New physics searches at the LHC

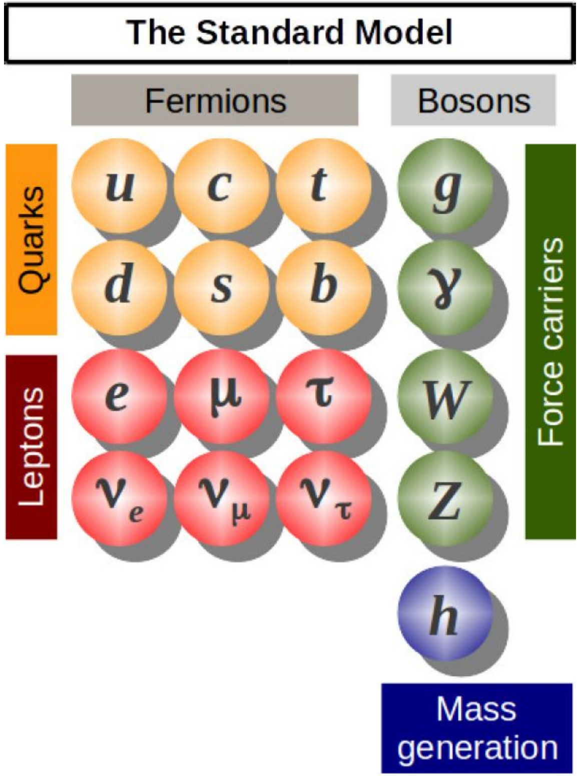
status and future prospects

Frascati, 21 March 2019

Tina Potter

UNIVERSITY OF CAMBRIDGE

Our wonderful Standard Model

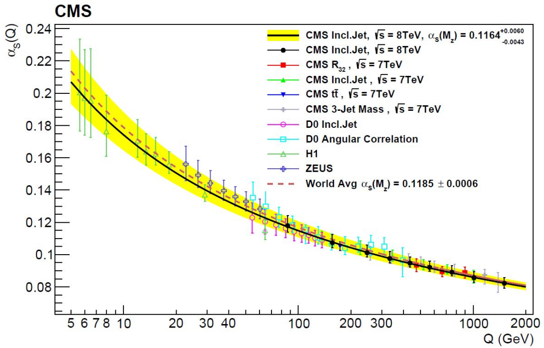


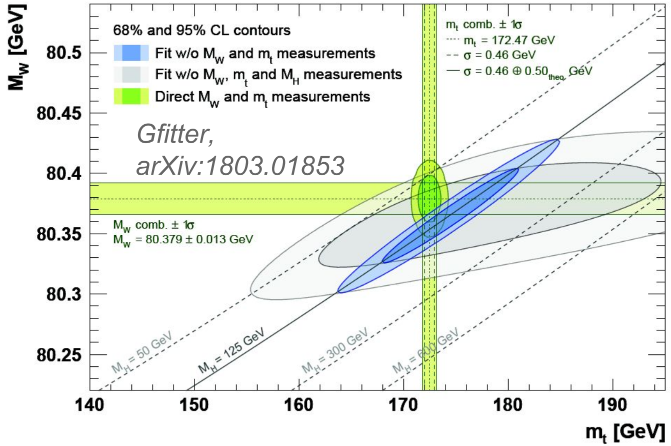
SU(2)xU(1) GWS

SU(3) QCD

Higgs mechanism generates mass

Probed successfully to high precision at LEP, Tevatron, LHC…





Problems

Dark matter

Matter-antimatter asymmetry

Neutrino oscillations

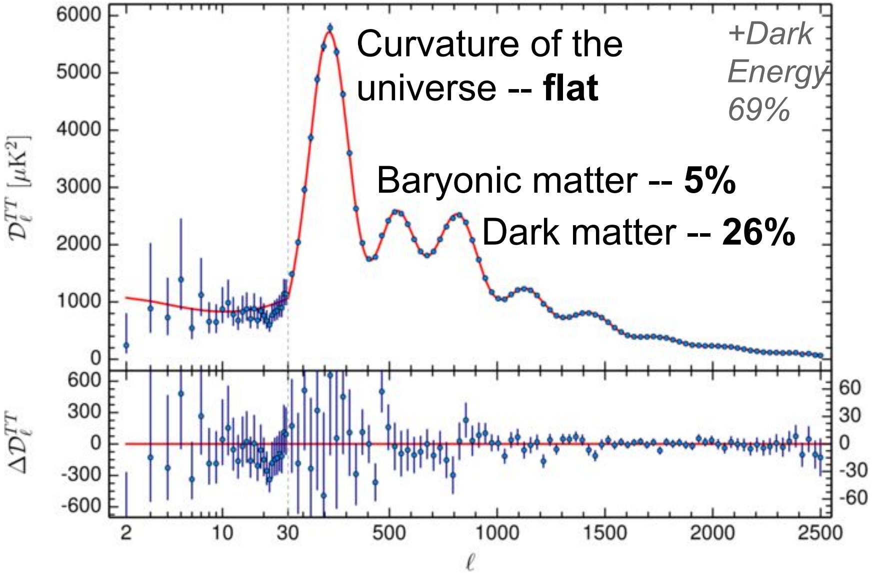
Higgs mass hierarchy

g-2 anomalous magnetic dipole moment

Grand Unification?

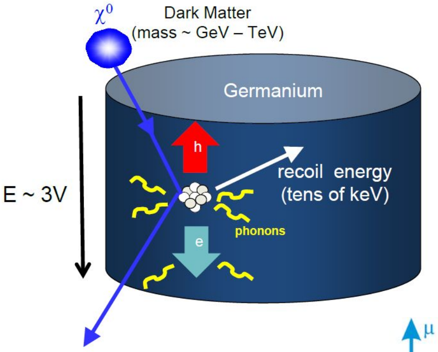
Gravity?

Planck 2015 CMB power spectrum



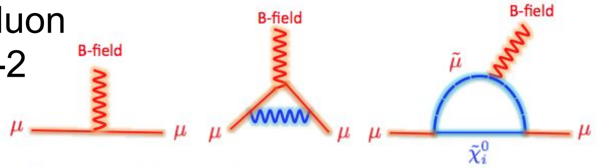
Where to start?

Dark matter direct detection

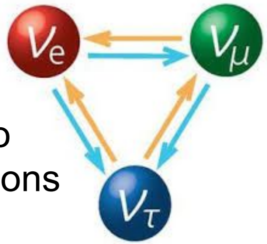


Cosmic rays (AMS)

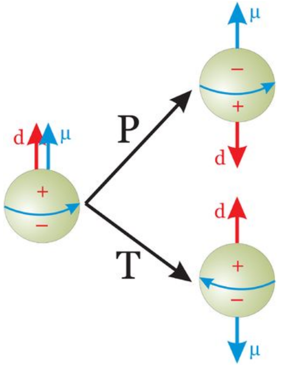
Muon g-2

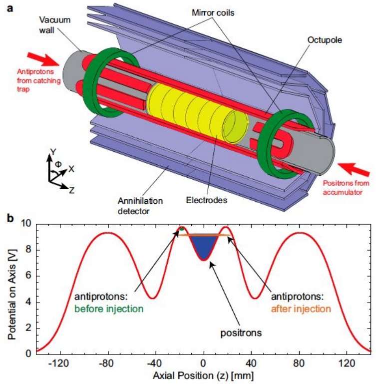


Neutrino Oscillations

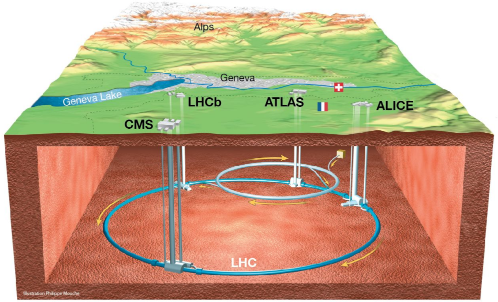


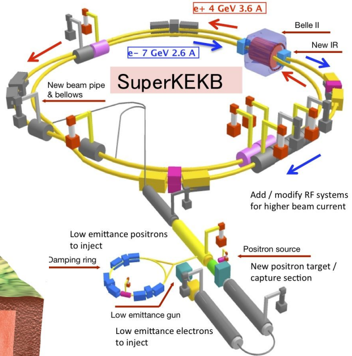
Neutron EDM





Antihydrogen

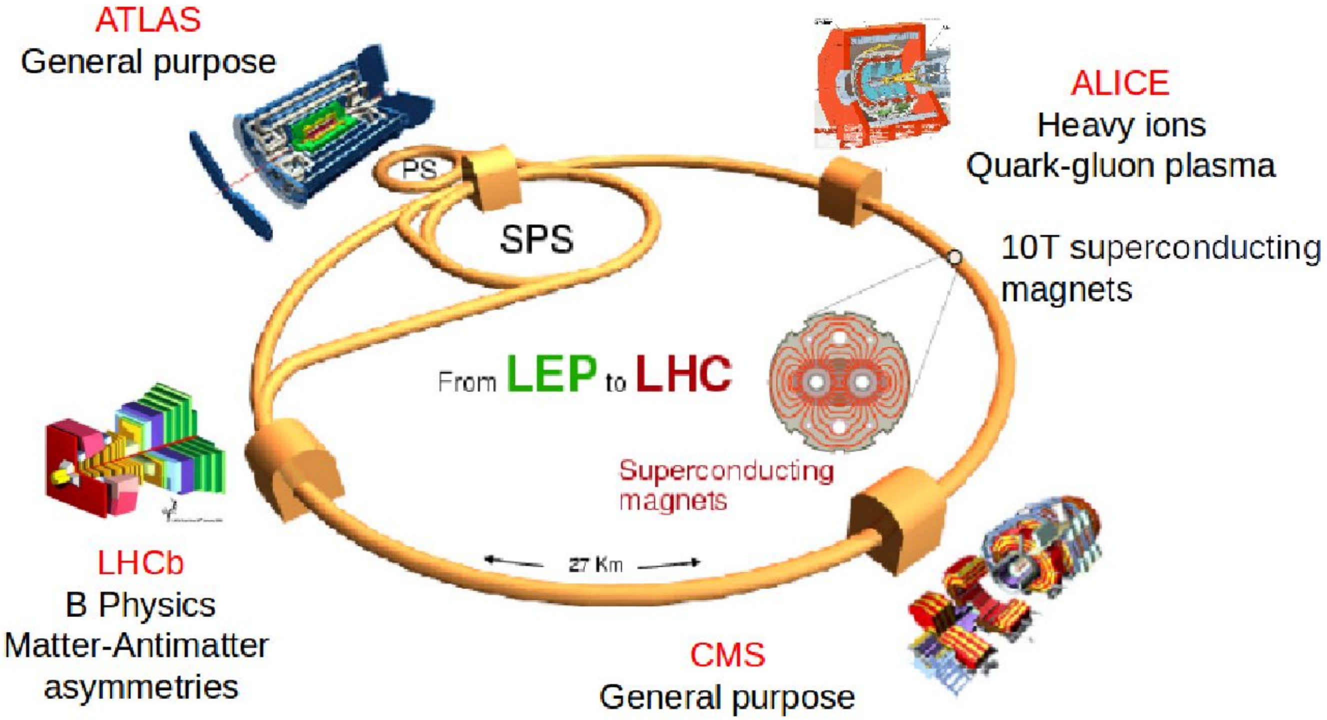




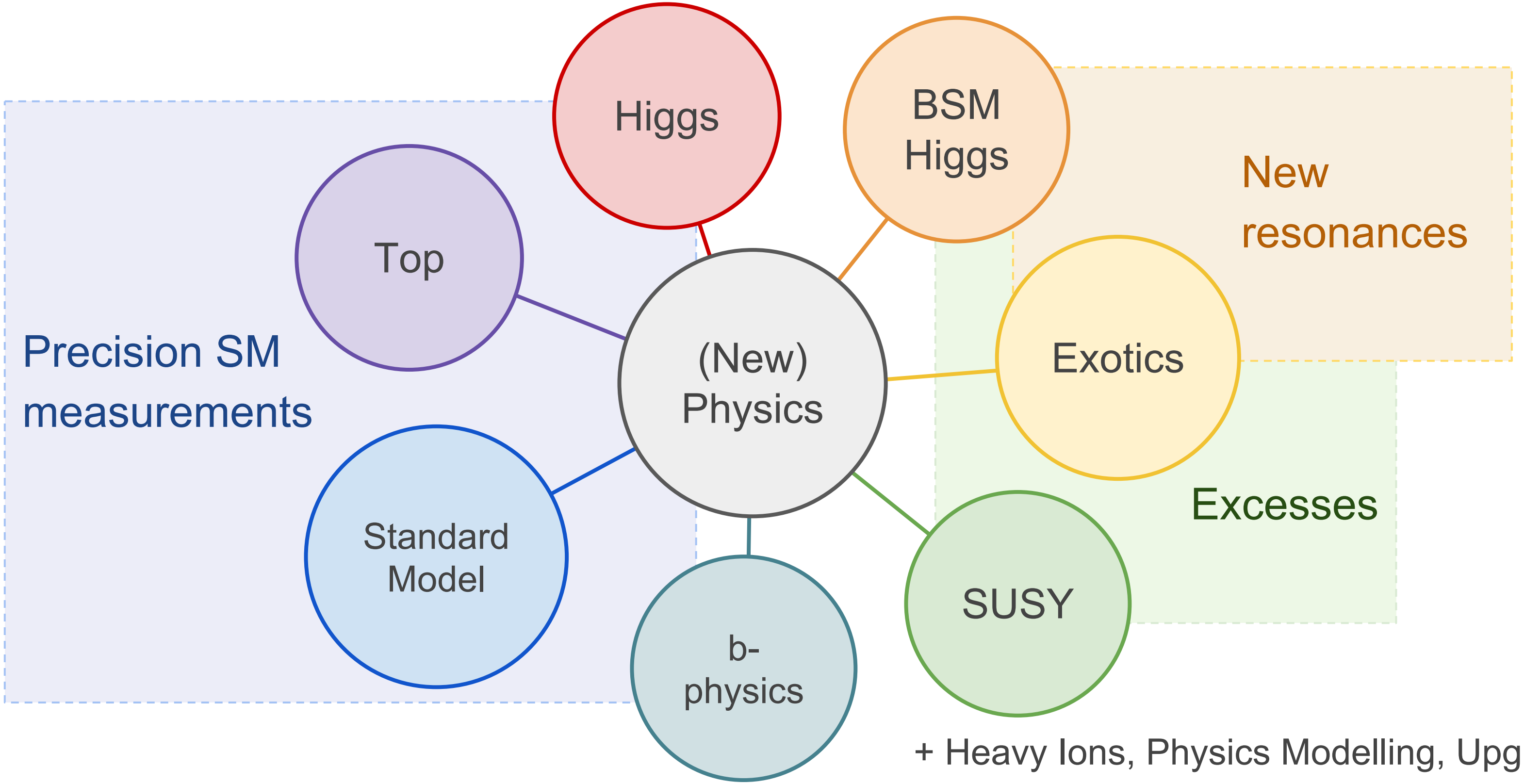
High energy colliders

High energy colliders

Mankind's biggest experiment



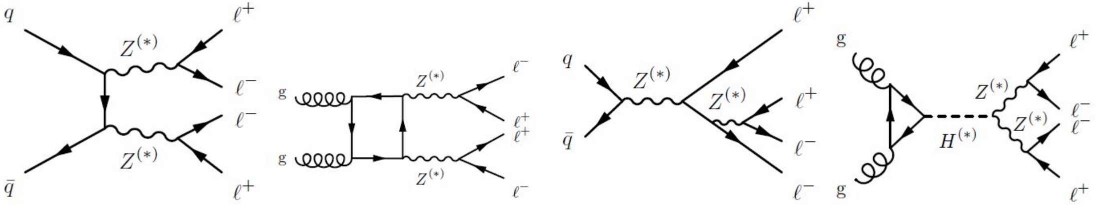
Collider searches



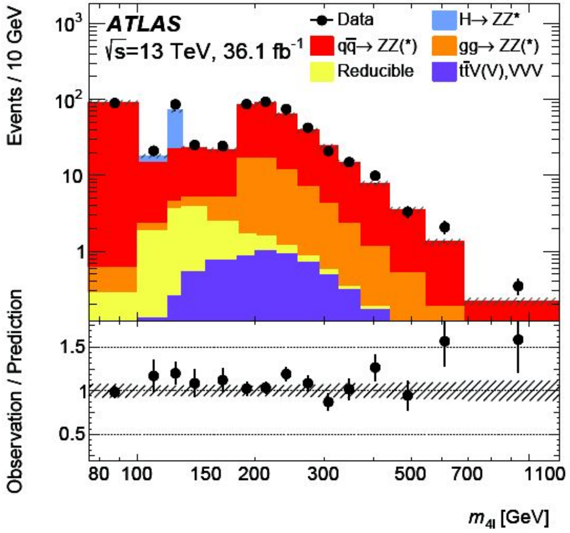
+ Heavy Ions, Physics Modelling, Upgrade ...

Precision measurements: ZZ production

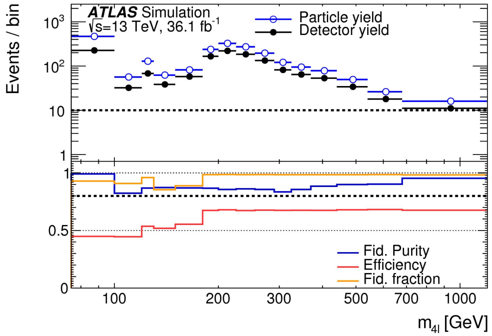
ATLAS √s = 13 TeV, 36 fb^{-1} arXiv:1902.05892

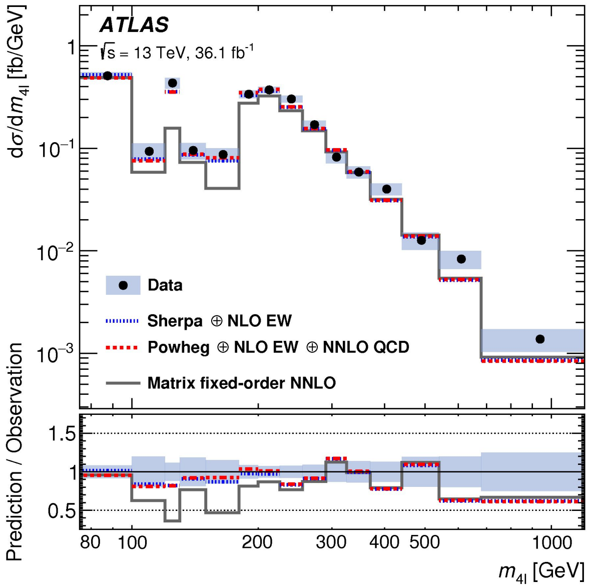


Select ZZ → 4L events (e,μ only)



Unfold kinematic variables and (double) differential spectra for experimental effects (trigger, efficiency, resolution...)





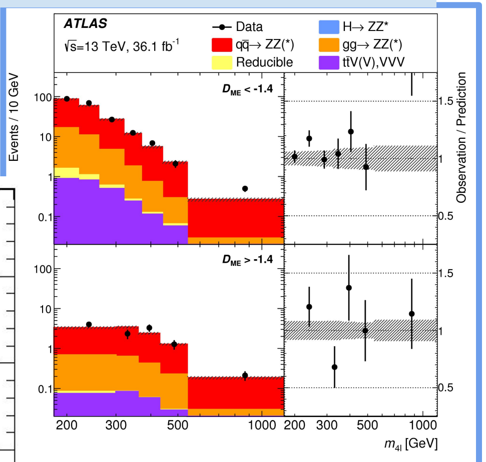
Precision measurements: ZZ production

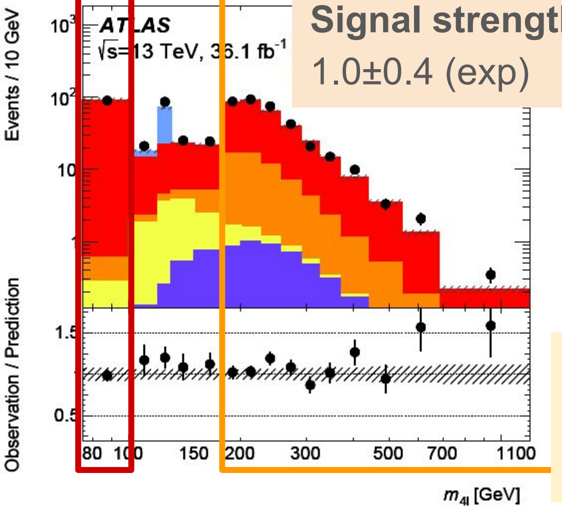
Reinterpret results for precise SM calculations or BSM scenarios **ATLAS** $\sqrt{s}$ = 13 TeV, 36 fb^{-1} arXiv:1902.05892

Measurement	$\mathcal{B}_{Z\to 4\ell}/10^{-6}$
ATLAS, $\sqrt{s}$ = 7 TeV and 8 TeV [8]	4.31±0.34(stat)±0.17(syst)
CMS, $\sqrt{s}$ = 13 TeV [6]	$4.83\ ^{+0.23}_{-0.22}$(stat) $^{+0.32}_{-0.29}$(syst)±0.08(theo)±0.12(lumi)
ATLAS, $\sqrt{s}$ = 13 TeV	**4.70 ± 0.32(stat) ± 0.21(syst) ± 0.14(lumi)**

Signal strength for H* → 4L

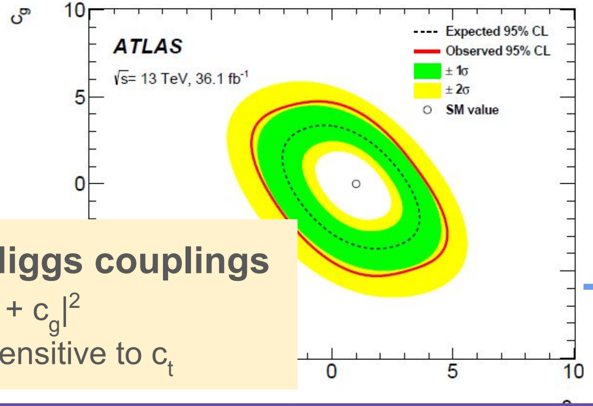
<5.4 (exp) <6.5 (obs) 95% CL





Signal strength for gg → 4L

1.0±0.4 (exp) 1.3±0.5 (obs)

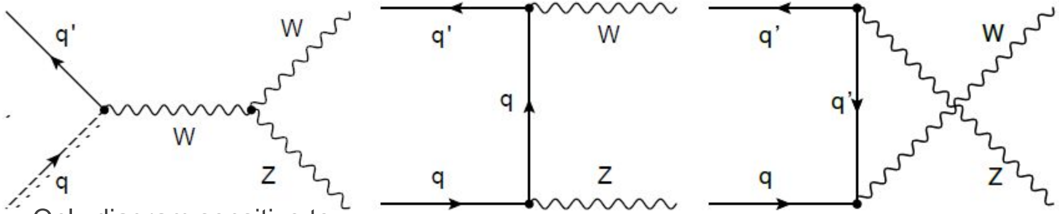


Anomalous Higgs couplings

ttH measures $|c_t + c_g|^2$

High m_{4L} more sensitive to c_t

Precision measurements: WZ production



Only diagram sensitive to TGC with Z in final state

CMS $\sqrt{s}$ = 13 TeV, 36 fb^{-1} arXiv:1901.03428
ATLAS $\sqrt{s}$ = 13 TeV, 36 fb^{-1} arXiv:1902.05759

Select WZ → $ll\nu$ events (e.μ only)

Cross-section measurements mostly agree with SM

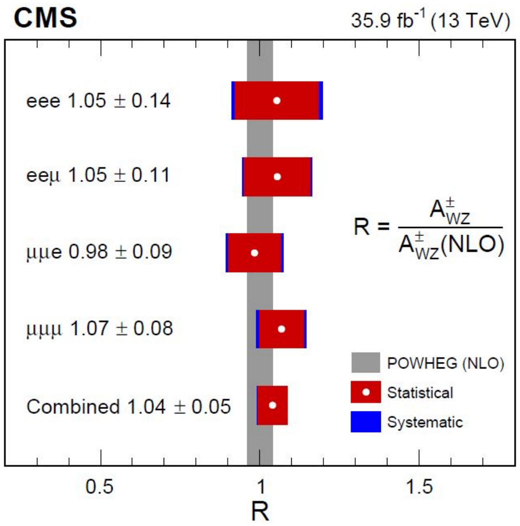
Category	$\sigma_{tot}(pp \to WZ)$ [pb]
eee	$47.11^{+5.01}_{-4.63}$ (total) $= 47.11^{+2.88}_{-2.79}$ (stat)$^{+0.46}_{-0.41}$ (theo)$^{+3.89}_{-3.47}$ (syst) ± 1.41 (lumi)
eeμ	$47.16^{+3.87}_{-3.61}$ (total) $= 47.16^{+2.31}_{-2.29}$ (stat)$^{+0.45}_{-0.38}$ (theo)$^{+2.83}_{-2.52}$ (syst) ± 1.33 (lumi)
e$\mu\mu$	$47.70^{+3.58}_{-3.55}$ (total) $= 47.70^{+2.00}_{-1.96}$ (stat)$^{+0.45}_{-0.39}$ (theo)$^{+2.66}_{-2.61}$ (syst) ± 1.42 (lumi)
$\mu\mu\mu$	$49.00^{+3.18}_{-3.03}$ (total) $= 49.00^{+1.57}_{-1.53}$ (stat)$^{+0.41}_{-0.35}$ (theo)$^{+2.42}_{-2.22}$ (syst) ± 1.39 (lumi)

Category	Fiducial cross section [fb]
eee	$63.7^{+3.8}_{-3.7}$ (stat)$^{+0.6}_{-0.6}$ (theo)$^{+5.3}_{-4.7}$ (syst) ± 1.9 (lumi)
eeμ	$61.6^{+3.0}_{-2.9}$ (stat)$^{+0.6}_{-0.5}$ (theo)$^{+3.7}_{-3.3}$ (syst) ± 1.9 (lumi)
e$\mu\mu$	$63.4^{+2.6}_{-2.6}$ (stat)$^{+0.6}_{-0.5}$ (theo)$^{+3.5}_{-3.2}$ (syst) ± 1.9 (lumi)
$\mu\mu\mu$	$67.1^{+2.1}_{-2.0}$ (stat)$^{+0.6}_{-0.5}$ (theo)$^{+3.3}_{-3.0}$ (syst) ± 1.9 (lumi)
Combined	$257.5^{+5.3}_{-5.0}$ (stat)$^{+2.3}_{-2.0}$ (theo)$^{+12.8}_{-11.6}$ (syst) ± 7.4 (lumi)

> $\sigma^{\text{POWHEG}}_{\text{fid}} = 227.6^{+9.4}_{-8.0}$ fb

Charge asymmetry measurements agree with SM

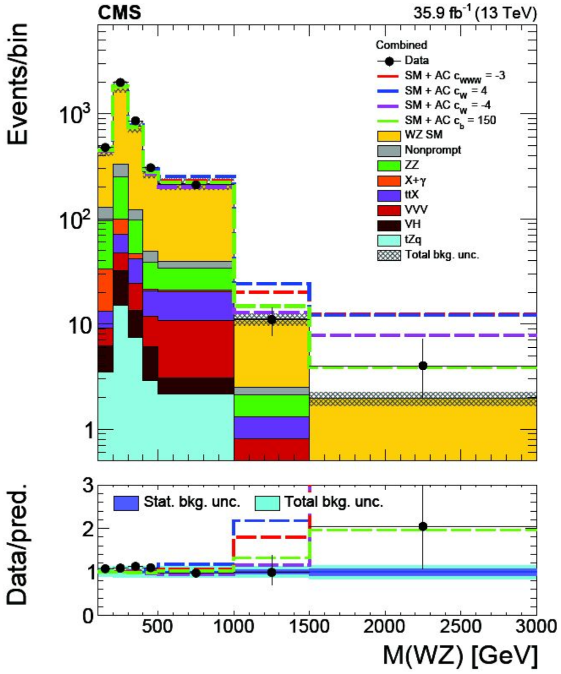
$$A^{+-}_{WZ} = \frac{\sigma_{tot}(pp \to W^+Z)}{\sigma_{tot}(pp \to W^-Z)}$$



Precision measurements: WZ production

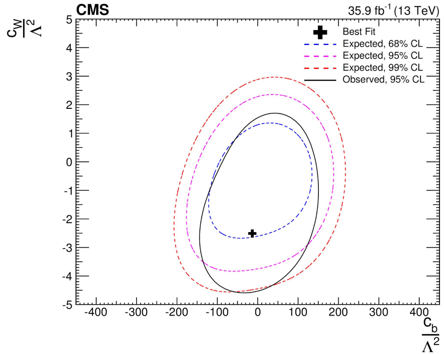
CMS √s = 13 TeV, 36 fb^{-1} arXiv:1901.03428

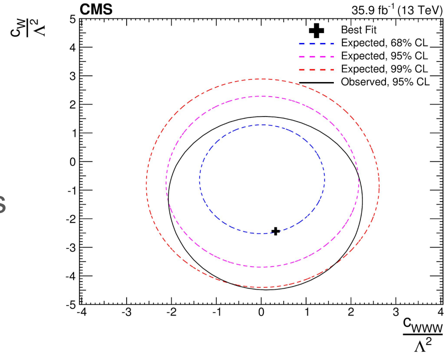
$$\delta\mathcal{L}_{AC} = \frac{c_{WWW}}{\Lambda^2}\mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}] + \frac{c_W}{\Lambda^2}(D_\mu H)^\dagger W^{\mu\nu}(D_\nu H) + \frac{c_b}{\Lambda^2}(D_\mu H)^\dagger B^{\mu\nu}(D_\nu H)$$

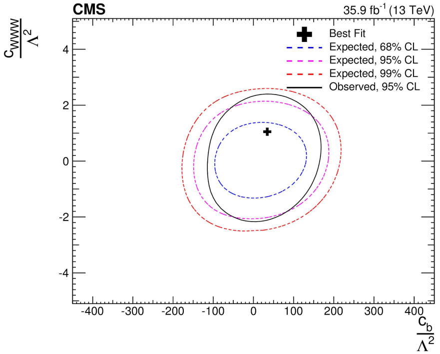


Use m(WZ) in a maximum likelihood fit to extract 1D & 2D limits on the anomalous triple gauge couplings.

Typical energy scale Λ^2 where BSM dominates absorbed into couplings



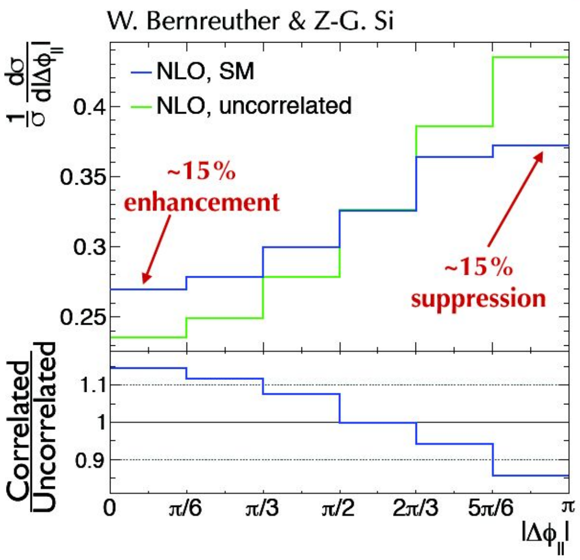


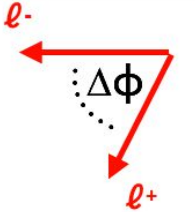


Precision measurements: Top spin correlations

ATLAS √s = 13 TeV, 36 fb^{-1} arXiv:1903.07570

Ttbar production is unpolarised in SM, but spins are correlated. BSM could change spin correlations.
Fully reconstruct t and anti-t for direct measurement of spin. **HARD** (no deviation from SM so far).
Or… use lepton angular distributions in lab frame to indirectly probe top spin. **EASIER**



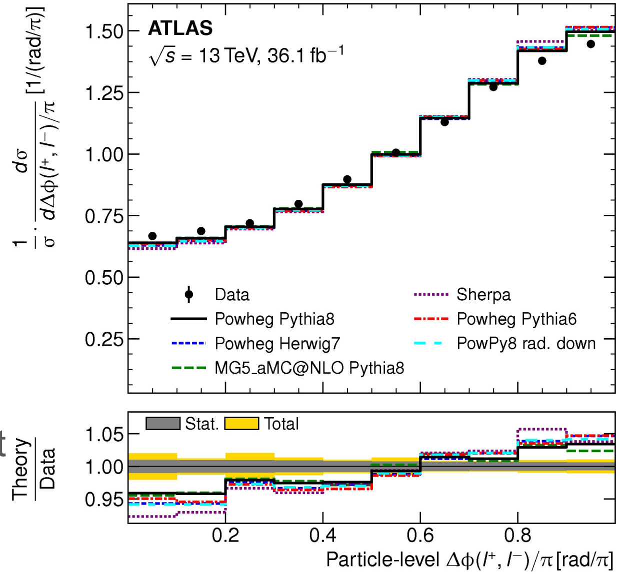


~3σ discrepancy between data and NLO predictions
(full & fiducial phase space)

Spin correlation strength / SM pred.

$f_{SM} = 1.25 \pm 0.02 \pm 0.06 \pm 0.04$

CMS see similar, but reduced effect using NNLO, arXiv:1901.05407
Problem with NLO description?

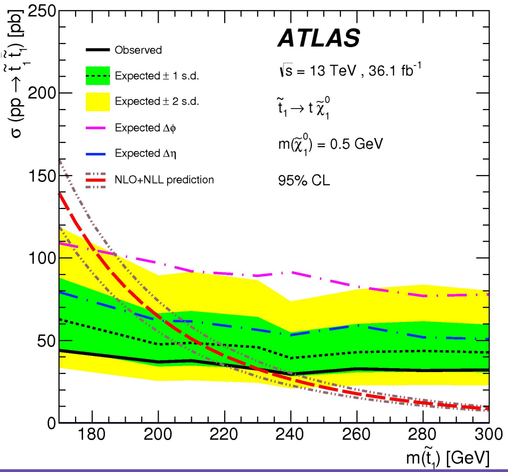


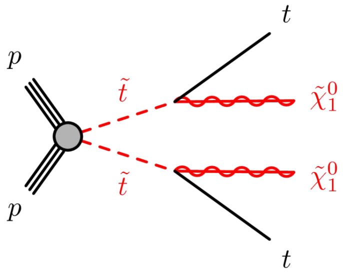
Precision measurements: Top spin correlations

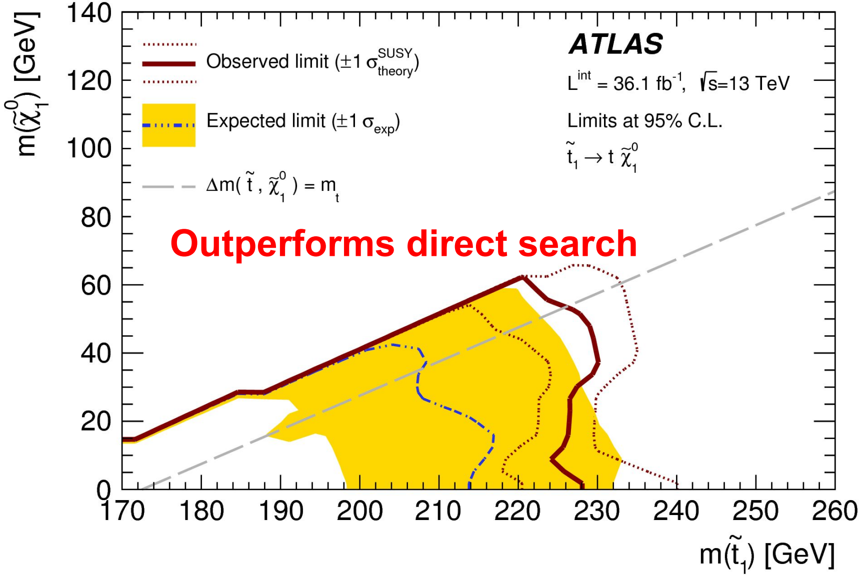
ATLAS $\sqrt{s}$ = 13 TeV, 36 fb^{-1} arXiv:1903.07570

Ttbar production is unpolarised in SM, but spins are correlated. **BSM** could change spin correlations.
Stop pair production would affect the lepton $\Delta\eta$ (more central), $\Delta\varphi$, and total rate.

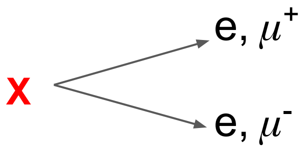
Set limits on stop pair production using
+ total rate
+ double diffl distributions in $\Delta\eta$ and $\Delta\varphi$







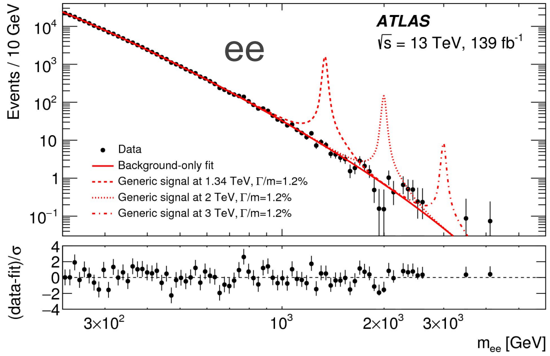
New resonances: dileptons

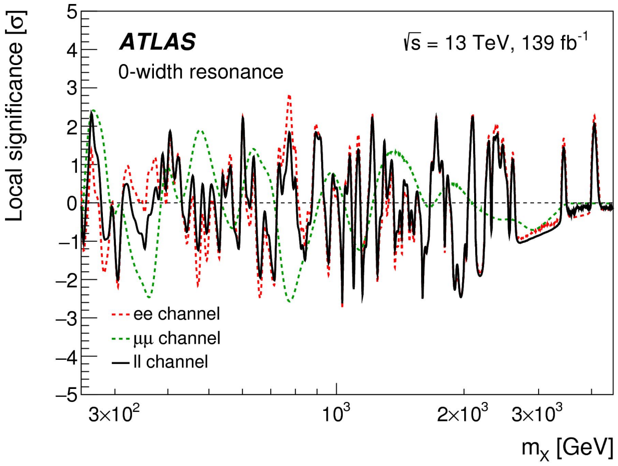


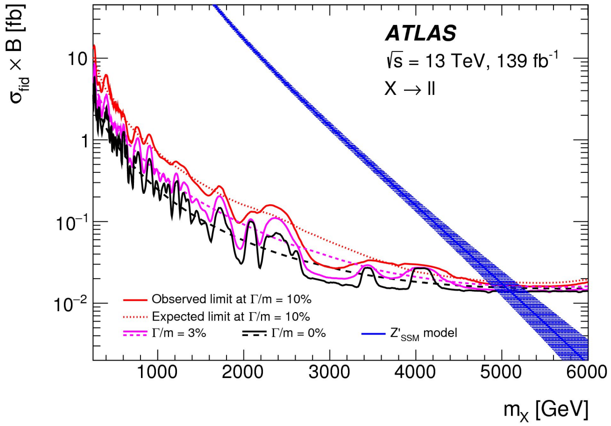
ATLAS $\sqrt{s}$ = 13 TeV, **140 fb^{-1}** arXiv:1903.06248

Select high m(ll) > 250 GeV events.

Look for new resonance.







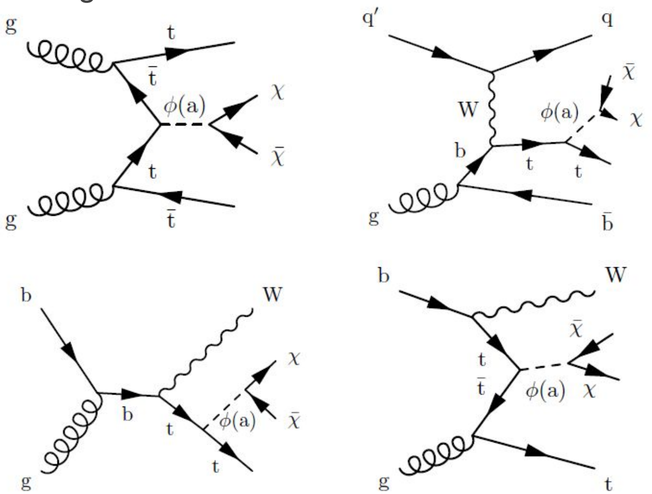
ee and $\mu^+\mu^-$ channels combined to calculate local significance.

No significant excesses seen.

Limits set on gauge boson models m(Z') ~ 5 TeV

Excesses: Dark Matter + top

dominating
diagram



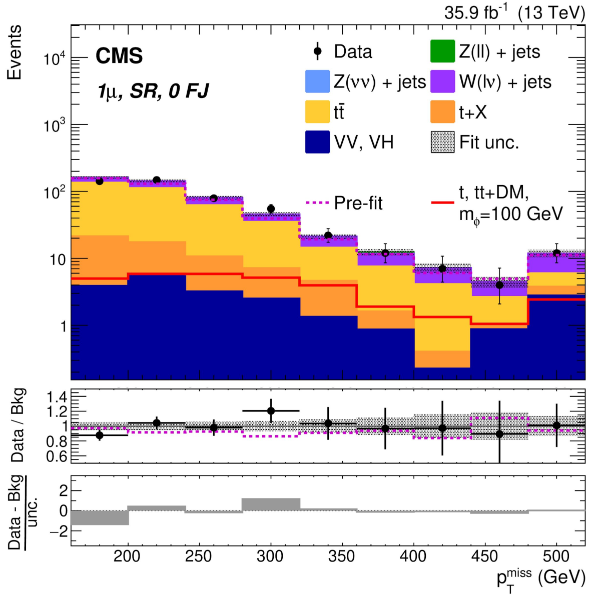
CMS $\sqrt{s}$ = 13 TeV, 36 fb^{-1} arXiv:1901.01553

$$\mathcal{L}_\phi \supset g_\chi \phi \bar{\chi}\chi + \frac{g_q \phi}{\sqrt{2}} \sum_f (y_f \bar{f} f),$$

$$\mathcal{L}_a \supset i g_\chi a \bar{\chi}\gamma^5\chi + \frac{i g_q a}{\sqrt{2}} \sum_f (y_f \bar{f}\gamma^5 f)$$

Look for the production of spin-0 mediator particle: scalar φ or pseudoscalar *a*

χ are escaping dark matter particles



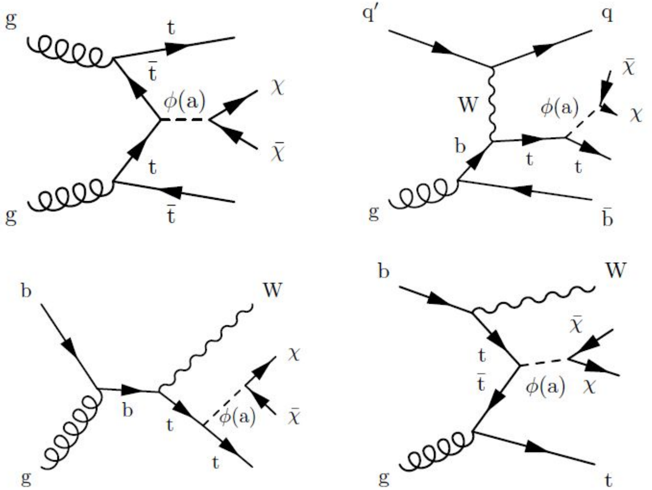
NEW: consider DM+t (DM+mono-top)
Look for excess in p_T^{miss} in events with 0/1L, 1-2bjets, 0/1 forward jets

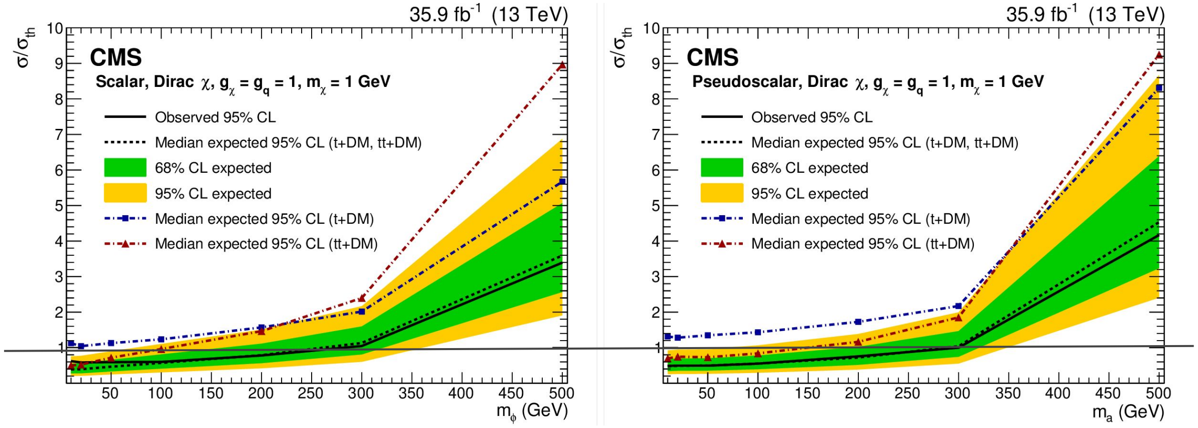
Use p_T^{miss} in a maximum likelihood fit to extract signal

Excesses: Dark Matter + top

dominating
diagram

CMS $\sqrt{s}$ = 13 TeV, 36 fb^{-1} arXiv:1901.01553





DM+tt dominates sensitivity at low m(φ/*a*).

But σ(DM+tt) drops more rapidly with mass than σ(DM+t)

Adding DM+t improves limits at high mass.

m(φ)<290 GeV and m(*a*)<300 GeV are excluded in these models

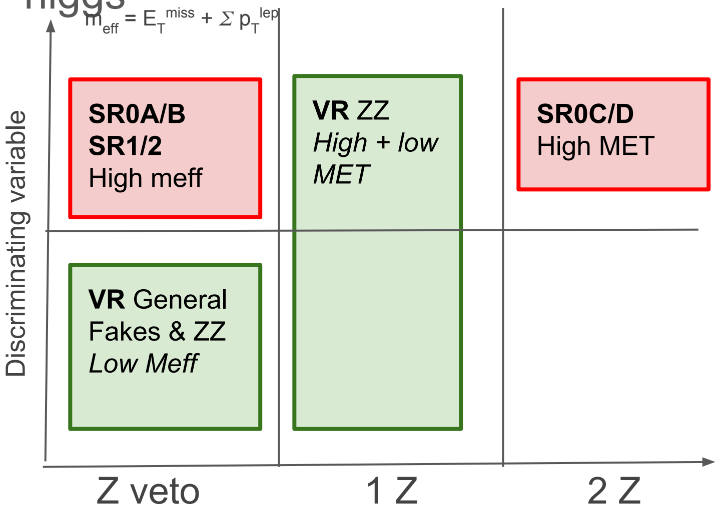
Excesses: Flexible Four Leptons

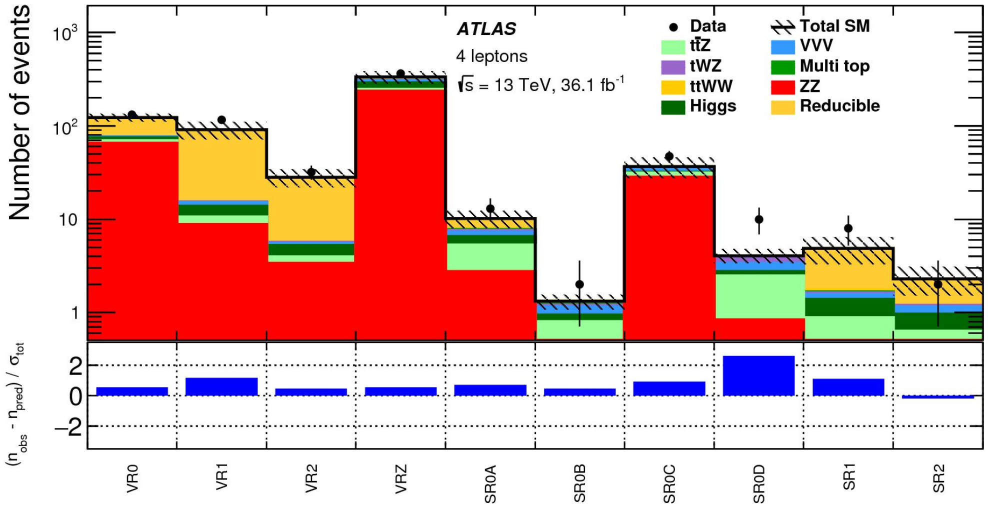
The four-lepton final state is sensitive to a wide variety of new physics.

Approach is as model-independent as possible: $\sqrt{s}$ = 13 TeV, 36 fb^{-1} PRD **98** (2018) 032009

4L0τ, 2L1τ, 2L2τ, Z-rich/depleted, high E_T^{miss} or m_{eff}

Data-driven background estimation for fake leptons (ttbar, Z+jets). MC for ZZ, ttZ, VVV, higgs



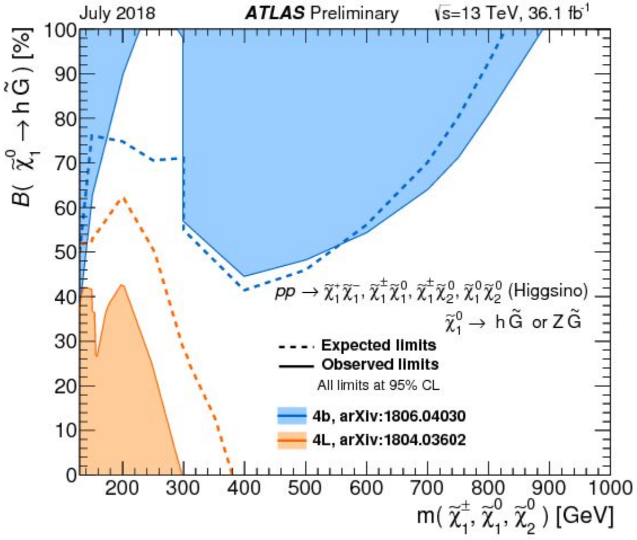


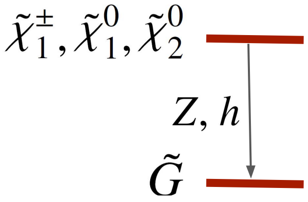
Excesses: Flexible Four Leptons

$\sqrt{s}$ = 13 TeV, 36 fb^{-1} PRD **98** (2018) 032009

General Gauge Mediated SUSY

Higgsino triplet decaying to 1 GeV gravitino LSP (spin 3/2 superpartner of graviton)

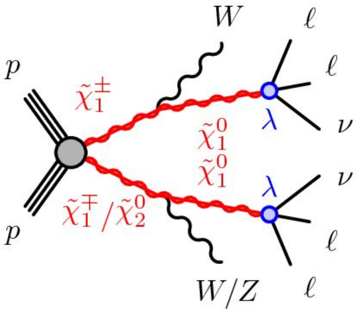


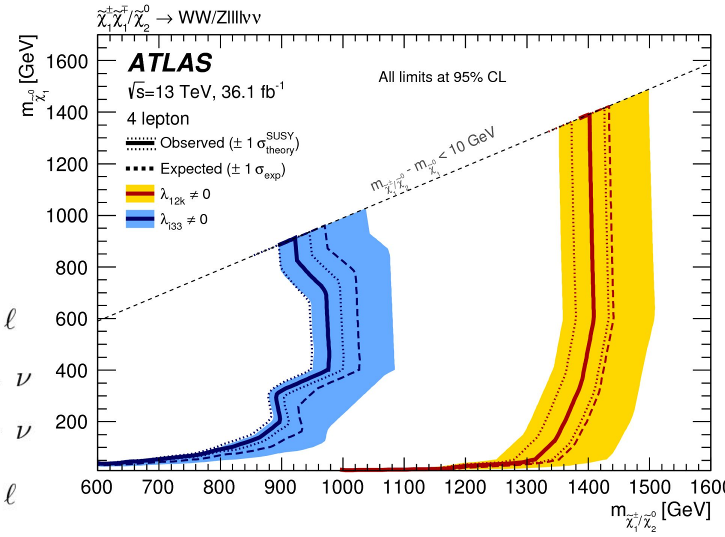


R-Parity Violating SUSY

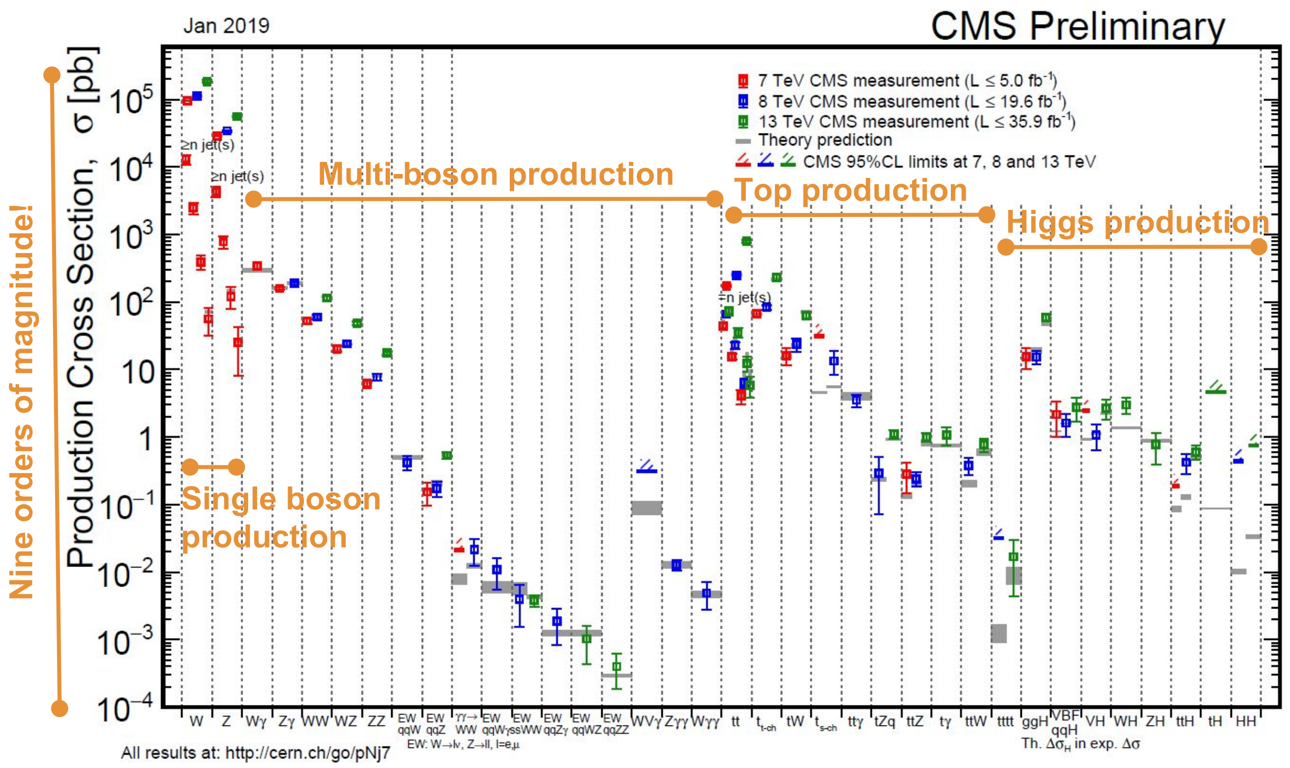
e.g. Wino doublet decaying to unstable LSP.

LFV RPV couplings considered: λ_{12k} or λ_{i33}



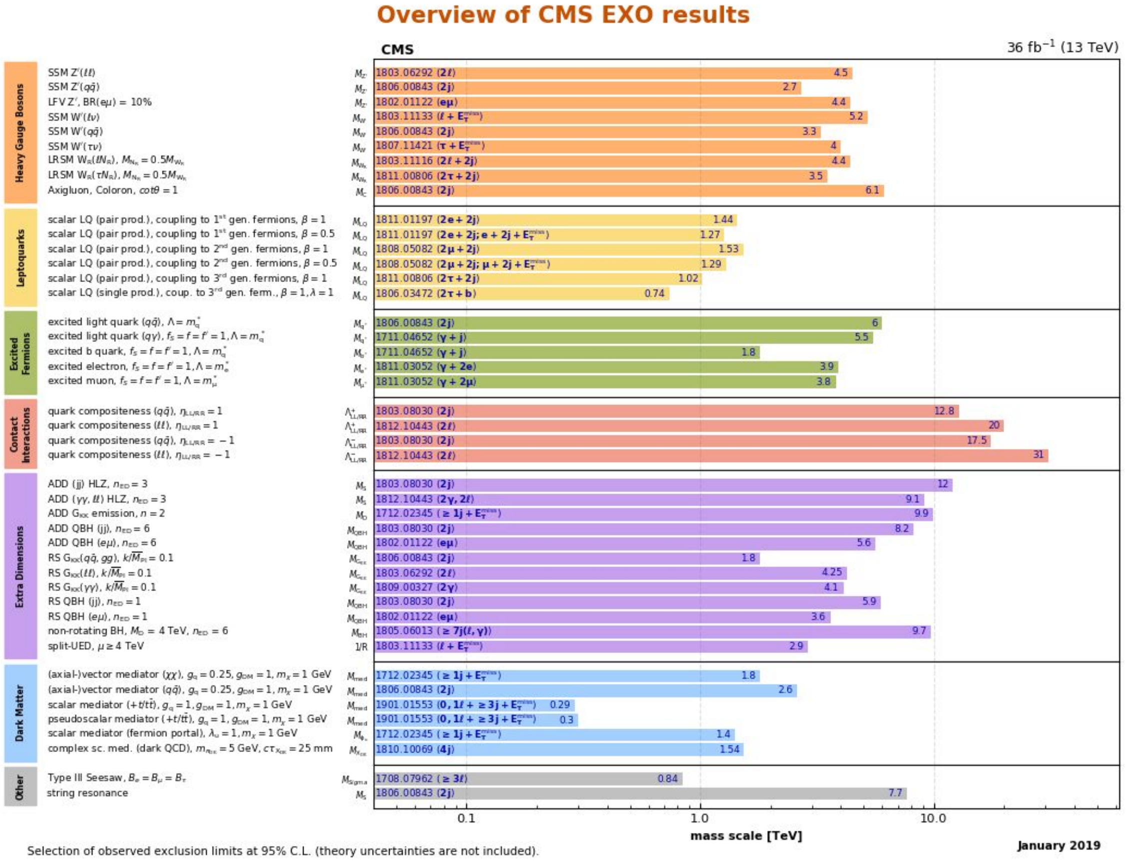


Precision SM measurements: status



The general picture from ATLAS & CMS shows excellent agreement between the data & SM.

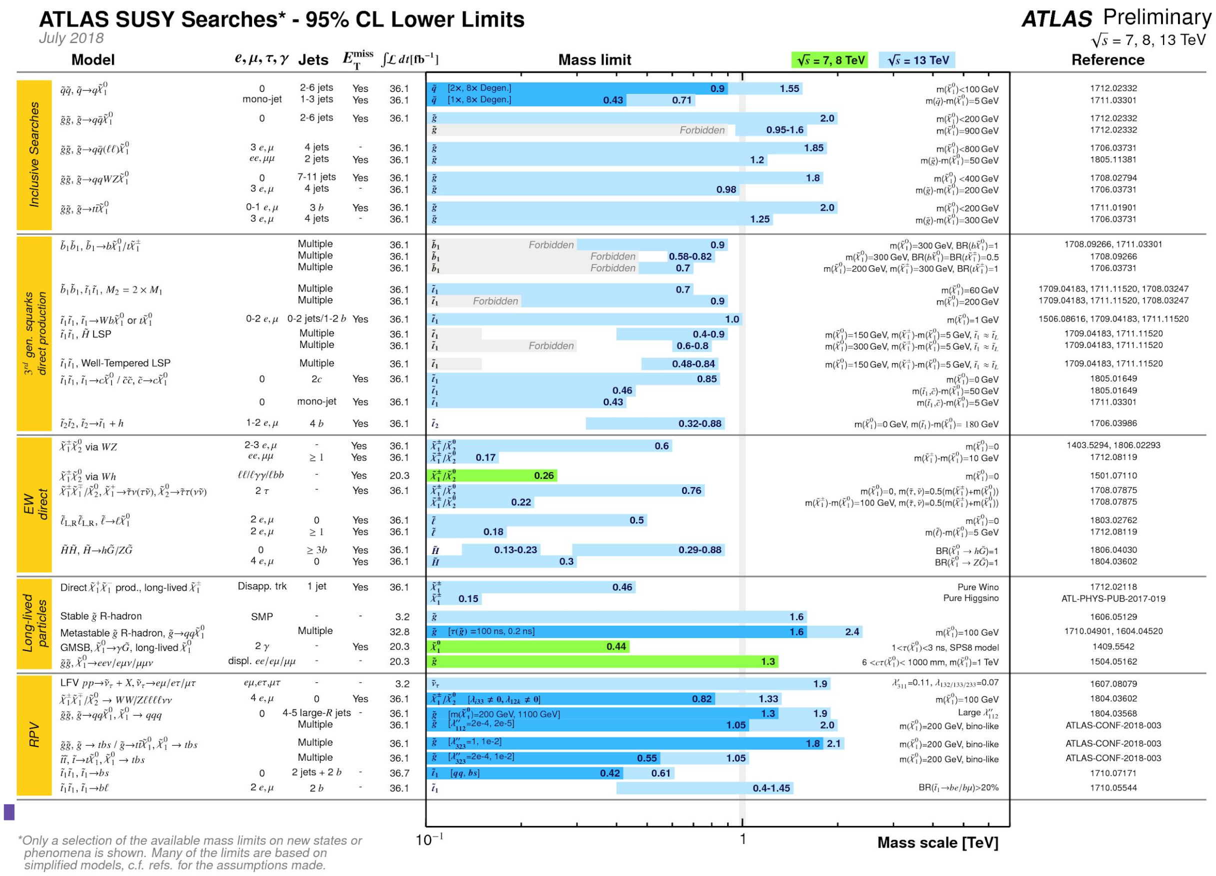
Non-SUSY new physics: status



No new bumps!

Set stringent limits on new resonances.

SUSY: status



No significant excesses!

Set stringent limits on masses (model-dependence).

Using LHC results: HEPdata

All new physics searches are available as HEPdata entries https://www.hepdata.net/

Search records by keywords and year

✖ SUSY ✖ ATLAS Search

HEPData

Browse tables in a record

Helpful visualisation

Various formats supported for download

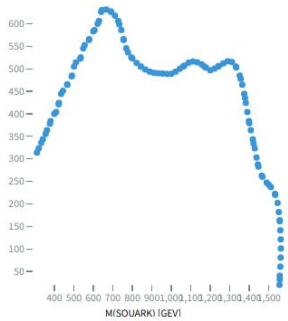
Download All

- YAML
- YODA
- ROOT
- CSV

Showing 50 of 109 values — Show All 109 values

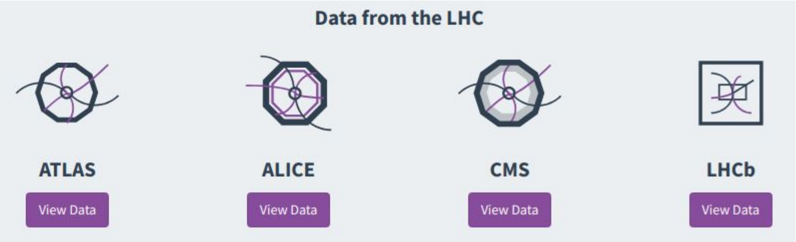
SQRT(S)	13000.0 GEV
M(SQUARK) [GEV]	M(NEUTRALINO1) [GEV]
1555.0	20.2
1556.0	32.35
1556.0	40.4
1559.0	60.61
1561.0	80.81
1562.0	101.0
1561.0	121.2
1559.0	141.4
1556.0	161.6
1556.0	163.7

Visualize



Sum errors ☑ Log Scale (X) ☐ Log Scale (Y) ☐

Deselect variables or hide different error bars by clicking on them.



Using LHC results: HEPdata

Records have approximately same content as public page for paper

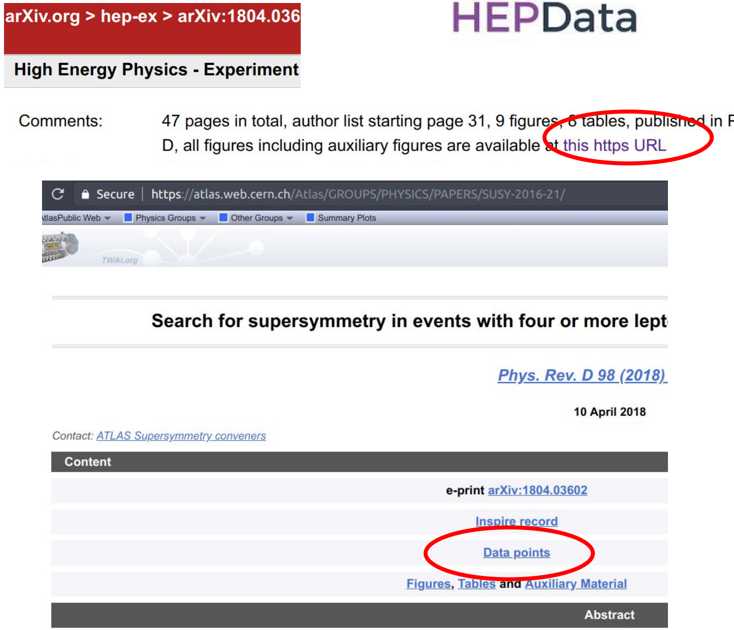
- Exclusion contours
- Upper limits on signal cross-sections
- Signal acceptance and efficiency for all signal regions
- Cutflows for example signals + SLHA file + truth code snippet
- Key kinematic distributions

We want the scientific community to use the publication data we make available.
No need to manually extract from figures or type in.
If you need more information -- ask!

More details in HEP data paper,
[J. Phys.: Conf. Ser. 898 (2017) 102006]

Connect to the HEPdata entry for your favourite result using the twiki link

HEPData



Using LHC results: Rivet

Compare theory predictions to measurements from colliders using Rivet.

Rivet analysis coverage

Rivet analyses exist for 309/5493 papers = 6%. 177 priority analyses required.

Total number of Inspire papers scanned = 6927, at 2019-02-19

Breakdown by identified experiment (in development):

Key	ALICE	ATLAS	CMS	LHCb	B-factories	HERA	Other
Rivet wanted (total):	200	254	345	161	1498	450	2276
Rivet REALLY wanted:	35	40	74	10	2	14	2
Rivet provided:	**20**/220 = **9%**	**145**/399 = **36%**	**74**/419 = **18%**	**11**/172 = **6%**	**14**/1512 = **1%**	**4**/454 = **1%**	**41**/2317 = **2%**

Takes experimental phase space into account.

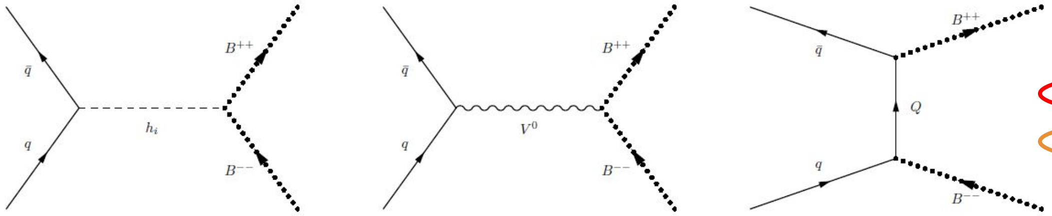
Already contains many measurements.

Easy to add your own analysis.

Using LHC results: model-independent limits

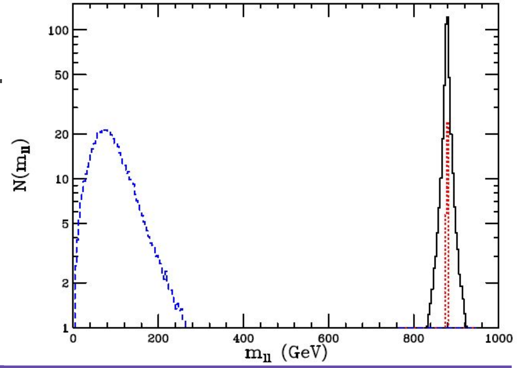
Take your favourite new physics scenario and compare directly to the most relevant LHC result.

e.g.
Bileptons, Corcella *et. al*, PLB 785 (2018) 73-83



Benchmark Point		
$m_{h_1} = 126.3$ GeV	$m_{h_2} = 1804.4$ GeV	$m_{h_3} = 2474.0$ GeV
$m_{h_4} = 6499.8$ GeV	$m_{h_5} = 6528.1$ GeV	
$m_{a_1} = 1804.5$ GeV	$m_{a_2} = 6496.0$ GeV	$m_{a_3} = 6528.1$ GeV
$m_{h_1^\pm} = 1804.5$ GeV	$m_{h_2^\pm} = 1873.4$ GeV	$m_{h_3^\pm} = 6498.1$ GeV
$m_{h_1^{\pm\pm}} = 878.3$ GeV	$m_{h_2^{\pm\pm}} = 6464.3$ GeV	$m_{h_3^{\pm\pm}} = 6527.7$ GeV
$m_{Y^{\pm\pm}} = 878.3$ GeV	$m_{Y^\pm} = 881.8$ GeV	$m_{Z'} = 3247.6$ GeV
$m_D = 1650.0$ GeV	$m_S = 1660.0$ GeV	$m_T = 1700.0$ GeV

Each Bilepton B^{++} decays into two leptons with the same charge and flavour.
High momentum leptons with low-background from the Standard Model.



The benchmark scenario has a spectacular signature at the LHC
4 leptons (l^+l^+ and l^-l^-), with $m(ll) = m(B^{++})$

Using LHC results: model-independent limits

No ATLAS or CMS search designed for bileptons.
H^{++} searches set narrow limits on masses.

Look at non-resonant searches
e.g. ATLAS 4L SUSY search is highly sensitive to Bilepton scenarios

PRD 98 (2018) 032009 (36 fb^{-1} @$\sqrt{s}$ = 13 TeV)

SUSY-centered, but designed for ***model-independence***

$\geq$ 4 $e/\mu/\tau$, Z veto/request, high m_{eff} or E_T^{miss}

$m_{eff} = E_T^{miss} + \Sigma p_T^{lep}$

m_{eff}>600 >1100 GeV

Sample	SR0A	SR0B
Observed	13	2
SM Total	10.2 ± 2.1	1.31 ± 0.24
$\langle\epsilon\sigma\rangle^{95}_{obs}$ fb	0.32	0.14
S^{95}_{obs}	12	4.9

No significant excess.

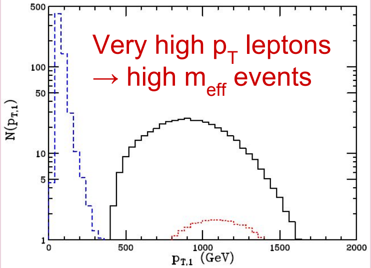
Set 95% CL limits on new physics in SRs

Apply to Bilepton scenario m(Y/H)=878.3 GeV
for 4L, p_T>20 GeV, $|\eta|$<2.5, ΔR>0.1

$$\sigma(pp \to YY \to 4l) \simeq 4.3 \text{ fb}$$

155 $YY \to 4L$ events in 36 fb^{-1} dataset

x ε_L^4 x ε_{SR}
(95% e/μ efficiency) (50-100% SR efficiency)



→ 126 events (SRA)
→ 63 events (SRB)
Ruled out* by ATLAS observations.
*some dilution expected if the BR(Y → $ee/\mu\mu$) <100%

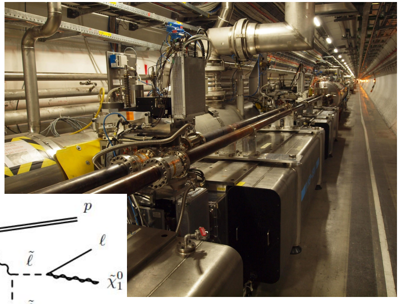
$$\sigma(pp \to HH \to 4l) \simeq 0.3 \text{ fb}$$

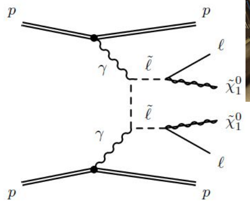
→ 9 events (SRA) → 4.5 events (SRB)
Not quite ruled out by ATLAS observations.

Prospects?

Is new physics at the LHC dead? **A loud and emphatic NO!**

Absolute Luminosity For ATLAS





The LHC experiments are progressing very well, but we still have a way to go

- \+ full Run2 dataset (13TeV, 2015-2018, 140 fb^{-1}),
- \+ Run3 (14TeV, 2021, 300 fb^{-1})
- \+ HL-LHC (14TeV, 3000 fb^{-1}), Yellow Report

Some signatures are only recently technically possible to search for (trigger, phase space, statistics).

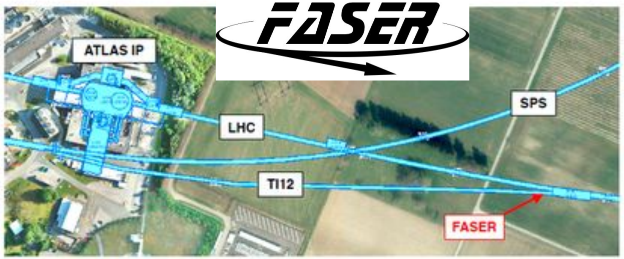
New physics has not appeared as low-hanging fruit

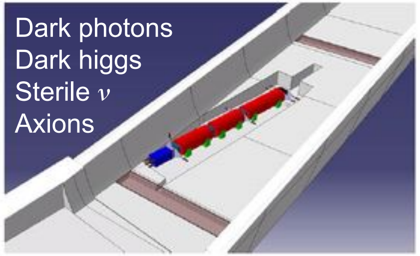
- High-mass? Low cross-section?
- Kinematically similar to SM?
- Are we looking in the wrong place?

  New signatures?

  Some interesting ideas how to further exploit the LHC FASER, ALFA

ForwArd Search ExpeRiment at the LHC, *pp* → *LLP* + *X*





Summary

Exciting times!

Results from measurements and searches continue to pour from the LHC.
High hopes of new physics discovery at the LHC

Explanation for shadowy Dark Matter?

Dig deep into the data!

Will the Run2 data throw us a surprise?

Rencontres de Moriond ongoing this & next week where many updates are being presented.

Keep your eye on results from ATLAS, CMS & LHCb

ATLAS 4L SUSY search

	≥ 4 e/μ				3 e/μ + ≥ 1 τ	2 e/μ + ≥ 2 τ
	Z veto		Z request		Z veto	Z veto
	m_{eff} > 600 GeV,	>1.1 TeV	E_T^{miss} >50 GeV,	>100 GeV	m_{eff} > 700 GeV	m_{eff} > 650 GeV
Sample	SR0A	SR0B	SR0C	SR0D	SR1	SR2
Observed	13	2	47	10	8	2
SM Total	10.2 ± 2.1	1.31 ± 0.24	37 ± 9	4.1 ± 0.7	4.9 ± 1.6	2.3 ± 0.8
ZZ	2.7 ± 0.7	0.33 ± 0.10	28 ± 9	0.84 ± 0.34	0.35 ± 0.09	0.33 ± 0.08
$t\bar{t}Z$	2.5 ± 0.6	0.47 ± 0.13	3.2 ± 0.4	1.62 ± 0.23	0.54 ± 0.11	0.31 ± 0.08
Higgs	1.2 ± 1.2	0.13 ± 0.13	0.9 ± 0.8	0.28 ± 0.25	0.5 ± 0.5	0.32 ± 0.32
VVV	0.79 ± 0.17	0.22 ± 0.05	2.7 ± 0.6	0.64 ± 0.14	0.18 ± 0.04	0.20 ± 0.06
Reducible	2.4 ± 1.4	$0.000^{+0.005}_{-0.000}$	$0.9^{+1.4}_{-0.9}$	$0.23^{+0.38}_{-0.23}$	3.1 ± 1.5	1.1 ± 0.7
Other	0.53 ± 0.06	0.165 ± 0.018	0.85 ± 0.19	0.45 ± 0.10	0.181 ± 0.022	0.055 ± 0.012
$\langle\epsilon\sigma\rangle^{95}_{obs}$ fb	0.32	0.14	0.87	0.36	0.28	0.13
S^{95}_{obs}	12	4.9	31	13	10	4.6
S^{95}_{exp}	$9.3^{+3.6}_{-2.3}$	$3.9^{+1.6}_{-0.8}$	23^{+8}_{-5}	$6.1^{+2.1}_{-1.3}$	$6.5^{+3.5}_{-1.3}$	$4.7^{+2.0}_{-1.3}$
CL_b	0.76	0.74	0.83	0.99	0.86	0.47
$p_{s=0}$	0.23	0.25	0.15	0.011	0.13	0.61
Z	0.75	0.69	1.0	2.3	1.2	0