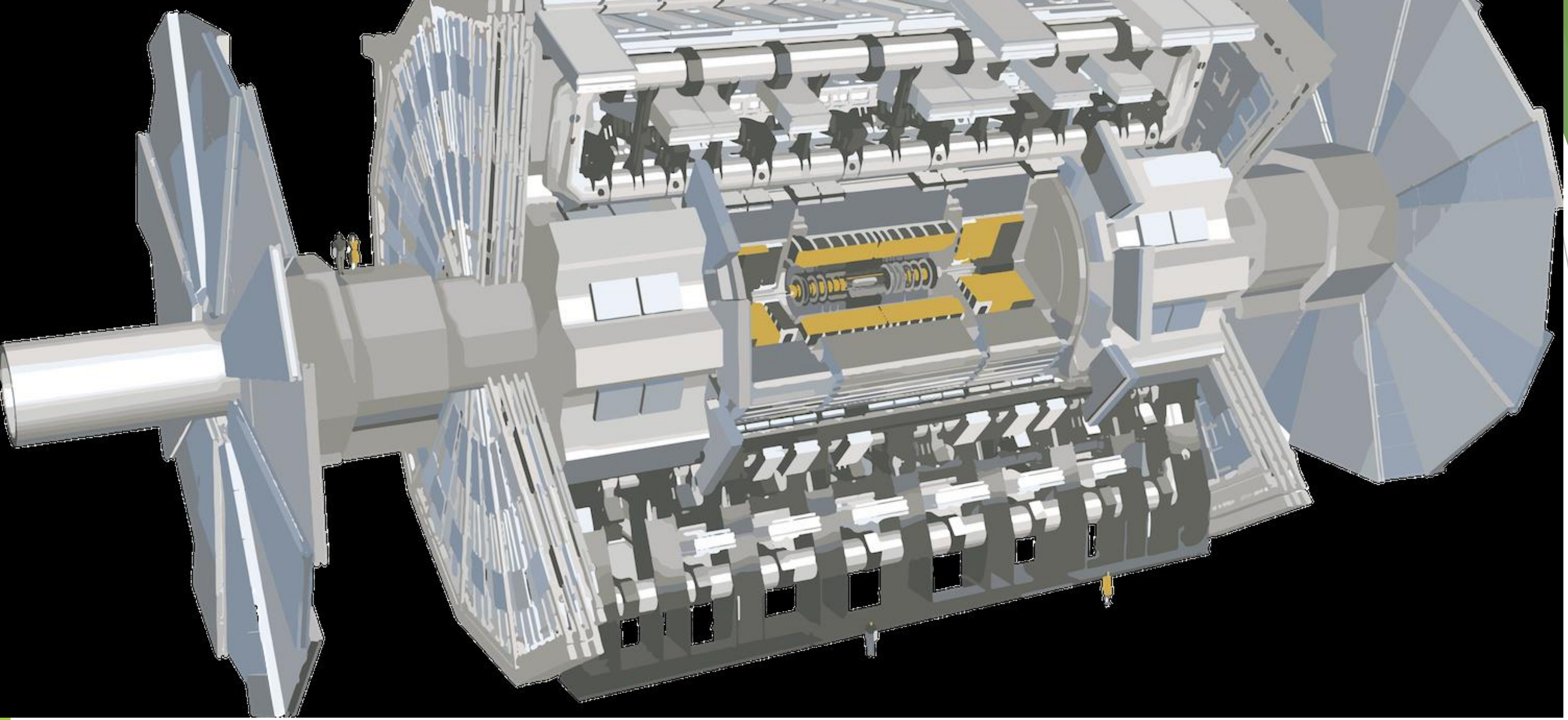
New searches in ATLAS experiments

A.Myagkov
NIC KI - IHEP



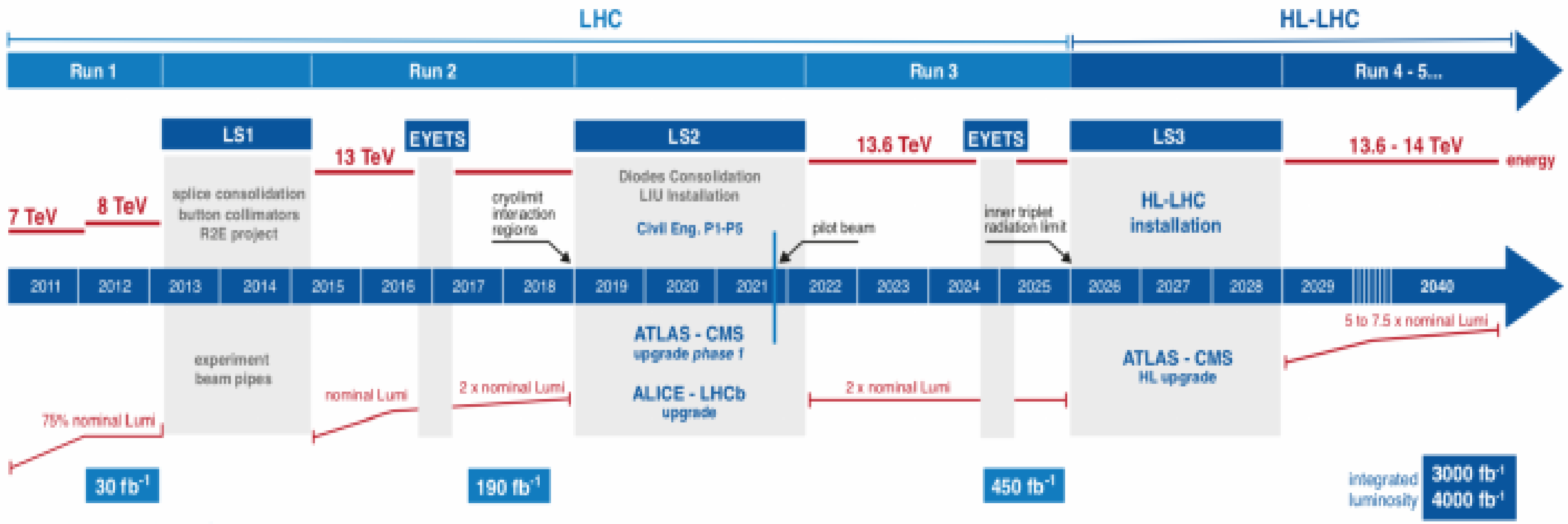
A ‘general purpose’ detector

1% measurement of muon **momentum and electron energy**

Excellent calorimetry for jet energy and missing energy

Triggering on muons, electrons, photons and jets

LHC: status and plans



Run 3 6.8 TeV

ATLAS, CMS target 250 /fb

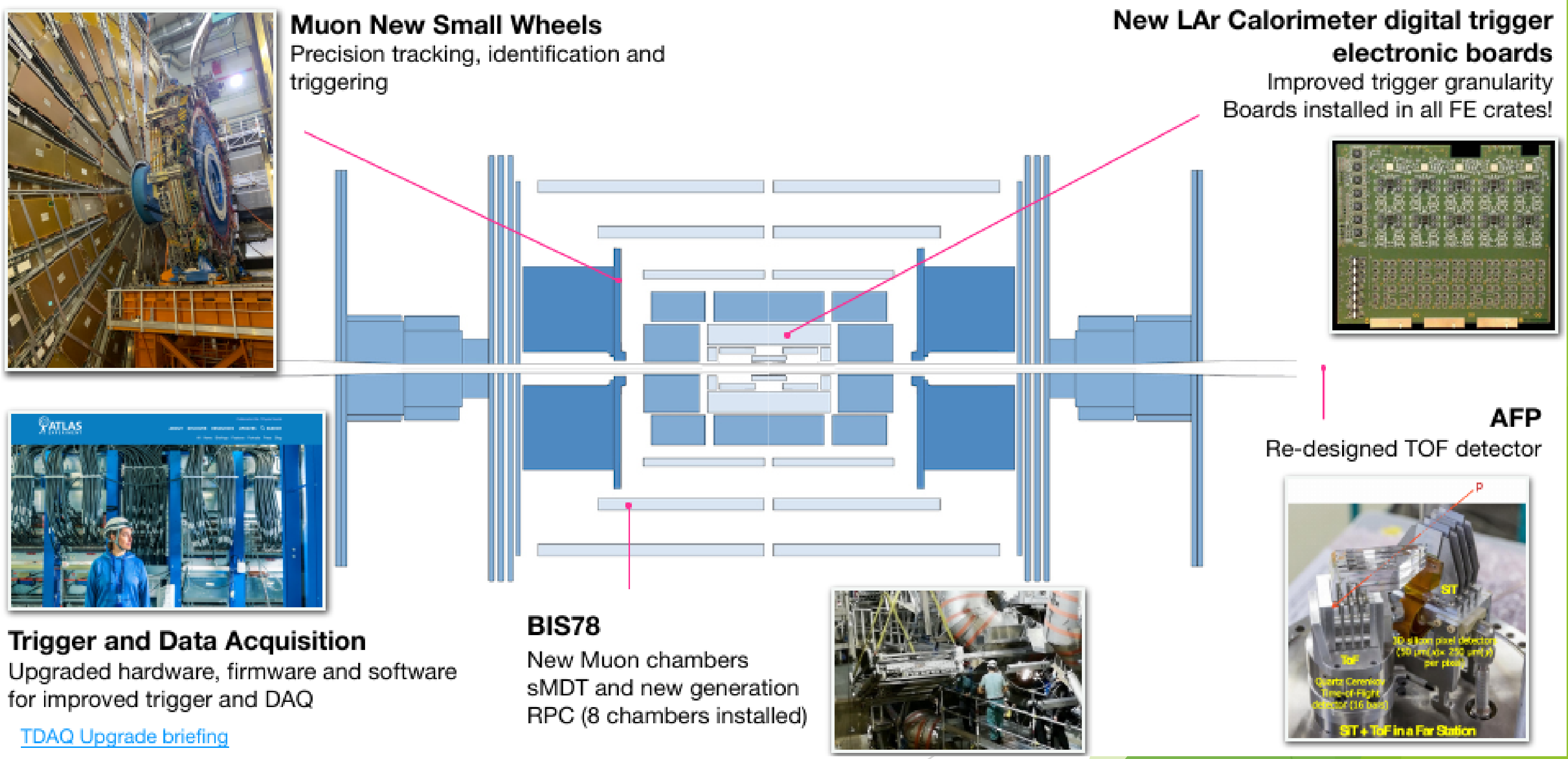
Run 4 (HL_LHC) High pileup up to ‹μ›=140-200, high particle multiplicity, plan ~3/ab

ATLAS Upgrade Phase 1

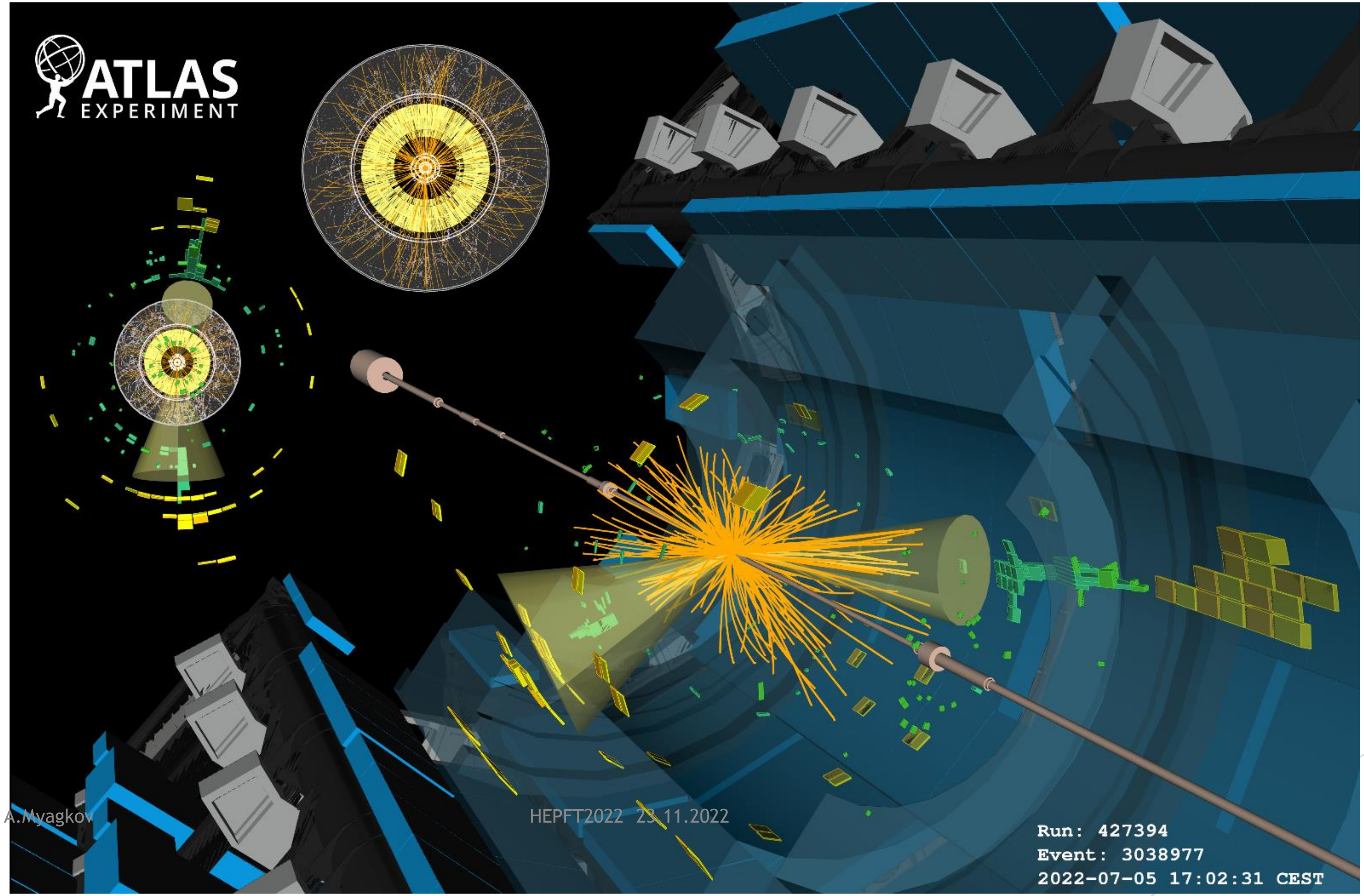
New Small Wheel muon detector: replacement of previous end-cap CSC based detector with a sTGC+MicroMega

BIS78-RPC muon detector: new RPCs in the barrel to improve the rejection rate of the L1 trigger in the barrel-endcap transition region

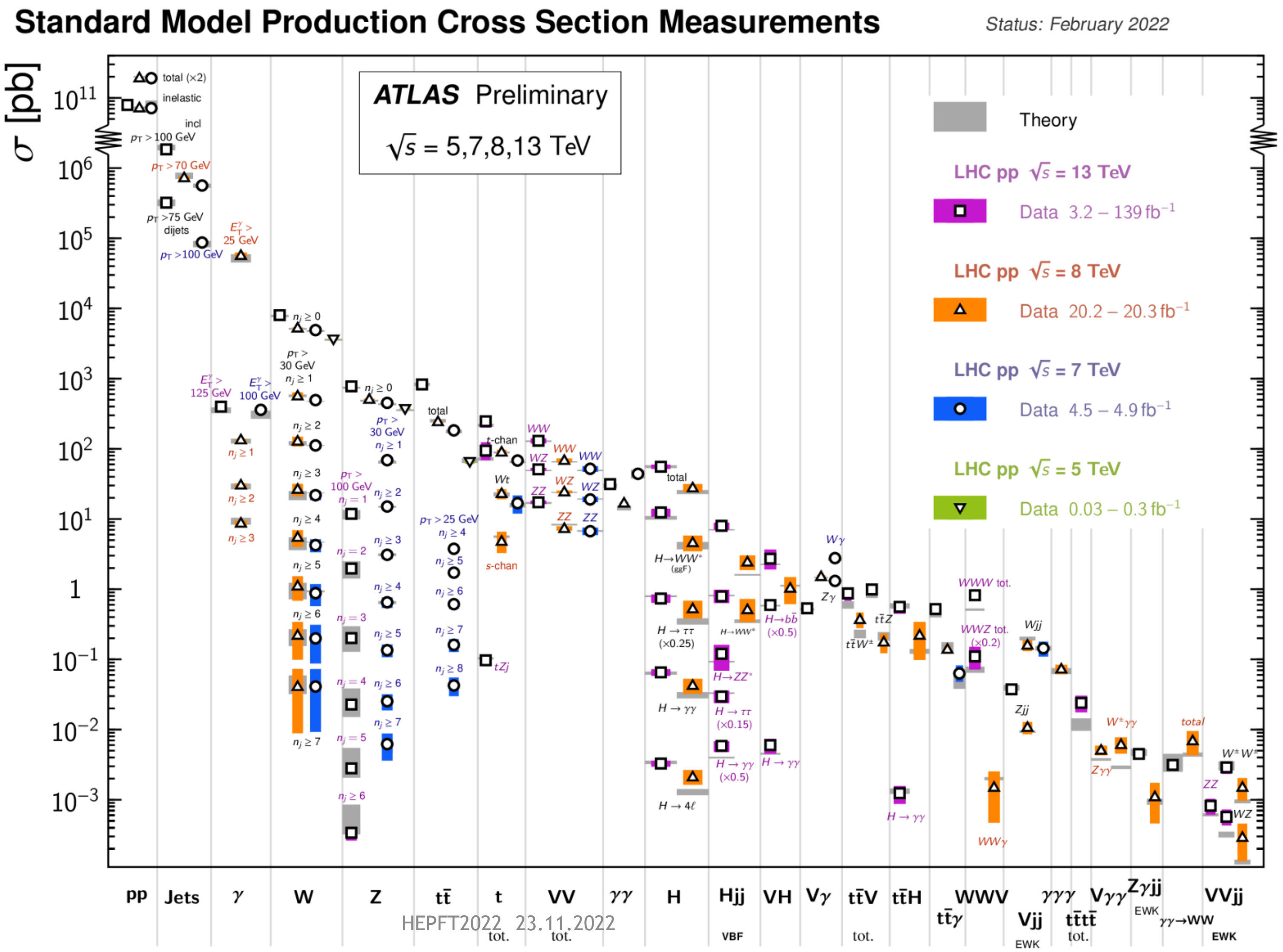
LAr front-end: new electronics with higher granularity for improved performances of the detector and of the Level-1 Calorimeter electromagnetic trigger



First events Run 3

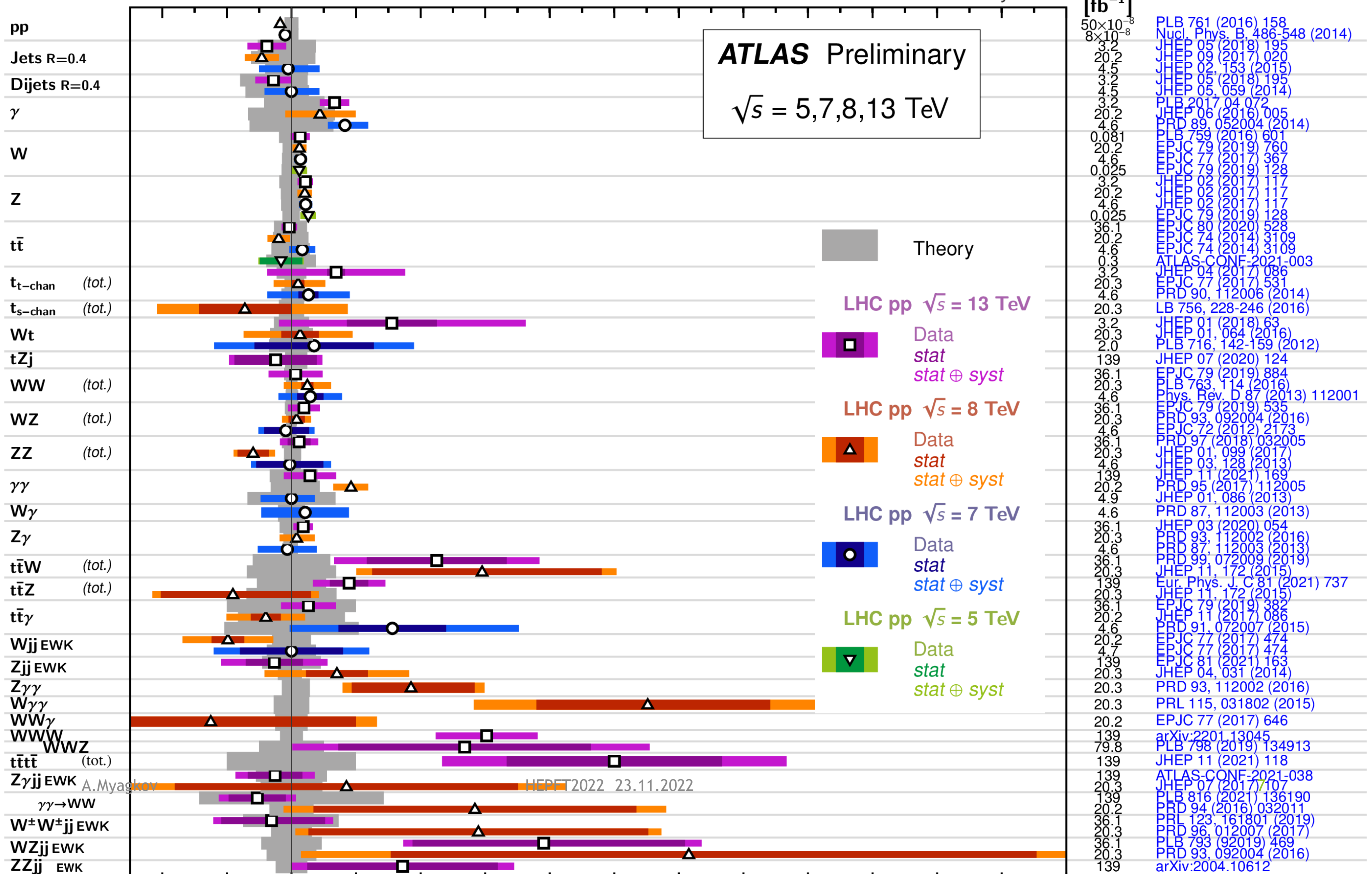


Main SM processes and measured X-sec



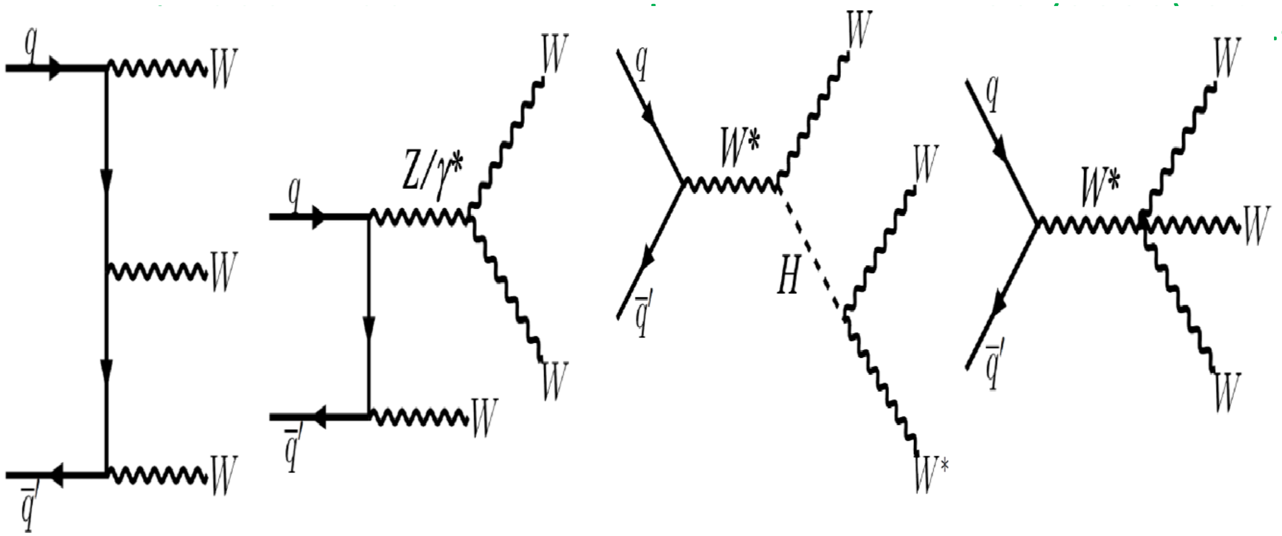
Standard Model Production Cross Section Measurements

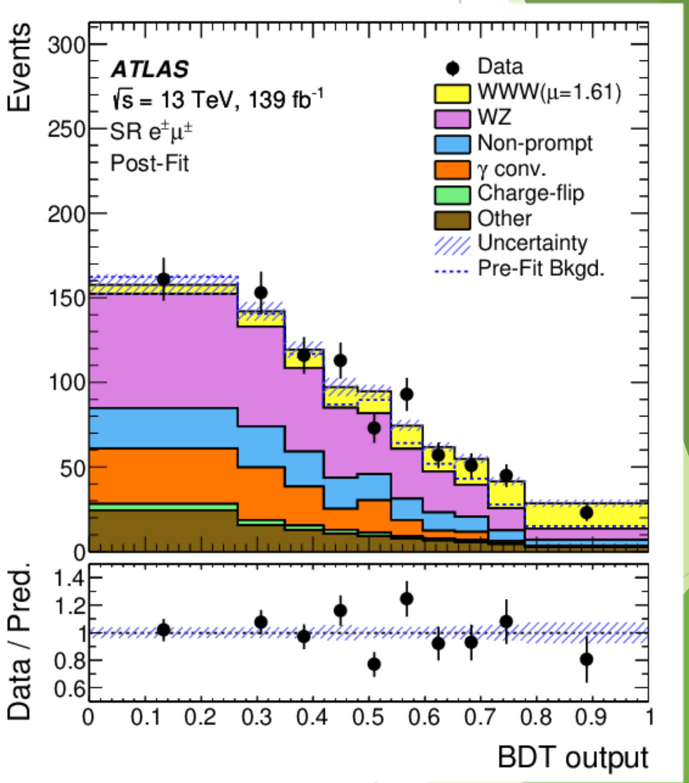
Status: February 2022



ATLAS first observation of production *WWW*

.803





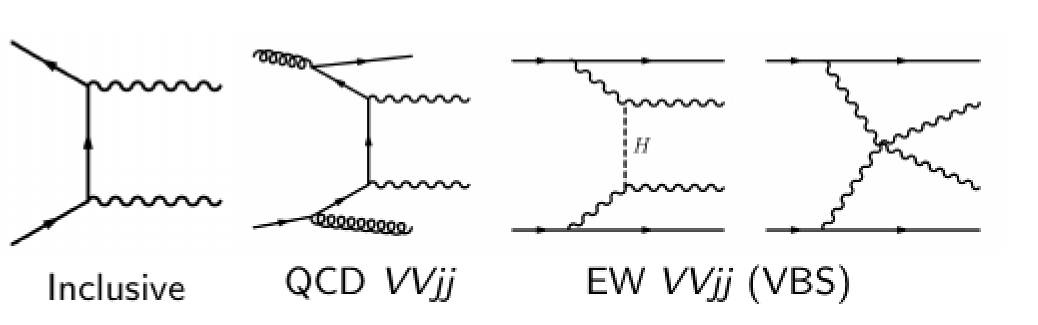
Measurements of triboson production are a direct test of SM gauge boson self-interactions, deviations would hint at NP

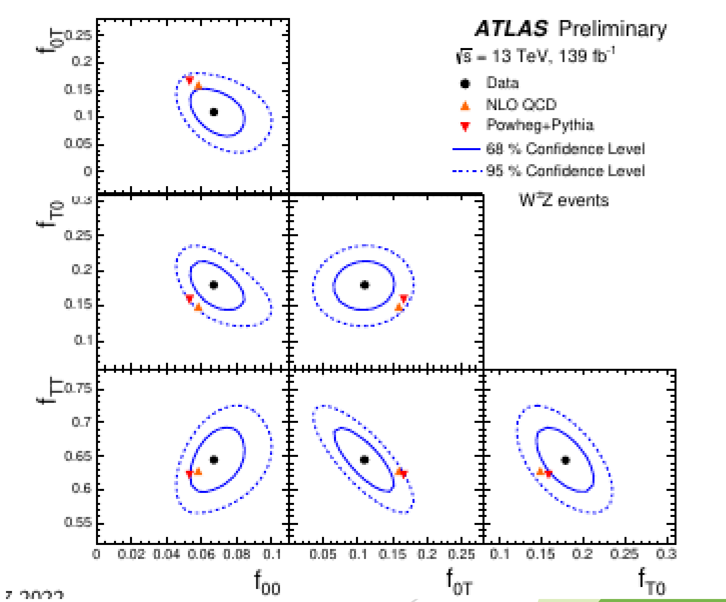
• Triboson states are among the least-understood SM processes given the small production cross sections

• WWW production looked for by ATLAS in 2l (SS) and 3l states
Observed for first time with a significance of 8.0 σ (5.4 expected)
σ WWW(incl) = 820 ± 100(stat) ± 80(syst) fb
compatible with SM at 2.6 σ (SM: 511 ± 18 fb)

WZ (lvll) polarisation
ATLAS-CONF-2022-053

- Electroweak VVjj production can proceed in transverse (T) or longitudinal (0) polarisation states
- Longitudinal (00) component intertwined with Higgs mechanism VBS unitarization: long term goal
- Probes for the HL-LHC
- currently measurements focus on polarisation or VBS
- New: first measurement of joint polarisation states in inclusive WZ production by ATLAS using DNN
- reconstruction techniques - observation of double-longitudinal component with > 7σ





Measured joint helicity fractions f00, f0T, fT0 and fTT of the W and Z bosons in W±Z events, compared to NLO QCD fixed-order predictions

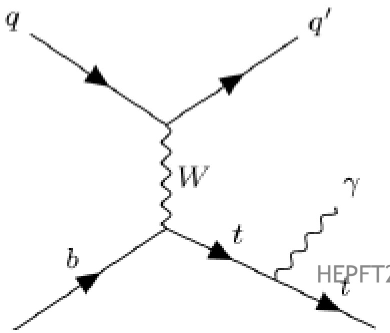
Rare single top production ATLAS-CONF-2022-013 ATLAS-CONF-2022-031

- Rare single top process observation
- Tqγ Single-top quark and a photon of all single-top processes
- Powerful probe of top-EW coupling

(and constraints on new physics)

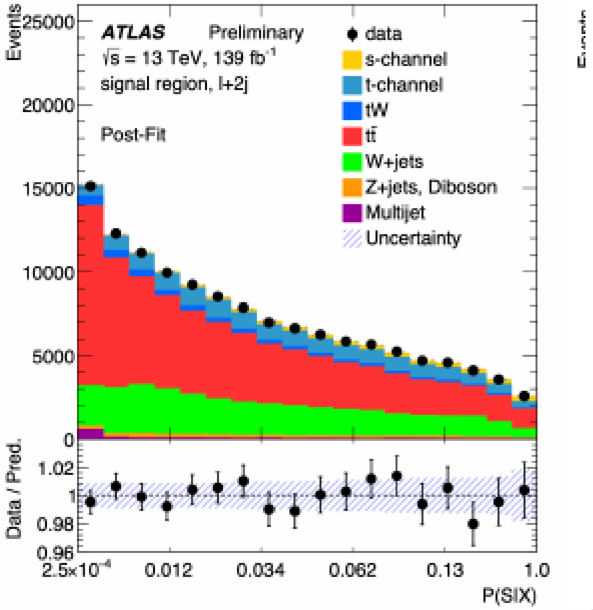
- semileptonic top-quark decays ($t \to l\nu b$)
- The observed (expected) significance

of the tqγ signal is 9.1σ (6.7σ)



S-channel single top production

Lowest cross-section measurement



3.3σ Observed (3.9 σ expected)

Higgs boson

Monday 4 Jul 2022, CERN

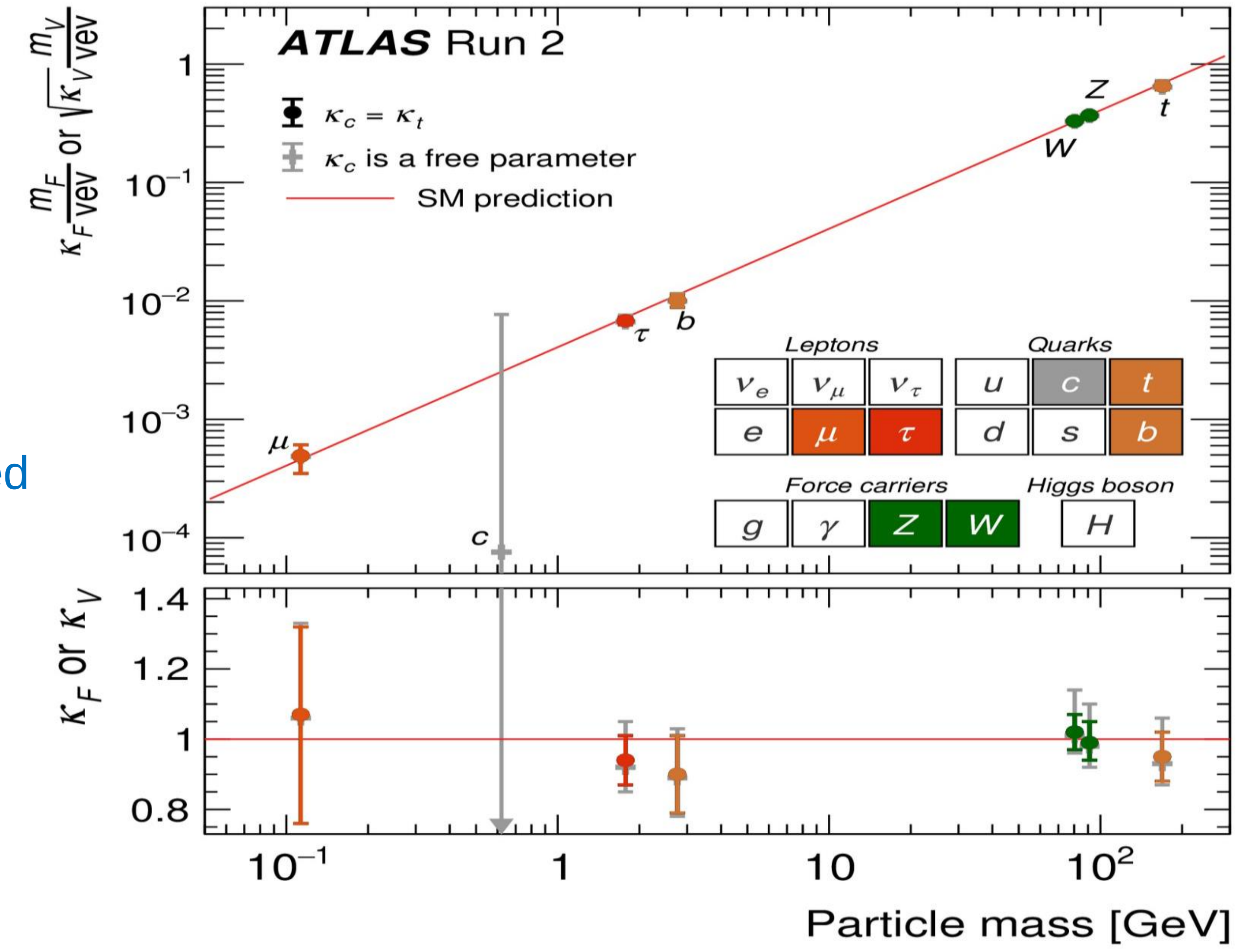
Nature volume 607, pages52–59 (2022)
2207.00092 A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery

Nature 607 (2022) 60
2207.00043 A portrait of the Higgs boson by the CMS experiment ten years after the discovery

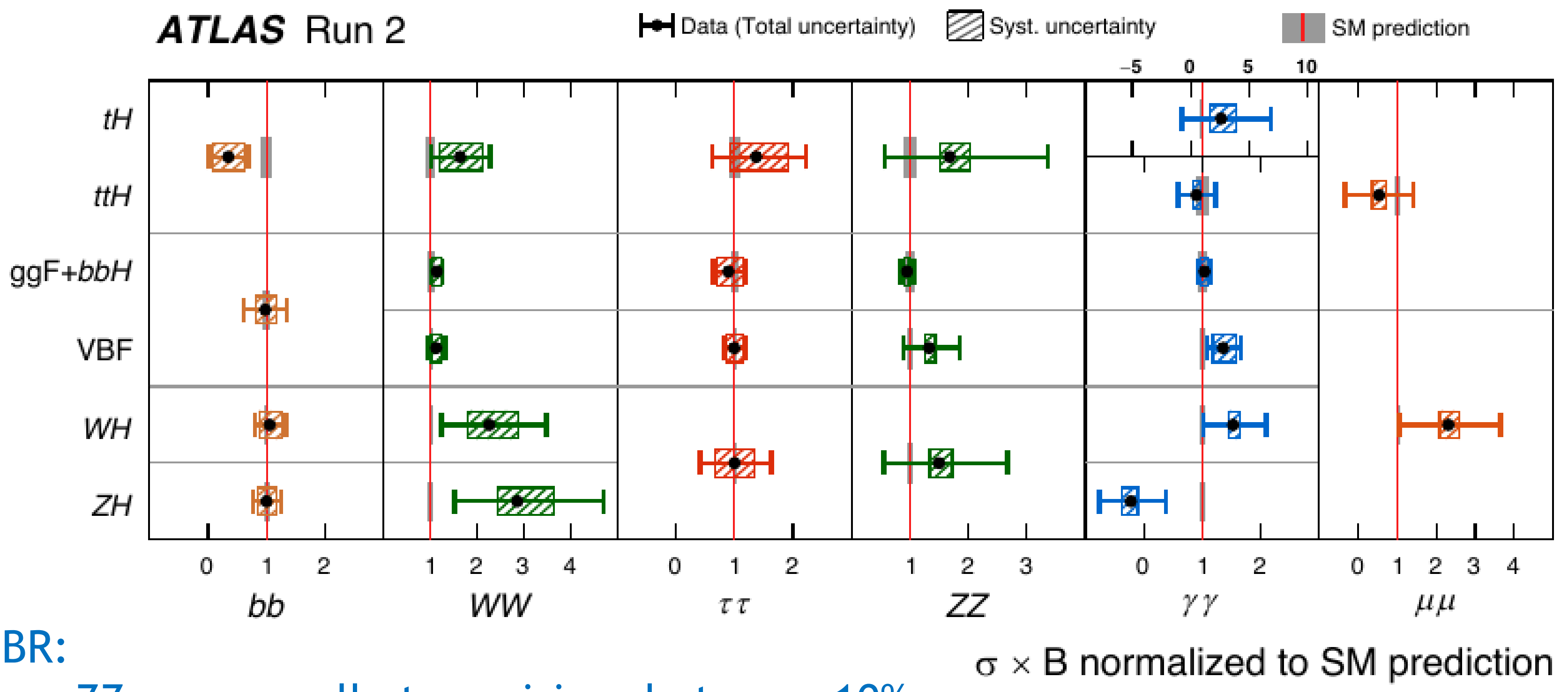
Couplings vs mass

Nature 607, 52–59 (2022)

- Interaction should scale with mass
- Confirmed for vector bosons and all 3rd generation fermions
- 2nd generation fermions now being constrained too



Coupling in productions and decays

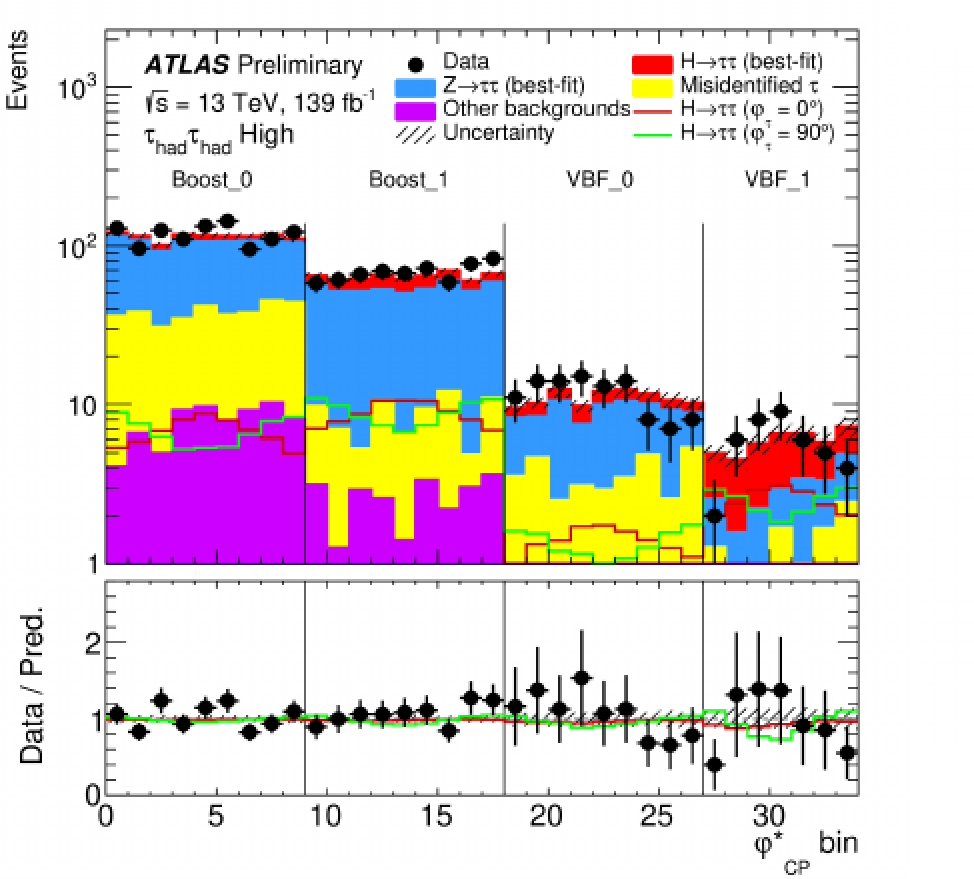


For decay BR:

- H→WW, ττ, ZZ, γγ now all at precisions between 10% and 12%
- H→bb observed with 7.0σ (7.7σ)
- H→ μμ with significances of 2.0σ (1.7σ) and Zγ with 2.3σ (1.1σ)

CP properties Higgs boson

- ATLAS-CONF-2022-032
- H → τ+ τ- (at least one decay hadronically)
- CP-sensitive angular distribution was measured
  Pure CP odd (φ τ = ± 90∘) disfavoured at 3.4σ
- CP-odd contribution not observed



Heavy Resonance Searches

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

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 $G_{KK} \to WV \to \ell\nu qq$	1 e, μ	2 j / 1 J	Yes	139	G_{KK} mass 2.0 TeV	$k/\overline{M}_{Pl} = 1.0$	2004.14636
	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 $Z' \to tt$	0 e, μ	≥ 1 b, ≥ 2 J	Yes	139	Z' mass 4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	139	W' mass 6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $W' \to WZ \to \ell\nu qq$ model B	1 e, μ	2 j / 1 J	Yes	139	W' mass 4.3 TeV	$g_V = 3$	2004.14636
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	139	V' mass 3.8 TeV	$g_V = 3$	1906.08589
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	1712.06518
	HVT $W' \to WH$ model B	0 e, μ	≥ 1 b, ≥ 2 J		139	W' mass 3.2 TeV	$g_V = 3$	CERN-EP-2020-073
	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	–	–	139	Λ 35.8 TeV η_{LL}^-		CERN-EP-2020-066
	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	$\mathcal{B}(LQ_3^u \to b\tau) = 1$	1902.08103
	Scalar LQ 3rd gen	0-1 e, μ	2 b	Yes	36.1	LQ_3^d mass 970 GeV	$\mathcal{B}(LQ_3^d \to t\tau) = 0$	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 $T_{5/3} T_{5/3} \lvert T_{5/3} \to Wt + X$	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^*, $\Lambda = m(q^*)$	1910.08447
	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

$\sqrt{s}$ = 8 TeV $\sqrt{s}$ = 13 TeV partial data $\sqrt{s}$ = 13 TeV full data

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

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

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

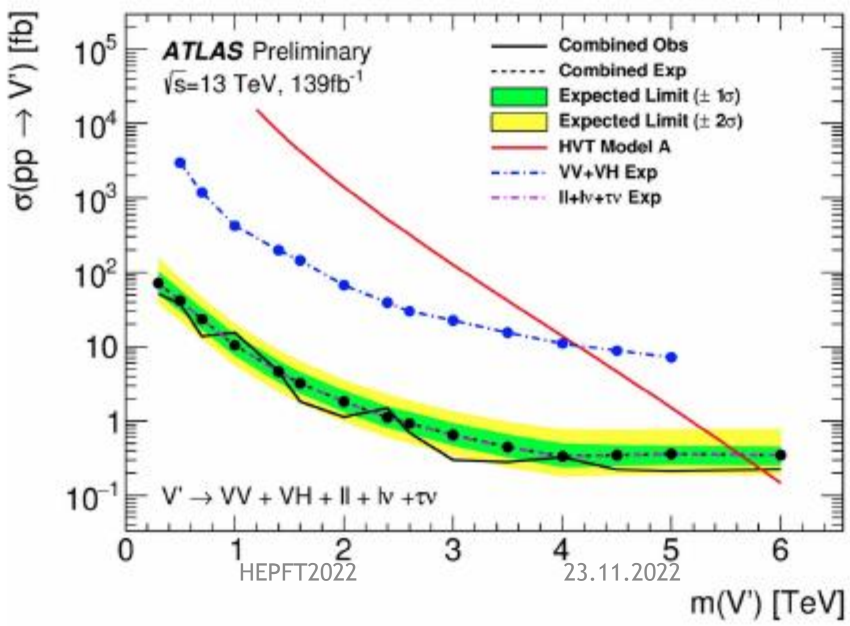
Heavy-resonance searches

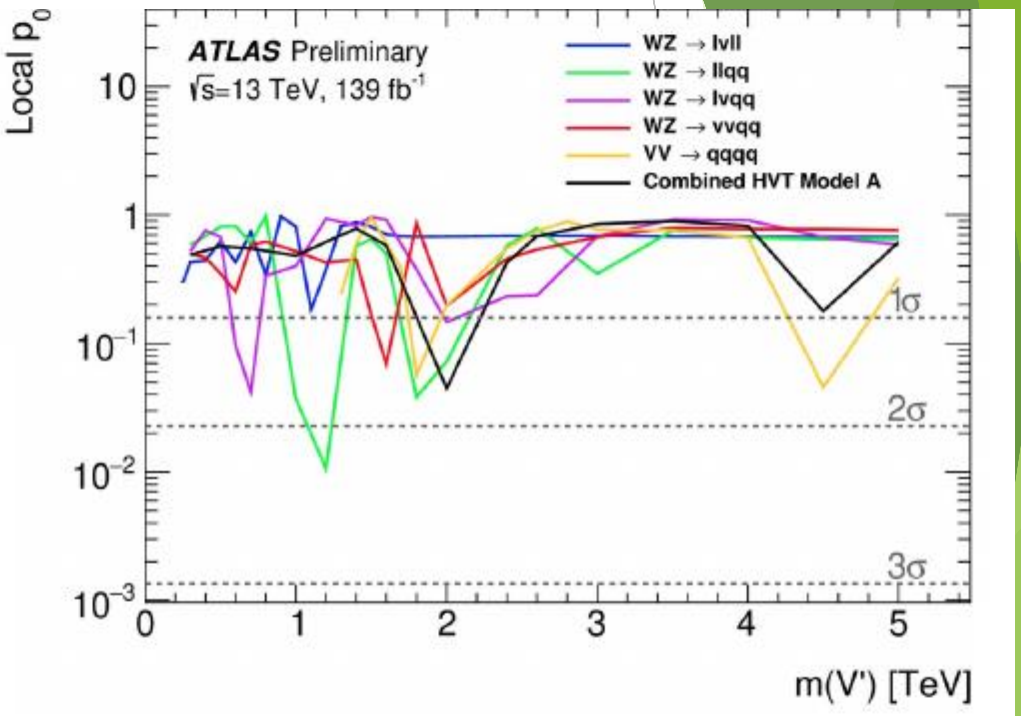
- ~100 decay channels studied for various models that predict certain production rate (extra dimensions, gauge bosons, contact interactions, dark matter, heavy quarks, excited fermions, leptoquarks etc)
- - Commonly excluded masses ~ **0.4 - 12 TeV**

Combination of searches for heavy resonances

- ATLAS-CONF-2022-028
- Uses 16 (orthogonal) ATLAS publications during 2018 - 2022
- Combine bosonic decay modes qqqq, vvqq, lvqq, llqq, lvll, qqbb, vvbb, lvbb
- Results are interpreted in terms in the context of Spin-1 Heavy Vector Tripl
- V' is collectively denotes W'+ and Z'

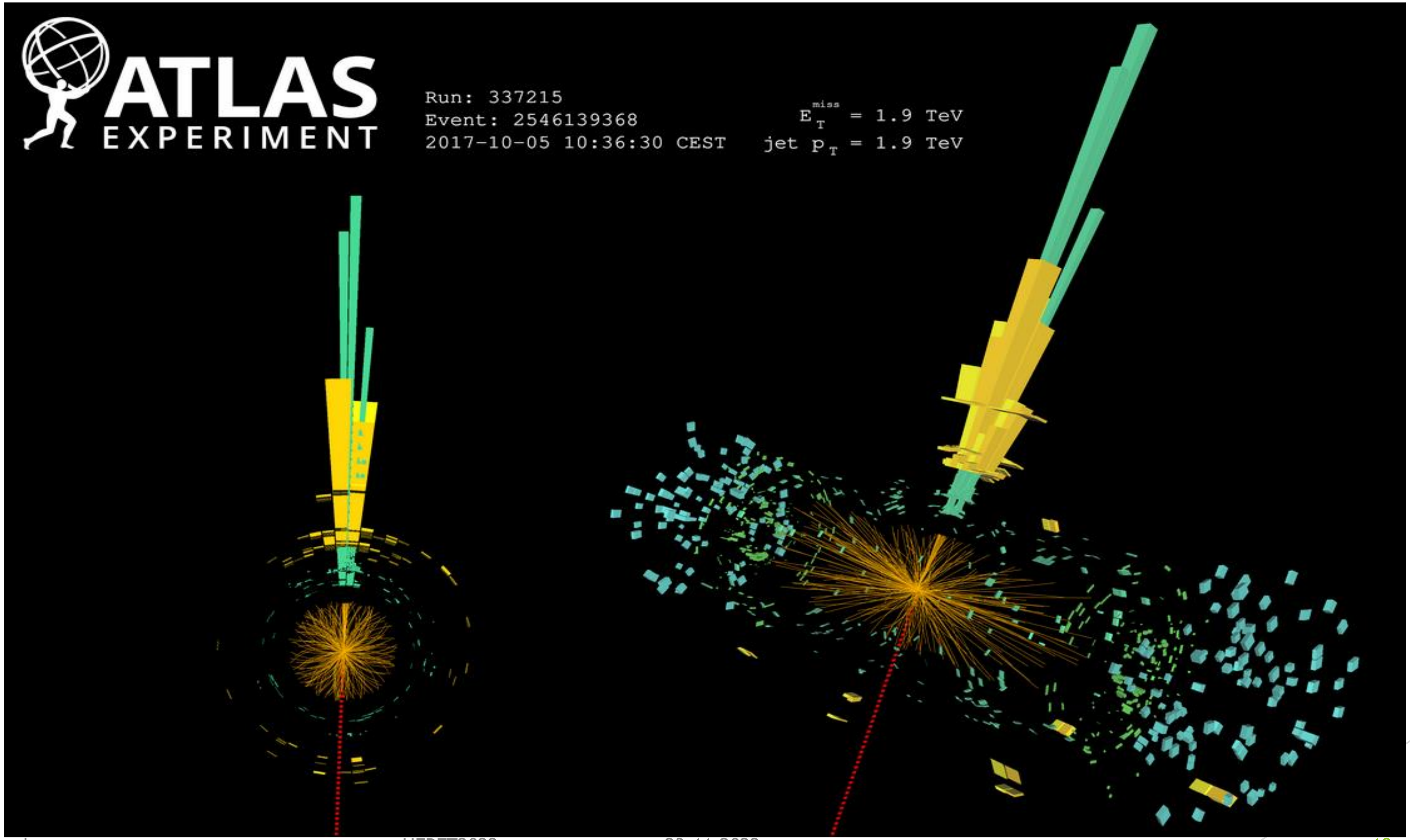
Weakly coupled HVT-A coupling



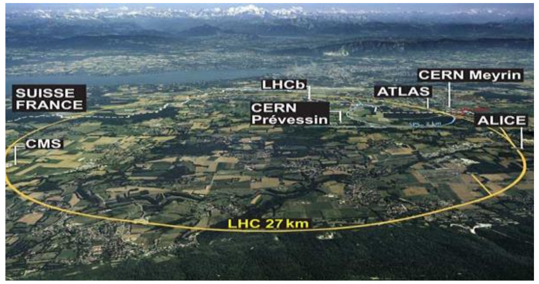


Typical example of p-value scan over the HVT pole masses up to 5 TeV

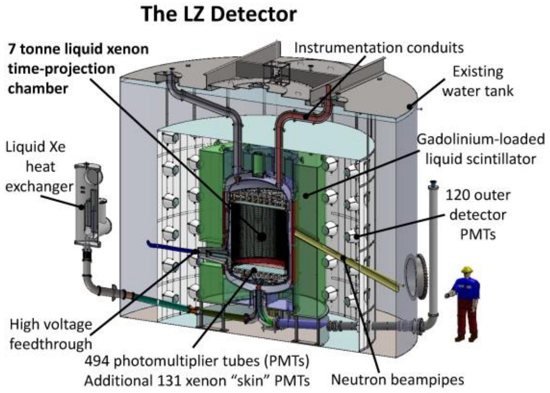
Searches for Dark Matter (DM)

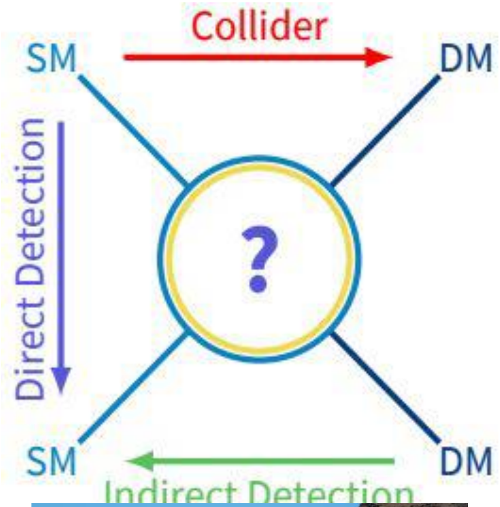


Searches for Dark Matter (DM)

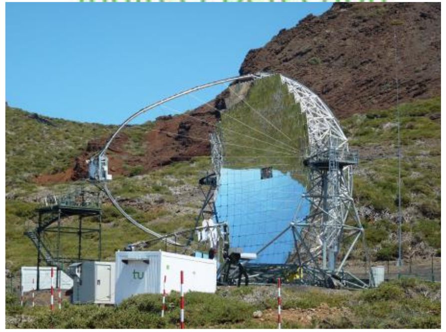


Direct production
of DM
ATLAS, CMS





Direct detection
Detect interactions between dark matter and ordinary matter (e.g. nuclear recoils):
XENON, SNOLAB

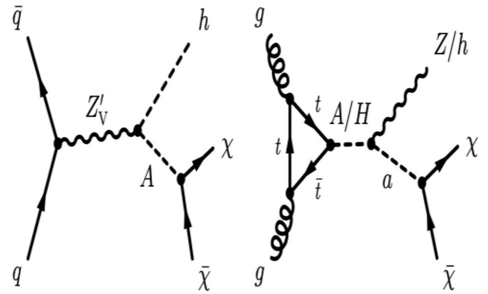


Indirect detection
Detect ordinary matter resulting from decay/annihilation of dark matter
(ICECUBE, HESS)

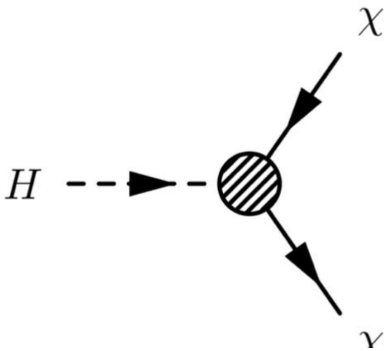
There are three complementary philosophies to search for DM at the LHC

- **Effective Field Theory (EFT) - typically depends on two Degrees of Freedom (M_DM and M* - UV cut off scale)**
- **Simplified (or simple) models - minimal number of DOF, typically 4 or more**
- **Complete models like SUSY, possibly with a smaller, phenomenologically motivated parameter set like the pMSSM.**

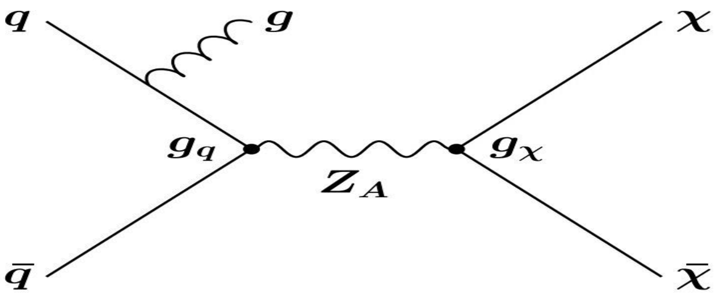
Dark matter models at



Simplified models



Higgs portal



Extended
Higgs sector

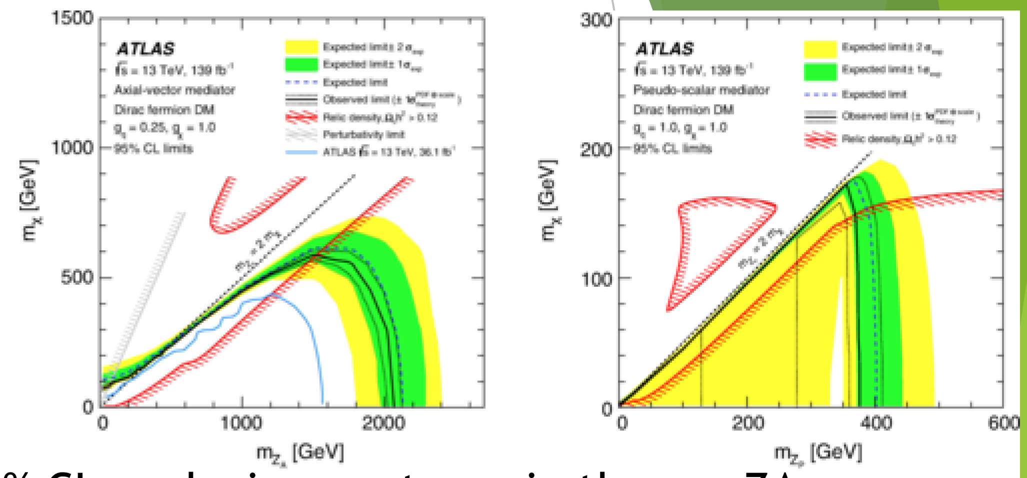
Experimental signatures

- searches for missing transverse momentum (EmissT) plus X signatures (mono-X, where the EmissT resulting from the DM particles leaves the detectors unnoticed and the visible, i.e. detectable,final state X is used for triggering
- searches containing only visible particles such as pairs of leptons or jets that aim to detect the particles mediating the interactions between the DM and the SM particles through observation of a new resonance or a modification of the kinematics of the final-state particles.

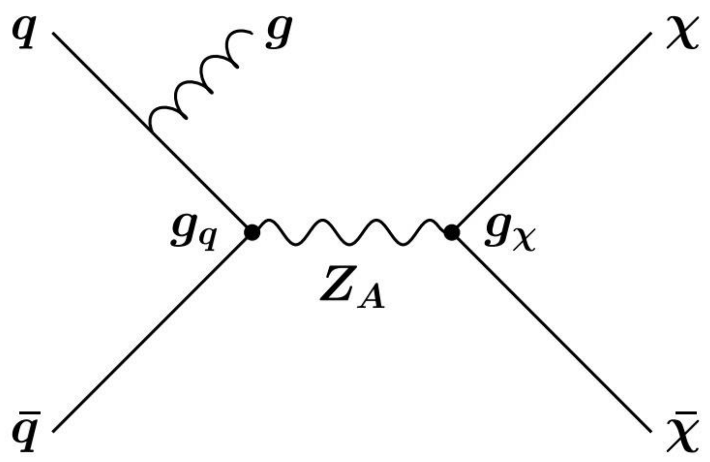
Jet + *ET_miss* (Phys. Rev. D 103, 112006)

Sensitive to both pseudoscalar and axial-vector mediators, $H \rightarrow inv$, as well as many other interesting models (SUSY, axion-like particles, etc)

- **Multijet: data driven jet smearing method**
- **Simultaneous fit EmissT in signal + control regions**



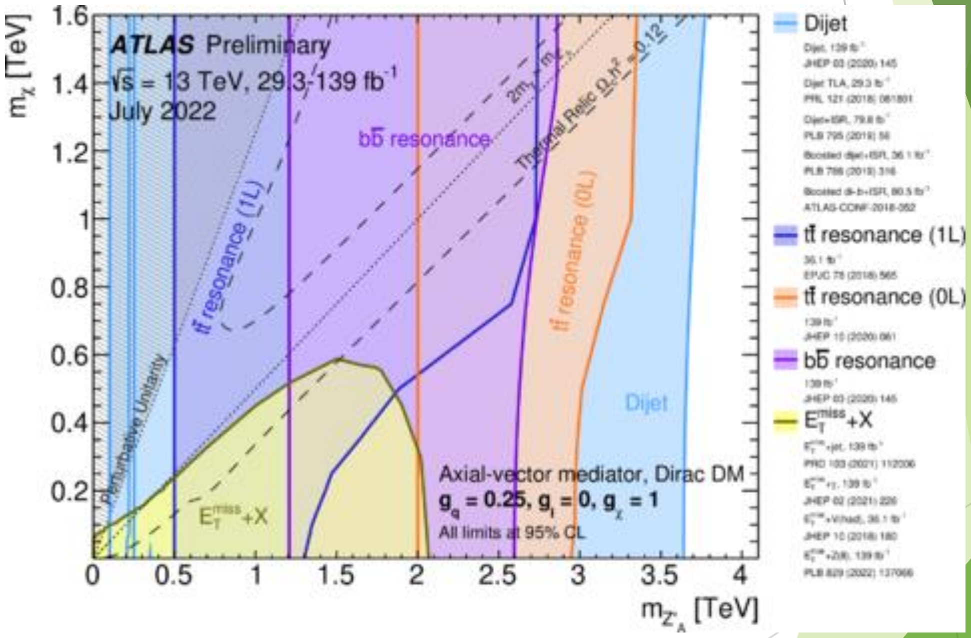
(a) 95% CL exclusion contours in the m_ZA- m_x parameter plane for the axial-vector mediator model.
(b) 95% CL exclusion contours in the m_ZP- m_x parameter plane for the pseudoscalar mediator model.



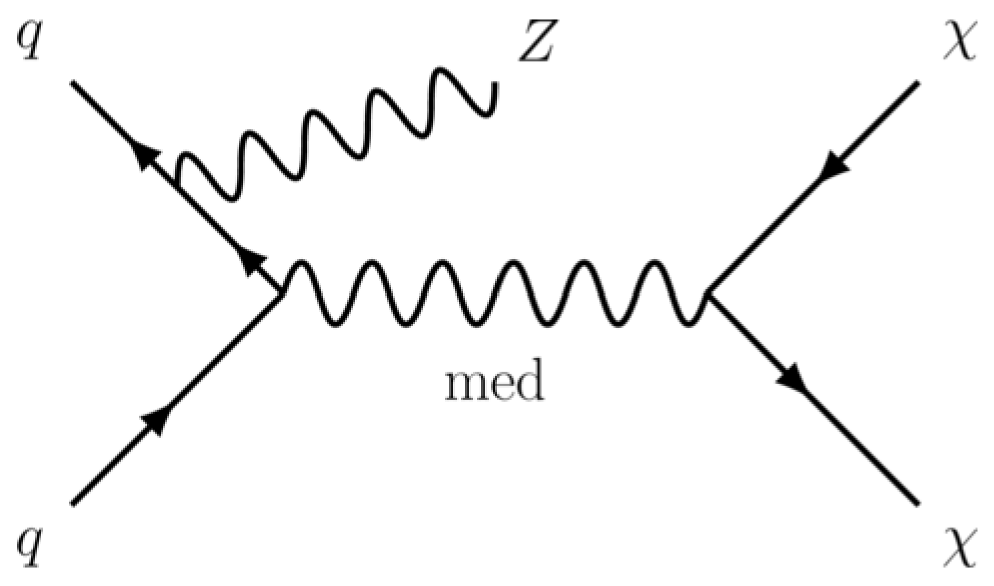
2D limits set on 𝑚x vs 𝑚+
- Excluded values up to 𝑚+% = 2.1 TeV for A-V mediators
- Sensitivity to exclude very light pseudoscalar masses (𝑚+& < 376 GeV) for the first time in this final state
- Results compared with direct/indirect detection
- Limits also set on $H \rightarrow inv$ of 0.34 observed (0.39 expected)

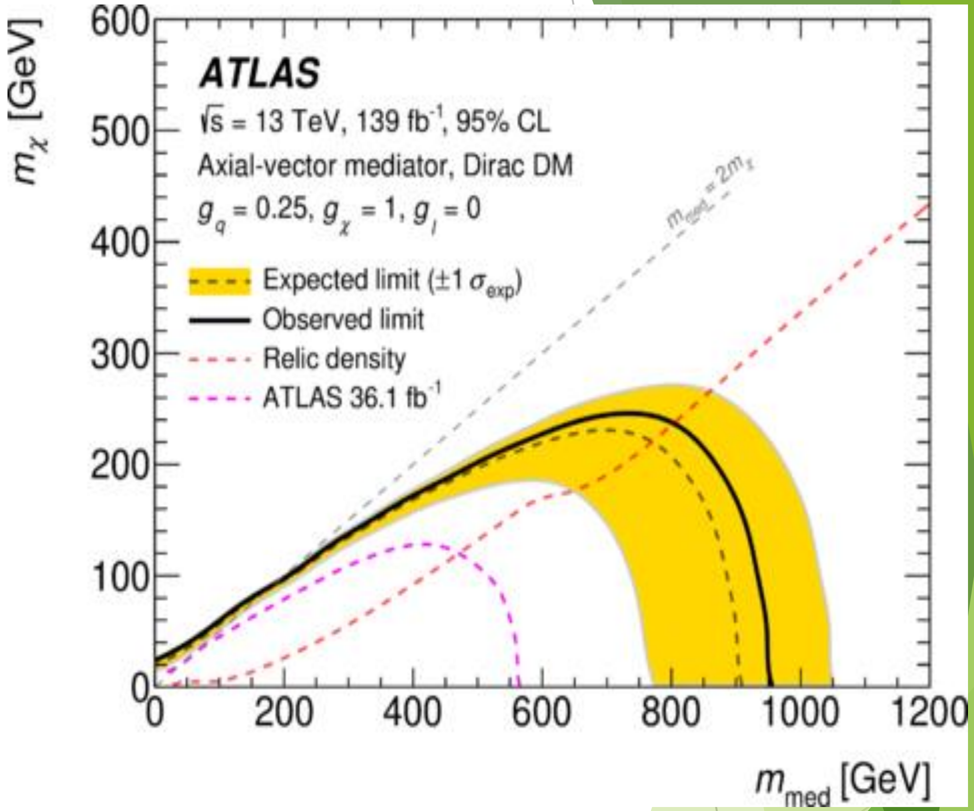
Simplified DM model summary (ATL-PHYS-PUB-2022-036) summary plots for for s-channel, 2HDM+a and Dark Higgs models

Regions in the (mediator-mass, DM-mass) plane excluded at 95% CL by visible and invisible searches, for leptophobic axial-vector mediator simplified models.



$Z\ ll + ET\_miss$, Phys. Lett. B 829 (2022) 137066





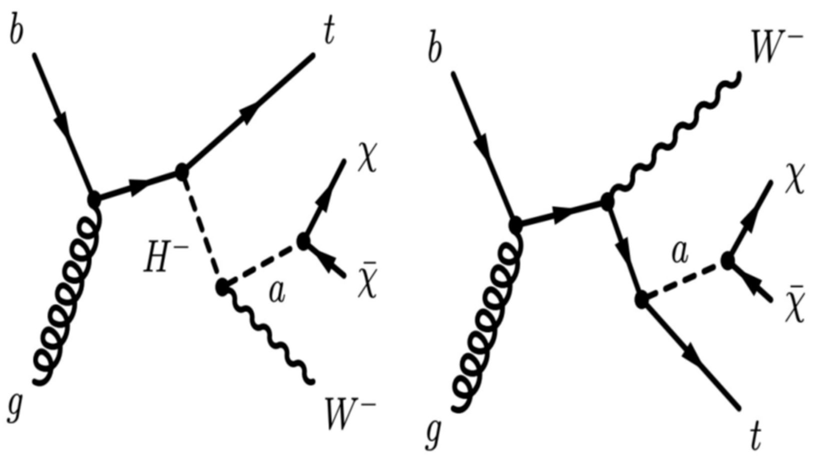
Sensitive to many types of models; particularly competitive for $H \rightarrow inv$ and 2HDM+a

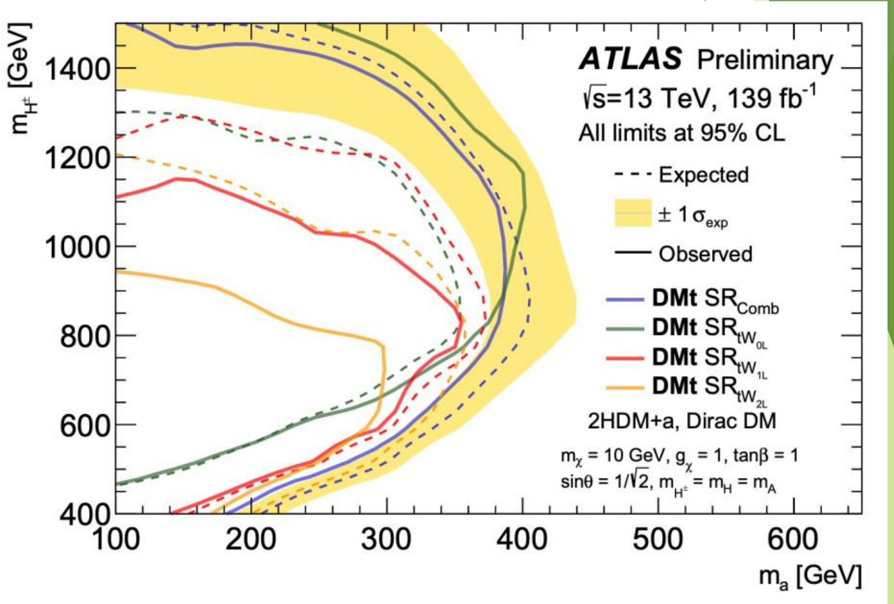
Exclusion limits for simplified DM models with gx = 1.0, gq = 0.25, and gℓ = 0, when assuming (a) an axial-vector mediator or (b) a vector mediator.

$tW + E_{T\_miss}$ (ATLAS-CONF-2022-012)

2HDMa

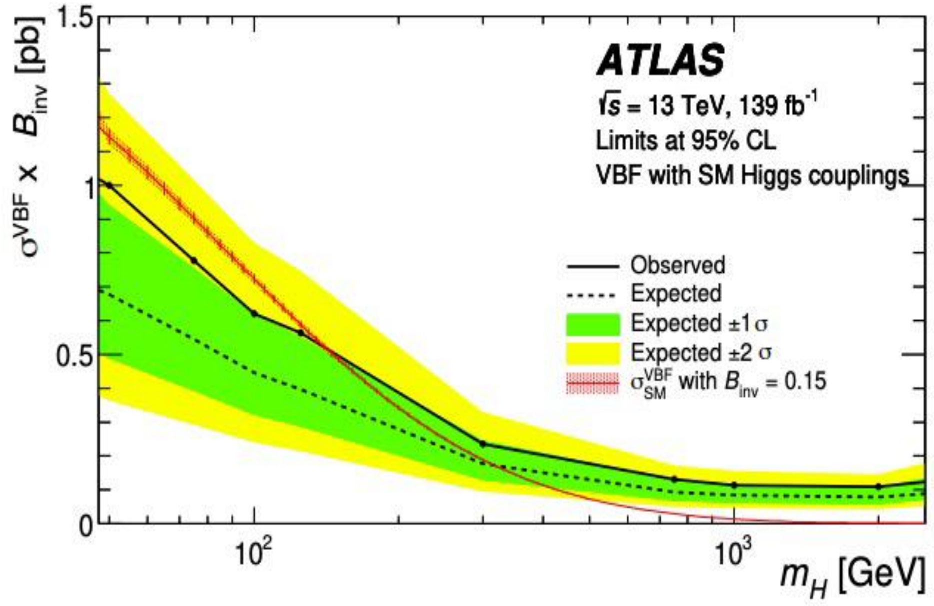
Combined with tW2L channel (Eur. Phys. J. C 81 (2020) 860)
The dominant single top-quark final state for the 2HDM+a model,



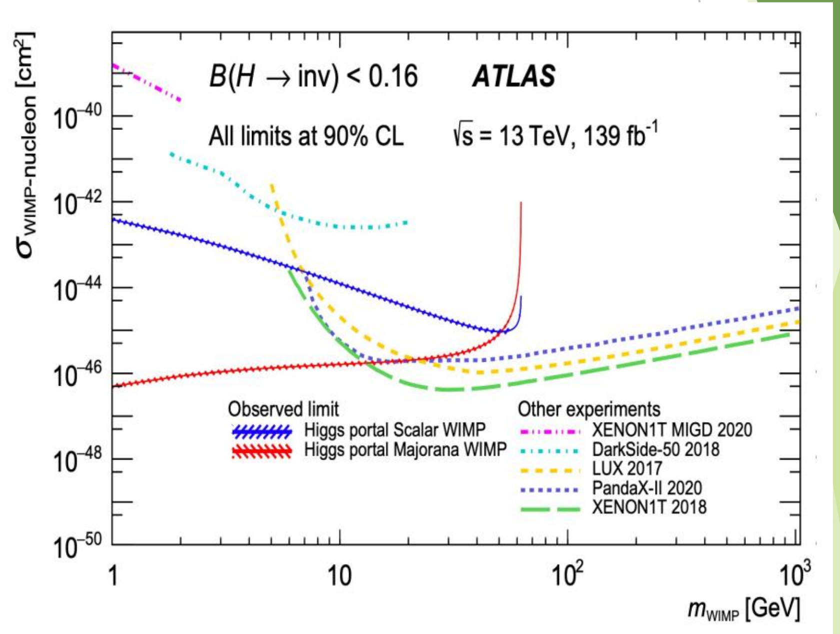


- : The expected and observed exclusion contours as a function of $(ma, m\mathrm{H})$

VBF Higgs + ET_miss (JHEP 08 (2022) 104) Higgs portal

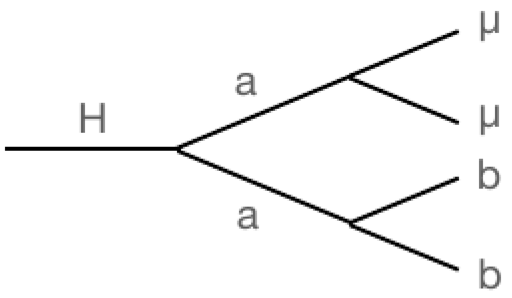


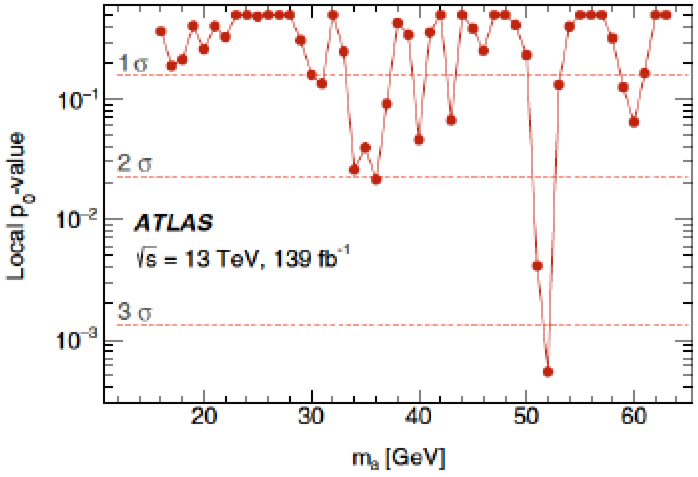
Upper limit on cross section times branching ratio to invisible particles for a scalar mediator as a function of its mass.

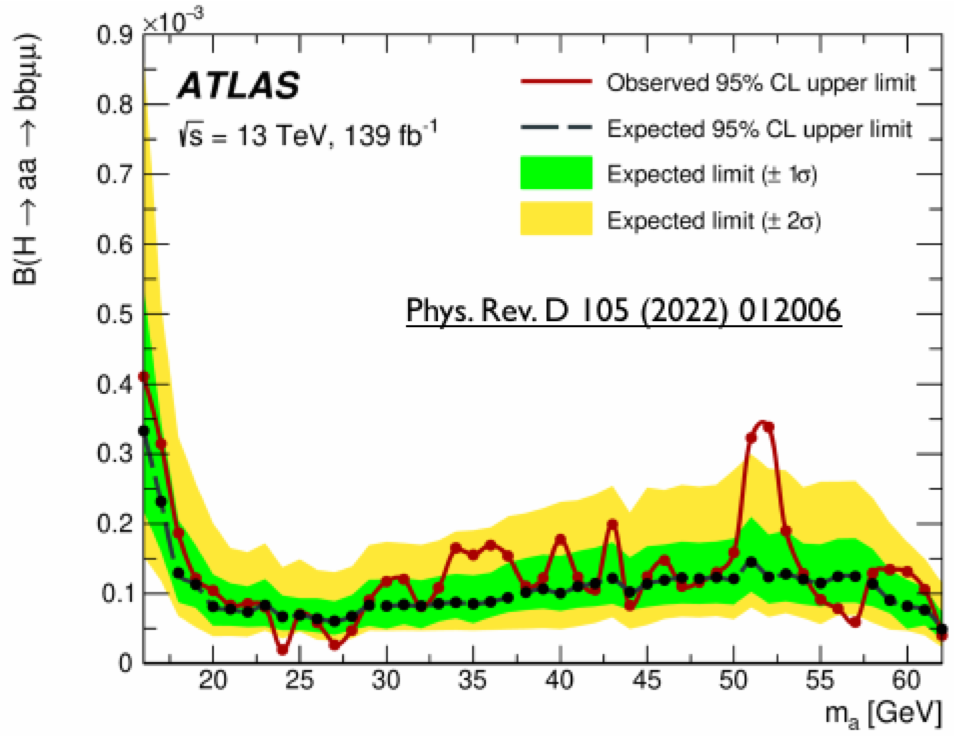


Upper limits on the spin-independent WIMP-nucleon cross section using Higgs portal interpretations of Binv at 90% CL vs mWIMP

Exotic Higgs: nMSSM







Long-lived particles (LLP)

Long-lived particles (LLPs) predicted in many BSM scenarios with **unique signatures** which are **difficult to reconstruct** and for which **estimating the background** rates is also a challenge

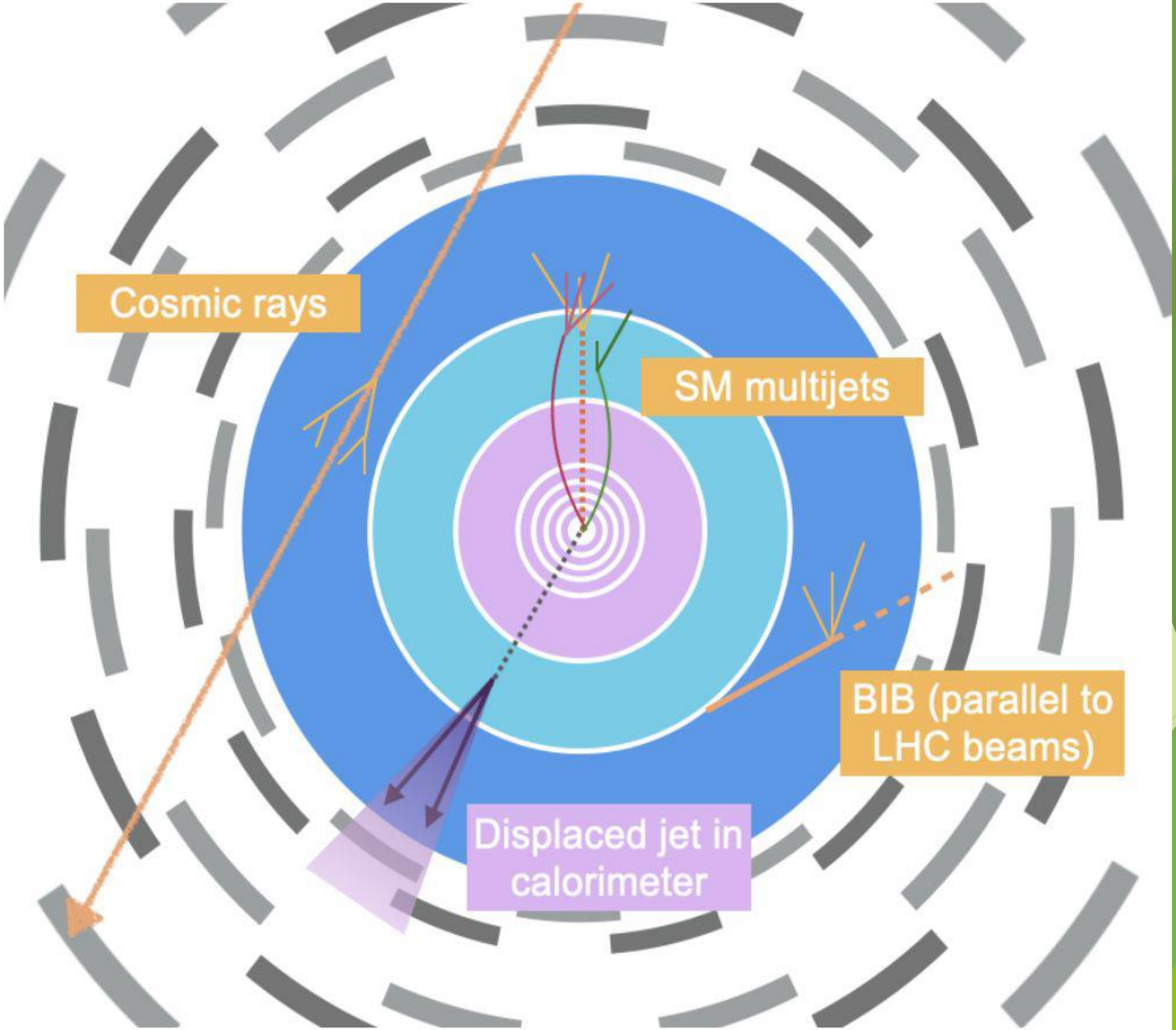
- For a **model** to predict LLPs, it usually satisfies at least one of the following:
  - (nearly) mass-degenerate spectra
  - small couplings
  - highly virtual intermediate states
- The talk focuses on the most recent exotics results using 13 TeV pp collision data collected by the ATLAS detector

LLP:

a proper lifetime $c\tau_0$ is greater than or comparable to the characteristic size of the (sub)detectors

✓ small $c\tau_0$ that comparable to the inner tracker size, no displaced tracks →"standard" prompt decay

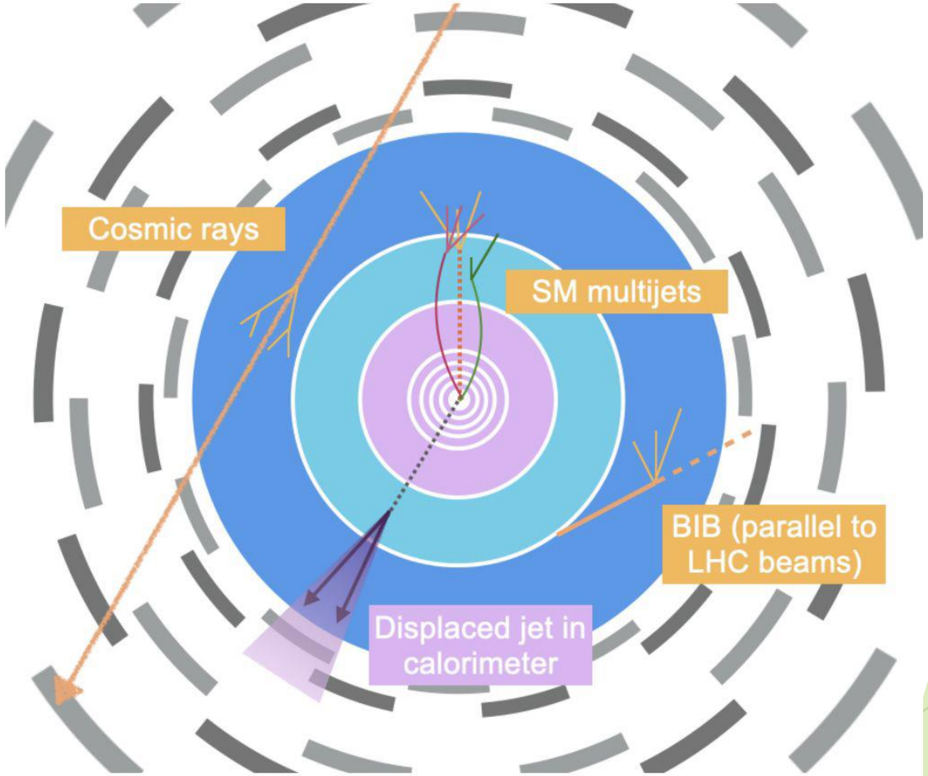
✓ intermediate $c\tau_0$ → LLP



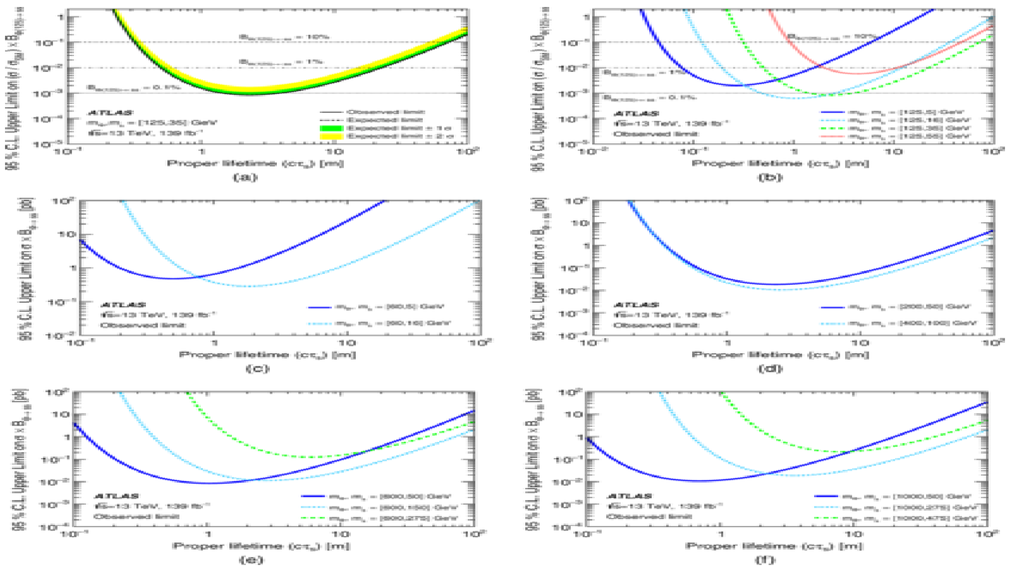
Search for displaced hadronic jets in the calorimeter

Search for pair-produced neutral LLPs decaying to SM fermions

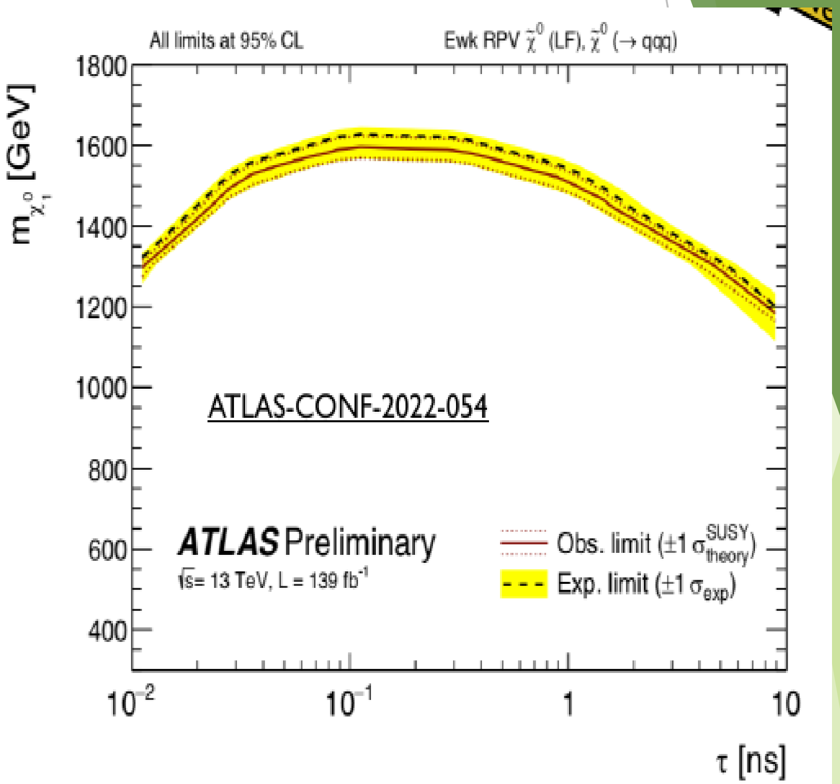
- Hidden Sector (HS) model: $\Phi \to ss \to f\bar{f}f'\bar{f}'$
- Signature: two reconstructed displaced jets in the Calorimeter
- Dedicated triggers identify jets with highly unconventional signatures:
  - narrow: shower starts late
  - trackless: no tracks in Inner Detector pointing towards the jet
  - energy deposited in HCAL: high Calorimeter Ratio (CalRatio) → EH/EEM
- Background contribution: SM multijets, Beam-induced background (BIB), Cosmic muons



Search for displaced hadronic jets in MS



Comparison between observed and expected 95% C.L. limits on ratio of cs [Phys. Rev. D 106, 032005]



Vertex isolation criteria: based on the angular distance .R between the direction of the tracks or jets and the vertex axis > to reject background vertices created by punch-through jets

A data-driven method is used to estimate the background in events passing either the MS DV trigger or a zero-bias trigger

No events with two reconstructed displaced vertices in the MS are observed in the signal region

Exclusion limits at 95% CL on the lifetime and mass of the x̃10 in electroweakino pair production models.

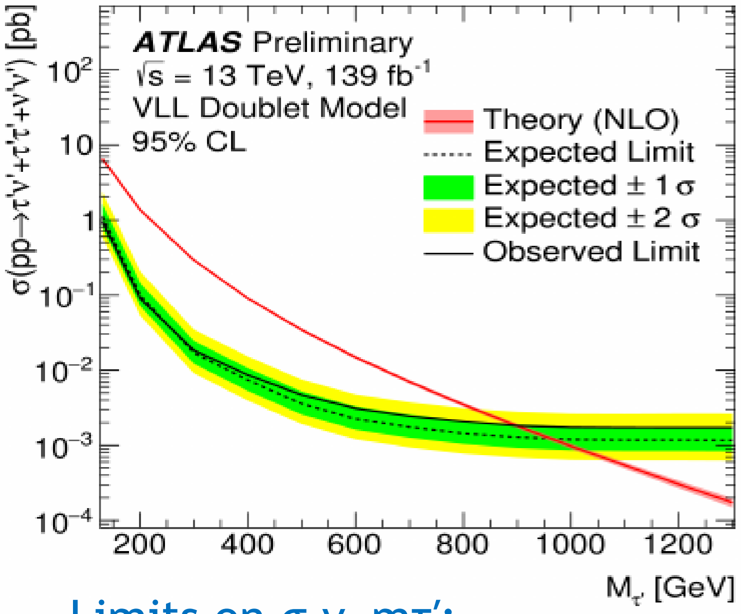
Displaced dark photon jets (DPJs)

- A search for light long-lived neutral particles with masses in the O(MeV–GeV) range
- The analysis targets the production of long-lived dark photons in the decay of a Higgs boson.
- Events that contain displaced collimated Standard Model fermions reconstructed in the calorimeter or muon spectrometer are selected
- The observed event yields are consistent with the expected background. Exclusion limits are reported on the production cross-section times branching fraction as a function of the mean proper decay length $c\tau$ of the dark photon, or as a function of the dark-photon mass
- **A Higgs boson branching fraction above 1% is excluded at 95% CL for a Higgs boson decaying into two dark photons for dark-photon mean proper decay lengths between 10 mm and 250 mm and dark photons with masses between 0.4 GeV and 2 GeV.**

Vector-like Quarks and Leptons

- **Higgs- good agreement with SM: Hard to accommodate new particle masses.**
- **Vector-like fermions: Dirac masses— decouple from EWK scale at large mass.**
- **Motivated by string theory or extra dimensions.**

Additional motivation from recent B flavor anomalies. Relevant: Searches for 3rd gen L!



Limits on σ v. mτ′:
967 GeV (exp) / 898 GeV (obs)

Anomaly Detection

- This is a unique time in history: we have no solid prediction of what might come next (unlike W/Z, top, Higgs). Robin Erbacher

- New approach: anomaly detection via
- • bump hunting (a la $H \rightarrow \gamma\gamma$) with background from data
- • unsupervised networks (autoencoders, adversarial nets, …)
- • weakly or semi-supervised networks

Papers in hep-ph with ML,NN etc in title

2012	2013	2014	2015	2016	2017	2018	2019	2020	21
11	14	17	35	55	110	221	373	520	697

In inspire: f t machine learning or t neural network or t deep learning
TensorFlow 2015
Scikit-lean 2014
Review in Nature (2018) Machine learning at the energy and intensity frontiers of particle physics,

Conclusion

- Run3 is started 5 of July, ATLAS and CMS plan to add 250/fb to data
- Very broad spectrum of the tasks.
- Several hints give a hope.

- This is a great time to search for surprises!