High p_t searches at ATLAS and CMS

New Frontiers in Lepton Flavour,
Pisa May 2023

Prof. Adrian Bevan on behalf of the ATLAS & CMS collaborations

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Outline

- Motivation
- The Large Hadron Collider (LHC)
- GPDs: ATLAS and CMS
- Indirect searches:
  - Higgs couplings to fermions
  - CP violation searches
- Direct searches:
- Summary

See links for listings of:
ATLAS Results
CMS Results

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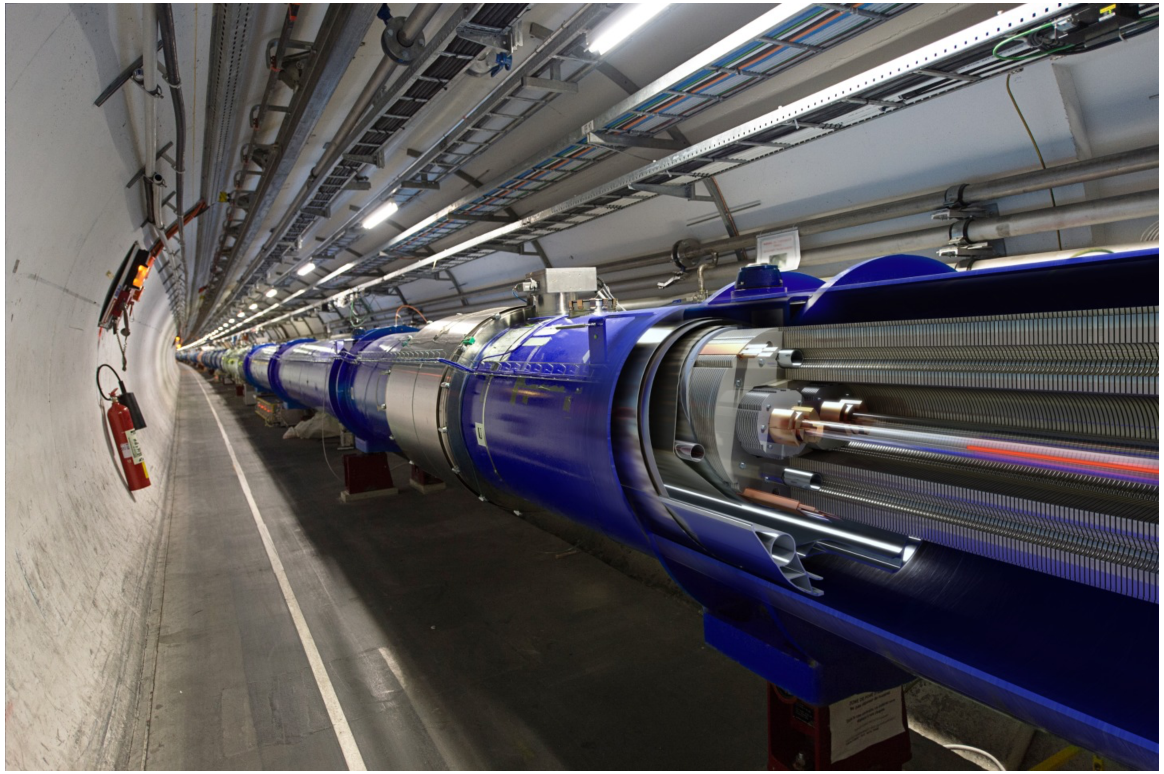
Motivation

- Indirect searches (e.g. CP violation) at high p_t complement low energy CP studies and give new routes to answering fundamental questions in particle physics
- High p_t searches offer direct means to observe physics beyond the Standard Model (SM)
- Theory motivations can date back decades: e.g:
  - Higgs Yukawa couplings to fermions linked to the CKM matrix via diagonalisation of the mass matrix
  - New types of CP violation searches target understanding the origins of the matter-antimatter asymmetry of the universe
  - Access to high energy via the LHC and HL-LHC upgrade allow for direct searches for new types of coupling (i.e. particles)

The Large Hadron Collider (LHC)

- pp collider at CERN on the Swiss-French border
- Superconducting magnets targeting $\sqrt{s} = 14TeV$
- Taking data now during Run 3



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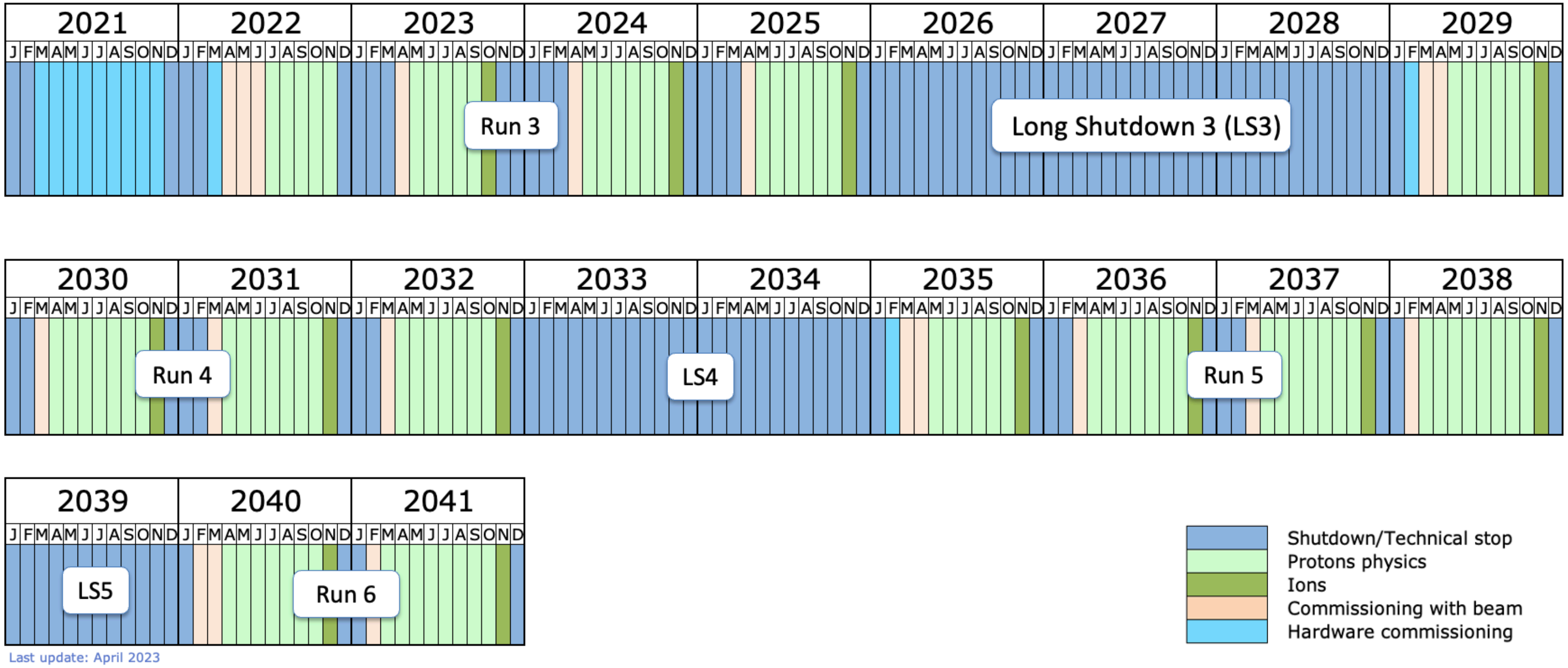
The LHC

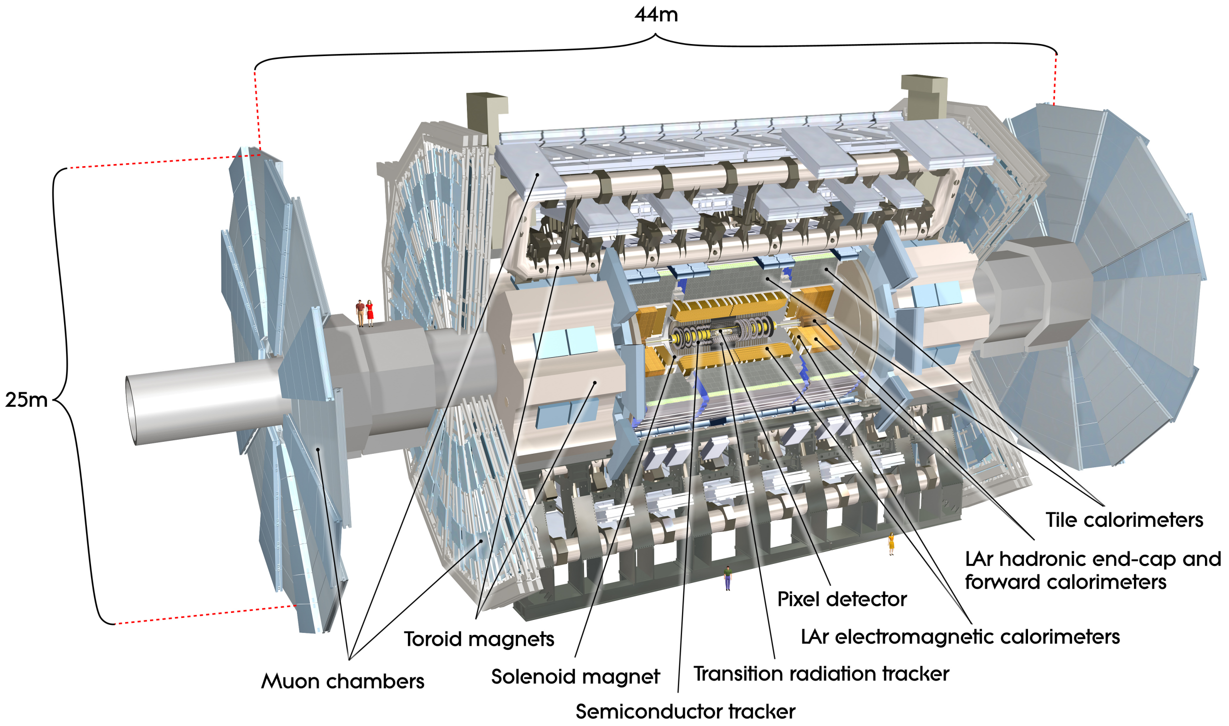
- Results shown use data from Run 1+2
- Run 3 in progress
- High Luminosity upgrade start up to follow long shutdown 3

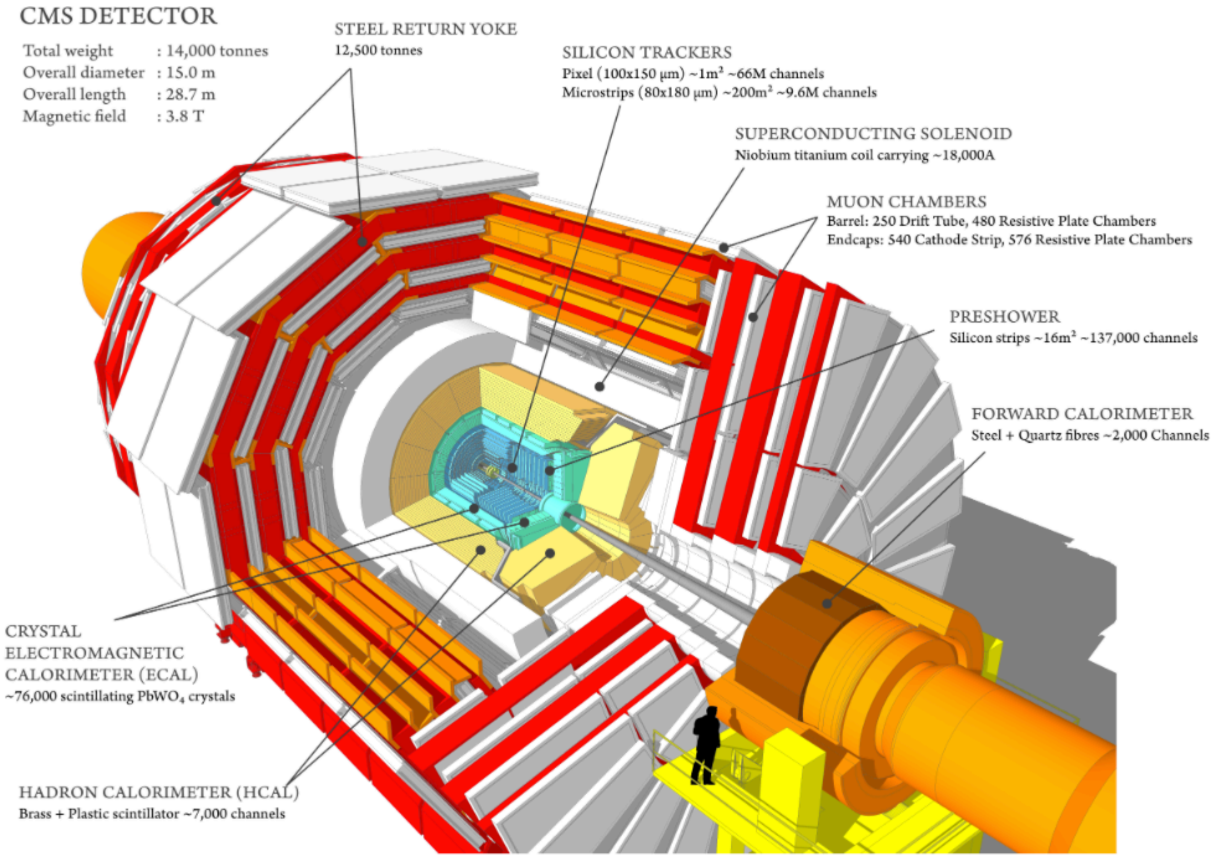
https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm



GPDs: ATLAS and CMS

- Designed for a wide range of physics, with tracking systems, calorimeters and trigger systems;
- Magnet systems allow 4-vector reconstruction of charged particles





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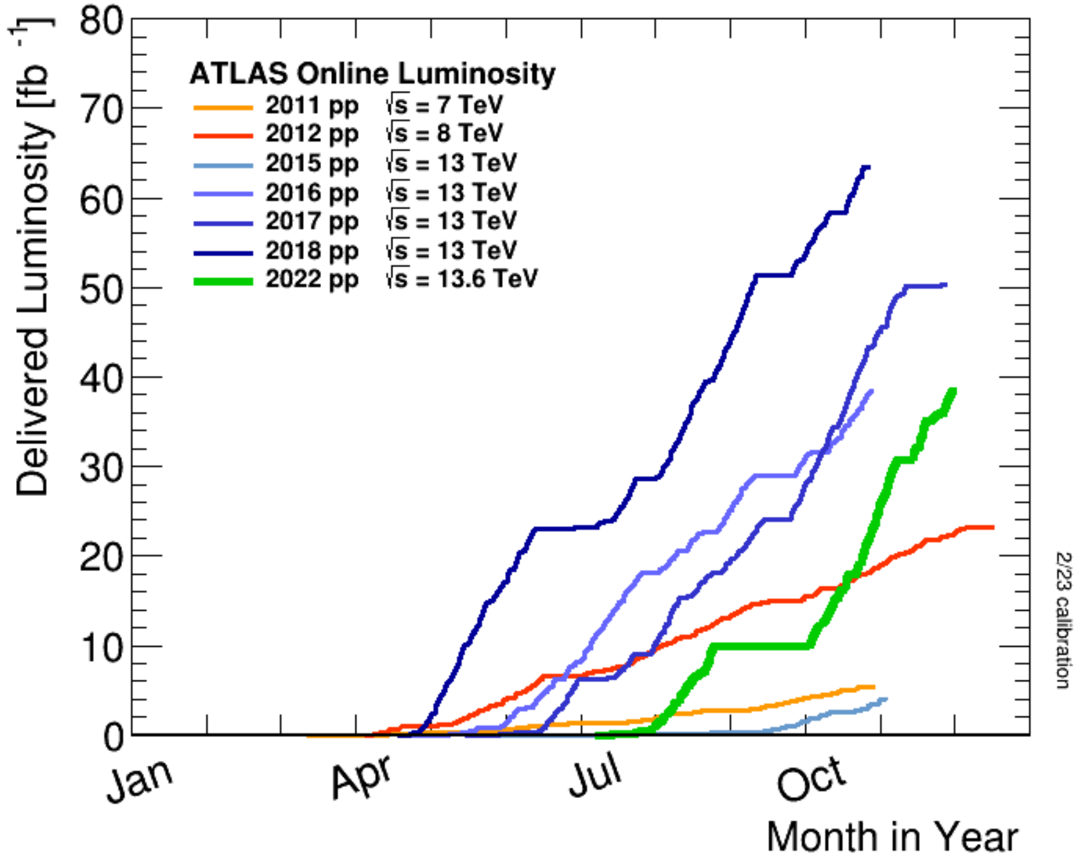
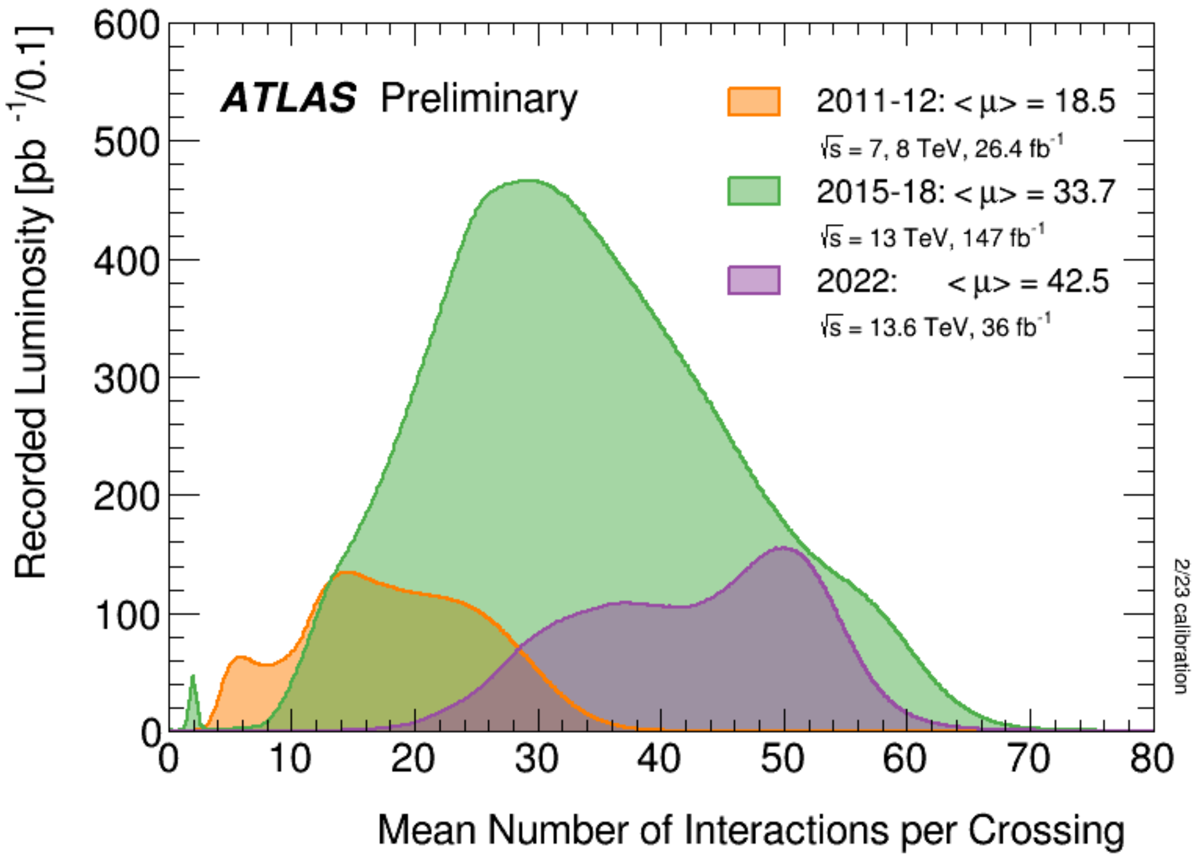
GPDs: ATLAS and CMS

- Run 3 data taking performance similar to run 2





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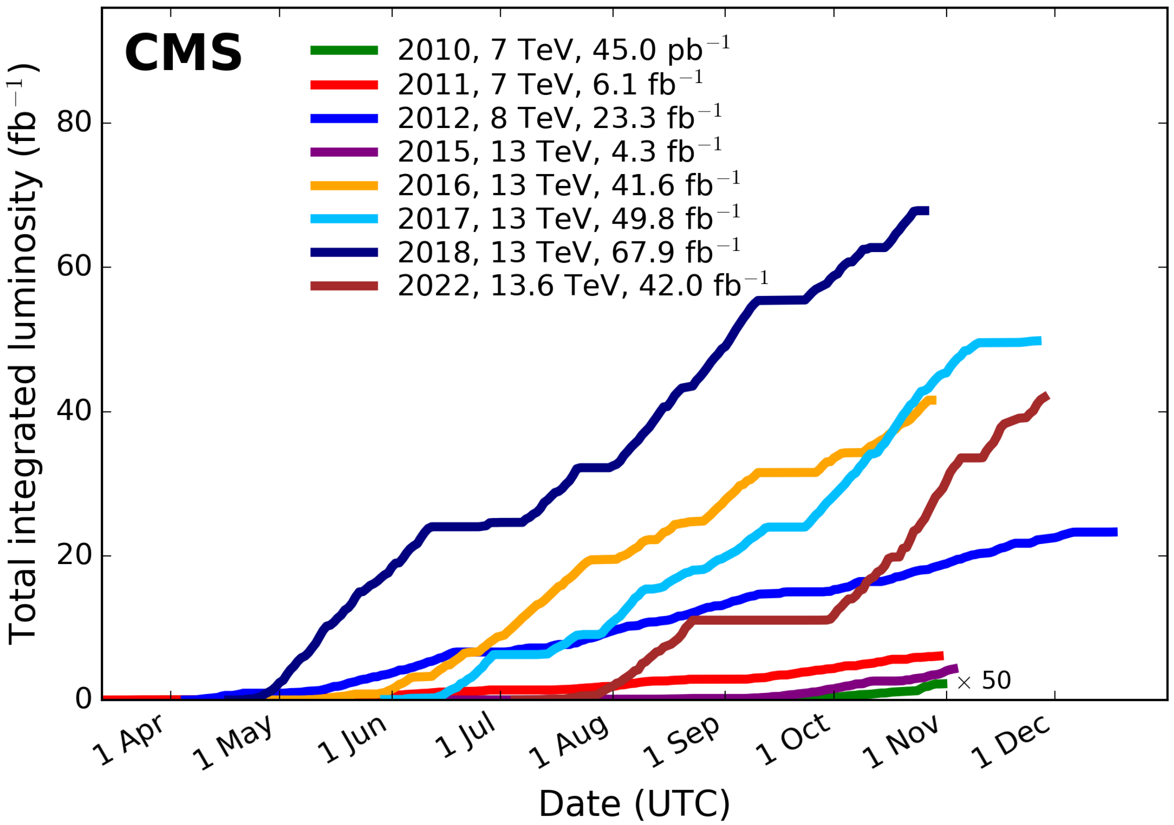

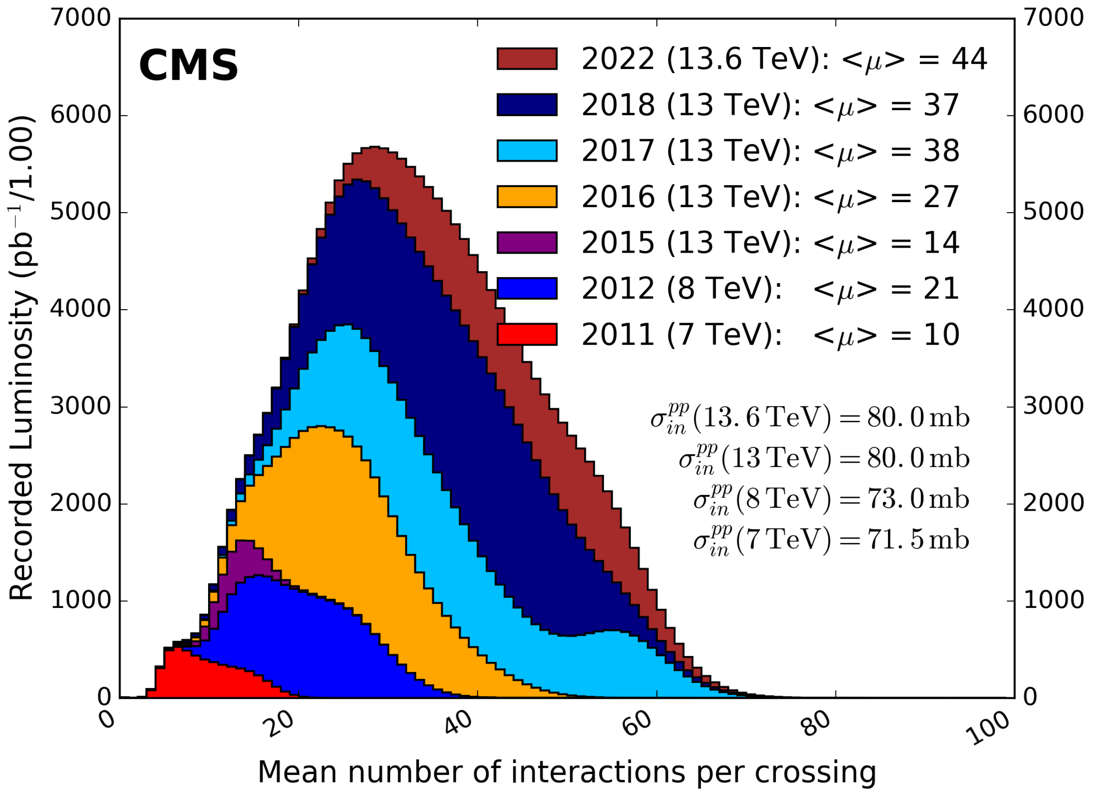

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Indirect searches

Higgs couplings and two example of high p_t CP violation searches

Other high p_t searches, including study of b CP asymmetries using semi-leptonic top decays exist; but not covered here.

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Couplings to fermions

CMS Collaboration, Nature 607, pages 60–68 (2022)

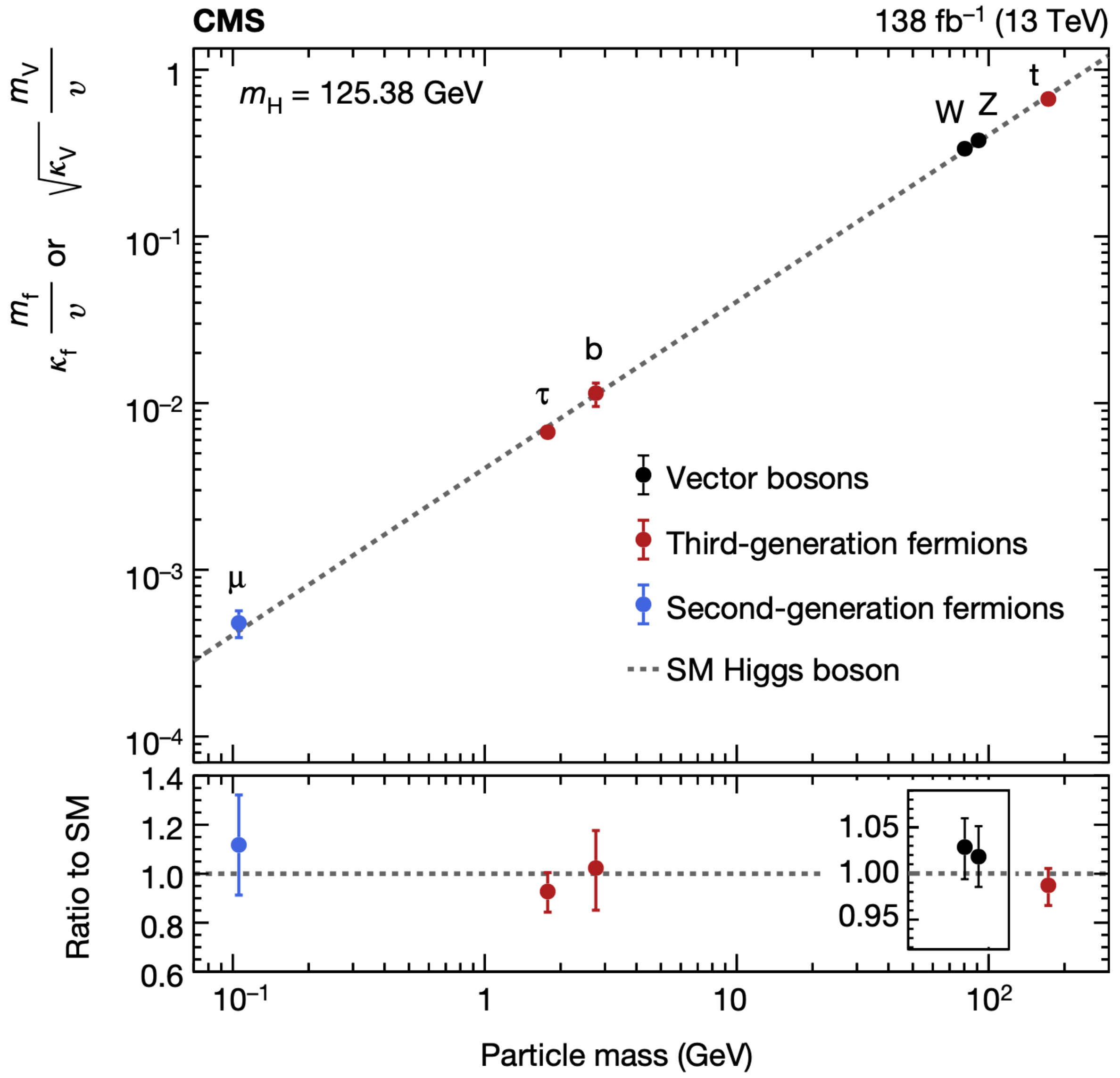
- **The CKM matrix is derived from fermion mass diagonalisation in the SM**

$$U'M'U'^{\dagger} = D' = \mathrm{diag}\left(\frac{m_d}{m_b}, \frac{m_s}{m_b}, 1\right)$$

$$UMU^{\dagger} = D = \mathrm{diag}\left(\frac{m_\mu}{m_t}, \frac{m_c}{m_t}, 1\right),$$

$$V_{CKM} = UU'^{\dagger}$$

- **Couplings deviating from the SM would have implications for the for the CKM picture**



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CMS Collaboration, Nature 607, pages 60–68 (2022)

Couplings to fermions

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$U'M'U'^{\dagger} = D' = \mathrm{d}$

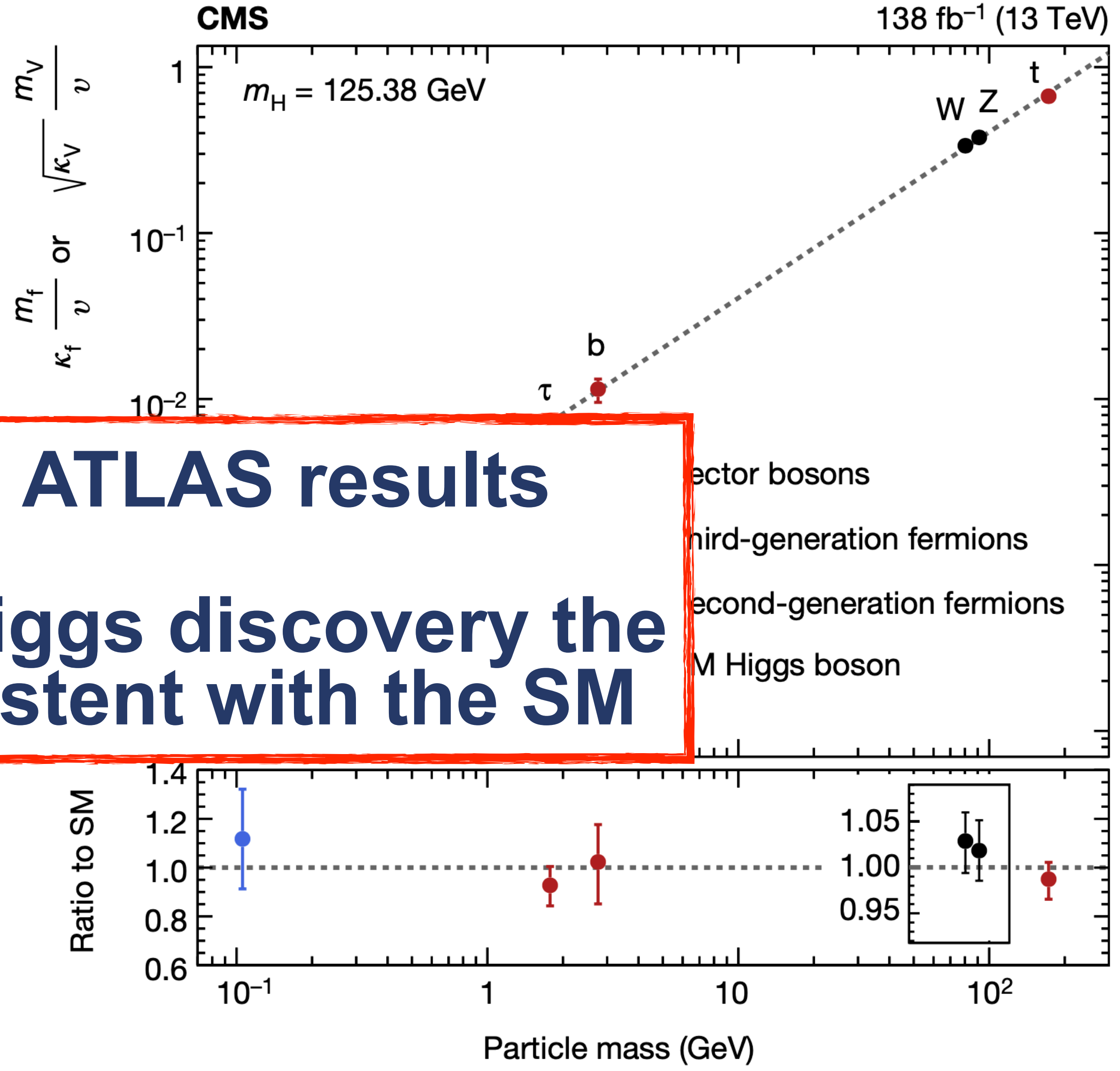
$UMU^{\dagger} = D = \mathrm{di}$

$$V_{CKM} = UU'^{\dagger}$$

Similar picture from ATLAS results

10 years after the Higgs discovery the couplings are consistent with the SM

- Couplings deviating from the SM would have implications for the for the CKM picture



For ATLAS results see: ATLAS Collaboration, Nature 607, pages 52–59 (2022)

CP violation

- In the 1980's new CP violation tests were being explored
- An important paper stood out among others

NOTES ON THE OBSERVABILITY OF *CP* VIOLATIONS IN B DECAYS

I.I. BIGI

Institut für Theor. Physik der RWTH Aachen, D-5100 Aachen, FR Germany

A.I. SANDA[1]

Rockefeller University, New York 10021, USA

Received 16 June 1981

We describe a general method of exposing *CP* violations in on-shell transitions of B mesons. Such *CP* asymmetries can reach values of the order of up to 10% within the Kobayashi–Maskawa model for plausible values of the model parameters. Our discussion focuses on those (mainly non-leptonic) decay modes which carry the promise of exhibiting clean and relatively large *CP* asymmetries at the expense of a reduction in counting rates. Accordingly we address the complexities encountered when performing *CP* tests with a high statistics B meson factory like the Z^0 (and a toponium) resonance.

Nuclear Physics B193 (1981) 85-108

- CKM, superweak and Higgs multiplet theories could all give rise to sources of CP violation.
  - What description was correct?
  - How do we test that?
- Superweak ruled out by ε'
- B Factory consistent with CKM picture.
- What about Higgs multiplets?

CP violation: ttH and tH searches

- SM Higgs is CP even
- Presence of a CP odd component in t-H coupling would constitute CP violation (and more than one Higgs)

$$\mathcal{L}_{\mathrm{t\bar{t}H}} = \frac{m_{\mathrm{t}}}{v}\bar{\psi}_{\mathrm{t}}(\kappa_{\mathrm{t}} + i\gamma_5\tilde{\kappa}_{\mathrm{t}})\psi_{\mathrm{t}}\mathrm{H}$$

- $\kappa_t, \overline{\kappa}_t$ are CP even / odd couplings
- $\psi' s$ are Dirac spinors
- v is the Higgs VEV

- Introduce a mixing angle α: $\cos\alpha$ / $\sin\alpha$ describe CP even/odd terms
- $\alpha = 0^{\circ}, 180^{\circ}$ for a purely CP even state
- $\alpha = 90^{\circ}$ for a purely CP odd state
- otherwise the state is mixed

CMS result (https://arxiv.org/abs/2208.02686)

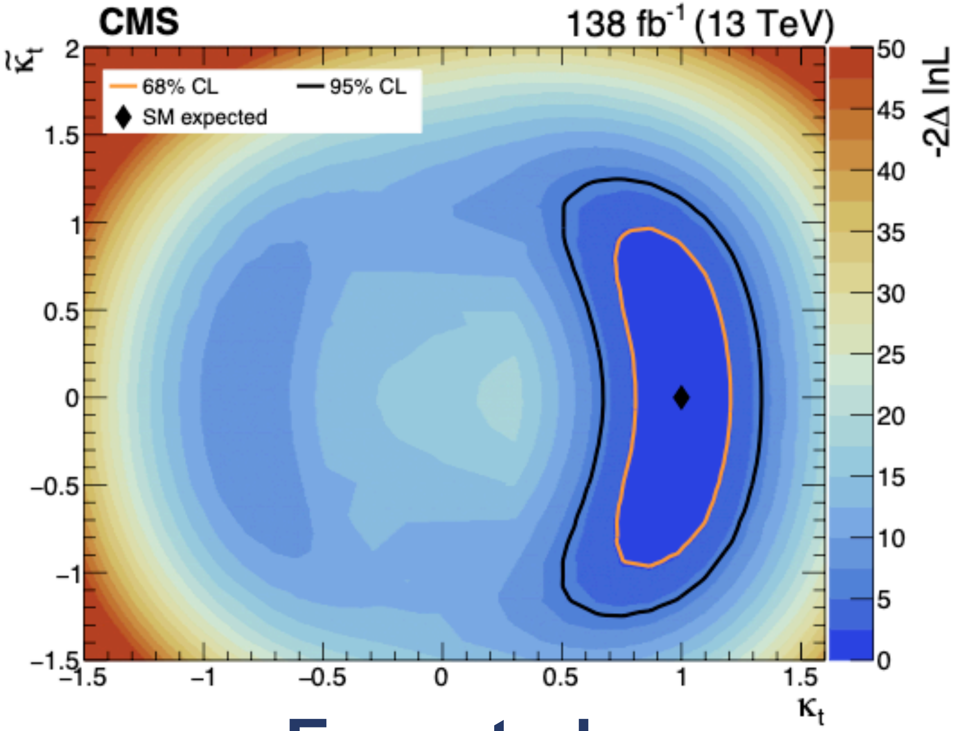
CP violation searches e.g ttH and tHq, tHW

- Trigger on multi (1, 2, 3) lepton final states
- Reconstruct Higgs via WW, ZZ or $\tau^+\tau^-$ in leptonic or hadronic decay modes
- Multivariate discriminator for background suppression
- Reducible backgrounds:
  - mainly from $t\bar{t}$ events
  - $t\bar{t}\gamma$ leads to photon conversion background
  - leptonic charge flipping from events with both tops decaying semileptonically (issue for electron mode)
- Irreducible backgrounds from rare processes also considered
- Additional discriminator for CP-odd/even determination

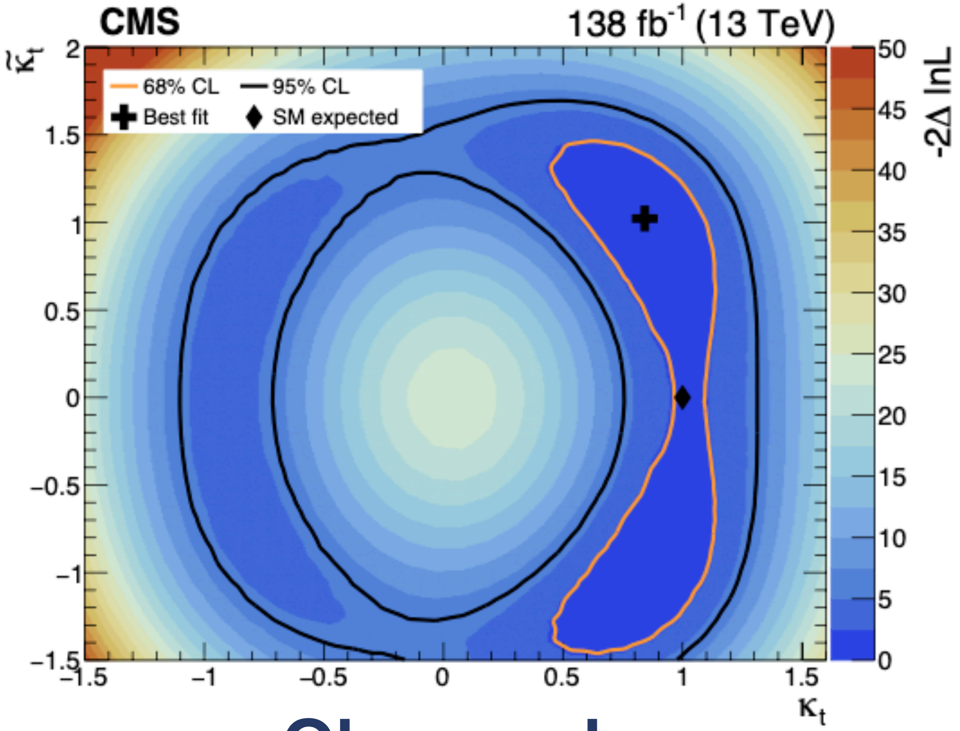
CMS result (https://arxiv.org/abs/2208.02686)

CP violation searches e.g ttH and tHq, tHW

- 138 /fb of data used
- Result obtained compatible with the SM
- No significant CP odd component found



Expected



Observed

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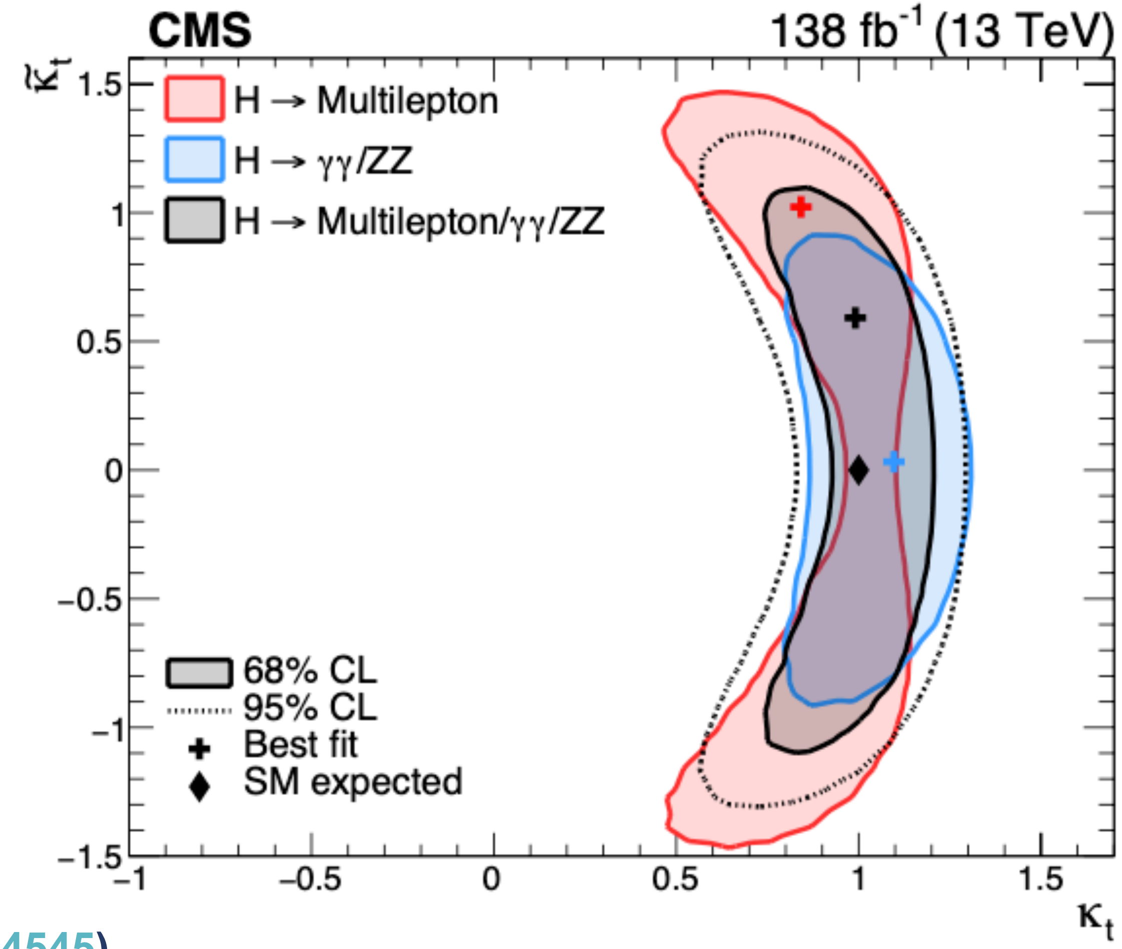
CP violation searches e.g ttH and tHq, tHW

- Likewise combination (with previous CMS results) is compatible with the SM

Parameter	68% CL	95% CL
κ_t	(0.96, 1.16)	(0.86, 1.26)
$\tilde{\kappa}_t$	(-0.86, 0.85)	(-1.07, 1.07)



- Validates a way to disentangle CP even and odd t-H couplings for future CP violation searches

(also see ATLAS result detailed in https://arxiv.org/abs/2004.04545)

ATLAS (https://arxiv.org/abs/2212.05833 accepted by EPJC)

CP violation searches e.g $H \to \tau^+\tau^-$

- Same motivation as for the previous example, this time looking for CP violation in the τ-H coupling

$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H$$

- ϕ_τ is the mixing angle
- $\cos\phi_\tau$, $\sin\phi_\tau$ are CP even/odd terms
- v is the Higgs VEV
- κ_τ coupling strength

- $\alpha = 0^\circ$ for a purely CP even state
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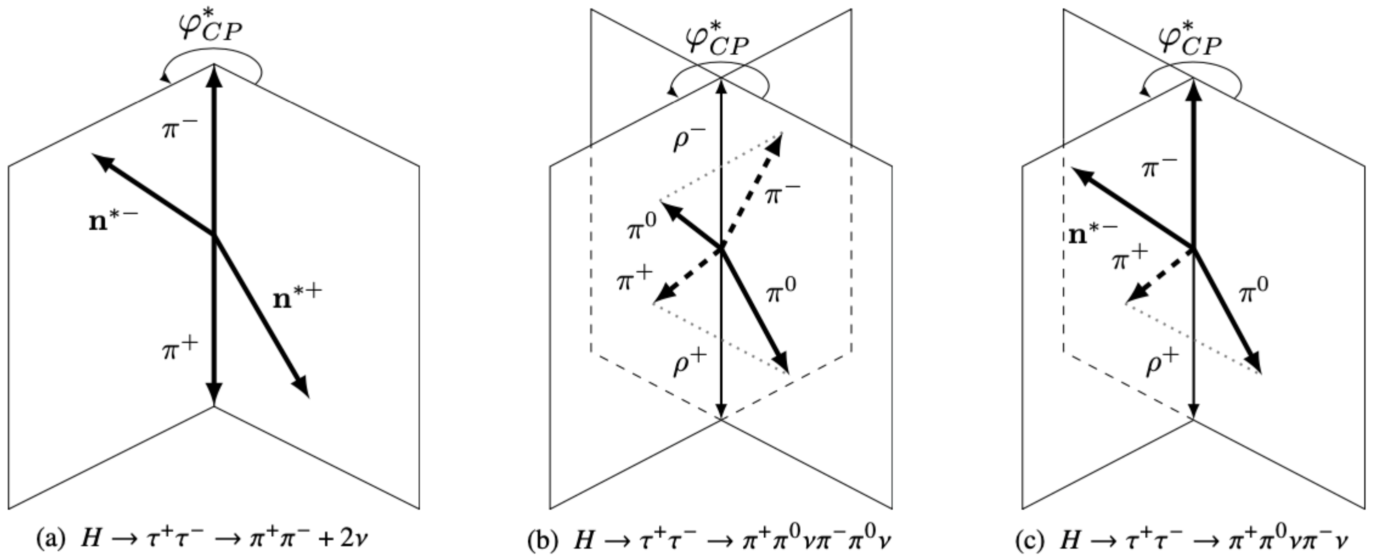
ATLAS (https://arxiv.org/abs/2212.05833 accepted by EPJC)

CP violation searches e.g $H \to \tau^+\tau^-$

- Reconstruct acoplanarity ϕ^*_{CP}, defined for different final states as



- Use leptonic and hadronic final states of the $\tau^\pm$ in lephad and hadhad final states
- Boost into the Zero Momentum Frame of the visible decay
- Use momentum vectors and impact parameter $n^{*\pm}$ to define the planes
- $\phi^*_{CP} = 180°$ for CP even
- $\phi^*_{CP} = 0°, 360°$ for CP odd

- Sensitive to ϕ_τ via rate as:

$$d\Gamma_{H\to\tau^+\tau^-} \approx 1 - b(E_+)b(E_-)\frac{\pi^2}{16}\cos(\varphi^*_{CP} - 2\phi_\tau)$$

- $E_\pm$ is the $\tau^\pm$ energy
- $b(E_\pm)$ is a spectral function describing the spin analysing power

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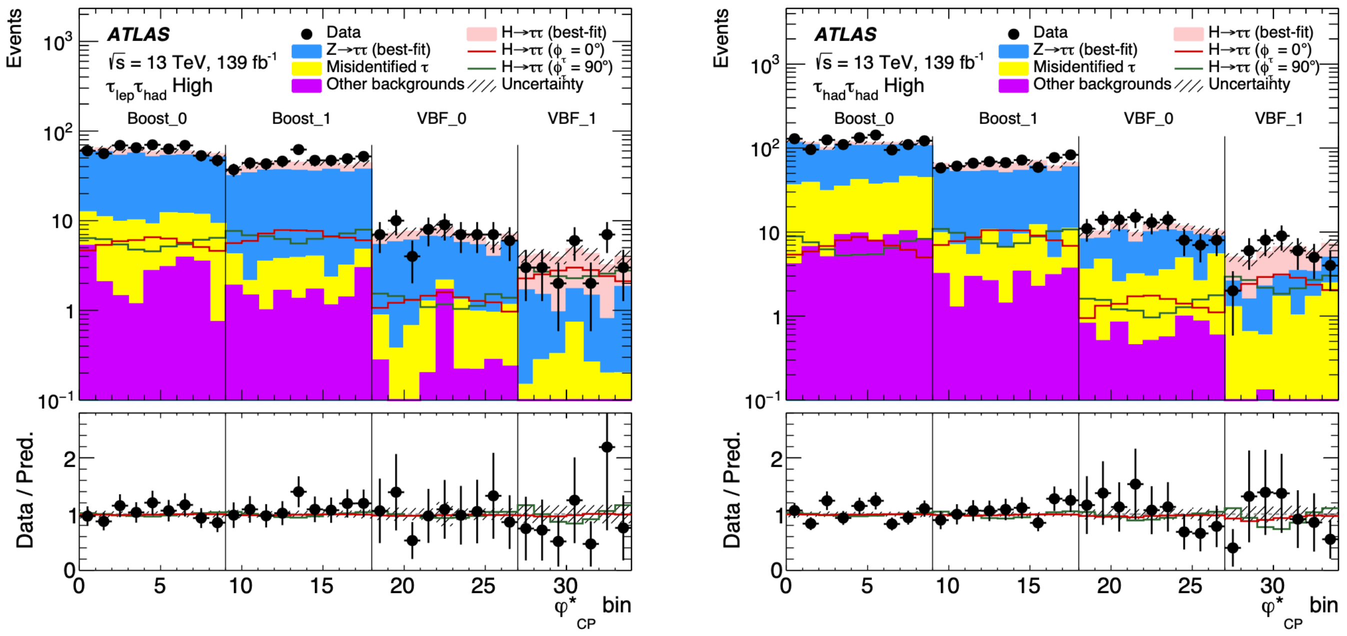
ATLAS (https://arxiv.org/abs/2212.05833 accepted by EPJC)

CP violation searches e.g $H \rightarrow \tau^+\tau^-$

- Define 4 signal regions for VBF and boost categories of event with common selection criteria (resolved vs boosted jets)
- and additional criteria for the lephad and hadhad final selections

VBF		Boost	
$p_T^{j_2} > 30$ GeV $m_{jj} > 400$ GeV $\lvert\Delta\eta_{jj}\rvert > 3.0$ $\eta_{j_1} \cdot \eta_{j_2} < 0$ Central τ-leptons		Not VBF $p_T^{\tau\tau} > 100$ GeV	
Signal region ($110 < m_{\tau\tau}^{MMC} < 150$ GeV)			
VBF_1	VBF_0	Boost_1	Boost_0
BDT(VBF) > 0	BDT(VBF) < 0	$\Delta R_{\tau\tau} < 1.5$ and $p_T^{\tau\tau} > 140$ GeV	$\Delta R_{\tau\tau} > 1.5$ or $p_T^{\tau\tau} < 140$ GeV
$Z \rightarrow \tau\tau$ control regions ($60 < m_{\tau\tau}^{MMC} < 110$ GeV)			
VBF_1 Z CR	VBF_0 Z CR	Boost_1 Z CR	Boost_0 Z CR



(a) $\tau_{lep}\tau_{had}$ High SR

(b) $\tau_{had}\tau_{had}$ High SR

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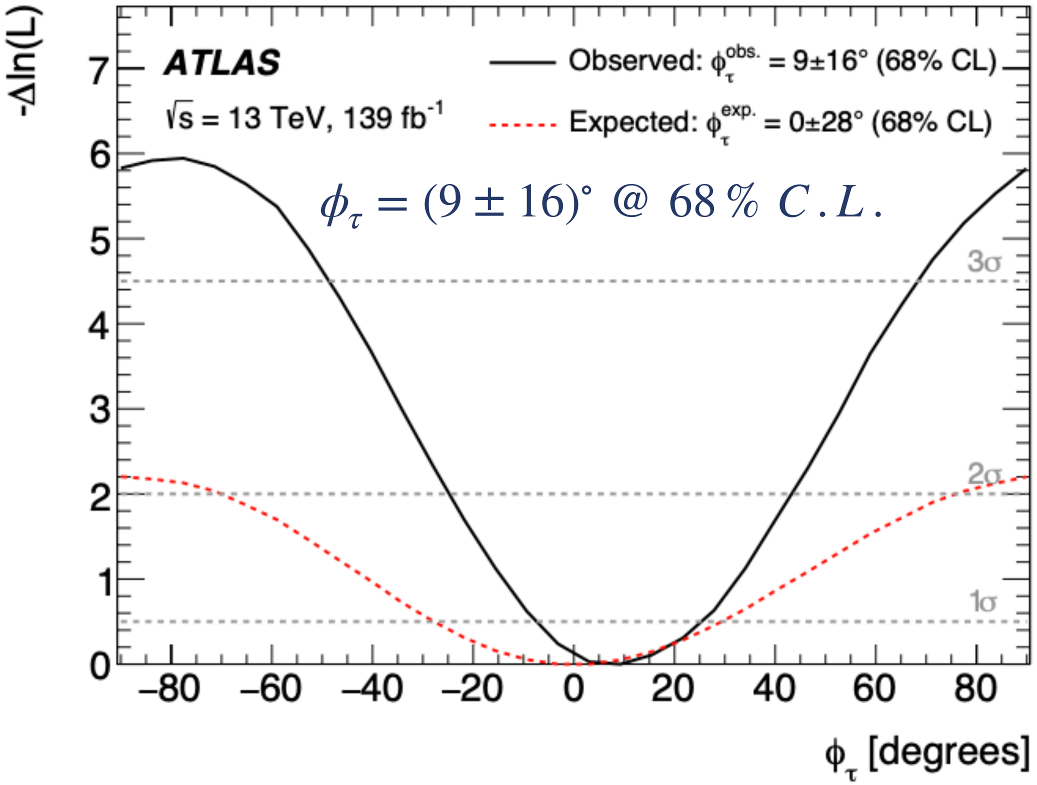
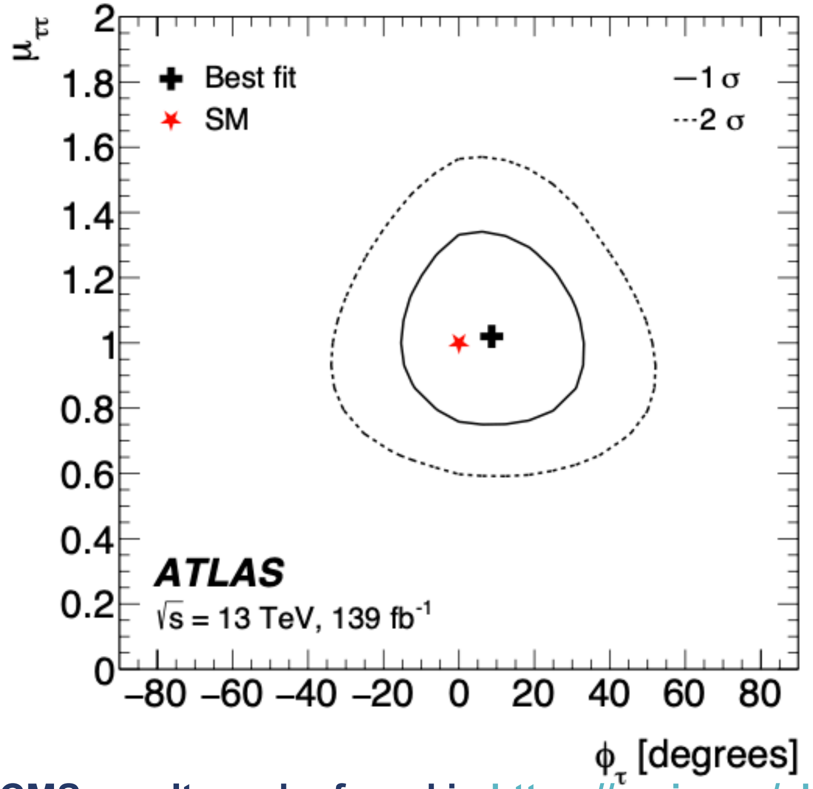
CP violation searches e.g $H \to \tau^+\tau^-$

- Signal strength and mixing phase compatible with SM
  - i.e. Signal strength ($\mu_{\tau\tau}$) and ϕ_τ SM-like
  - CP odd scenario is disfavoured at 3.4 σ





CMS result can be found in https://arxiv.org/abs/2110.04836

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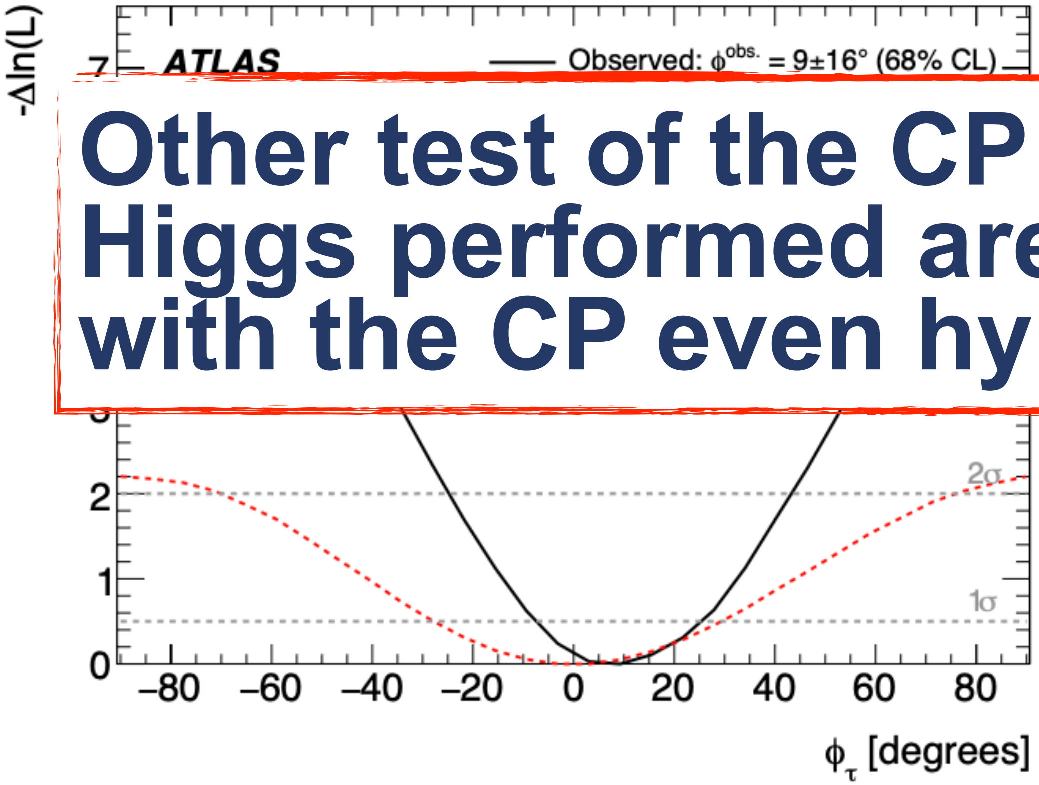

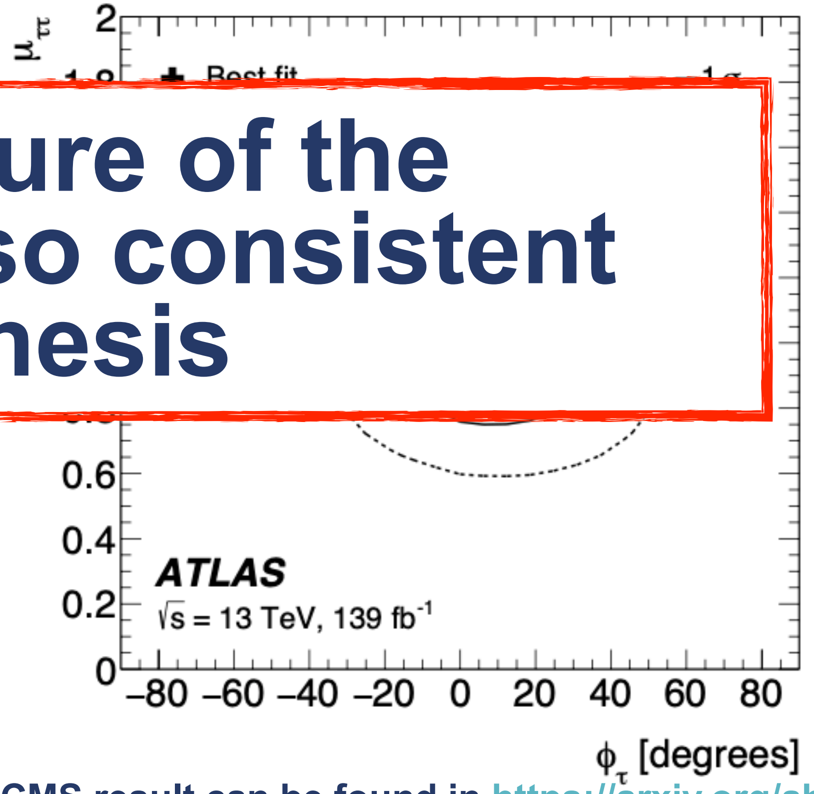

Other test of the CP nature of the Higgs performed are also consistent with the CP even hypothesis

CMS result can be found in https://arxiv.org/abs/2110.04836

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Direct searches

Searching directly for new particles in the data that don't fit the Standard Model(*)

Show only a few examples of analyses in this area from ATLAS and CMS

(*)The LHC has discovered many new particles e.g. XYZ states and pentaquarks, those are beyond the scope of this talk

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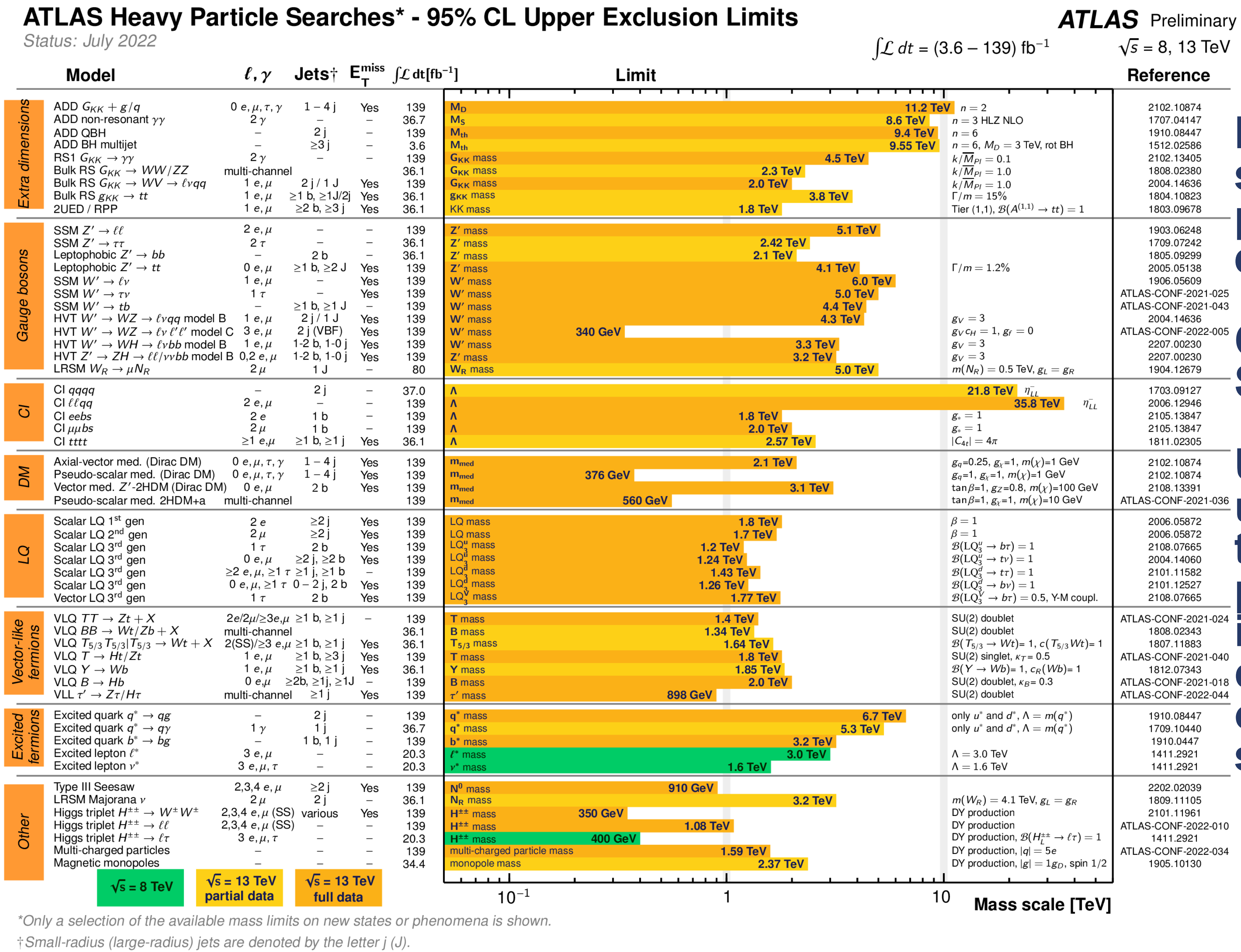
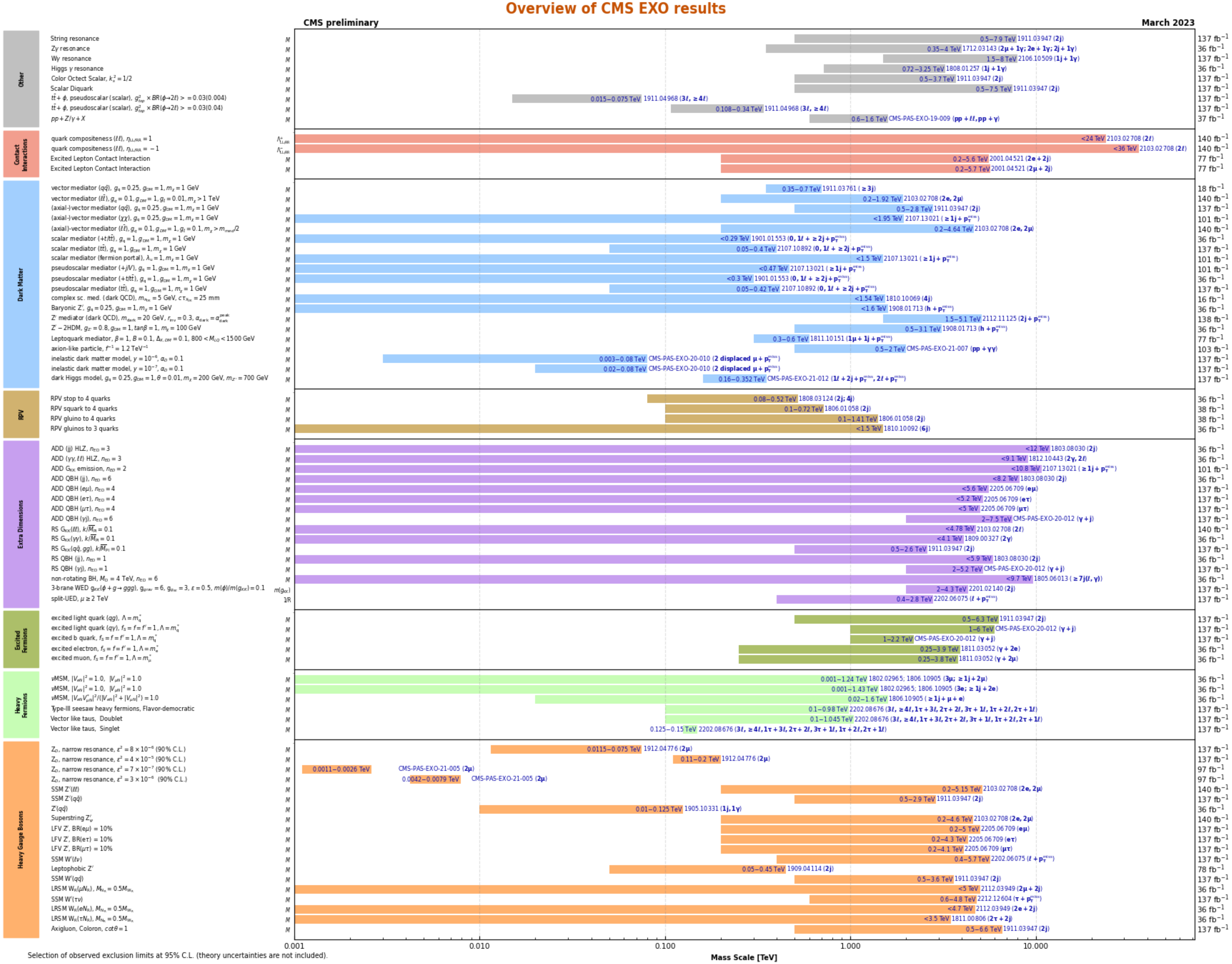
(Exotics)



Huge industry of searches for new particles by both experiments

Covers exotic and SUSY searches

Using a better understanding of the detectors to push exploration into more challenging areas of analysis e.g. semi-visible jets



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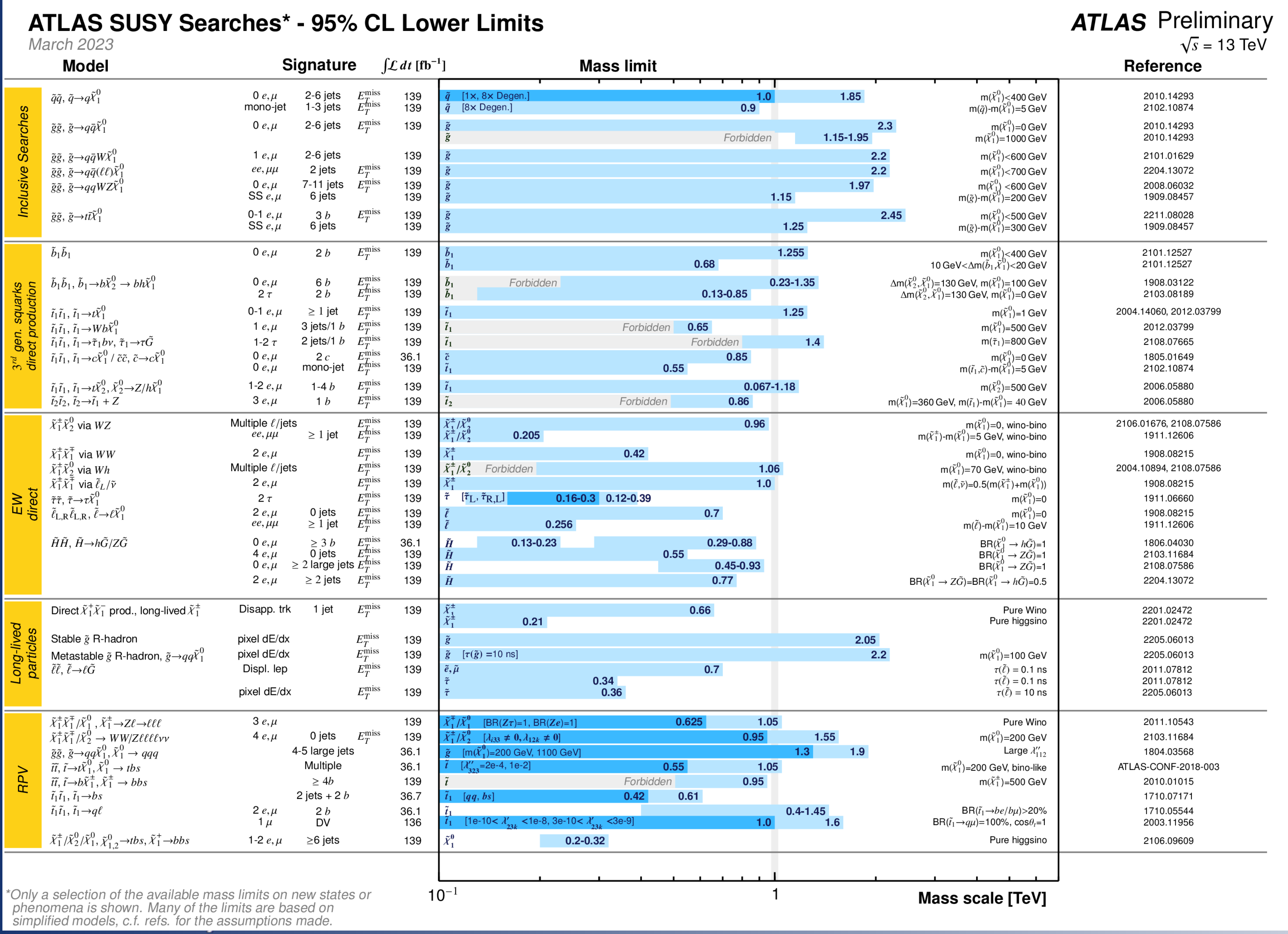

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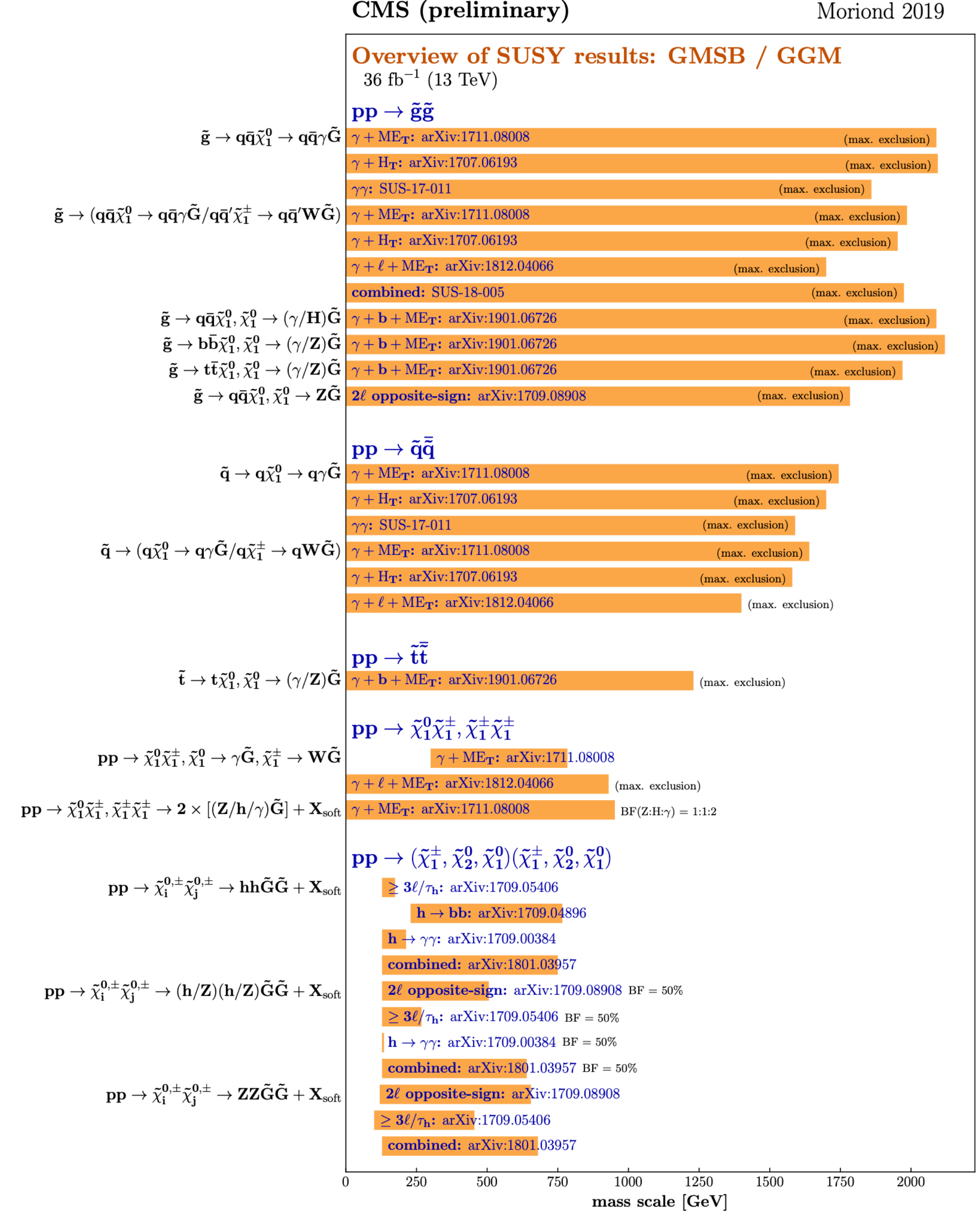

Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.

Huge industry of searches for new particles by both experiments

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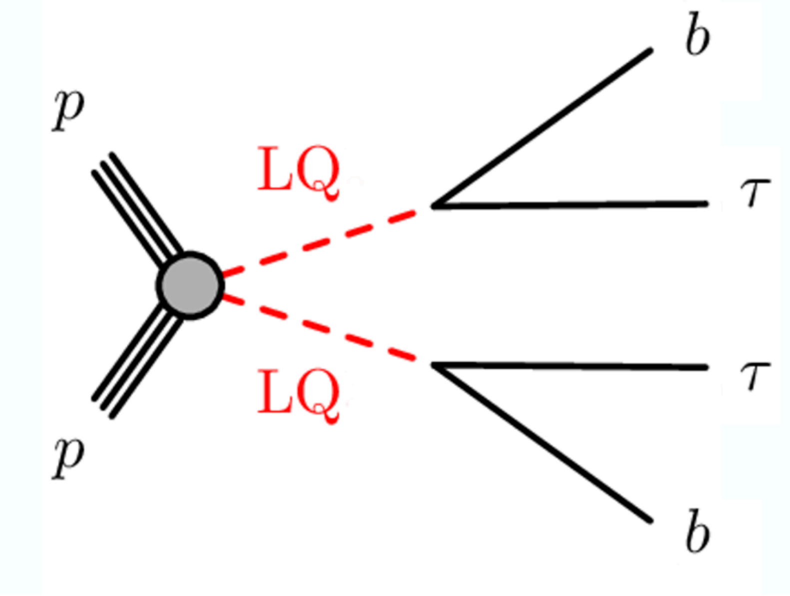
Using a better understanding of the detectors to push exploration into more challenging areas of analysis e.g. semi-visible jets

ATLAS (https://arxiv.org/abs/2303.01294 submitted to journal)

Direct searches: Leptoquark decay to $b\tau$

- Assumes leptoquark (LQ) pair production
- Assume decay only into the same generation
- Use $b\tau b\tau$ selection
- τ's are reconstructed into lep(tonic) and had(ronic) final states:
  - τ_{had} is seeded by jets
  - τ_{lep} is seeded by e and μ
- Backgrounds include $t\bar{t}$, single top, mis-reconstructed τ's, Z+jets



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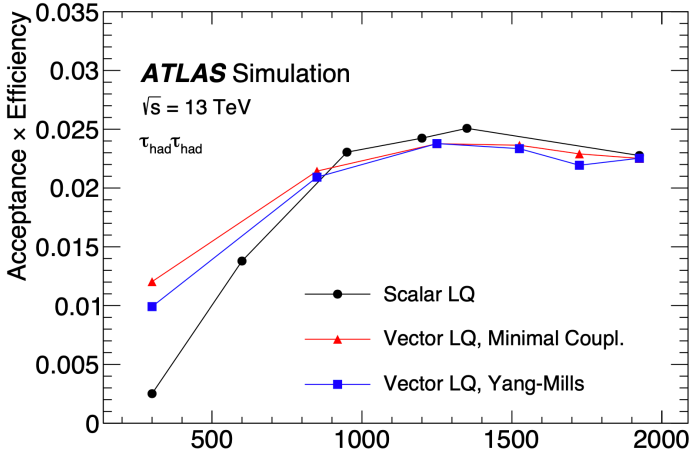
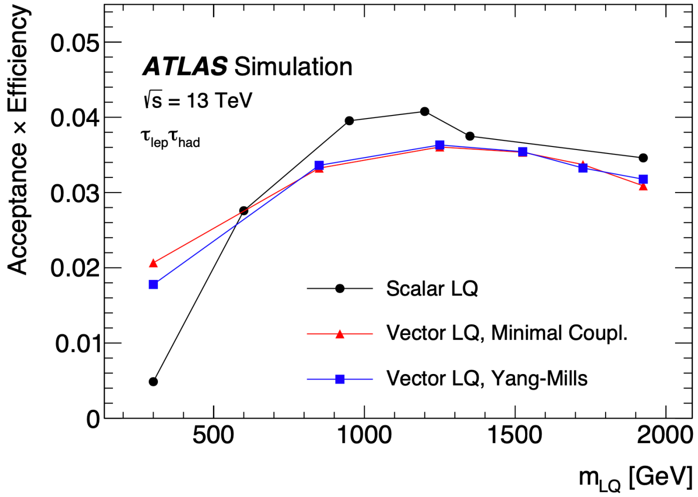
ATLAS (https://arxiv.org/abs/2303.01294 submitted to journal)

Direct searches: Leptoquark decay to $b\tau$

- Selection focuses on 1 prong τ_{lep} and 1 and 3 prong τ_{had} events
- O(%) overall efficiency (depends on model/mass)

	$\tau_{\text{lep}}\tau_{\text{had}}$ channel	$\tau_{\text{had}}\tau_{\text{had}}$ channel
e/μ selection	= 1 'signal' e or μ $p_T^e > 25, 27$ GeV $p_T^\mu > 21, 27$ GeV	No 'veto' e or μ
$\tau_{\text{had-vis}}$ selection	$= 1\ \tau_{\text{had-vis}}$ $p_T^\tau > 100$ GeV	$= 2\ \tau_{\text{had-vis}}$ $p_T^\tau > 100, 140, 180\ (20)$ GeV
Jet selection	≥ 2 jets $p_T^{\text{jet}} > 45\ (20)$ GeV 1 or 2 b-jets	
Additional selection	Opposite charge $e, \mu, \tau_{\text{had}}$ and τ_{had} $m_{\tau\tau}^{\text{MMC}} \notin 40 - 150$ GeV $E_T^{\text{miss}} > 100$ GeV $s_T > 600$ GeV	





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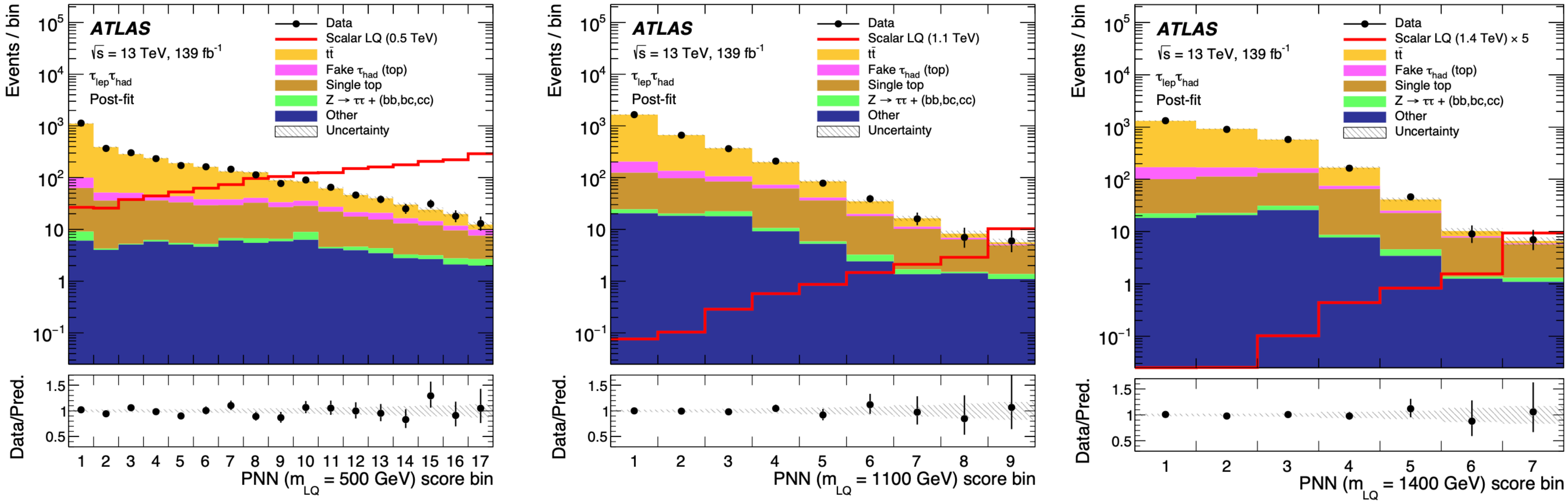
Direct searches: Leptoquark decay to $b\tau$

- **Uses parameterised NN (with LQ mass) to extract signal from background**



lephad

Direct searches: Leptoquark decay to $b\tau$

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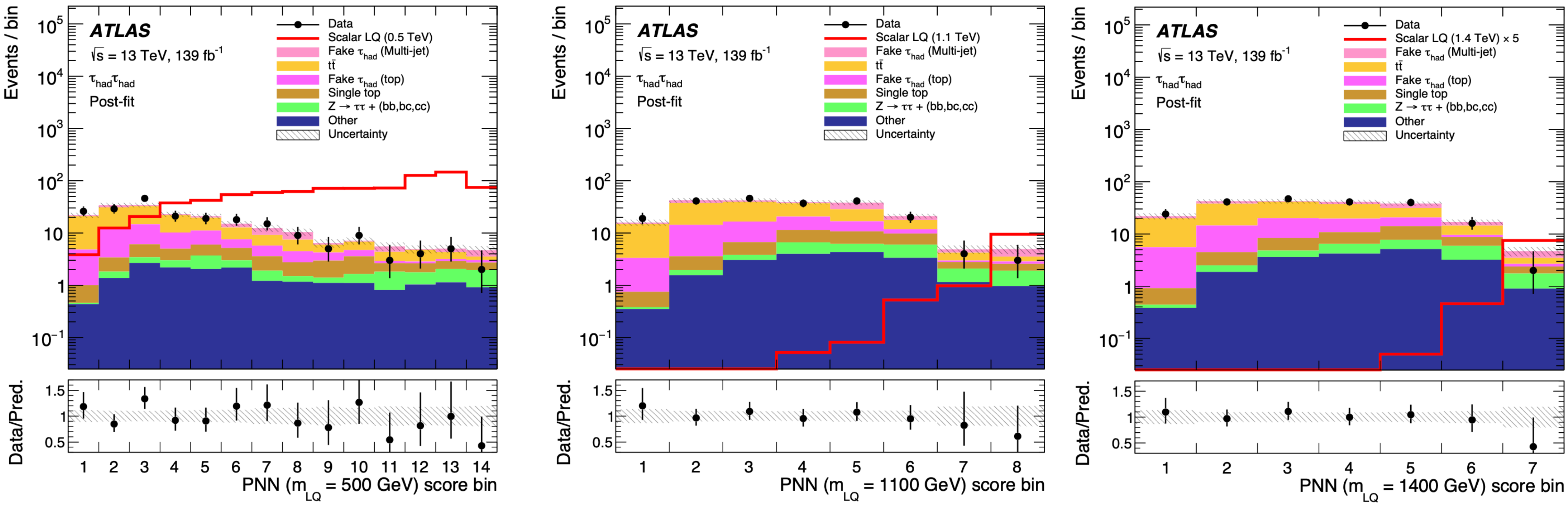
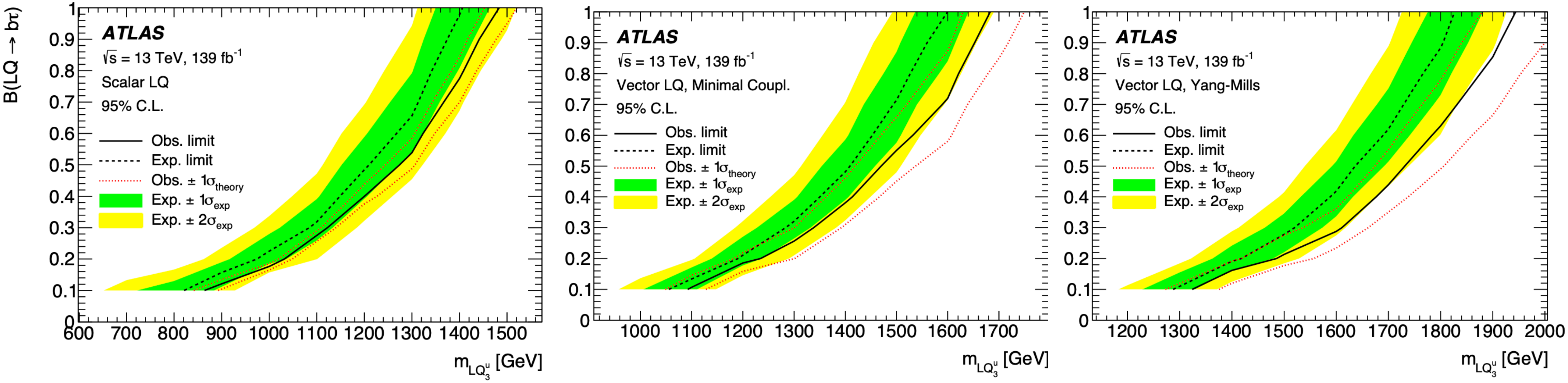


hadhad

Direct searches: Leptoquark decay to $b\tau$

- No signal observed: place limits on models

	Obs. limit [GeV]	Exp. limit [GeV]
Scalar LQ	1490	1410
Vector LQ (minimal-coupling)	1690	1600
Vector LQ (Yang–Mills)	1960	1840



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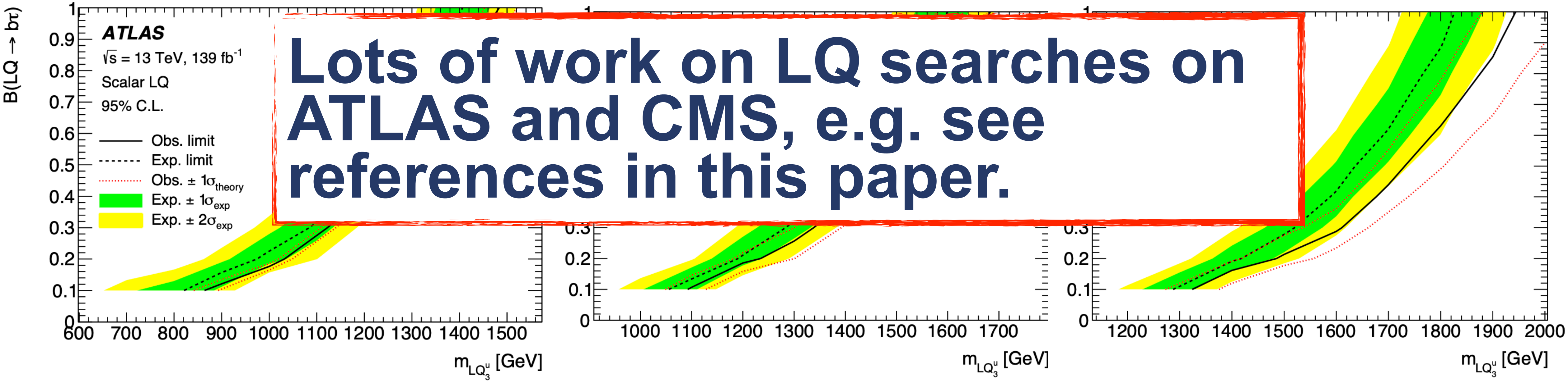

Lots of work on LQ searches on ATLAS and CMS, e.g. see references in this paper.

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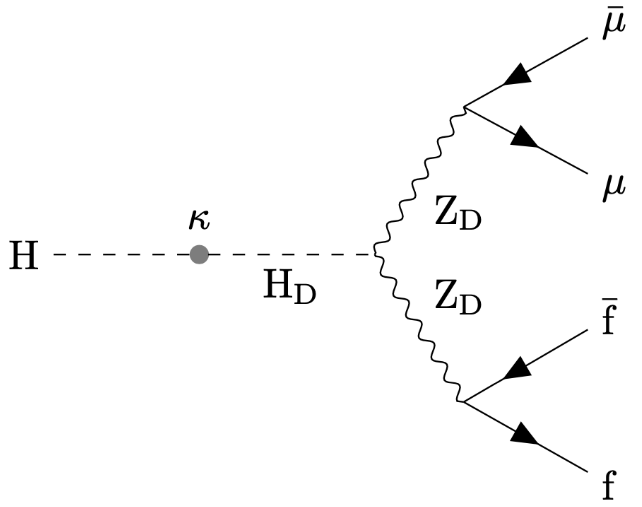
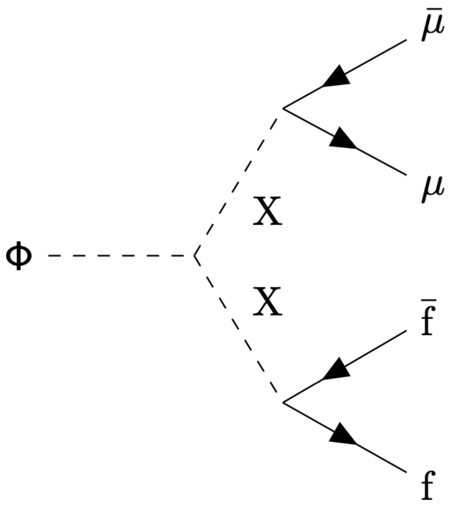
Direct searches: Long Lived Particles (LLPs)

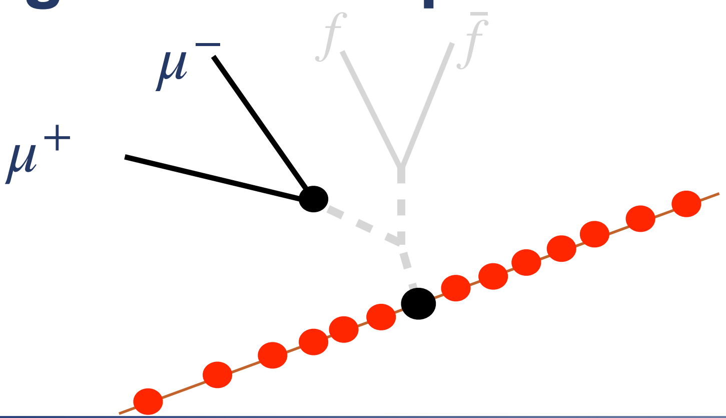
- Wide range of theoretical possibilities examples include:





- Higgs portal model dark photon (Z_D) decay [left]
- Heavy scalar (Φ) decaying to LLPs (X) [right]

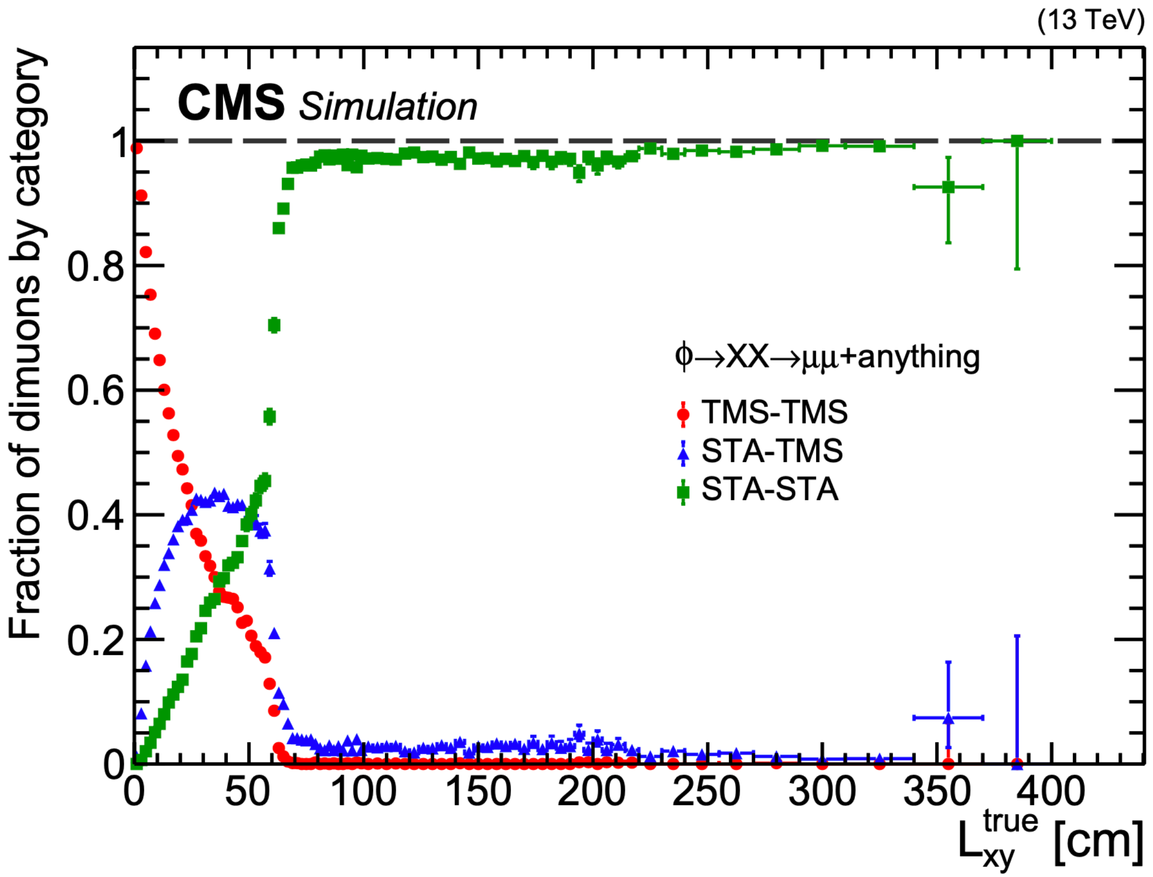
- Signature: displaced vertices from dimuons



- Select primary vertex as hardest scattering in event (based on tracks)
- Common displaced vertex fitted to a pair of tracks consistent with $\mu^+\mu^-$

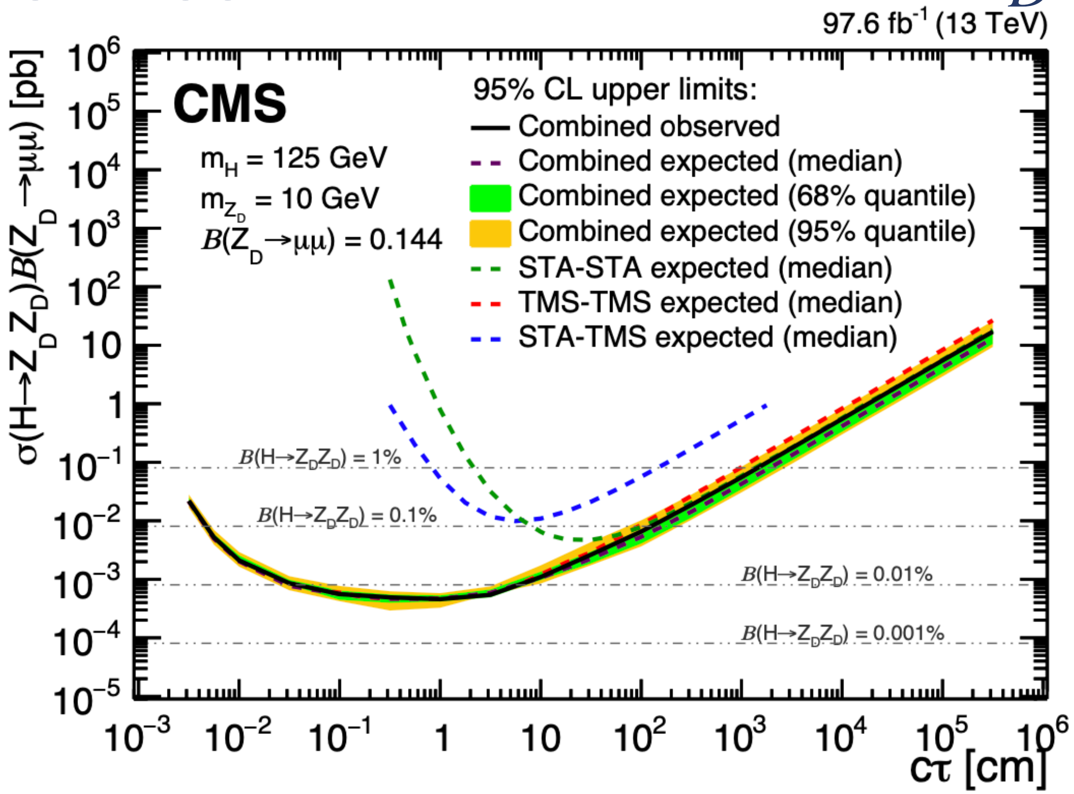
Direct searches: Long Lived Particles (LLPs)

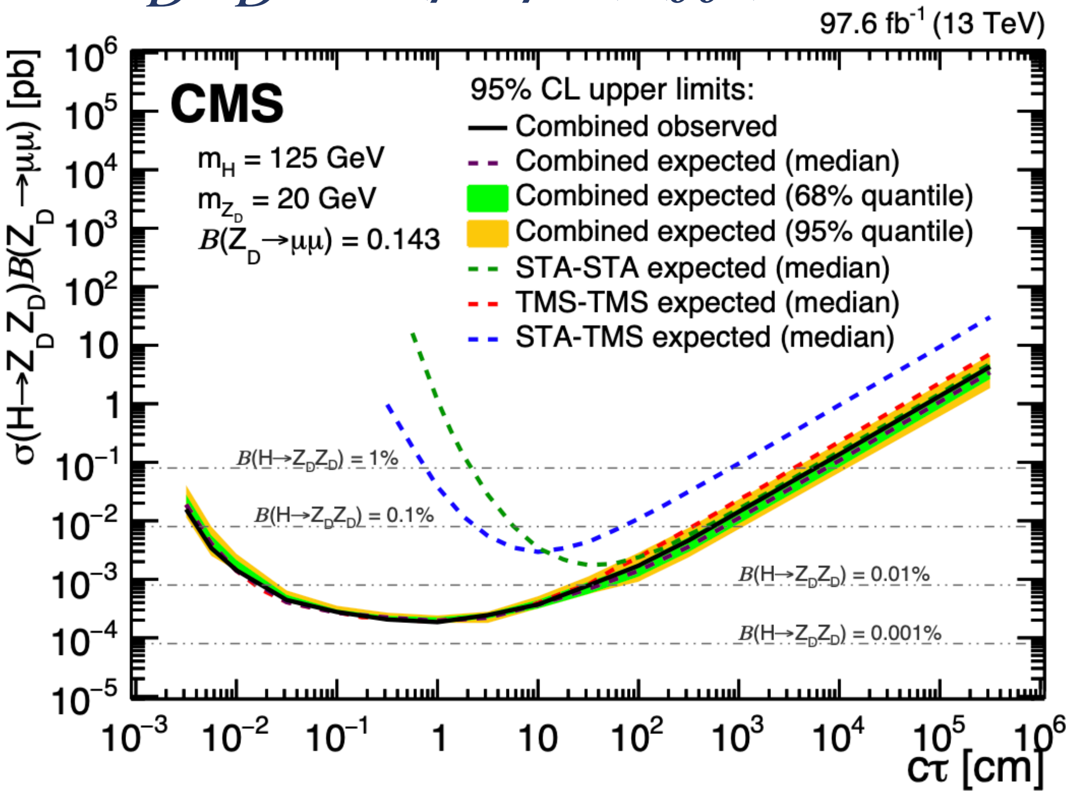
- TMS muons:
  - tracker + muon system
  - good momentum resolution
  - range limited by tracker radius
- STA muons:
  - muon system only
  - lower momentum resolution
  - works out to several meters
- Combinations of these muons provide coverage out to 4m in transverse decay length: L_{xy}



Direct searches: Long Lived Particles (LLPs)

- No dimuon resonances found
- Limits placed for different assumed intermediate particle masses e.g. Higgs portal model: $H \to H_D \to Z_D Z_D \to (\mu^+\mu^-)(f\bar{f})$





Direct searches: Long Lived Particles (LLPs)

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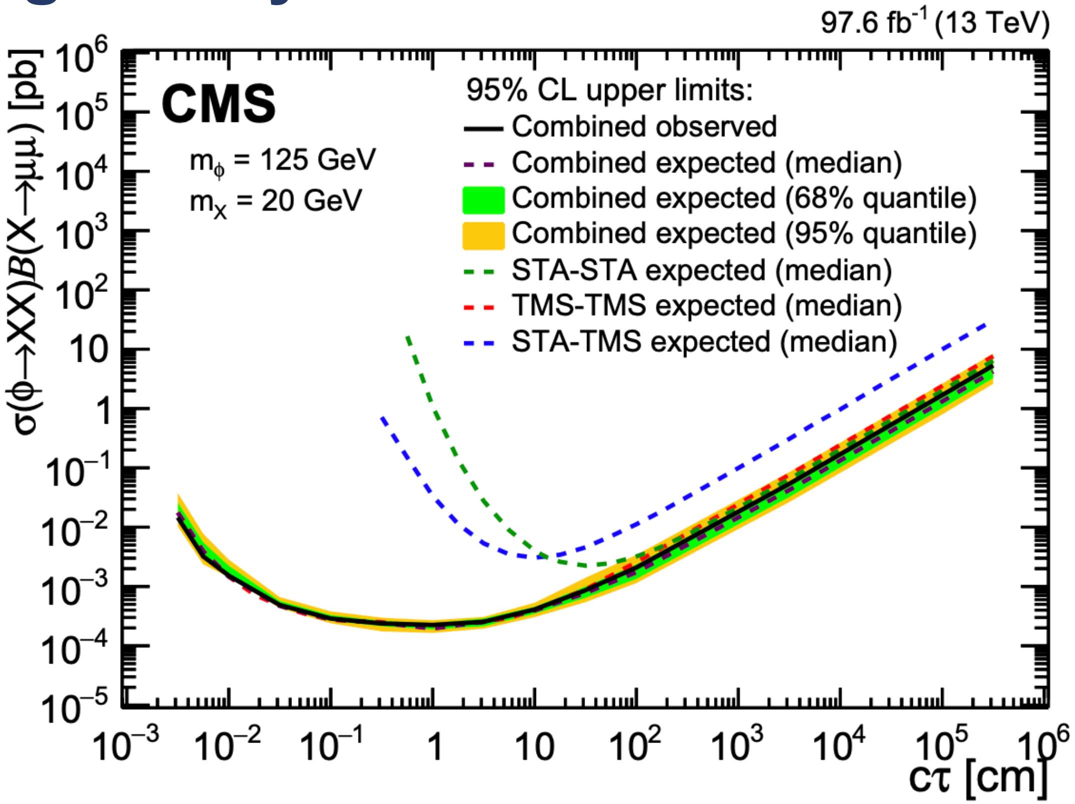
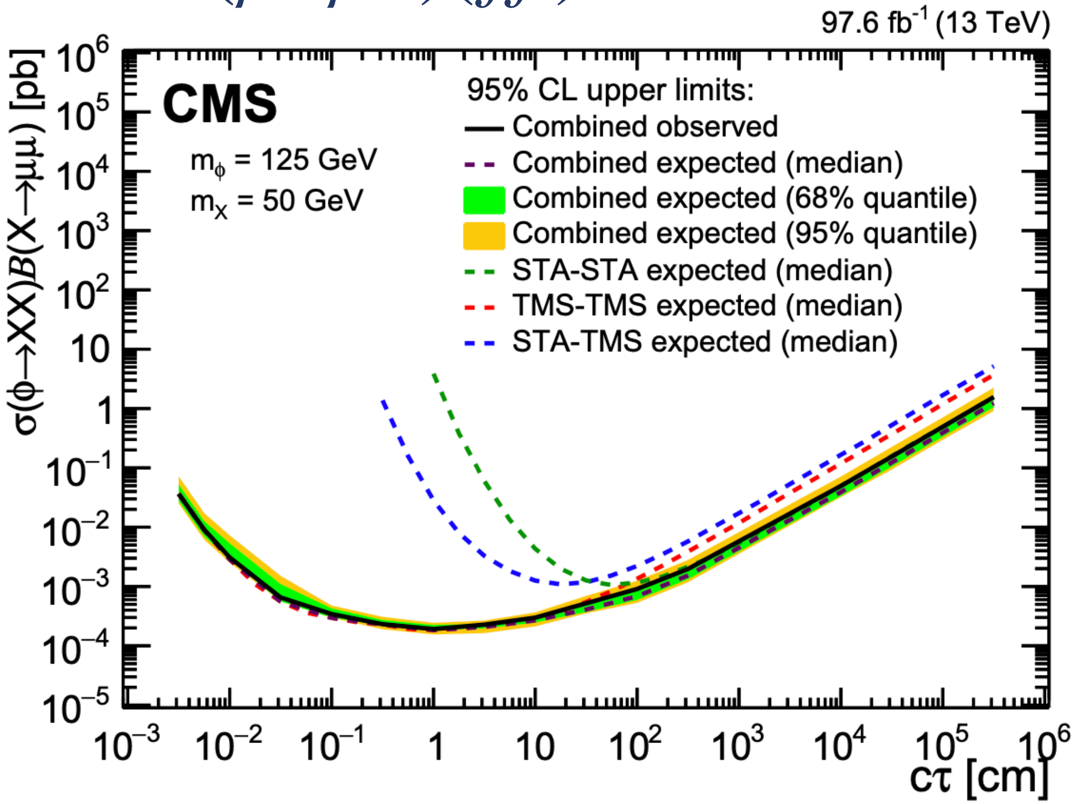
- Limits placed for different assumed intermediate particle masses e.g. Heavy scalar scenario: $\Phi \rightarrow XX \rightarrow (\mu^+\mu^-)(f\bar{f})$





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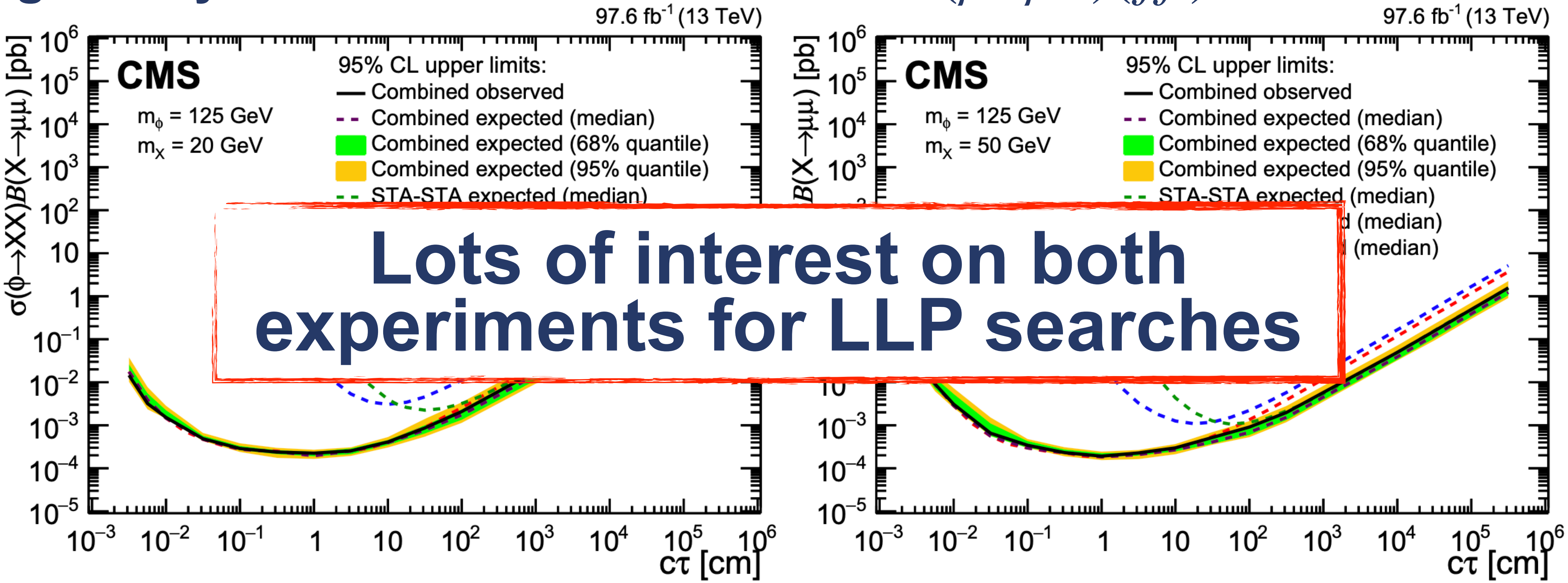

Lots of interest on both experiments for LLP searches

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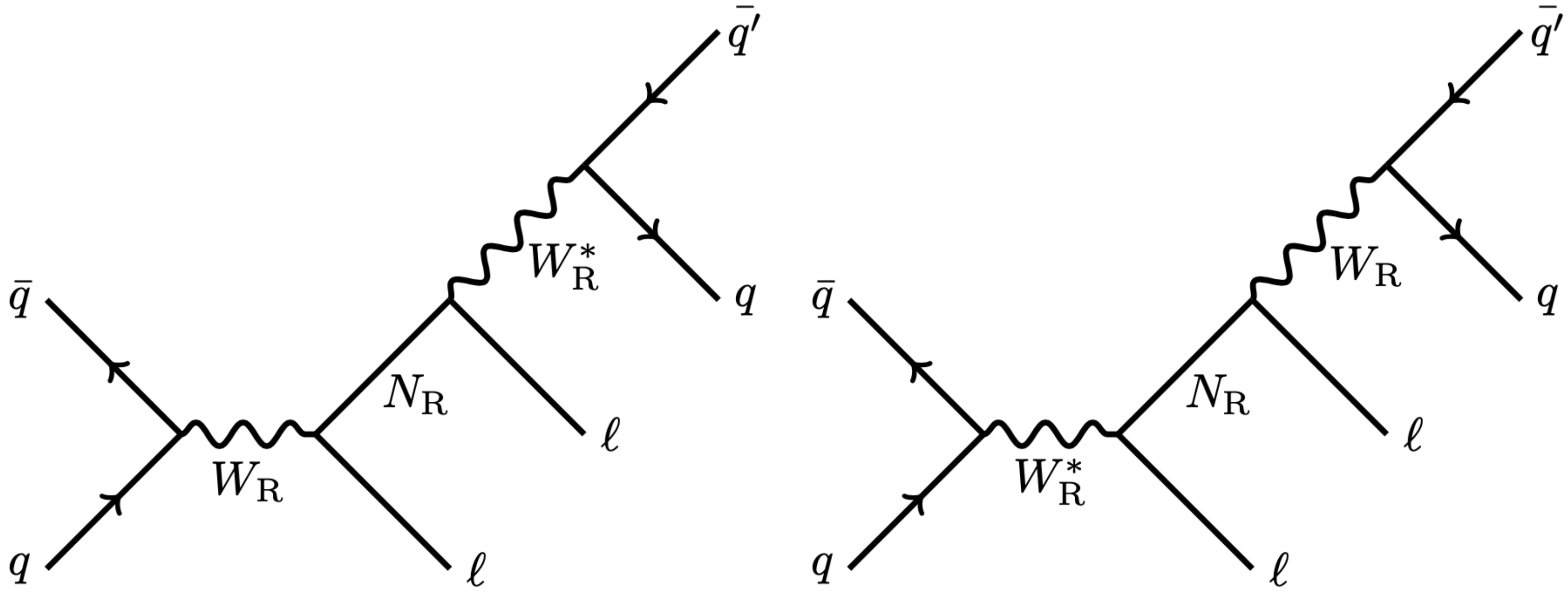
ATLAS (https://arxiv.org/abs/2304.09553 submitted to journal)

Direct searches: Heavy neutral lepton

- Sea Saw mechanism predicts right handed neutrinos
- The Left-Right Symmetric Model extension predicts a heavy right handed neutrino N_R and parters of the W and Z boson, W_R and Z_R



$m(W_R) > m(N_R)$ $m(W_R) < m(N_R)$

Lepton charge distinguishes between Dirac and Majorana neutrino structure

Analysis neglects lepton flavour mixing

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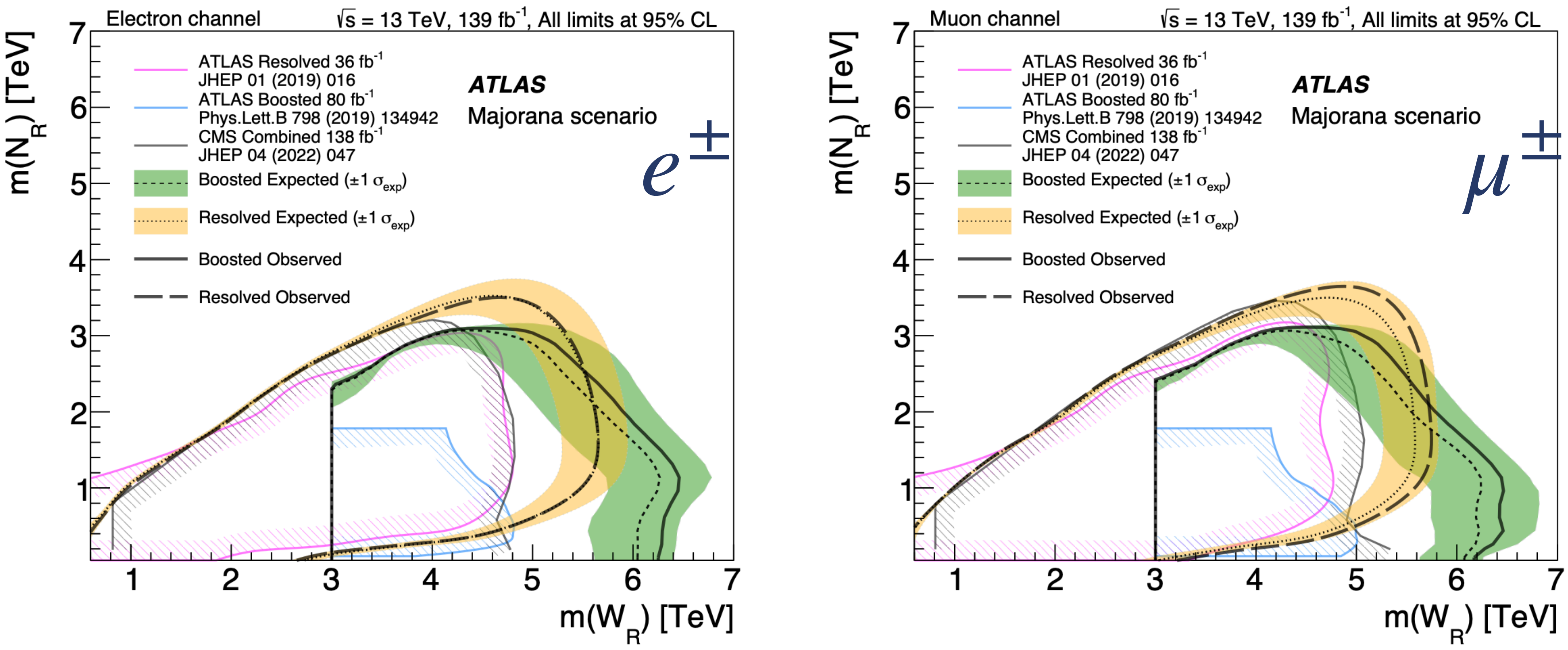
Direct searches: Heavy neutral lepton

- No signal found
- Exclusion limits for the Majorana neutrino scenario set



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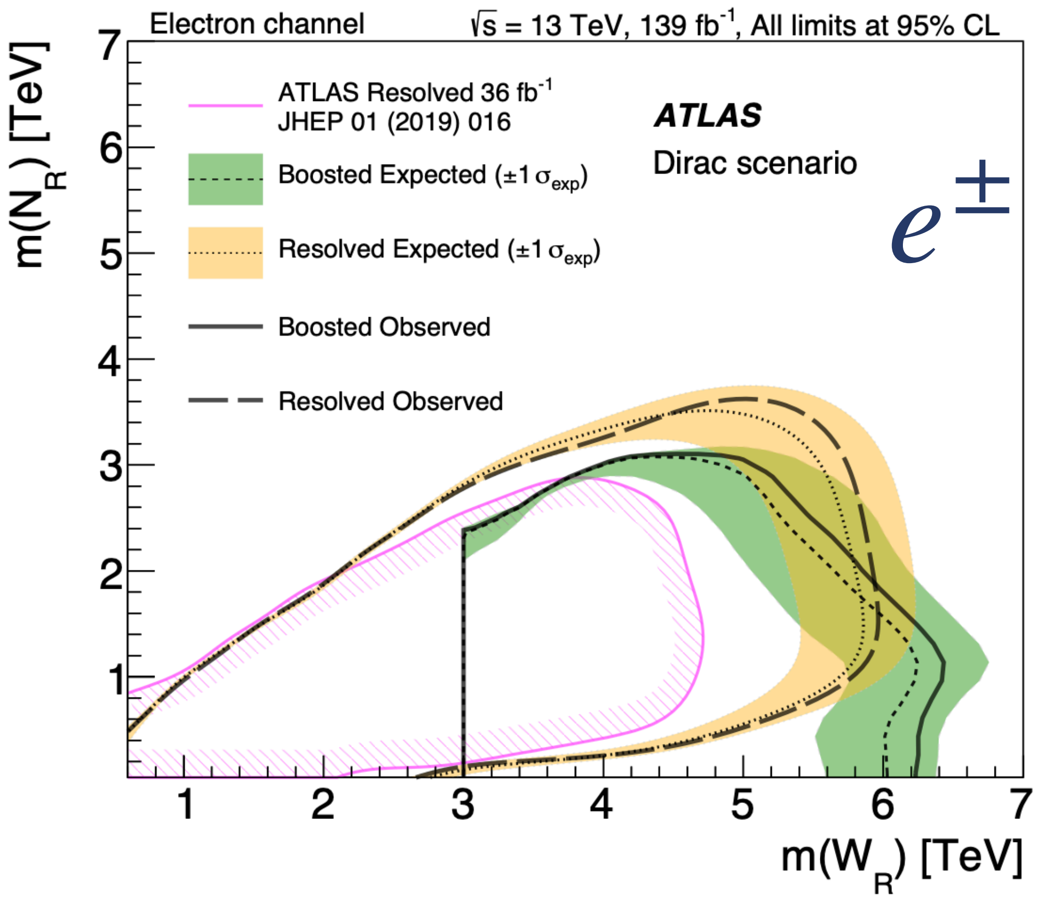
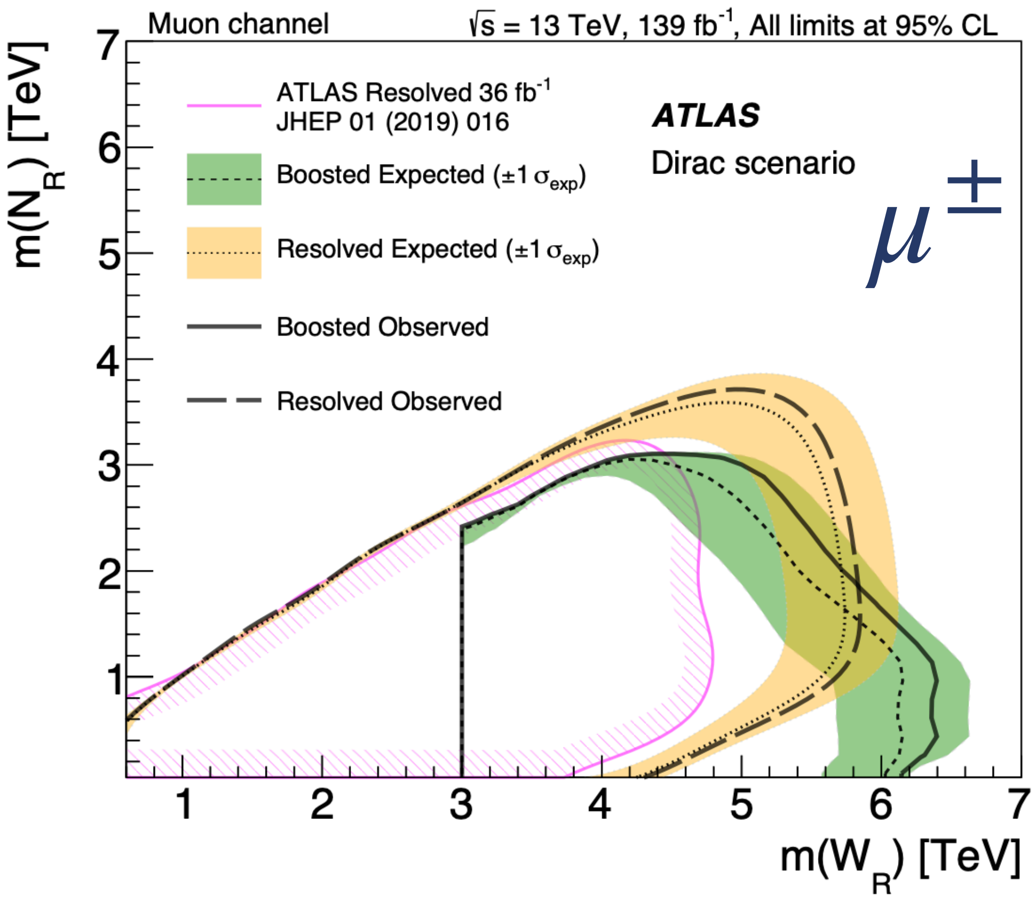
Direct searches: Heavy neutral lepton

- No signal found
- Exclusion limits for the Dirac neutrino scenario set





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Summary

- High p_t physics linked to our understanding of flavour via the Higgs
- CP violation searches using Higgs couplings complement searches performed at low energy B, D, K (ν's) and with top
- Searches for effects beyond the SM, either directly or indirectly using high p_t data have not paid dividend (yet)
- Run 3 has only just started, and with the High Luminosity upgrade construction underway, expect significant increases in data to continue the quest for new physics
- New ideas are constantly being tested, and the increase of data will ensure this trend continues through into the HL-LHC era

Additional slides

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ATLAS Collaboration, Nature 607, pages 52–59 (2022)

Couplings to fermions

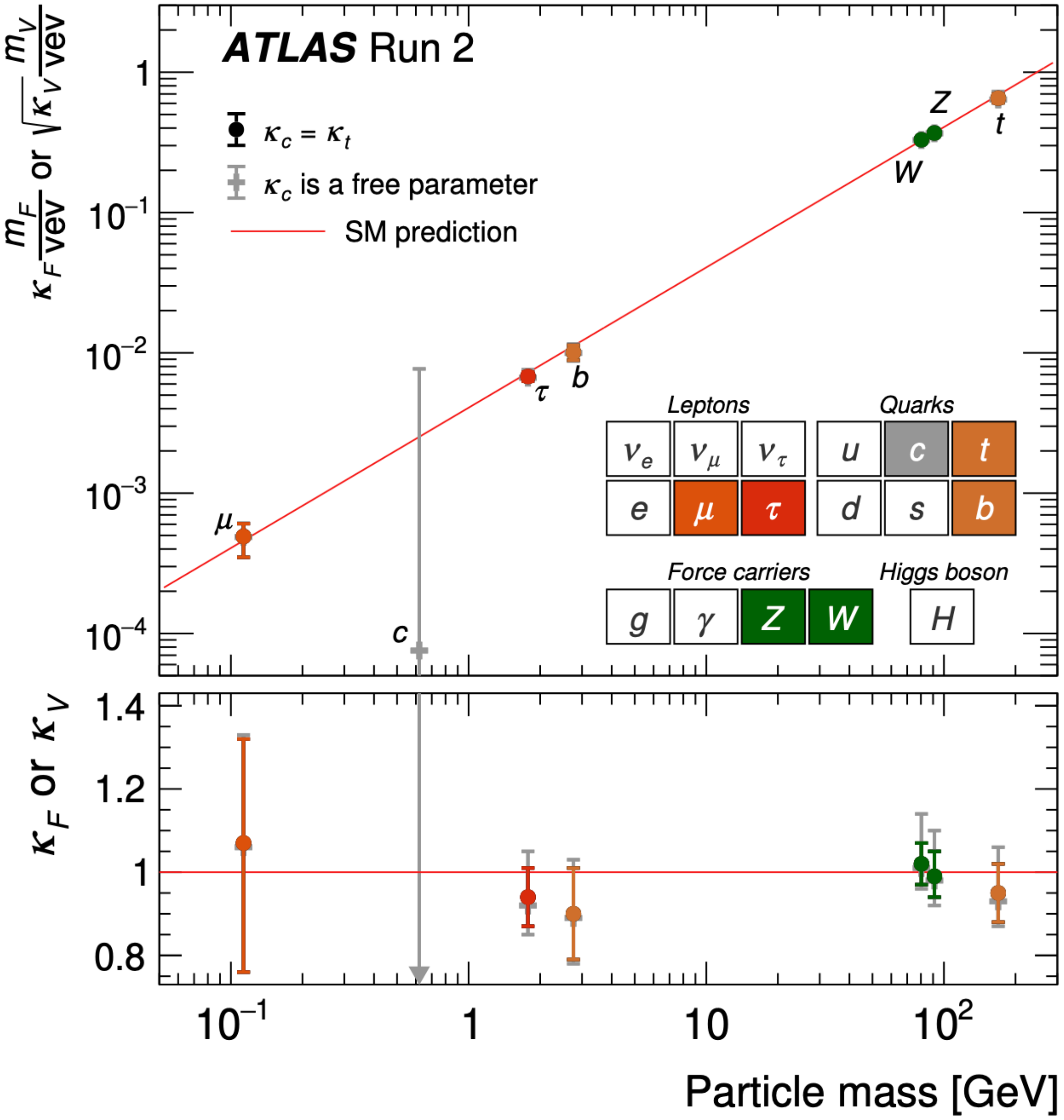
- **The CKM matrix is derived from fermion mass diagonalisation in the SM**

$$U'M'U'^{\dagger} = D' = \mathrm{diag}\left(\frac{m_d}{m_b}, \frac{m_s}{m_b}, 1\right)$$

$$UMU^{\dagger} = D = \mathrm{diag}\left(\frac{m_\mu}{m_t}, \frac{m_c}{m_t}, 1\right),$$

$$V_{CKM} = UU'^{\dagger}$$

- **Couplings deviating from the SM would have implications for the for the CKM picture**



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CMS result (https://arxiv.org/abs/2208.02686)

CP violation searches e.g ttH and tHq, tHW

- **XGBoost used for CP determination**
- **Shape differences in m_{ttH}, Δη and ΔR feed into CP determination**
- **e.g. the 2lSS + 0τh channel**

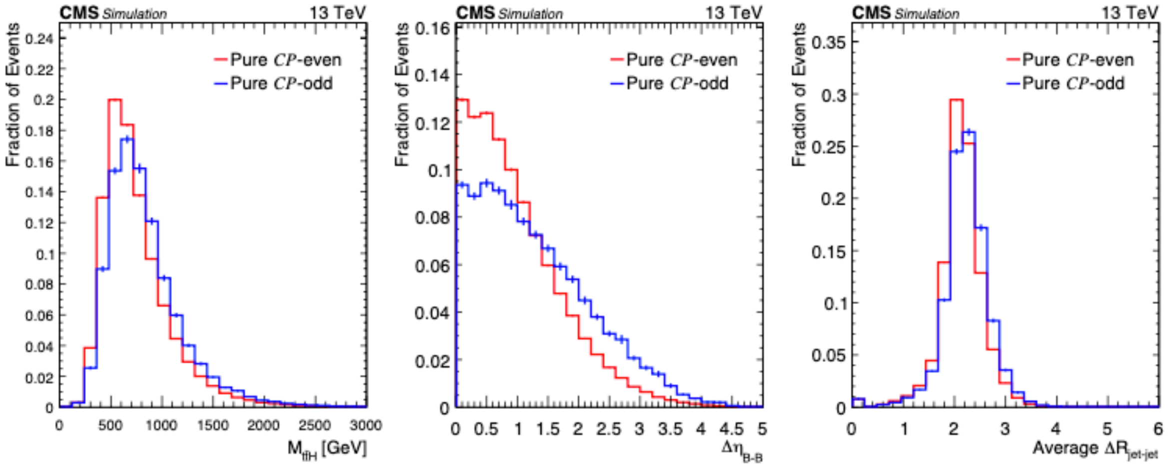

Table 4: Input features for the three BDTs. A check mark (✓) indicates the variable is used in a given final state, whereas a long dash (—) indicates the variable is not used in that final state.

Variable description	$2\ell SS + 0\tau_h$	$2\ell SS + 1\tau_h$	$3\ell + 0\tau_h$
p_T of jet 1	—	—	✓
p_T of jet 2	—	—	✓
p_T of lepton 1	✓	✓	✓
p_T of lepton 2	✓	✓	✓
p_T of lepton 3	—	—	✓
p_T of τ lepton	—	✓	—
η of lepton 1	✓	✓	—
η of lepton 2	✓	✓	—
η of τ lepton	—	✓	—
ϕ of lepton 1	✓	✓	—
ϕ of lepton 2	✓	✓	—
ϕ of τ lepton	—	✓	—
$m_T(l_1, p_T^{miss}) + p_T^{miss}$	✓	—	—
$m_T(l_2, p_T^{miss}) + p_T^{miss}$ system	✓	—	—
ΔR of lepton 1 to its closest jet	✓	✓	✓
ΔR of lepton 2 to its closest jet	✓	✓	✓
Invariant mass of the reconstructed $t\bar{t}H$ system ($M_{t\bar{t}H} = \sum_i p^{lep_i} + \vec{p}_T^{\,miss} + \sum_{i \leq k} p^{jet_i *}$)	✓	✓	✓
$\Delta\eta$ of two jets with highest b score in the laboratory frame ($\Delta\eta_{BB}$)	✓	✓	✓
$\Delta\eta$ of the two leptons in frame of two most-likely b jets	✓	✓	—
$\Delta\eta$ of two jets with highest b score in the dilepton system frame	✓	✓	—
$\Delta\eta$ of two jets with highest b score in the ℓ_1-ℓ_2 system frame	—	—	✓
$\Delta\eta$ of two jets with highest b score in the ℓ_1-ℓ_3 system frame	—	—	✓
$\Delta\phi$ of the two leptons in frame of two most-likely b jets	—	✓	—
$\Delta\phi$ of two jets with highest b score in the dilepton system frame	—	✓	—
Average ΔR among all jets	✓	✓	—
Jet multiplicity	✓	✓	—
p_T^{miss}	✓	✓	—
Azimuthal angle of $\vec{p}_T^{\,miss}$	✓	✓	—
Highest BDT score of jet triplet from t	✓	✓	—
Higgs jet tagger	—	✓	—
Angle of $t\bar{t}$ and H boson in $t\bar{t}H$-system	—	✓	—
Angle between two t in $t\bar{t}$-frame	—	✓	—
$\Delta R_{l_3-l_1} = \sqrt{(\eta_{\ell_3} - \eta_{\ell_1})^2 + (\phi_{\ell_3} - \phi_{\ell_1})^2}$	—	—	✓
$\Delta R_{l_1-l_2} = \sqrt{(\eta_{\ell_1} - \eta_{\ell_2})^2 + (\phi_{\ell_1} - \phi_{\ell_2})^2}$	—	—	✓
$\Delta R_{l_2-l_3} = \sqrt{(\eta_{\ell_2} - \eta_{\ell_3})^2 + (\phi_{\ell_2} - \phi_{\ell_3})^2}$	—	—	✓
$\eta_{jet1} - \eta_{jet2}$	—	—	✓
$p_T^{jet1} + p_T^{jet2} + p_T^{jet3} + p_T^{miss}$	—	—	✓
Total number of variables	19	25	16

* k = 6 (4) in the $2\ell SS + 0\tau_h$ ($2\ell SS + 1\tau_h$ and $3\ell + 0\tau_h$) final state

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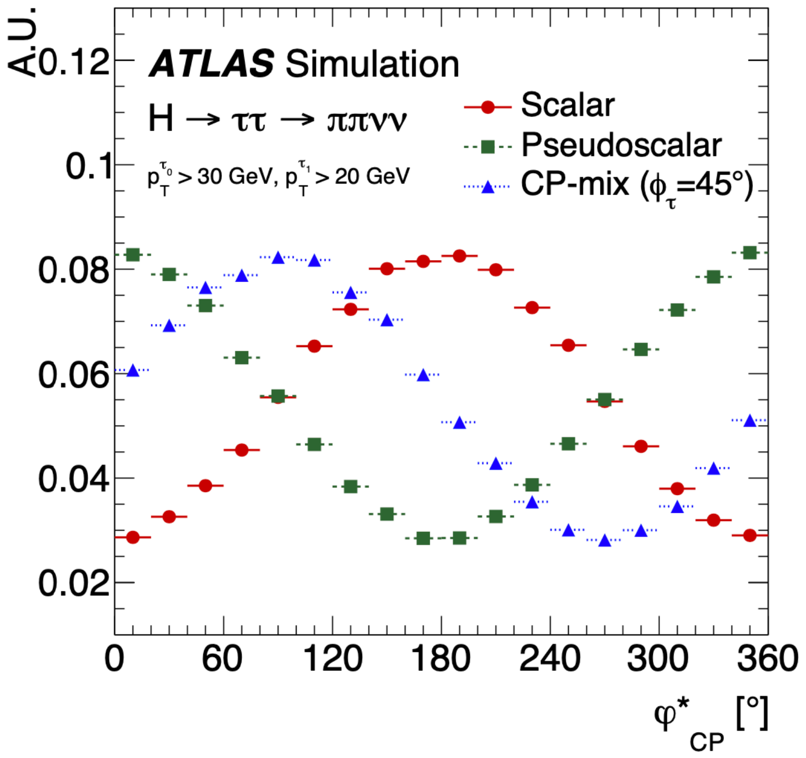
CP violation searches e.g $H \to \tau^+\tau^-$

- **cos/sin dependence is used to determine the CP content of the data: Scalar is CP even (SM-like), pseudoscalar is CP odd.**

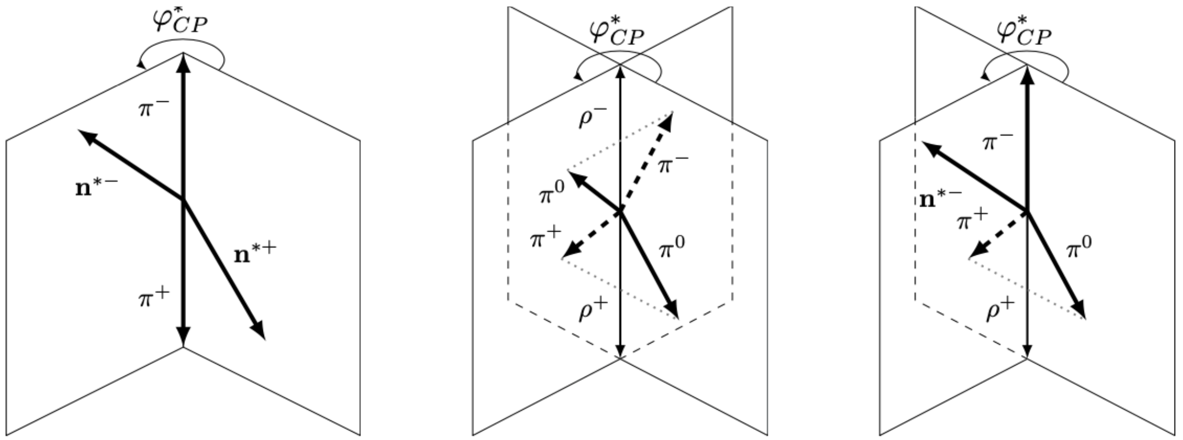


Set of nuisance parameters	Impact on ϕ_τ [°]
Jet energy scale	3.4
Jet energy resolution	2.5
Pile-up jet tagging	0.5
Jet flavour tagging	0.2
E_T^{miss}	0.4
Electron	0.3
Muon	0.9
τ_{had} reconstruction	1.0
Misidentified τ	0.6
τ_{had} decay mode classification	0.3
π^0 angular resolution and energy scale	0.2
Track ($\pi^\pm$, impact parameter)	0.7
Luminosity	0.1
Theory uncertainty in $H \to \tau\tau$ processes	1.5
Theory uncertainty in $Z \to \tau\tau$ processes	1.1
Simulated background sample statistics	1.4
Signal normalisation	1.4
Background normalisation	0.6
Total systematic uncertainty	5.2
Data sample statistics	15.6
Total	16.4

CP violation searches e.g $H \rightarrow \tau^+\tau^-$

- **Use different reconstruction methods to account for the missing ν when reconstructing the plane:**
  - **1 prong decays - use impact parameter (IP) vector (directional distance between the point of closest approach of the charged particle primary track and the position of the primary vertex) and charged particle momentum**
  - **ρ decay - use the two pion momenta**
  - **a_1 method - use the sum of the neutral pion 4 momenta in place of the neutral pion in the ρ method**
  - **Some channels require combination of the IP and**

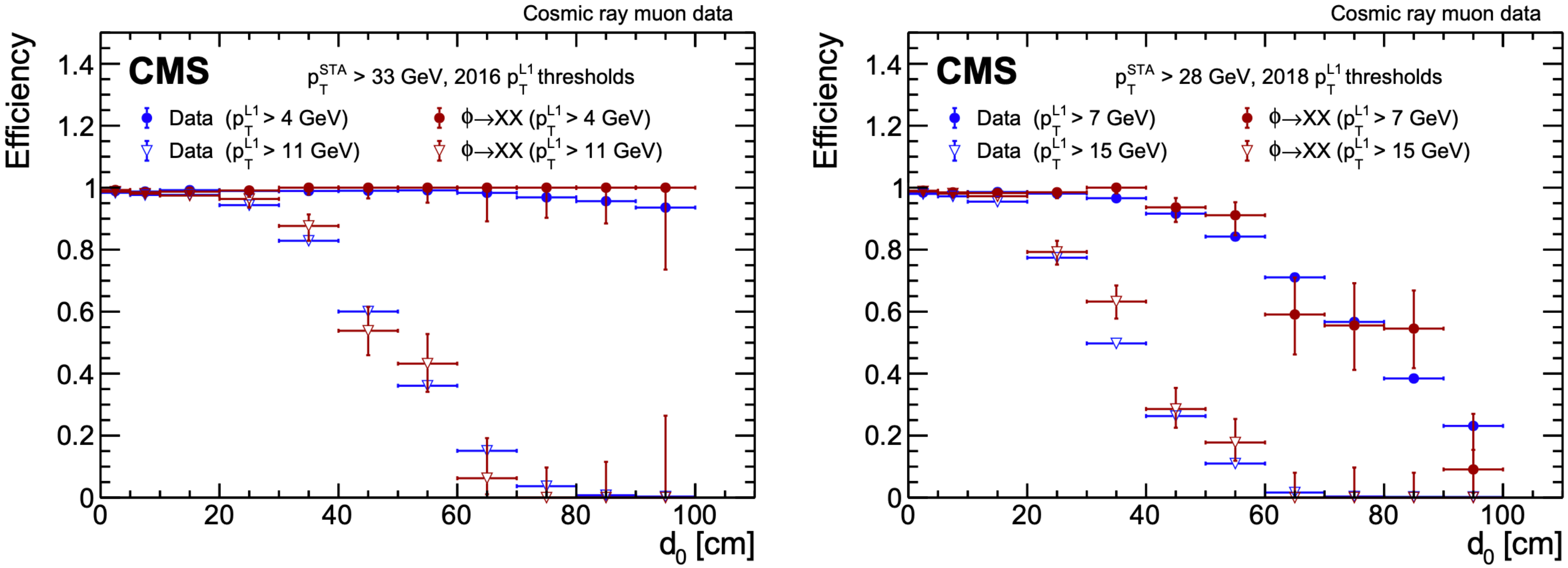
Decay channel	Decay mode combination	Method	Fraction in all τ-lepton-pair decays
$\tau_{lep}\tau_{had}$	ℓ–1p0n	IP	8.1%
	ℓ–1p1n	IP–ρ	18.3%
	ℓ–1pXn	IP–ρ	7.6%
	ℓ–3p0n	IP–a_1	6.9%
$\tau_{had}\tau_{had}$	1p0n–1p0n	IP	1.3%
	1p0n–1p1n	IP–ρ	6.0%
	1p1n–1p1n	ρ	6.7%
	1p0n–1pXn	IP–ρ	2.5%
	1p1n–1pXn	ρ	5.6%
	1p1n–3p0n	ρ–a_1	5.1%



(a) $H \rightarrow \tau^+\tau^- \rightarrow \pi^+\pi^- + 2\nu$ (b) $H \rightarrow \tau^+\tau^- \rightarrow \pi^+\pi^0\nu\pi^-\pi^0\nu$ (c) $H \rightarrow \tau^+\tau^- \rightarrow \pi^+\pi^0\nu\pi^-\nu$

Direct searches: Long Lived Particles (LLPs)

- **Use either full tracking or muon system only for track reconstruction (TMS and STA track combinations)**
- **di-muon trigger efficiency strongly depends on impact parameter d_0**
- **Cosmic rays used to validate Monte Carlo expectations - good agreement gives confidence that this type of analysis can be done**



Direct searches: Heavy neutral lepton

- **Leptons and jets categorised for resolved and boosted studies**

		Resolved		Boosted		
		Baseline	**Fake estimation**	**Baseline**	**Leading**	**Fake estimation**
Electrons	$\lvert\eta\rvert$	$(0, 1.37]$ or $[1.52, 2.47]$				
	p_T (GeV)	> 25		> 25	> 200	
	Quality	Tight	Loose	Medium	Tight	
	Isolation	Loose	Fail Loose or Tight	Loose	HighPtCaloOnly	Loose but fail HighPtCaloOnly
Muons		**Baseline**	**Fake estimation**	**Baseline**	**Leading**	
	p_T (GeV)	> 25		> 28	> 200	—
	$\lvert\eta\rvert$	< 2.5		< 2.5		—
	Quality	High-p_T if pT > 300 GeV else Medium		Medium	Tight	—
	Isolation	FixedCutTightTrackOnly	fail FixedCutTightTrackOnly	—	Tight	—
Small-*R* jet	p_T (GeV)	> 20				
	$\lvert\eta\rvert$	< 2.5				
Large-*R* jet	p_T (GeV)	—		> 200		
	$\lvert\eta\rvert$	—		< 2		

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Direct searches: Heavy neutral lepton

- **Resolved analysis targets $\Delta m = m(W_R) - m(N_R) < 4\, TeV$ and breaks data down into same and opposite sign (SS/OS) selections**

Variable	rSRSS2e	rSRSS2mu	rSROS2e	rSROS2mu
Number of electrons	2	0	2	0
Number of muons	0	2	0	2
Lepton charge	same sign		opposite sign	
Leading lepton p_T [GeV]	> 40			
Dilepton mass $m_{\ell\ell}$ [GeV]	> 400			
$\Delta R_{\ell\ell}$	< 3.9		—	
Number of small-R jets with $p_T > 100$ GeV	≥ 2			
Number of b-tagged jets	0			
Dijet mass m_{jj} [GeV]	> 110			
$h_T \equiv p_T(\ell_1) + p_T(\ell_2) + p_T(j_1) + p_T(j_2)$ [GeV]	> 400			

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Direct searches: Heavy neutral lepton

- **Boosted analysis targets larger Δm where the large R jet overlaps with a high p_t lepton**

Region	bSR1e (higher Δm)	bSR2e (lower Δm)	bSR2mu
Number of large-R jets		1	
Number of electrons	1	2	0
Number of muons	0	0	2
Leading lepton p_T [GeV]		> 200	
E_T^{miss} [GeV]	< 200		—
$\lvert\cos\theta\rvert$	> 0.7	—	—
$\Delta\phi_{J,\ell_1}$		> 2.0	
$\Delta\eta_{J,\ell_1}$	< 2.0	—	—
Dilepton p_T (GeV)	—	—	> 200
Dilepton mass $m_{\ell\ell}$[GeV]	—	> 200	
Number of b-tagged small-R jets		0	

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