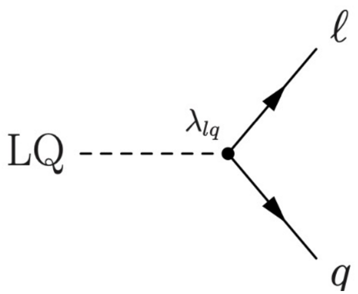
# Leptoquark searches with electrons and muons in the final state

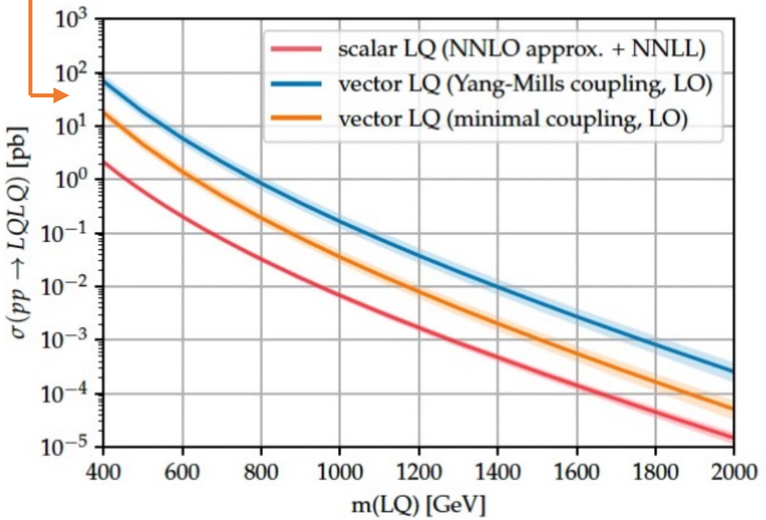
M. Primavera (INFN Lecce) on behalf of the ATLAS Collaboration

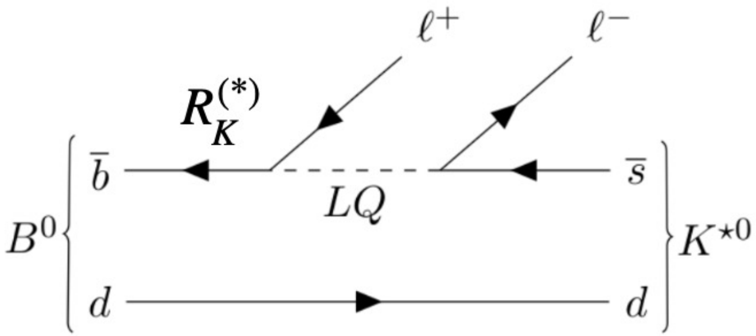
12th Large Hadron Collider Physics Conference, 3–7 Jun 2024, Boston

# Leptoquarks: generalities

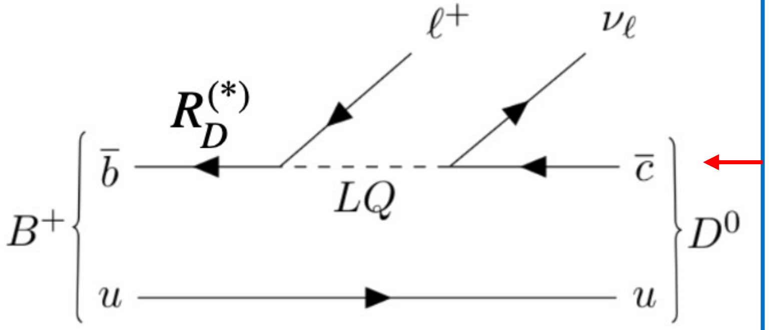
- Leptoquarks (LQ), introduced in several BSM theories → a possible explanation of **potential violation of lepton flavour universality (LFU)** in measurements of B-meson decays ('B-anomalies'), and of the g-2 anomaly measured at Fermilab
- LQ →bosons with fractional electric charge and color, baryon and lepton quantum #, interact with both leptons and quarks
- LQ scalars (spin 0) or vectors (spin 1, U) → Vector LQ pair-production cross-sections larger than scalar, small differences in kinematics between vector and scalar LQs. Scenarios for vector LQ: Yang–Mills type **coupling to gluons present ($vLQ_{YM}$)** or **absent ('minimal coupling', $vLQ_{min}$)**



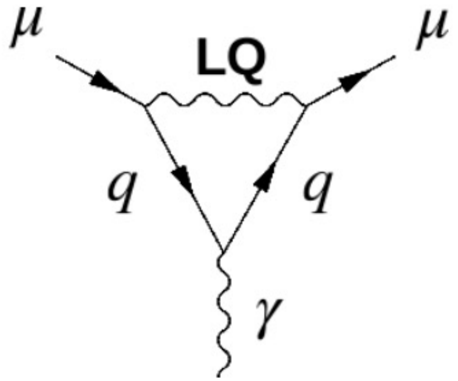




New LHCb result compatible with SM: Phys. Rev. Lett. 131 (2023) 051803




Deviation wrt the SM ~3.3σ for the combination R(D)-R(D∗): https://hflav-eos.web.cern.ch/hflav-eos/semi/moriond24/html/RDsDsstar/RDRDs.html

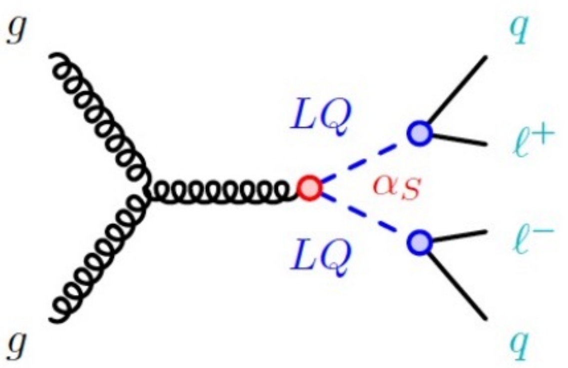



New results from Fermilab Muon g–2 (Phys.Rev.Lett. 131 (2023) 16, 161802) confirm the tension with SM, but new Lattice QCD calculations: Nature 593, 51–55 (2021)

# Leptoquarks: production and decay

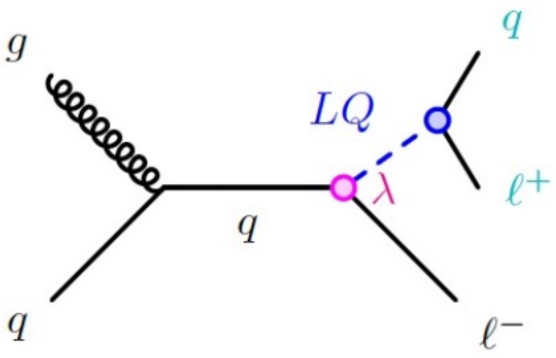
- LQs produced at the LHC via **pair, single, or non-resonant production, e.g.**:

**Pair production**



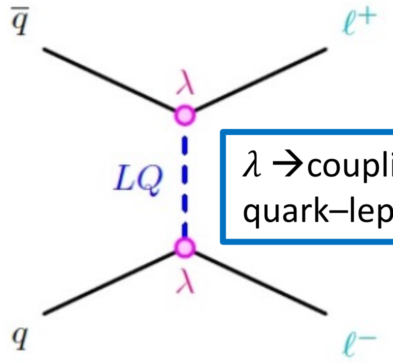

$\sigma$ depends only on $m_{LQ}$
(sensitivity to low $m_{LQ}$)

**Single production**




$\sigma \sim \lambda^2$ (sensitivity to higher $m_{LQ}$
if $\lambda$ sufficiently large)

**Off-shell production**




$\lambda$ → coupling strength of quark–lepton–LQ interaction.

DY in t channel $\sigma \sim \lambda^4$ (sensitivity to very high $m_{LQ}$ if $\lambda$ sufficiently large)

- Leptoquarks decay into quarks and leptons ruled by the **$\beta$ parameter** ($\beta \in [0, 1]$) → defines the coupling of LQs to charged leptons → sqrt($\beta$)$\lambda$ ⟹ $\mathcal{B}$ (BR to quark+charged leptons) related to $\beta$, 1- $\mathcal{B}$ (BR quark+neutrino)

  **$\mathcal{B}$ = 0 → only decays into $\nu$ + quark, $\mathcal{B}$ = 1 → only decays into a charged $\ell$ + quark**

- Allowed decays:

⟹ into a quark and lepton of the **same generation** (Patrick's talk on 3rd generation final states)

⟹ **mixed generational ("$LQ_{mix}$")** into first- or second-generation lepton and a third-generation quark

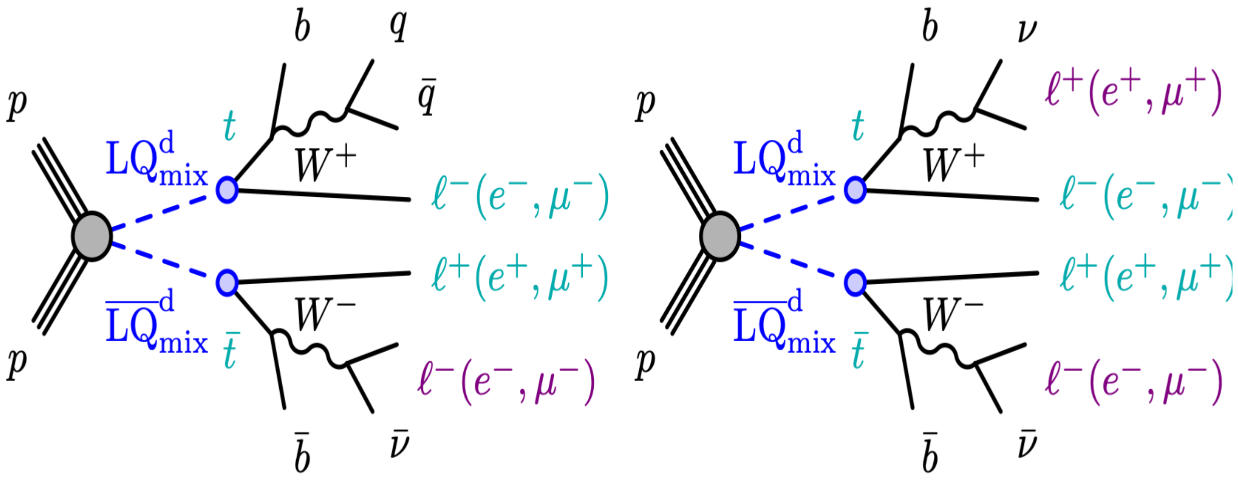
# Leptoquarks: ATLAS searches

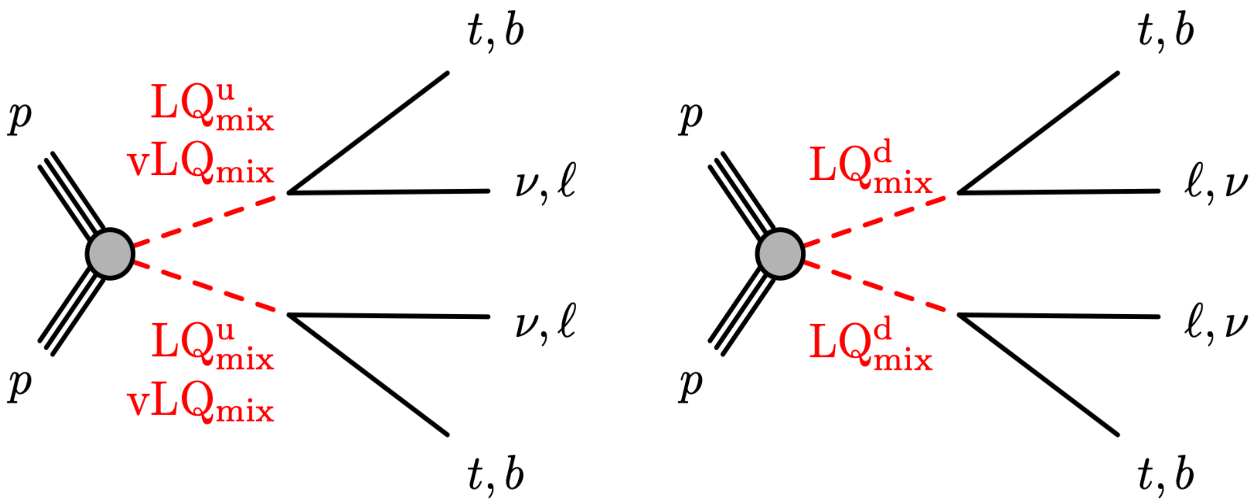
- Broad program of searches for pair-produced LQs searches ⟹ Focus on couplings to **3rd gen. quarks (b,t)**, but also **u, d, c, s considered and $\ell$= $e, \mu, \tau, \nu$.** Results presented as a function of the **LQ mass and $\mathcal{B}$**

- Growing program of singly-produced LQs searches. Increasing focus on non-resonant production, in order to reach highest masses.

**In this talk focus on:**

**Some recent results (>=2023) on scalar and vector leptoquark pair production and decay in 3$^{rd}$ generation quarks and first- or second-generation leptons ($LQ_{mix}$): $LQ^u_{mix}$ → ±(2/3)e, $LQ^d_{mix}$ → ±(1/3)e, $U_1$ → ±(2/3)e, $\tilde{U}_1$ → ±(5/3)e**




[2306.17642] **139 fb$^{-1}$ of Run 2 (2015–2018) ATLAS data** [JHEP 06 (2023) 188]

**LQLQ searches combination** [2401.11928]

# LQLQ → tt $\ell^+ \ell^-$ ($\ell$ = $e,\mu$)

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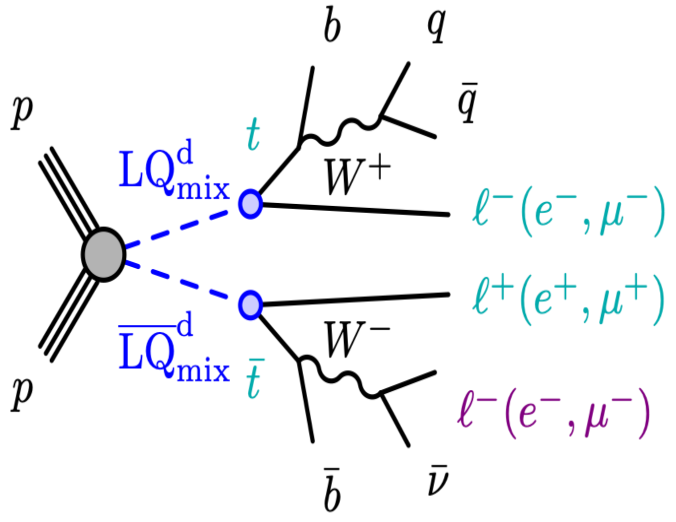
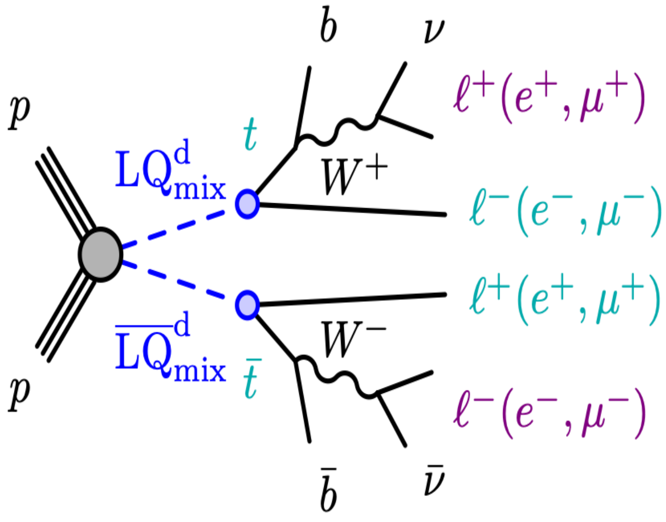



Pair-produced scalar and vector( $\tilde{U}_1$) $LQ^d_{mix}$ → t $\ell$:

- 1 or 2 leptons from top quarks in the final state
- same flavour $\ell$ (*ee,μμ*)

Selected events with:

- ≥ 2 $\ell$ (*e or μ*), ≥ 2 jets (at least one of them b-tagged)
- 3 final states → 2SS $\ell$, *3* $\ell$, *4* $\ell$ (at least 4)

Main backgrounds:

- ttW, ttZ, VV (mainly WZ), non-prompt $\ell$

Signal against background final discriminant:

- effective mass: $m_{eff} = \sum_{\ell} p_T + \sum_{jet} p_T + E_T^{miss}$

➢ **Signal regions (SRs):**

1 top decaying leptonically

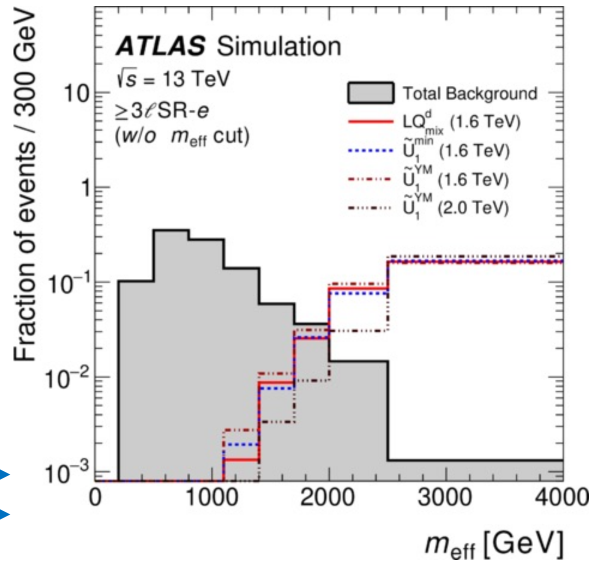
- *3 $\ell$SR-e* (3*e* /2*e*1*μ*, for *tete* channel)
- *3 $\ell$SR-μ* (3*μ* /2*μ*1*e*, for *tμtμ* channel)

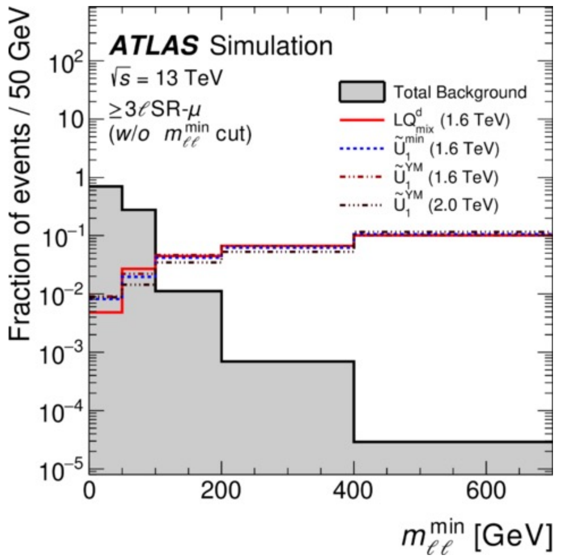
Z veto
$m_{eff}$ > 500 GeV
$m_{\ell\ell}^{min}$ > 200 GeV

Both top decaying leptonically

- *4 $\ell$SR-e* (4*e*/3*e*1*μ*/2*e*2*μ* (lead *e*))
- *4 $\ell$SR-μ* (4*μ*/3*μ*1*e*/2*μ*2*e* (lead *μ*))

Z veto
$m_{eff}$ > 500 GeV
$m_{\ell\ell}^{min}$ > 100 GeV



# LQLQ → tt $\ell^+ \ell^-$($\ell$= $e,\mu$) [2306.17642]

➢ **Background estimate:**

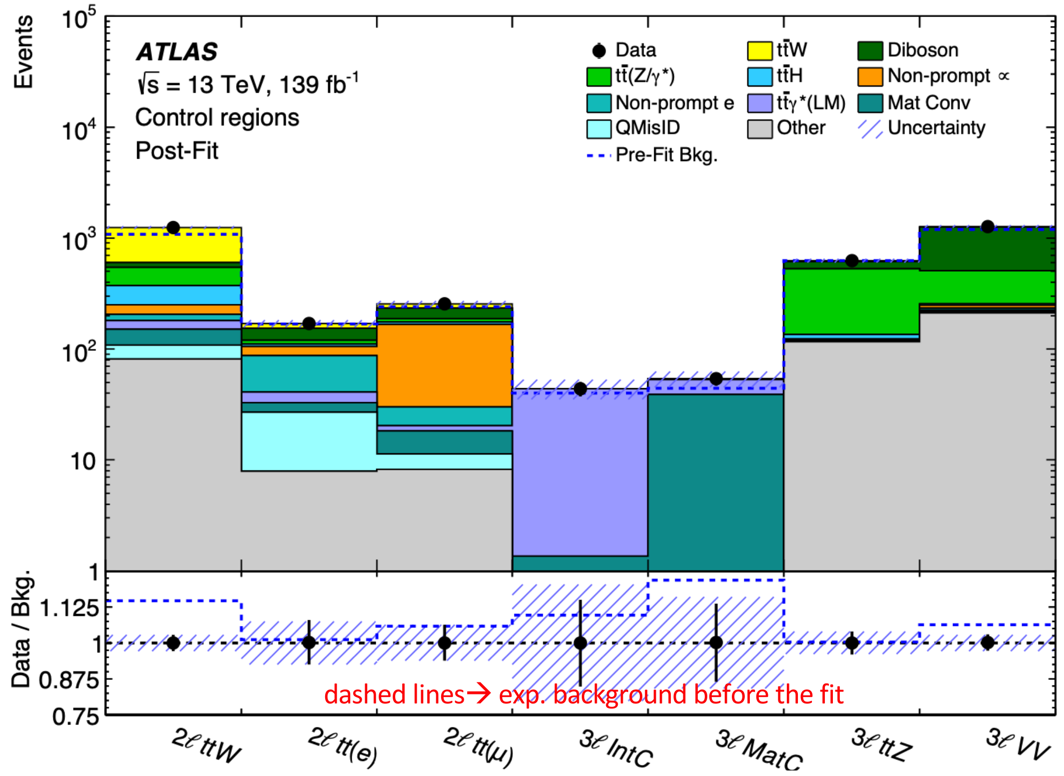
**ttW**, **ttZ**, **VV**, non-prompt $\ell$ → Normalised by a likelihood fit to data in background enriched Control Regions (CRs) and validated in Validations Regions (VRs) close to the signal regions.

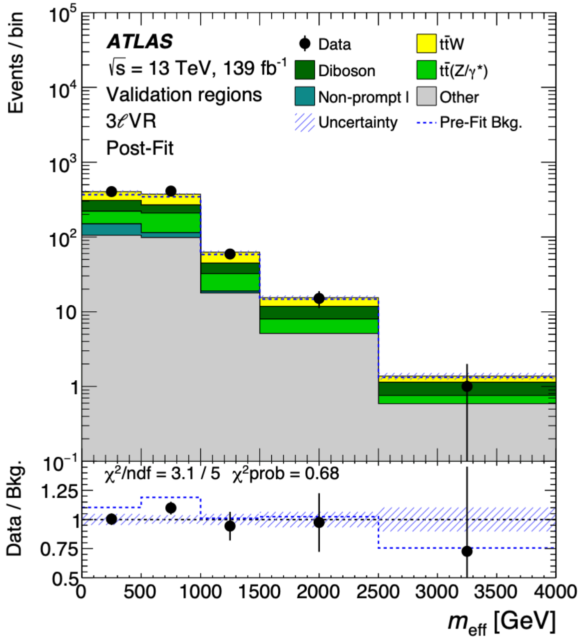
**7 CRs:**

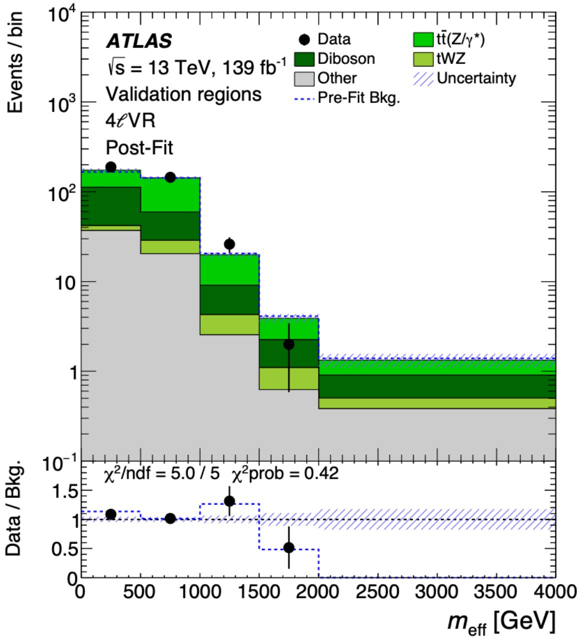
- **3 regions 2SS$\ell$** with conversion veto → **2$\ell$ttW** ttW enriched, *2$\ell$tt(e/$\mu$)* HF non-prompt $\ell$ enriched
- **2 regions 3$\ell$** with no Internal/Material conversion veto → 3$\ell$IntC, 3$\ell$MatC enriched in photon conversion from $Z \to \mu\mu\gamma*(\to ee)$
- **2 regions 3$\ell$** with 1 Z candidate → **3$\ell$VV** diboson enriched, **3$\ell$ttZ** ttZ enriched

**2 VRs :**

- 3$\ell$VR and 4$\ell$VR → similar selection as SRs but no $m_{eff}$ request and inverted cut on $m_{\ell\ell}^{min}$



# LQLQ → tt $\ell^+ \ell^-$($\ell$= $e,\mu$)

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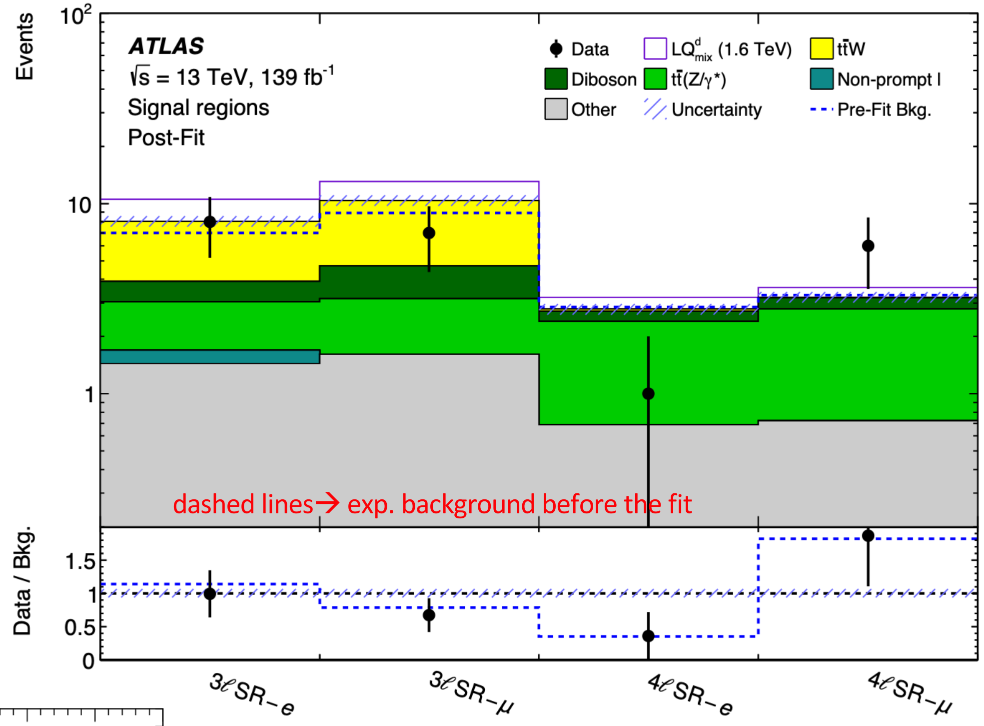
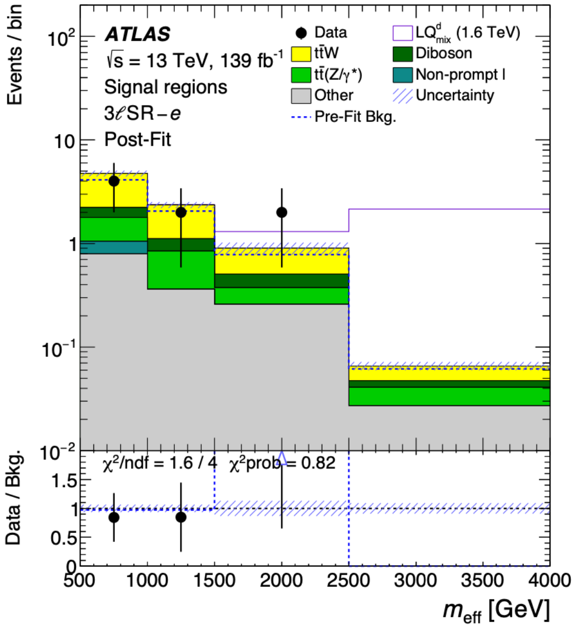
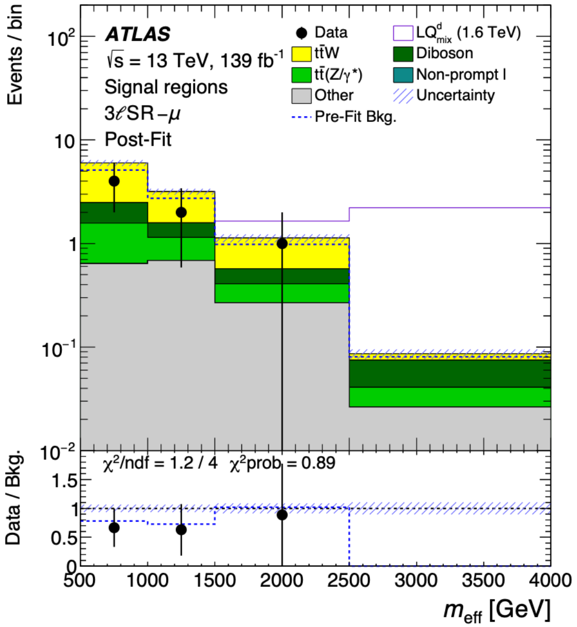
## ➢ Uncertainties and Results

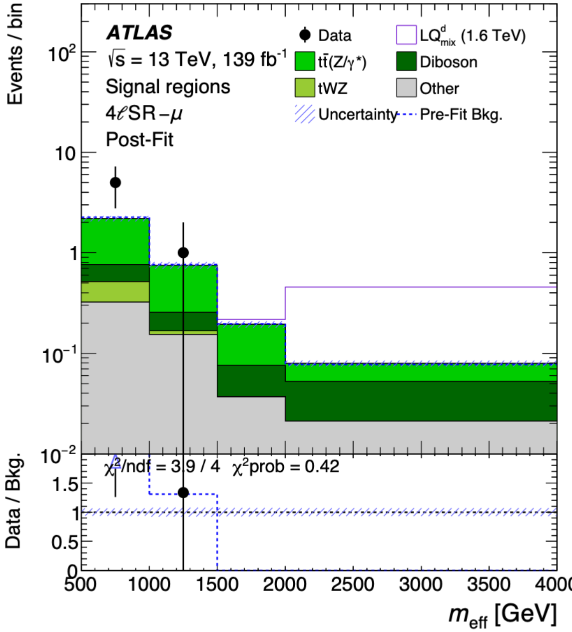
Systematics uncertainties (from experimental effects and theoretical modelling) small compared to the statistical ones → the largest impact on the likelihood fit results from lepton identification

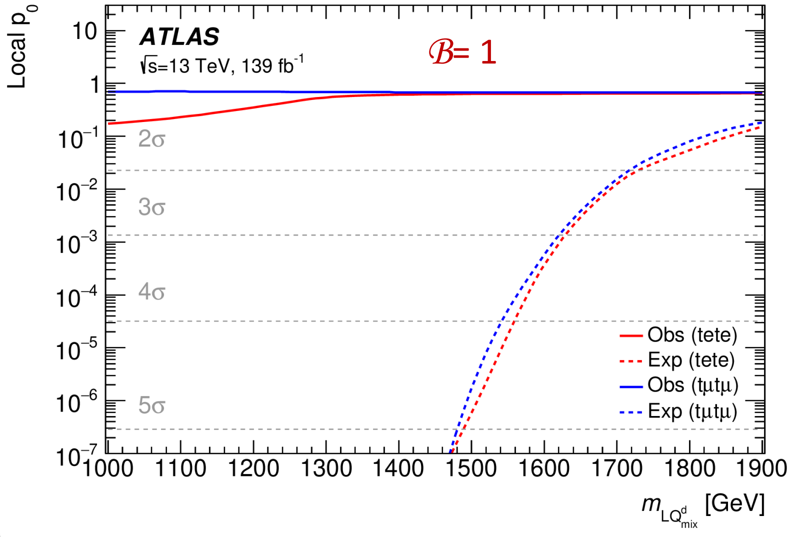
The search reaches an expected significance of 5 standard deviations for a scalar leptoquark decaying ($\mathcal{B}$ = 1) to $t$ and $\ell$ with mass below about 1.5 TeV.



# LQLQ → tt $\ell^+ \ell^-$ ($\ell$= e,$\mu$)

2306.17642

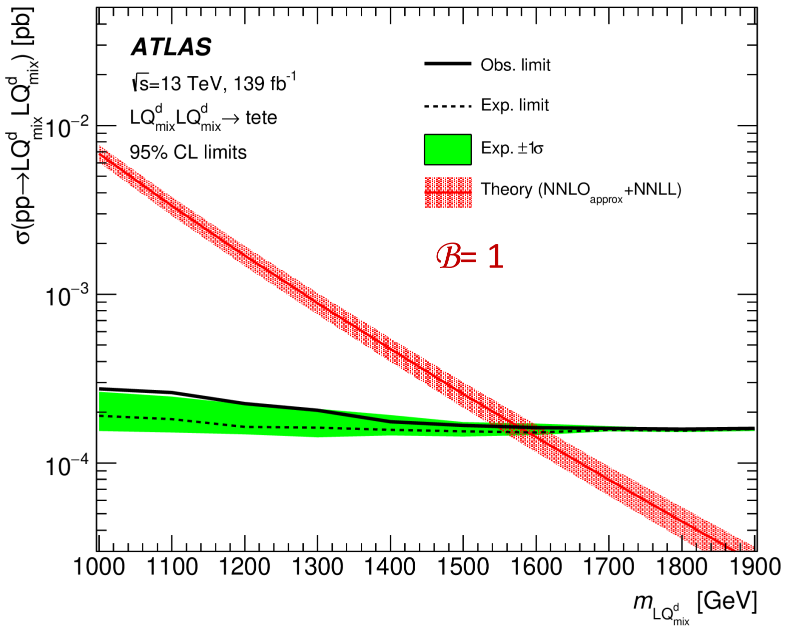
## ➢ Observed 95% C.L. limits

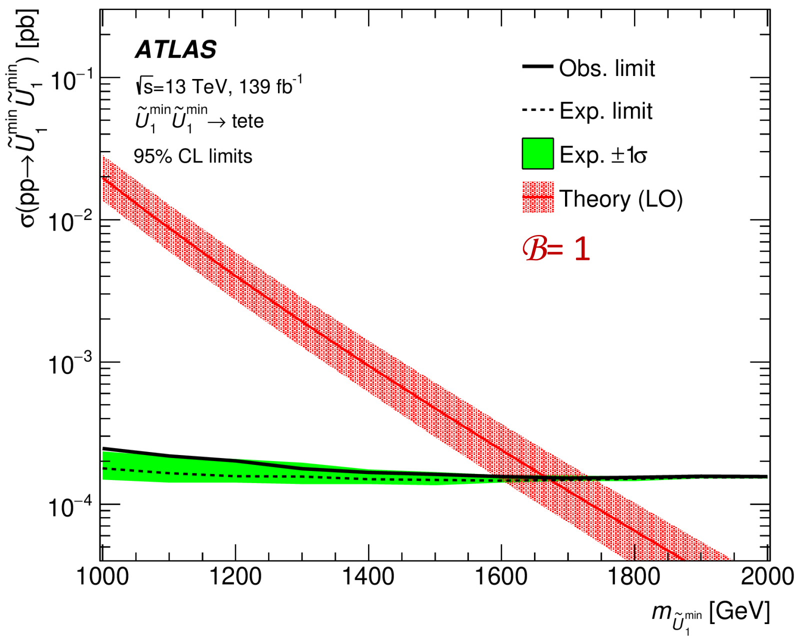
| | $\mathcal{B}$(LQ-> $te$) = 1 | $\mathcal{B}$(LQ-> $t\mu$) = 1 |
|---|---|---|
| $LQ^{d}_{mix}$ | 1.58 TeV | 1.59 TeV |
| $vLQ_{min}$ | 1.67 TeV | 1.67 TeV |
| $vLQ_{YM}$ | 1.95 TeV | 1.95 TeV |
| | $\mathcal{B}$(LQ-> $te$) = 0.5 | $\mathcal{B}$(LQ-> $t\mu$) = 0.5 |
| $LQ^{d}_{mix}$ | 1.31 TeV | 1.37 TeV |

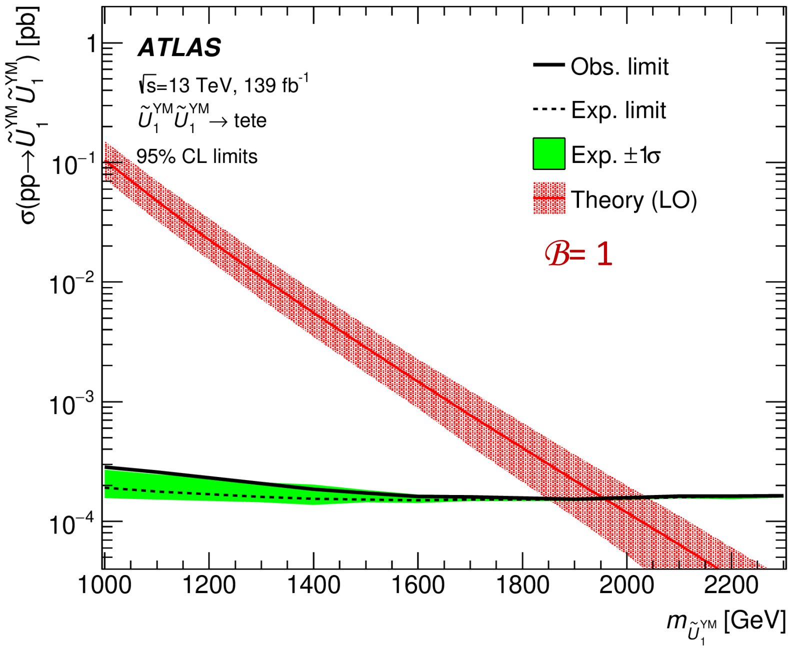
improved wrt previous searches with multi-light-leptons → **JHEP 06 (2021) 179**

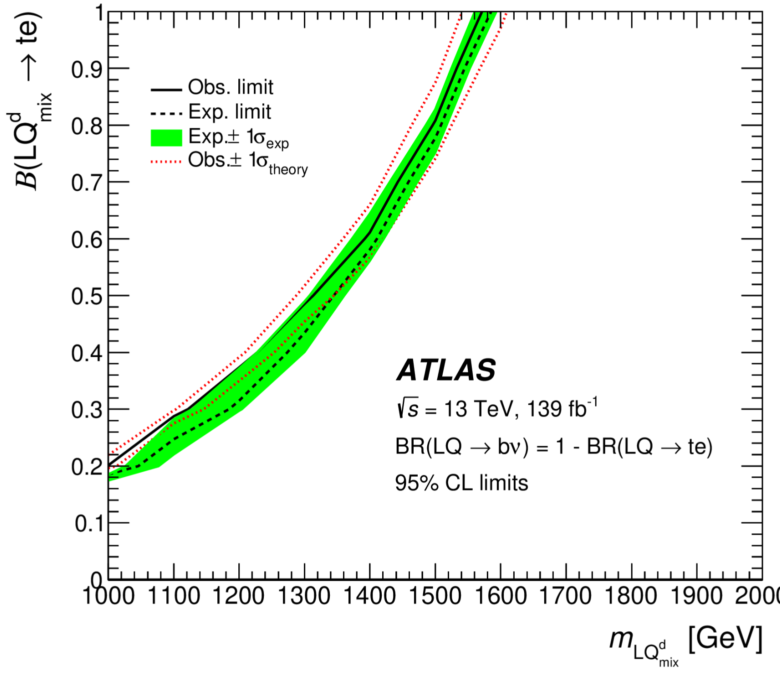
complementary to searches with hadronically-decaying tt →**Eur. Phys. J. C 81 (2021) 313**

Competitive with the **JHEP 06 (2023) 188** analysis



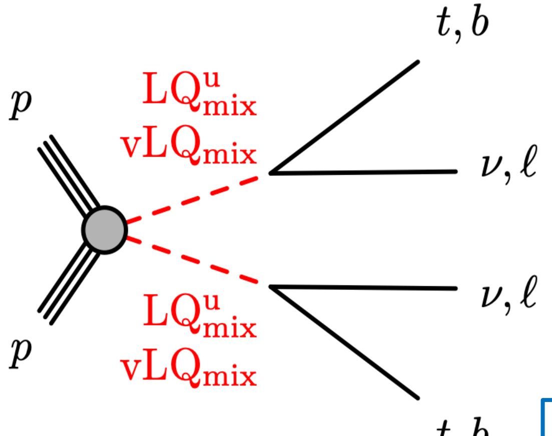



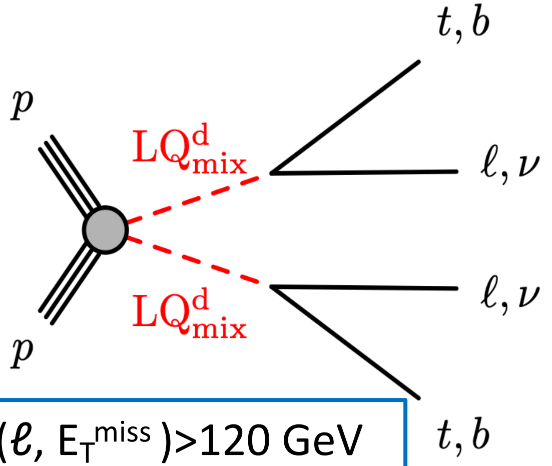



# LQLQ → tν bℓ /tℓ bν (ℓ= e,μ)

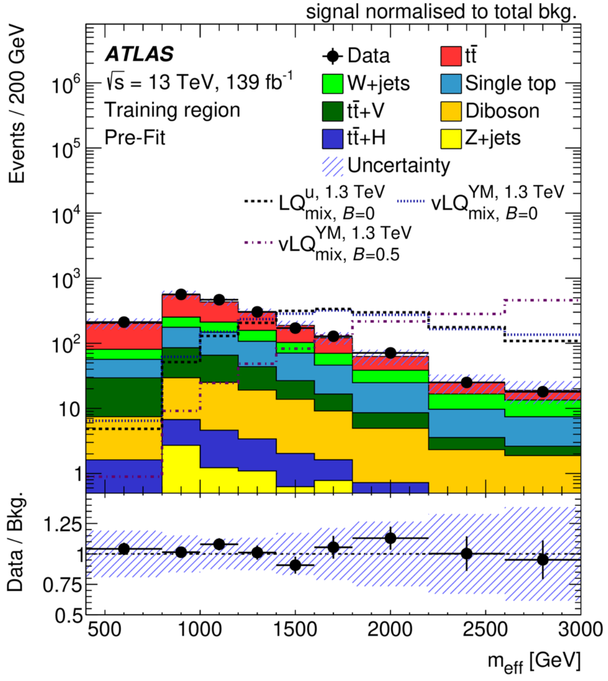
JHEP 06 (2023) 188

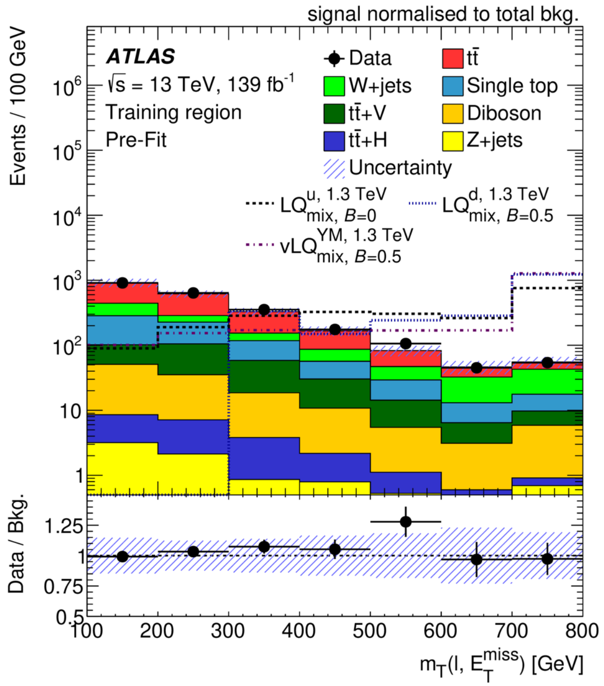



- **Training region**
- **Signal region (SR)**

$m_T(\ell, E_T^{miss})$ >120 GeV
$am_{T2}$ (**) > 200 GeV
$NN_{out} \geq 0.5$




Pair-produced scalar $LQ^{u}_{mix}$ or $LQ^{d}_{mix}$, but search also optimized for up-type vector LQs ( $U_1$ $vLQ_{mix}$):

- $3^{rd}$ generation quarks (t,b)
- 1st or 2nd generation leptons (*e,μ,ν*)

Selected events with:
= 1(*) *ℓ (e or μ)*, ≥ 4 jets, ≥ 1 *b*-jet, $E_T^{miss}$ (from *ν*) >250 GeV, $m_T(\ell, E_T^{miss})$>30 GeV, $\Delta\phi(E_T^{miss}, j_{1,2})$> 0.4

Main backgrounds:

- tt, W+jets, single top

Neural networks trained separately for scalar and vector LQ, signal against background final discriminant:

- NN output ($NN_{out}$)

(*) single-lepton final state optimised for medium to small $\mathcal{B}$
(**) $am_{T2}$ → asymmetric transverse mass

# LQLQ → tν bℓ /tℓ bν (ℓ= e,μ)

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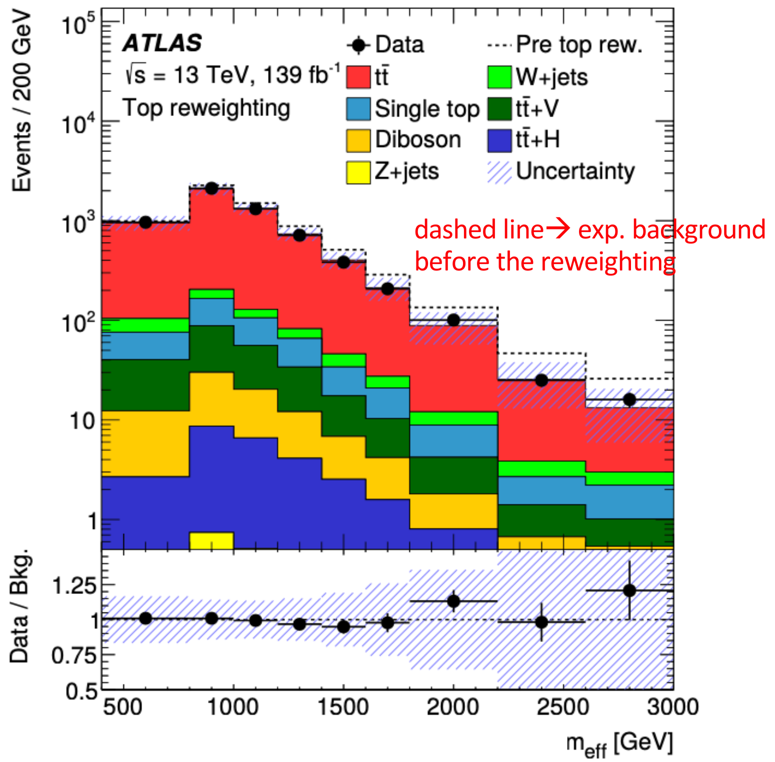
- **Background estimate:**

'Top reweighting' (tt + single top) applied in jet multiplicity bins as a function of $m_{eff}$ (to improve modelling at high $p_T$) →

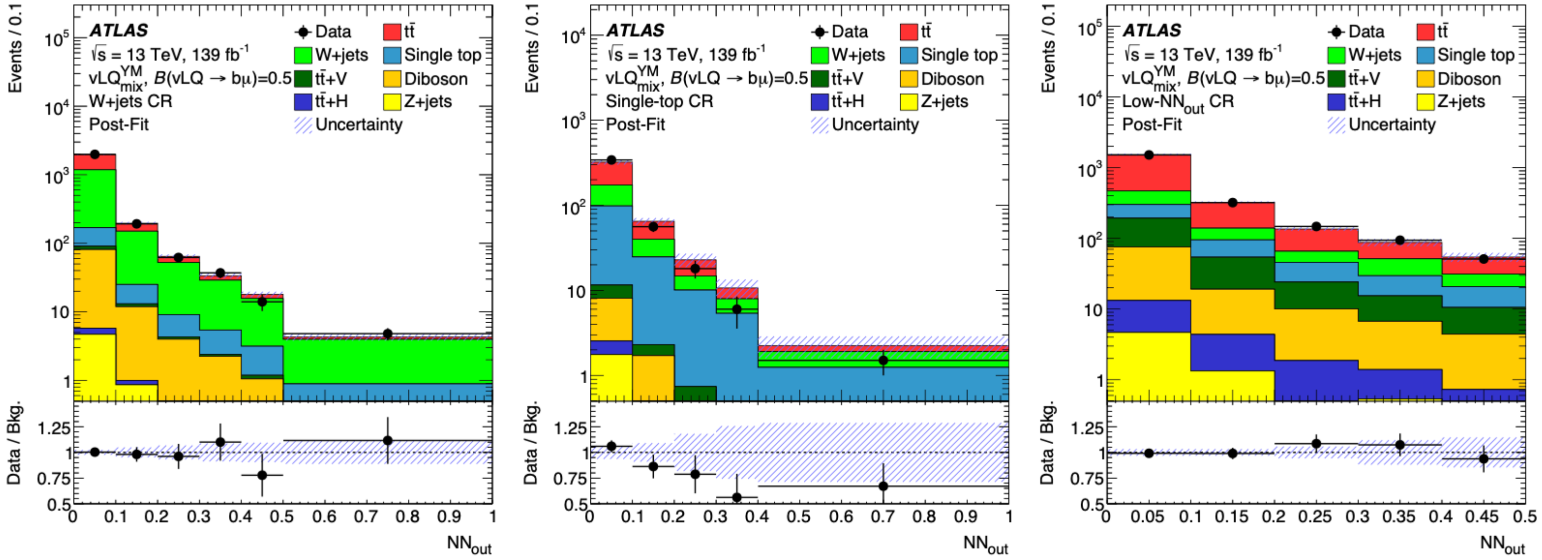
Reweighting region
$m_T(\ell, E_T^{miss}) > 120$ GeV
$am_{T2} < 200$ GeV




W+jets, single top → Normalised to data in background enriched CRs orthogonal to SRs and to Reweighting region

3 CRs:
- W+jets → $am_{T2} > 200$ GeV, $50 < m_T(\ell, E_T^{miss}) < 120$ GeV, 1 *b*-jet
- Single top → $am_{T2} > 200$ GeV, $m_T(\ell, E_T^{miss}) < 120$ GeV, 2 *b*-jet
- Low-$NN_{out}$ CR (mainly tt enriched) → same requests as SR, but $NN_{out} < 0.5$

NN training:
15 variables, different $m_{LQ}$ combined,
$LQ^u_{mix}$ → 4 NNs per lepton flavour at $\mathcal{B}$ = 0.,0.25,0.5, 0.9 (scalar and vector)
$LQ^d_{mix}$ → 1 NNs per lepton flavour at $\mathcal{B}$ = 0.5



# LQLQ → tν bℓ /tℓ bν (ℓ= e,μ)

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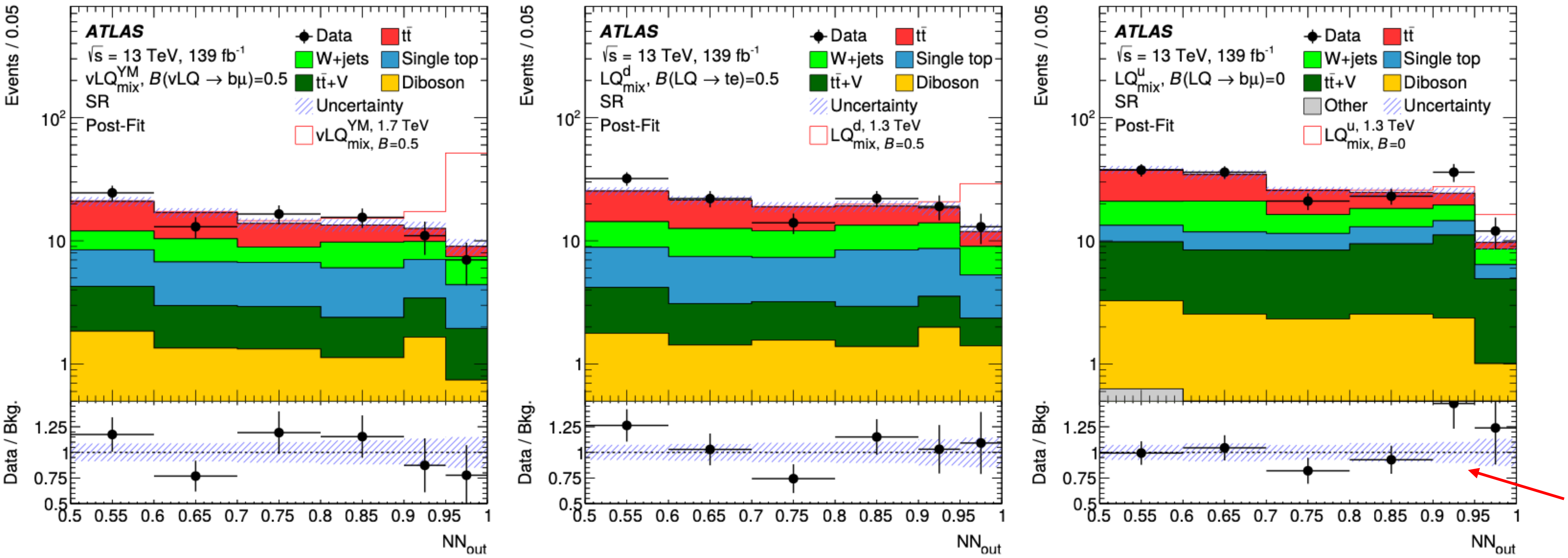
## ➢ Uncertainties and Results

Systematics uncertainties → the largest contributions from the modelling of the background processes (tt, theoretical) and jet energy scale and resolution (experimental)

For each NN training → a separate fit to the $NN_{out}$ distribution, and the normalisation parameters obtained from fits to data are consistent across all trainings.



# LQLQ → tν bℓ /tℓ bν (ℓ= e,μ)

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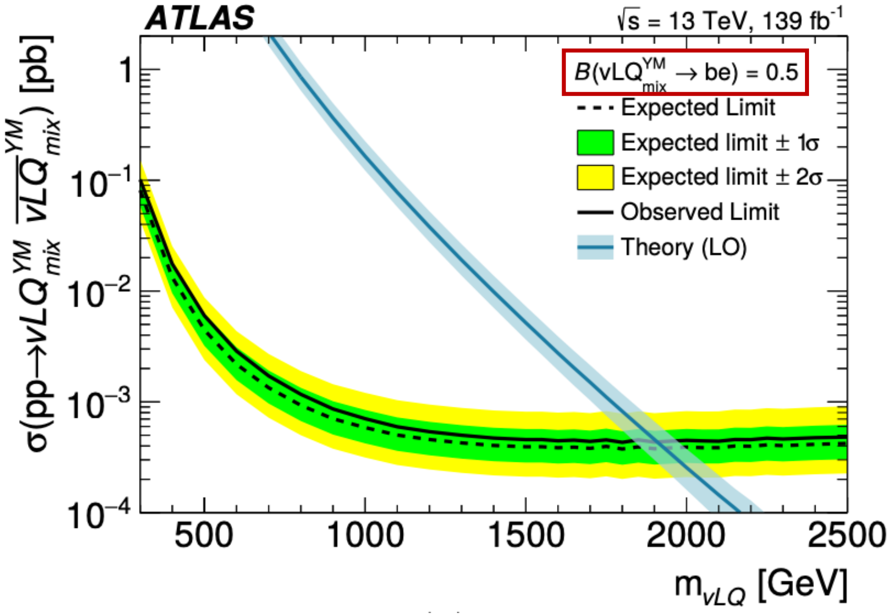
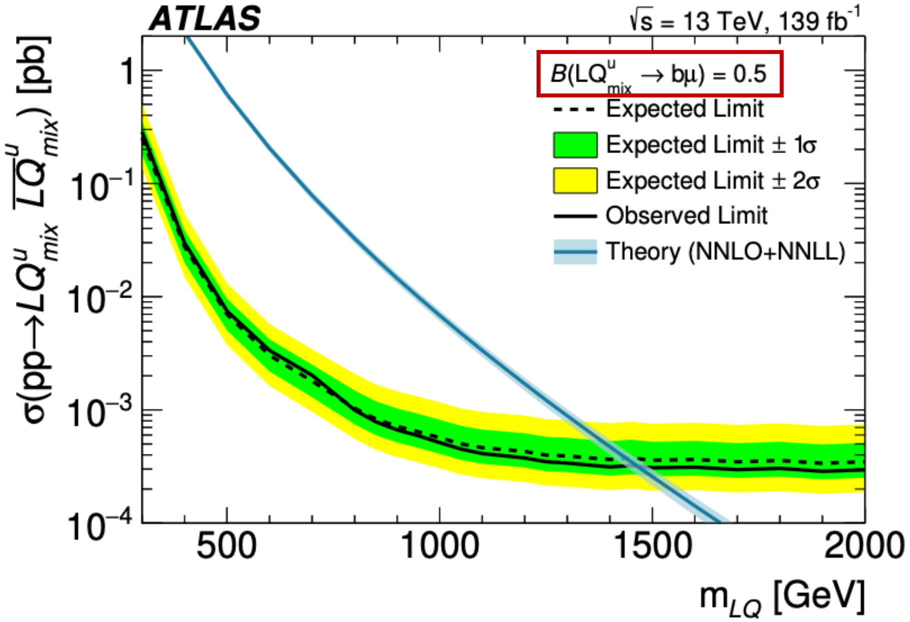
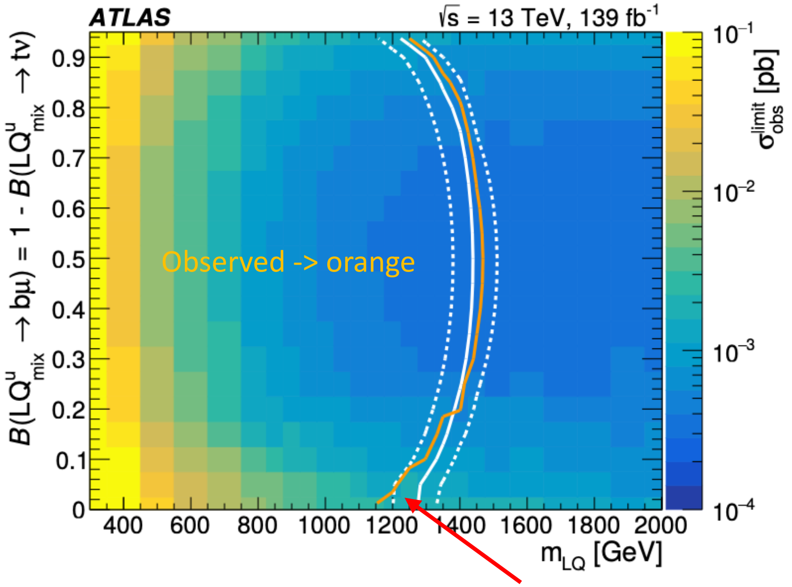
➢ **Observed 95% C.L. limits**

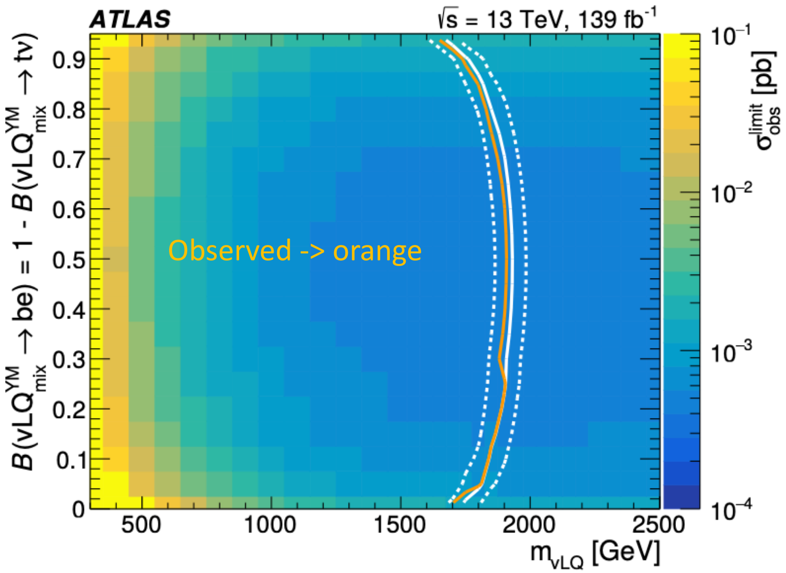
| | $\mathcal{B}$(LQ-> $t\nu$ /be) = 0.5 | $\mathcal{B}$(LQ-> $t\nu$ /b$\mu$) = 0.5 |
|---|---|---|
| $LQ^{u}_{mix}$ | 1.44 TeV | 1.46 TeV |
| $LQ^{YM}_{mix}$ | 1.90 TeV | 1.98 TeV |
| $LQ^{min}_{mix}$ | 1.62 TeV | 1.71 TeV |
| | $\mathcal{B}$(LQ-> te/bν) = 0.5 | $\mathcal{B}$(LQ-> t$\mu$/bν)= 0.5 |
| $LQ^{d}_{mix}$ | 1.39 TeV | 1.37 TeV |

For the first time, dedicated neural networks to search for $U_1$ leptoquarks



# LQLQ searches combination

2401.11928

Statistical combination of searches for LQLQ →3rd generation quarks and charged/neutral $\ell$ of any generation

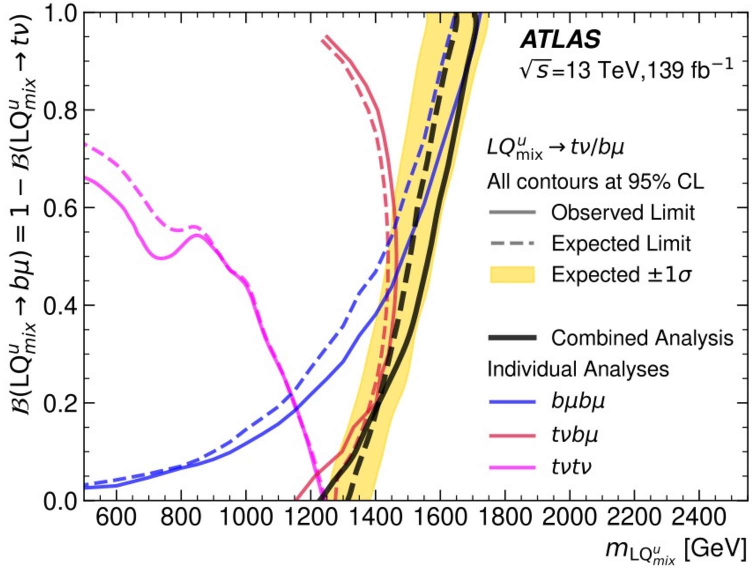
Statistical combination → same formalism as the individual analyses (9, independent)

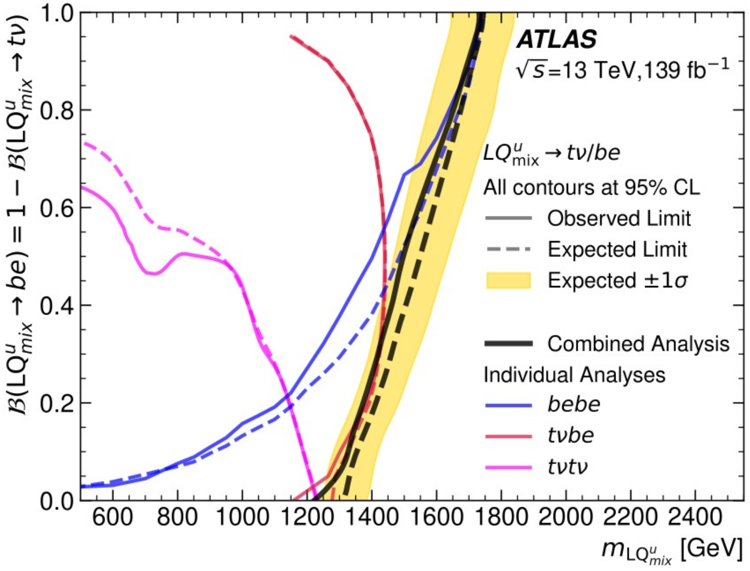
Overlap among regions and uncertainties correlations carefully checked

With respect to individual analyses:

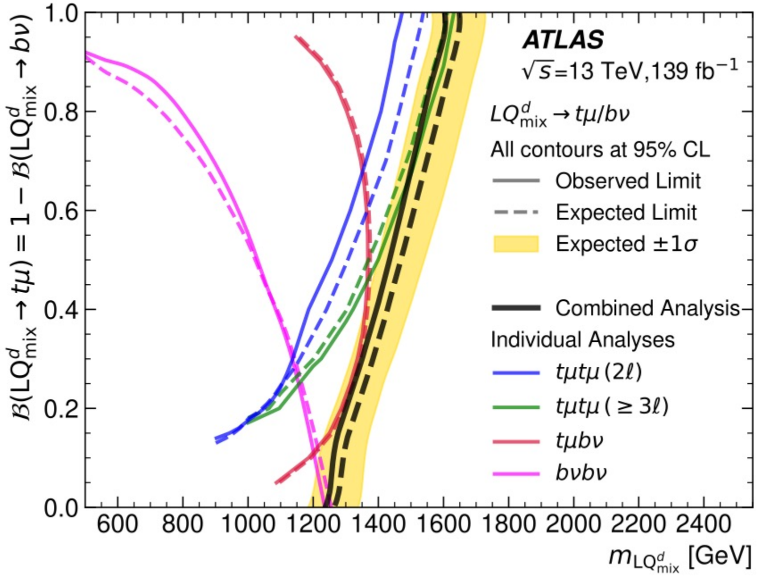
- Limits on scalar $LQ^{u}_{mix}$ to muons (electrons) **improved up to 80 (90) GeV (3 analyses combined)**
- Limits on $LQ^{d}_{mix}$ to muons (electrons) **improved up to 60 (80) GeV (4 analyses combined)**

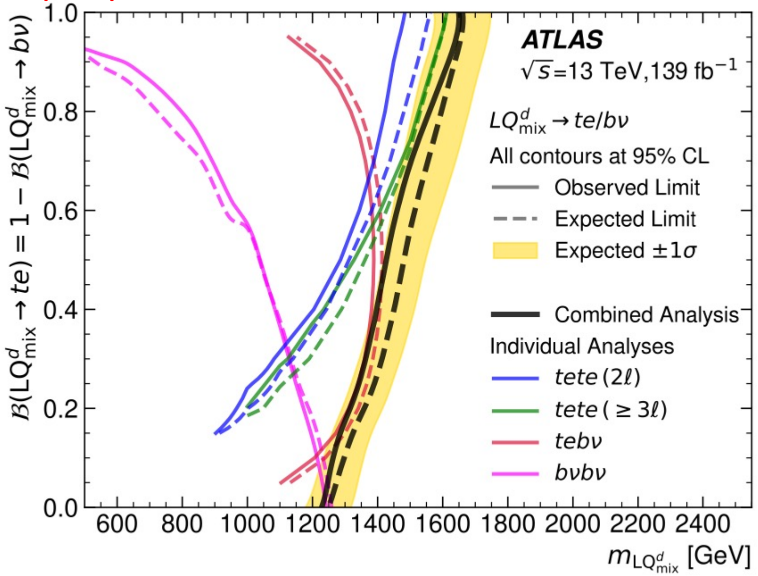
Eur. Phys. J. C 80 (2020) 737 JHEP 06 (2023) 188 JHEP 10 (2020) 112




JHEP 05 (2021) 093 JHEP 06 (2023) 188 2306.17642 Eur. Phys. J. C 81 (2021) 313



# Conclusions

- ATLAS published wide range of searches for LQs with cross-generational couplings using data recorded during Run 2 at LHC

**All ATLAS results in [https://twiki.cern.ch/twiki/bin/view/AtlasPublic](https://twiki.cern.ch/twiki/bin/view/AtlasPublic)**

- No clear new physics evidence in Run 2 dataset in searches for leptoquarks (both vector and scalar)

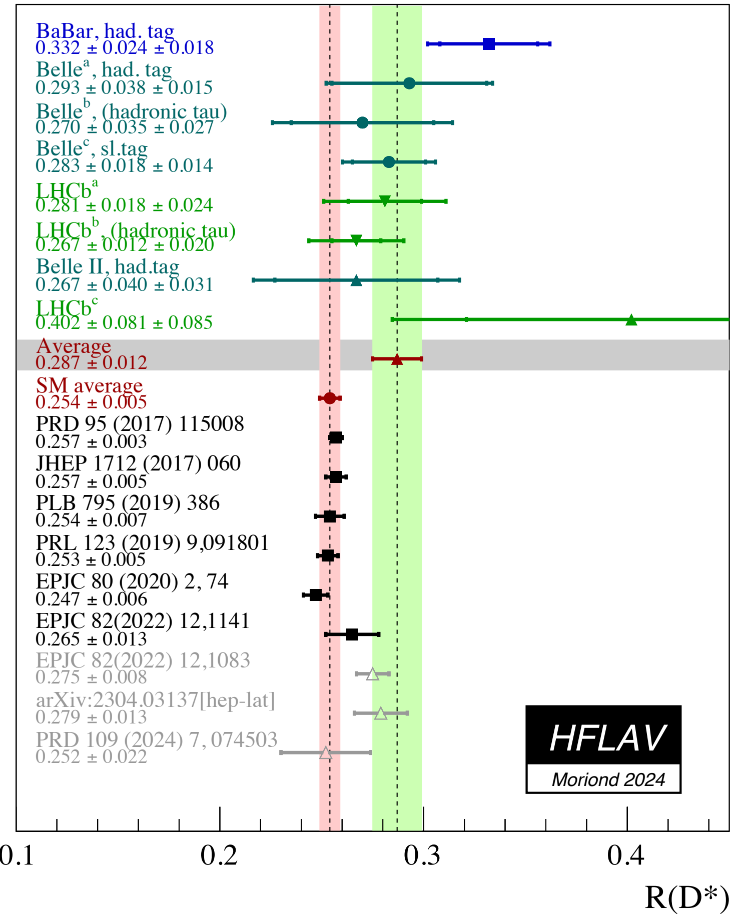
- LQ analyses often statistically limited, but LHC Run 3 is going on and HL-LHC will follow: looking forward to more data to be analyzed (≈ 20 times more data expected!)

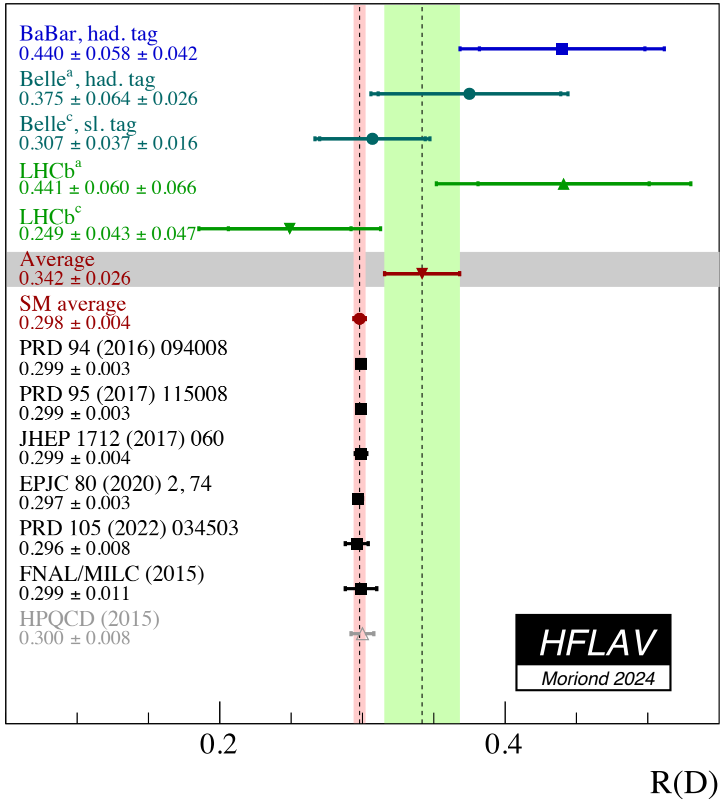
- Benefits will come from improvements (e.g. in flavour tagging)

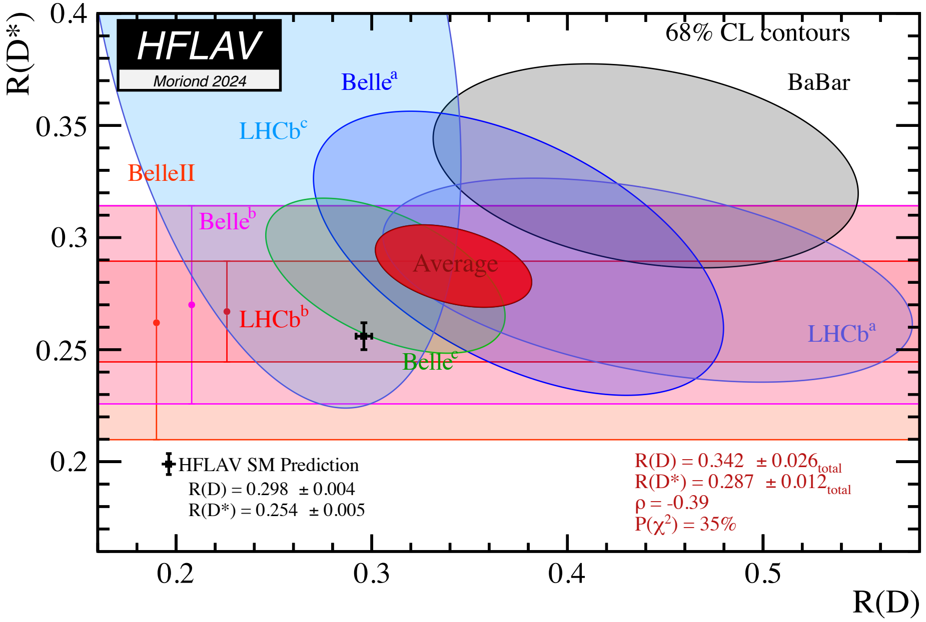
*Thank you!*

# Backup Slides

https://hflav-eos.web.cern.ch/hflav-eos/semi/moriond24/html/RDsDsstar/RDRDs.html

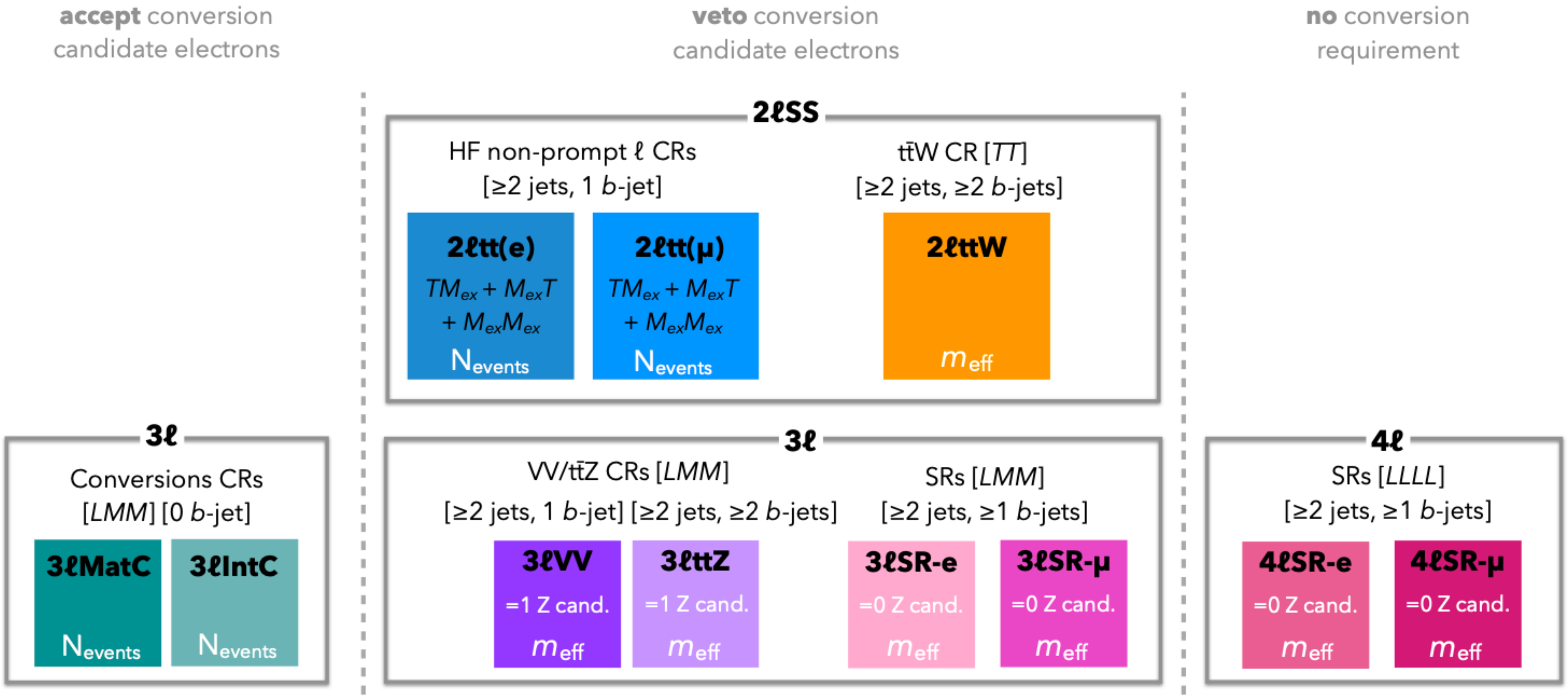


# LQLQ → tt $\ell^+ \ell^- (\ell = e,\mu)$

2306.17642




Illustrative sketch of the definition of the signal and control regions. The corresponding observable used in the simultaneous fit is given at the bottom of each region box.

# LQLQ → tt $\ell^+ \ell^-$ ($\ell$= $e,\mu$)

2306.17642

| | $3\ell$SR-$e$ | $3\ell$SR-$\mu$ | $4\ell$SR-$e$ | $4\ell$SR-$\mu$ |
|---|---|---|---|---|
| Data | 8 | 7 | 1 | 6 |
| Total background | $8.1 \pm 0.6$ | $10.2 \pm 0.7$ | $2.8 \pm 0.2$ | $3.3 \pm 0.2$ |
| $t\bar{t}W$ | $4.2 \pm 0.6$ | $5.6 \pm 0.8$ | — | — |
| Diboson | $0.9 \pm 0.1$ | $1.5 \pm 0.2$ | $0.32 \pm 0.05$ | $0.40 \pm 0.04$ |
| $t\bar{t}Z/\gamma^*$ | $1.33 \pm 0.14$ | $1.55 \pm 0.15$ | $1.69 \pm 0.18$ | $2.09 \pm 0.21$ |
| $tWZ$ | — | — | $0.23 \pm 0.12$ | $0.22 \pm 0.12$ |
| Non-prompt $\ell$ | $0.25 \pm 0.16$ | — | — | — |
| Other | $1.44 \pm 0.22$ | $1.61 \pm 0.31$ | $0.53 \pm 0.10$ | $0.54 \pm 0.12$ |
| $\mathrm{LQ}^{\mathrm{d}}_{\mathrm{mix}}$ 1.6 TeV | $2.5 \pm 0.2$ | $2.7 \pm 0.2$ | $0.42 \pm 0.11$ | $0.40 \pm 0.05$ |
| $\tilde{U}_1^{\mathrm{min}}$ 1.6 TeV | $4.5 \pm 0.2$ | $4.6 \pm 0.3$ | $0.7 \pm 0.1$ | $0.7 \pm 0.1$ |
| $\tilde{U}_1^{\mathrm{YM}}$ 1.6 TeV | $27 \pm 1$ | $29 \pm 2$ | $4.4 \pm 0.2$ | $4.2 \pm 0.3$ |
| $\tilde{U}_1^{\mathrm{YM}}$ 2.0 TeV | $2.0 \pm 0.2$ | $2.0 \pm 0.2$ | $0.31 \pm 0.08$ | $0.30 \pm 0.03$ |

Summary of observed and predicted yields in the four signal region categories. The background prediction is shown after the combined likelihood fit to data under the background-only hypothesis across all control region and signal region categories. The expected signal yields that are obtained by using their theoretical cross sections are also shown with their pre-fit uncertainties, assuming $\mathcal{B}$=1 and $\mu$=1. The "Other" contribution is dominated by $t\bar{t}t\bar{t}$ and $t\bar{t}WW$ in the $3\ell$ SRs, whereas it is dominated by $tWZ$ and $t\bar{t}WW$ in the $4\ell$ SRs. Dashes refer to components that are negligible or not applicable.

# LQLQ → tν bℓ /tℓ bν (ℓ= e,μ)

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| Variable | Description |
| --- | --- |
| $m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$ | transverse mass of lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$ |
| $m_{\mathrm{eff}}$ | scalar sum of the transverse momenta of leptons, jets, and $E_{\mathrm{T}}^{\mathrm{miss}}$ |
| Lepton flavour | flavour of the signal lepton |
| $p_{\mathrm{T}}(\ell)$ | transverse momentum of the lepton |
| $m_{\mathrm{inv}}(b_1, \ell)$ | invariant mass of the leading-$p_{\mathrm{T}}$ $b$-jet and the lepton |
| $n_{\mathrm{large}}$ | reclustered large-$R$ jet multiplicity |
| $am_{\mathrm{T2}}$ | asymmetric transverse mass |
| $E_{\mathrm{T}}^{\mathrm{miss}}$ significance | measure for assessing the compatibility of the observed $E_{\mathrm{T}}^{\mathrm{miss}}$ with zero, taking resolutions into account |
| $m_{\mathrm{T}}(b_1, E_{\mathrm{T}}^{\mathrm{miss}})$ | transverse mass of leading-$p_{\mathrm{T}}$ $b$-jet and $E_{\mathrm{T}}^{\mathrm{miss}}$ |
| $p_{\mathrm{T}}(t_{\mathrm{had}})$ | transverse momentum of $t_{\mathrm{had}}$ |
| $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, b_2)$ | azimuthal angle separation between $E_{\mathrm{T}}^{\mathrm{miss}}$ and subleading-$p_{\mathrm{T}}$ $b$-jet |
| $m_{\mathrm{inv}}(b_2, \ell)$ | invariant mass of subleading-$p_{\mathrm{T}}$ $b$-jet and lepton |
| $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, b_1)$ | azimuthal angle separation between $E_{\mathrm{T}}^{\mathrm{miss}}$ and leading-$p_{\mathrm{T}}$ $b$-jet |
| $\Delta\phi(t_{\mathrm{had}}, \ell)$ | azimuthal angle separation between $t_{\mathrm{had}}$ and lepton |
| $p_{\mathrm{T}}(b_1)$ | transverse momentum of leading-$p_{\mathrm{T}}$ $b$-jet |

$$amt2 = \min_{\vec{p}_{\mathrm{T},1}+\vec{p}_{\mathrm{T},2}=\vec{E}_{\mathrm{T}}^{\mathrm{miss}}} \left\{\max\left[m_{\mathrm{T}}\left(\vec{p}_{b_1}+\vec{p}_{\ell}, \vec{p}_{\mathrm{T},1}\right), m_{\mathrm{T}}\left(\vec{p}_{b_2}, \vec{p}_{\mathrm{T},2}\right)\right]\right\}$$

$b_1$,$b_2$ the 2 jets with the highest b-tagging score

Input variables for the NN training, approximately sorted in descending ability to discriminate between signal and background. The order is not absolute as there is some dependence on the signal model and $\mathcal{B}$. Some variables might not be defined in every event.

# LQLQ → tν bℓ /tℓ bν (ℓ= $e,\mu$)

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| Top reweighting region | $W$+jets CR | Single-top CR | Training region Low-$NN_{\text{out}}$ CR/SR |
|---|---|---|---|
| $n_b \geq 1$ | $n_b = 1$ | $n_b = 2$ | $n_b \geq 1$ |
| $m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}}) \geq 120\,\text{GeV}$ | $50\,\text{GeV} \leq m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}}) < 120\,\text{GeV}$ | $m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}}) < 120\,\text{GeV}$ | $m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}}) \geq 120\,\text{GeV}$ |
| $am_{\text{T2}} < 200\,\text{GeV}$ | $am_{\text{T2}} > 200\,\text{GeV}$ | $am_{\text{T2}} > 200\,\text{GeV}$ | $am_{\text{T2}} > 200\,\text{GeV}$ |
| - | $t_{\text{had}}$ candidate veto | large-$R$ jet veto | - |
| - | lepton charge = $+1e$ | - | - |
| - | - | $\Delta R(b_1, b_2) > 1.2$ | - |
| - | - | - | $NN_{\text{out}} < 0.5 / \geq 0.5$ |

Event selections applied in the different regions of the analysis.

# LQLQ → tν bℓ /tℓ bν (ℓ= $e,\mu$)

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| | $W$+jets CR | Single-top CR | Low-$NN_{\text{out}}$ CR | SR |
|---|---|---|---|---|
| $t\bar{t}$ | $860 \pm 140$ | $186 \pm 35$ | $1370 \pm 150$ | $53 \pm 10$ |
| Single top | $103 \pm 87$ | $131 \pm 47$ | $200 \pm 110$ | $36 \pm 14$ |
| $W$+jets | $1240 \pm 130$ | $101 \pm 28$ | $265 \pm 55$ | $32.4 \pm 6.9$ |
| $t\bar{t}+V$ | $11.0 \pm 1.8$ | $4.47 \pm 0.79$ | $180 \pm 28$ | $16.7 \pm 2.6$ |
| Diboson | $94.3 \pm 9.8$ | $7.6 \pm 1.9$ | $94 \pm 11$ | $11.1 \pm 1.2$ |
| $t\bar{t}+H$ | $1.27 \pm 0.16$ | $1.00 \pm 0.12$ | $14.4 \pm 1.7$ | $1.34 \pm 0.18$ |
| $Z$+jets | $6.46 \pm 0.32$ | $2.18 \pm 0.11$ | $7.20 \pm 0.36$ | $1.31 \pm 0.07$ |
| Total background | $2308 \pm 48$ | $433 \pm 21$ | $2126 \pm 46$ | $152 \pm 13$ |
| Observed events | 2310 | 430 | 2124 | 157 |
| $\text{vLQ}^{\text{YM}}_{\text{mix}}$ (1.7 TeV, $\mathcal{B} = 0.5$) | $0.109 \pm 0.022$ | $0.097 \pm 0.016$ | $1.57 \pm 0.10$ | $38.9 \pm 2.6$ |

Observed and expected event yields in the control and signal regions for a training for $\text{vLQ}^{\text{YM}}_{\text{mix}} \to b\mu/t\nu$ and $\mathcal{B} = 0.5$ after the background-only fit. The uncertainties in the background predictions include both the statistical and systematic components. For comparison, expected event yields are shown for a $\text{vLQ}^{\text{YM}}_{\text{mix}}$ signal at a mass point of 1700 GeV and $\mathcal{B} = 0.5$ including its pre-fit uncertainties.