Exotic Searches with ATLAS

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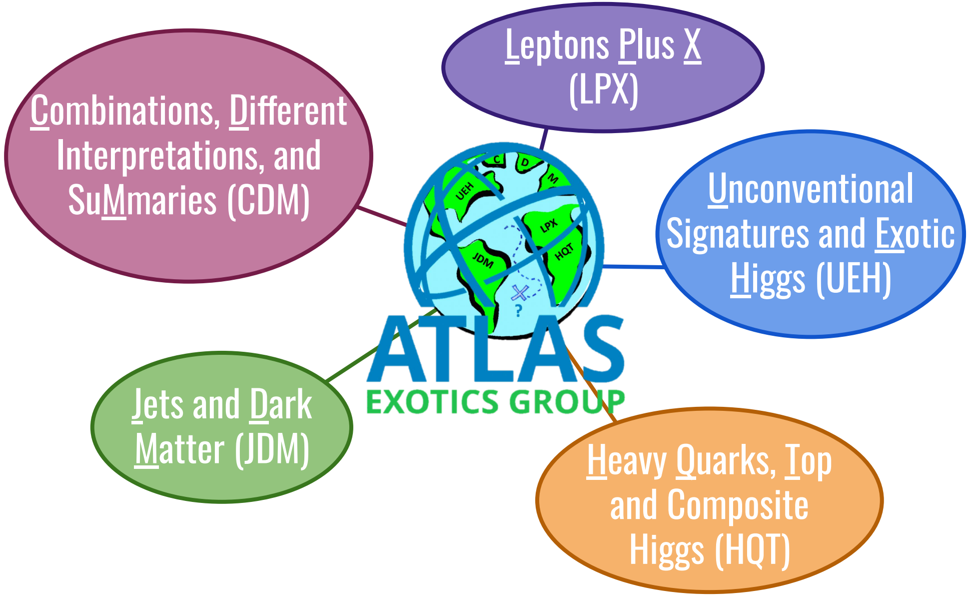
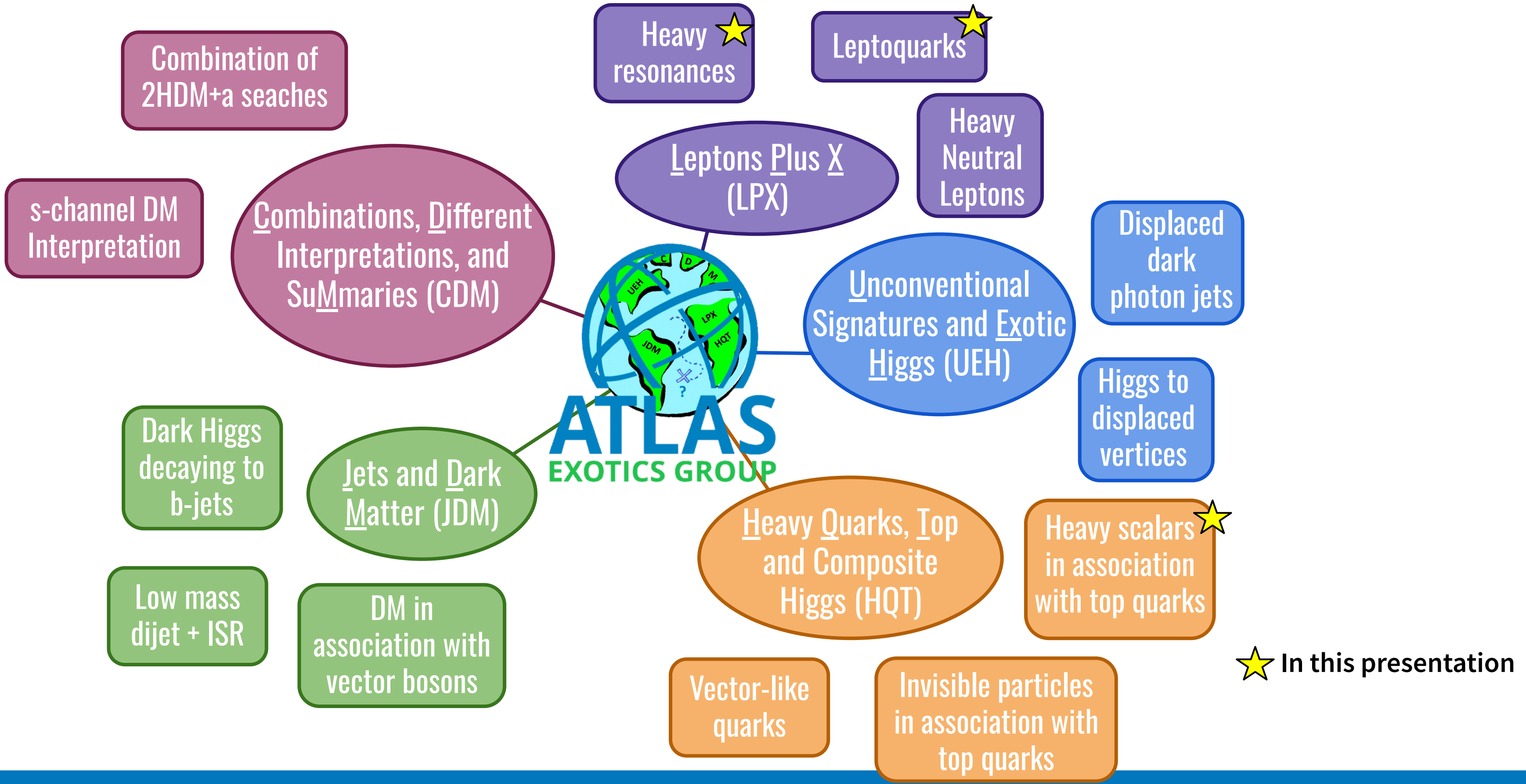
On Behalf of the ATLAS Collaboration
Moriond EW 2024

ATLAS Exotic Searches



ATLAS Exotic Searches @ Moriond EW



Leptoquarks

What?

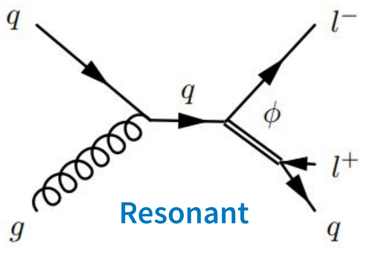
- Hypothetical scalar/vector particles with non-zero baryon & lepton number, carrying colour charge & fractional electric charge
- Decay into quark-lepton pair

Why?

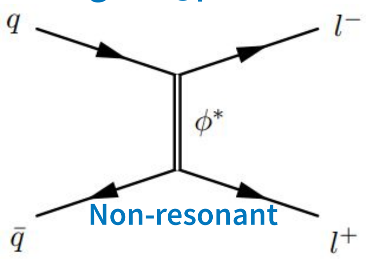
- Appear in many BSM scenarios (e.g. SU(5), SO(10) GUTs)
- Connect quark & lepton sector
- May explain certain anomalies, such as $b \to s\mu\mu$, $b \to c\ell\nu$

How? 1810.10017, 1307.6213

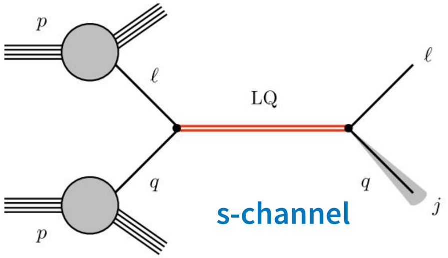
Single LQ production



Resonant



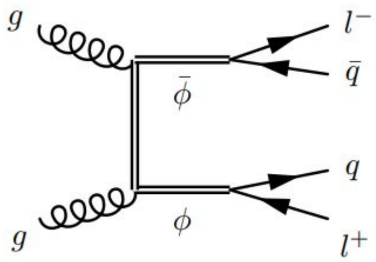
Non-resonant



s-channel

- Dependence on Yukawa coupling λ, m_{LQ}, lepton/quark PDFs

LQ pair production



- Largely independent of λ

3rd Generation LQ Combination

CERN-EP-2023-288

- Input from 9 analyses, including dedicated searches, SUSY re-interpretations (★) & SUSY re-optimisation (★)

	Scalar				Vector		SR		
Final State	LQ^u_3	LQ^d_3	LQ^u_{mix}	LQ^d_{mix}	$U_1^{YM/MC}$	$\tilde{U}_1^{YM/MC}$	N_ℓ	$N_{\tau had}$	$N_{b\text{-}jet}$
★ $t\nu b\tau$	✔	✔			✔		0	1	≥ 2
$b\tau b\tau$	✔				✔		{0, 1}	{1, 2}	{1, 2}
$t\tau t\tau$		✔				✔	{1, 2, 3}	≥ 1	≥ 1
$t\nu b\ell$			✔	✔			1		≥ 1
$b\ell b\ell$			✔				2		{0, 1, 2}
$t\ell t\ell$				✔			2		
$t\ell t\ell$				✔			{3, 4}		≥ 2
★ $t\nu t\nu$	✔		✔		✔		0	0	≥ 2
★ $b\nu b\nu$		✔		✔			0		≥ 2

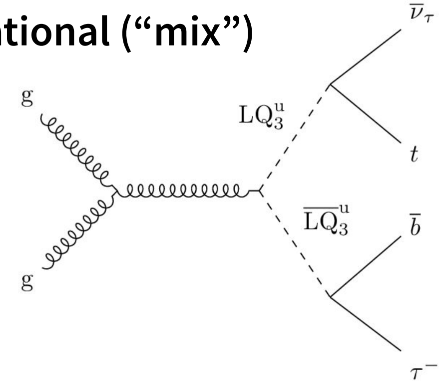
- Aim to improve sensitivity through statistical combination of analyses
- Signal regions designed to be orthogonal
  - Overlapping events identified & removed
- All final states from ℓ (e/μ), τ_{had}, (b-)jets and E_T^{miss}
  - With different selection criteria, based on analysis

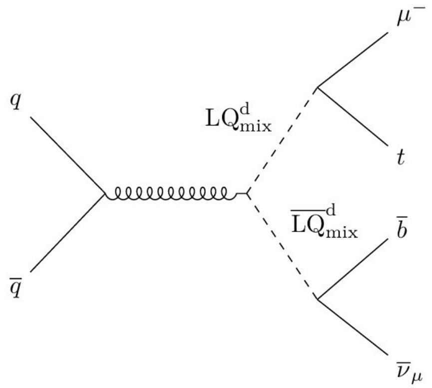
3^{rd} Generation LQ Combination

CERN-EP-2023-288

- Pairs of LQ produced mainly via ggF or $q\bar{q}$ annihilation
- Scalar LQ: up (±⅔e) and down (±⅓e), flavour-diagonal or cross-generational ("mix")

	Scalar				Vector		SR		
Final State	LQ^u_3	LQ^d_3	LQ^u_{mix}	LQ^d_{min}	$U_1^{YM/MC}$	$\tilde{U}_1^{YM/MC}$	N_ℓ	$N_{\tau had}$	$N_{b\text{-}jet}$
$t\nu b\tau$	✔	✔			✔		0	1	≥ 2
$b\tau b\tau$	✔				✔		{0, 1}	{1, 2}	{1, 2}
$t\tau t\tau$		✔				✔	{1, 2, 3}	≥ 1	≥ 1
$t\nu b\ell$			✔	✔			1		≥ 1
$b\ell b\ell$			✔				2		{0, 1, 2}
$t\ell t\ell$				✔			2		
$t\ell t\ell$				✔			{3, 4}		≥ 2
$t\nu t\nu$	✔		✔		✔		0	0	≥ 2
$b\nu b\nu$		✔		✔			0		≥ 2





3rd Generation LQ Combination

CERN-EP-2023-288

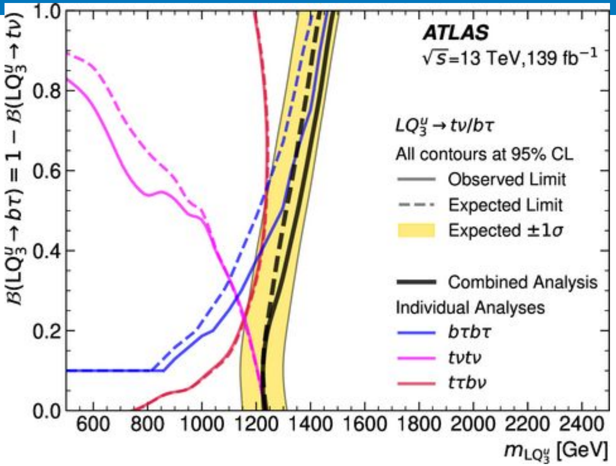
- Vector LQ: stronger model dependence - pair-production σ dependent on coupling to gluons
- Yang-Mills (YM, κ = 0) & Minimal Coupling (MC, κ = ±1) scenarios

	Scalar				Vector		SR		
Final State	LQ^u_3	LQ^d_3	LQ^u_{mix}	LQ^d_{min}	$U_1^{YM/MC}$	$\tilde{U}_1^{YM/MC}$	N_ℓ	$N_{\tau had}$	$N_{b\text{-}jet}$
$t\nu b\tau$	✔	✔			✔		0	1	≥ 2
$b\tau b\tau$	✔				✔		{0, 1}	{1, 2}	{1, 2}
$t\tau t\tau$		✔				✔	{1, 2, 3}	≥ 1	≥ 1
$t\nu b\ell$			✔	✔			1		≥ 1
$b\ell b\ell$			✔				2		{0, 1, 2}
$t\ell t\ell$				✔			2		
$t\ell t\ell$				✔			{3, 4}		≥ 2
$t\nu t\nu$	✔		✔		✔		0	0	≥ 2
$b\nu b\nu$		✔		✔			0		≥ 2

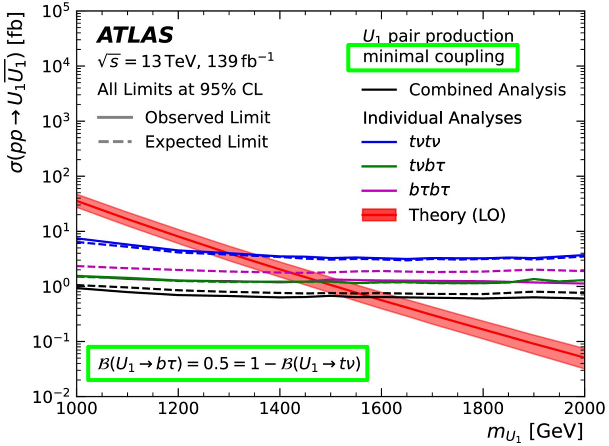
- U_1: favoured explanation for $R(D^{(*)})$ and $R(K^{(*)})$
  1903.11517
- Additional reinterpretation of $t\tau t\tau$ search in context of $\tilde{U}_1^{YM/MC}$
  - $\tilde{U}_1$ carries ±5/3 e

3^{rd} Generation LQ Combination

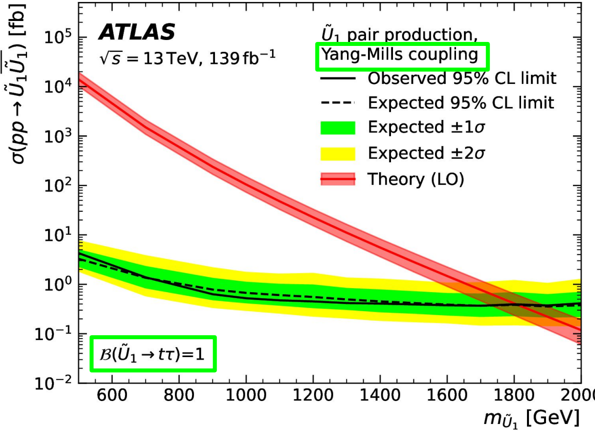
CERN-EP-2023-288



- Exclusion reach of scalar LQ combination improved by up to 100 GeV w.r.t individual analyses



- Limit on production σ of U_1 vector LQs, assuming $\mathcal{B} = 0.5$, improves upon individual results by 70 GeV (U_1^{YM}) and 80 GeV (U_1^{MC})

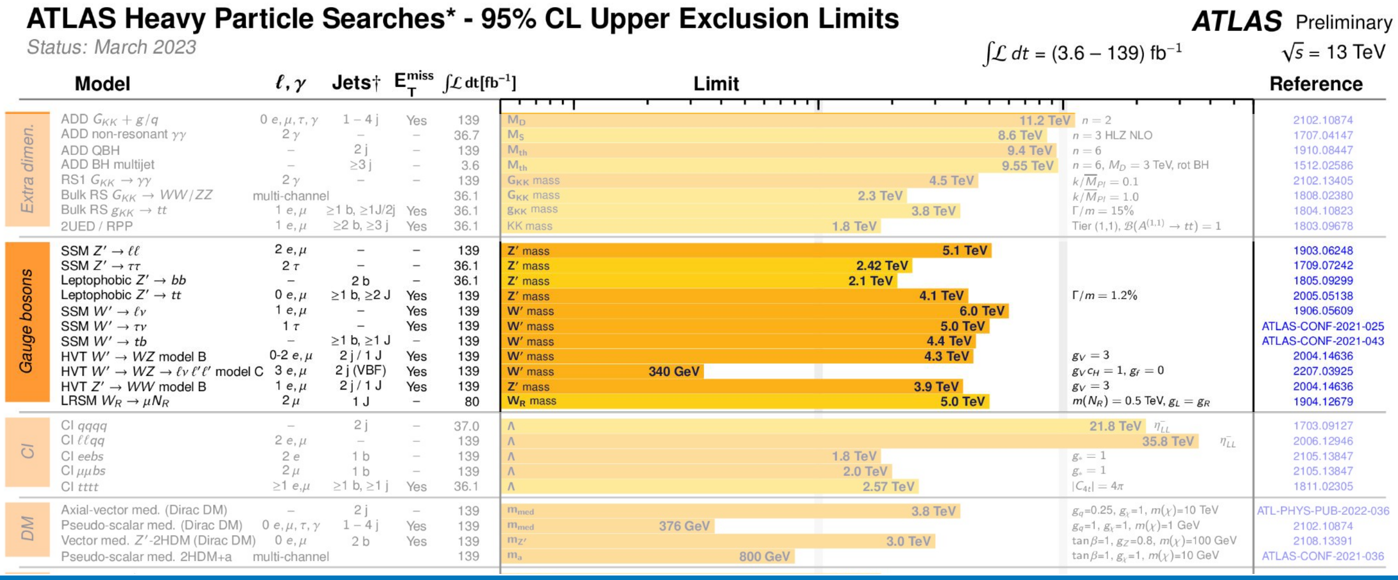


- No combination possible in case of $\tilde{U}_1$
- Set lower limits on mass of 1810 GeV for $\tilde{U}_1^{YM}$ and 1540 GeV for $\tilde{U}_1^{MC}$

Heavy Gauge Boson Searches

- ➟ Many BSM scenarios predict new heavy gauge bosons (Extra dimensions, Little Higgs, LRSM…)
- ➟ The LHC allows us to probe increasingly higher masses
- ➟ Many searches undertaken, often in the context of simplified benchmark models, e.g. Sequential Standard Model (SSM) 1107.5830, Heavy Vector Triplet (HVT) 1402.4431, 2207.05091

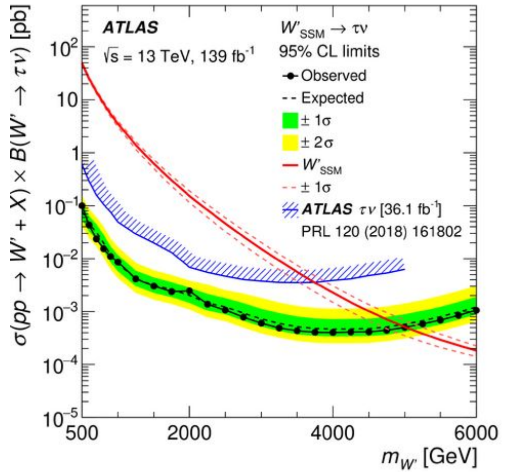
ATL-PHYS-PUB-2023-008



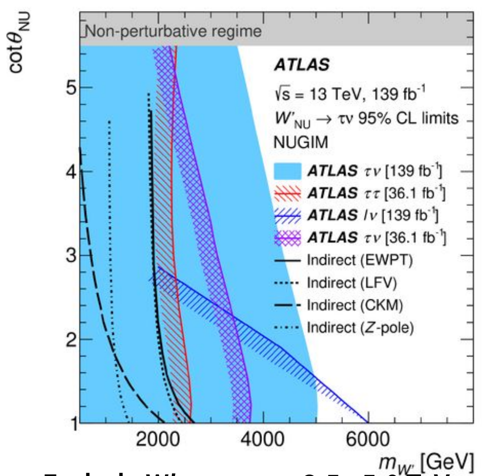
W′→$\tau\nu$

CERN-EP-2023-298

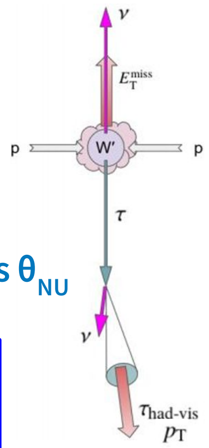
- Profit from improved τ-ID w.r.t Run-1, complement light lepton W′ searches for flavour-universal model (SSM)
- Also motivated by models which favour $\tau\nu$: Non-Universal Gauge Interaction Models (NUGIM)
  - Non universality of couplings to SM fermions parameterised as θ_{NU}

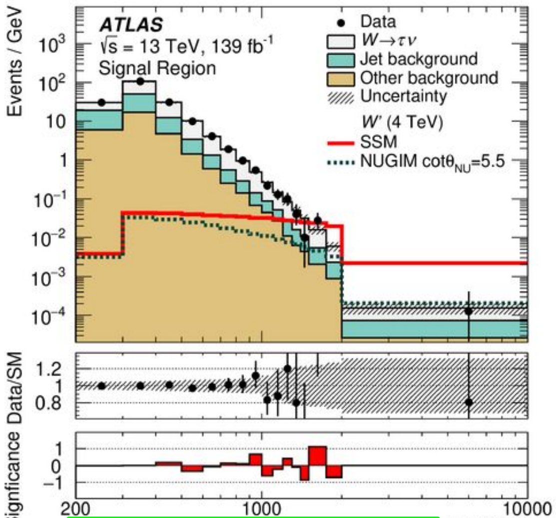


Exclude W′ mass up to 5 TeV in SSM



Exclude W′ masses < 3.5 - 5.0 TeV in NU coupling models





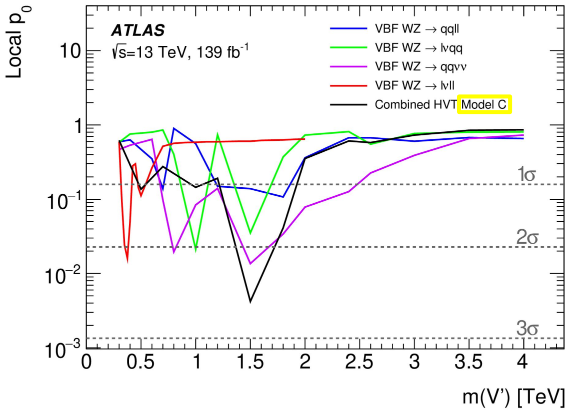
$$m_T = \sqrt{2E_T^{miss} p_T^{\tau_{had\text{-}vis}} (1 - \cos \Delta\phi_{\tau_{had\text{-}vis}, E_T^{miss}})}$$

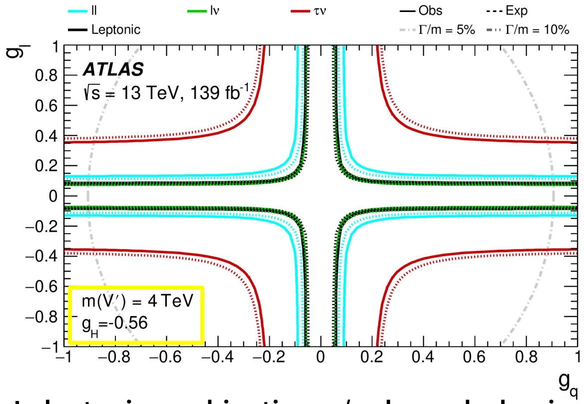
- Also derive model-independent limits on visible σ for m_T thresholds of 200 - 2950 GeV
  - Improvement of up to 5x w.r.t previous results

Heavy Resonance Combination

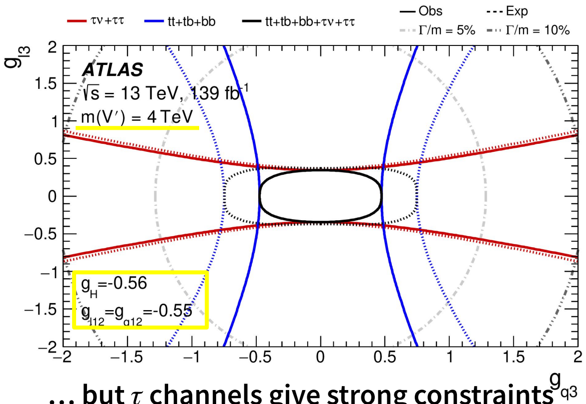
CERN-EP-2024-039

- Combine searches for diboson, di-quark, dilepton resonances (NEW)
  - Fully leptonic, semileptonic, fully hadronic
  - Including $\tau\nu$, $\tau\tau$ (NEW)
- Validate individual results, check for overlaps, combine analyses
- Set limits on couplings of HVT model (g_q, g_ℓ, g_H…)
  - Consider benchmark coupling points, e.g. HVT model C ($g_H = 1$, $g_f = 0$) targets VBF production channels

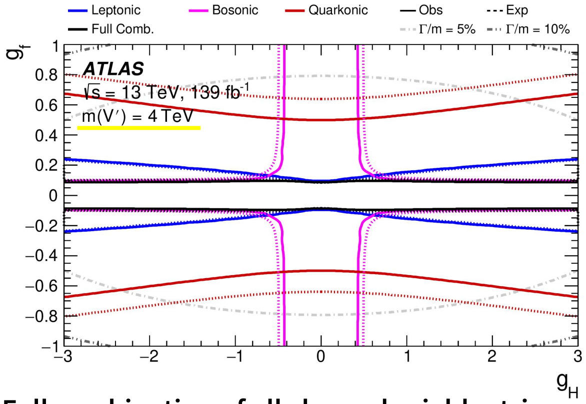




In leptonic combination, e/μ channels dominate for couplings which consider all fermions



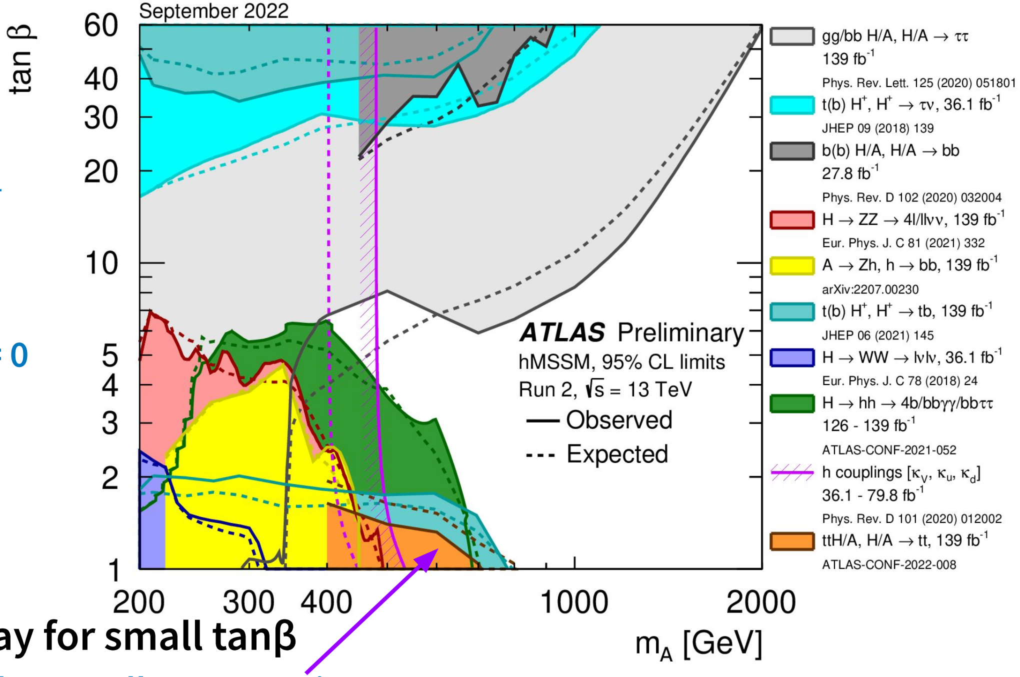
… but τ channels give strong constraints in 3rd generation couplings



Full combination of all channels yields stringent limits, improving on previous result by up to 60%

Searches for Heavy Scalars

- New massive (pseudo-) scalar states with strong couplings to top quarks predicted in numerous BSM models
- e.g. Two-Higgs-Doublet Models (2HDMs)
  - Introduce 5 physical states: h^0, H^0, A^0, H^+, H^- (CP-even: h^0, H^0; CP-odd: A^0)
  - Ratio of VEVs for two doublets: $\tan\beta$
  - Mixing angle of h^0 and H^0: α
  - Precision measurements dictate $\cos(\beta-\alpha) = 0$ if h^0 is SM Higgs (alignment limit)



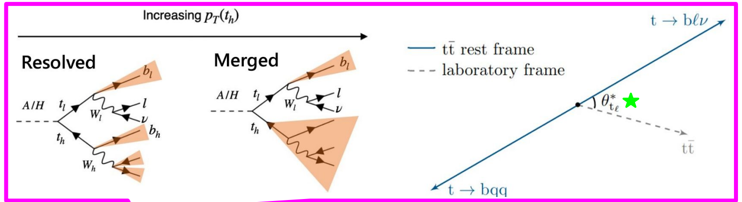
- In type-II 2HDM, $A/H \rightarrow t\bar{t}$ is dominant decay for small $\tan\beta$
  - $t\bar{t}A/H$ has distinct experimental signature, but small cross-section
  - Dominant production mode for A/H is ggF

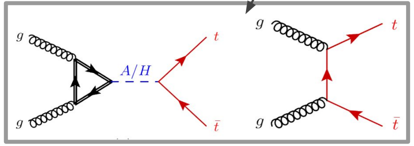
ATL-PHYS-PUB-2022-043

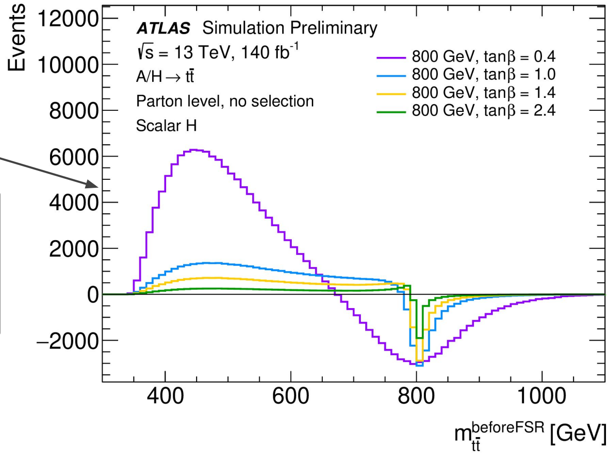
A/H → $t\bar{t}$

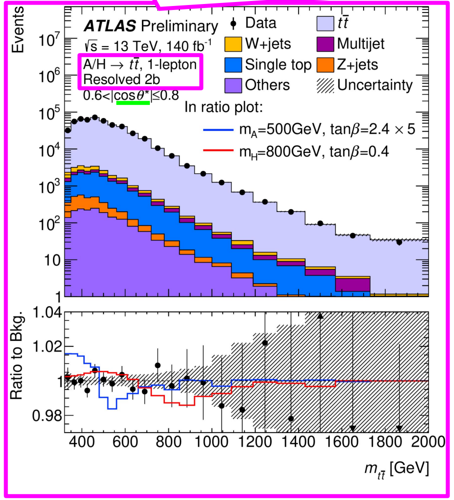
ATLAS-CONF-2024-001

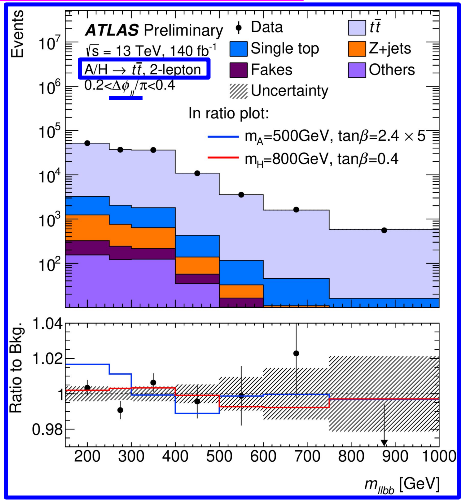
- Inclusive A/H → $t\bar{t}$ performed with full Run-2 dataset
  - Challenging, due to strong interference between signal & SM $t\bar{t}$ BG
- Consider 1L (lepton+jets) and 2L (dileptonic) final states



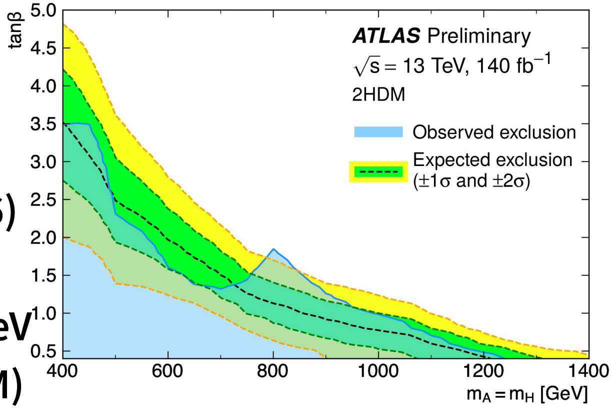






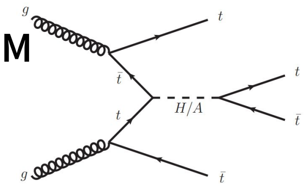


- Set limits on 2HDM, 2HDM+a, hMSSM…
- tanβ < 3.49 (3.16) excluded for $m_A = m_H$ = 400 GeV in 2HDM (hMSSM)

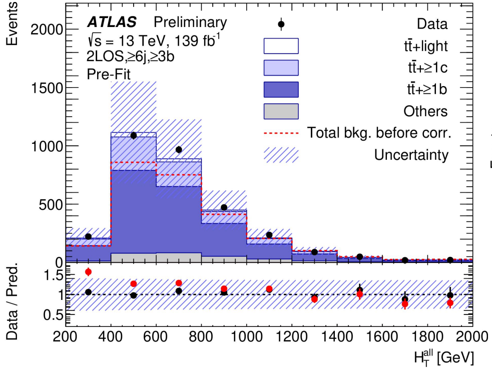


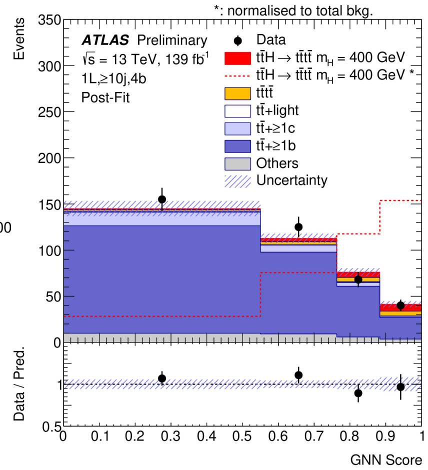
$t\bar{t}$ H/A -> $t\bar{t}t\bar{t}$

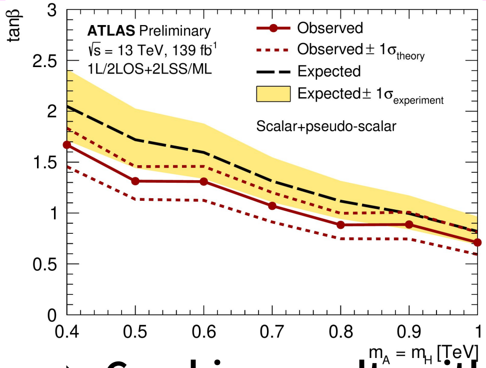
ATLAS-CONF-2024-002

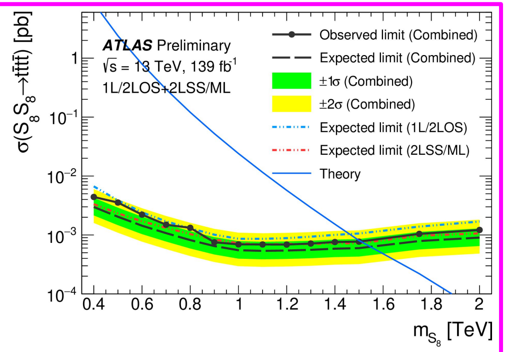


- H/A production in association with $t\bar{t}$ is much less susceptible to interference with SM
- Latest search focuses on 1-lepton / 2 Opposite-Sign (OS) lepton final states
- High jet & b-jet multiplicities in final state
- Use data-driven approach with neural network to correct known mismodelling of $t\bar{t}$+jets BG
- Use Graph Neural Network (GNN) to distinguish signal from BG









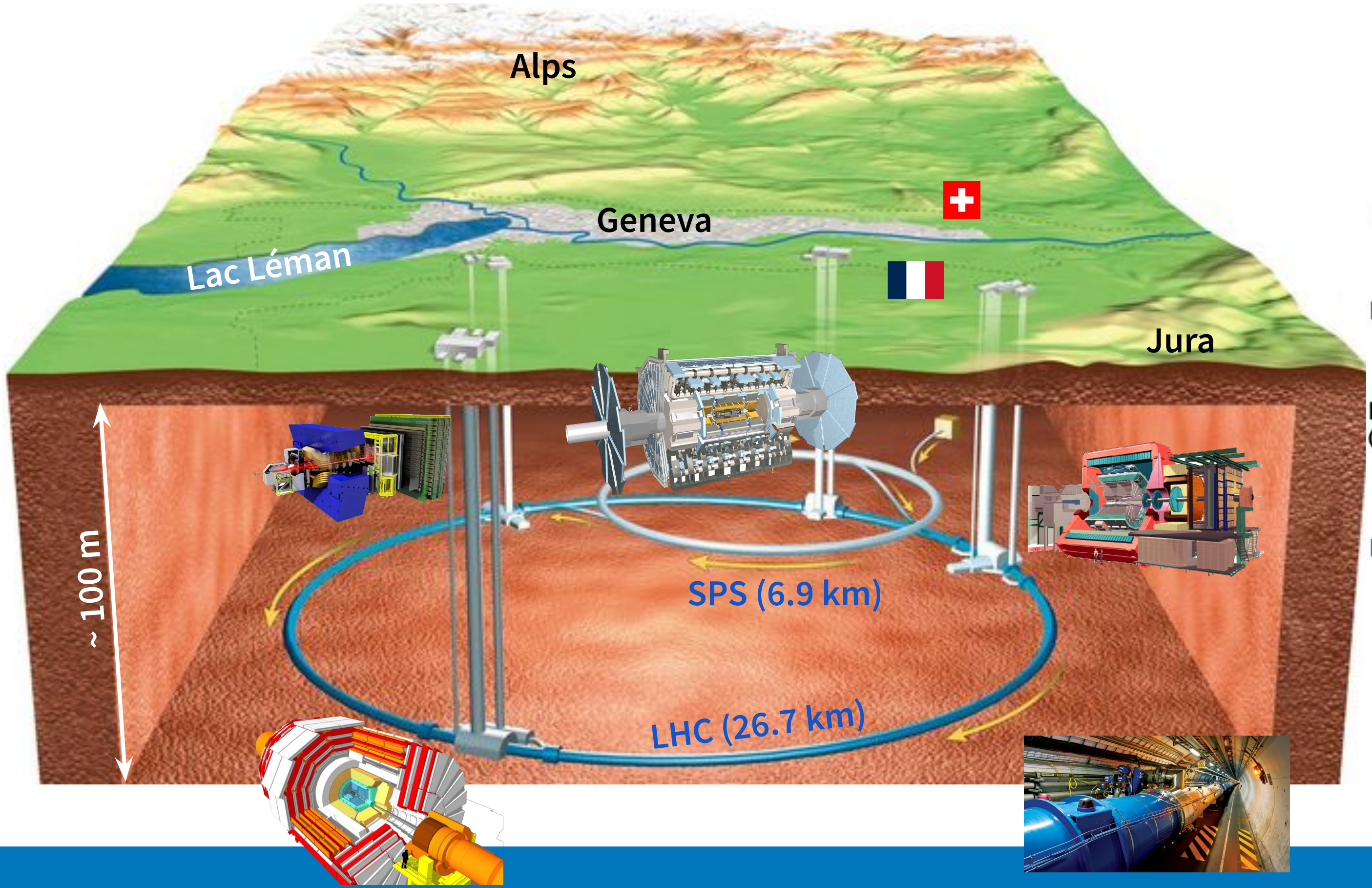
- Combine results with 2 Same-Sign (SS) lepton / multi-lepton search
- For 2HDM scenario as well as a colour-octet sgluon (S_8)

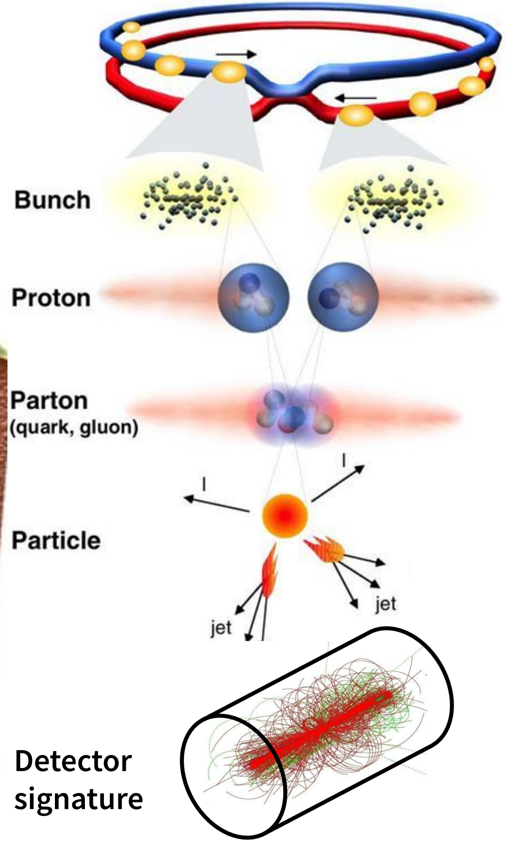
Conclusions & Outlook

- ATLAS has an diverse BSM search programme, with many new results published and in progress for the full LHC Run-2 dataset
  - Only a handful of the latest results presented here
  - See the list of all public results on the AtlasPublic twiki, and catch up on latest news with ATLAS briefings
- We unfortunately did not detect BSM physics… but not for lack of trying
- On top of performing many analyses, there have been huge efforts to make the most of our results by combining them
- And huge improvements have been made thanks to novel analysis techniques, such as employment of neural networks
- Run-3 of the LHC is ongoing, with 13.6 TeV collision energy and the inclusion of multiple upgrades
  - Looking forward to new searches with this dataset

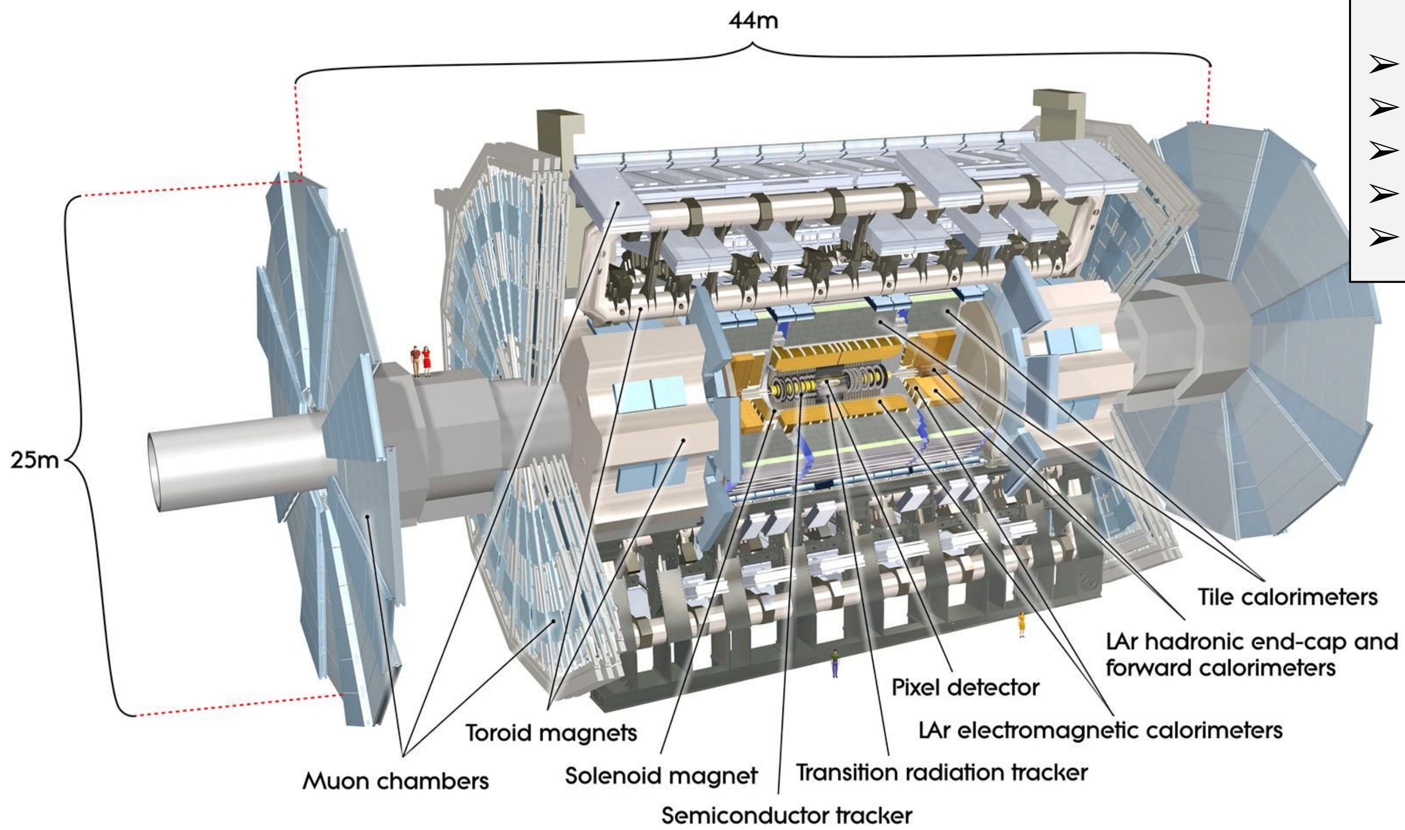
Backup

The Large Hadron Collider Complex



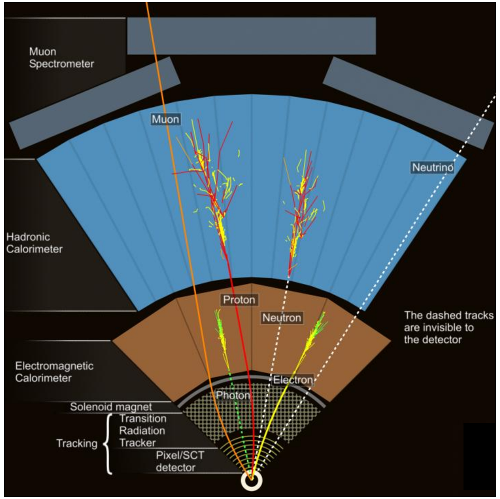


The ATLAS Detector

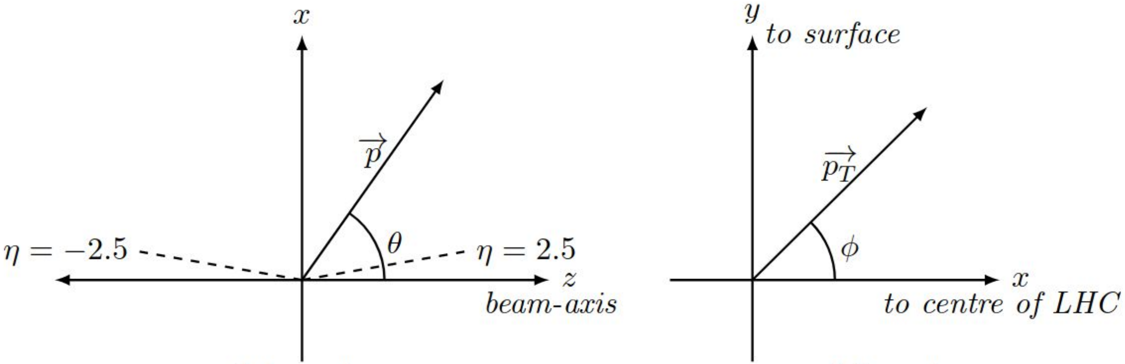


<u>*Letter of Intent*</u> *(1992)*

- ➢ *Hermetic jet & $E_{T,miss}$ calorimetry*
- ➢ *Excellent particle identification*
- ➢ *Excellent electron & photon resolution*
- ➢ *Standalone muon measurement*
- ➢ *Large acceptance*



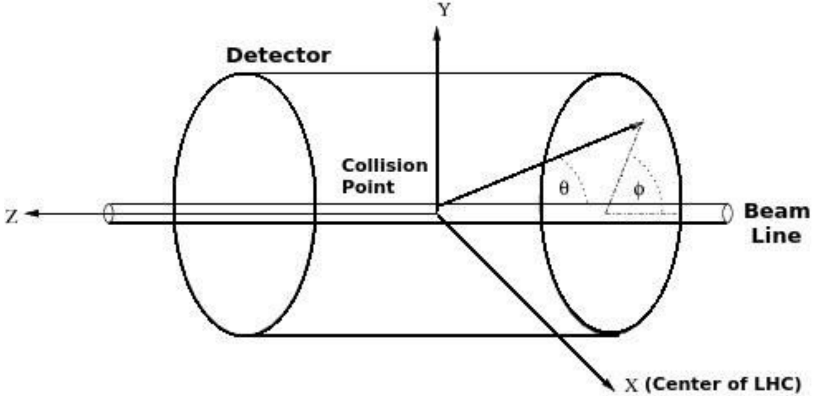
ATLAS Coordinate System



(a) xz-plane **(b)** xy-plane

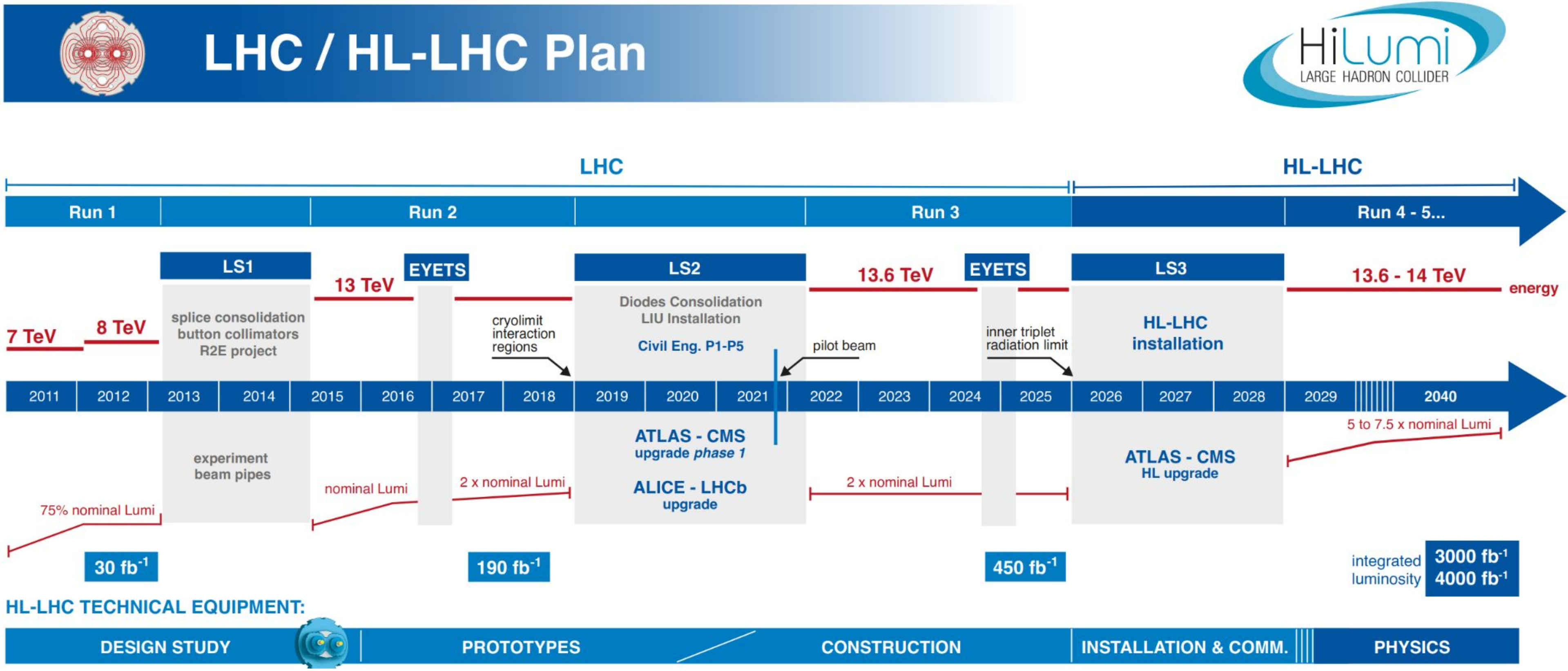
$$\eta = -\ln \tan\left(\frac{\theta}{2}\right)$$

$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$



LHC Schedule

https://hilumilhc.web.cern.ch/content/hl-lhc-project



Upgrades for Run-3

https://home.cern/press/2022/ATLAS-upgrades-LS2

MUON NEW SMALL WHEELS (NSW)

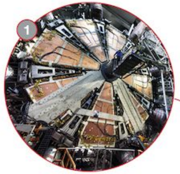
Installed new muon detectors with precision tracking and muon selection capabilities. Key preparation for the HL-LHC.

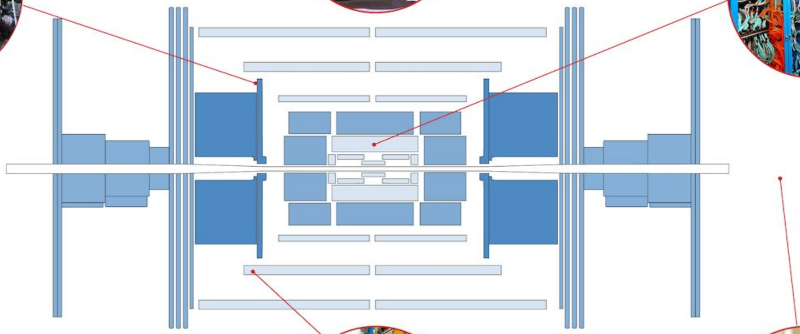
NEW READOUT SYSTEM FOR THE NSWs

The NSW system includes two million micromega readout channels and 350 000 small strip thin-gap chambers (sTGC) electronic readout channels.

LIQUID ARGON CALORIMETER

New electronics boards installed, increasing the granularity of signals used in event selection and improving trigger performance at higher luminosity.





TRIGGER AND DATA ACQUISITION SYSTEM (TDAQ)

Upgraded hardware and software allowing the trigger to spot a wider range of collision events while maintaining the same acceptance rate.

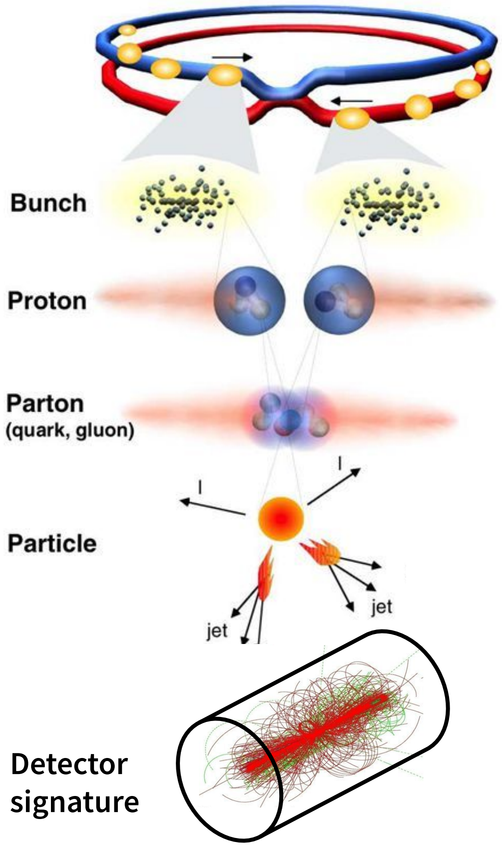
NEW MUON CHAMBERS IN THE CENTRE OF ATLAS

Installed small monitored drift tube (sMDT) detectors alongside a new generation of resistive plate chamber (RPC) detectors, extending the trigger coverage in preparation for the HL-LHC.

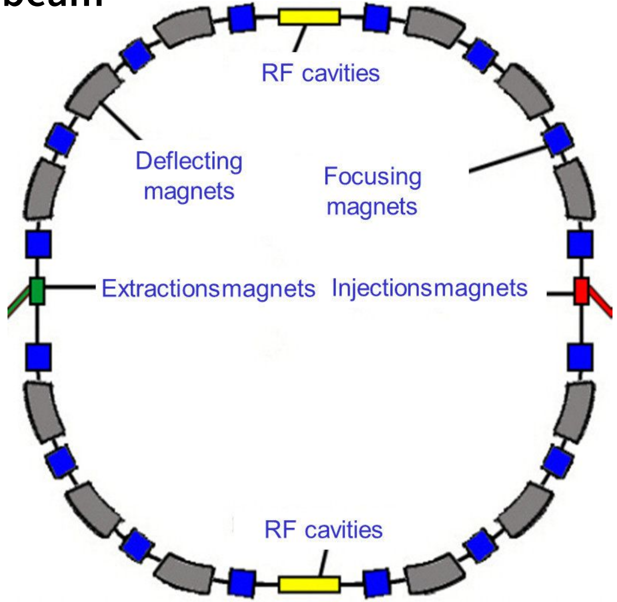
ATLAS FORWARD PROTON (AFP)

Re-designed AFP time-of-flight detector, allowing insertion into the LHC beamline with a new “out-of-vacuum” solution.

LHC Proton Beams



- > 50 kinds of magnets
- 1232 superconducting dipole magnets operating at -271.3°C
  - ➥ Sextupole, octupole & decapole magnets correct the beam
- 8 RadioFrequency (RF) cavities per beam



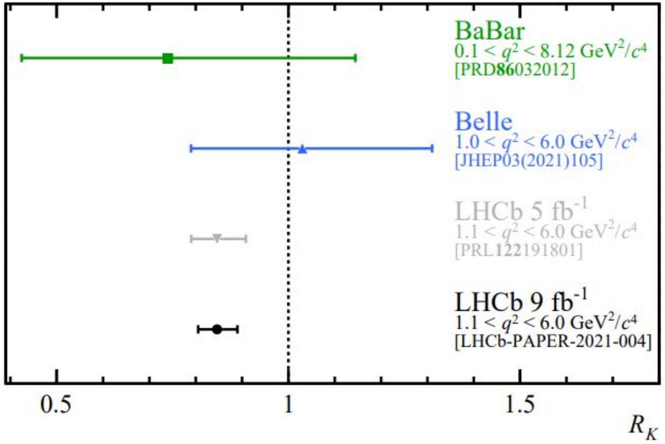
- Proton beam energy = 6.5 TeV
- 1.2 x 10^{11} protons/bunch
- ~ 2800 bunches/beam
- 25ns bunch spacing
  - ➥ 40,000,000 collisions per second

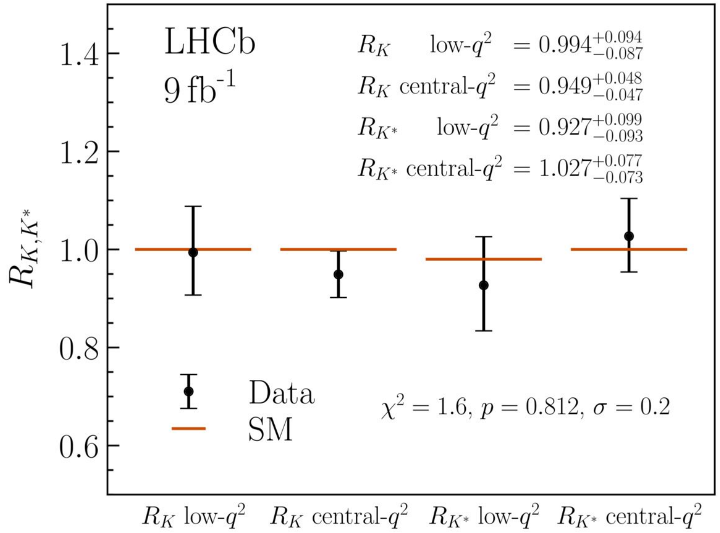
The Elephant in the Room

LHCb-PAPER-2022-045
LHCb-PAPER-2022-046

- Results of LHCb Run-1 + Run-2 measurement of R_K and R_{K^*} presented in recent LHC seminar
  - Simultaneously analysing $B^+ \to K^+ \ell^+ \ell^-$ and $B^0 \to K^{*0} \ell^+ \ell^-$, data-driven modelling of mis-ID backgrounds, MVA in two mass (q^2) ranges…

2103.11769





- What does this mean for our analyses motivated by LFU?

The Elephant in the Room

2304.01694