Interplay between flavour and high energy measurements at colliders

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ATLAS EXPERIMENT

Open Questions and Future Directions in Flavour Physics

Mainz - 13 November 2024

The Standard Model of Particle Physics
... and beyond ?

No gravity!

No verified theory of quantum gravity

No neutrino masses!

Are they Dirac or Majorana particles?

Naturalness!

Higgs field parameters seem highly fine-tuned

No dark matter!

But needed to explain astrophysical observations

No dark energy!

The universe is in accelerated expansion
invisible source of energy?

Not enough matter-antimatter asymmetry!

To explain dominance of matter today

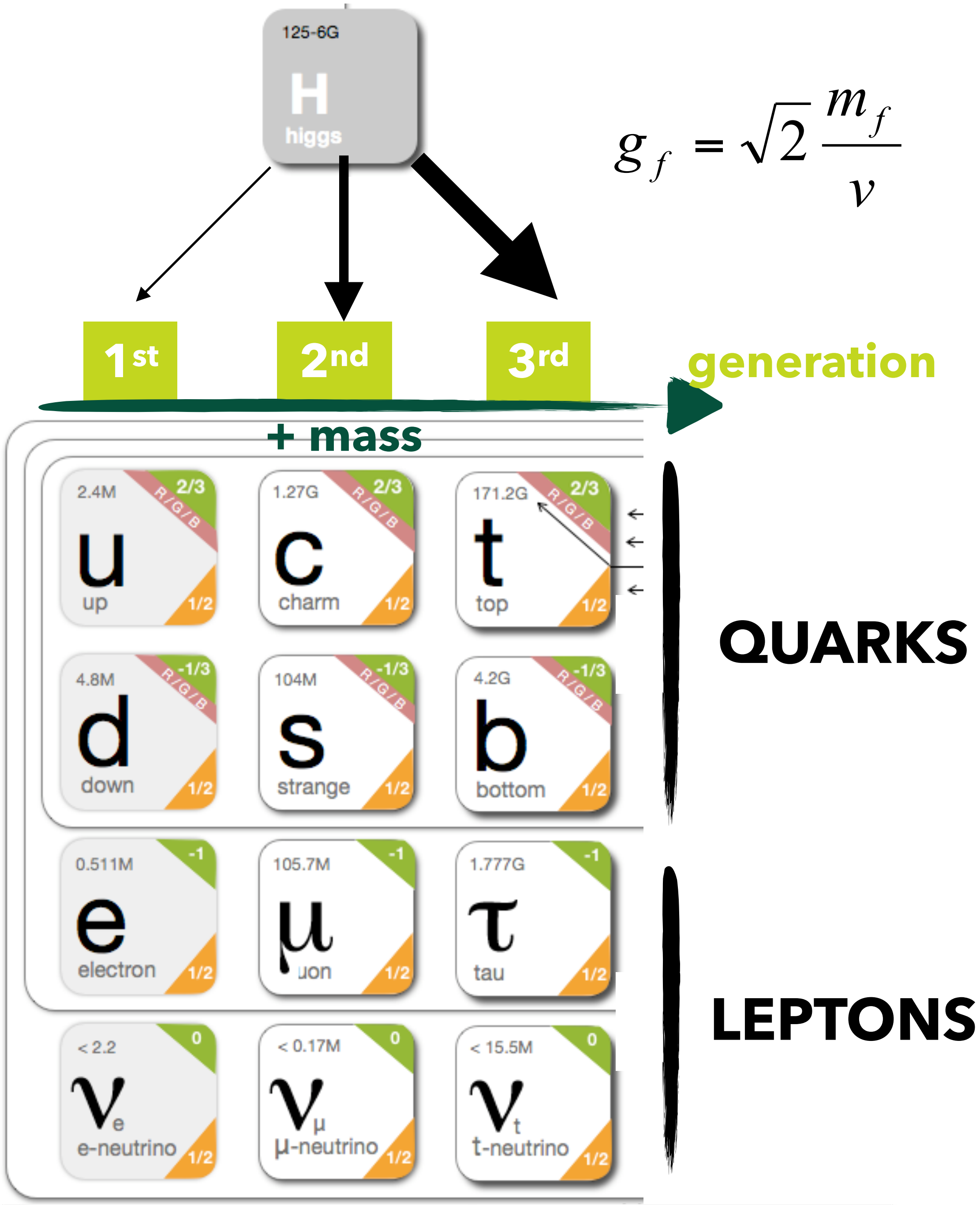
Why 3 fermion generations?

Underlying symmetry connecting quark and lepton sectors?

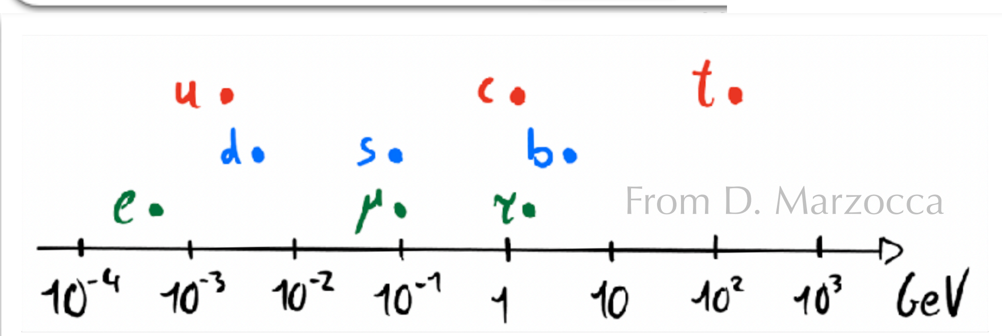
Why hierarchical Yukawa coupling?

Why is the top quark so heavy?

Theoretical puzzle: SM flavour



$$g_f = \sqrt{2}\,\frac{m_f}{v}$$



An extensive flavour puzzle…

- **Why** similar structure of quarks and leptons?
- **Why** three generations of particles?
- **How** do they get different masses?

Only the Higgs boson can **distinguish** between electron, muon and tau leptons
Gives them different **masses**

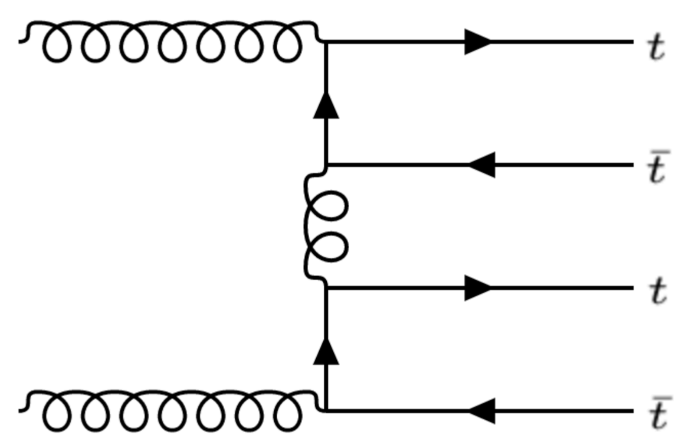
But… what is the underlying mechanism to do so and assign arbitrary Yukawa coupling?

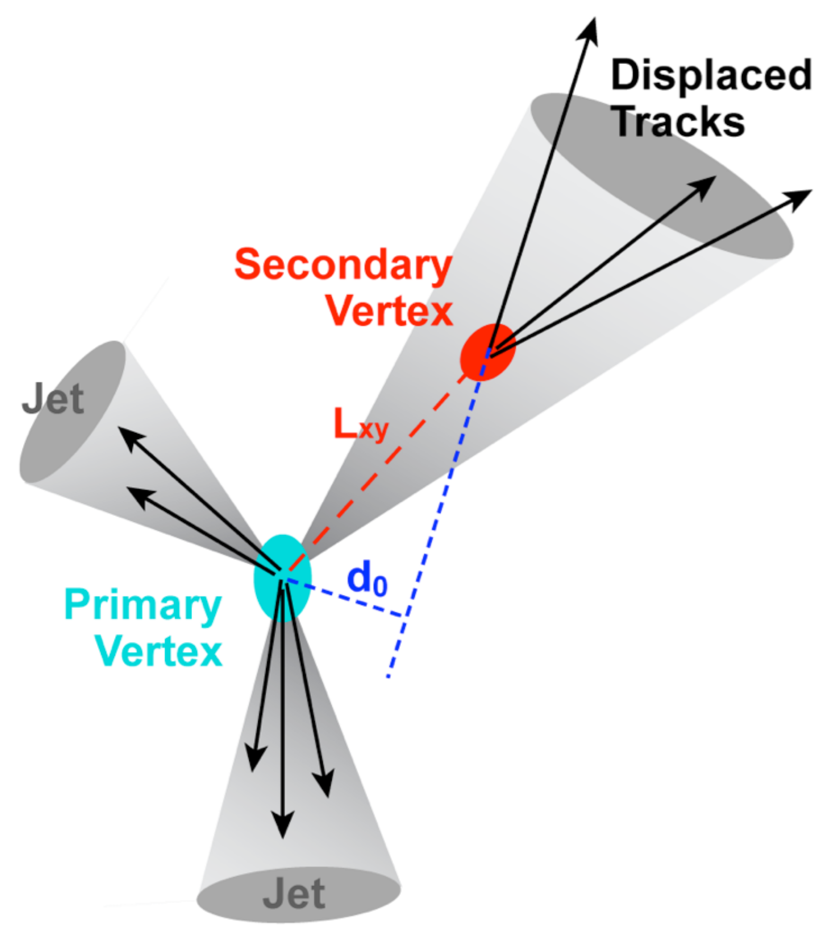
New physics needed to tell the difference
e vs. μ vs. τ
u vs. c vs. t

Experimental choice: top quark & b-jets

- If new physics has a Yukawa-like structure, it would couple preferably to **3rd generation** fermions
  - Quarks: top and b quark
- **Top quark**: only quark with y_{top} ~ 1
  - It decays before it can hadronise, $t \rightarrow Wb$
- The b-quark hadronises and becomes a **b-jet**
  - But special experimentally!
  - b-quarks live long enough (~ps) to create a secondary vertex at the decay
  - Finding these jets from b-quarks is known as ***b-tagging***
- In some cases, take advantage of final states with **multiℓeptons** and **multibjets**

4tops production → up to 4ℓ and 4b-jets!





Experimental puzzle: flavour anomalies in B decays

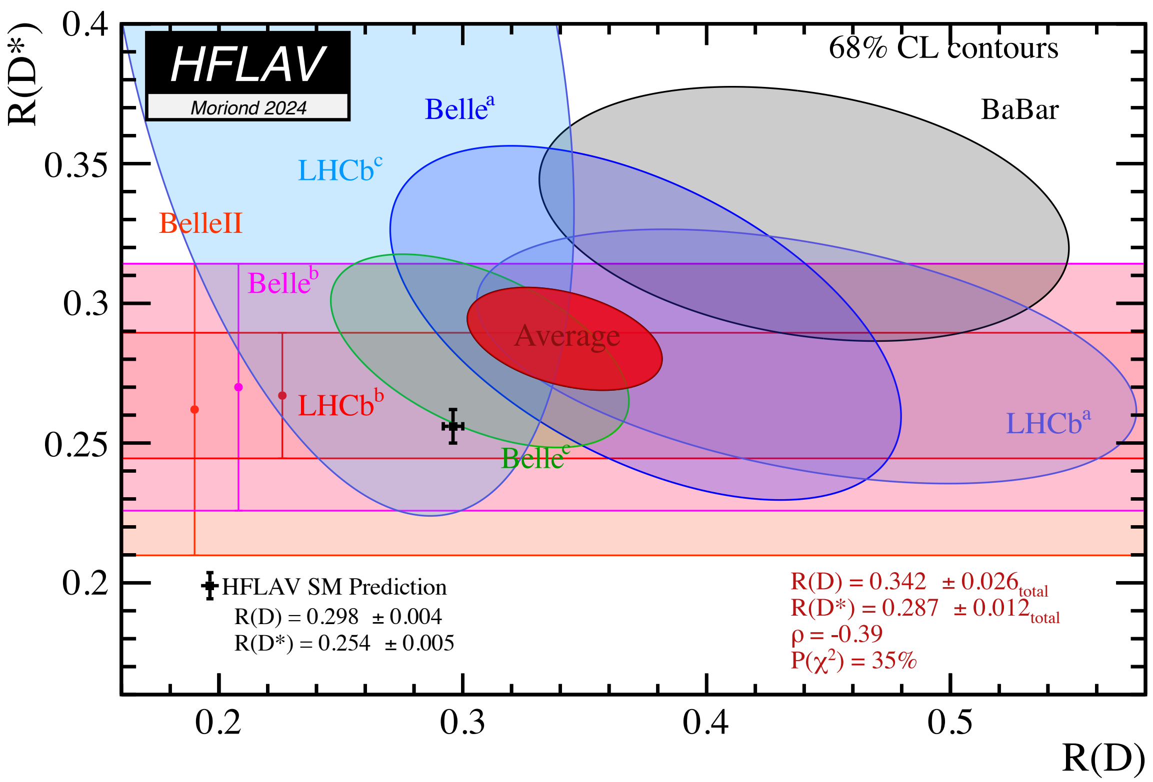
- Flavour physics provides great potential to explore physics beyond the SM
- Hints for lepton flavour universality violation observed in **charged** and ~~**neutral**~~ current processes in B-physics

τ vs e/μ

$$R(D^{(*)}) \equiv \frac{\mathcal{B}(B^0 \to D^{(*)+}\tau\nu)}{\mathcal{B}(B^0 \to D^{(*)+}\ell\nu)};$$

$$\ell = \mu, e$$

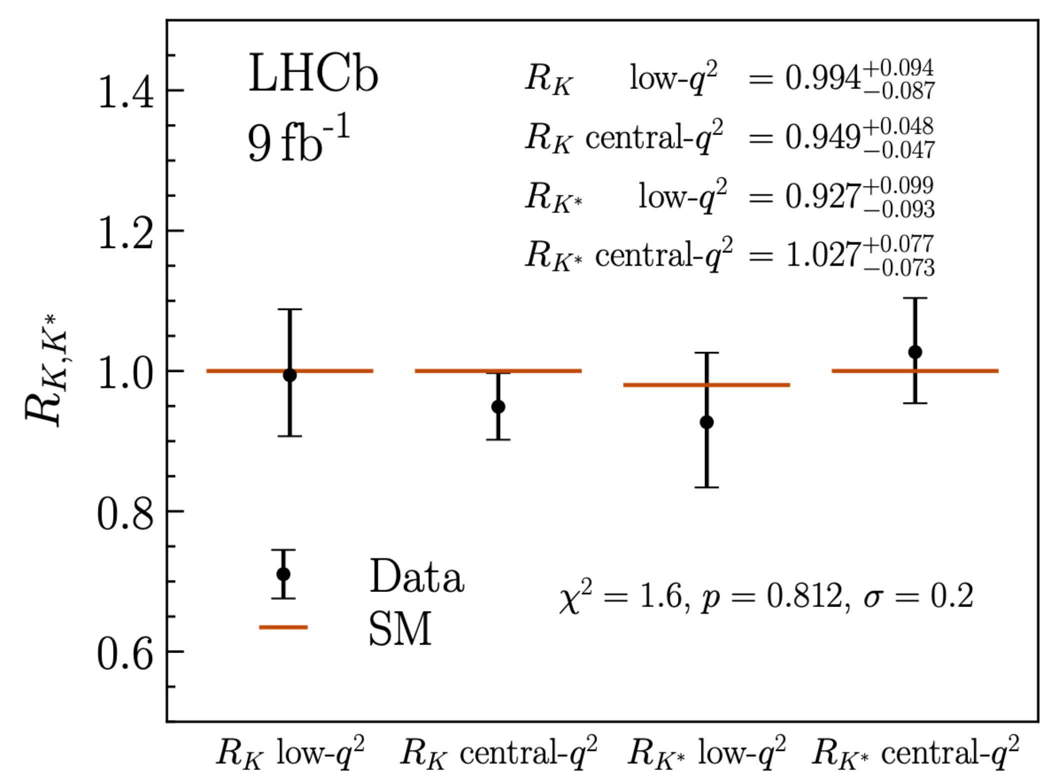
3.3σ excess in R_D and R_{D^*} combination



e vs μ

$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

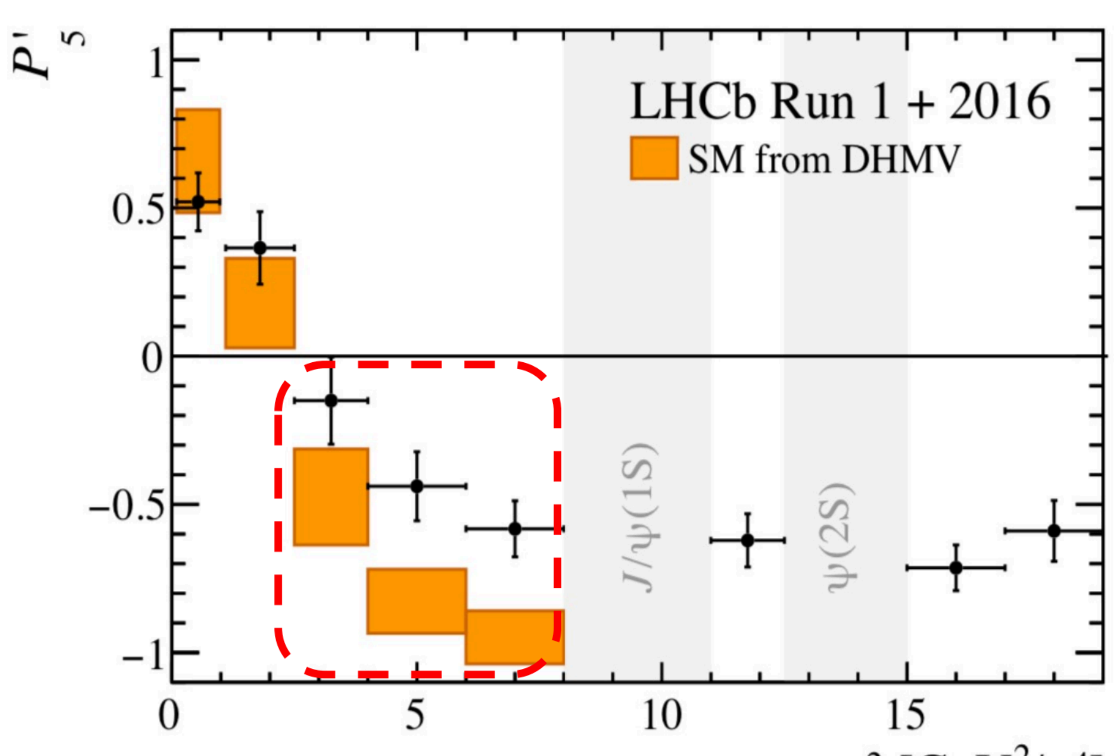
No longer evidence of μ/e universality violation in updated full Run 1 + Run 2 result and revisited misidentified background estimation in electron mode [LHCb:2212.09153]



Experimental puzzle: flavour anomalies in B decays

- Flavour physics provides great potential to explore physics beyond the SM
- Hints for lepton flavour universality violation observed in **charged** and **neutral** current processes in B-physics

*still tensions in **angular observables** and **BRs** of $b \to s\mu^+\mu^-$*



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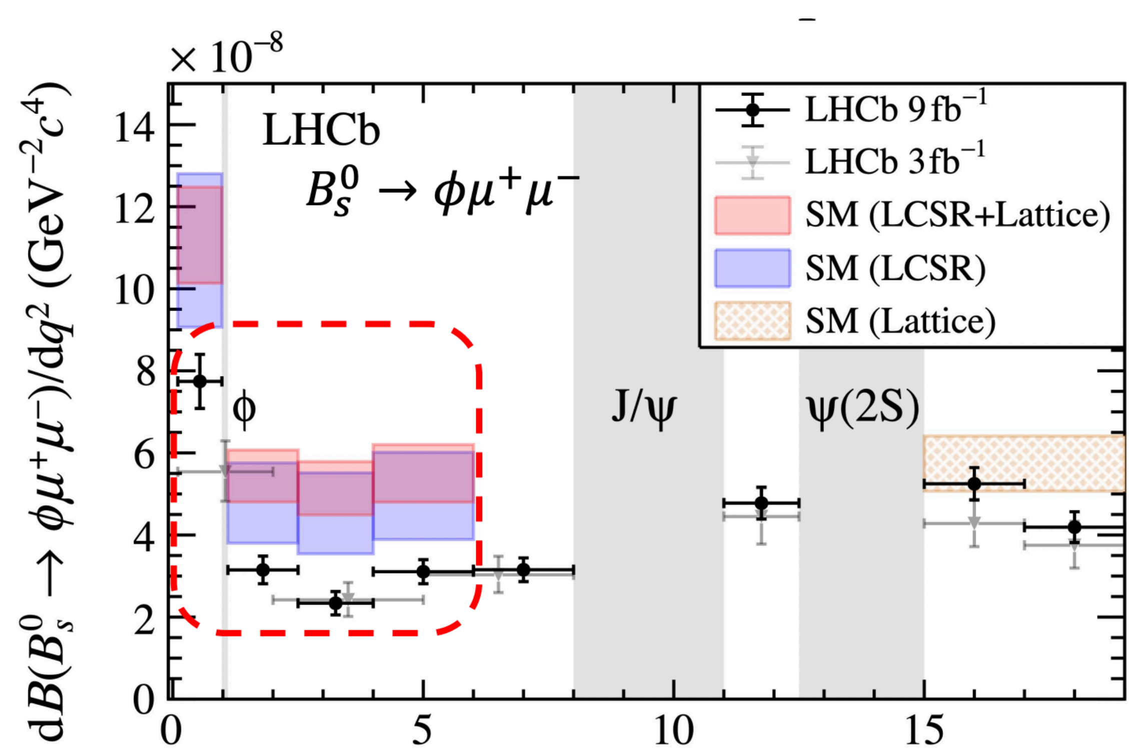
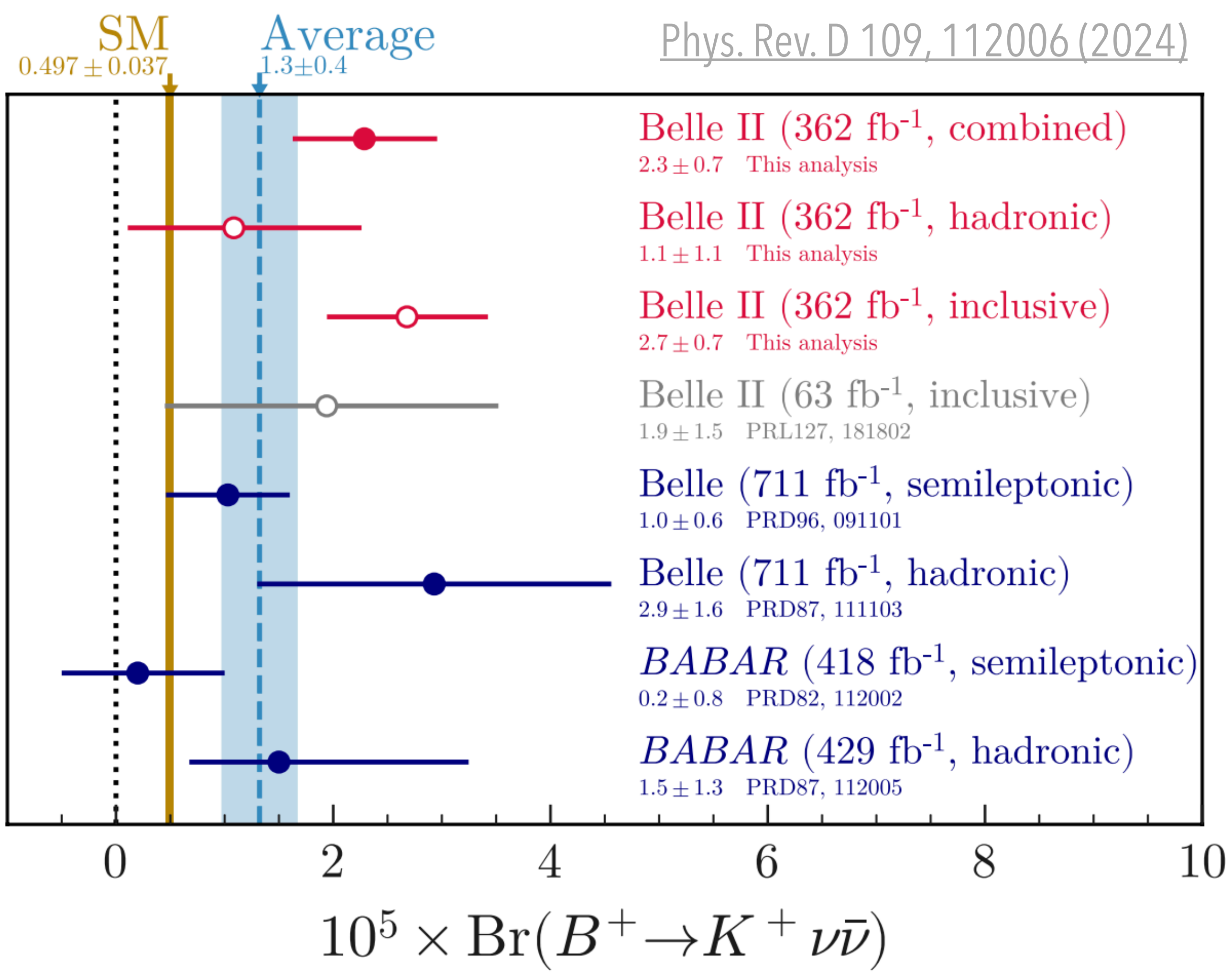


Phys. Rev. Lett. 127 (2021) 15

Experimental puzzle: flavour anomalies in B decays

- Flavour physics provides great potential to explore physics beyond the SM
- Hints for lepton flavour universality violation observed in **charged** and **neutral** current processes in B-physics

?

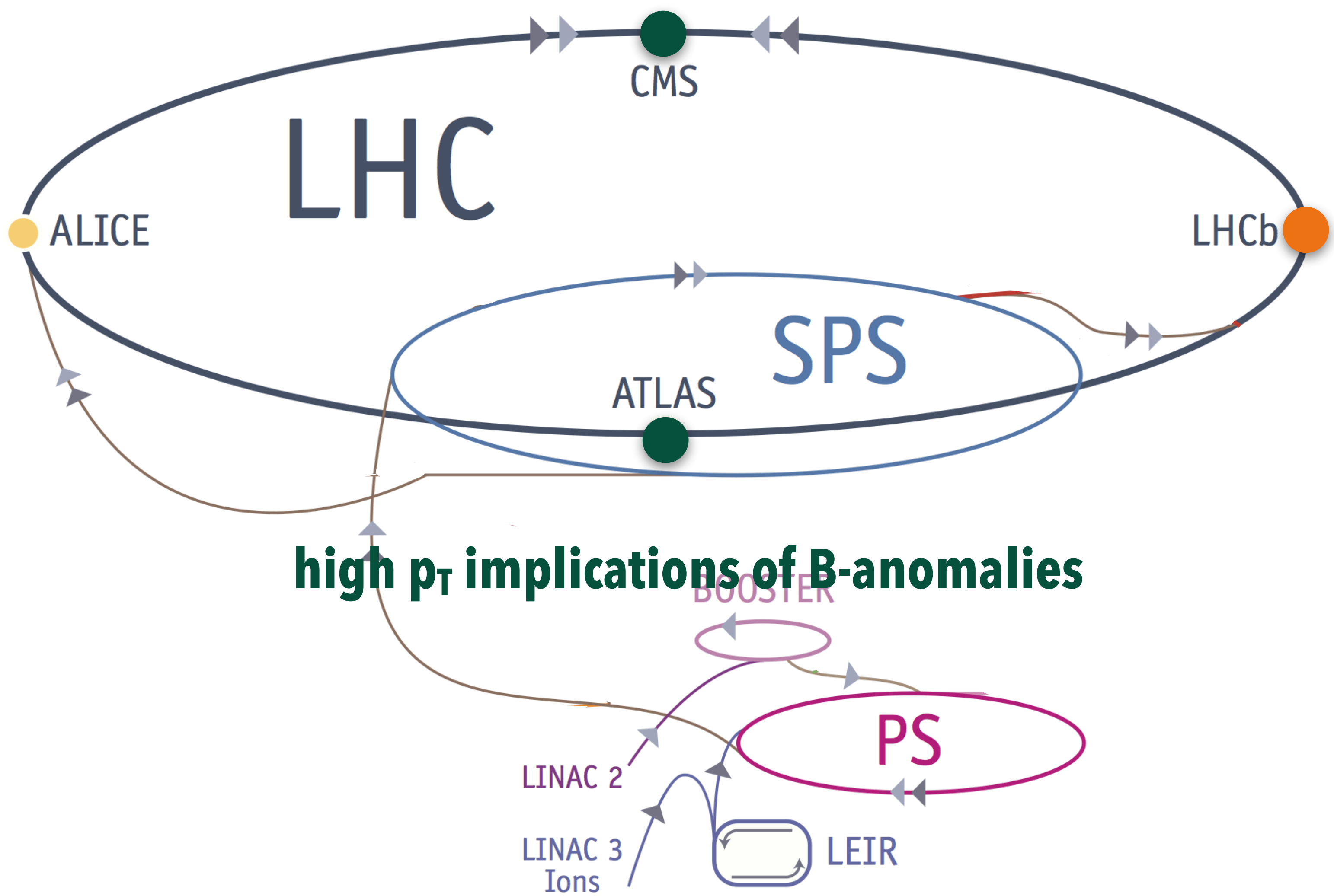


- **Search for $B^+ \to K^+ \nu\bar{\nu}$ is unique to Belle II**
- Challenge: two neutrinos in the final state
- First evidence of the $B^+ \to K^+ \nu\bar{\nu}$ decay

Tension with SM of 2.7σ significance

The versatility of the LHC

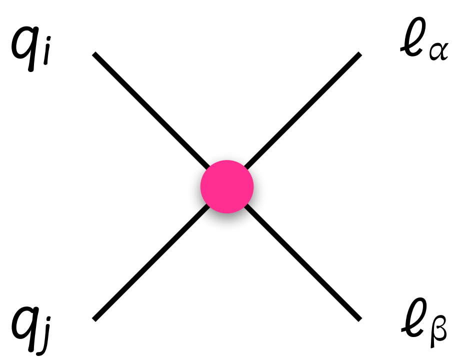
high p_T implications of B-anomalies

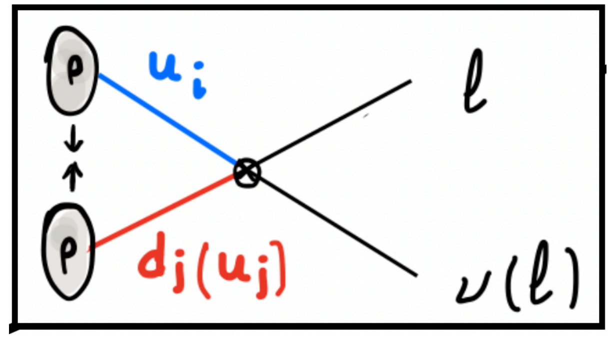


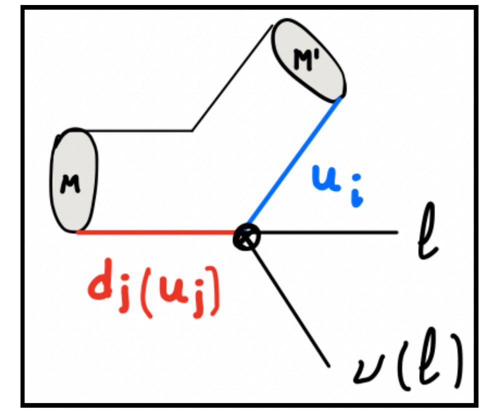
high p_T implications of B-anomalies

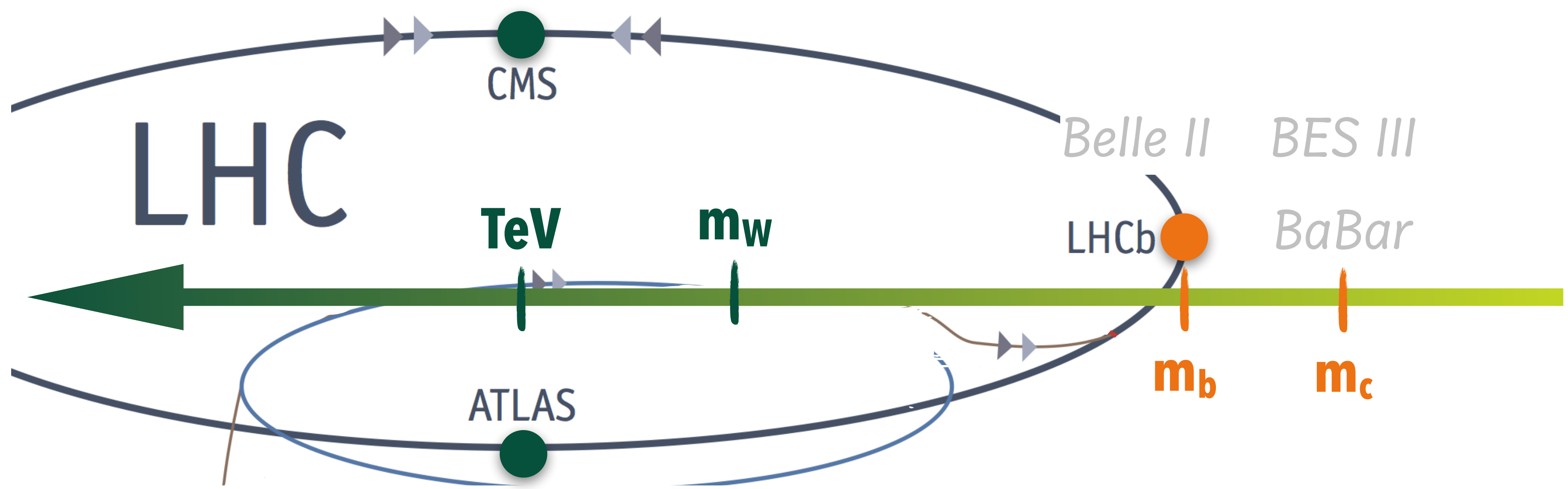
precision B-sector measurements

The versatility of the LHC + *friends*









Explore (possible) same underlying new physics in different kinematical regimes

$pp \to \ell\nu$

$pp \to \ell\ell$

$M \to M'\ell\nu$

$M \to \ell\nu$

$M \to M'\ell\ell$

$M \to \ell\ell$

Competitive limits at high-p_T

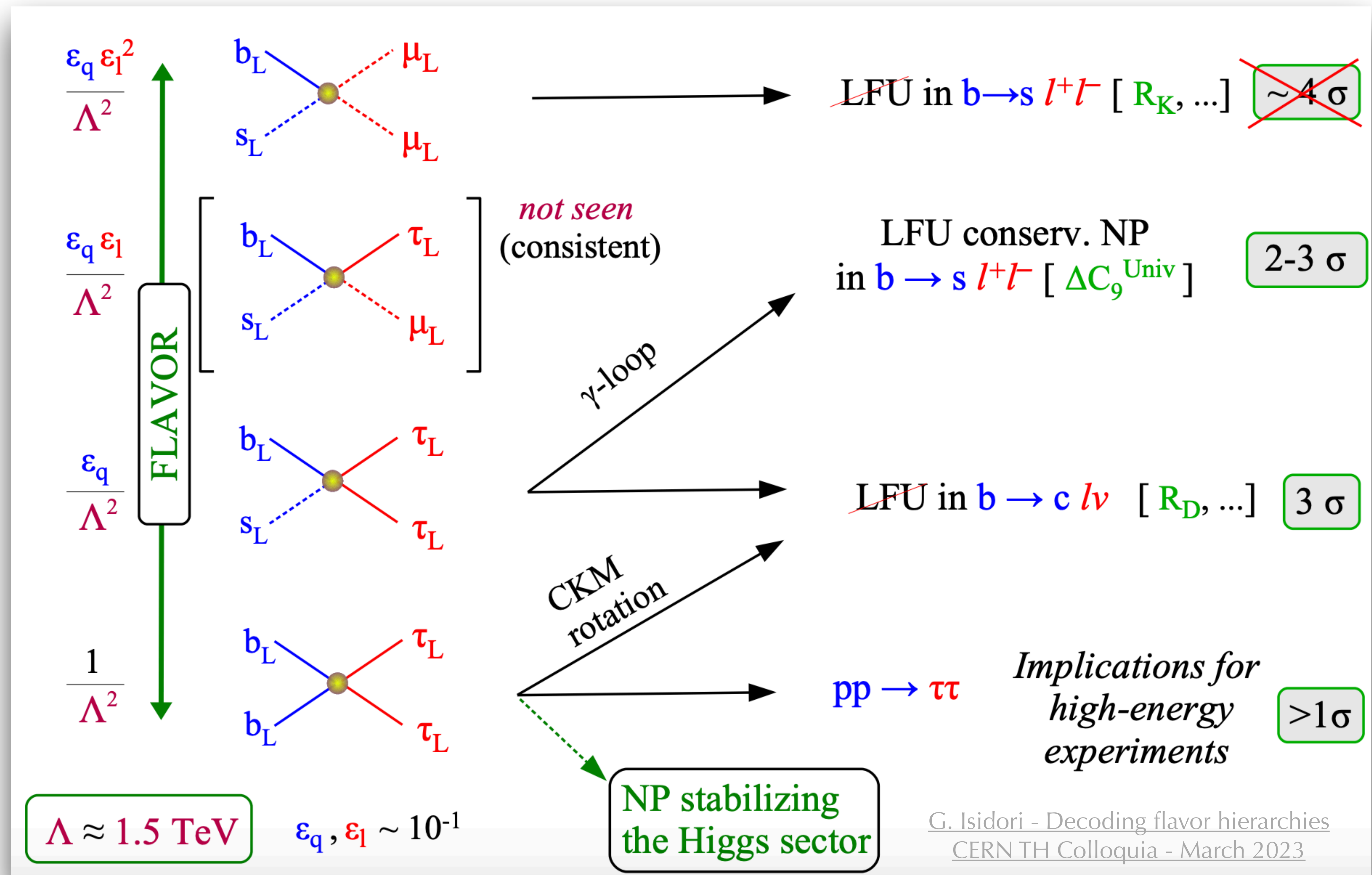
Can these results be reconciled under a coherent NP explanation?

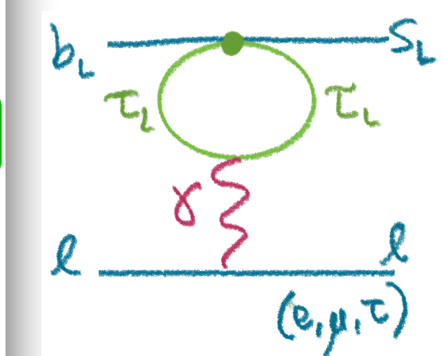
- Multi-scale UV completion with **flavour non-universal interactions**

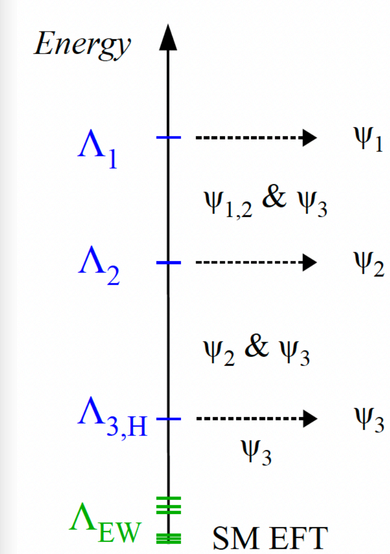
Allwicher, Isidori, Thomsen '20
Davighi & Isidori '23

e.g.:

  - Explain the origin of the flavour hierarchies
  - Allow TeV-scale NP **coupled (mainly) to 3rd gen.** → Higgs sector stabilisation

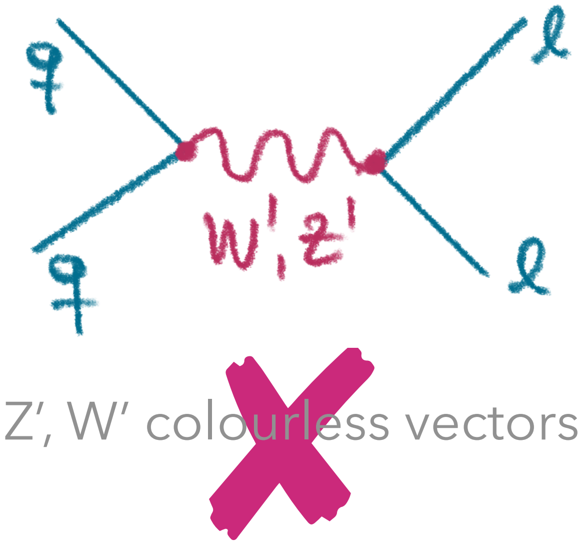




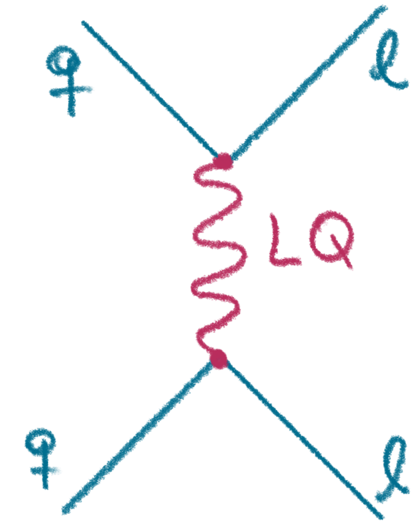


Simplified models

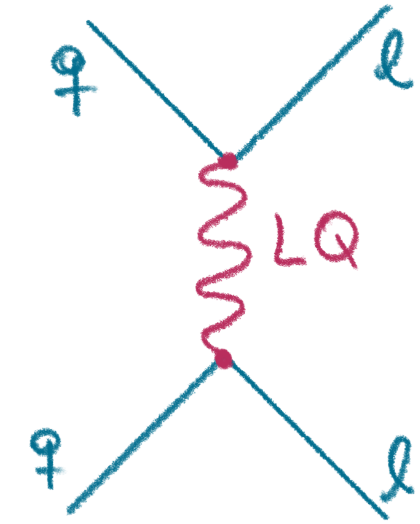
- The size of the anomalies suggest a tree-level mediator, such as **leptoquarks (LQ)**



Z', W' colourless vectors



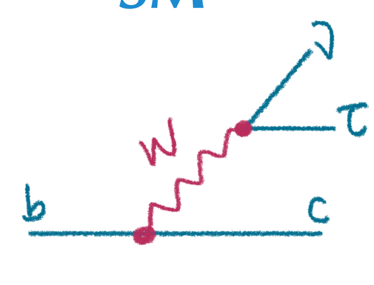
U_1, U_3 **vector** LQs (spin = 1)



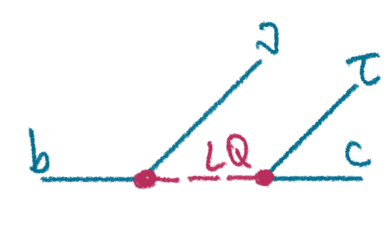
S_1, S_3, R_2 **scalar** LQs (spin =0)

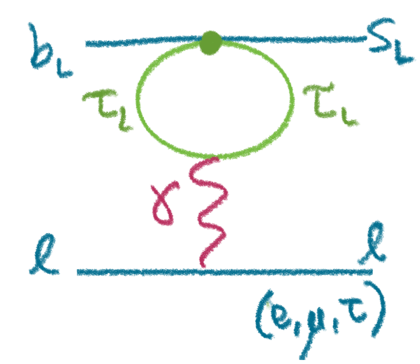
- **Leptoquarks**: Colour triplet bosons with a *fractional* electric charge, carrying both lepton and baryon number
- Predicted in many grand unified theories (GUT SU(5), Pati-Salam SU(4), RPV SUSY)
  - Can enable violation of lepton flavour universality!
- Only the U_1 vector LQ also gives a flavour universal effect in $b \to s\ell\ell$ via RGE:
  - Study LQ decays into *flavour-diagonal* and *cross-generational* final states

SM



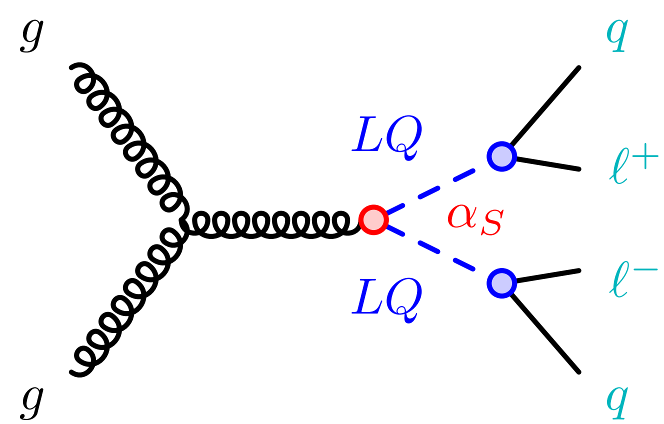
possible BSM?





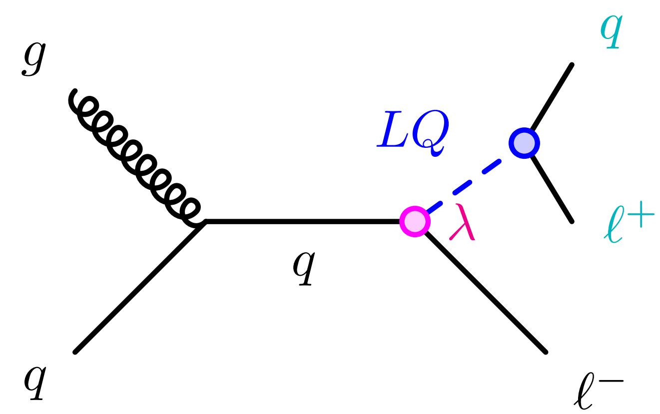
Leptoquark production

Pair production



large QCD production
cross section only depends on m_{LQ}
resonant LQs

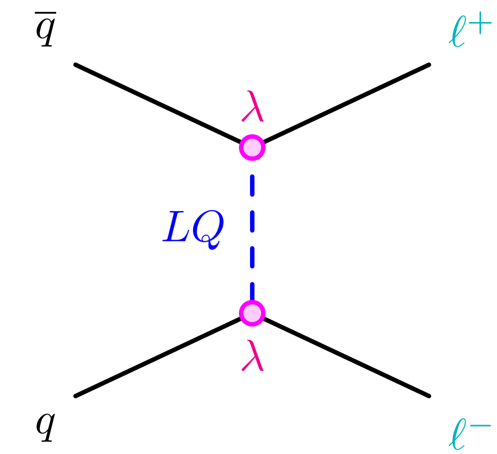
Single production



cross section ∝ λ^2

sensitive to higher m_{LQ}
for sufficiently high λ

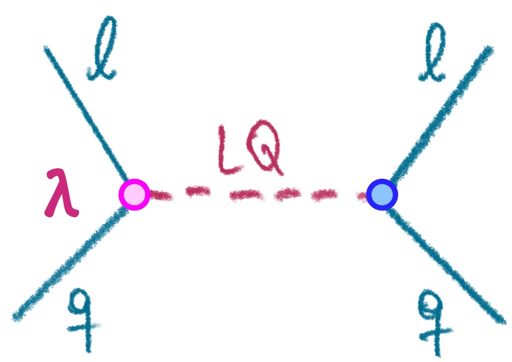
Off-shell production



cross section ∝ λ^4

non-resonant
sensitive to very high m_{LQ}
for sufficiently high λ

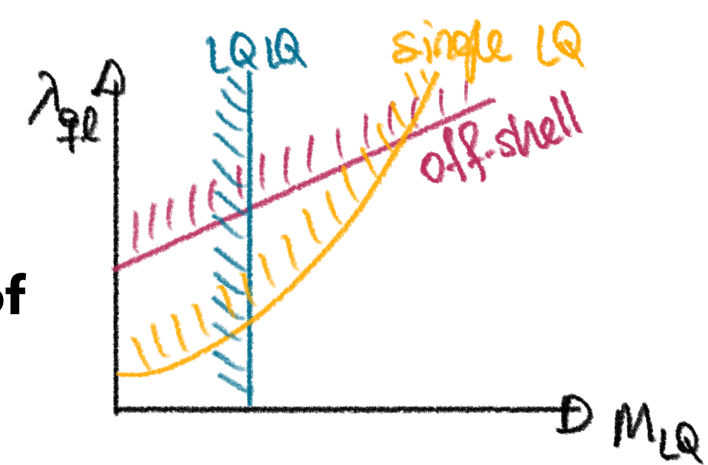
Single resonant production



although PDF for leptons inside the proton minuscule, compensated by resonant enhancement

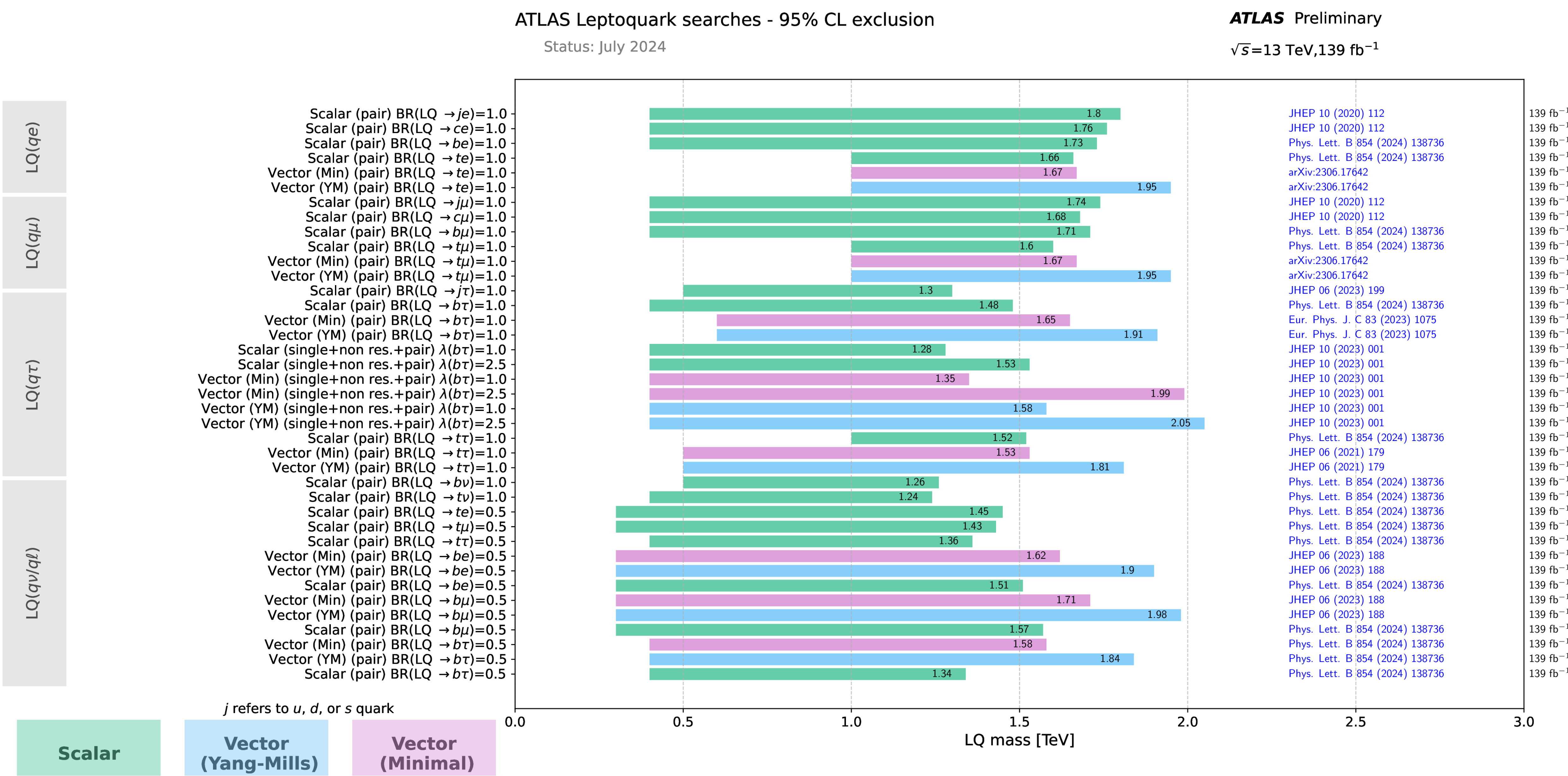
- Couplings determined by the **parameter λ** via Yukawa interaction

- Important to search in all **production** modes and all **combinations of ℓ & q** in final states!



ATLAS LQ search

- **Initially**: simplified search strategy targeting specific final states from LQ decays at ATLAS
  - Extended Buchmüller, Rückl, Wyler (BRW) model [Phys. Lett. B 191 (1987) 442]
    - **up**- (Q=2/3e) or **down**- (Q=-1/3e) type LQs
  - Thorough search for pair production of **scalar LQs**
- **Now**: explore scalar & vector (Yang-Mills and Minimal coupling) LQs in all production modes



ATL-PHYS-PUB-2024-012

Explore all types in all production modes

- **Vector LQs**: U_1 (Q=2/3e; decay to $b\ell/t\nu$ with BR=0.5) or $\tilde{U}_1$ (Q=5/3e; decay only to $t\ell$) with Yang-Mills (k=1) or minimal coupling (k=0) to gluons

[1512.01560]

$$\mathcal{L}_U = -\frac{1}{2}U^\dagger_{\mu\nu}U^{\mu\nu} + M_U^2 U^\dagger_\mu U_\mu + \mathcal{L}_{an}$$

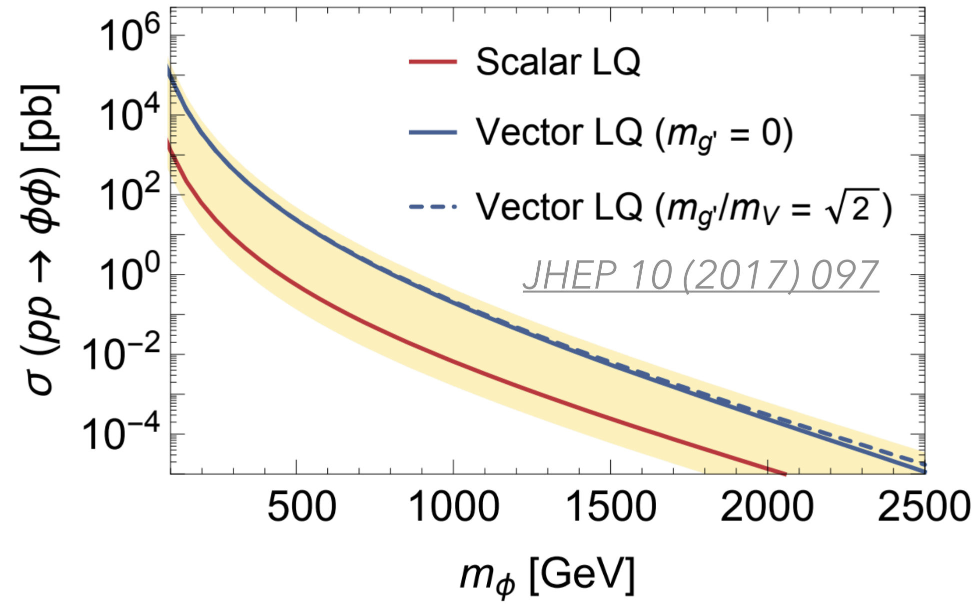
where

$$U_{\mu\nu} = D_\nu U_\mu - D_\nu U_\mu \qquad D_\mu \equiv \partial_\mu - i g_s \frac{\lambda^a}{2} G^a_\mu - i g' \frac{2}{3} B_\mu,$$

and

$$\mathcal{L}_{an} = -i g_s k_s (U^\dagger_\mu \frac{\lambda^a}{2} U_\nu) G^{\mu\nu a} - i g' \frac{2}{3} k_Y U^\dagger_\mu U_\nu B^{\mu\nu}$$

- Comparison of cross-sections (3rd gen):
  - **$\sigma_{YM}(LQ_V) \sim 5\sigma_{MC}(LQ_V) \sim 20\sigma(LQ_{up/down})$** for m(LQ)=1.5 TeV

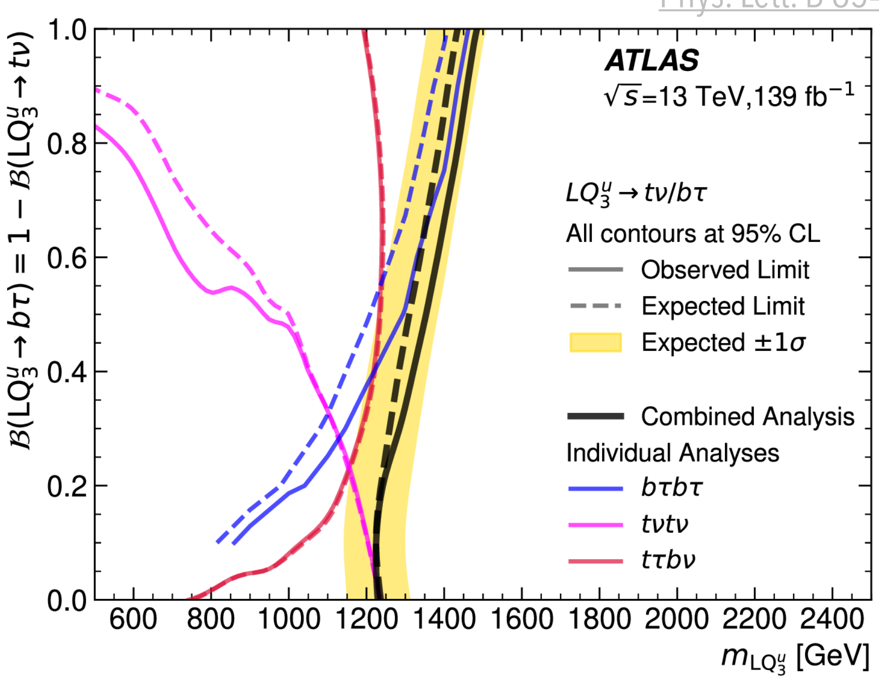


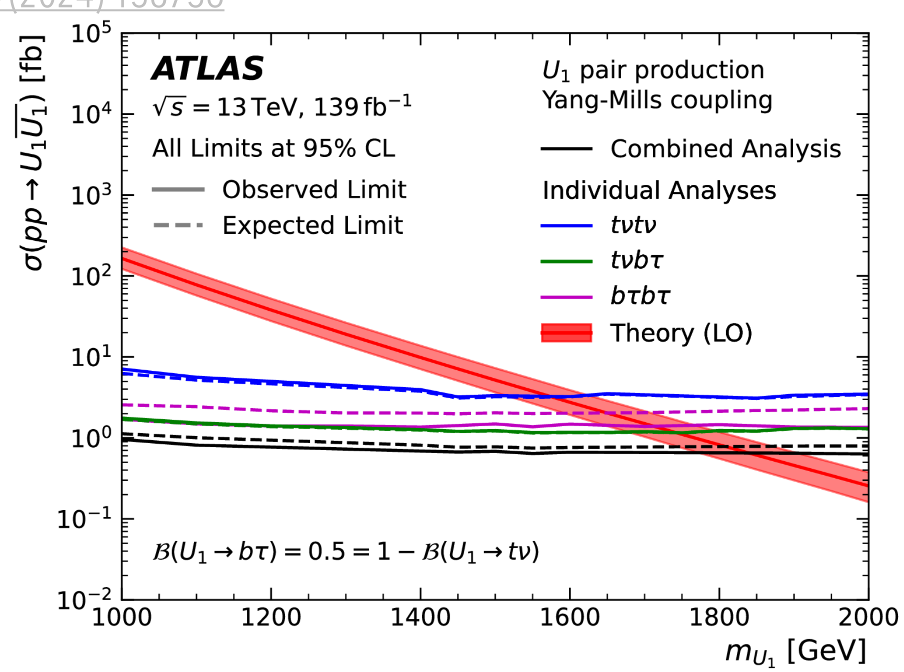
Scalar LQ pair-production combination

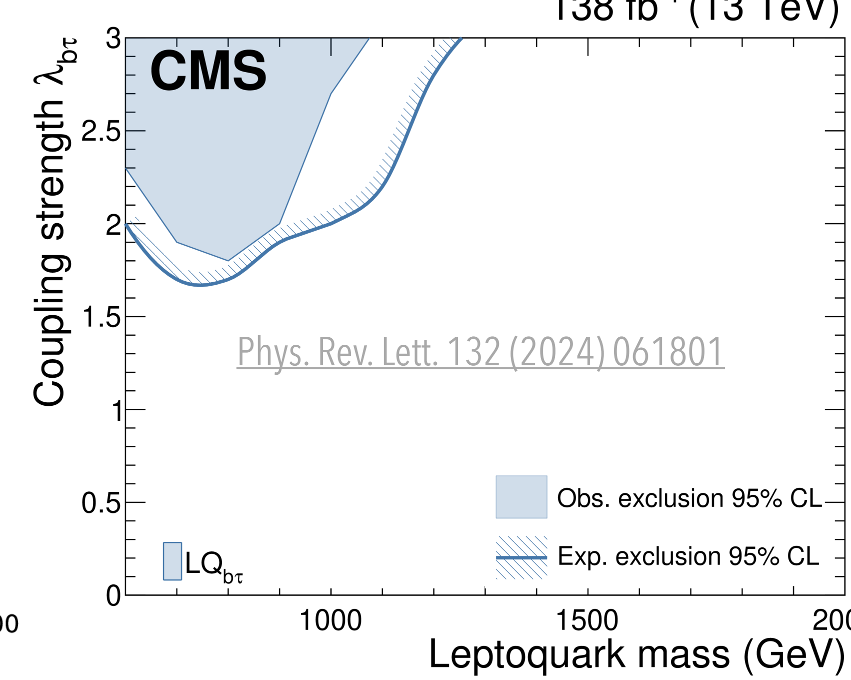
Vector LQ pair-production combination

Scalar LQ single-resonant production

Phys. Lett. B 854 (2024) 138736





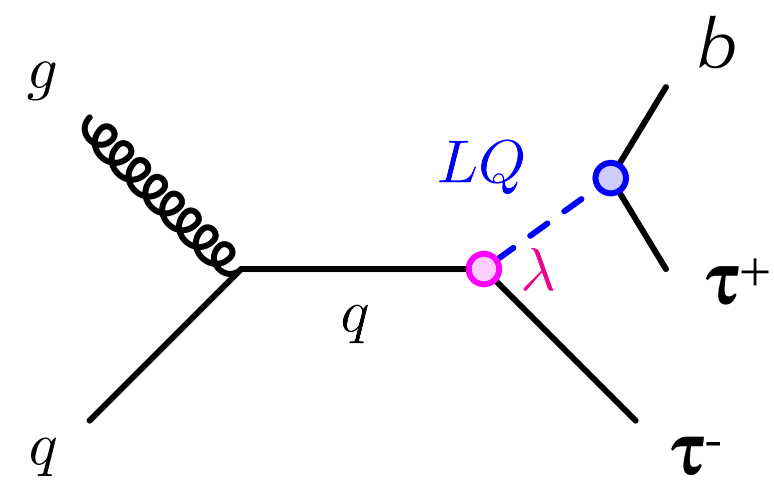


Single/Pair LQ→bτ strategy

JHEP 10 (2023) 001

EXOT-2022-39 (Aux Fig)

- Event preselection:
  - $\tau_{had}\tau_{had}$, $\tau_{lep}\tau_{had}$ (lep=e,μ) channels
- ≥1 jets, ≥1 b-jets (p_T>25 GeV)
- Single τ_{had} triggers and single-lepton triggers
- Main backgrounds: Top, Z+jets, Fake τ_{had}
- Event categorisation:
  - High b-jet p_T: ≥1 b-jets (p_T>200 GeV)
  - Low b-jet p_T: ≥1 b-jets (**25**<p_T<200 GeV)
- *Targeting single LQ production, but also sensitive to pair and non-resonant production!*
- Final discriminating variable: S_T (=Σ(τ,b_1) p_T + MET)



ATLAS vs CMS differences

b-jet p_T
- CMS uses b-jet p_T > 50 GeV; i.e. the "low b-jet p_T ATLAS SR" also may include events that would fall in the "0-bjet CMS SR"

Follow-up in progress to estimate contribution from ***the LQ interference with the SM***

Single/Pair LQ→bτ SRs

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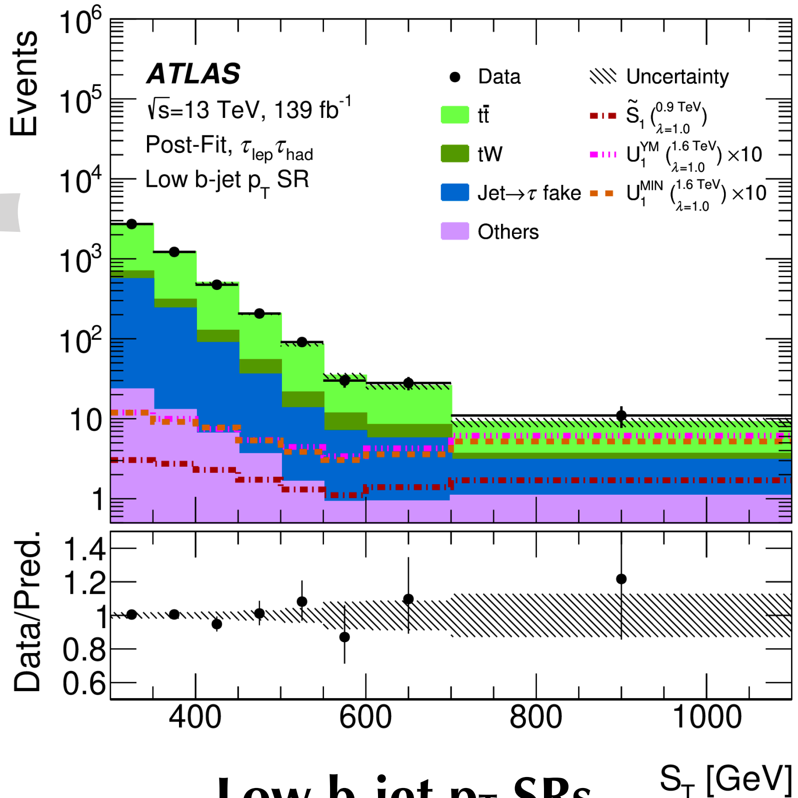
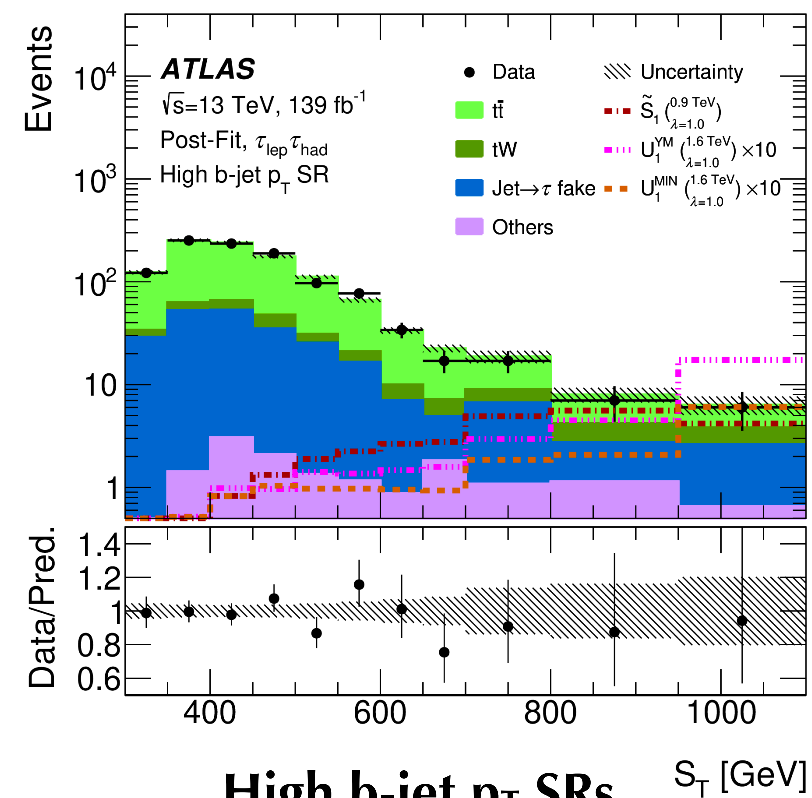
EXOT-2022-39 (Aux Fig)



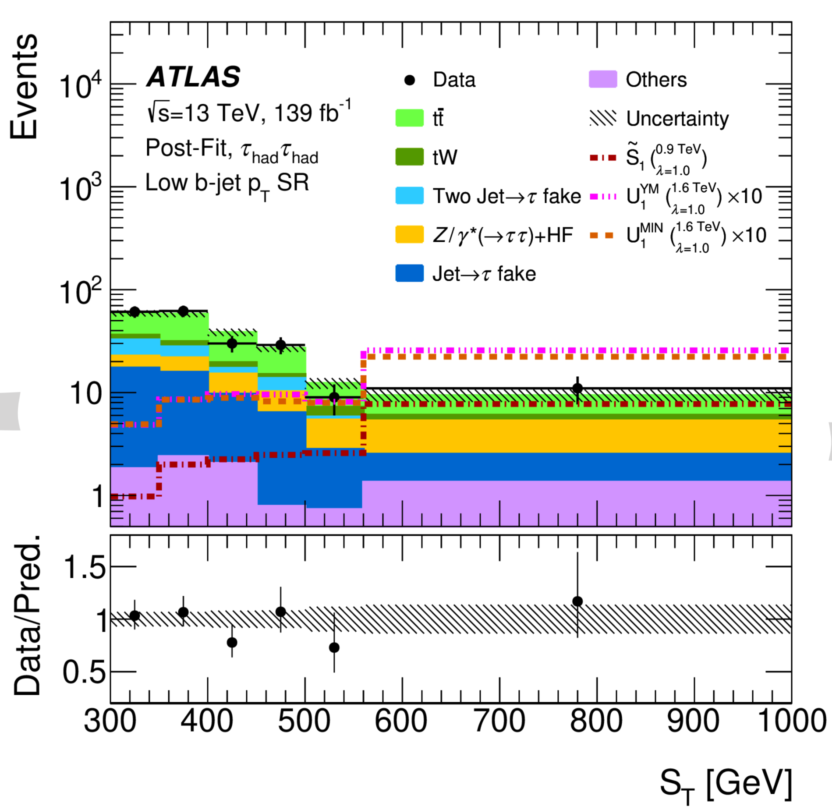


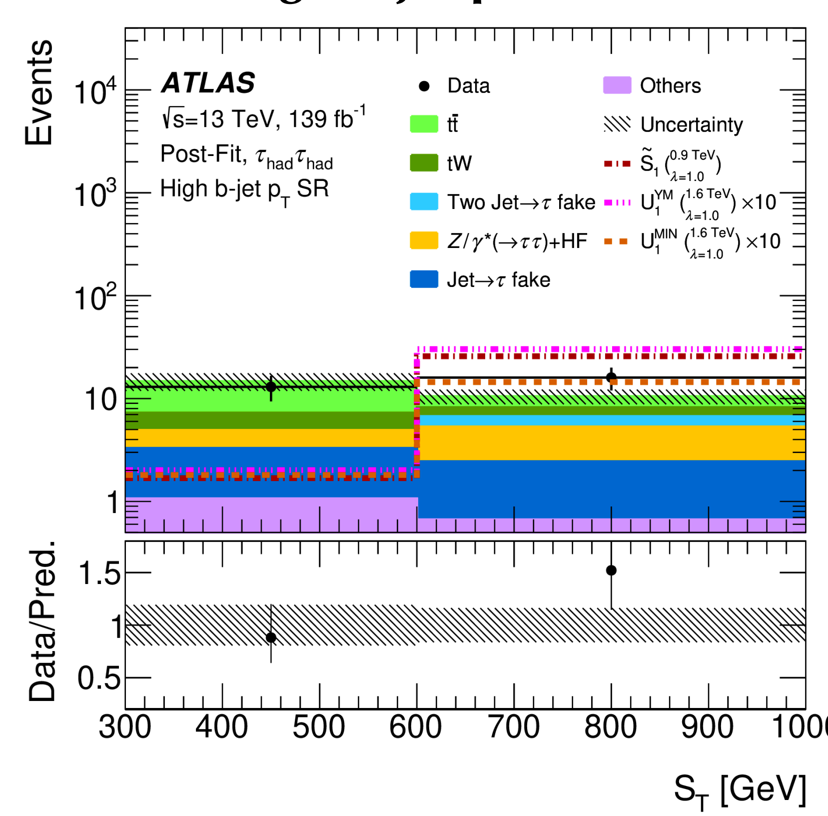
τhadτhad

Low b-jet pT SRs

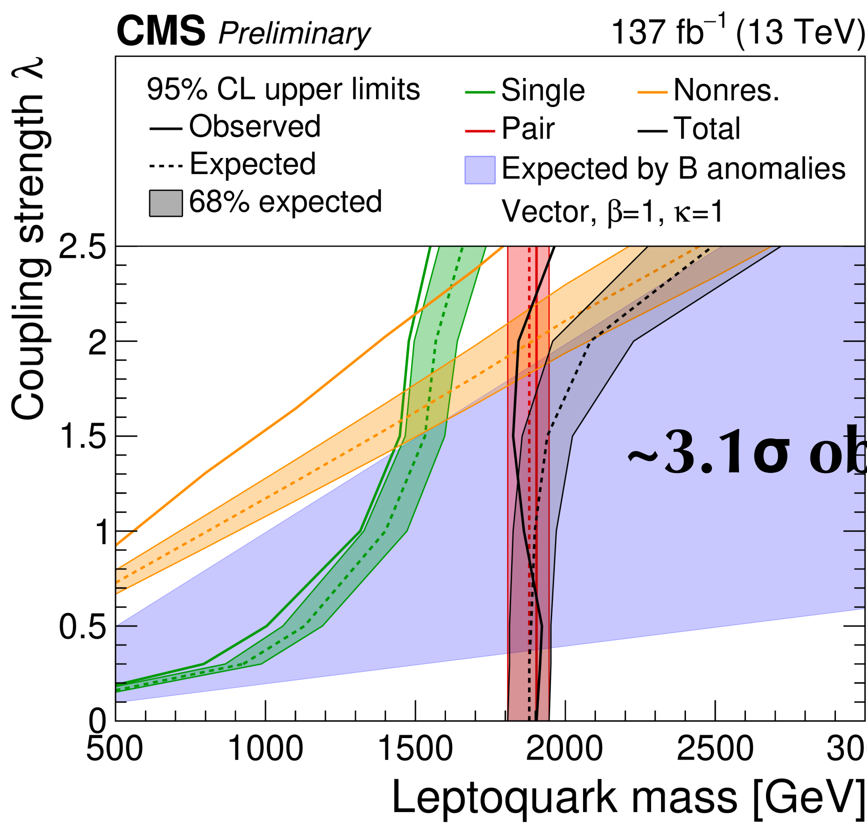
High b-jet pT SRs

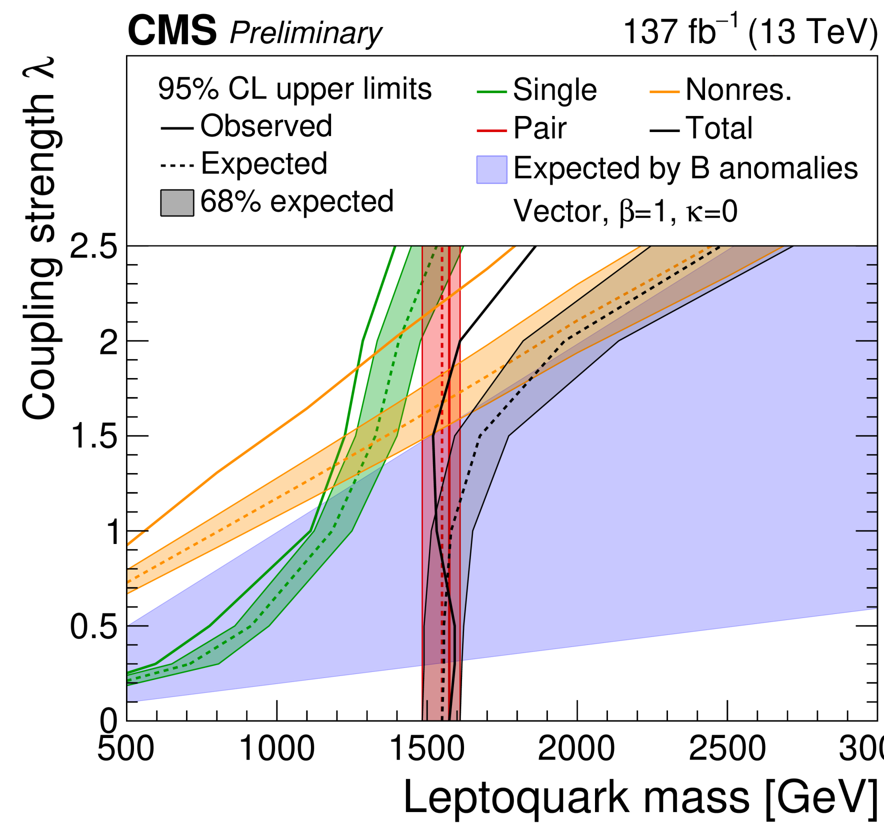
τlepτhad



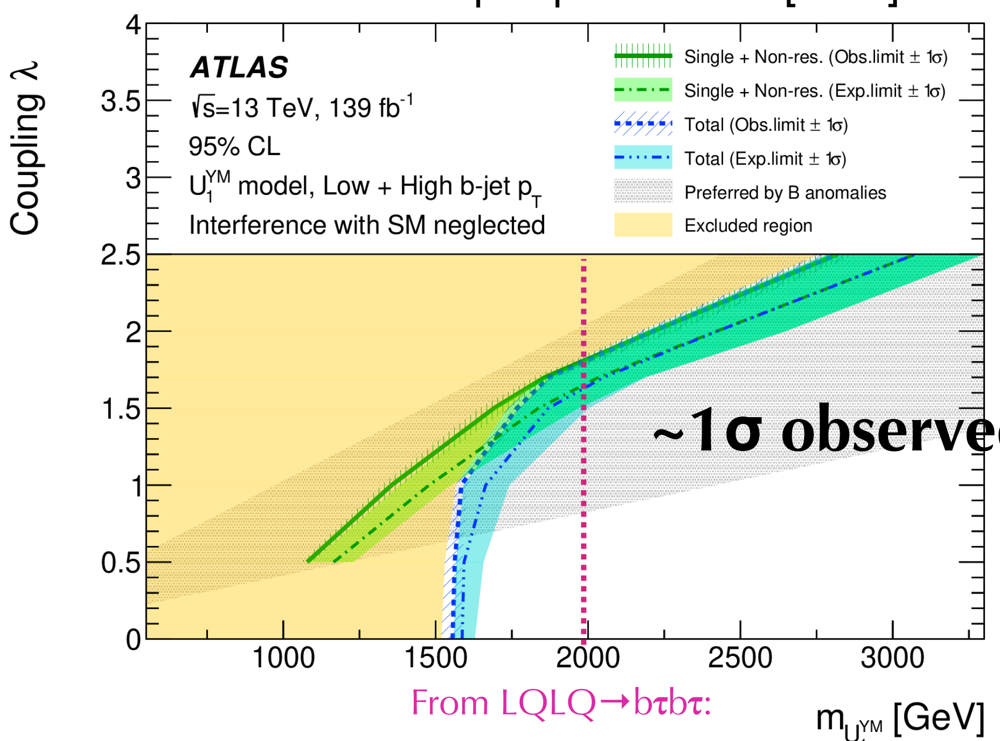


Single/Pair LQ→bτ results (comparison)

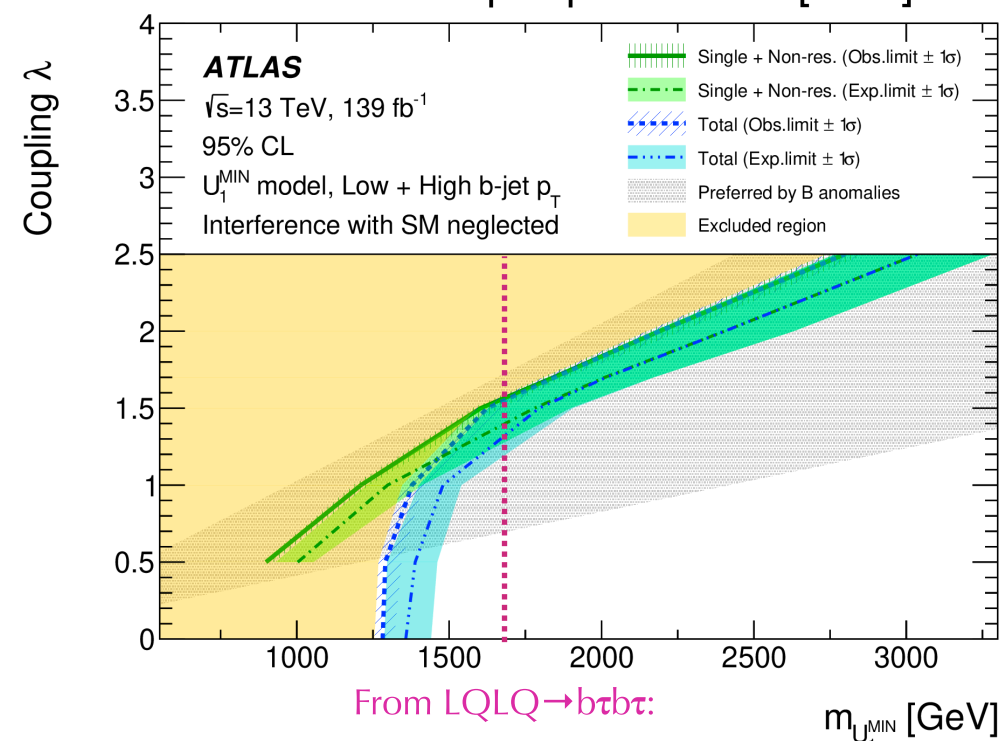




CMS-PAS-EXO-19-016



From LQLQ→bτbτ: 2303.01294

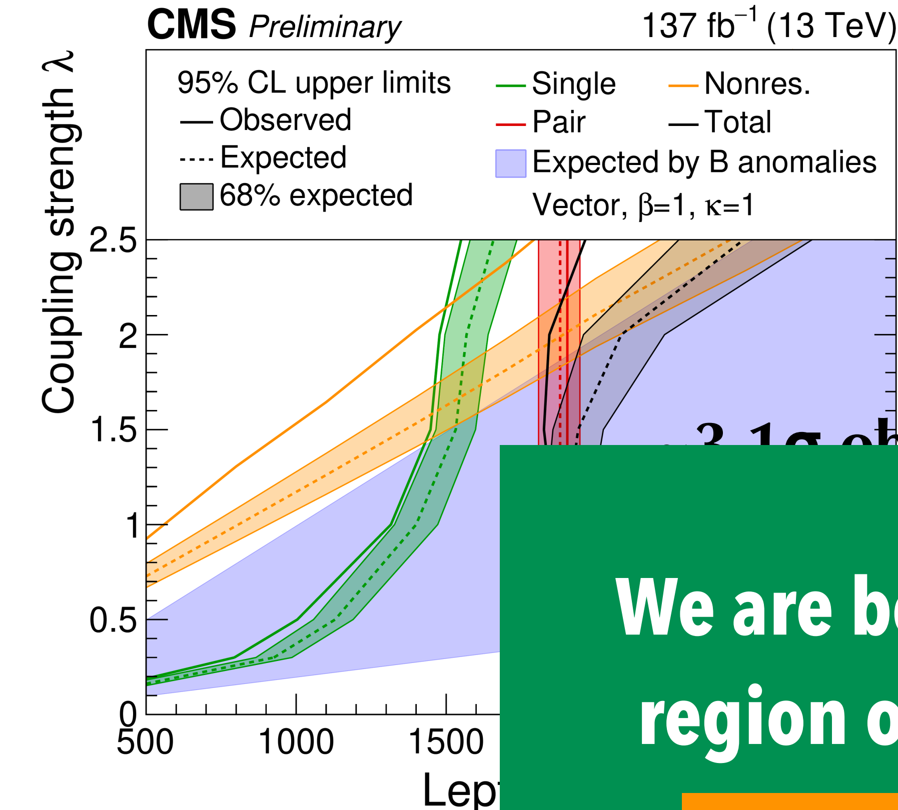


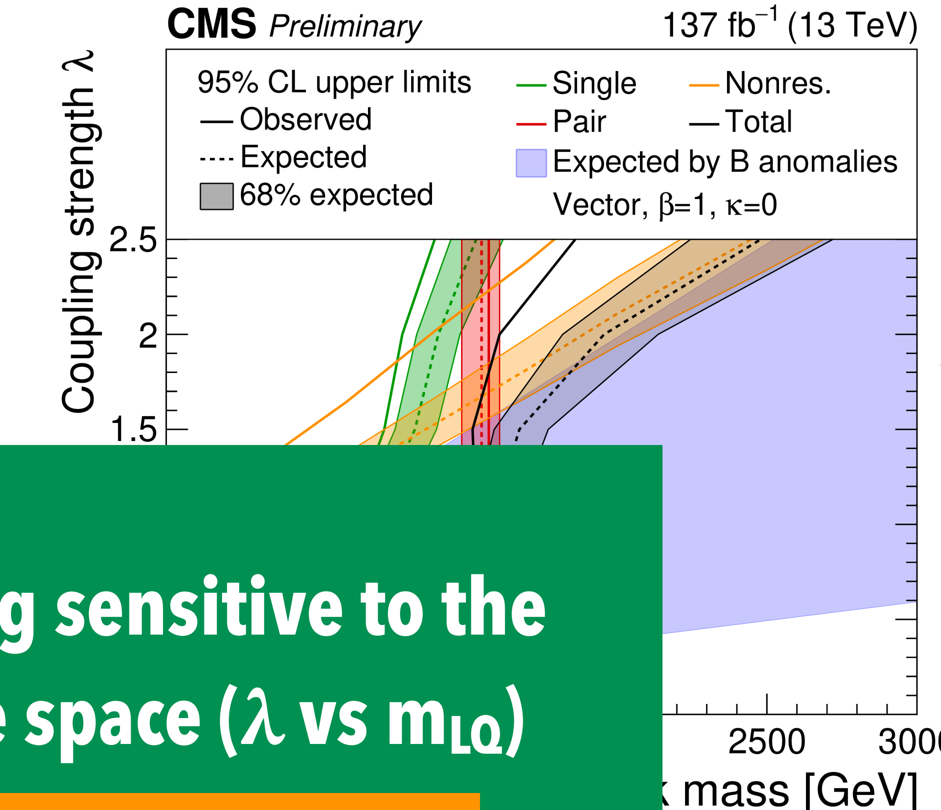
From LQLQ→bτbτ: 2303.01294

EXOT-2022-39 (Aux Fig)

ATLAS excludes CMS' excess when considering both low and high b-jet p_T SRs

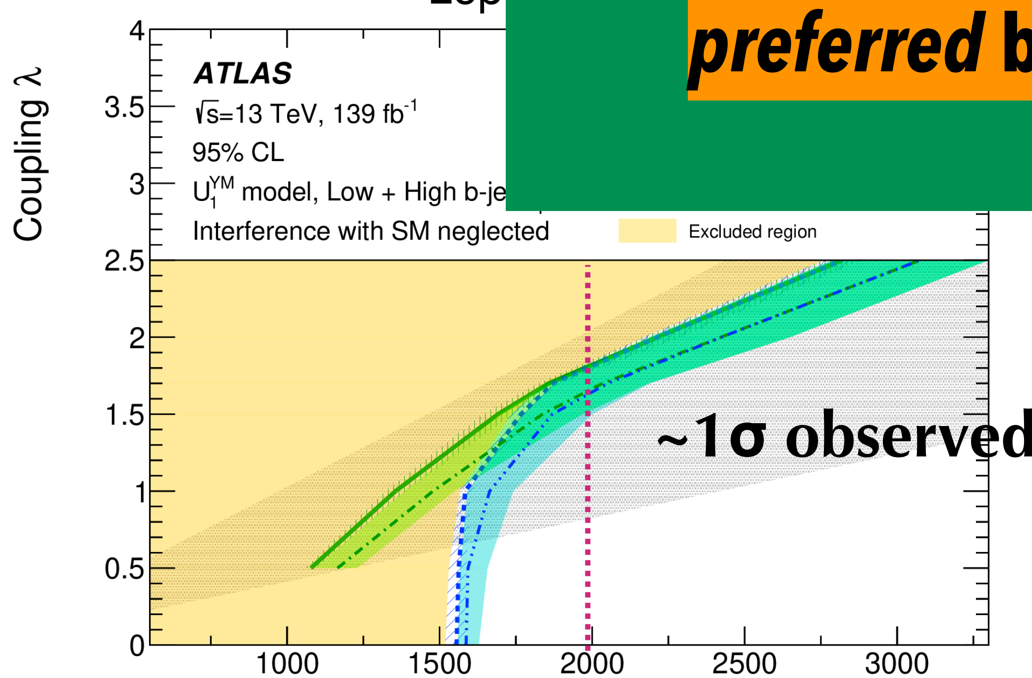
Single/Pair LQ→bτ results (comparison)





CMS-PAS-EXO-19-016

We are becoming sensitive to the region of phase space (λ vs m_{LQ}) ***preferred* by the B-anomalies**



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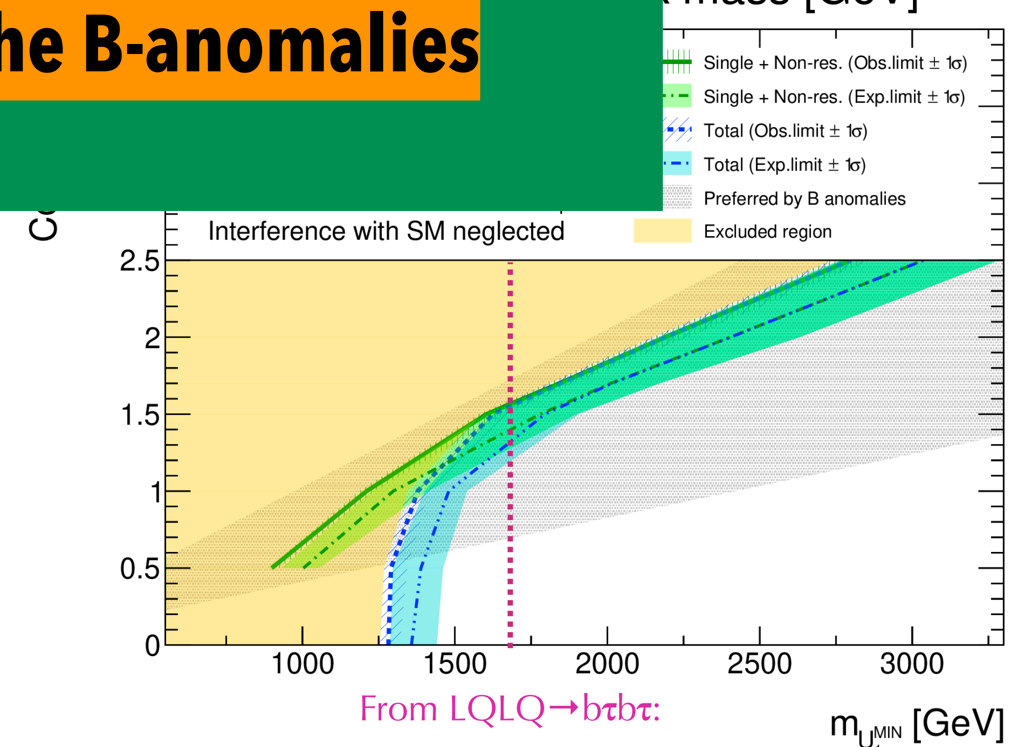


From LQLQ→bτbτ: 2303.01294

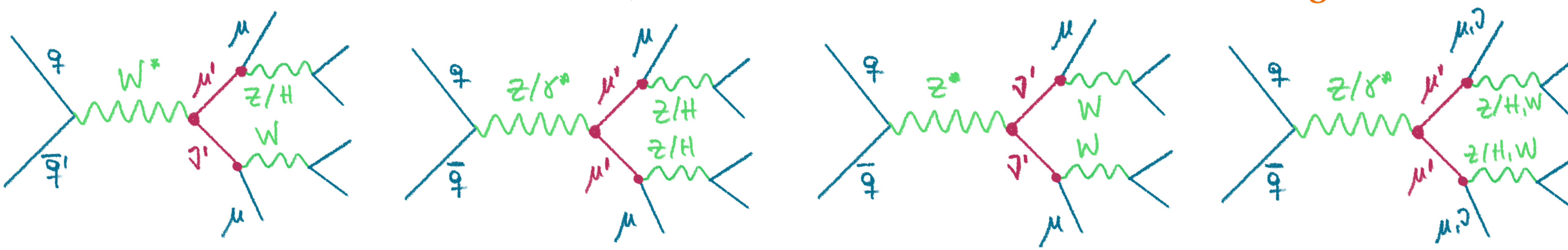
EXOT-2022-39 (Aux Fig)

ATLAS excludes CMS' excess when considering both low and high b-jet p_T SRs

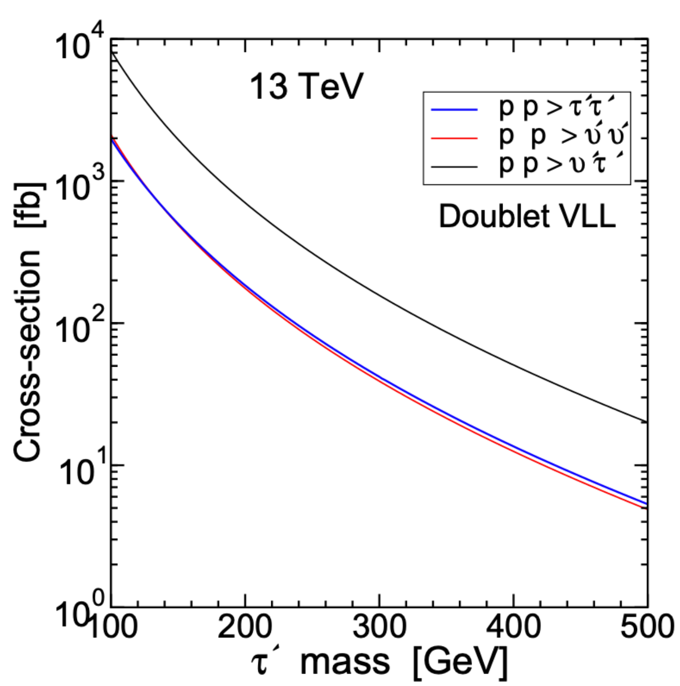
Vector-like leptons

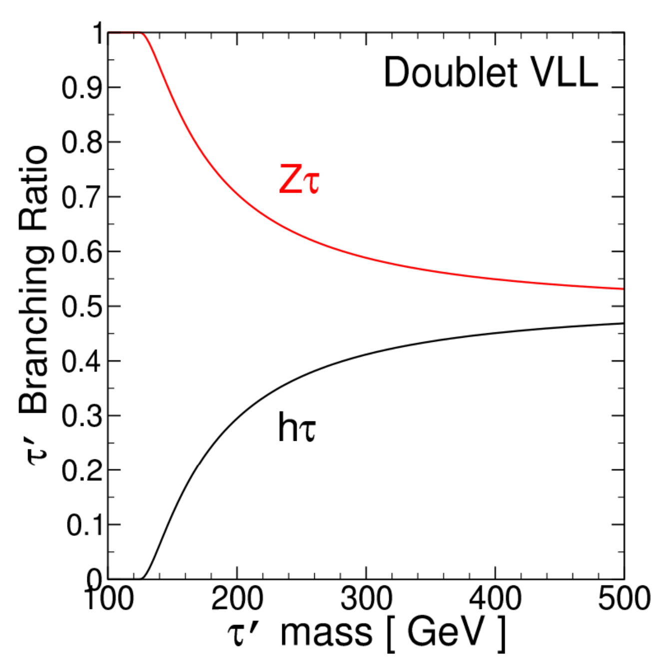
- Hypothetical **heavy fermions** with both chiralities having the same gauge quantum numbers, and can mix with SM ℓ via the **Higgs / W / Z bosons**
- VLLs (e′, μ′, **τ**′, $\nu_{e'}$, $\nu_{\mu'}$, $\nu_{\tau'}$) and their associated SM leptons: *identical lepton numbers*
- Multilepton final states: with and without b-jets (from H or Z decay)

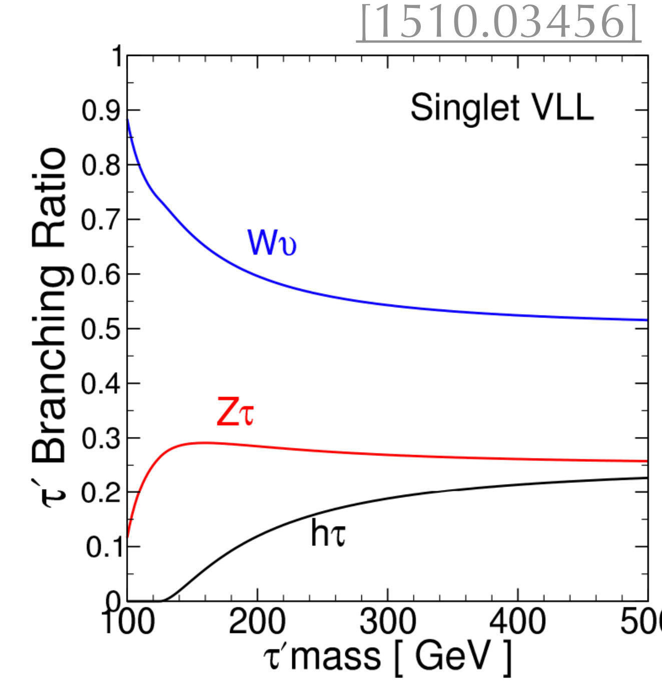
Doublet (ℓ′,ν′) **Singlet (ℓ′)**



[1510.03456]







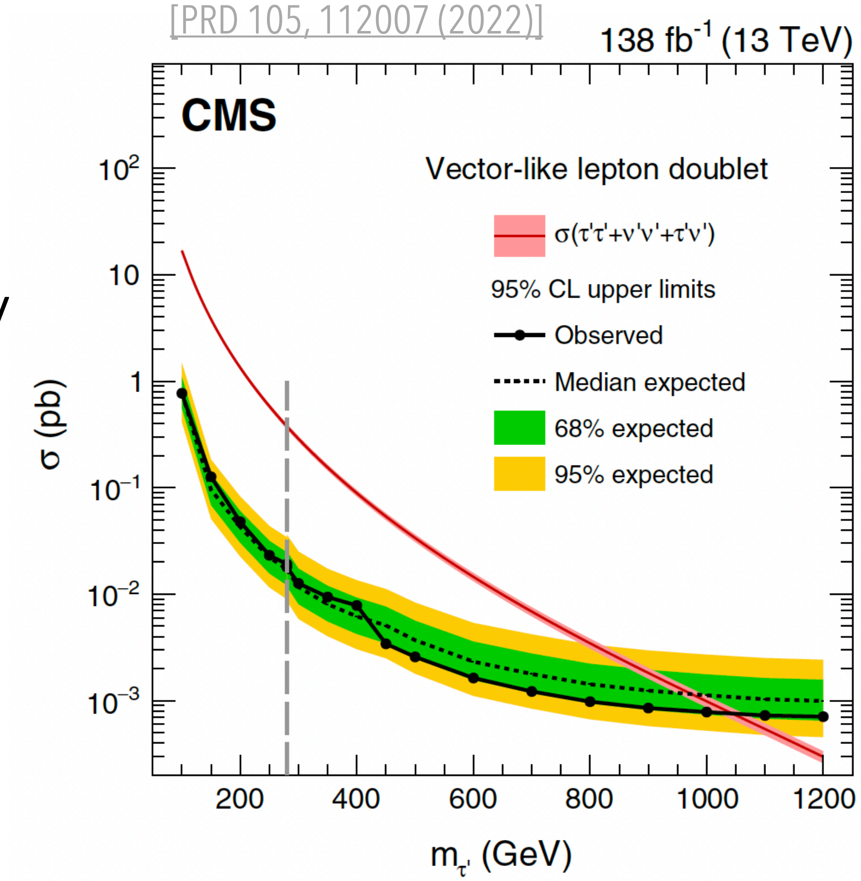
Vector-like τ (τ')

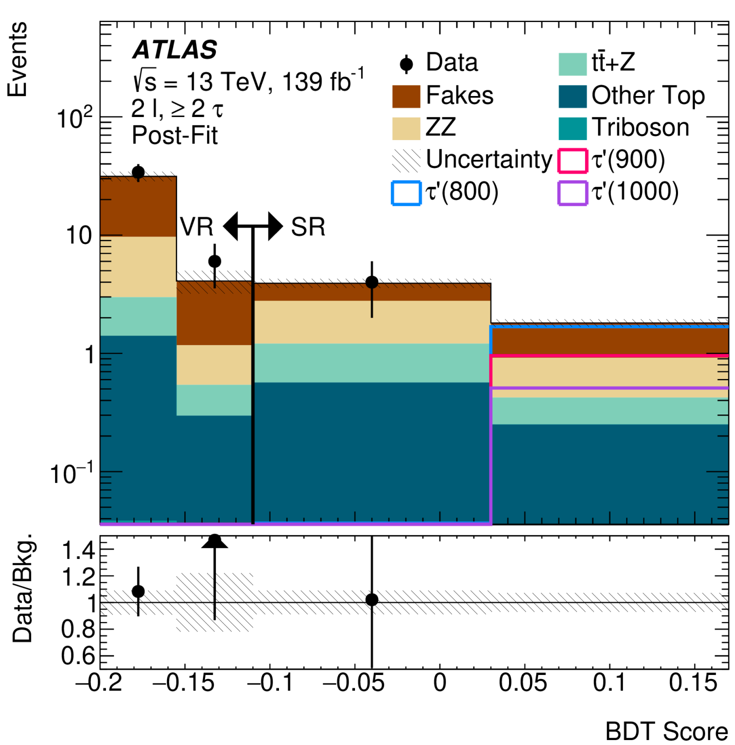
- CMS searched for τ': 100 - 1045 GeV (125 - 150 GeV) $m_{\tau'}$ excluded for the doublet (singlet) model scenario
- ATLAS set limits on τ' with full Run 2 dataset: 130-900 GeV $m_{\tau'}$ excluded for the doublet scenario

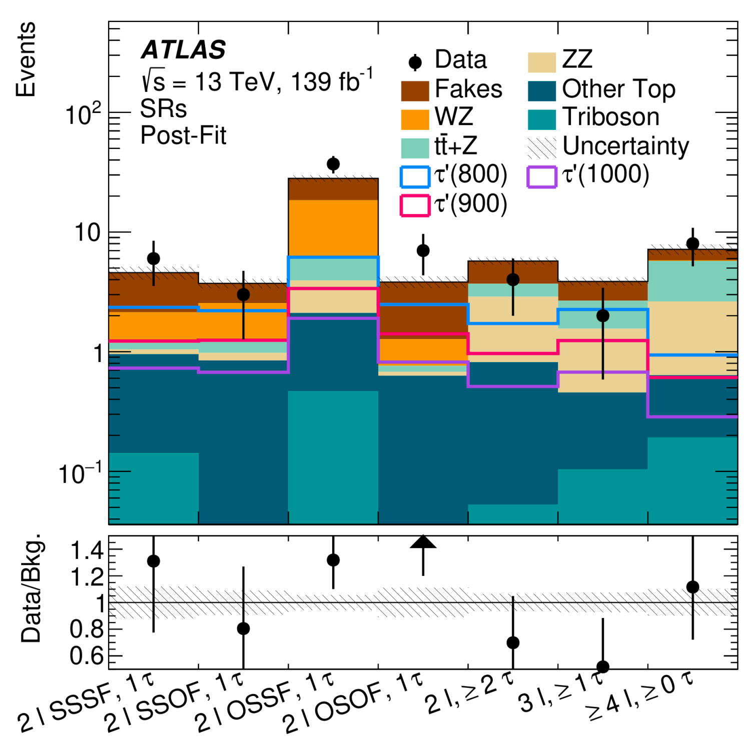
Signal Regions						
2ℓ SSSF, 1τ	2ℓ SSOF, 1τ	2ℓ OSSF, 1τ	2ℓ OSOF, 1τ	2ℓ, $\geq 2\tau$	3ℓ, $\geq 1\tau$	4ℓ, $\geq 0\tau$

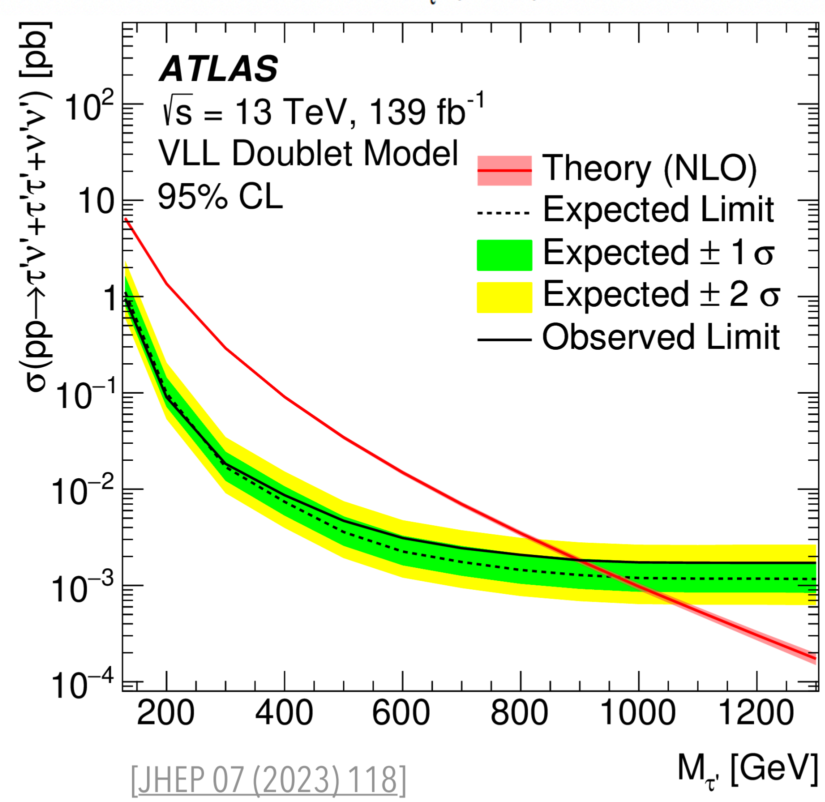
- 2ℓ (same-sign, opposite-sign) ⊗ (same-flavour, opposite-flavour); 3ℓ; 4ℓ
- ≥0, 1, or 2 τ_{had}
- Use a Boosted Decision Tree to discriminate between τ' and SM

[PRD 105, 112007 (2022)]









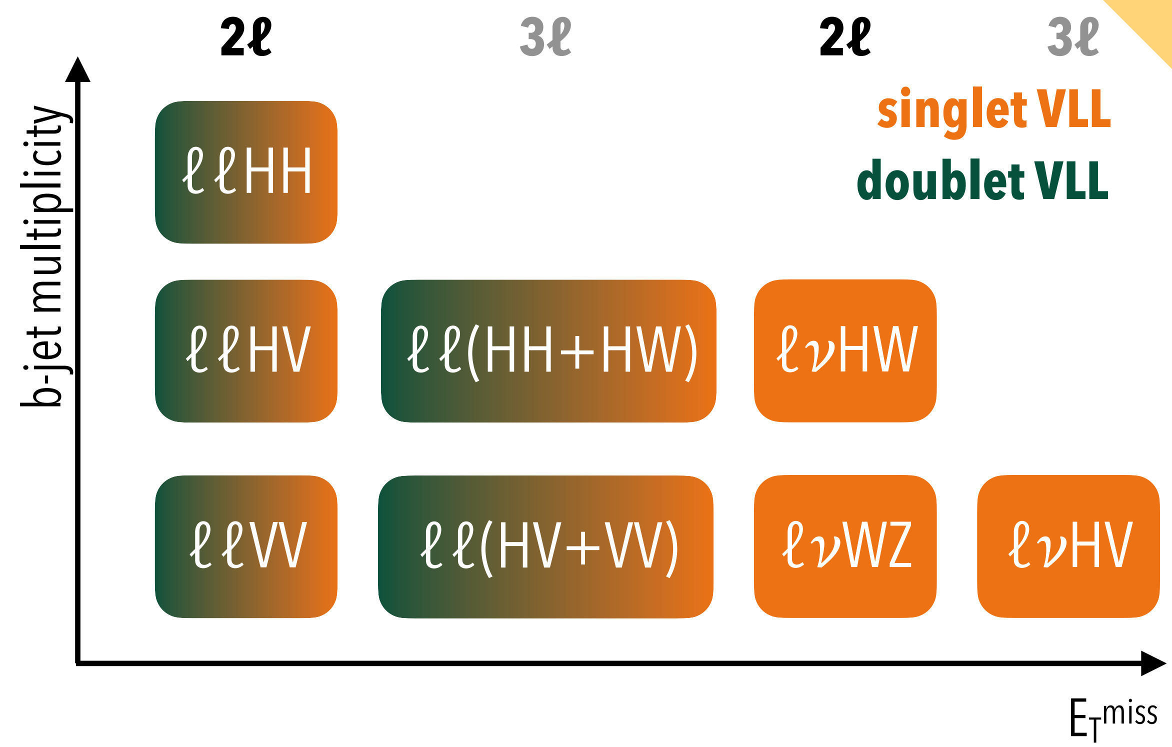
[JHEP 07 (2023) 118]

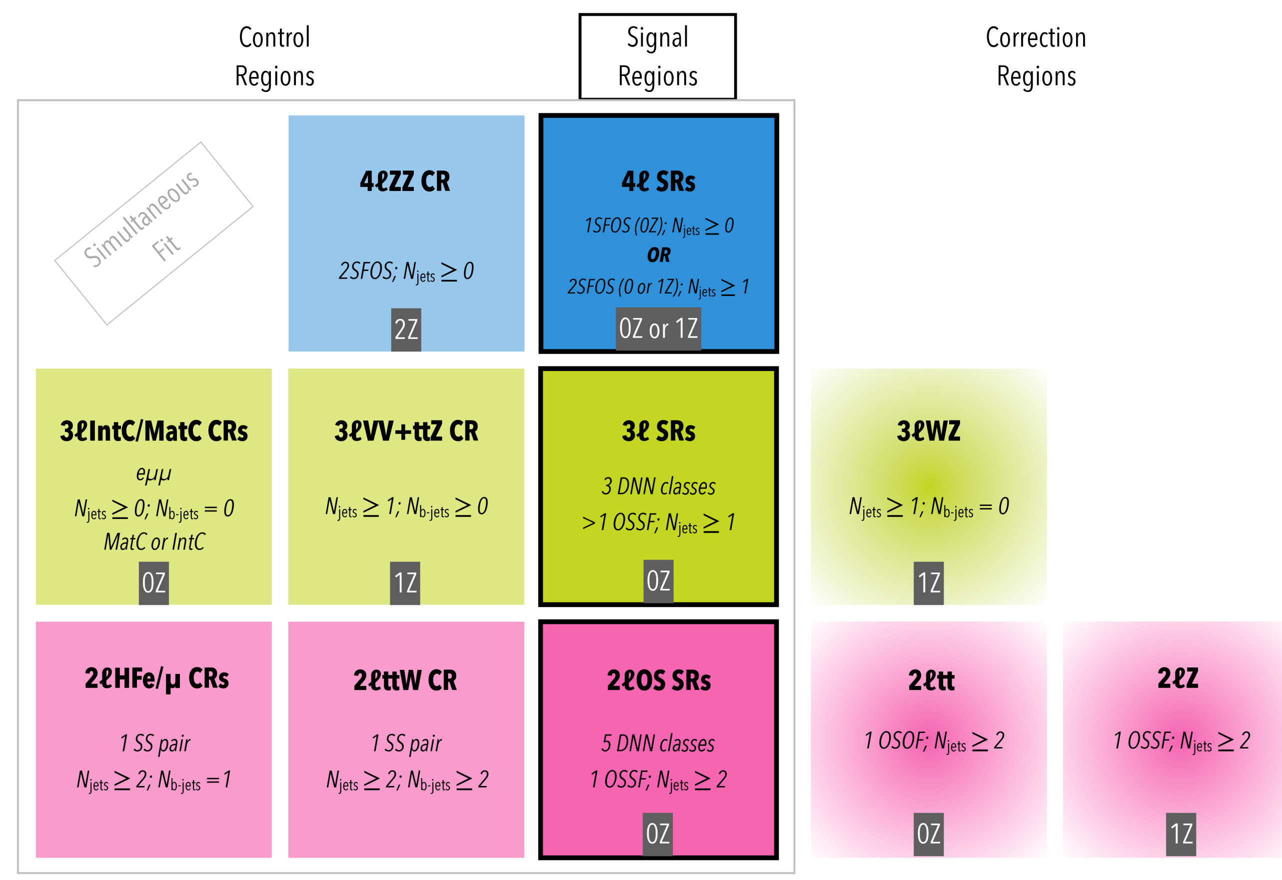
Vector-like electrons / muons

[arXiv 2411.07143]

NEW

- Final states with two opposite sign, three or four light leptons and jets
- VLLe (VLLμ) targeted in signal regions with at least one pair of same-flavour opposite-sign electrons (muons):
  - 2ℓOS/3ℓ: dedicated **signal-vs-signal-vs-background NN** to define signal regions targeting specific topologies while rejecting SM background
  - 4ℓ: cut & count analysis
- Modelling or correction of major SM backgrounds ($t\bar{t}$, Z+jets, WZ+light/heavy flavour jets, $t\bar{t}Z$, $t\bar{t}W$, ZZ)
- Simultaneous profile likelihood fit of BSM signal together with major SM backgrounds
  - Fit variable in SRs: Sum of p_T of leptons (H_T^{lep}) plus missing transverse energy (E_T^{miss})
  - Fit variable in CRs: Number of events (except in WZ+ttZ CR, where $N_{b\text{-jets}}$ is used)





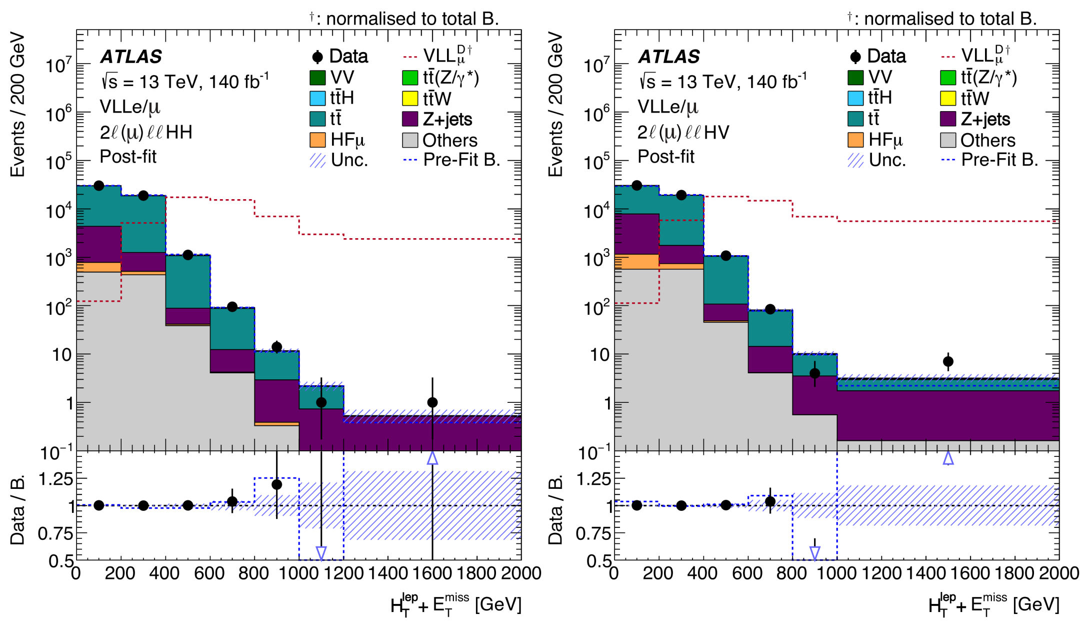
Vector-like e/μ: signal regions

[arXiv 2411.07143]

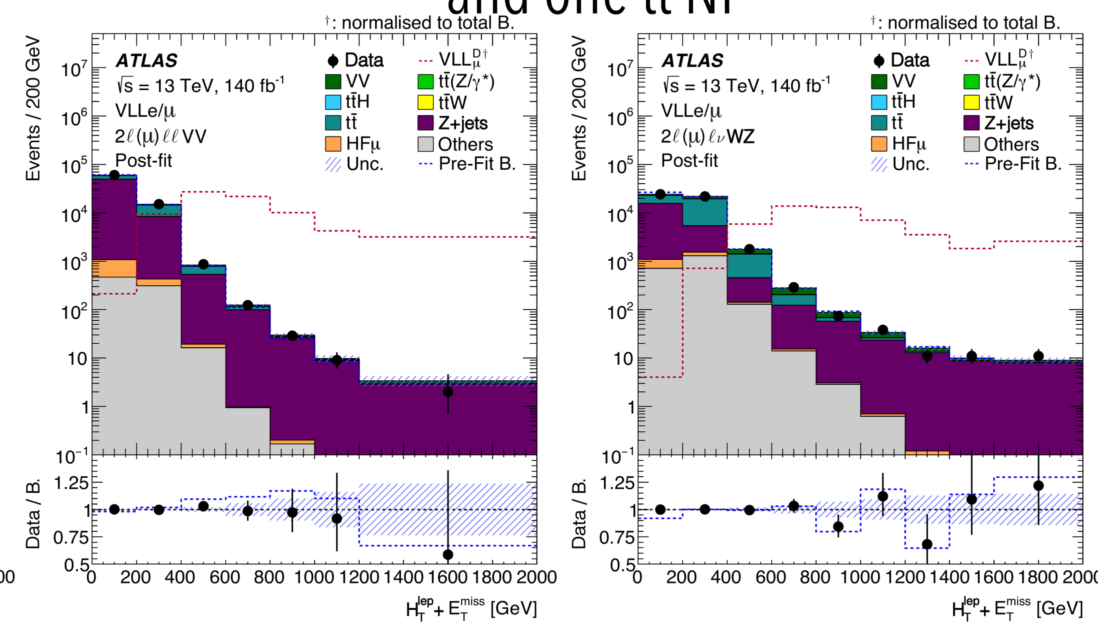
NEW

- **No excess observed** over the SM background prediction

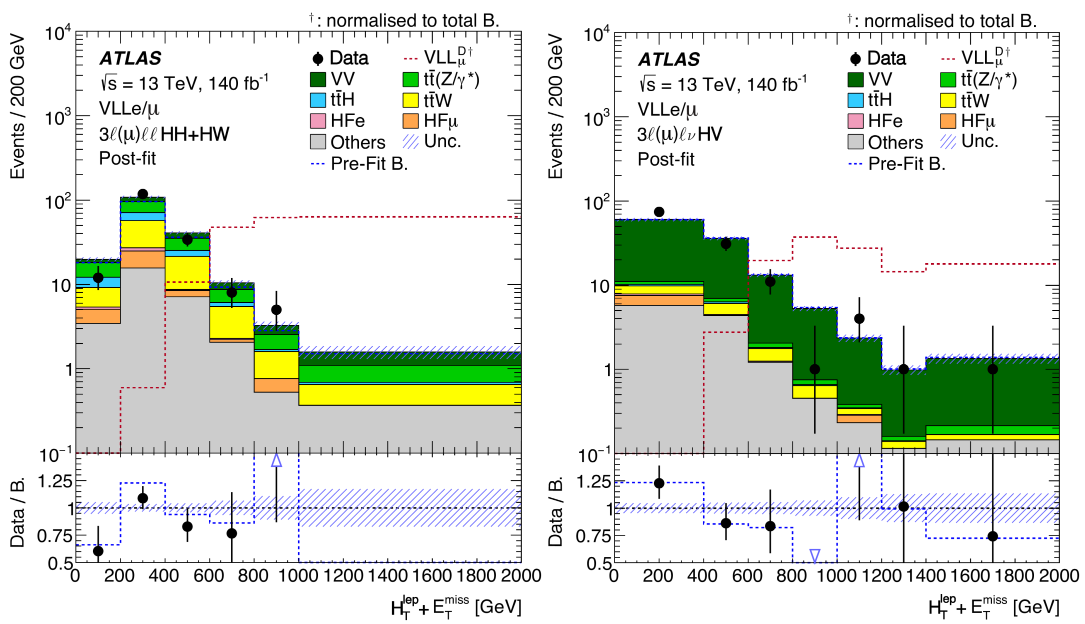
2ℓOS SRs with dedicated $t\bar{t}$ NFs



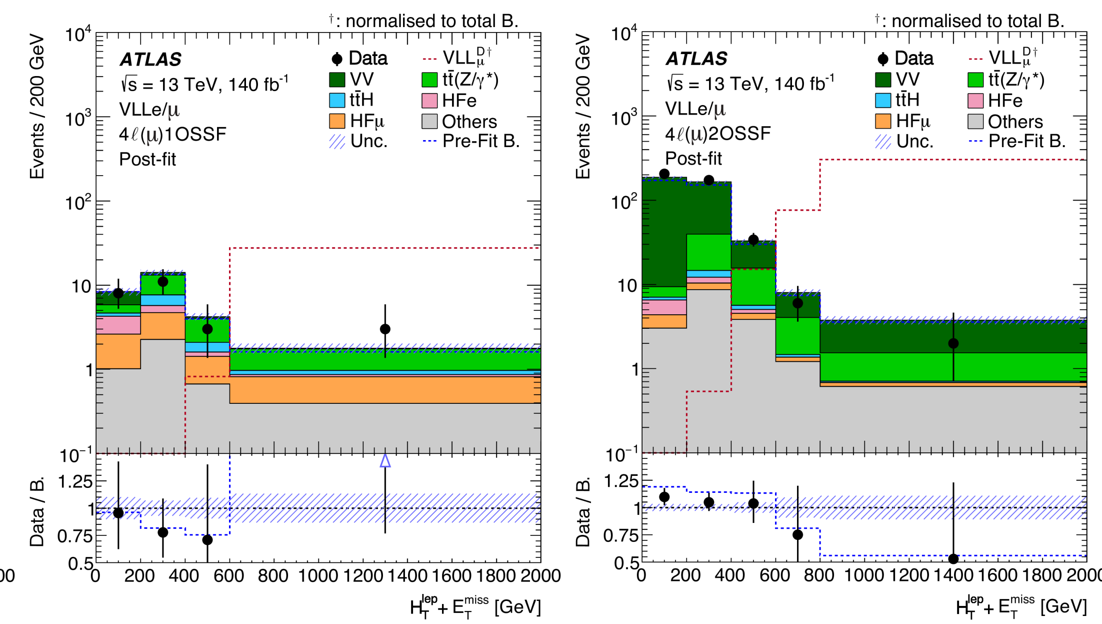
2ℓOS SRs with dedicated Z+jets NFs and one $t\bar{t}$ NF



3ℓ SRs



4ℓ SRs

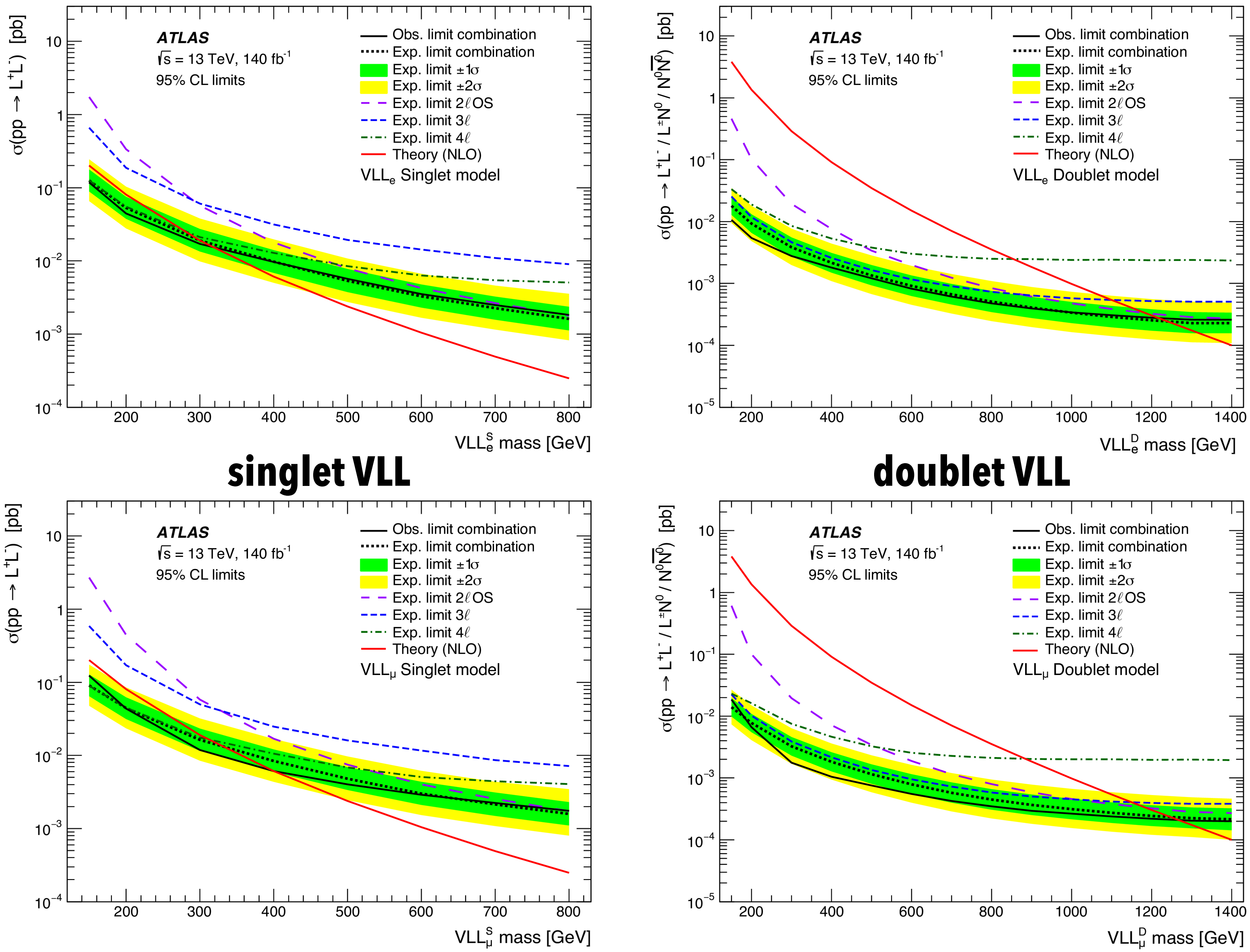


Vector-like e/μ: results

[arXiv 2411.07143]

NEW

- **Most stringent limits** on **VLLe** and **VLLμ**, improving those from Run 1 on the singlet scenario, and setting limits **on the doublet scenario for the <u>first time</u>**



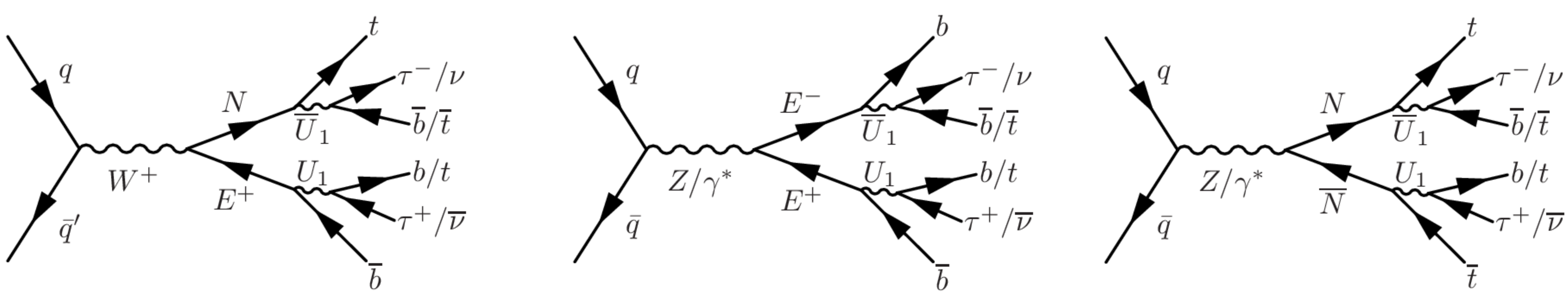
Vector-like ℓ: summary

NEW

	SU(2) doublet	SU(2) singlet	
VLL_e		129 -176 GeV (except 144-164 GeV)	Run 1 ATLAS: JHEP 09 (2015) 108 (no CMS result)
	150 - 1220 GeV	150 - 320 GeV	Run 2 ATLAS: this result [arXiv 2411.07143]
VLL_μ		114 -168 GeV (except 153-160 GeV)	Run 1 ATLAS: JHEP 09 (2015) 108 (no CMS result)
	150 - 1270 GeV	150 - 400 GeV	Run 2 ATLAS: this result [arXiv 2411.07143]
VLL_τ	130 - 900 GeV		Run 2 ATLAS: JHEP 07 (2023) 118
	100 - 1045 GeV	125 - 150 GeV	Run 2 CMS: PRD 105, 112007 (2022)

Vector-like τ *and LQs:* 4321 model

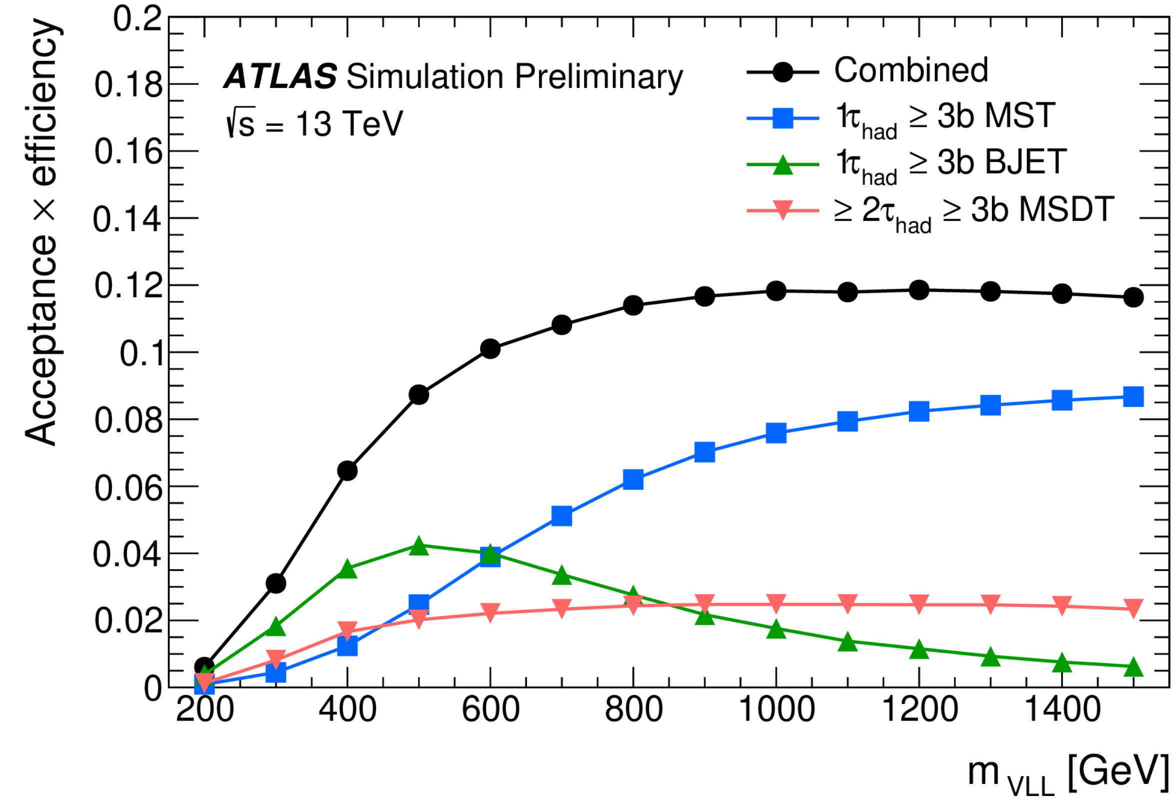
- UV-complete 4321 model: arXiv:1808.00942
- Extends the SM with a new symmetry group: SU(4) x SU(3)′ x SU(2)$_L$ x U(1)′
  - 3 heavy gauge bosons: Color octet **(G′)**, Vector LQ **(U)**, Color singlet **(Z′)**
  - VLQ doublets: U/D, C/S, T/B
  - VLL doublets: N_1/E_1, N_2/E_2, N_3/E_3
- Can accommodate B-meson anomalies
- VLLs favour **decays via vector LQ U₁** into **third generation** quarks and leptons
- Signature with **multiple taus**, **b-jets**, **jets**, **leptons** and **MET**

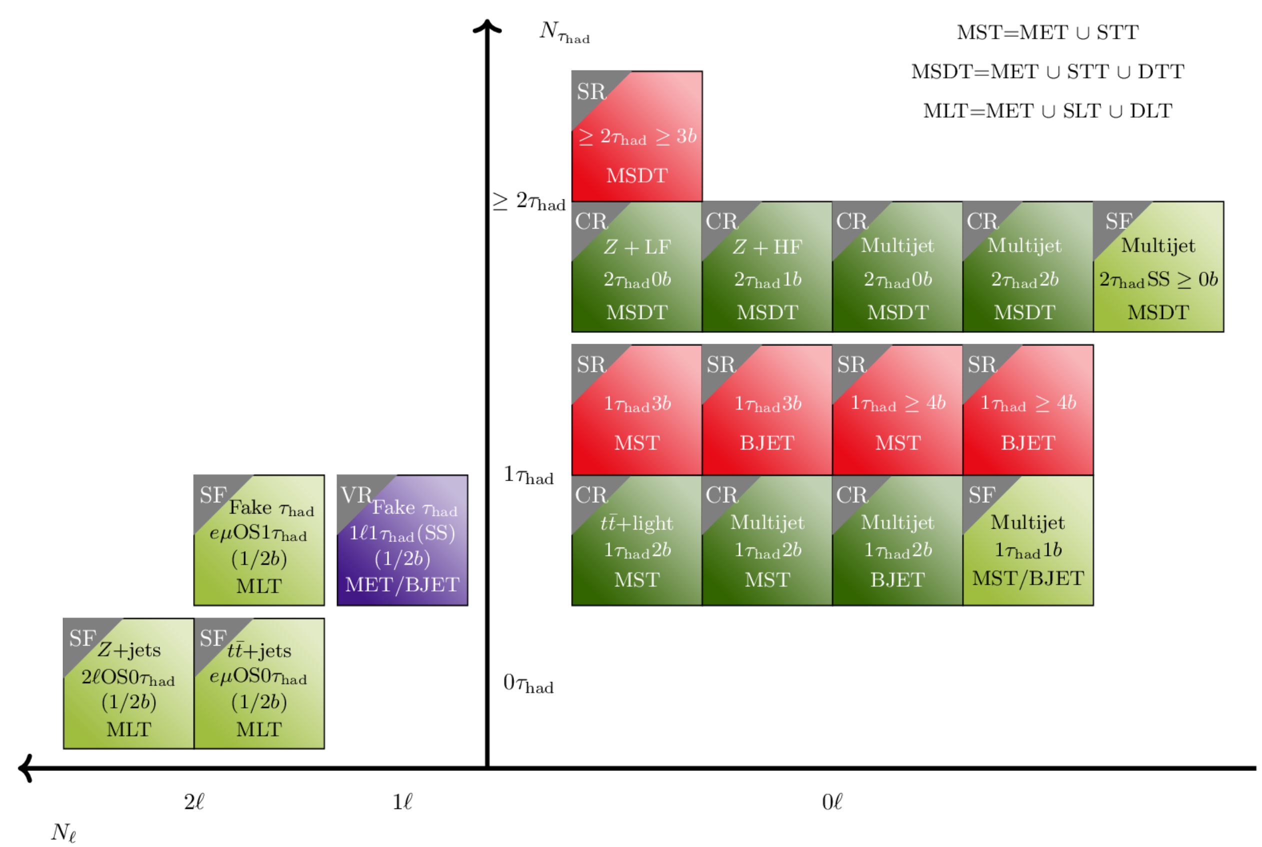


4321 VLLs: ATLAS strategy

ATLAS-CONF-2024-008

- **Signal regions:** 0ℓ, {1τ or ≥2τ}, ≥3b
- **Control regions:** {1τ, 2b} or {≥2τ, (0b, 1b, 2b)}
- **Trigger *bucket* division**: E_T^{miss} (MET), single-tau (STT), di-tau (DTT), and b-jet (BJET) triggers
- ≥1ℓ channels used to derive $t\bar{t}$, V+jets, and fake **τ** corrections
- Norm Factors: $t\bar{t}$+LF/c/b, Z+LF/HF, QCD (separated by **τ** multiplicity and trigger buckets)
- Final simultaneous fit:
  - 1**τ** SRs split into **3b** / **≥4b** and MET-STT (**MST**) / **BJET**
  - Mass-parametrised NN score as discriminating variable

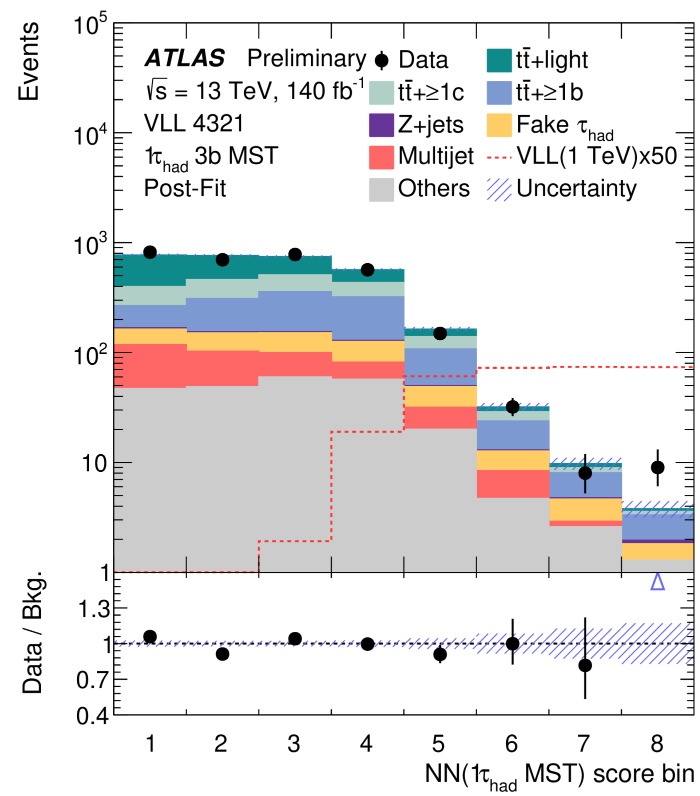


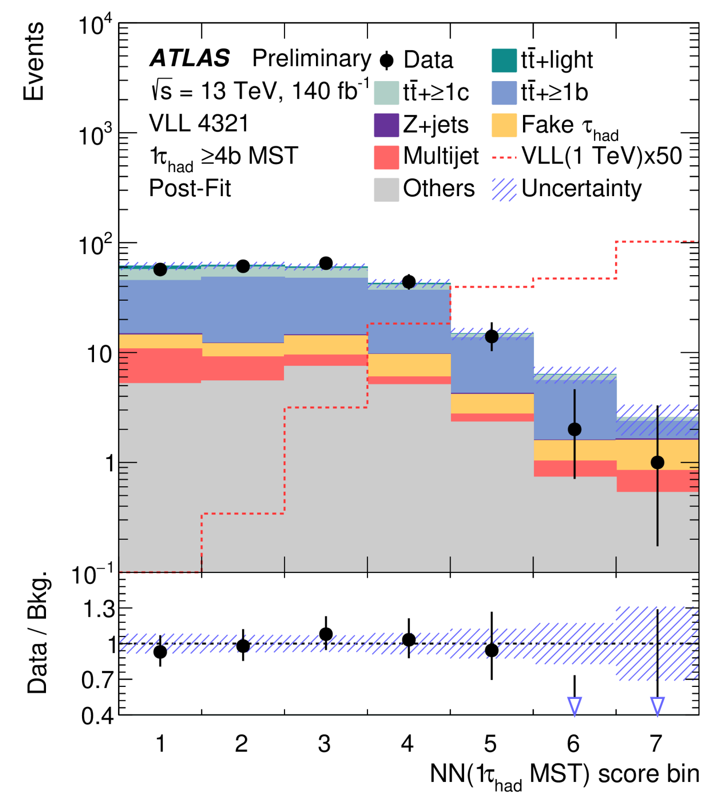


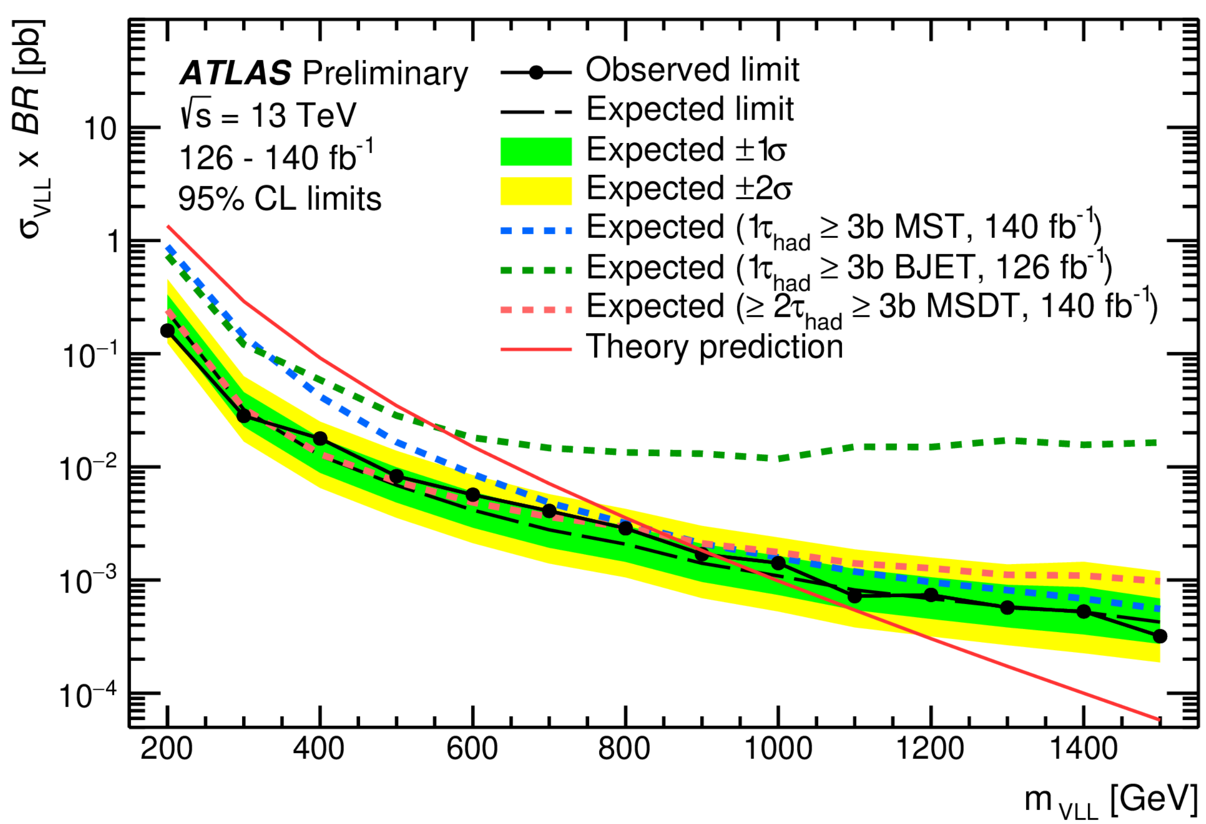
4321 VLLs: ATLAS results

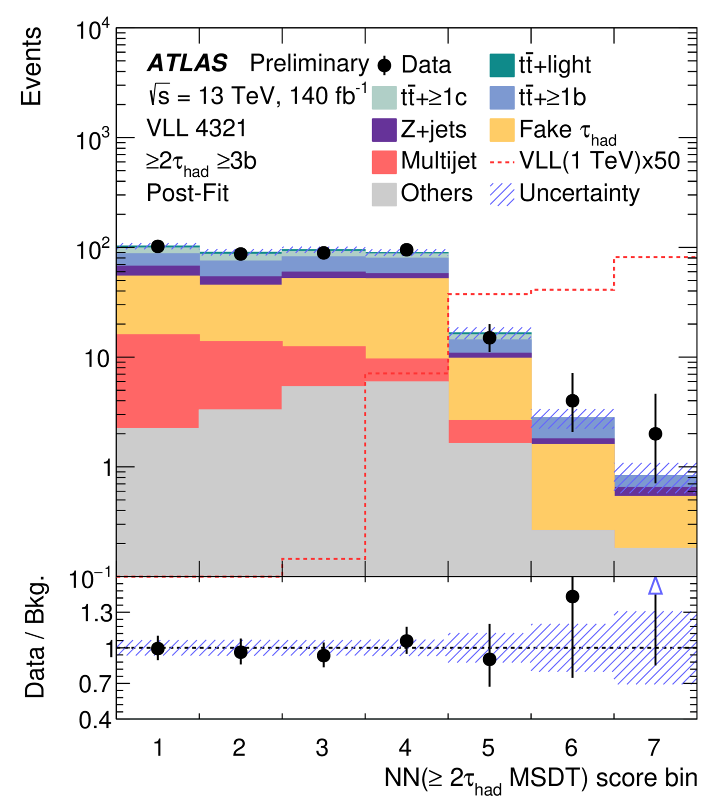
ATLAS-CONF-2024-008

- **No significant excess** observed for VLL masses between 200 and 1500 GeV
- Highest significance 1.1σ for the 400 GeV mass point
- Observed (expected) 95% CL exclusion limits for VLL mass lower than 910 GeV (970 GeV)







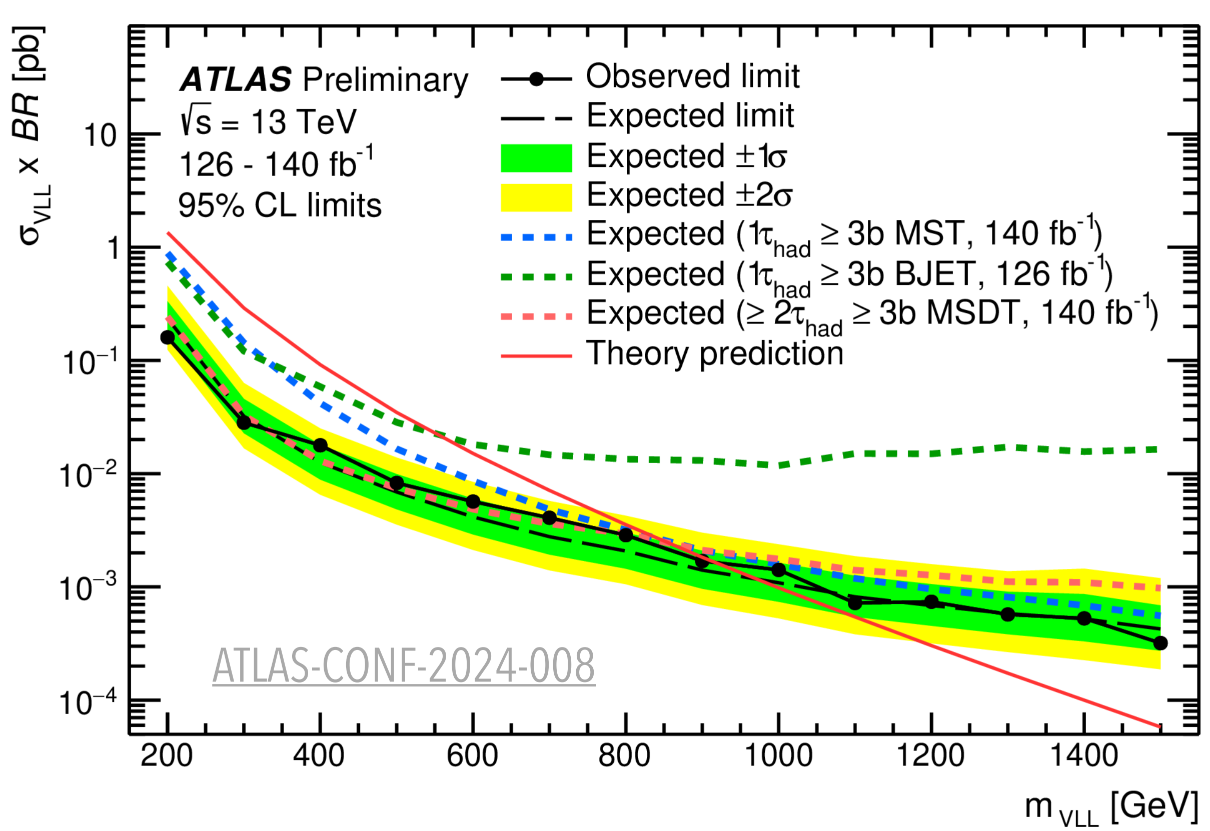


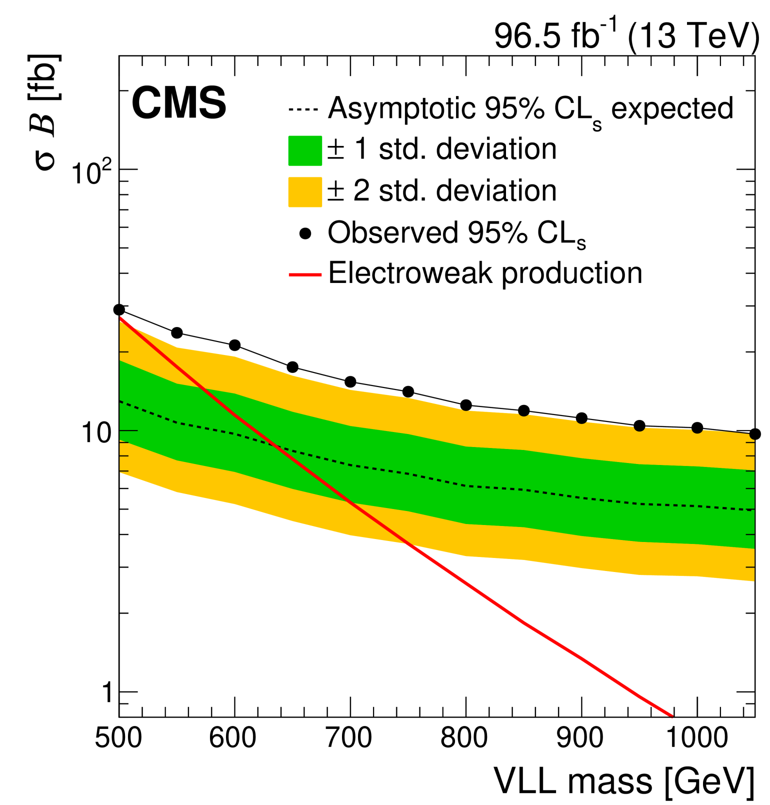
4321 VLLs: ATLAS vs CMS

- Comparison to CMS:
  - CMS also including 0τ 0ℓ channels
  - CMS has a **2.8 σ** tension with the SM at τ′ mass = 600 GeV (excesses in the highest DNNtt̄ bins for both the 1τ and 2τ channels, for both 2017 and 2018)
- **Significant improvement in sensitivity** with ATLAS result
  - Expected exclusion limits for VLL masses lower than 970 (~640) GeV for ATLAS (CMS)

Tau multiplicity	VLL production + decay mode	Final state
	$EE \to b(t\nu_\tau)b(t\nu_\tau)$	$4b + 4j + 2\nu_\tau$
$0\,\tau$	$EN \to b(t\nu_\tau)t(t\nu_\tau)$	$4b + 6j + 2\nu_\tau$
	$NN \to t(t\nu_\tau)t(t\nu_\tau)$	$4b + 8j + 2\nu_\tau$
	$EE \to b(b\tau)b(t\nu_\tau)$	$4b + 2j + \tau + \nu_\tau$
$1\,\tau$	$EN \to b(t\nu_\tau)t(b\tau)$	$4b + 4j + \tau + \nu_\tau$
	$EN \to b(b\tau)t(t\nu_\tau)$	$4b + 4j + \tau + \nu_\tau$
	$NN \to t(b\tau)t(t\nu_\tau)$	$4b + 6j + \tau + \nu_\tau$
	$EE \to b(b\tau)b(b\tau)$	$4b + 2\tau$
$2\,\tau$	$EN \to b(b\tau)t(b\tau)$	$4b + 2j + 2\tau$
	$NN \to t(b\tau)t(b\tau)$	$4b + 4j + 2\tau$

PLB 846 (2023) 137713





4321 VLLs: exclusions

- Approaching the **1 TeV exclusion** for VLL

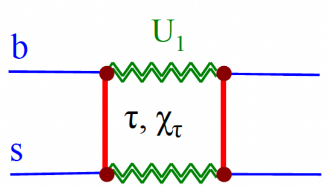
▶ *Leptoquarks & 4321: implications*

III The vector-like fermions

On general grounds, the vector-like fermions are expected to be lighter that the heavy gauge bosons:

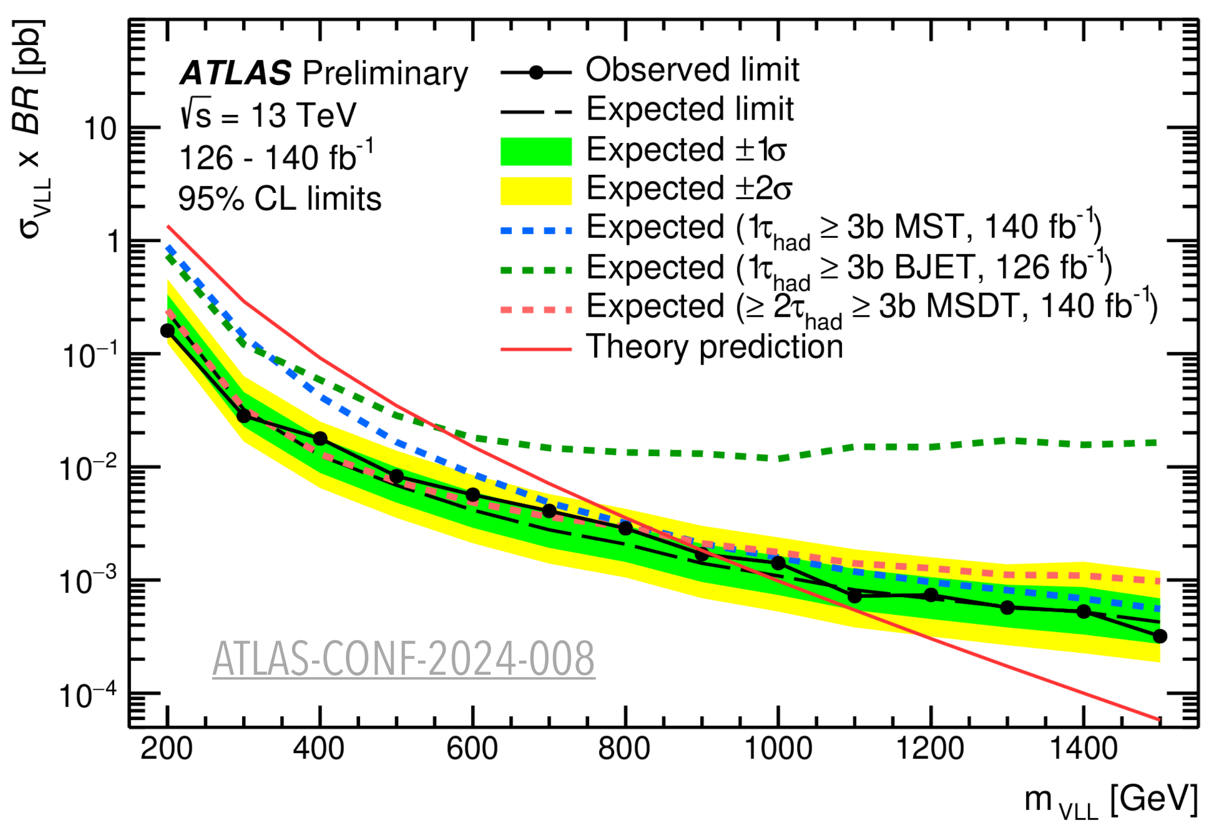
$$M_\chi \lesssim 2\text{ TeV} \qquad M_{U,G',Z'} \sim 2-5\text{ TeV}$$

The lightest vector-like (VL) fermions are the VL leptons for which a clear upper bound follows from B_s mixing & R_D:

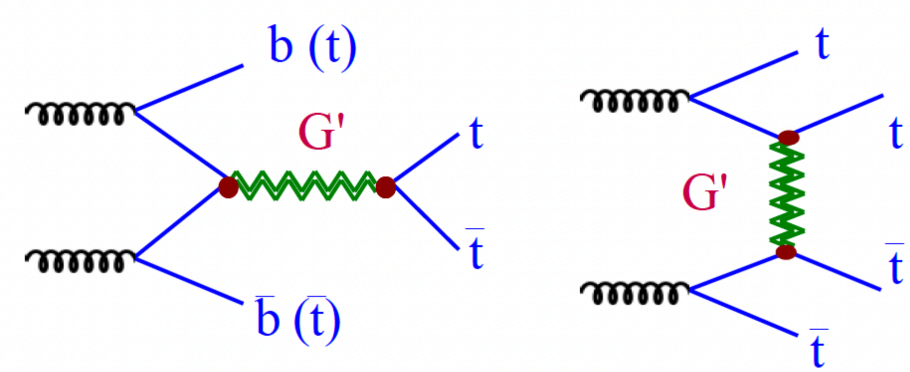


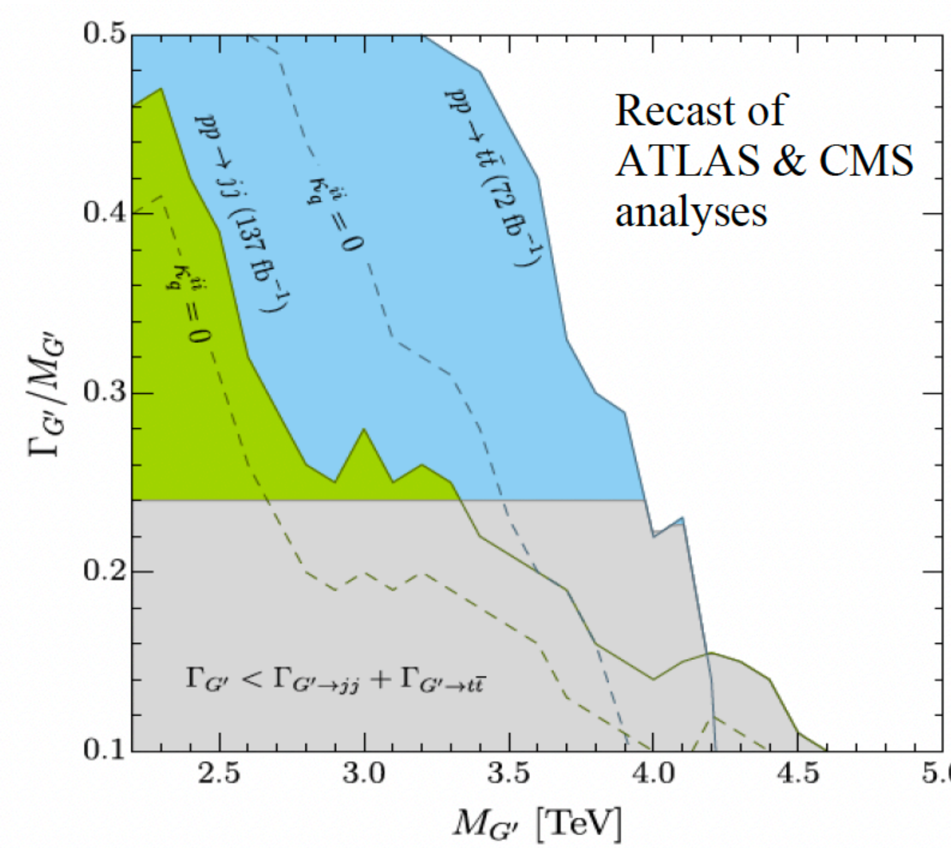
GIM-like cancellation → $M(\chi_\tau) \lesssim 1$ TeV

Di Luzio *et al.* '18



- New striking collider signature: G' ("coloron") = heavy color octet, coupled mainly to 3rd generation quarks
- Constraints on the scale of the model from $pp \to t\bar{t}$



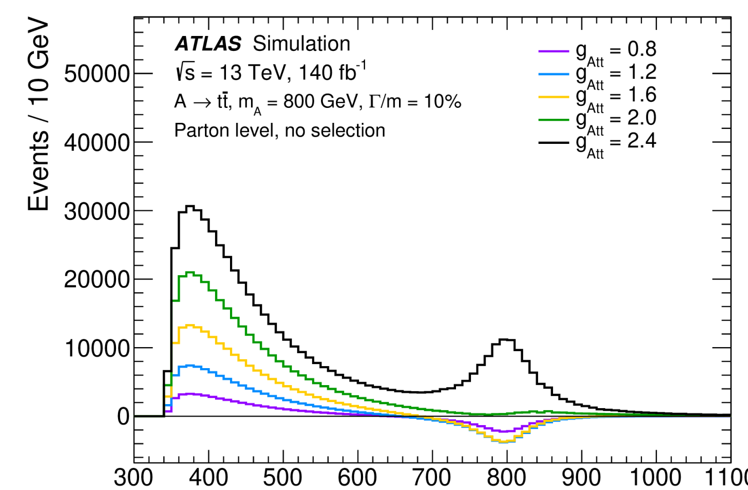


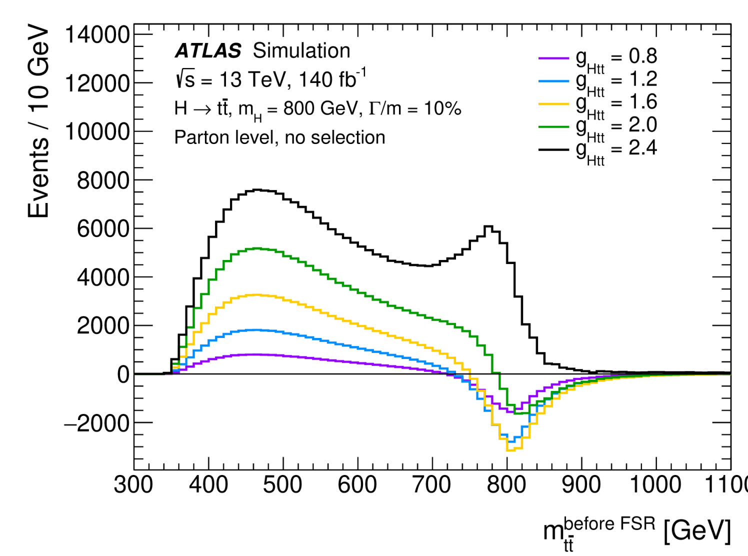
$t\bar{t}$ resonances: analysis strategies

JHEP 08 (2024) 013

CMS-PAS-HIG-22-013

- Recent results on A/H→$t\bar{t}$ searches from ATLAS and CMS
- Target: production of new heavy scalars and pseudoscalars decaying to $t\bar{t}$ (2HDMs, hMSSM, 2HDM+a, ALPs, …)
- **Two orthogonal sets of regions:** 1ℓ (e or μ) + 2ℓ opposite-sign (ee, eμ, μμ)
  - **2ℓ channel**: m_{llbb} as proxy for $m_{t\bar{t}}$; 1L channel: reconstruct full $t\bar{t}$ system, $m_{t\bar{t}}$
  - **Resolved**: ≥4 small-radius jets assigned via Chi2 algorithm
  - **Merged**: large variable-radius jet optimised for intermediate top boosts ($m_{t\bar{t}}$ ~ 1 TeV)
  - **CMS** on the other hand:
    - Reconstructs $m_{t\bar{t}}$ in 2ℓ channel as well
    - Includes == 3 small-radius jet category for 1ℓ
    - No merged category in 1ℓ channel
- Challenge: **strong interference between signal and SM ttbar background**
  - Non-trivial to model and treat statistically
  - Interference pattern depends strongly on signal parameters (model dependence!)
  - Low-$m_{t\bar{t}}$ peak expected even for high resonance masses
  - Especially pronounced for pseudoscalar

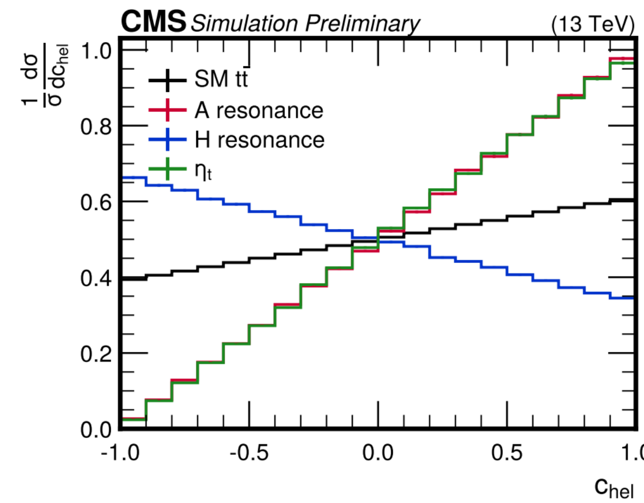




$t\bar{t}$ resonances: discrimination and modelling

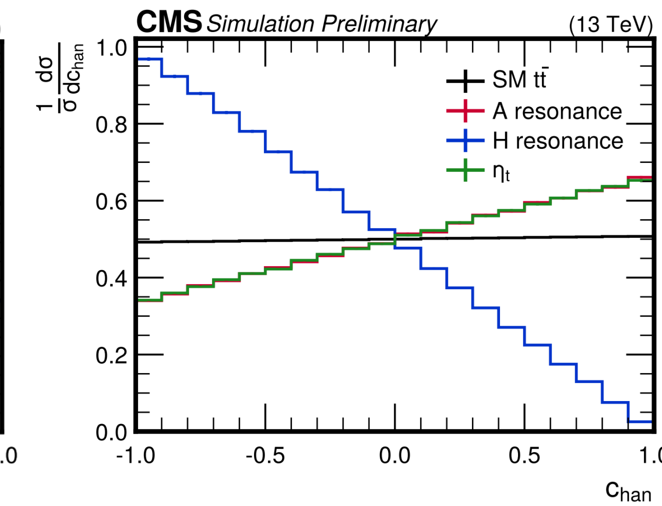
- Split resolved signal regions into bins of **angular variables** sensitive to spin state of the $t\bar{t}$ system:
  - 1ℓ: $\cos\theta^*$, 2ℓ: $\Delta\varphi(\ell\ell)$
- Main difference with CMS:
  - CMS has binning in 2ℓ based on c_{han} and c_{hel}

CMS-PAS-HIG-22-013



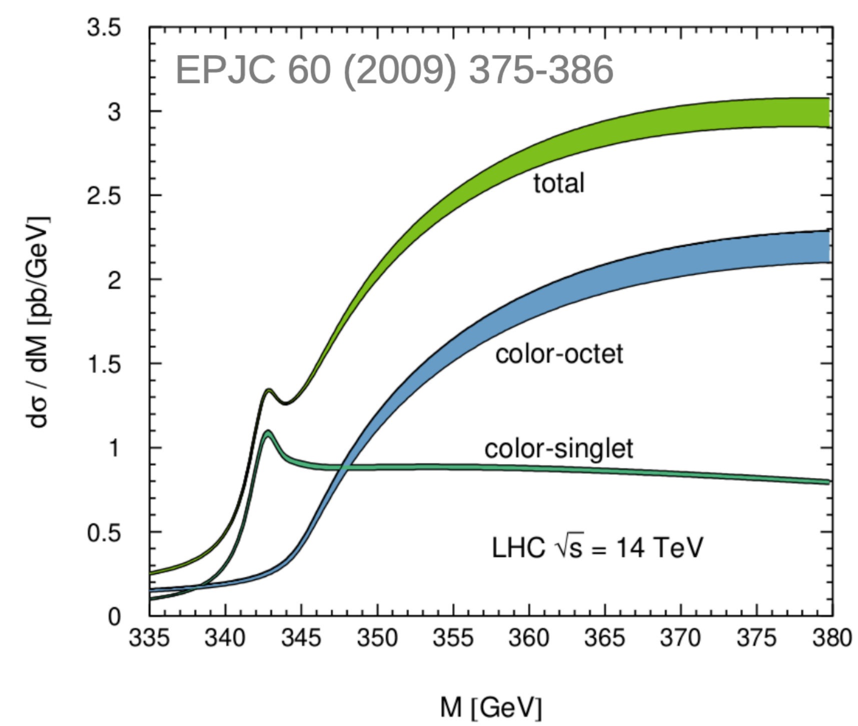
$$c_{\text{hel}} = \hat{\ell}^{+}_{\text{t}} \cdot \hat{\ell}^{-}_{\bar{\text{t}}}$$

Boost leptons into rest frames of their parent tops



Built similarly from lepton momenta, with sign flip for component parallel to top momentum

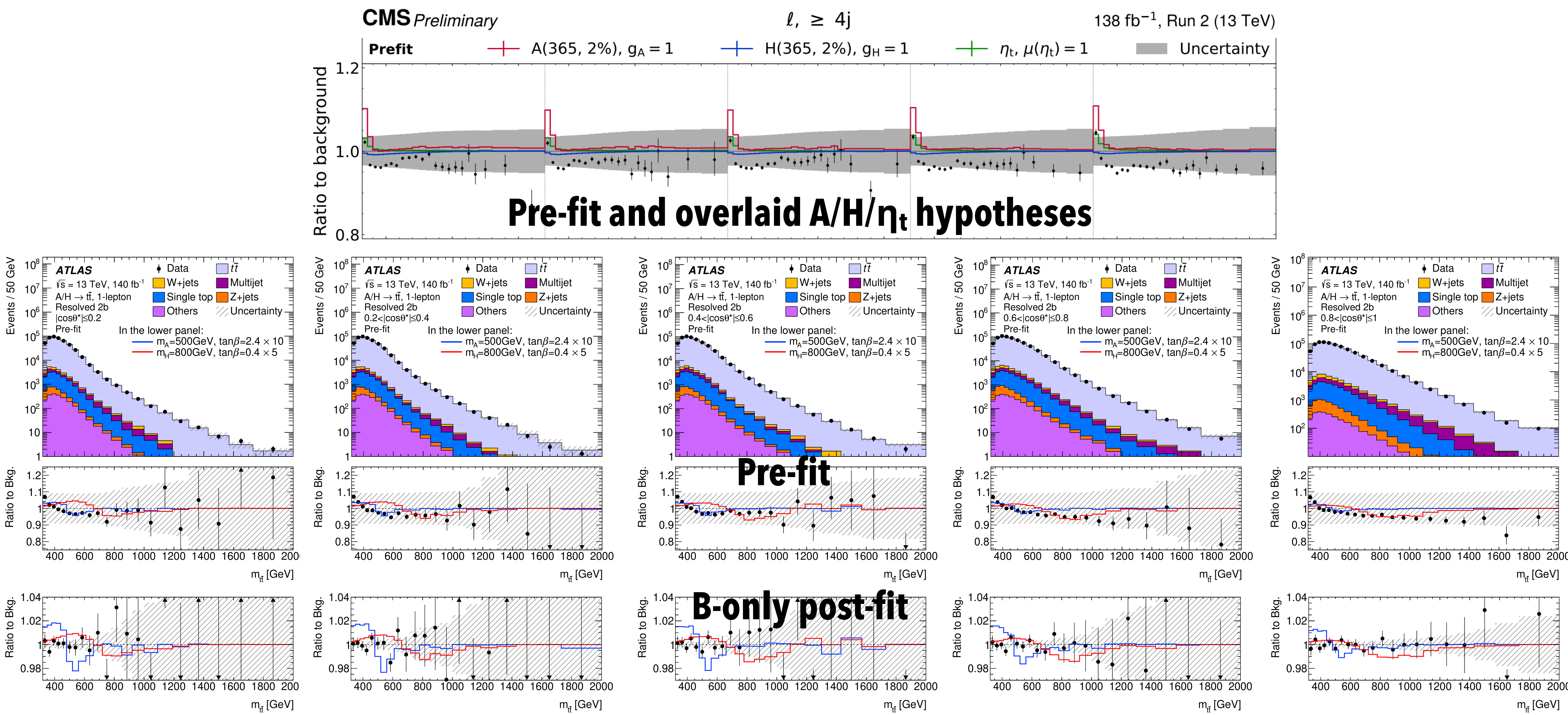
- SM $t\bar{t}$ corrected to different higher-order prediction with different reweighting approach
  - ATLAS: $\{m_{t\bar{t}}, p_T(t), p_T(\bar{t})\}$ vs CMS: $\{m_{t\bar{t}}, \cos\theta^*_t\}$
- Some differences in systematics and correlation scheme
- CMS considers the η_t **colour-singlet model**



Extract cross section using the η_t colour-singlet model (missing e.g. colour-octet states)

$t\bar{t}$ resonances: data/background

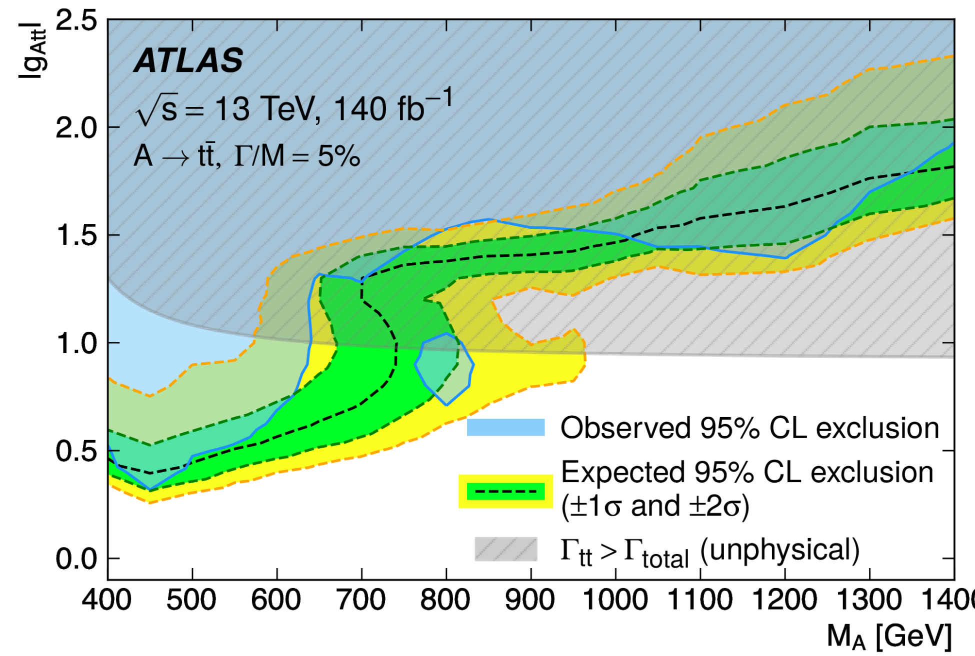
- Pre-fit **disagreement** in data/background also seen by ATLAS
- After background-only hypothesis fit to data, tension absorbed by $t\bar{t}$ systematic uncertainties
- Studies of comparison ATLAS vs CMS ongoing



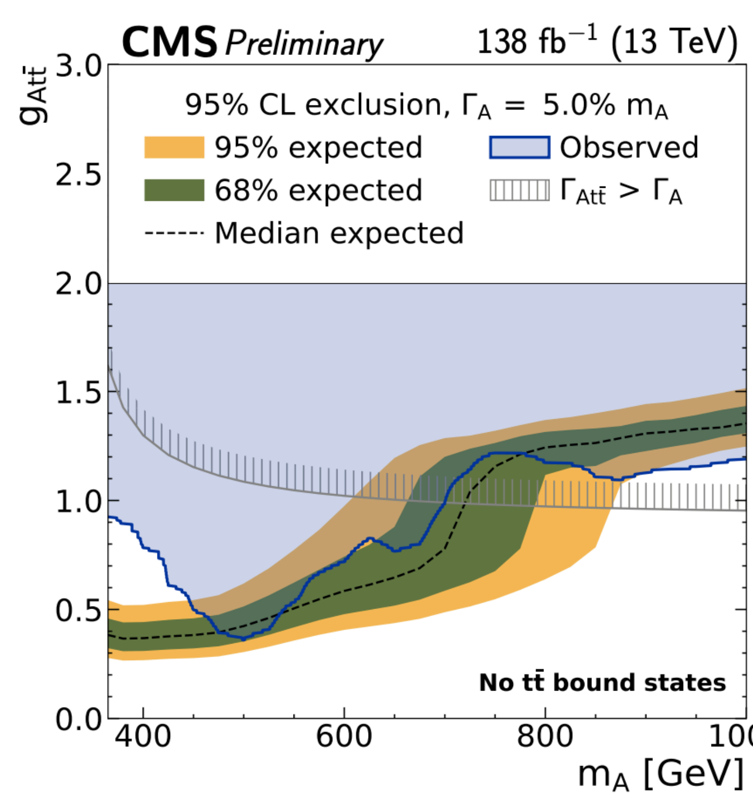
A/H→$t\bar{t}$ interpretation

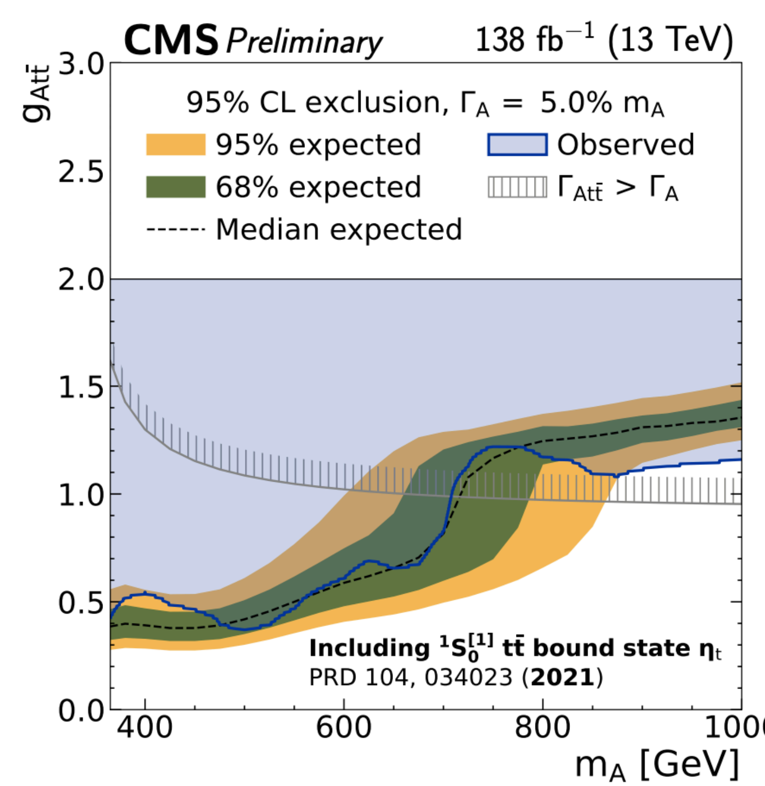
JHEP 08 (2024) 013
CMS-PAS-HIG-22-013

- Tested agreement between data and S+I+B hypotheses with masses [400,1400] GeV and widths [1, 40]%
- Most significant deviation from SM-only (2.3σ local): m_A = 800 GeV, Γ_A/m_A = 10% and $\sqrt{\mu}$ = 4.0
- Driven by narrow upward fluctuation ~ 800 GeV in merged region
- **No exclusion regions calculated for masses < 400 GeV:**
  - LO signal model considered bad approximation of actual interference pattern
  - Large k-factors (up to 10 at 350 GeV)



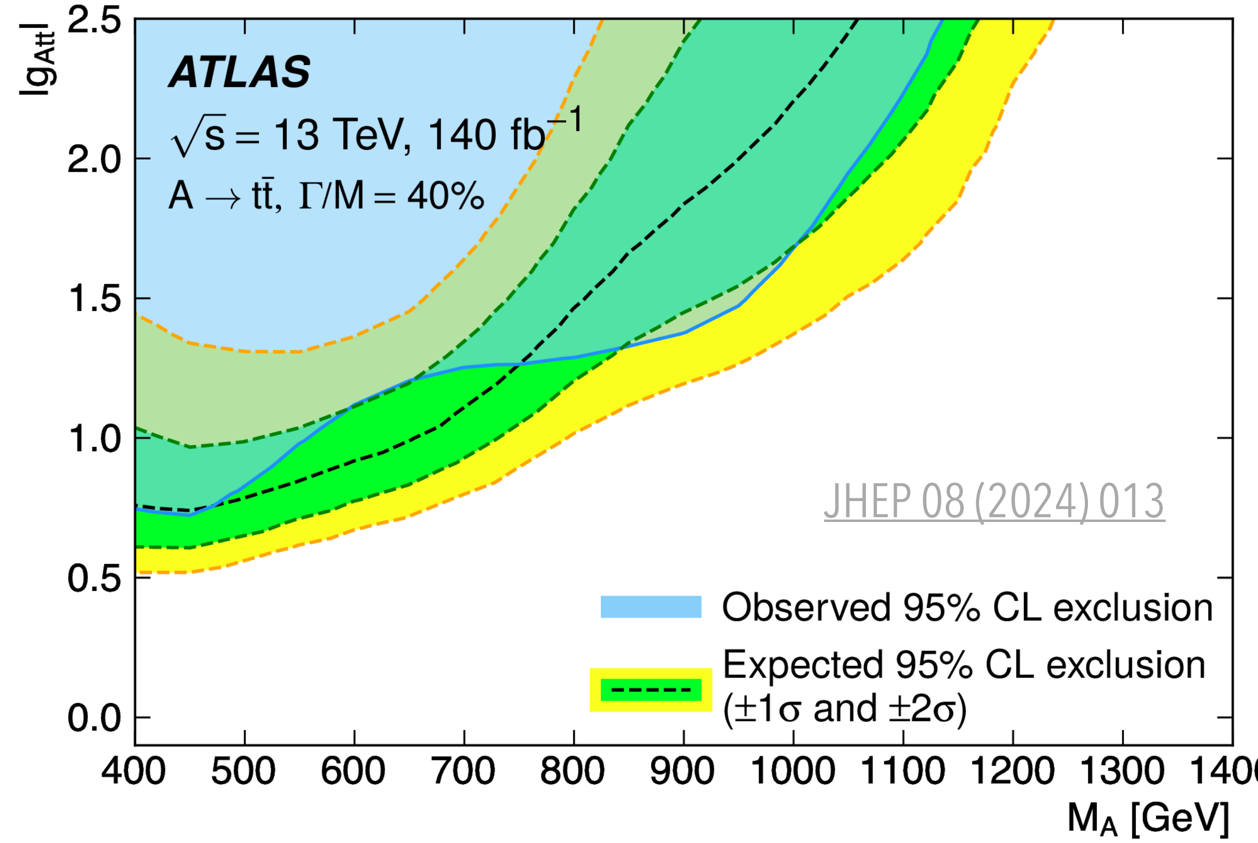
- CMS interprets the search for **masses < 400 GeV**
- By introducing the η_t hypothesis, excess at low $m_{t\bar{t}}$ at low A/H masses (stronger for A) **no longer present**



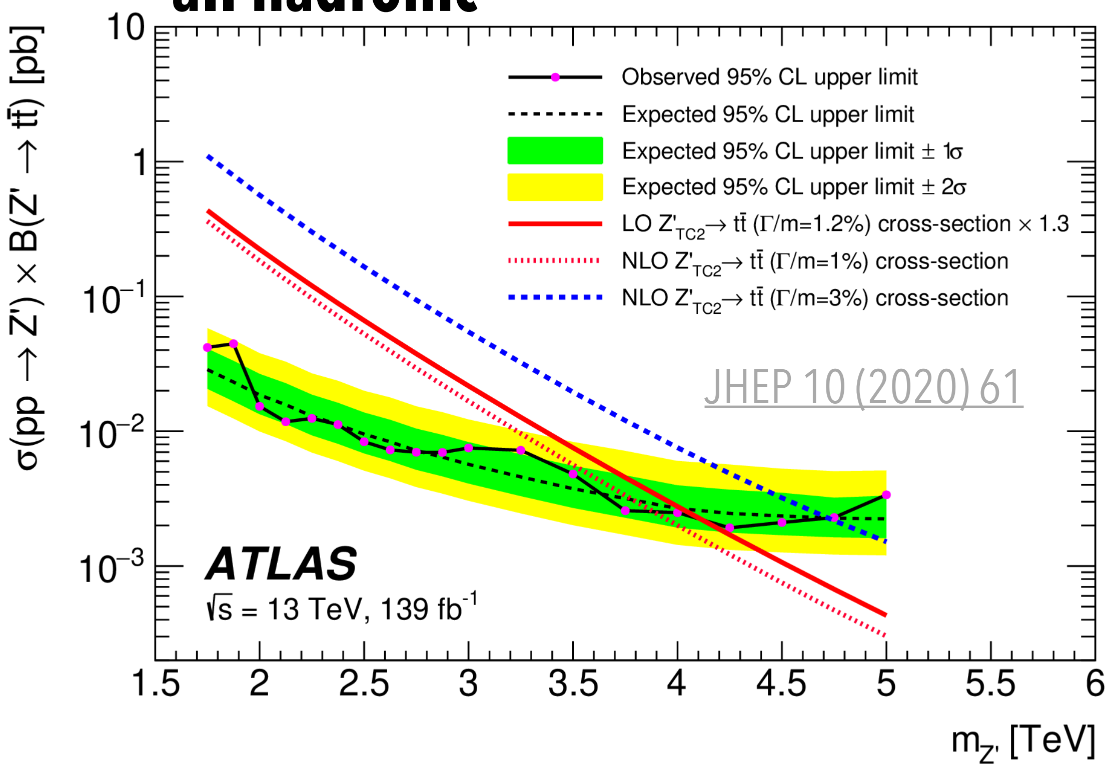


Wider $t\bar{t}$ resonances

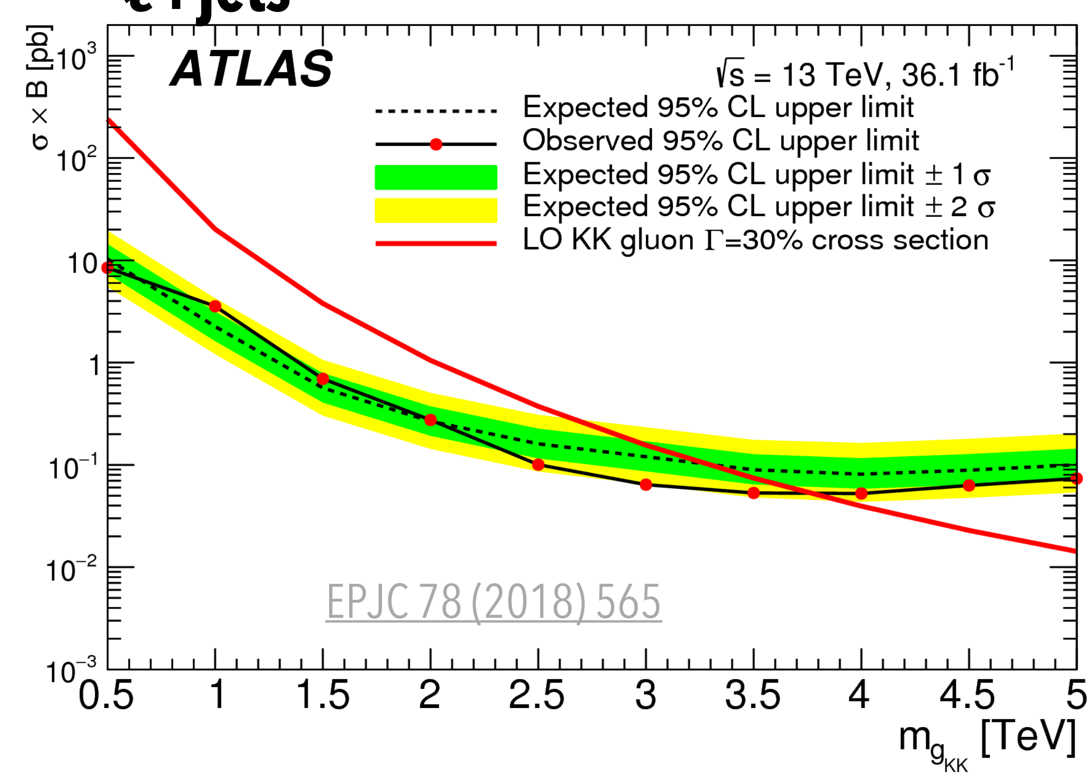
- **Search for wider resonances decaying to $t\bar{t}$**
  - Maximum width probed by A/H→$t\bar{t}$ (ATLAS) is 40%
  - Previous searches looking into g_{KK} (30% max width) with 36/fb Run 2 data or $t\bar{t}$ hadronic resonance search with full Run 2 (3% max width)
  - *The search must continue, full Run 2 dataset to be analysed!*



all hadronic



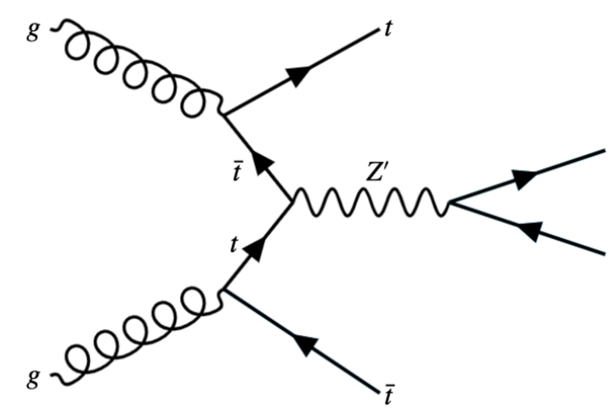
ℓ+jets

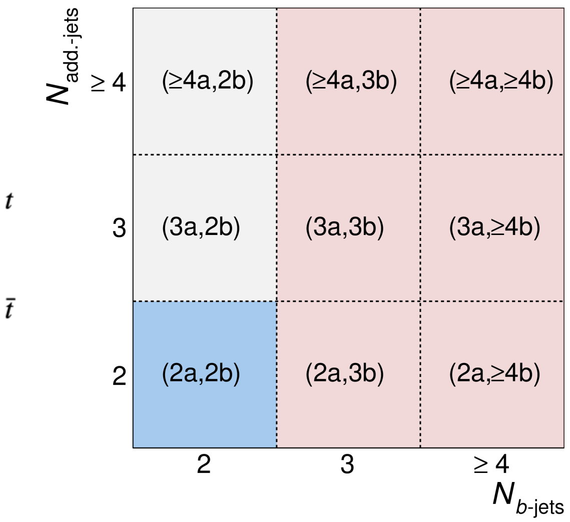


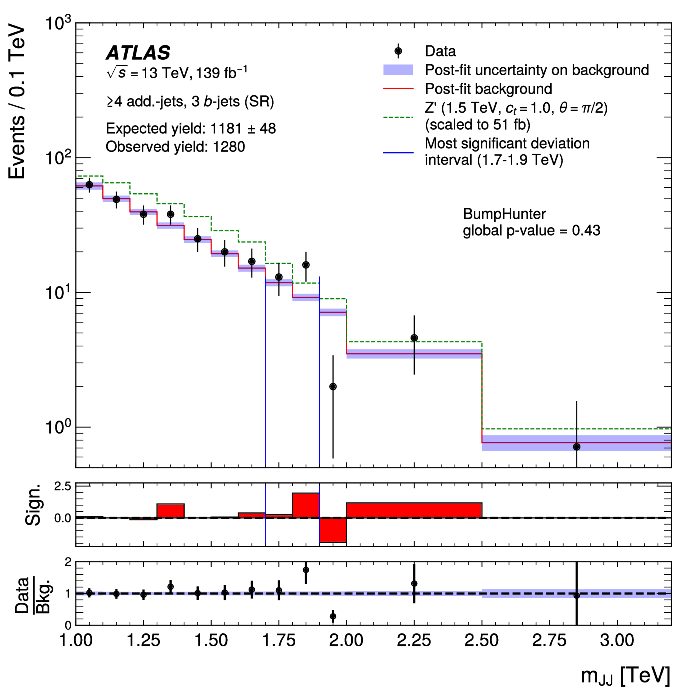
$t\bar{t}$ resonance search in $t\bar{t}t\bar{t}$

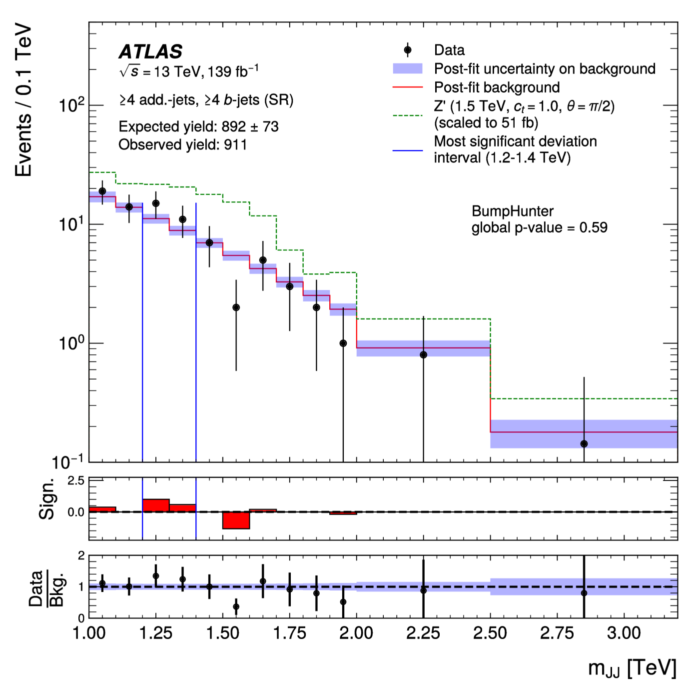
Eur. Phys. J. C 84 (2024) 157

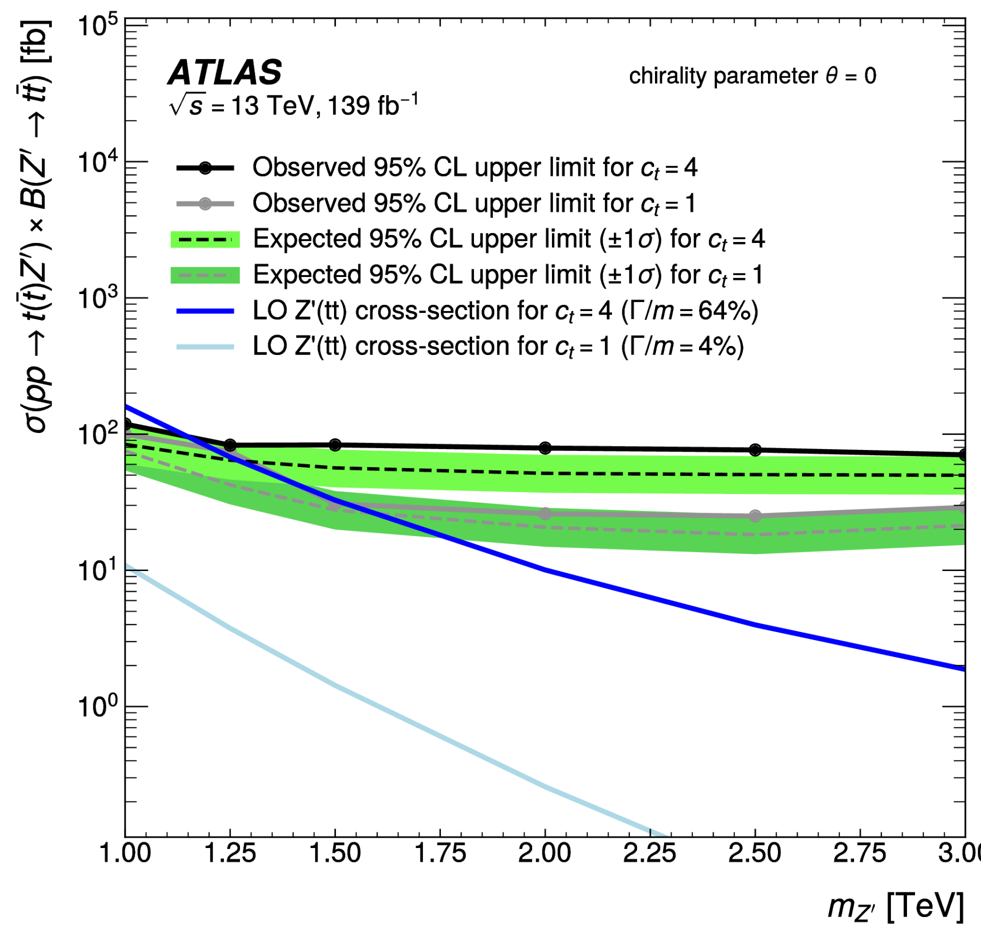
- Search for top-philic resonances coupling exclusively to top quarks in multi-top-quark final state with 1 lepton
- Resonance constructed in **fully hadronic decay mode** using reclustered jets
  - Main discriminant: resonance top quark pair **invariant mass m_{JJ}**
- Main background **tt+jets (90%)** is estimated with a dijet fit to the $m_{t\bar{t}}$ spectrum in data in a signal-depleted source region
  - Extrapolated to the signal regions using ratios of total background m_{JJ} spectra from MC simulation
- **No significant excess is observed** over the background expectation



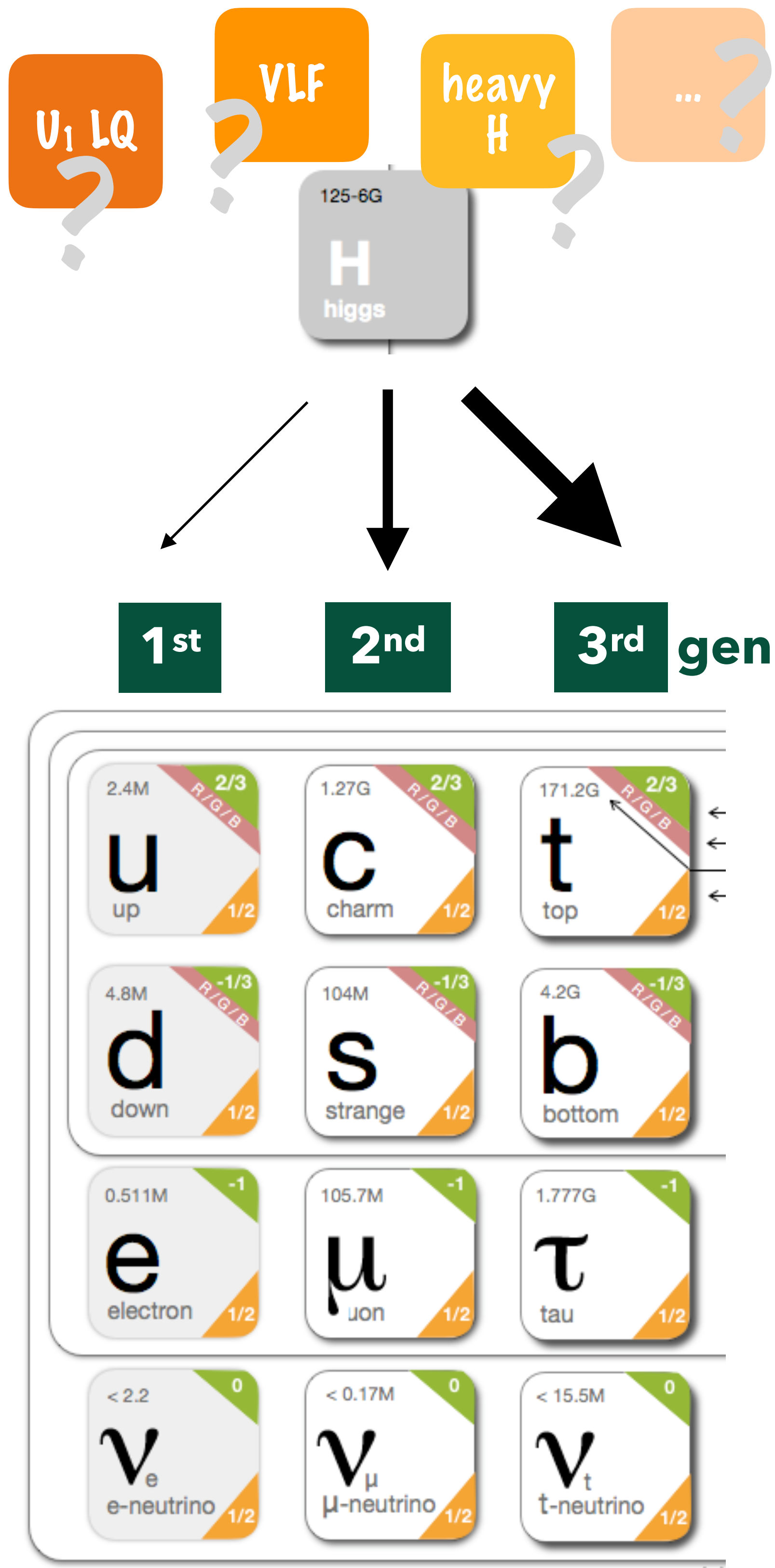




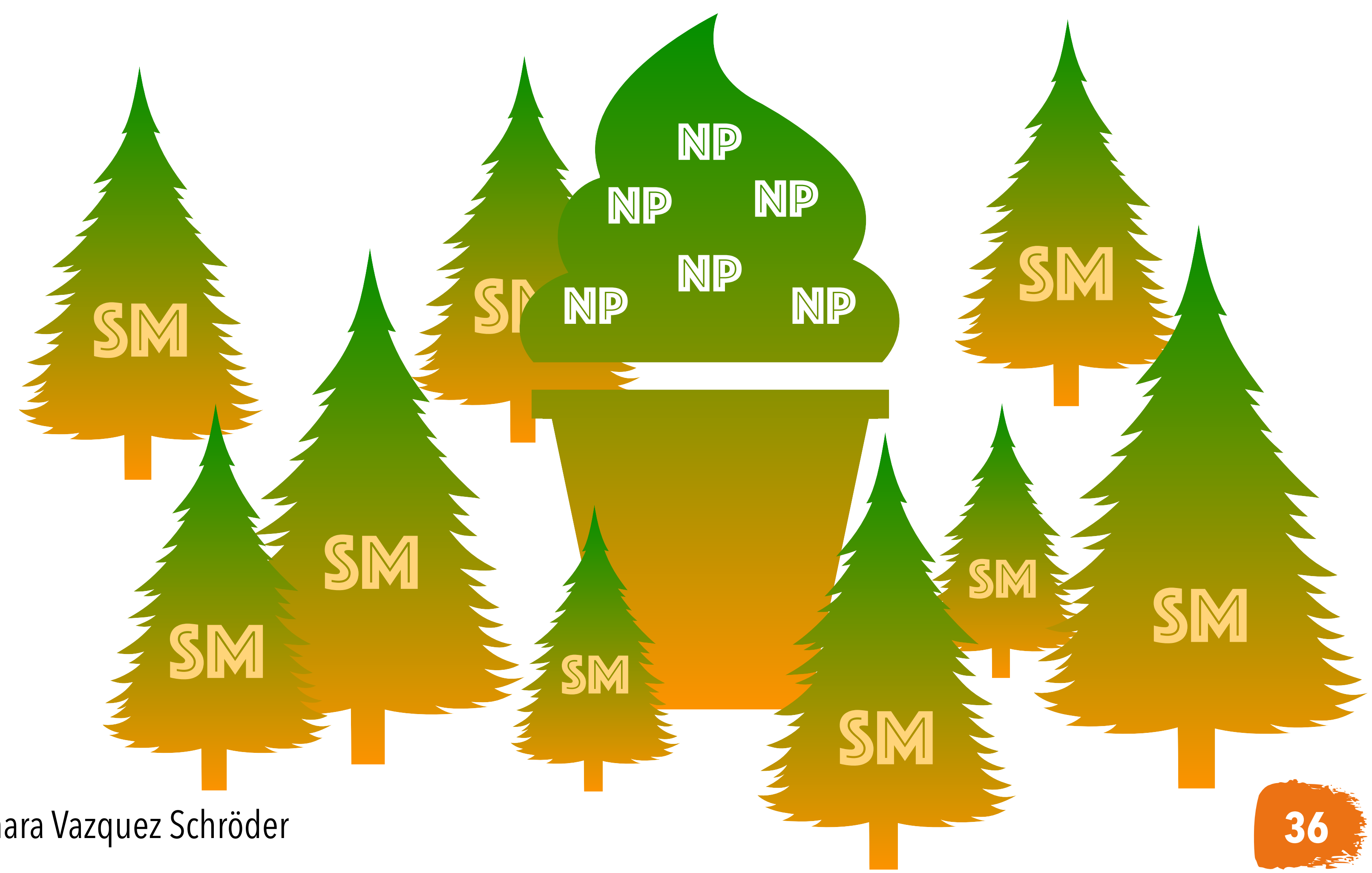




Conclusions



- From both the theoretical side and the persistent experimental hints, new physics could have a specific **flavour structure**
  - Resembling the very hierarchical structure in the Higgs Yukawa couplings? **Special role of the 3rd generation fermions?**
- Continue the exploration with the *continuously* incoming data from the LHC, re-interpreting it in **newer ways** than done before!



More material

g2HDM with flavour violation

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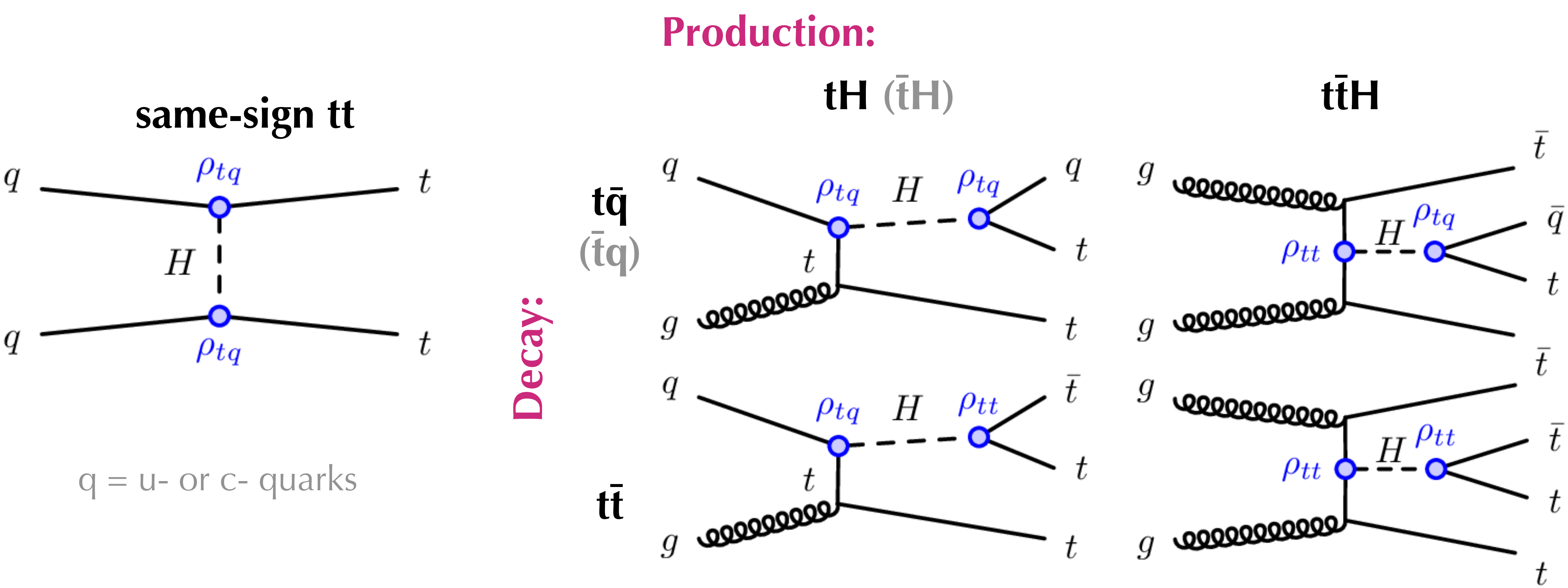
- What if **flavour changing** neutral Higgs couplings are allowed?
  - extra **sub-TeV** Higgs bosons (H) with extra Yukawa couplings: ρ_{tt}, ρ_{tu}, ρ_{tc}
  - the heavy Higgs sector would be **flavour violating**, resulting in dominant production and decay modes different from the ones that are being searched
  - these scenarios can address several shortcomings of the SM: electroweak baryogenesis, strong CP problem, flavour problem, etc.
  - various references in the literature: [1], [2], [3], [4], [5], [6], [7], [8], [9]

+ similar features to $t\bar{t}W$ and $t\bar{t}t\bar{t}$ in multilepton final states



g2HDM analysis strategy

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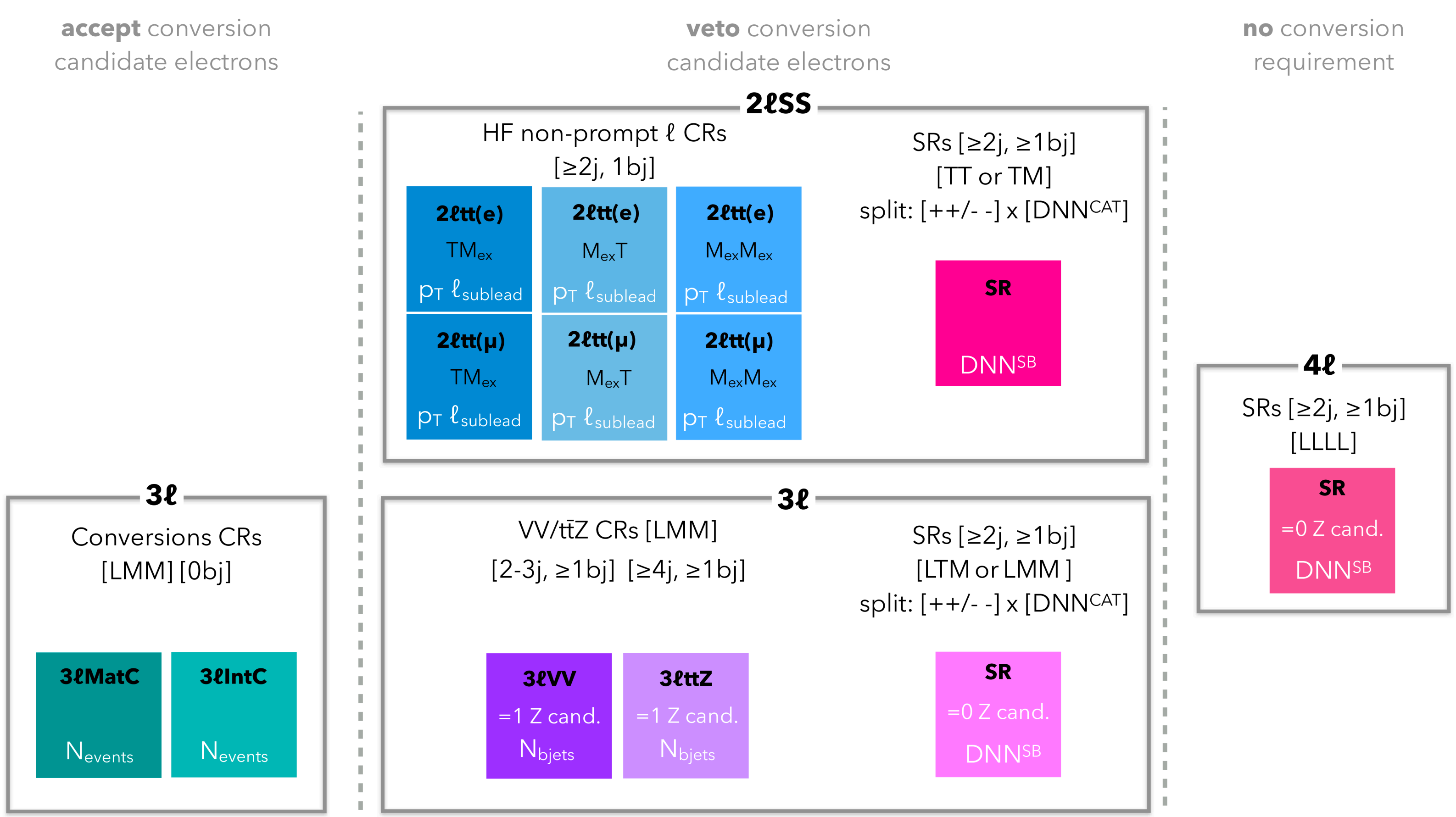
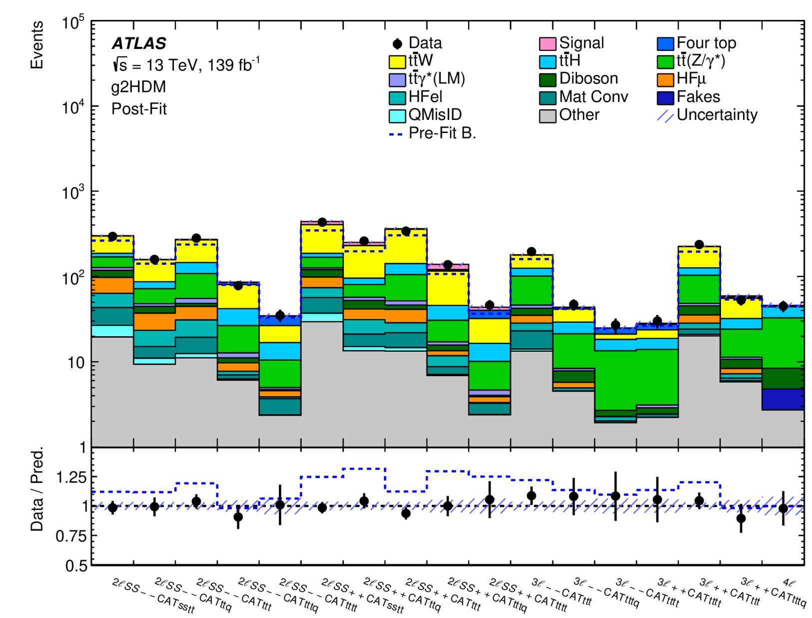
- Non-prompt/conversion leptons estimated with an **extended template fit method**
- NN-based multi-D classification to categorise the different signals (BSM signal A vs BSM signal B):
  - Orthogonal regions are defined for **each signal category (CATs)**, based on lepton, jet and b-jet multiplicities, including pseudo continuous b-tagging scores as input variables
  - Each CAT is also split in ++ and - - lepton charges
- A NN is trained in each CAT to discriminate BSM signal vs SM backgrounds
- Simultaneous profile likelihood fit of the BSM signal and some normalisations of SM backgrounds



The negative-lepton-charged SRs and low NN SRs are also enriched in **tt̄W events**!

$$\hat{\lambda}_{t\bar{t}W} = 1.50 \pm 0.14$$

(with $\sigma(t\bar{t}W)_{SM} = 614.7$ fb)



g2HDM results

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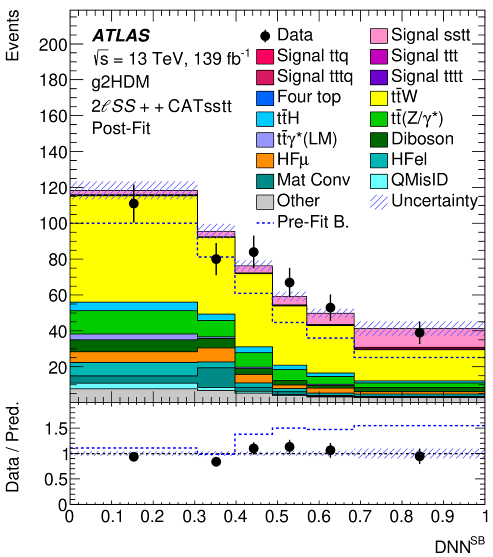
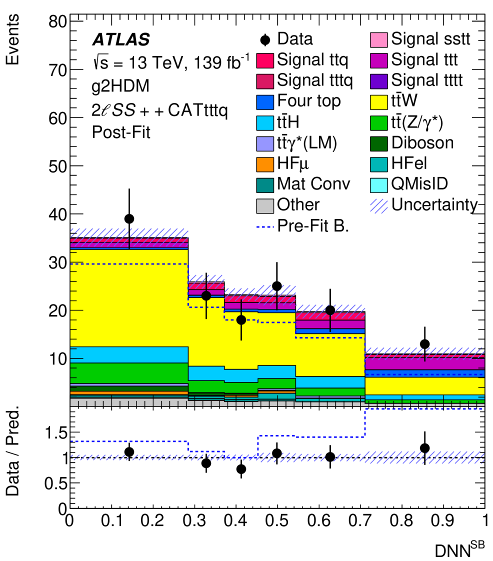
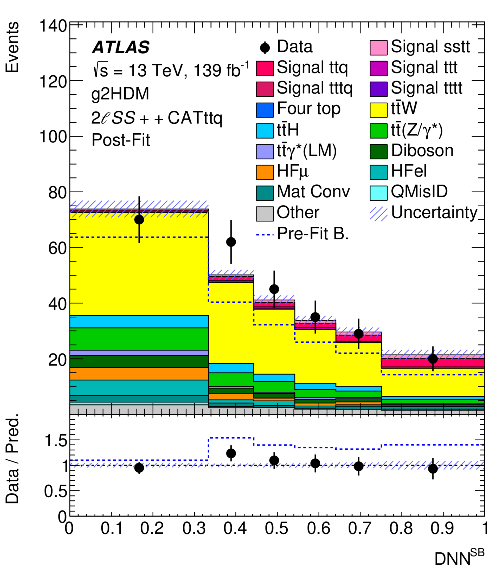
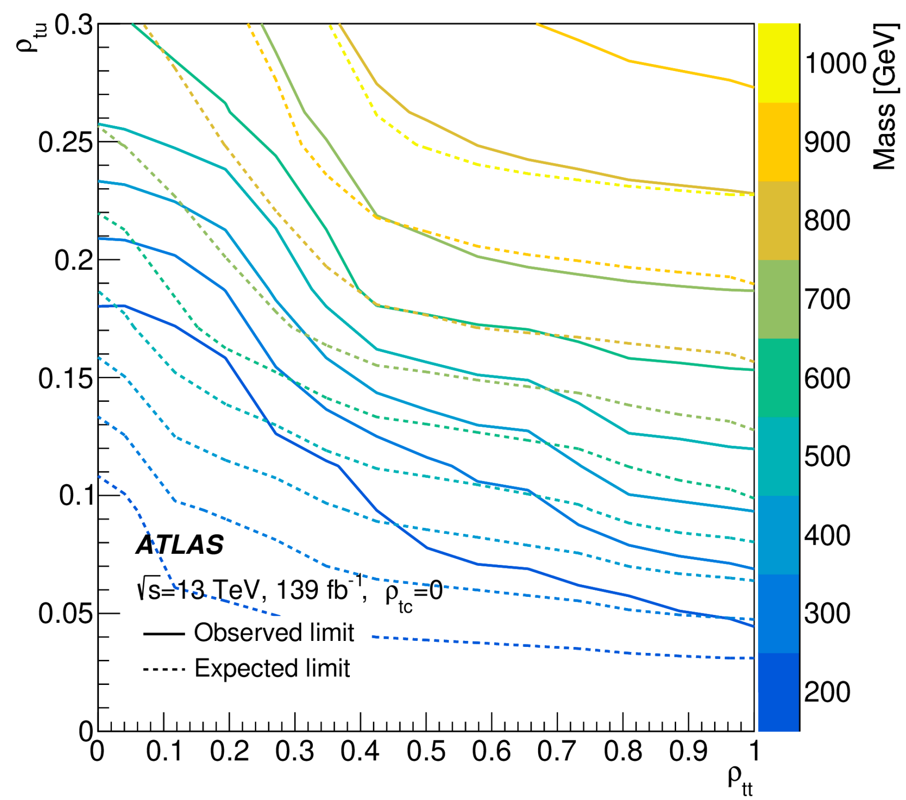
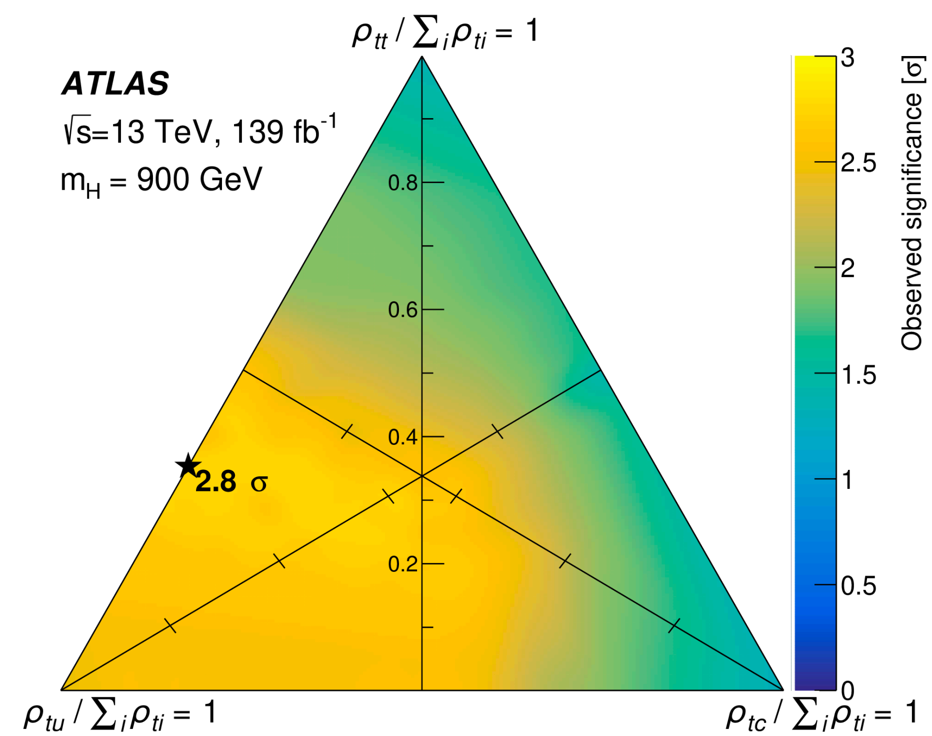






- Mild excess observed over the SM with a local significance of **2.8σ** for a signal with **m_H = 900 GeV** and **(ρ_{tt}=0.6, ρ_{tc}=0.0, and ρ_{tu}=1.1)**
- Observed charge-asymmetric tensions are accommodated by the best fit g2HDM signal
  - Largest signal contributions in the 2ℓSS ++ CAT tttq and the 2ℓSS ++ CAT tttt SRs mainly from **ttq and ttt** processes *(excess at high jet multiplicities)*
  - Largest signal contributions in the 2ℓSS ++ CAT sstt and the 2ℓSS ++ CAT ttq regions mainly from **sstt and ttq** processes *(excess at low jet multiplicities)*





First collider result on general two Higgs doublet model **with flavour violation**
and
first search to target explicitly BSM production of **ttt**!