±1.7 (1.7)	±1.7 (1.7)	±1.7 (1.7)	±1.7 (1.7)	±1.7 (1.7)	±1.7 (1.7)
Electron energy scale	$^{-1.7}_{-4.0}\left(^{+1.0}_{-1.8}\right)$	$^{-1.9}_{-6.0}\left(^{+1.7}_{-2.9}\right)$	$^{+0.1}_{-0.4}$ (±0.8)	-	-	-
Electron energy resolution	$^{+7.9}_{-8.3}\left(^{+1.1}_{-0.9}\right)$	$^{+9.0}_{-11.8}\left(^{+0.7}_{-0.5}\right)$	$^{+0.4}_{-0.9}$ (±0.1)	-	-	-
Muon ID resolution	-	-	-	$^{+0.8}_{-2.3}\left(^{+0.3}_{-0.8}\right)$	$^{+0.9}_{-1.3}\left(^{+0.7}_{-1.1}\right)$	$^{+0.6}_{-0.4}\left(^{+0.5}_{-0.3}\right)$
Muon MS resolution	-	-	-	$^{+2.8}_{-3.8}\left(^{+1.0}_{-1.3}\right)$	$^{+3.2}_{-3.0}\left(^{+2.6}_{-2.4}\right)$	±2.4 (2.1)
‘Good muon’ requirement	-	-	-	±0.6 (0.6)	$^{+9.0}_{-8.2}\left(^{+9.0}_{-8.2}\right)$	$^{+55}_{-35}\left(^{+55}_{-35}\right)$

ATLAS SUSY reach (so far)



ATLAS SUSY Searches* - 95% CL Lower Limits

October 2019

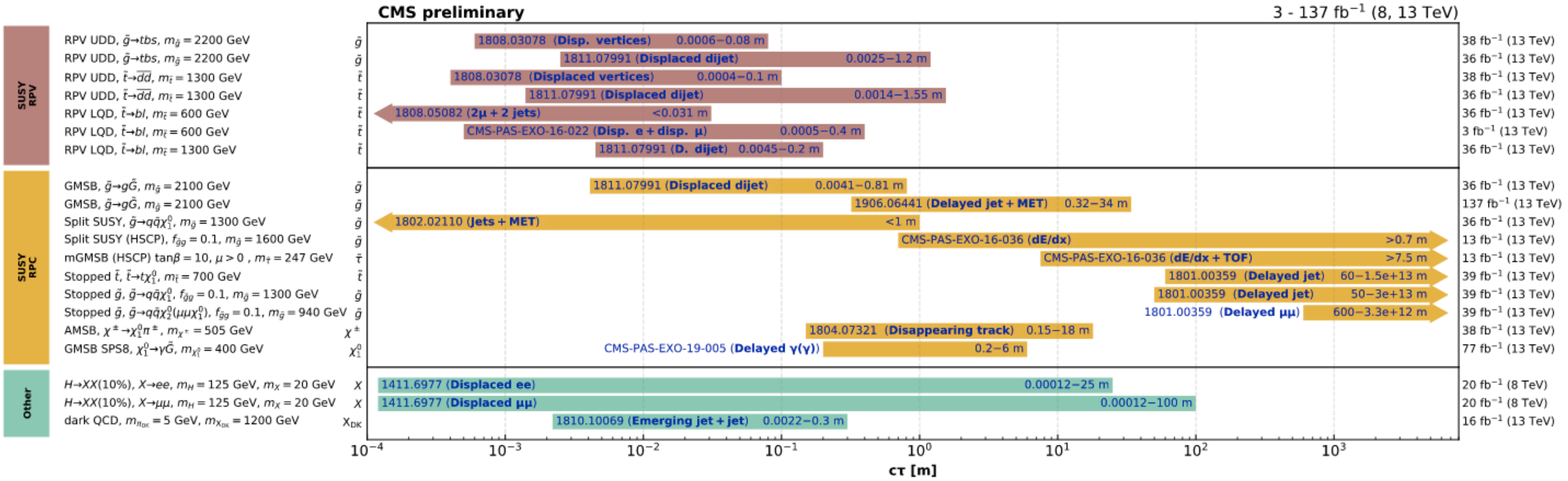
ATLAS Preliminary

$\sqrt{s}$ = 13 TeV

	Model	Signature			$\int \mathcal{L}\, dt$ [fb^{-1}]	Mass limit			Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	139	$\tilde{q}$	[10× Degen.] 1.9	m($\tilde{\chi}^0_1$)<400 GeV	ATLAS-CONF-2019-040
		mono-jet	1-3 jets	$E_T^{\rm miss}$	36.1	$\tilde{q}$	[1×, 8× Degen.] 0.43 0.71	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	139	$\tilde{g}$	2.35	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2019-040
						$\tilde{g}$	Forbidden 1.15-1.95	m($\tilde{\chi}^0_1$)=1000 GeV	ATLAS-CONF-2019-040
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	3 e,μ	4 jets		36.1	$\tilde{g}$	1.85	m($\tilde{\chi}^0_1$)<800 GeV	1706.03731
		$ee,\mu\mu$	2 jets	$E_T^{\rm miss}$	36.1	$\tilde{g}$	1.2	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}^0_1$	0 e,μ	7-11 jets	$E_T^{\rm miss}$	36.1	$\tilde{g}$	1.8	m($\tilde{\chi}^0_1$) <400 GeV	1708.02794
		SS e,μ	6 jets		139	$\tilde{g}$	1.15	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=200 GeV	1909.08457
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	$E_T^{\rm miss}$	79.8	$\tilde{g}$	2.25	m($\tilde{\chi}^0_1$)<200 GeV	ATLAS-CONF-2018-041
		SS e,μ	6 jets		139	$\tilde{g}$	1.25	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=300 GeV	ATLAS-CONF-2019-015
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_1/t\tilde{\chi}^\pm_1$		Multiple		36.1	$\tilde{b}_1$	Forbidden 0.9	m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$	Forbidden 0.58-0.82	m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=BR($t\tilde{\chi}^\pm_1$)=0.5	1708.09266
			Multiple		139	$\tilde{b}_1$	Forbidden 0.74	m($\tilde{\chi}^0_1$)=200 GeV, m($\tilde{\chi}^\pm_1$)=300 GeV, BR($t\tilde{\chi}^\pm_1$)=1	ATLAS-CONF-2019-015
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_2\to bh\tilde{\chi}^0_1$	0 e,μ	6 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$	Forbidden 0.23-1.35	Δm($\tilde{\chi}^0_2$,$\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=100 GeV	1908.03122
						$\tilde{b}_1$	0.23-0.48	Δm($\tilde{\chi}^0_2$,$\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=0 GeV	1908.03122
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	0-2 e,μ	0-2 jets/1-2 b	$E_T^{\rm miss}$	36.1	$\tilde{t}_1$	1.0	m($\tilde{\chi}^0_1$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$	1 e,μ	3 jets/1 b	$E_T^{\rm miss}$	139	$\tilde{t}_1$	0.44-0.59	m($\tilde{\chi}^0_1$)=400 GeV	ATLAS-CONF-2019-017
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\to\tau\tilde{G}$	1 τ + 1 e,μ,τ	2 jets/1 b	$E_T^{\rm miss}$	36.1	$\tilde{t}_1$	1.16	m($\tilde{\tau}_1$)=800 GeV	1803.10178
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}^0_1$	0 e,μ	2 c	$E_T^{\rm miss}$	36.1	$\tilde{c}$	0.85	m($\tilde{\chi}^0_1$)=0 GeV	1805.01649
						$\tilde{t}_1$	0.46	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.01649
		0 e,μ	mono-jet	$E_T^{\rm miss}$	36.1	$\tilde{t}_1$	0.43	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+h$	1-2 e,μ	4 b	$E_T^{\rm miss}$	36.1	$\tilde{t}_2$	0.32-0.88	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 180 GeV	1706.03986
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ	1 b	$E_T^{\rm miss}$	139	$\tilde{t}_2$	Forbidden 0.86	m($\tilde{\chi}^0_1$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 40 GeV	ATLAS-CONF-2019-016
EW direct	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via WZ	2-3 e,μ		$E_T^{\rm miss}$	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	0.6	m($\tilde{\chi}^0_1$)=0	1403.5294, 1806.02293
		$ee,\mu\mu$	≥ 1	$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	0.205	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV	ATLAS-CONF-2019-014
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via WW	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1$	0.42	m($\tilde{\chi}^0_1$)=0	1908.08215
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via Wh	0-1 e,μ	2 b/2 γ	$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	Forbidden 0.74	m($\tilde{\chi}^0_1$)=70 GeV	ATLAS-CONF-2019-019, 1909.09226
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1$	1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2019-008
	$\tilde{\tau}\tilde{\tau}$, $\tilde{\tau}\to\tau\tilde{\chi}^0_1$	2 τ		$E_T^{\rm miss}$	139	$\tilde{\tau}$	[$\tilde{\tau}_{\rm L}$, $\tilde{\tau}_{\rm R,L}$] 0.16-0.3 0.12-0.39	m($\tilde{\chi}^0_1$)=0	ATLAS-CONF-2019-018
	$\tilde{\ell}_{\rm L,R}\tilde{\ell}_{\rm L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{\ell}$	0.7	m($\tilde{\chi}^0_1$)=0	ATLAS-CONF-2019-008
		2 e,μ	≥ 1	$E_T^{\rm miss}$	139	$\tilde{\ell}$	0.256	m($\tilde{\ell}$)-m($\tilde{\chi}^0_1$)=10 GeV	ATLAS-CONF-2019-014
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	$\geq 3\ b$	$E_T^{\rm miss}$	36.1	$\tilde{H}$	0.13-0.23 0.29-0.88	BR($\tilde{\chi}^0_1\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	$E_T^{\rm miss}$	36.1	$\tilde{H}$	0.3	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	$E_T^{\rm miss}$	36.1	$\tilde{\chi}^\pm_1$	0.46	Pure Wino	1712.02118
						$\tilde{\chi}^\pm_1$	0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron		Multiple		36.1	$\tilde{g}$	2.0		1902.01636,1808.04095
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$		Multiple		36.1	$\tilde{g}$	[$\tau(\tilde{g})$ =10 ns, 0.2 ns] 2.05 2.4	m($\tilde{\chi}^0_1$)=100 GeV	1710.04901,1808.04095
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$			3.2	$\tilde{\nu}_\tau$	1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	$E_T^{\rm miss}$	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	[$\lambda_{i33}\neq 0$, $\lambda_{12k}\neq 0$] 0.82 1.33	m($\tilde{\chi}^0_1$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$		4-5 large-R jets		36.1	$\tilde{g}$	[m($\tilde{\chi}^0_1$)=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$	[λ''_{112}=2e-4, 2e-5] 1.05 2.0	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to tbs$		Multiple		36.1	$\tilde{g}$	[λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$	[qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$	0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$	[1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9] 1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	ATLAS-CONF-2019-006

*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.

Current Coverage (CMS)

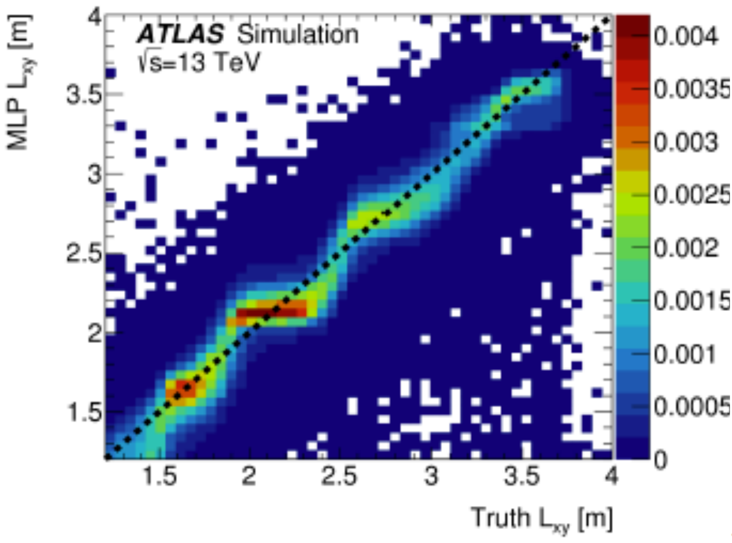


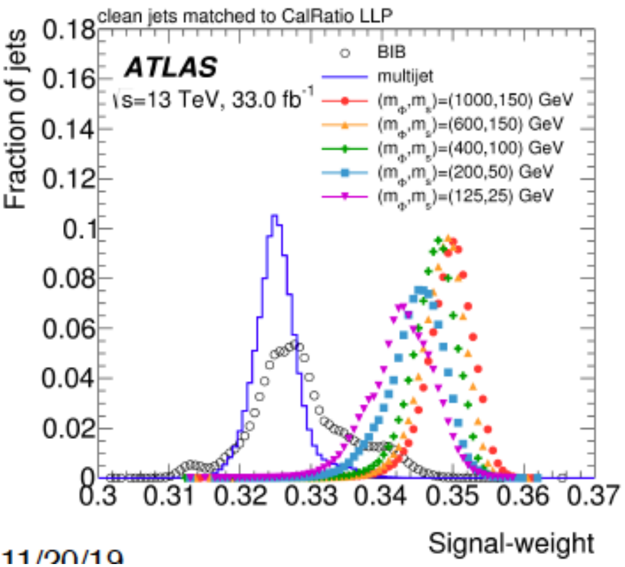
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

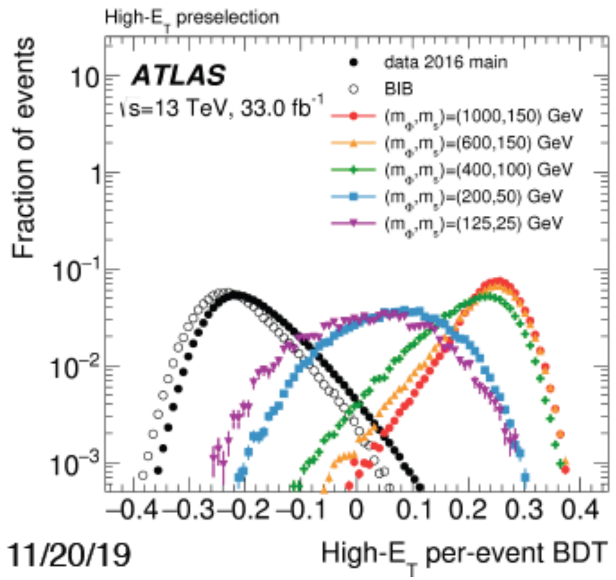
July 2019

Displaced Jets (Low EM Fraction)

- Multi layer perceptron trained to estimate LLP decay position





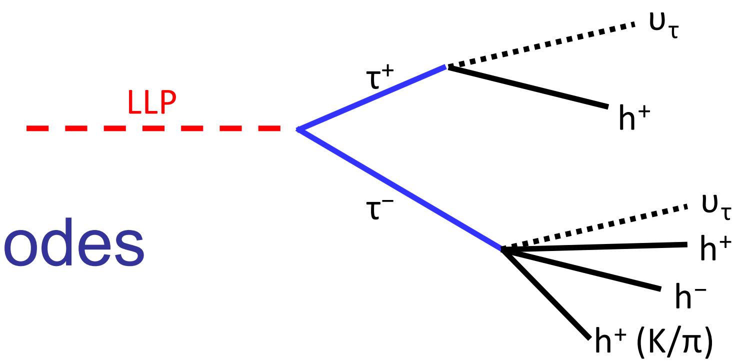


- Per-jet BDT (classify among QCD/signal, beam induced background)
- Per-event BDT (eliminate beam induced background)
- ABCD method to calculate remaining QCD background

S. Farrington, University of Edinburgh

Tau Trigger

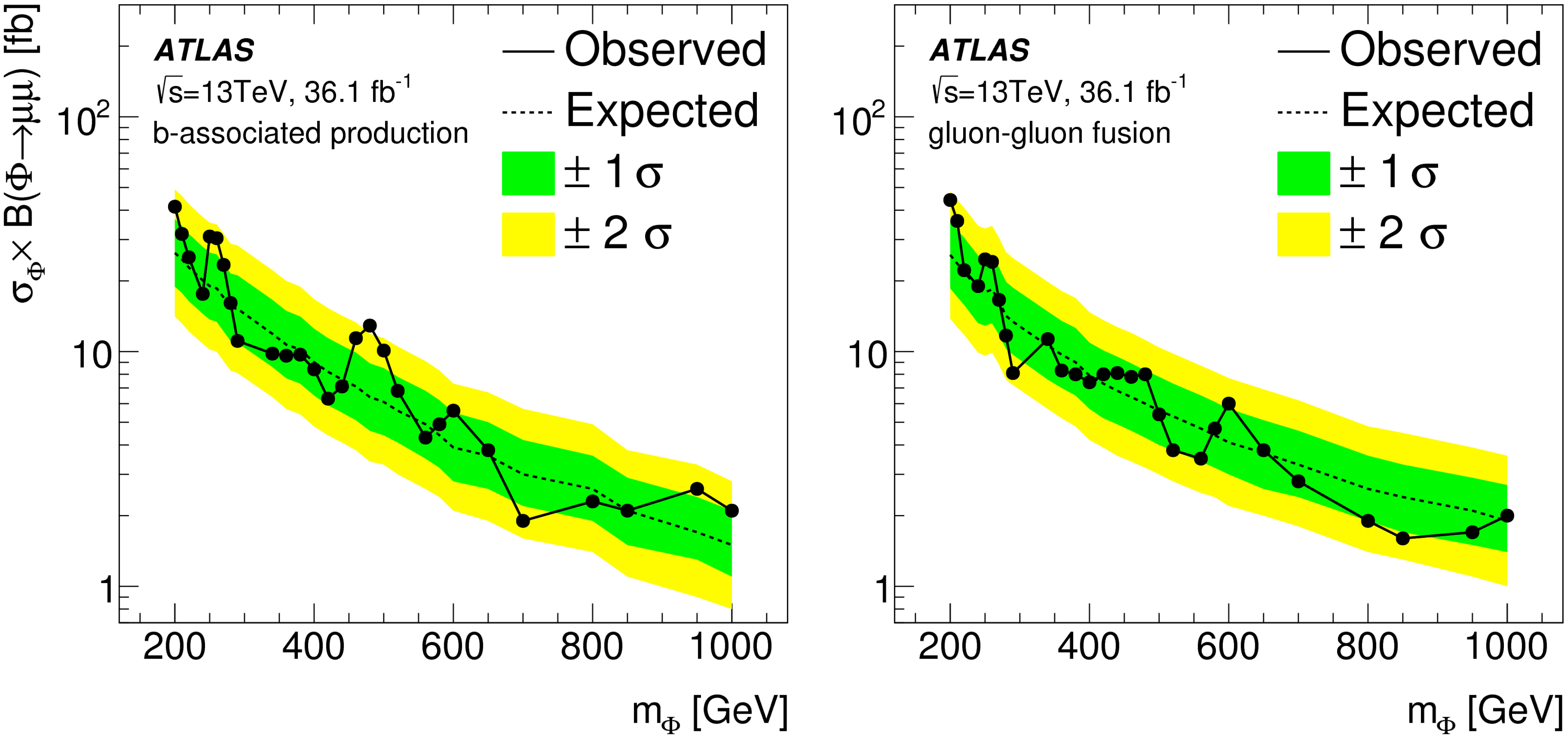
To maximise the sensitivity to LLP decays to third generation need to use fully hadronic decay modes



- Trigger currently allows only up to $|d_0| < 2$ (then 4 later in run 2) mm
  - Train MVA trigger for long-lived taus

Combine new τ_h trigger and ID

Scalar + b



S. Farrington, University of Edinburgh