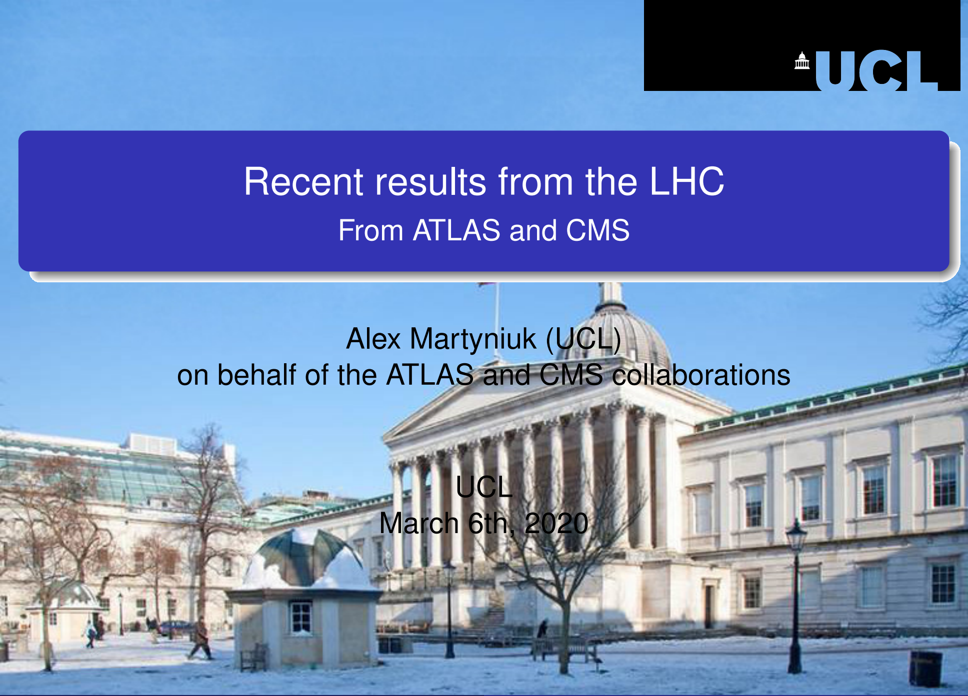
Recent results from the LHC

From ATLAS and CMS

Alex Martyniuk (UCL)
on behalf of the ATLAS and CMS collaborations

Lake Louise Winter Institute
March 6th, 2020



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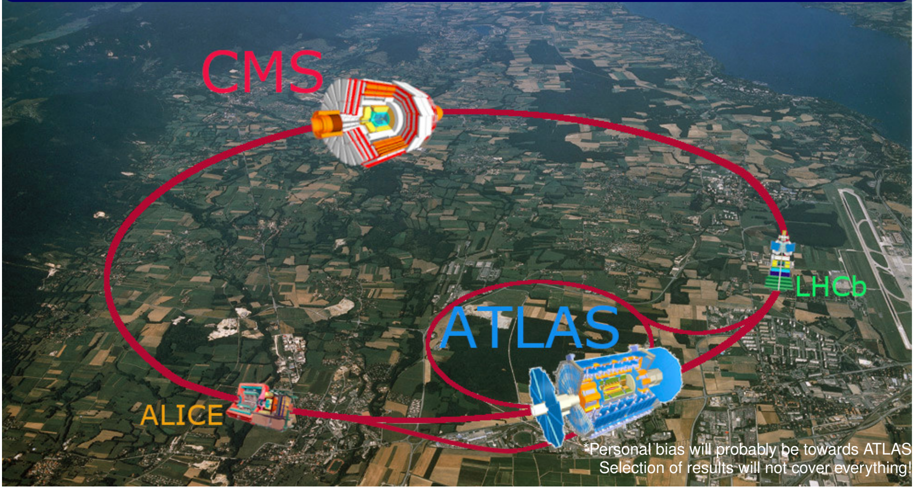
Not To Scale Birds Eye View

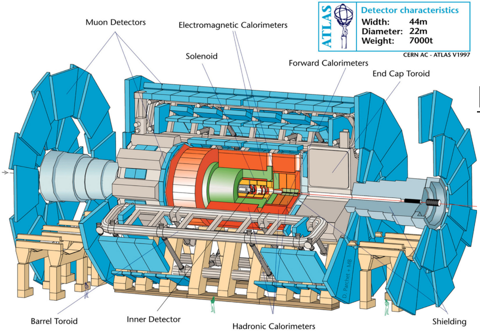
The General Purpose Detectors

- This talk will focus on the results from ATLAS* and CMS



*Personal bias will probably be towards ATLAS
Selection of results will not cover everything!

The General Purpose Detectors

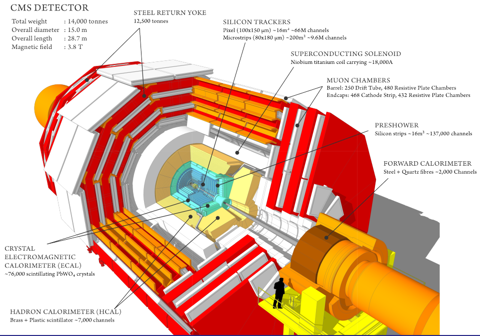


Similarities

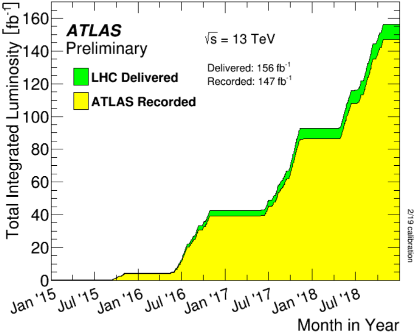
- **Cylindrical** detectors: barrel & end-caps
- **Concentric** detectors: Tracking, EM→had-calorimetry, muon chambers
- Close to 4π solid angle coverage
- Hardware/software **combined** trigger systems

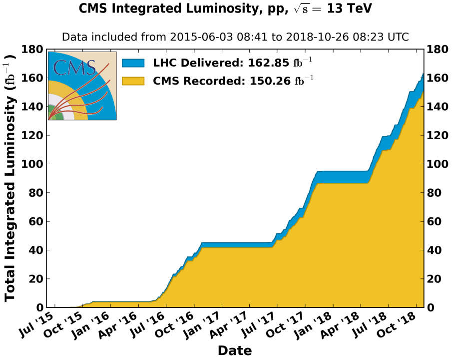
Differences

- Detector **technology** choices
- *B*-field **configuration**: Solenoid vs Solenoid+Toroid
- **Size/weight** (though both are colossal!)



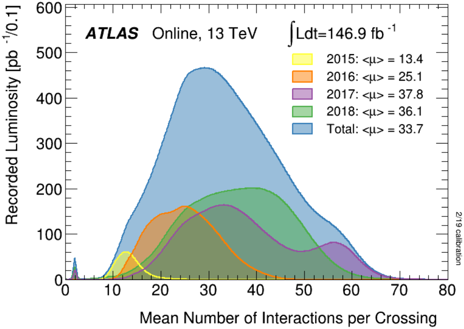
Run 2 Summary: Integrated Luminosity

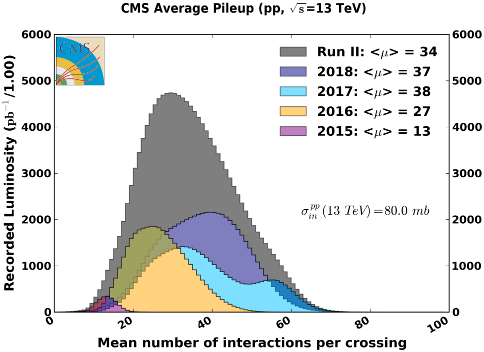




- The LHC had an **excellent** Run 2, delivering $\approx$ 160 fb^{-1} to both experiments!
- Both experiments recorded data with **superb** overall Run 2 data taking efficiency: ATLAS 94.2%, CMS 92.3%
  - This was achieved despite **challenging** pile-up conditions with $< \mu >$ 35: i.e. on average 35 **simultaneous** $p - p$ collisions per bunch crossing!
- The LHC is very **versatile** machine, delivering in **special** runs throughout Run 2: $Pb - Pb$, $p - Pb$, $Xe - Xe$ and low pileup $p - p$ data to both experiments

Run 2 Summary: Pileup





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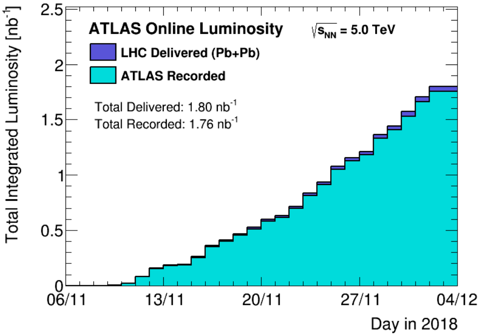
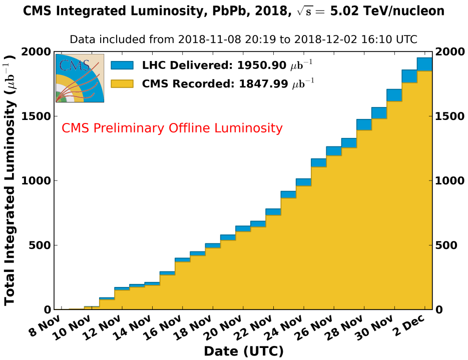
Run 2 Summary: Versatility





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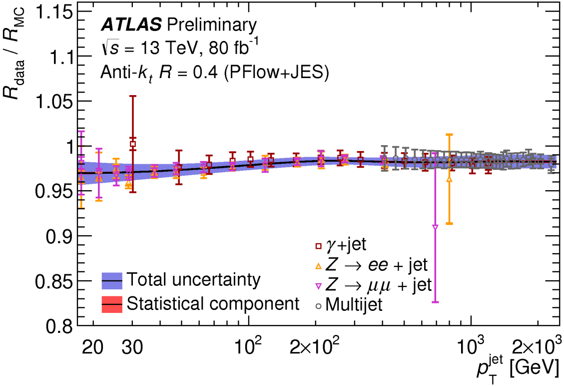
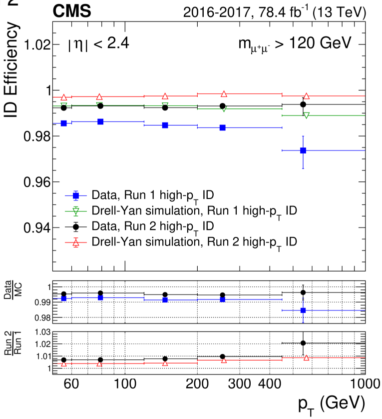
Reconstruction and Calibration

- **Both** experiments have **excellent** reconstruction and calibration performance, even in the **harsh** pileup conditions of Run 2
- **Continuous** improvements seen in the calibrations, understandings of efficiencies, systematic uncertainties etc. over a **wide** p_{T} range
  - A **better** understanding of the detectors along with **data-driven** and **machine learning** techniques mean that object calibrations and efficiencies are often now **better** even in the harsher environment of Run 2

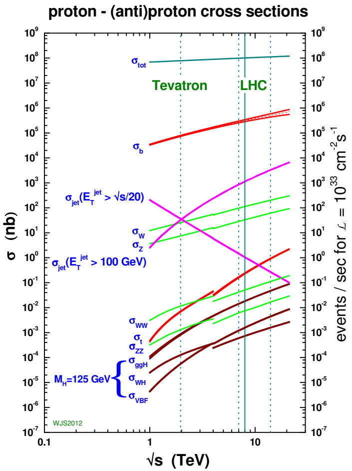




What is in this data?

- The LHC is an **EVERYTHING** factory (with additional background collisions)
  - Assuming 140 fb^{-1} at $\sqrt{s} = 13$ TeV both detectors have seen...

Particle	# produced
H boson	≈ 8 million
t quark	≈ 280million
Z boson	≈ 8 billion
W boson	≈ 26 billion
b quark	≈ 160 trillion



- These datasets give both experiments **broad** physics programme potential
  - **High-precision** SM measurements, including Higgs properties
  - Detection of extremely **rare** processes
  - Exploration of **new** kinematic regimes for potential **new physics** signals!

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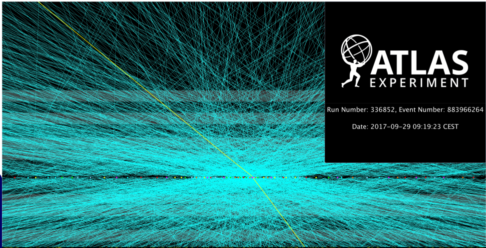

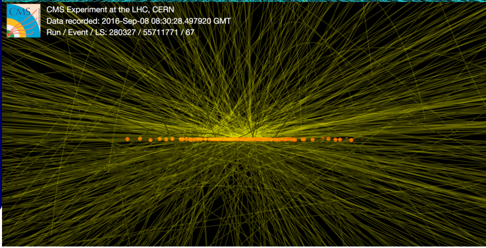

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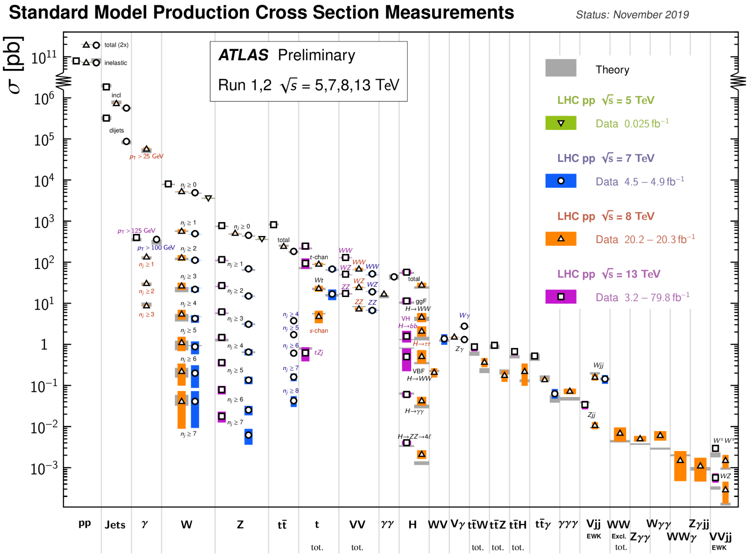
The Standard Model

Image from Symmetry Magazine

Remarkable agreement



Standard Model Production Cross Section Measurements

Status: November 2019

The amazing **predictive** power of the Standard Model is **confirmed** by both experiments (CMS versions)

Agreement spans over **14 orders of magnitude**, with measurements/evidence of diverse and extremely rare SM processes

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Improvements in theoretical calculations to NNLO level **complement** these results

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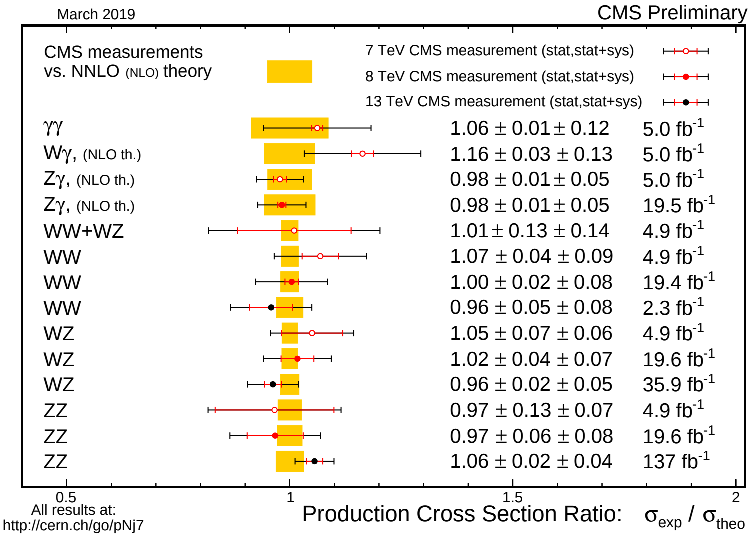

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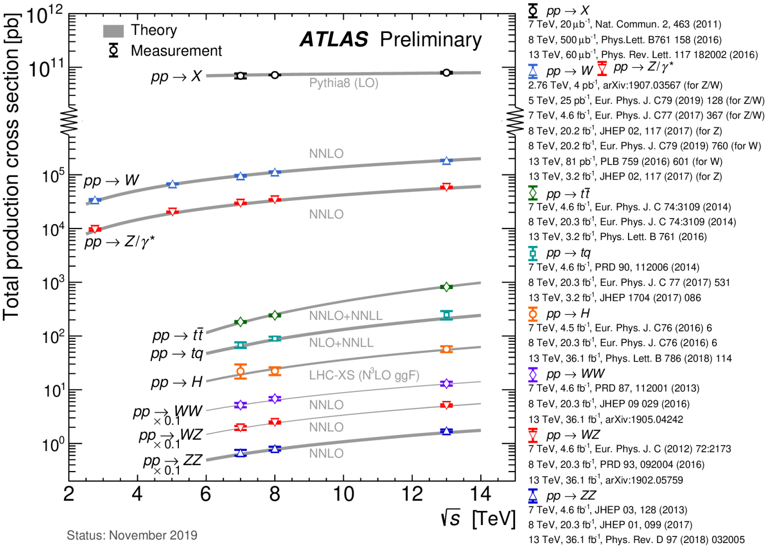

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Improvements in theoretical calculations to NNLO level **complement** these results

Let’s focus first on the new kid...

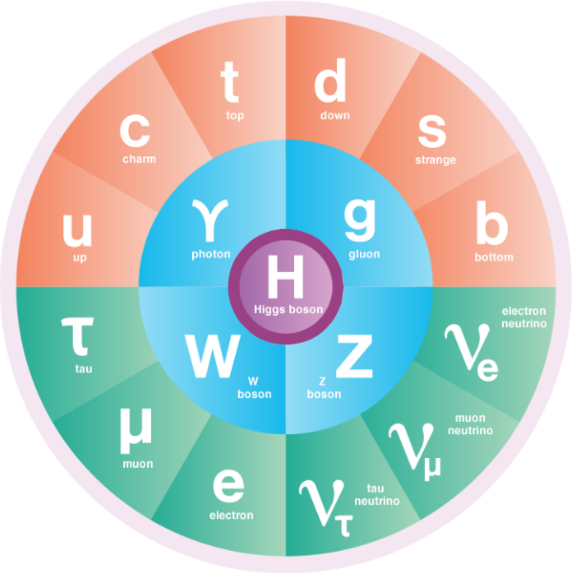


Image from Symmetry Magazine

The Higgs boson

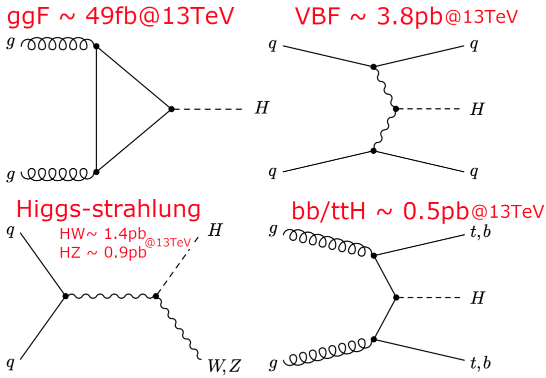
- The **discovery** of the Higgs boson ($m_H = 125.10$ GeV) in 2012 by ATLAS and CMS **together** fulfilled one of the **main aims** of the LHC: Identifying a **mass generation** mechanism for the SM
- Its discovery showed us that some form of the **Brout-Englert-Higgs*** mechanism is **realised** in nature!
- It has given us **access** to a new sector of the **SM Lagrangian** with new lines of enquiry to follow:
  - **Yukawa couplings**, a new type of interaction to investigate
  - Gauge–scalar boson **interactions**
  - The **parameters** of the Higgs potential, and its self coupling

*Please insert your own preferred naming convention for the mechanism

The Higgs Production/Decay

- In **Run 1** ATLAS and CMS observed the *gg* fusion and VBF production modes
- In **Run 2** we now have observed the Higgs-strahlung and *ttH* productions modes!

- The **discovery** channels ($\gamma\gamma$, ZZ, WW) **dominated** Run 1 results
- In Run 2 both experiments are **digging** into the more **challenging** decay modes


ggF ~ 49fb@13TeV

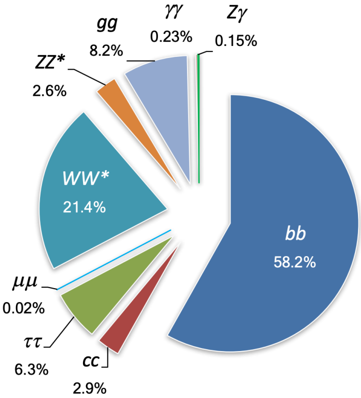
VBF ~ 3.8pb@13TeV

Higgs-strahlung

HW~ 1.4pb@13TeV

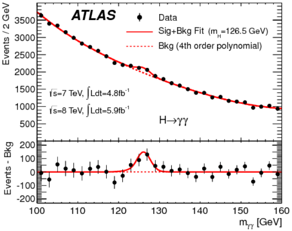
HZ ~ 0.9pb

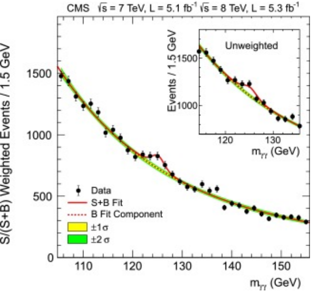
bb/ttH ~ 0.5pb@13TeV



Higgs Progress: Discovery→Measurement

Run 1: ATLAS & CMS

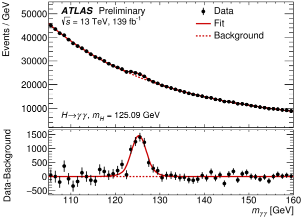


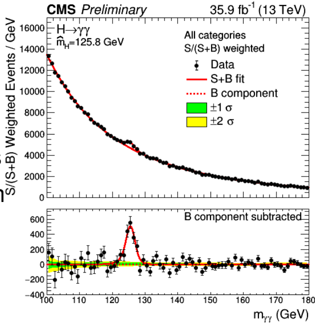


$$H \to \gamma\gamma$$

- **Significant** progress has been made in the discovery channels since 2012
- We have collected **thousands** of Higgs bosons candidate events with which to perform **differential** measurements
- Can really start to dig down into the **properties** and **couplings** of this new scalar boson

Run 2: ATLAS & CMS





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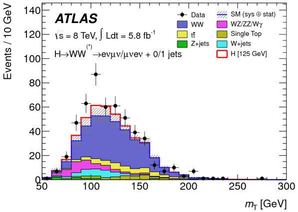

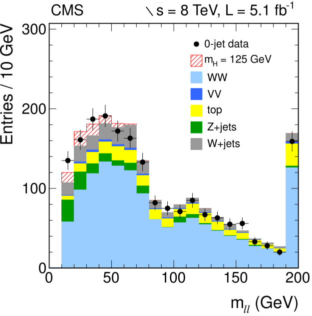

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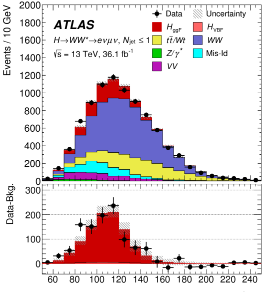

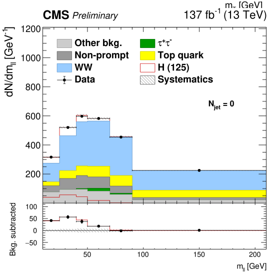

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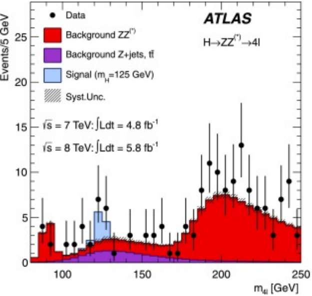

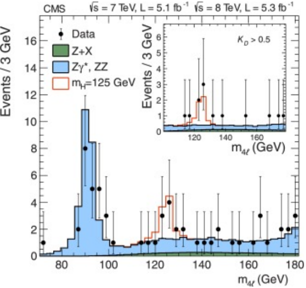

$H \rightarrow ZZ$

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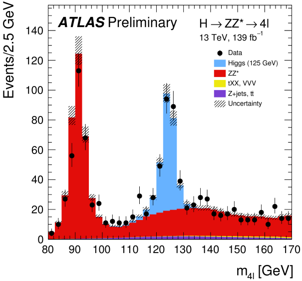
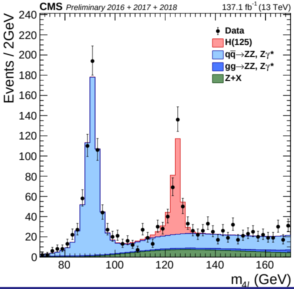
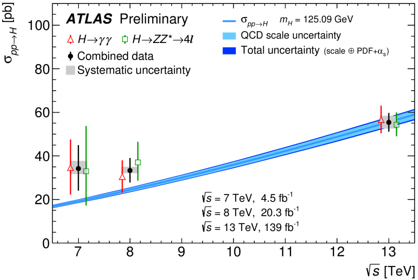


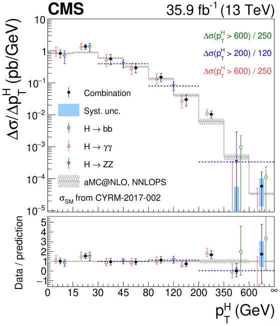


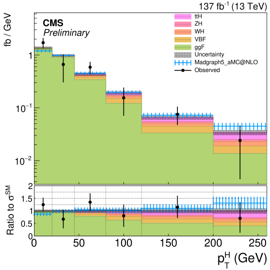
Differential Higgs Measurements

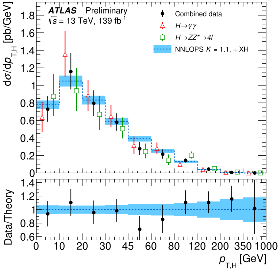
ATLAS-CONF-2019-029 & ATLAS-CONF-2019-032 &
HIG-17-028 & HIG-19-002

- Statistical **combinations** of the large Higgs samples allows both experiments to provide **total** and **differential** cross-section results
- **Deviations** from the SM expectations in these measurements and in Higgs couplings **could** point us towards new physics
  - Could be subtle, → needs high precision









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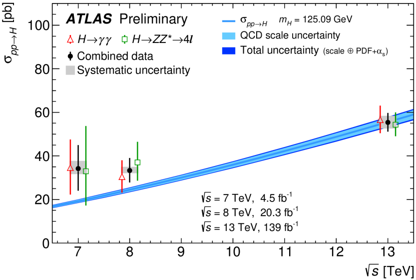
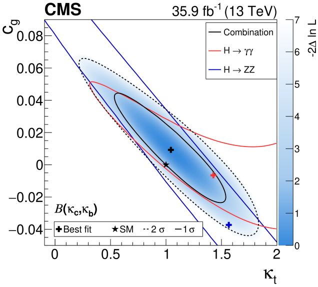
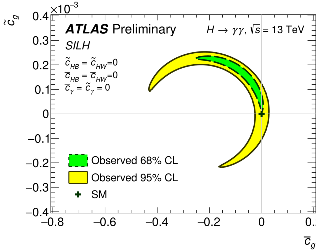
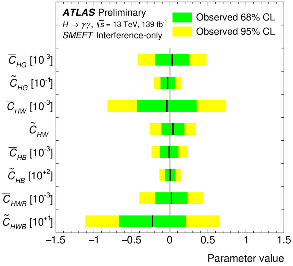




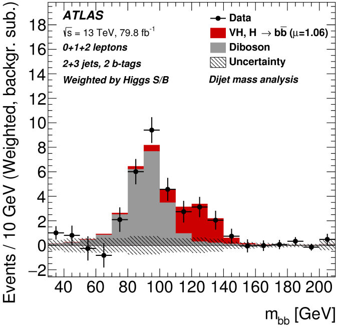


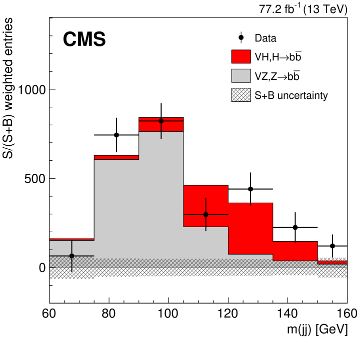


Two for one: $pp \rightarrow VH \rightarrow bb$

HIGG-2018-04 & HIG-18-016

- **Observation** of the Higgs production/decay $pp \rightarrow VH \rightarrow bb$ **directly** confirms both the low cross section **Higgs-strahlung** production mode and the abundant $H \rightarrow bb$ **decay** mode
- Made possible by triggering on **"clean"** leptonic V decays to reduce the **multi-jet** background
- An **incredible** achievement as the $H \rightarrow bb$ decay channel was considered by some a **lost cause** at a hadron collider



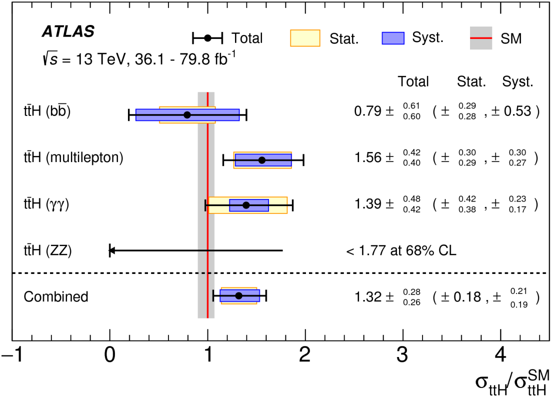


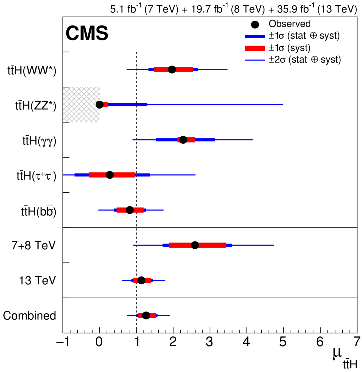
- Combined Run 1+2 $H \rightarrow bb$ significances
  –ATLAS–
  $5.4(5.5)\sigma$
  –CMS–
  $4.8(4.9)\sigma$
- Both agree with the SM signal strength

The rarest production mode: $t\bar{t}H$

HIGG-2018-13 & HIG-17-035

- **Combinations** of decay modes from both experiments have previously **confirmed** the presence of the $pp \rightarrow t\bar{t}H$ production channel at, ATLAS: 6.3(5.1)σ, CMS: 5.2(4.2)σ
- A **superb** confirmation of a **rare** Higgs production mode, confirming the **tree level coupling** of top quarks to the Higgs





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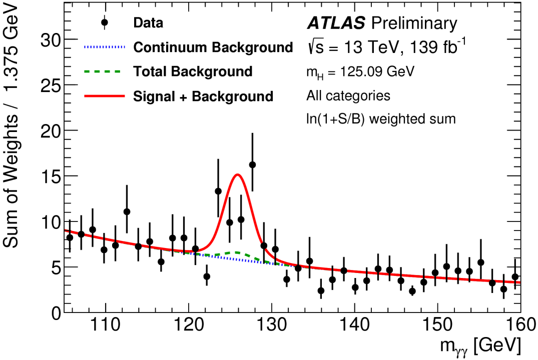
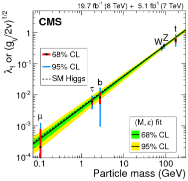


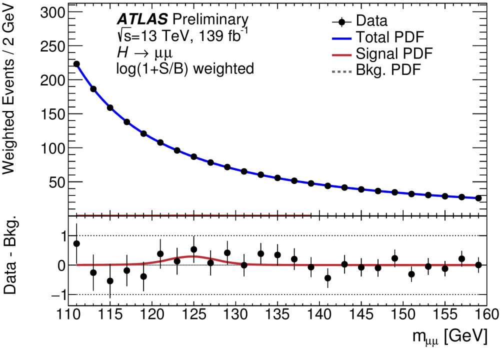
- ATLAS has now followed up with a **single channel** ($H \to \gamma\gamma$) observation of the $t\bar{t}H$ process at a significance of 4.9σ
- An **exceptionally** rare process with a measured, $\sigma_{t\bar{t}H} \times \mathcal{B}_{H\to\gamma\gamma} = 1.59^{+0.43}_{-0.39}$ fb

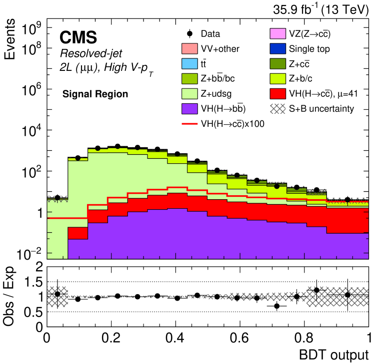
The Rarer Decay Modes: 2^{nd} Gen.

ATLAS-CONF-2019-028 & HIG-18-031

- ATLAS and CMS are digging down toward the **rare** second generation Higgs decay modes
- Using **multivariate** techniques and new reconstruction techniques
- **Nothing** is seen (or expected to be) seen yet, but these modes are starting their **journeys** now ready for Run 3/4
  - ATLAS $H \to \mu\mu$: $\mu = 1.7$ & CMS $H \to cc$: $\mu = 70$@ 95%CL



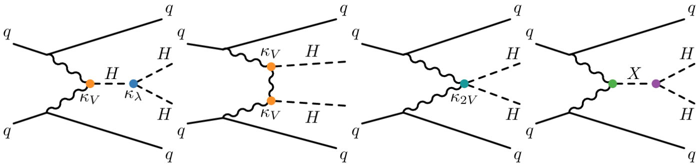


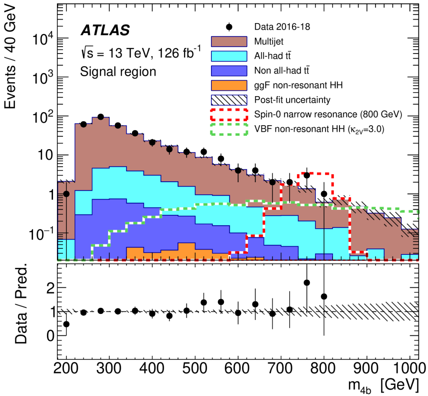


The "Future": Di-Higgs production

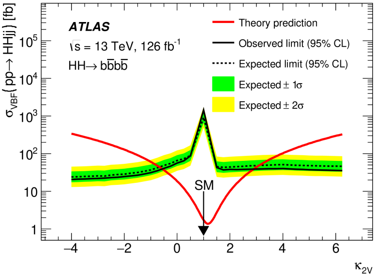
HDBS-2018-18 & HDBS-18-33 & ATLAS-CONF-2019-049 & HIG-17-030 & HIG-18-013

- *HH* production can be searched for through **VBF** production modes





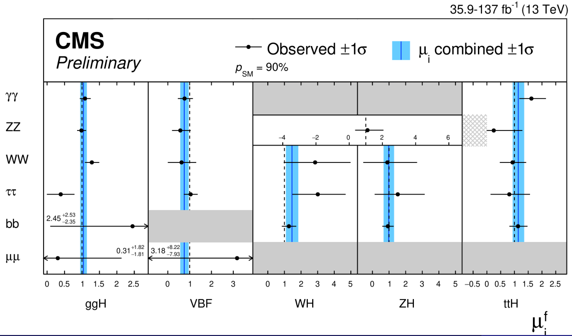
- Can be used to explore the Higgs **self coupling** λ, probing the **Higgs potential**
- Also useful to search for new **heavy resonances**

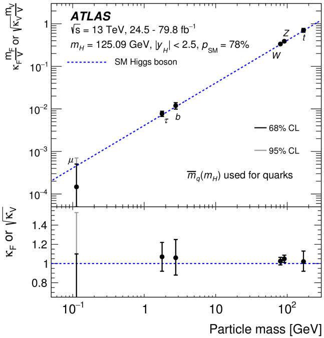


Run 2 Higgs Overview

HIGG-2018-57 & HIG-19-005

- The ATLAS and CMS Higgs programs are **switching** from discovery to measurements **quickly**
- Will be able to **compare** the results to the SM expectations with greater and greater **precision**
- The Higgs sector touches upon many **questions**: naturalness, vacuum stability, flavour...
- We will be **poking** this field for a long time to come





The Electroweak sector segue

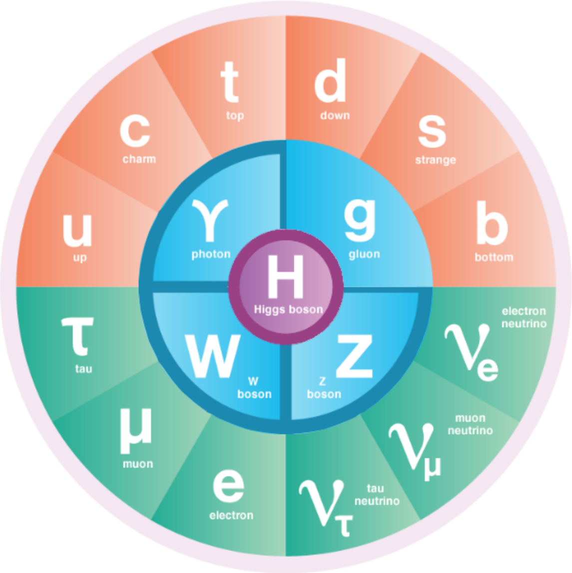
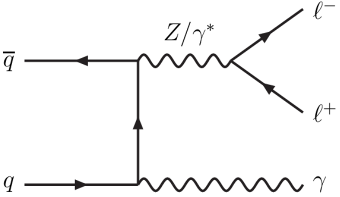


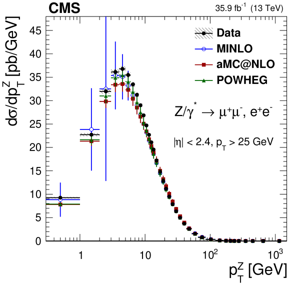
Image from Symmetry Magazine

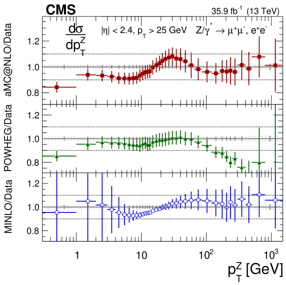
High-statistics probes: $Z\gamma$ cross section

ATLAS:1911.04813 CMS:1909.0413

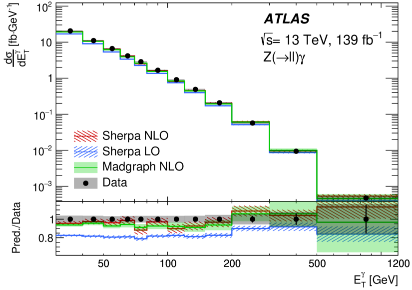


NB: FSR & q/g contributions suppressed





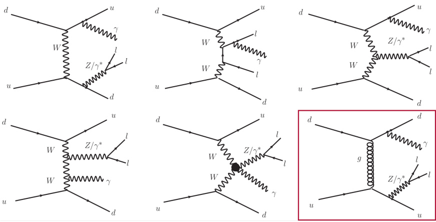
- **High** precision (at percent level) measurements of **differential** $Z\gamma$ cross-sections from **both** experiments
- In general **good** agreement seen with **NLO/NNLO** predictions
- Provides **high-statistics** probes of the electroweak gauge sector for the community to use

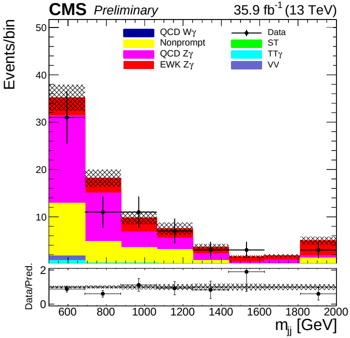


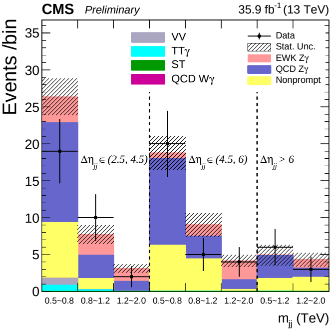
Rare processes: EW VBS $Z\gamma jj$

SMP-18-007 (ATLAS: arXiv:1910.09503)

- **Evidence** of the electroweak vector-boson scattering process $pp \to Z\gamma jj$ **directly** probes the EWK SM gauge structure
- Selection **reduces** contribution from strong production
- Signal **extracted** from 2D fit to m_{jj} and $\Delta\eta_{jj}$



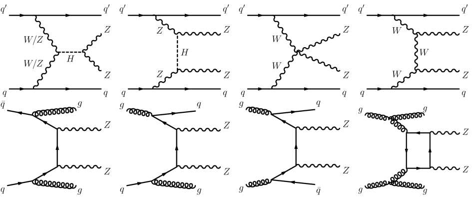




- Obs (exp) significance at 3.9 (5.2)σ with a cross-section of 3.20 ± 1.15 fb^{-1}
- Additionally, places **stringent** limits on anomalous quartic gauge couplings

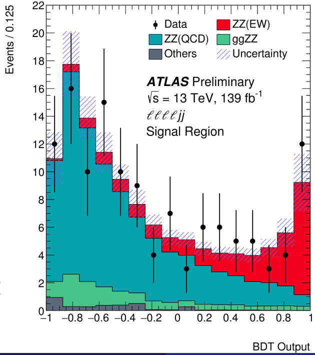
Rare Processes: EW VBS *ZZjj*

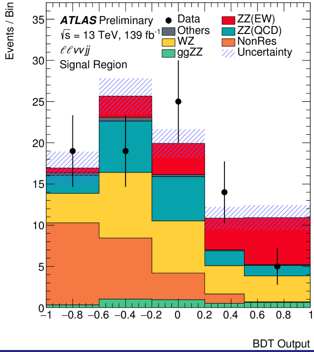
ATLAS-CONF-2019-033



- **Observation** of the electroweak vector-boson scattering process $pp \to ZZjj$ is a milestone in observing one of the **rarest processes** of the EW sector
- Selected from other QCD/EW diboson processes by a **Boosted Decision Tree**

- Observed at 5.5σ with a cross-section of 0.82 fb
    - One of the **rarest** SM process observed so far at the LHC
- CMS has plans (FTR-18-014) to measure the **longitudinal** component with 3 ab^{-1}

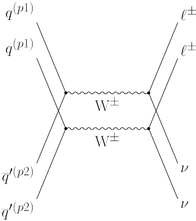


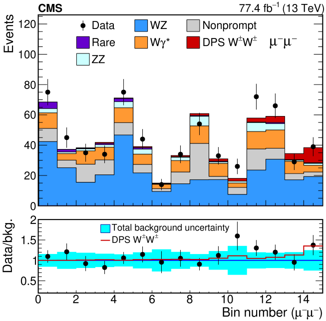


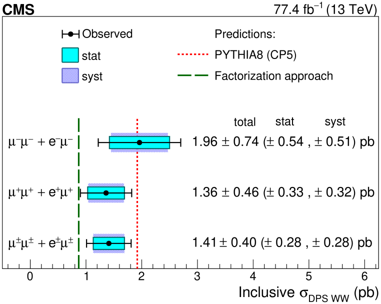
Double Parton Scattering: *WW*

arXiv:1909.06265

- **Evidence** of double parton scattering in the *pp* → $W^{\pm}W^{\pm}$ channel is a **first** for DPS at the LHC
  - Could become a background to new physics with longitudinal correlations at HL-LHC, as well as other diboson processes
- **Multivariate** classifiers used to **discriminate** DPS events from other diboson backgrounds
- **Evidence** at 3.9σ with a cross-section of 1.41 pb^{-1}







The Fermions

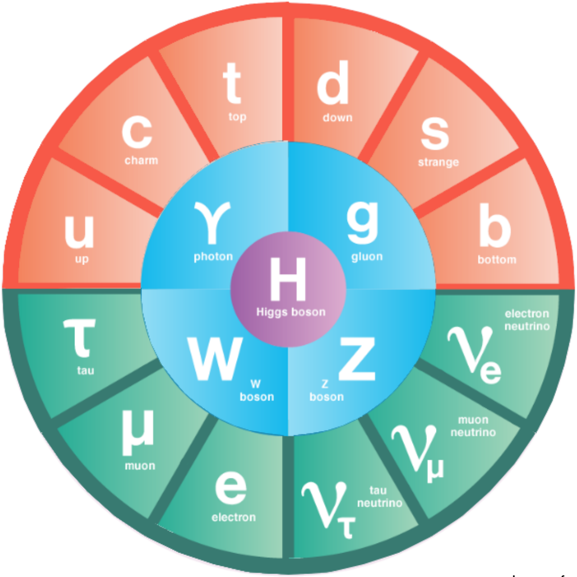
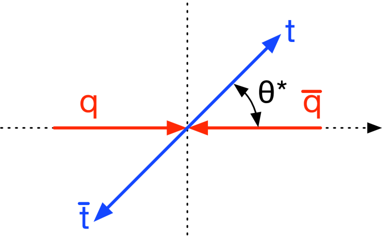


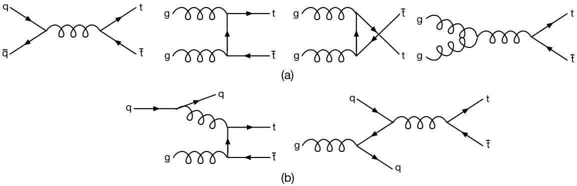
Image from Symmetry Magazine

$t\bar{t}$ Forward/Backward Asymmetry

TOP-15-018

- Top quarks are **predominantly** produced in pairs in the SM
- **Anomalous** production modes can be searched for by studying the the **angular** distribution of the produced $t\bar{t}$ pairs





- I.e. these anomalies would **impact**,

$$c^* = \cos\theta^*$$

- This can be **quantified** by using the forward/backwards asymmetry,

$$A_{FB} = \frac{\sigma(c^*>0)-\sigma(c^*<0)}{\sigma(c^*>0)+\sigma(c^*<0)} \; (A_{FB}^{SM} = 0.095)$$

  - Trickier than at the Tevatron as *gg* fusion production is dominant at the LHC which produces no A_{FB}, need to extract $q\bar{q}$ contribution

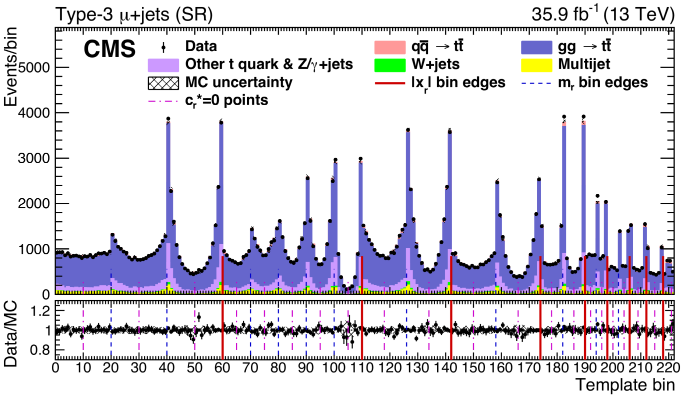
- Can also measure the anomalous **chromoelectric** ($\hat{d}_t$) and **chromomagnetic** ($\hat{\mu}_t$) dipole moments ($\hat{d}_t^{SM} = \hat{\mu}_t^{SM} = 0$)

$t\bar{t}$ Forward/Backward Asymmetry

TOP-15-018

- Record **differential** cross sections in a series of channels **defined** by decay topology, lepton charge and flavour
- A linear **combination** of 3D MC templates is fitted to this data to **independently** extract

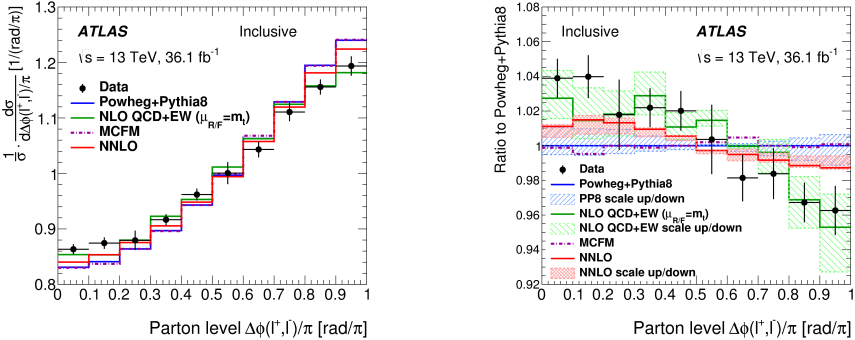
- $A_{FB}^{(1)} = 0.048^{+0.095}_{-0.087}(\mathrm{stat})^{+0.020}_{-0.029}(\mathrm{syst})$
- $\hat{\mu}_t = -0.024^{+0.013}_{-0.009}(\mathrm{stat})^{+0.016}_{-0.011}(\mathrm{syst})$
- $|\hat{d}_t| < 0.03$ 95% CL



Top Spin Correlations

TOPQ-2016-10 (TOP-18-006)

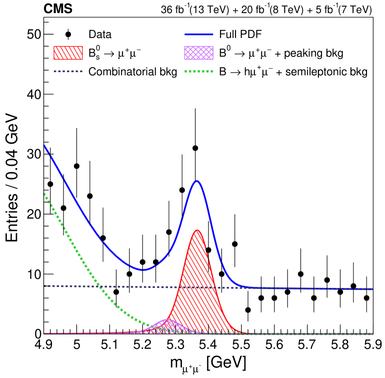
- Top quarks decay **before** their spins can be flipped by the strong interaction, passing this information to their **decay products**
- The initial $t\bar{t}$ spin states at the LHC depend on the **production mode** ($q\bar{q}$ annihilation/gg fusion), ∴ a **different** measurement at Tevatron c.f. LHC
- Measurements by ATLAS and CMS generally agree with fixed order predictions (ATLAS has some tension with the NNLO prediction)
  - ATLAS also has some tension with one NLO+PS prediction (POWHEG+PYTHIA8)

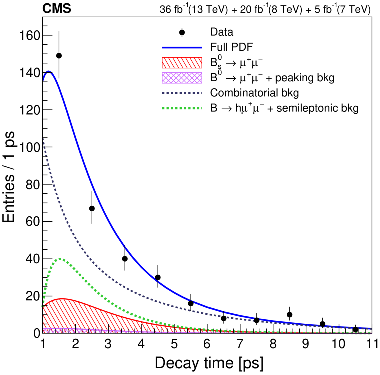


$B_s^0 \to \mu\mu$

BPH-16-004

- The decay of $B_S^0 \to \mu^+\mu^-$ is **observed** by CMS with a branching fraction of $\mathcal{B}(B_S^0 \to \mu^+\mu^-) = 2.9^{+0.7}_{-0.6} \times 10^{-9}$ with a significance of 5.6σ
  - **No** significant excess is seen for the $B^0 \to \mu^+\mu^-$, upper limits set at $\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.6 \times 10^{-10}$
- The results are **consistent** with the SM expectation, and provide a significant **constraint** on BSM models which could enhance this channel

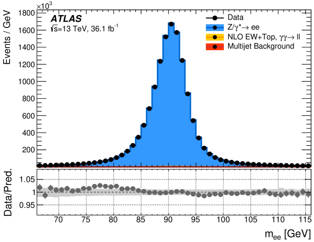


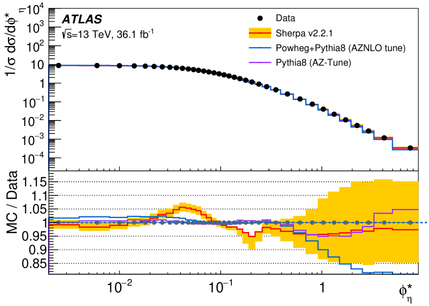


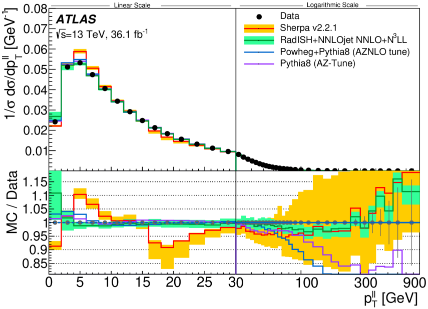
Drell-Yan: $pp \to Z/\gamma^* \to ll$

STDM-2018-14

- A **precise** measurement of transverse momentum and ϕ^*_η (a measure of the lepton's scattering angle w.r.t. the beam) in **Drell-Yan** events
- High statistics measurements of standard candle processes are **important** inputs to beyond the Standard Model searches
- Unfolded differential cross section provide information to improve the **modelling** of these channels







Beyond the Standard Model

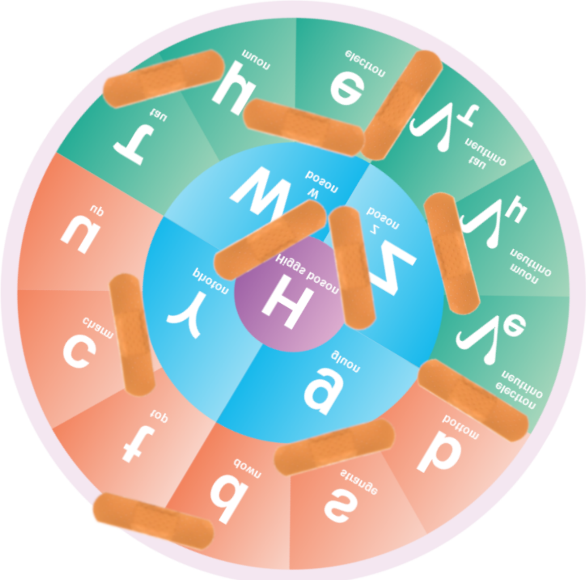
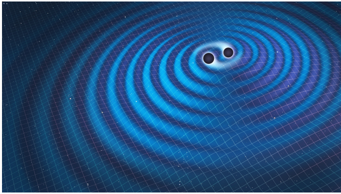
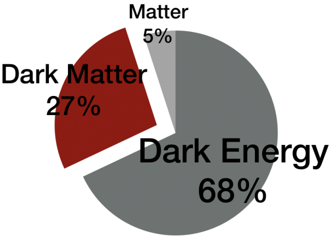


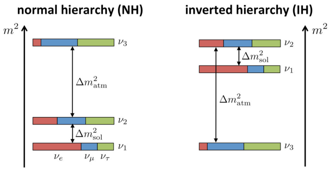
Image (kinda) from Symmetry Magazine

Some of the sticking plasters...

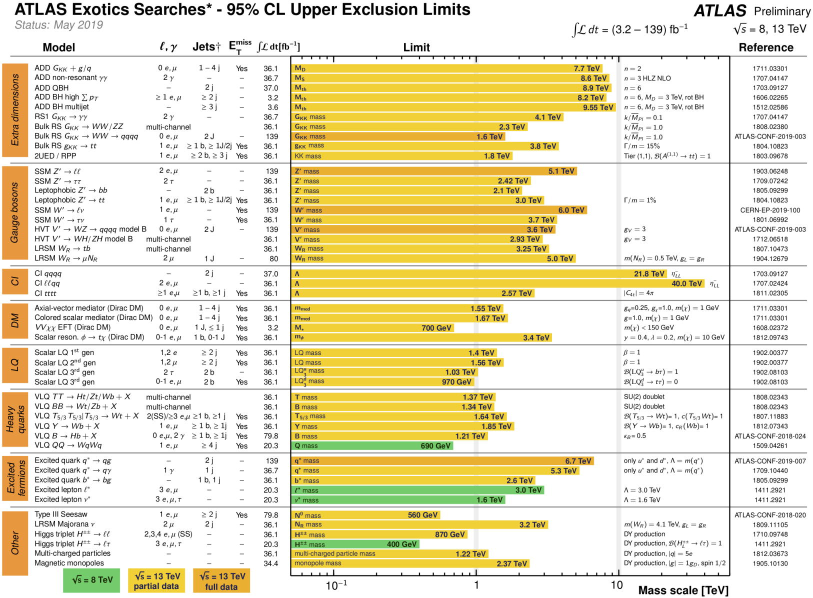
- **Gravity**... It's just not in there...
- **Dark Matter**... Astronomers/Cosmologists say that it is everywhere...
  - The SM looks blankly into the distance...
  - Neutrino mass not enough, and SM doesn't even include them anyway...
- **Neutrino masses**... Also missing...
  - We know they have mass, the SM says they don't...
  - No (observed) ν_R so no Yukawa coupling...
  - What is the correct way to stick that in?
- A complete list of sticking plasters, things lacking an explaination and omissions would be **quite long**...
  - The Higgs mass, mass hierarchies in general, vacuum stability of the universe, multiple generations of fermions...
- And so we go **searching**...







Exotics & SUSY: Searching high and low



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits
Status: May 2019

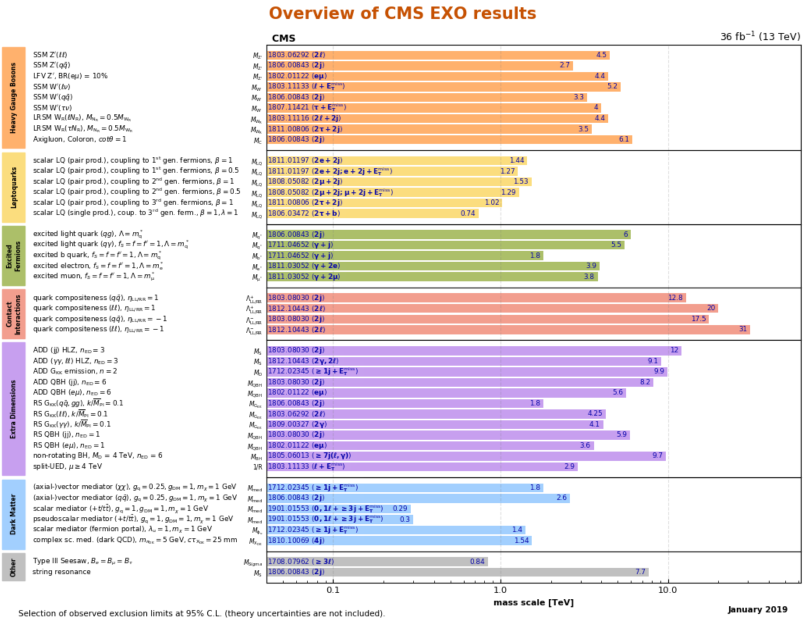
ATLAS Preliminary
$\int\mathcal{L}\,dt = (3.2 - 139)\ \mathrm{fb}^{-1}$
$\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	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 $tttt$	$\geq$1 e,μ	$\geq$1 b, $\geq$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	$\mathcal{B}(\mathrm{LQ}_3^u \to b\tau) = 1$	1902.08103
	Scalar LQ 3rd gen	0-1 e, μ	2 b	Yes	36.1	LQ_3^d mass 970 GeV	$\mathcal{B}(\mathrm{LQ}_3^d \to t\tau) = 0$	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)/$\geq$3 e,μ	$\geq$1 b, $\geq$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

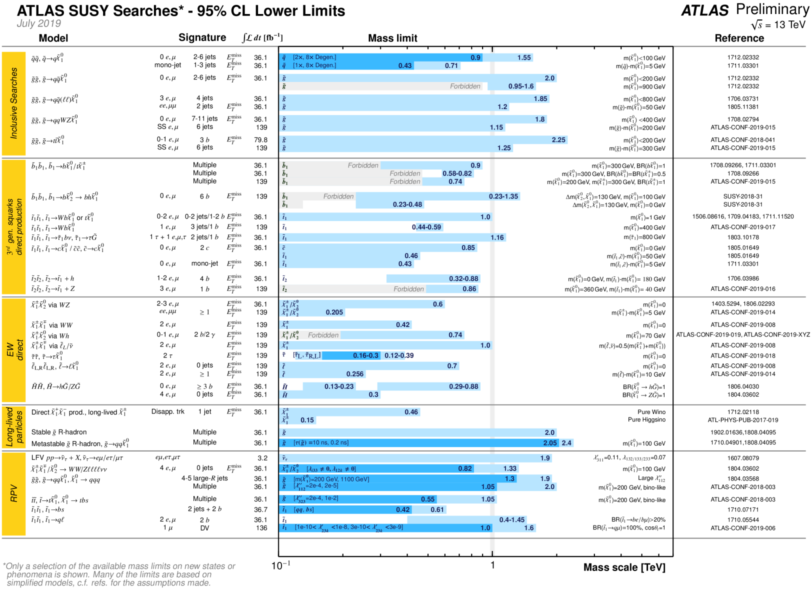
*Only a selection of the available mass limits on new states or phenomena is shown.

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

Exotics & SUSY: Searching high and low



Exotics & SUSY: Searching high and low



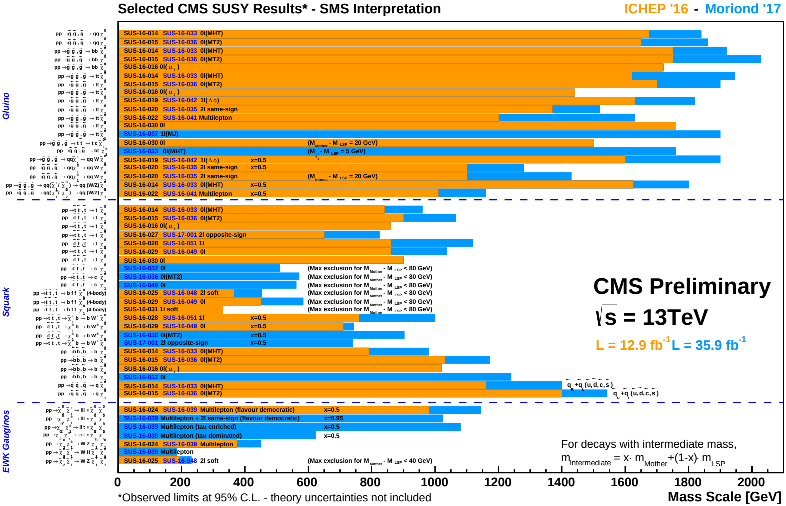
ATLAS SUSY Searches* - 95% CL Lower Limits
July 2019

ATLAS Preliminary
$\sqrt{s}$ = 13 TeV

	Model	Signature			$\int\mathcal{L}\,dt\ [\text{fb}^{-1}]$	Mass limit			Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0 e,μ	2-6 jets	E_T^{miss}	36.1	$\tilde{q}$ [2×, 8× Degen.]	0.9 1.55	m($\tilde{\chi}_1^0$)<100 GeV	1712.02332
		mono-jet	1-3 jets	E_T^{miss}	36.1	$\tilde{q}$ [1×, 8× Degen.]	0.43 0.71	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0 e,μ	2-6 jets	E_T^{miss}	36.1	$\tilde{g}$	2.0	m($\tilde{\chi}_1^0$)<200 GeV	1712.02332
						$\tilde{g}$	Forbidden 0.95-1.6	m($\tilde{\chi}_1^0$)=900 GeV	1712.02332
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	3 e,μ	4 jets		36.1	$\tilde{g}$	1.85	m($\tilde{\chi}_1^0$)<800 GeV	1706.03731
		$ee,\mu\mu$	2 jets	E_T^{miss}	36.1	$\tilde{g}$	1.2	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	0 e,μ	7-11 jets	E_T^{miss}	36.1	$\tilde{g}$	1.8	m($\tilde{\chi}_1^0$) <400 GeV	1708.02794
		SS e,μ	6 jets		139	$\tilde{g}$	1.15	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=200 GeV	ATLAS-CONF-2019-015
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	E_T^{miss}	79.8	$\tilde{g}$	2.25	m($\tilde{\chi}_1^0$)<200 GeV	ATLAS-CONF-2018-041
		SS e,μ	6 jets		139	$\tilde{g}$	1.25	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=300 GeV	ATLAS-CONF-2019-015
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$		Multiple		36.1	$\tilde{b}_1$	Forbidden 0.9	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$	Forbidden 0.58-0.82	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=BR($t\tilde{\chi}_1^\pm$)=0.5	1708.09266
			Multiple		139	$\tilde{b}_1$	Forbidden 0.74	m($\tilde{\chi}_1^0$)=200 GeV, m($\tilde{\chi}_1^\pm$)=300 GeV, BR($t\tilde{\chi}_1^\pm$)=1	ATLAS-CONF-2019-015
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_2^0\to bh\tilde{\chi}_1^0$	0 e,μ	6 b	E_T^{miss}	139	$\tilde{b}_1$	Forbidden 0.23-1.35	Δm($\tilde{\chi}_2^0,\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=100 GeV	SUSY-2018-31
						$\tilde{b}_1$	0.23-0.48	Δm($\tilde{\chi}_2^0,\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=0 GeV	SUSY-2018-31
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	E_T^{miss}	36.1	$\tilde{t}_1$	1.0	m($\tilde{\chi}_1^0$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	1 e,μ	3 jets/1 b	E_T^{miss}	139	$\tilde{t}_1$	0.44-0.59	m($\tilde{\chi}_1^0$)=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^{miss}	36.1	$\tilde{t}_1$	1.16	m($\tilde{\tau}_1$)=800 GeV	1803.10178
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}_1^0$	0 e,μ	2 c	E_T^{miss}	36.1	$\tilde{c}$	0.85	m($\tilde{\chi}_1^0$)=0 GeV	1805.01649
						$\tilde{t}_1$	0.46	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.01649
		0 e,μ	mono-jet	E_T^{miss}	36.1	$\tilde{t}_1$	0.43	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=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^{miss}	36.1	$\tilde{t}_2$	0.32-0.88	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 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^{miss}	139	$\tilde{t}_2$	Forbidden 0.86	m($\tilde{\chi}_1^0$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 40 GeV	ATLAS-CONF-2019-016
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	2-3 e,μ		E_T^{miss}	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.6	m($\tilde{\chi}_1^0$)=0	1403.5294, 1806.02293
		$ee,\mu\mu$	≥ 1	E_T^{miss}	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.205	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV	ATLAS-CONF-2019-014
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via WW	2 e,μ		E_T^{miss}	139	$\tilde{\chi}_1^\pm$	0.42	m($\tilde{\chi}_1^0$)=0	ATLAS-CONF-2019-008
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	0-1 e,μ	2 b/2 γ	E_T^{miss}	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	Forbidden 0.74	m($\tilde{\chi}_1^0$)=70 GeV	ATLAS-CONF-2019-019, ATLAS-CONF-2019-XYZ
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		E_T^{miss}	139	$\tilde{\chi}_1^\pm$	1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2019-008
	$\tilde{\tau}\tilde{\tau}$, $\tilde{\tau}\to\tau\tilde{\chi}_1^0$	2 τ		E_T^{miss}	139	$\tilde{\tau}$ [$\tilde{\tau}_{\text{L}}$, $\tilde{\tau}_{\text{R,L}}$]	0.16-0.3 0.12-0.39	m($\tilde{\chi}_1^0$)=0	ATLAS-CONF-2019-018
	$\tilde{\ell}_{\text{L,R}}\tilde{\ell}_{\text{L,R}}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0 jets	E_T^{miss}	139	$\tilde{\ell}$	0.7	m($\tilde{\chi}_1^0$)=0	ATLAS-CONF-2019-008
		2 e,μ	≥ 1	E_T^{miss}	139	$\tilde{\ell}$	0.256	m($\tilde{\ell}$)-m($\tilde{\chi}_1^0$)=10 GeV	ATLAS-CONF-2019-014
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	≥ 3 b	E_T^{miss}	36.1	$\tilde{H}$	0.13-0.23 0.29-0.88	BR($\tilde{\chi}_1^0\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	E_T^{miss}	36.1	$\tilde{H}$	0.3	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	E_T^{miss}	36.1	$\tilde{\chi}_1^\pm$	0.46	Pure Wino	1712.02118
						$\tilde{\chi}_1^\pm$	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, $\tilde{g}\to qq\tilde{\chi}_1^0$		Multiple		36.1	$\tilde{g}$ [$\tau(\tilde{g})$ =10 ns, 0.2 ns]	2.05 2.4	m($\tilde{\chi}_1^0$)=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
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	E_T^{miss}	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda_{i33}\neq 0,\lambda_{12k}\neq 0$]	0.82 1.33	m($\tilde{\chi}_1^0$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$		4-5 large-R jets		36.1	$\tilde{g}$ [m($\tilde{\chi}_1^0$)=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($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=2e-4, 1e-2]	0.55 1.05	m($\tilde{\chi}_1^0$)=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.

Exotics & SUSY: Searching high and low



*Observed limits at 95% C.L. - theory uncertainties not included

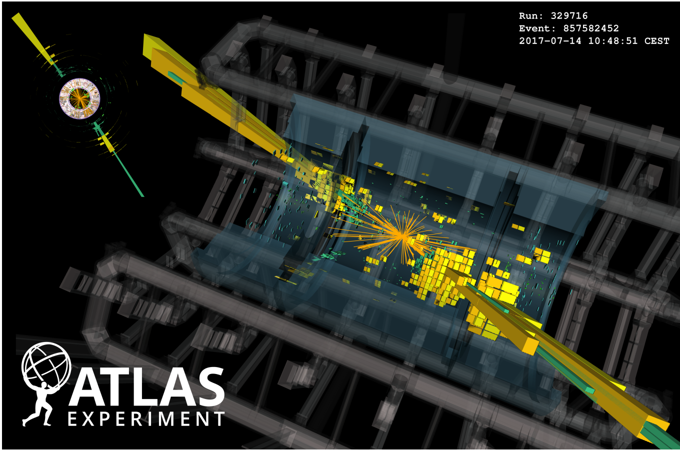
Only a selection of available mass limits. Probe *up to* the quoted mass limit for m_{LSP} ≈0 GeV unless stated otherwise

More up to date, but separated summaries can be found here

Pushing to the edges...

- Searches for exotic phenomena and SUSY partners push to extremes of phase space
- They also often turn the normal operation of the detectors upside down

- These **extremes** include...
- The **highest** invariant mass events
- **Low** mass particles
- **Compressed** spectra
- **Small** couplings
- **Long-lived** particles
- **Multi-charged** particles
- **Forbidden** decays
- **Complicated** decays

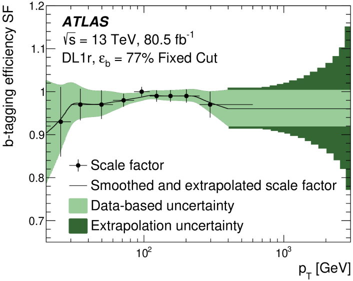


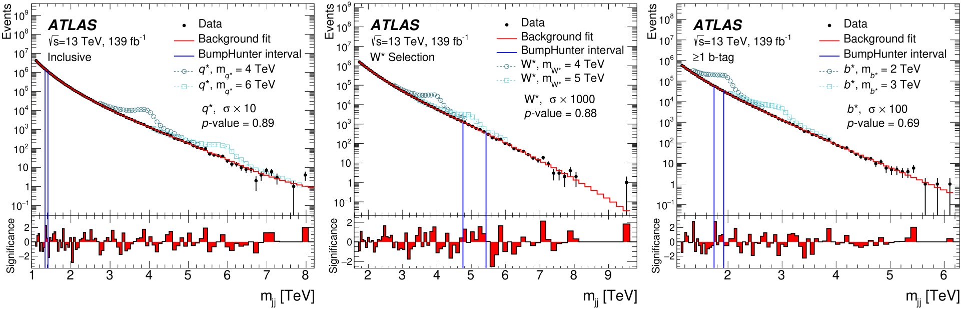
A $m_{jj} = 9.3$ TeV dijet event recorded by ATLAS

Dijet resonances

EXOT-2019-03 & EXO-19-012

- Dijet resonance searches probe the **highest** invariant mass events, $m_{jj} = 9.3$ TeV now for ATLAS, $m_{jj} = 8.2$ TeV in CMS
- This iteration from ATLAS is **expanding** on the inclusive search by requiring **additional** *b*-tagging selections to probe other models
- **No** excesses are seen in any of the spectra

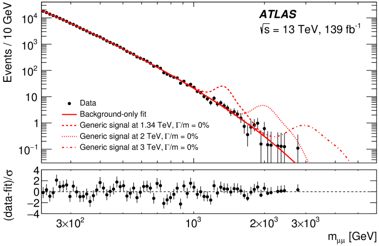


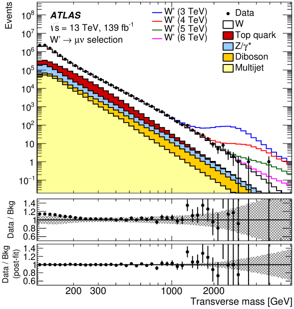


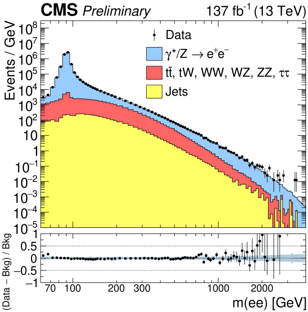
Dilepton resonances

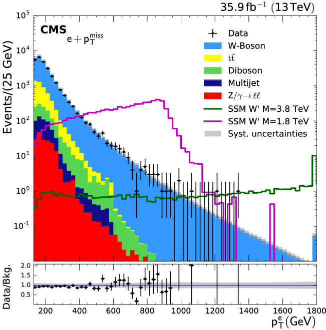
EXOT-2018-08 & EXOT-2018-30 & EXO-19-019 & EXO-16-033

- Dilepton resonance searches are **complimentary** searches to the dijet searches, exploring a **wide range** of BSM models
- Require **careful** treatment of SM backgrounds out to **high** invariant mass regions
- Again **no** excesses are seen in any of the spectra





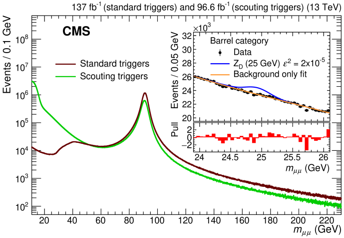


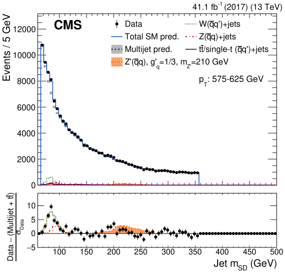


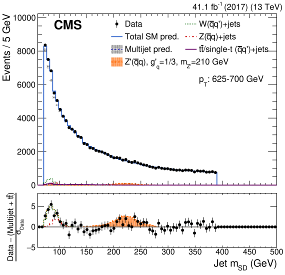
"Low" mass resonances

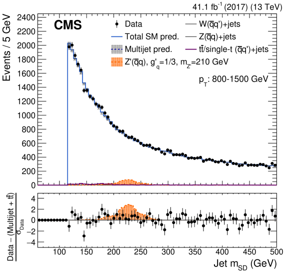
EXO-19-018&EXO-18-012&EXOT-2018-05&EXOT-2016-20

- Can **access** lower mass resonances than triggers would usually allow by **recoiling** the system against ISR, or by running on **reduced** size trigger level data
- Multiple examples from **both** experiments, pushing searches into areas **previously** thought inaccessible to the LHC
- **No excesses** seen in any of these searches either, but they demonstrate the **ingenuity** of collaboration members





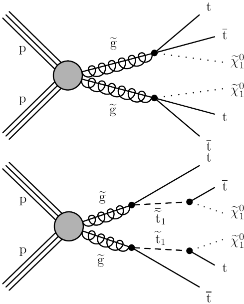


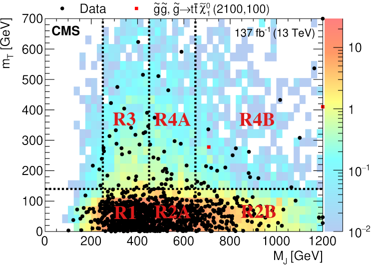


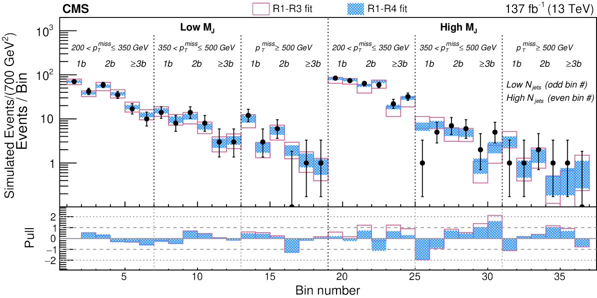
Strong SUSY

SUS-19-007

- A search for gluino pairs with a **spectacular** fireworks display of a final state of $t\bar{t}t\bar{t} + p_T^{miss}$
- The variables M_J,the scalar sum of large-R jets, and M_T, transverse mass of leading lepton + p_T^{miss}, offer **strong handles** on these busy events
- Regions ($R_{1,2,3}$) **dominated** by background are used to estimate the background in the signal region (R_4)
- Data is able to **exclude** gluinos with masses below 2.15 TeV



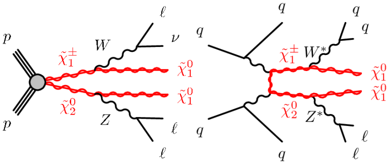


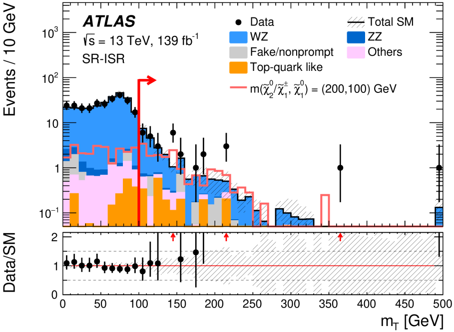


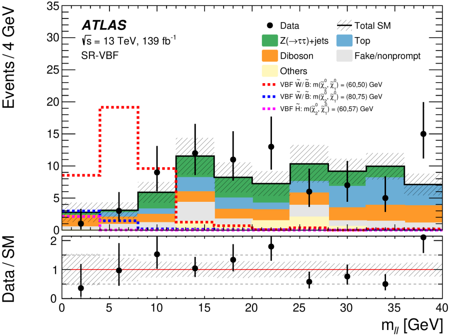
Electroweak SUSY

SUSY-2018-06 & SUSY-2018-16

- Searches also ongoing for **production** of electroweakinos, **close** to the EW mass scale, and in **compressed** spectra
- Push back into regions where the $m(\tilde{\chi}_2^0) \approx m(\tilde{\chi}_1^0) + m(Z)$ or $m(\tilde{\chi}_1^0) = m(\tilde{\chi}_2^0)$
- The "**easier**" search regions are longer term statistics driven games now







Long-Lived Particles

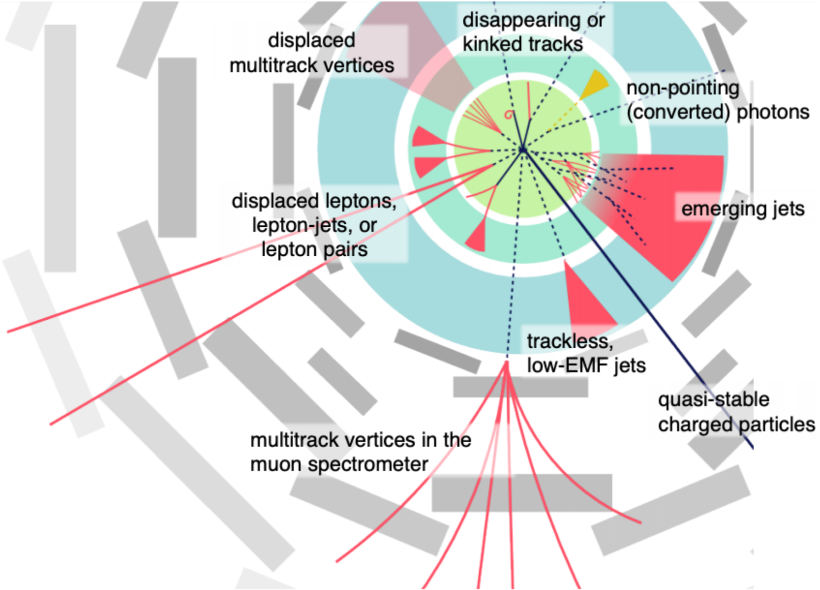
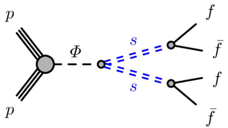


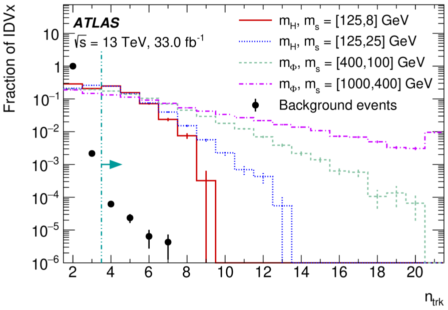
Image courtesy of Heather Russell

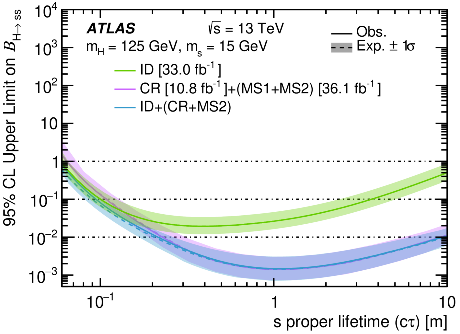
Long-Lived Particles

EXOT-2018-61

- Searches for LLPs require **novel** trigger and reconstruction techniques, often a complete **re-write**
- **New** reconstruction methods developed for displaced tracks in the ID and MS detectors
- **Unusual** backgrounds from material interactions, fake vertices or punch through jets
- Place **limits** on the $c\tau$ of the long lived particles



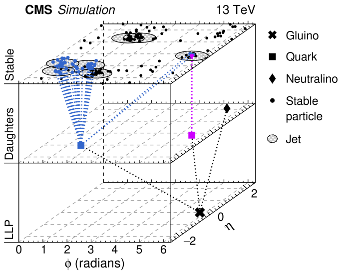


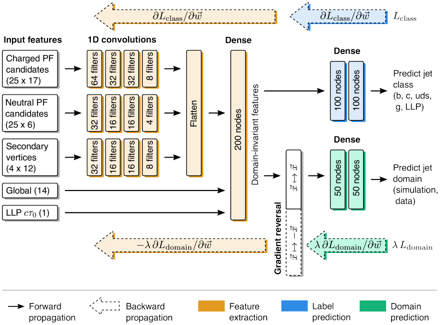


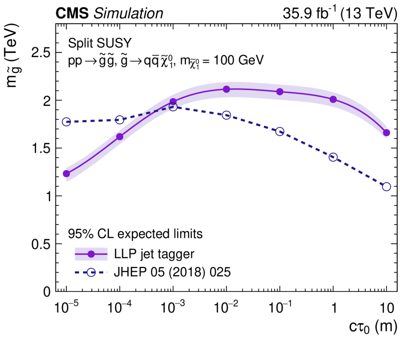
Long-Lived Particles: DNN Jet Tagging

EXO-19-011

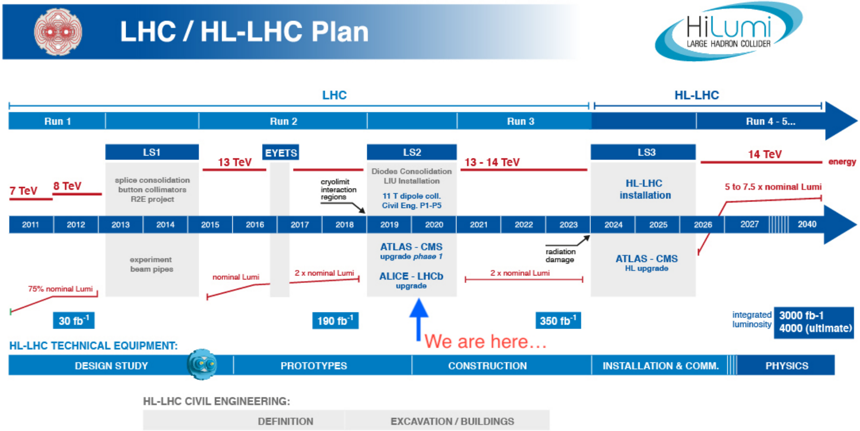
- CMS has **developed** a novel tagger to identify jets originating from LLP events
- Uses a Deep Neural Network which **achieves** a tagging efficiency of 30-80% for gluinos with $1mm \leq c\tau_0 \leq 10m$
- Expect an **improvement** in limits over **previous** results by using this **novel** technique







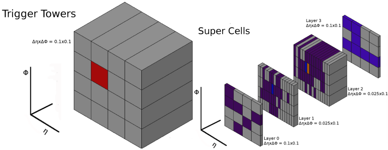
We are not done yet...

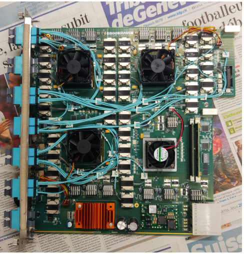


...not by a **long** way

ATLAS Phase-1 upgrades

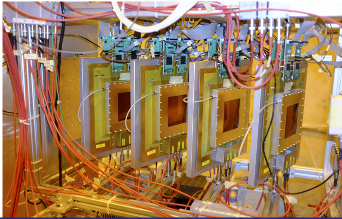
- **Liquid Argon Calorimeter Electronics**
  - Aiming to improve the Level-1 calorimeter decisions for Run 3 and beyond
  - Finer segmentation leading to enhanced jet rejection and pileup subtraction capabilities





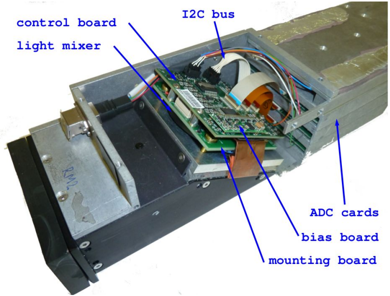
- **TDAQ** upgrades
  - Take advantage of finer segmentation in LAr electronics and improved muon trigger (NSW)

- Muons: **New Small Wheel**
  - Replacing the inner muon stations in the endcaps
  - Reduced muon fake rates, and maintain the same position resolution/efficiency for HL-LHC



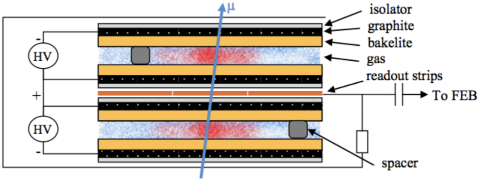
CMS Phase-1 upgrades

- CMS is well advanced on it’s Phase-1 upgrades
  - Upgrades of the pixels, L1Trigger system and replacement of some HCAL readout have already occured
  - Final upgrades ongoing in LS2 including replacing the inner layer of the pixel barrel



- **Hadronic Calorimeter Electronics**
  - Replace photosensors of hybrid photodetectors with silicon photomultipliers
  - Will improve the readout to 5Gbps and increase the longitudinal segmentation of the detector

- Muons: **GEM GEI/I detectors**
  - Technically already a Phase-2 upgrade, but going in now in LS2
  - Installing Gas-Electron-Multiplier chambers which can operate in high-rate environments



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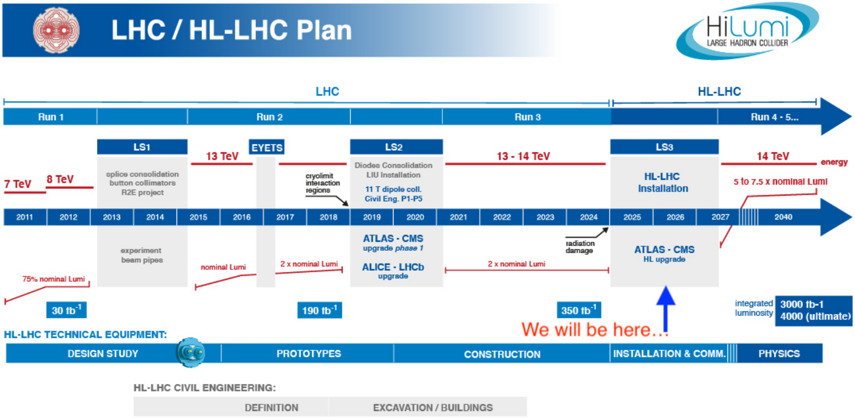
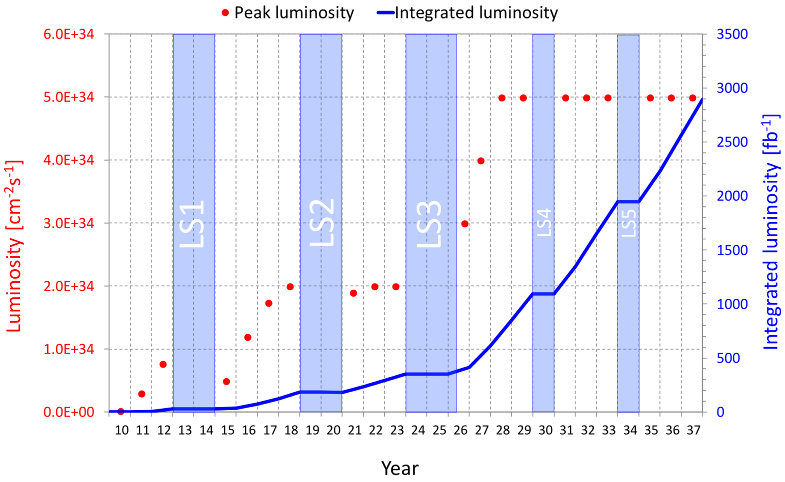


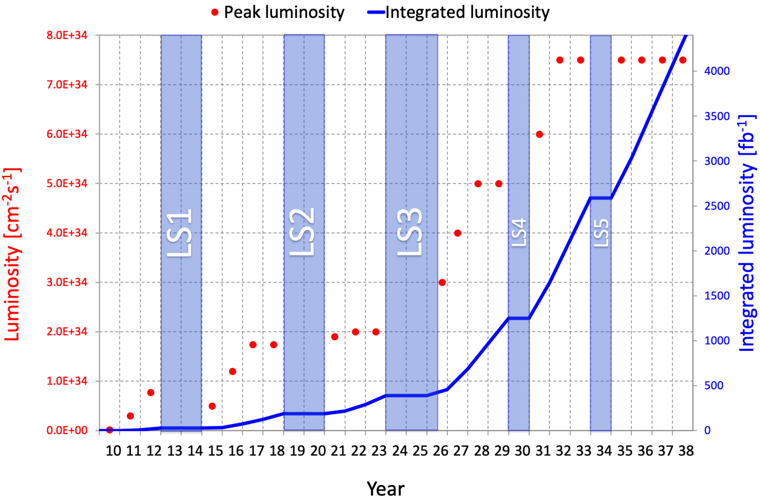
...not by a **long** way

We are not done yet...



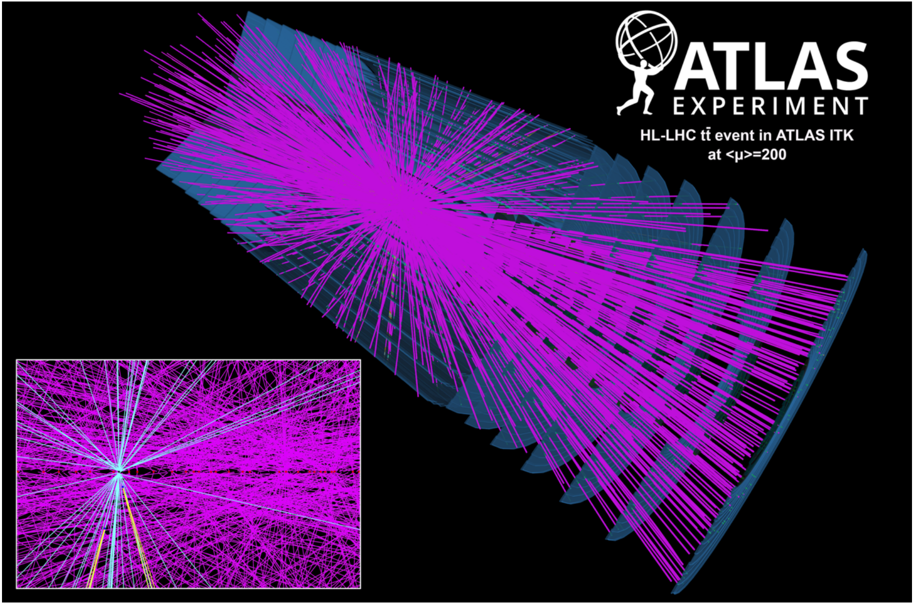
There is a lot of data incoming... **pessimistically** 3 ab^{-1}

We are not done yet...

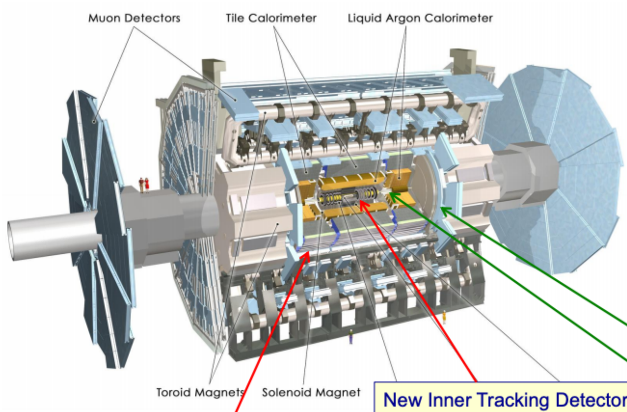


There is a lot of data incoming... or **optimistically** 4++ ab^{-1}

That data will be at $<\mu>= 200$



ATLAS Phase-2 upgrades



Upgraded Trigger and Data Acquisition System:

- L0: 1 MHz
- Improved High-Level Trigger

Electronics Upgrade :

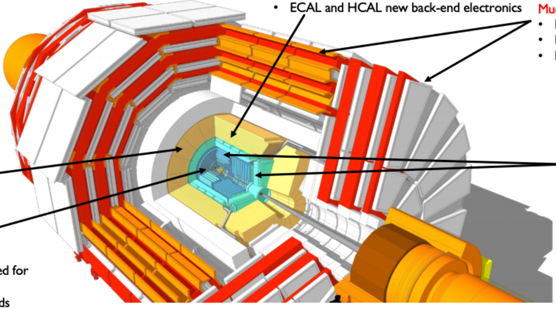
- LAr Calorimeter
- Tile Calorimeter
- Muon system

New Inner Tracking Detector
(all silicon tracker, up to $|\eta| =4$)

New muon chambers
in the inner barrel region

Options:
- High granularity timing detector (forward region)
- High-η muon tagger

CMS Phase-2 upgrades



L1 Trigger/HLT/DAQ
- L1 40 MHz in/750 kHz out with tracking for PF-like
- HLT 7.5 kHz out

Beam Radiation and Luminosity, Common Systems, Infrastructure

Calorimeter Endcap
- Si, Scint + SiPM in Pb-W-SS
- 3D shower imaging with precise timing

Tracker
- Si Strip Outer Tracker designed for L1 Track Trigger
- Pixelated Inner Tracker extends coverage to $|\eta|<3.8$

Barrel Calorimeters
- ECAL single crystal granularity in L1 Trigger with precise timing for e/γ at 30 GeV
- ECAL and HCAL new back-end electronics

Muon Systems
- DT & CSC new FE/BE readout
- New GEM/RPC $1.6<|\eta|<2.4$
- Extended coverage to $|\eta| < 2.8$

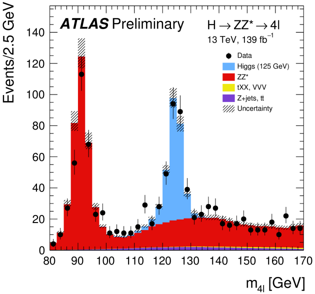
$|\eta|<3.0$

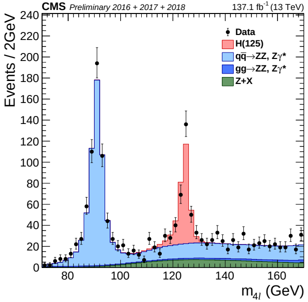
MIP Timing Detector
- 30 ps resolution
- Barrel: Crystals + SiPMs
- Endcap: LGADs

- Both of the upgrade programs are **major undertakings**
- Equivalent to (re-)building a **good fraction** of the detectors in each case, but while the collaboration is **still running** the existing system and producing physics results
- **Very challenging!**

Summary

- ATLAS & CMS are **ploughing** through their $\approx 140\mathrm{fb}^{-1}$ Run 2 datasets
- **No** new physics seen, but **exciting** results none the less
  - **Precision** differential Higgs cross section measurements, **progress** in rare Higgs decays and constraints on the *VVHH* system
  - **Observation** of the *WWjj*, *WZjj*, *ZZjj* electroweak scattering processes
  - **Precision** measurements of SM processes, increasing our understanding and constraining backgrounds to new physics
  - **Powerful** searches continue for new physics exploring new signatures and new parameter space
- Both experiments are **preparing** for the challenges of Run 3 and beyond into HL-LHC
- We already have a **gold mine** of experimental data, soon* we will be **spoiled** with $10\times$ as much data!





*For a generous definition of soon

The General Purpose Diagram