high-energy probes of the b-anomalies in the top sector

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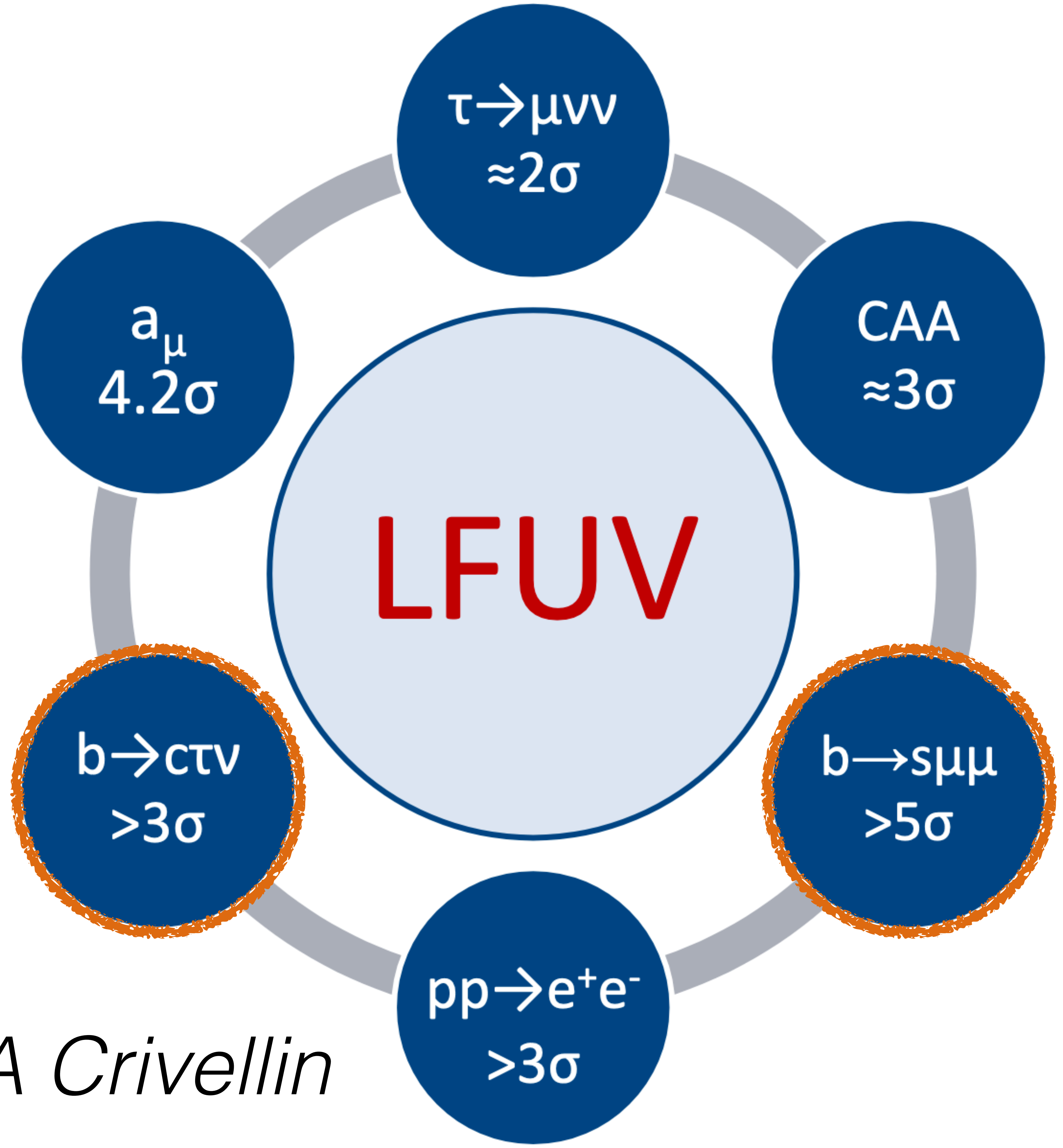
introduction

here we're focusing on implications of the $b \to \ell + X$ anomalies.



A Crivellin

but don't forget there are other hints of LFU-violating new physics!

reminder

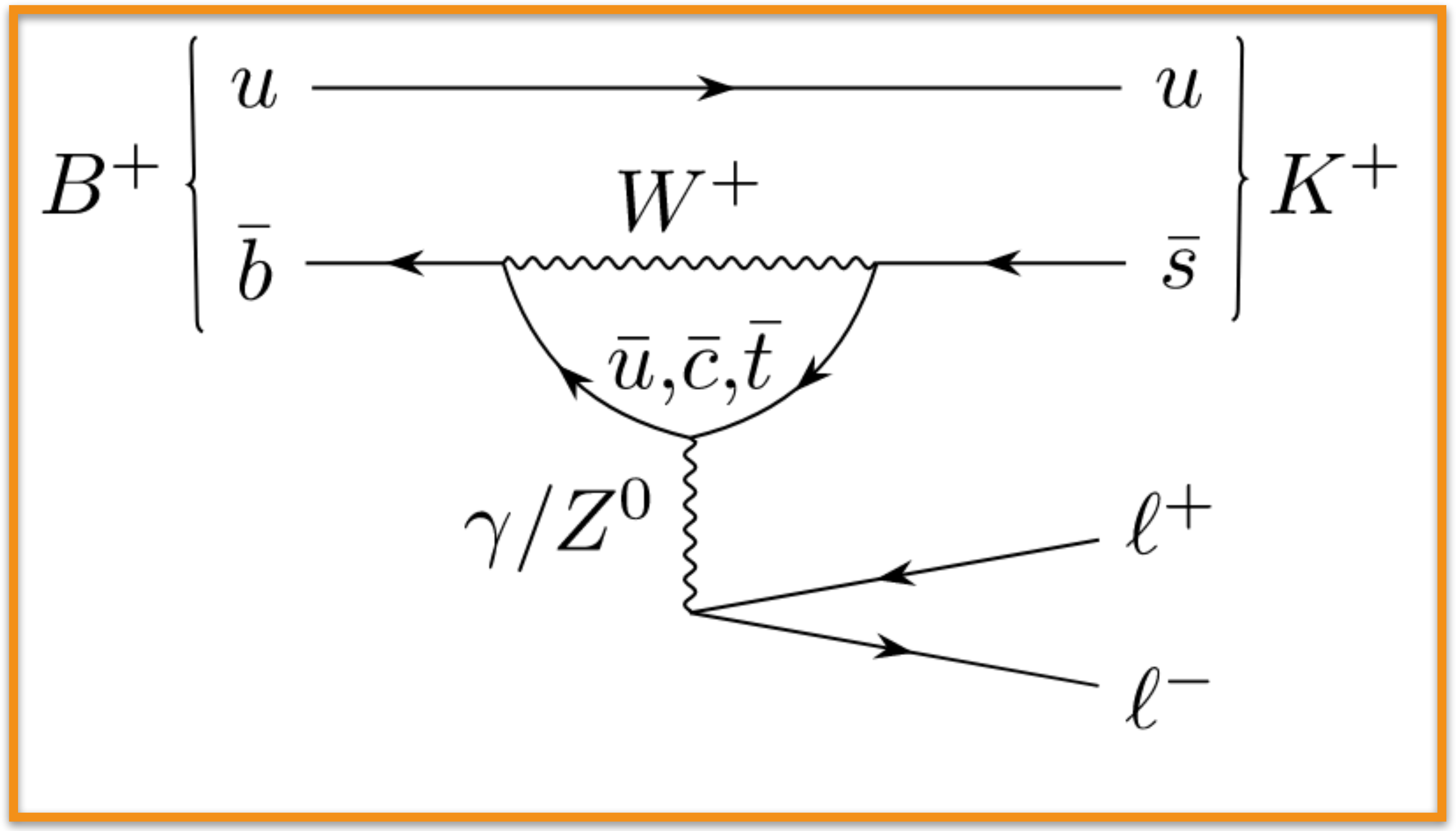
$$R(K) = \frac{BR(B \to K\mu\mu)}{BR(B \to Kee)}$$

arXiv 2103.16558

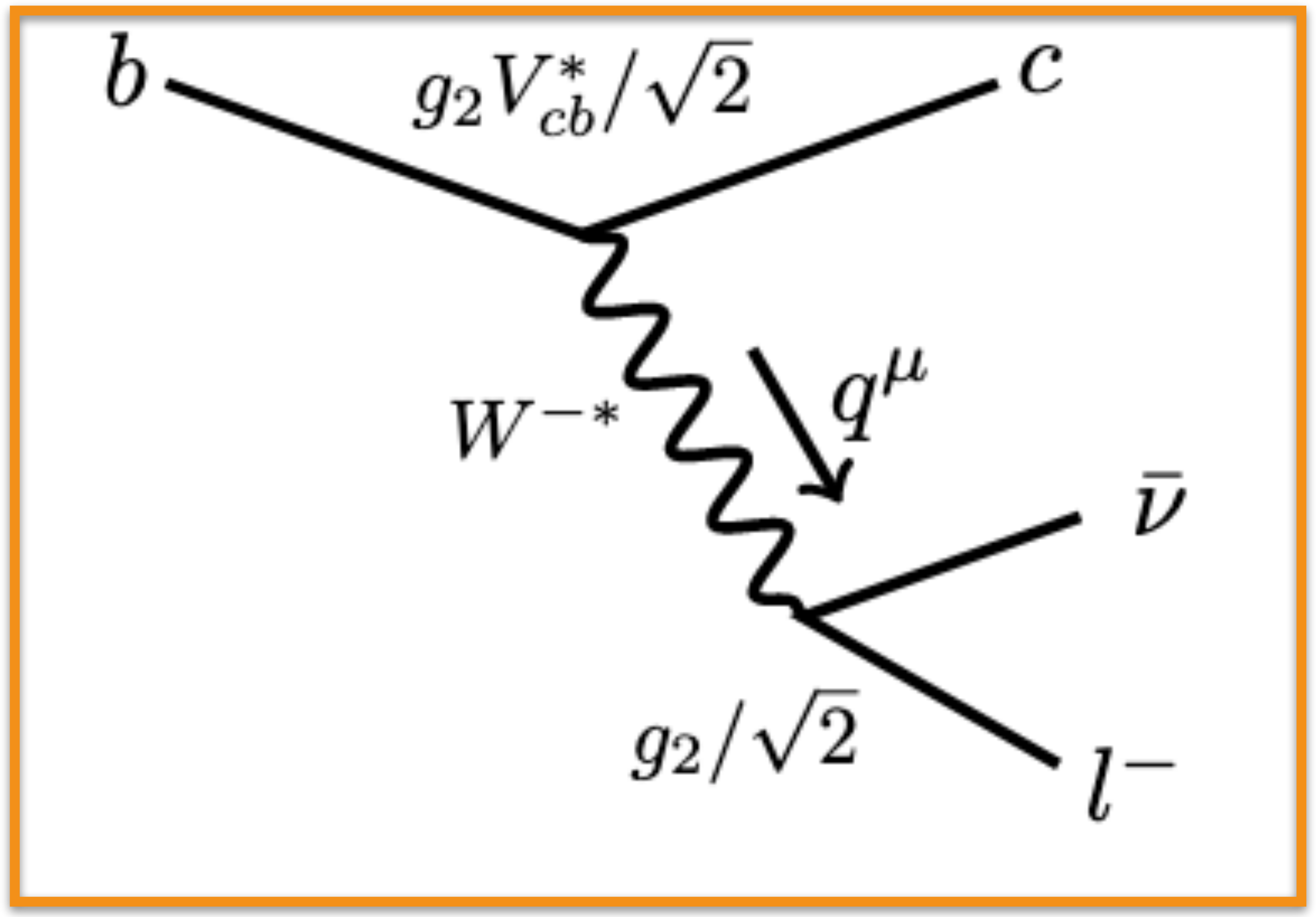
Observable	Experiment	SM
$R_{K^*}^{[0.045,1.1]}$	$0.66^{+0.11}_{-0.07} \pm 0.03$ [3]	0.906 ± 0.028 [64]
$R_{K^*}^{[1.1,6.0]}$	$0.69^{+0.11}_{-0.07} \pm 0.05$ [3]	1.00 ± 0.01 [64]
$R_{K}^{[1.1,6.0]}$	$0.846^{+0.042+0.013}_{-0.039-0.012}$ [1]	1.00 ± 0.01 [64]
$\mathcal{B}(B_s \to \mu^+\mu^-)$	$(2.85^{+0.32}_{-0.31}) \times 10^{-9}$ [65–67]	$(3.66 \pm 0.14) \times 10^{-9}$ [68]

$$R(D) = \frac{BR(B \to D\tau\nu)}{BR(B \to D\ell\nu)}$$

Observable	Experiment	SM
$\{R_D, R_{D^*}\}$	$\{0.337(30), 0.298(14)\}$ $\rho = -0.42$ [86]	$\{0.299(3), 0.258(5)\}$ [87]
$\mathcal{B}(B^- \to \tau\bar{\nu})$	$1.09(24) \times 10^{-4}$ [88]	$0.812(54) \times 10^{-4}$ [89]



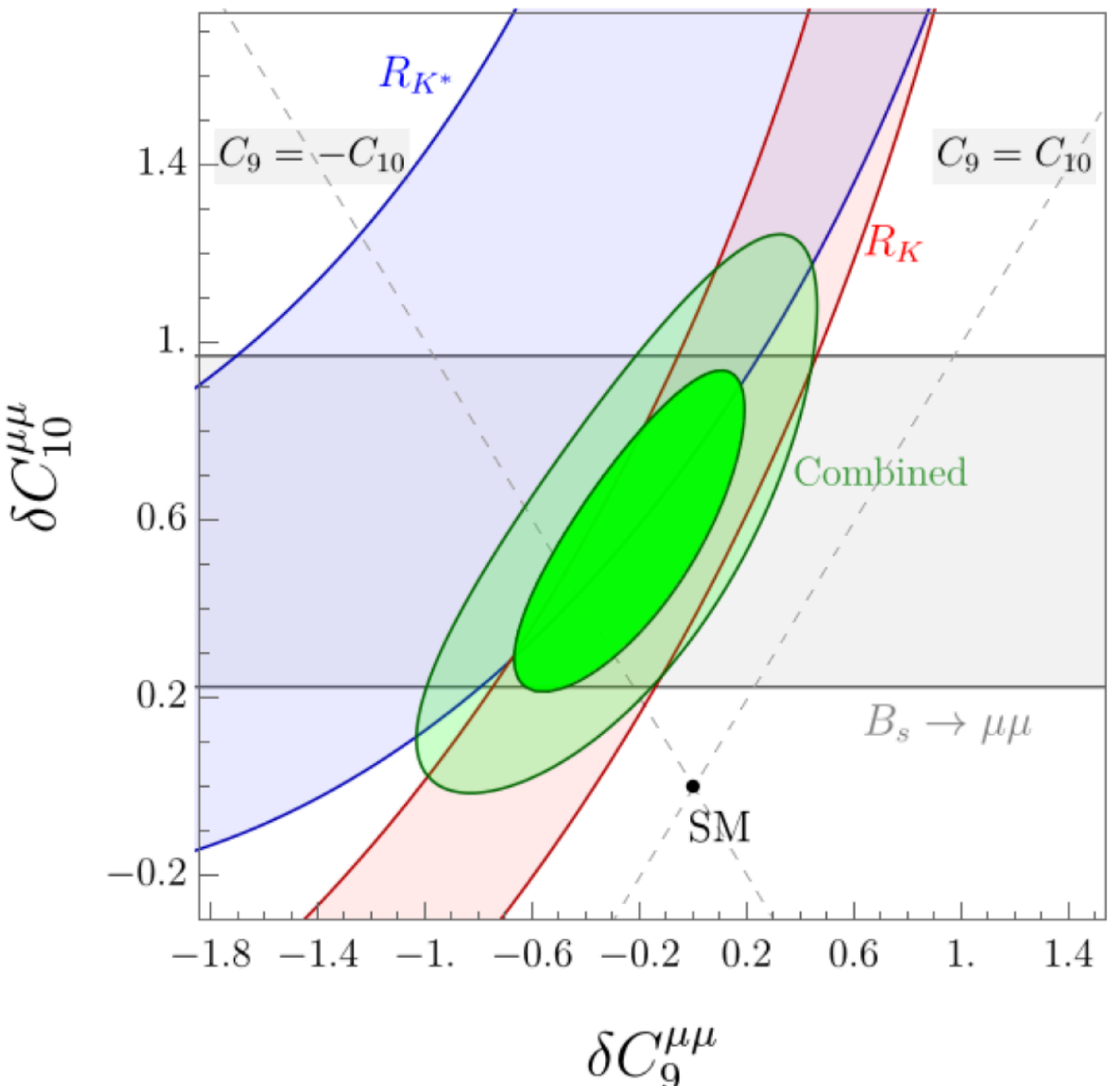
arXiv 2103.11769



arXiv 2103.11769

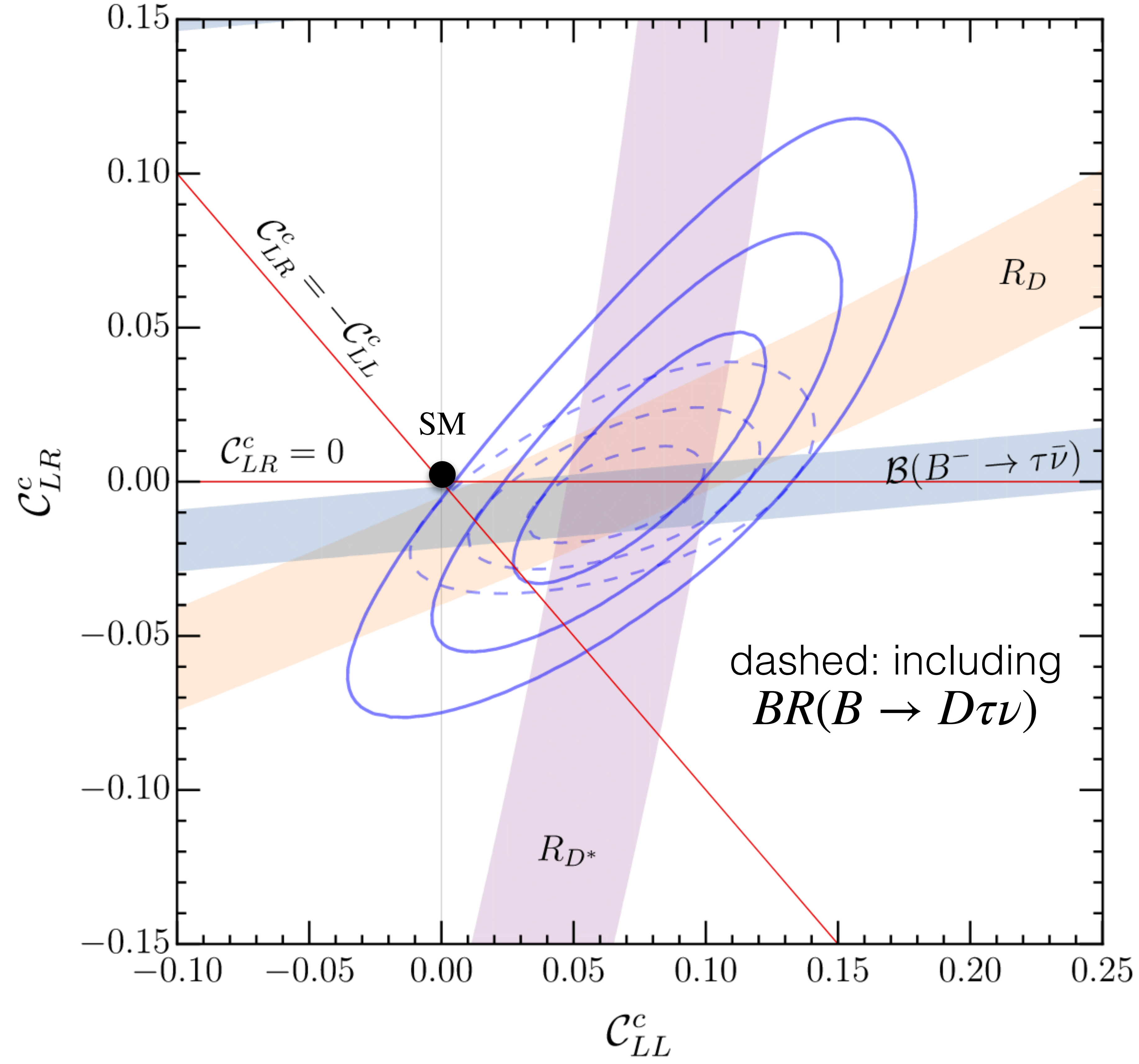
EFT deviations

$b \to \mu$ vs $b \to e$



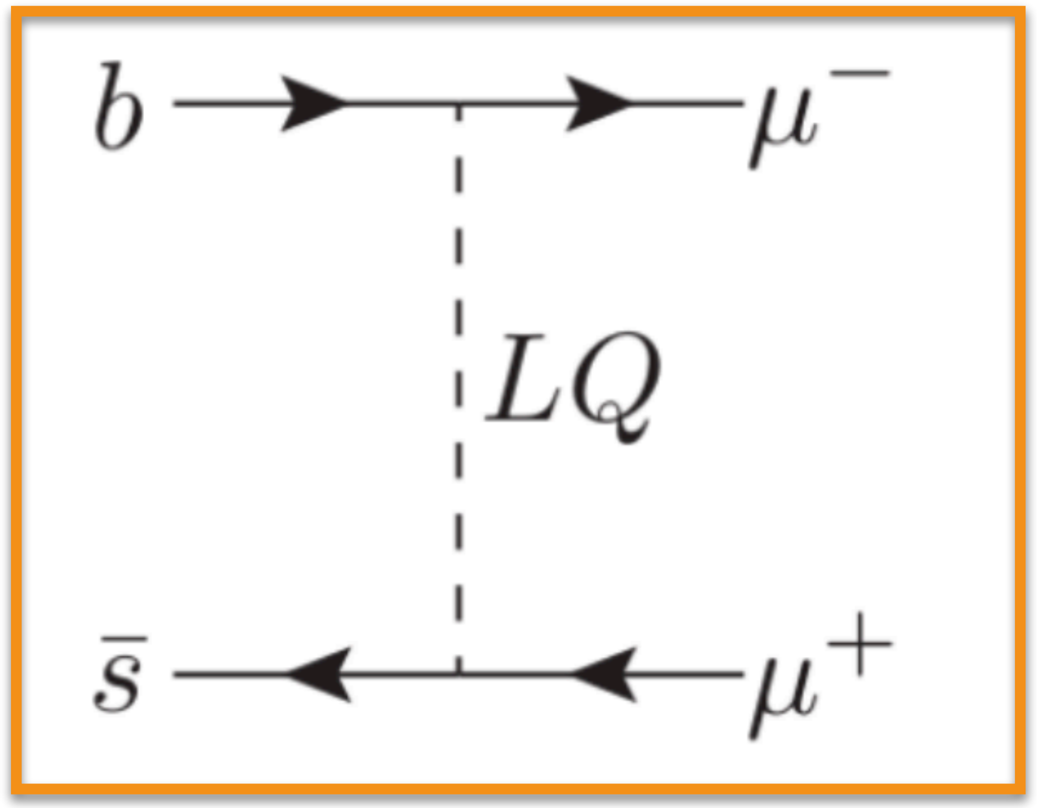
arXiv 2103.12504

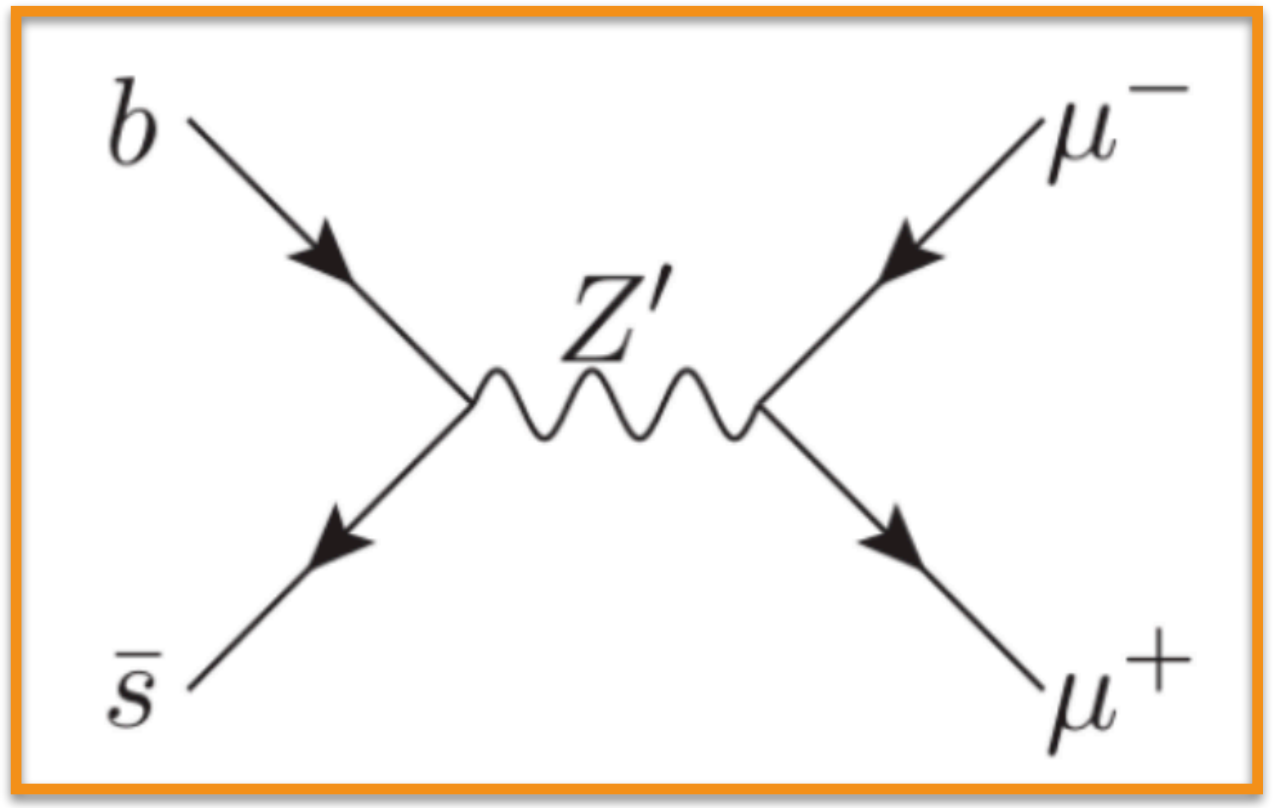
$b \to \tau$ vs $b \to e/\mu$



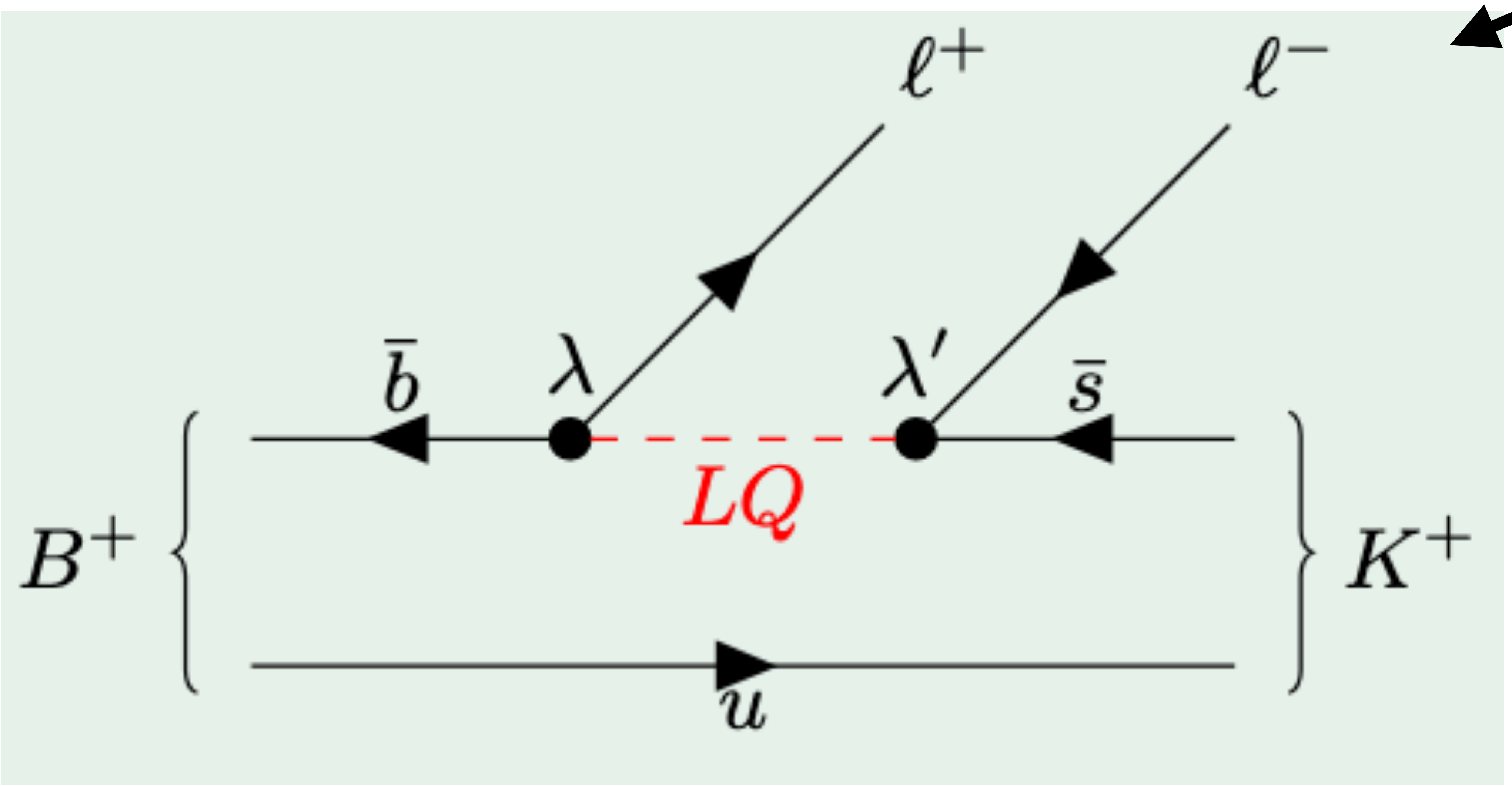
arXiv 2103.16558

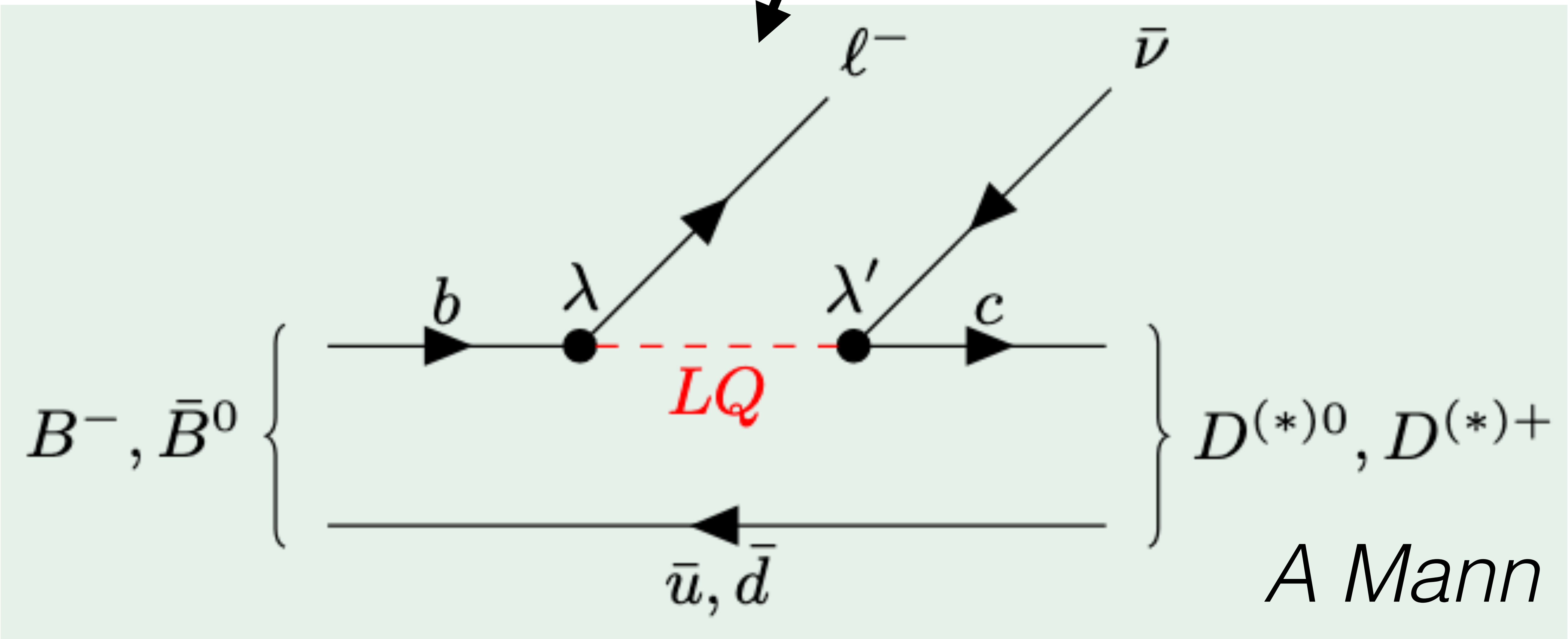
solutions?





flavor-dependent couplings
$\rightarrow$ alterations to relevant BRs





flavor structure of couplings I

- depending on choice of model structure + parameters and experimental results used…
- … there is a range of flavor-dependent couplings preferred by the data.
- for e.g. a generic vector leptoquark, the new interaction involves a current of the form

$$J_\mu^U = \beta_L^{i\alpha}\,(\bar{q}_L^i \gamma_\mu \ell_L^\alpha) + \beta_R^{i\alpha}\,(\bar{d}_R^i \gamma_\mu e_R^\alpha)$$

  where the $\beta_{L/R}^{i\alpha}$ are coupling matrices between generations of quarks and leptons.

- for example in arxiv:2103.16558 it's found, based on the previously-shown EFT fits, that
  - $\beta_{L/R}^{b\tau} \sim 1$
  - $|\beta_L^{d\tau,s\mu}| \ll |\beta_L^{s\tau,b\mu}| \ll 1$
  - others ~ 0

best-fit 2nd-3rd cross-generation couplings factor of 5 below 3rd-3rd

flavor structure of couplings II

- alternatively, many aspects of the b-anomalies can be explained by "simple" Z'.
- see for example arxiv:1809.01158
  - agreement with experimental data improves considerably w.r.t. the SM,
  - via introducing a new heavy Z' with flavor-dependent couplings.
  - introduces small non-flavor universal couplings to the SM Z, but more importantly…

Mode	BR	Mode	BR	Mode	BR
$t\bar{t}$	0.42	$b\bar{b}$	0.12	$\nu\bar{\nu}'$	0.08
$\mu^+\mu^-$	0.08	$\tau^+\tau^-$	0.30	other $f_i f_j$	$\sim \mathcal{O}(10^{-4})$

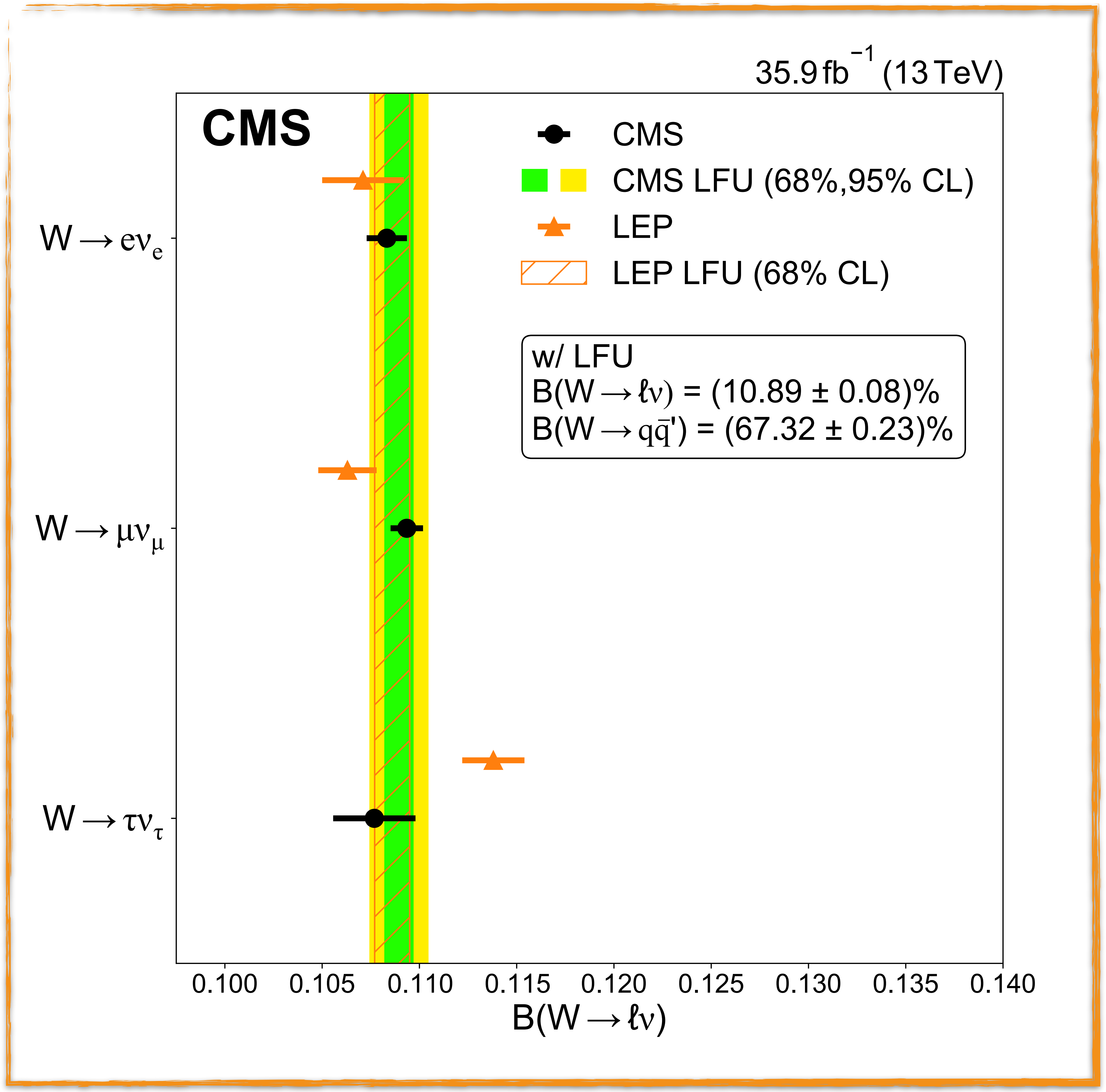
some experimental results

- will focus here on *recent* experimental results involving tops
  - that are generically sensitive to the flavor anomalies,
  - but it's not at all exhaustive!
- I'll also throw out some ideas of where we could improve our experimental program,
  - but given the number of models that have been proposed,
  - really there is a *lot* of ground to cover!
- split loosely into precision measurements, direct LQ searches, and tests via associated production.

understanding W decays in $t\bar{t}$ events

SMP-18-011; arxiv 2201.07861

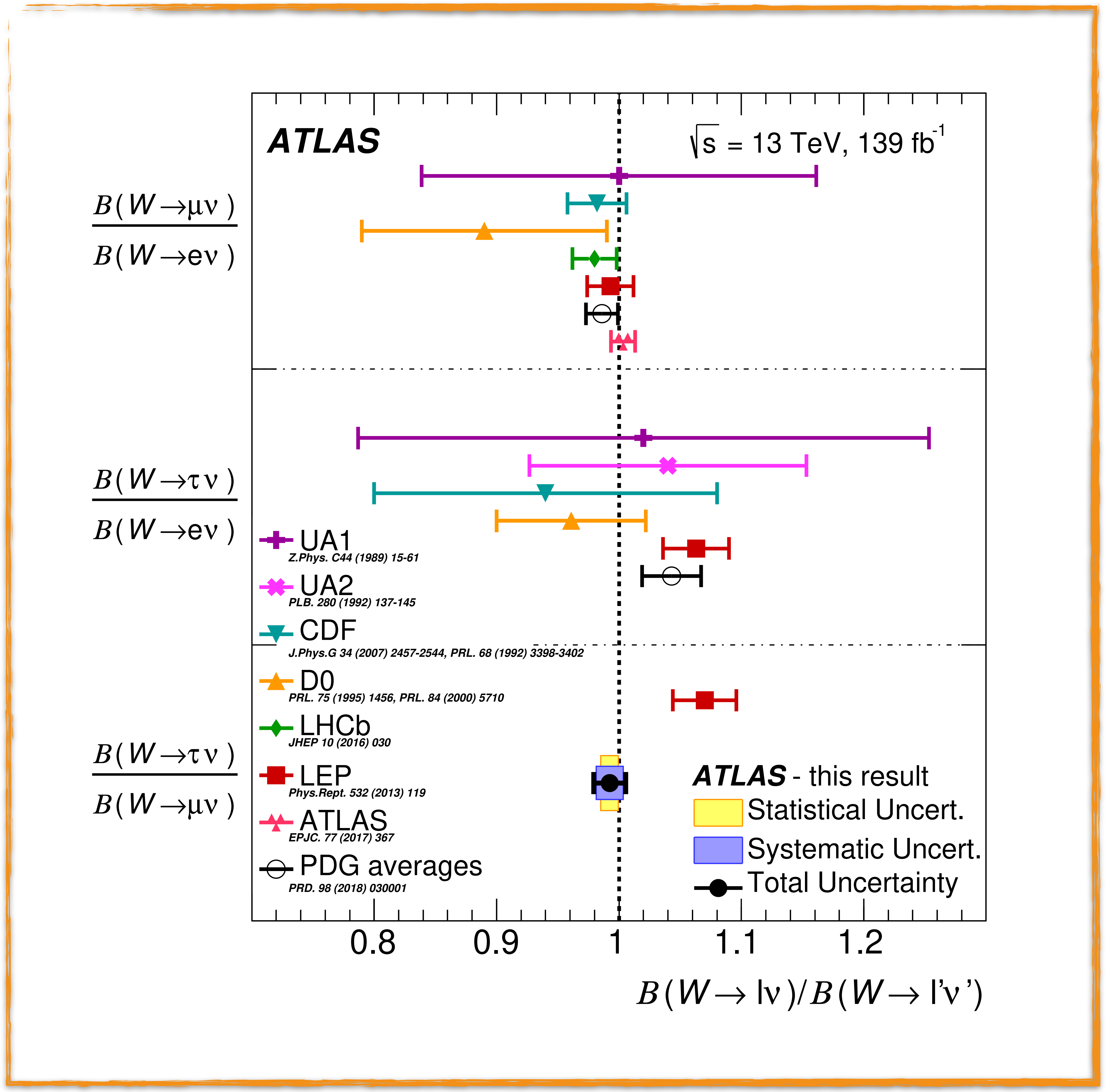
- LEP saw $\sim 2.5\sigma$ deviations from the SM in W decays:
  - $R^{LEP}_{\tau/\ell} = 1.066 \pm 0.025$
  - $R^{SM}_{\tau/\ell} = 0.9996$
- CMS data are much closer to universality and SM.



understanding W decays in $t\bar{t}$ events

TOPQ-2018-29; arxiv 2007.14040

- ATLAS has measured
  - $R_{e/\mu} = 0.997 \pm 0.010$
  - $R_{\tau/\mu} = 0.992 \pm 0.013$
- These measurements are also very much in line with universality and the SM.



understanding W decays in $t\bar{t}$ events

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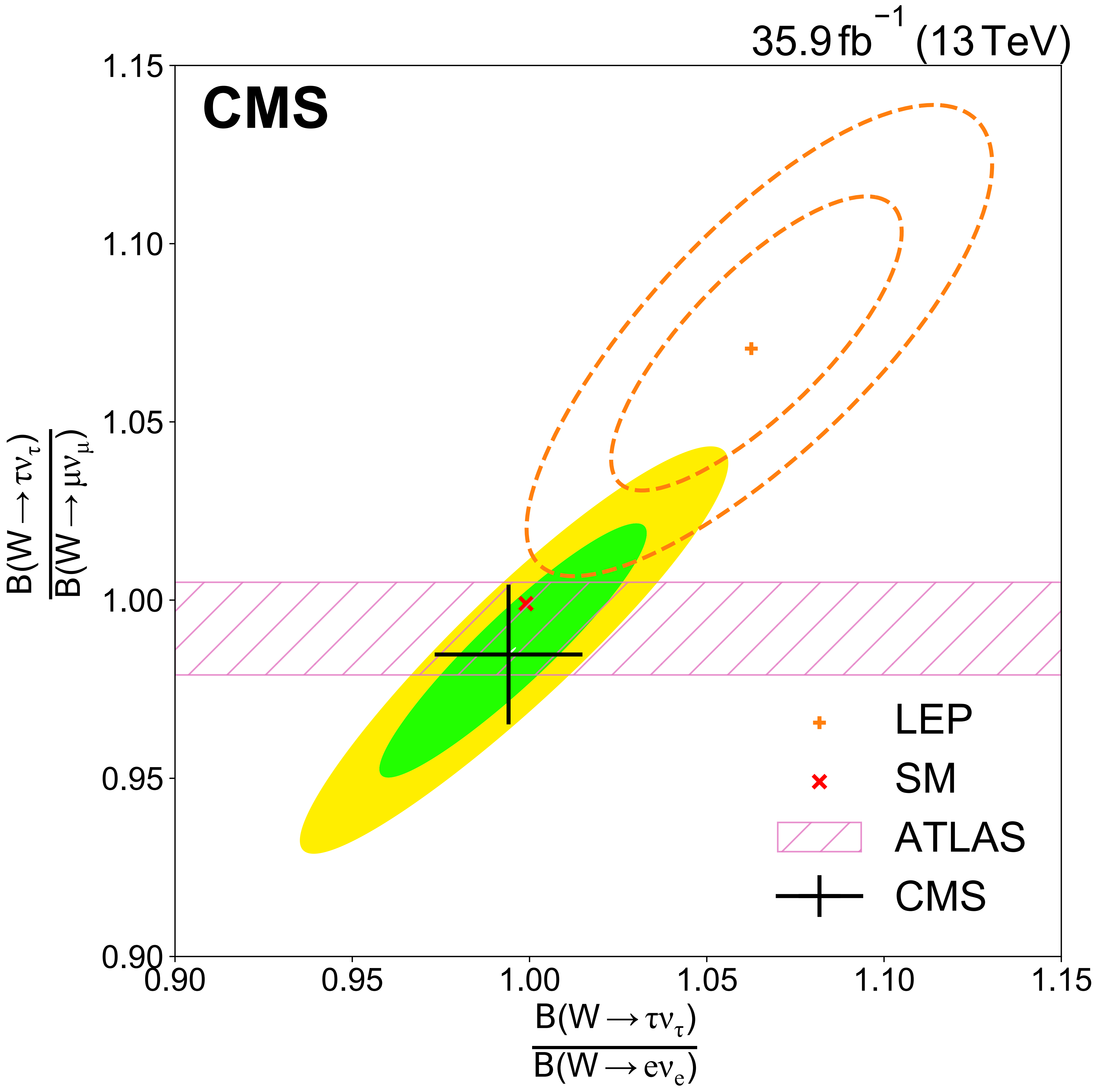
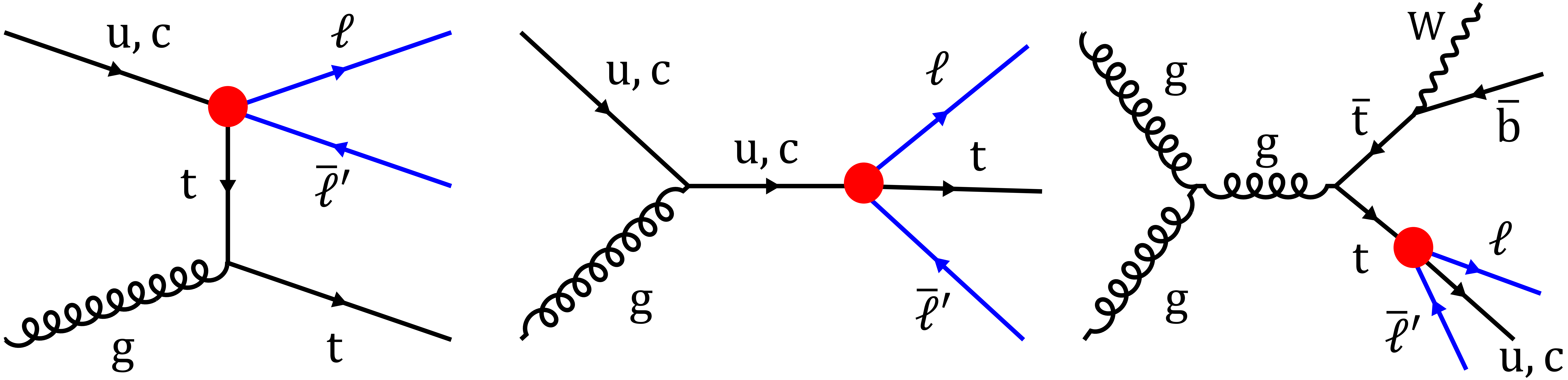


it appears
the LHC experiments
have ruled out LFUV
in W decays
for the time being…

see backup for CMS Drell-Yan
measurements vs $m_{\ell\ell}$

probing $tqe\mu$ vertices

TOP-19-006; arxiv 2201.07859

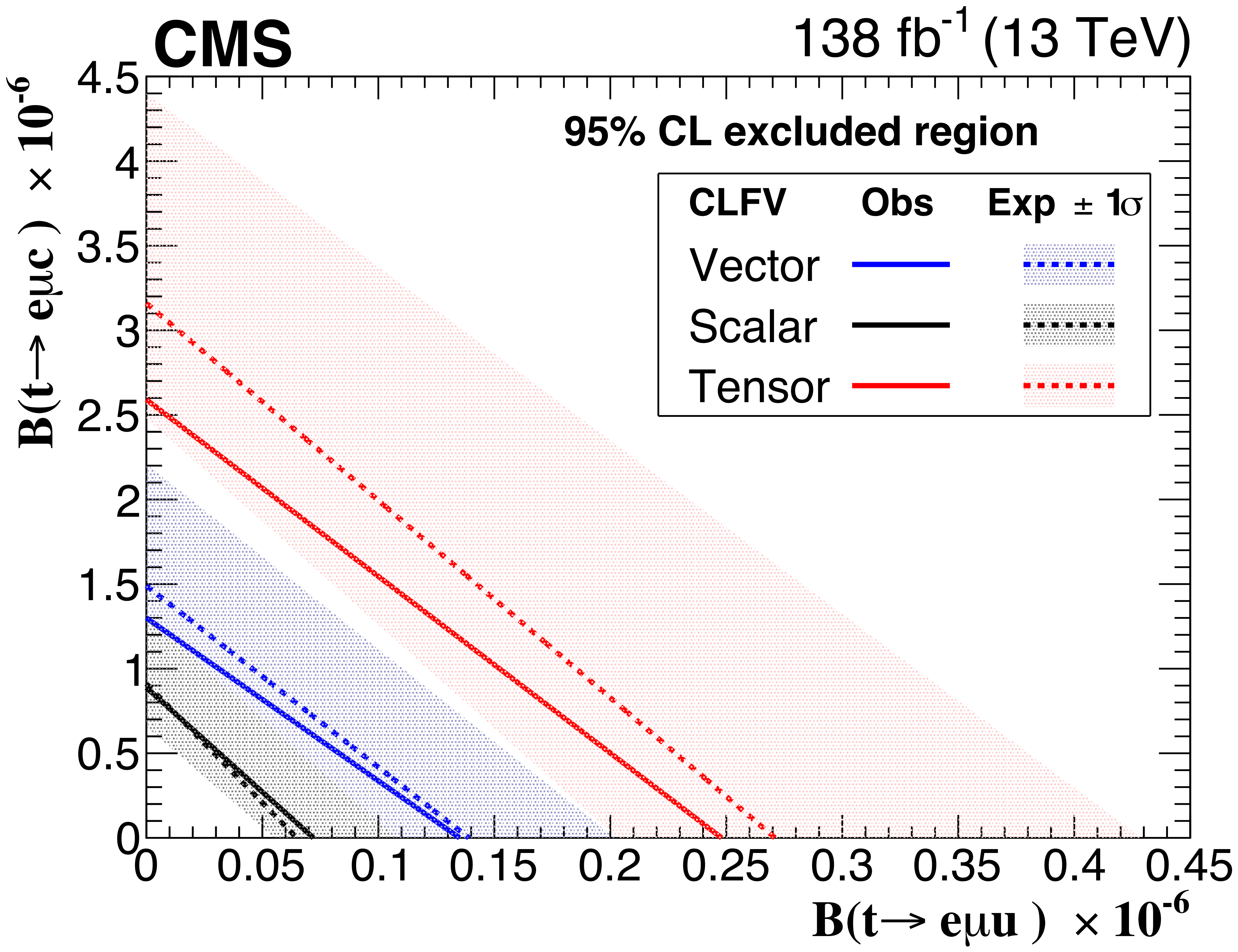


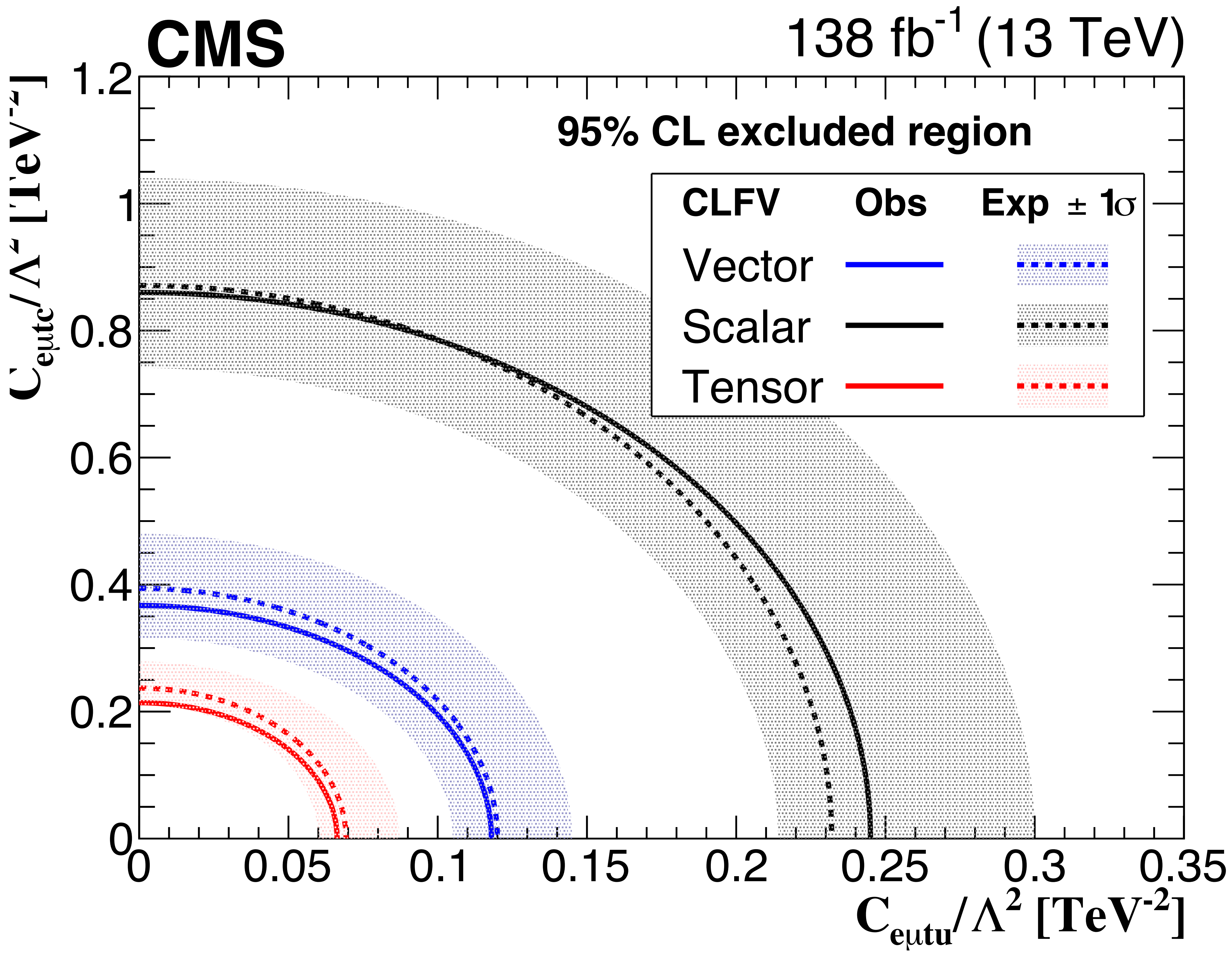
in a similar vein, CMS have also searched for anomalous 4-fermion interactions involving charged leptons and the top quark,

which would result in $t\ell\ell'$ production and BSM top decays.

probing $tqe\mu$ vertices

TOP-19-006; arxiv 2201.07859





no substantial deviations from the SM :-(

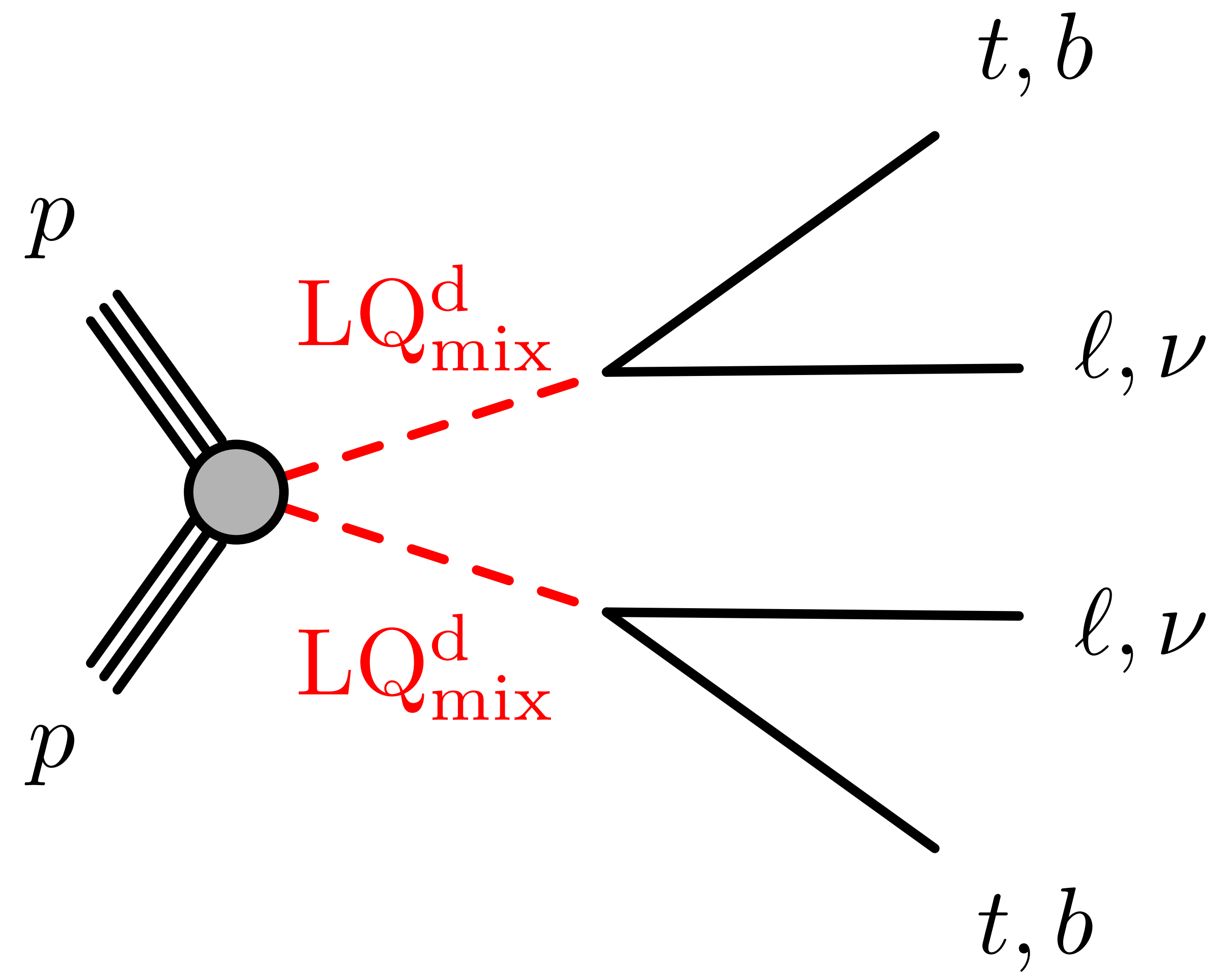
$LQ\,LQ \rightarrow bl + t\nu$

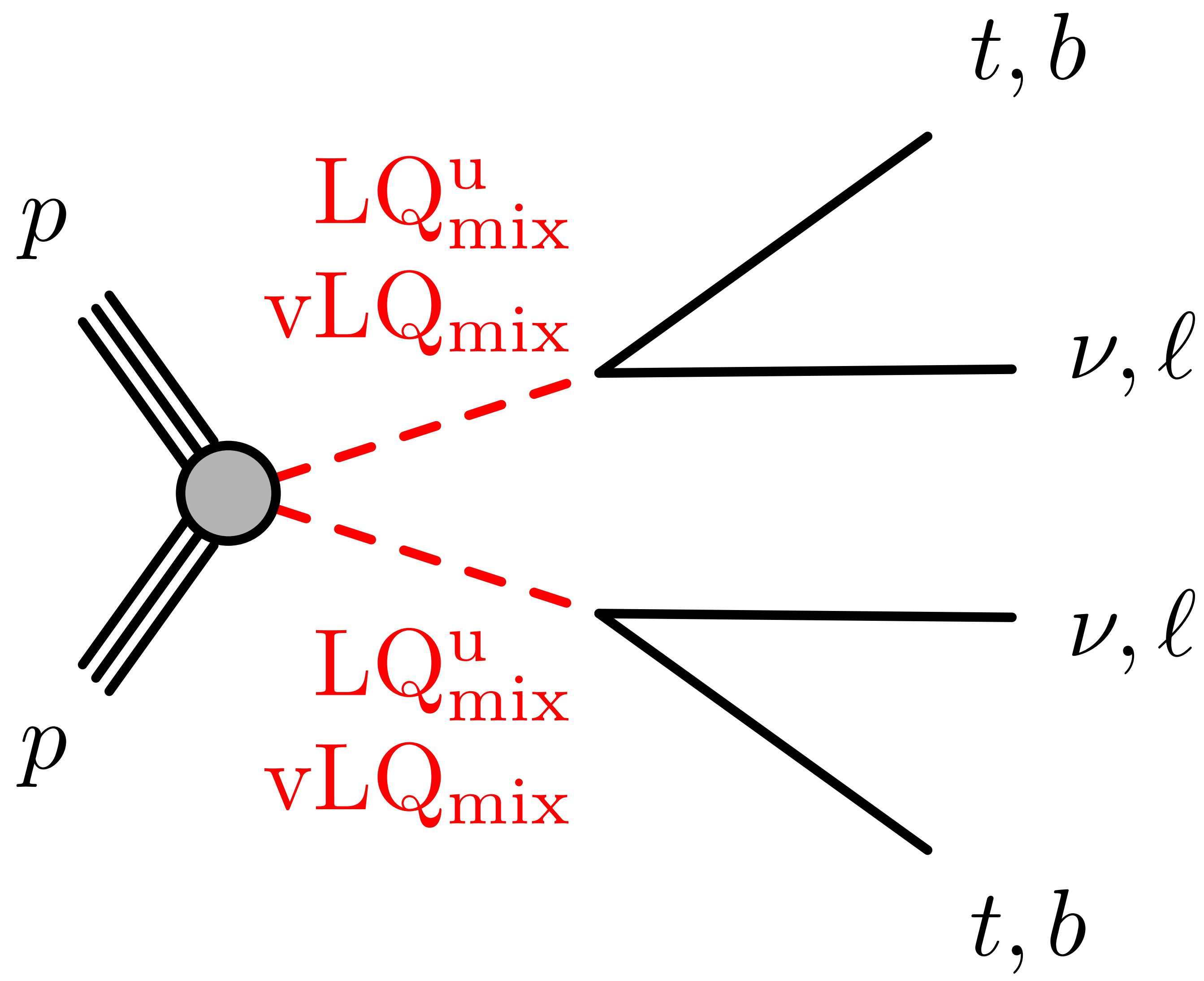
ATLAS-CONF-2022-009;
arxiv 2201.07861

new search for LQ pair production from ATLAS

focusing on single-light-lepton final state with cross-generational couplings

lepton comes from either LQ or top decay

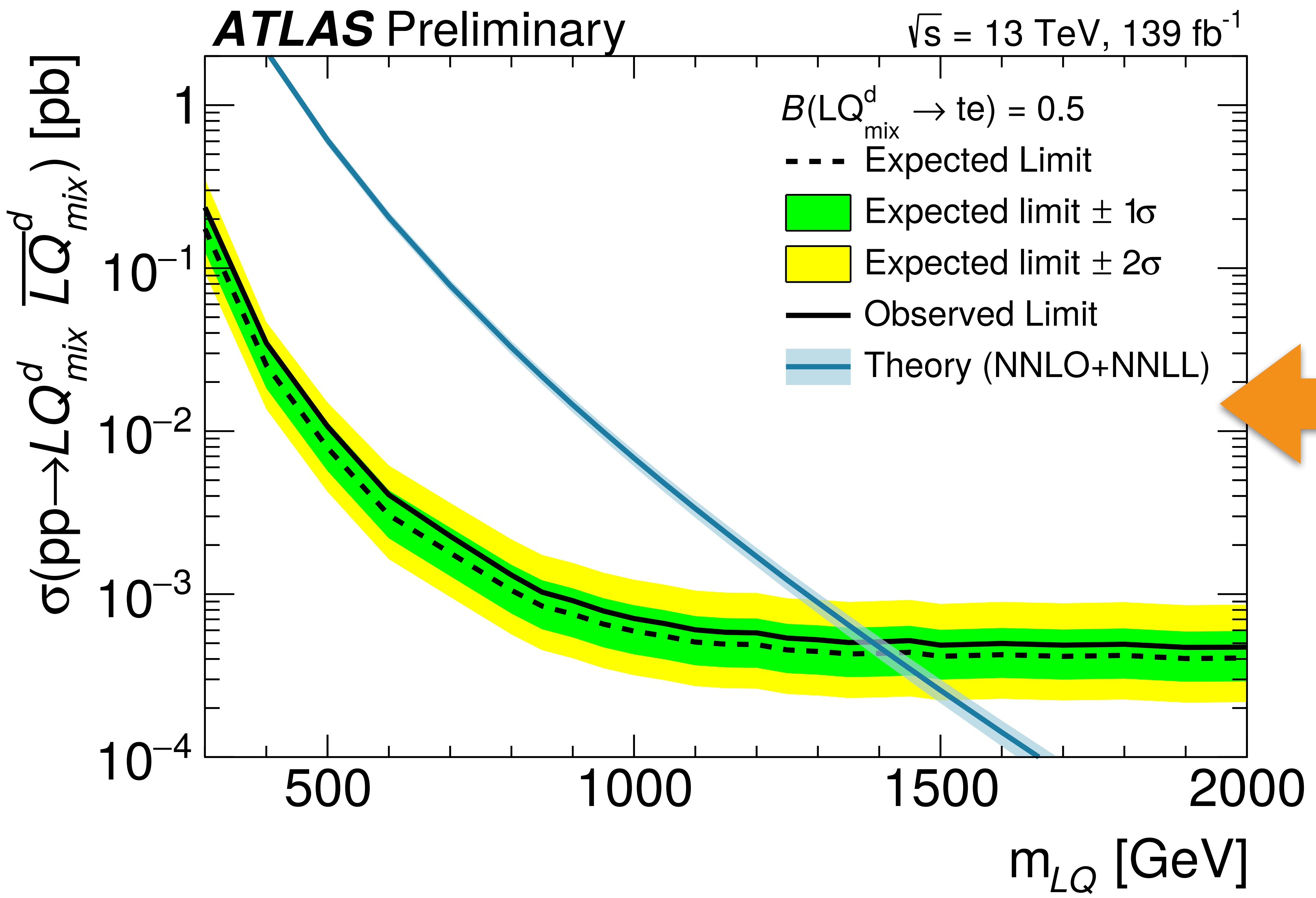


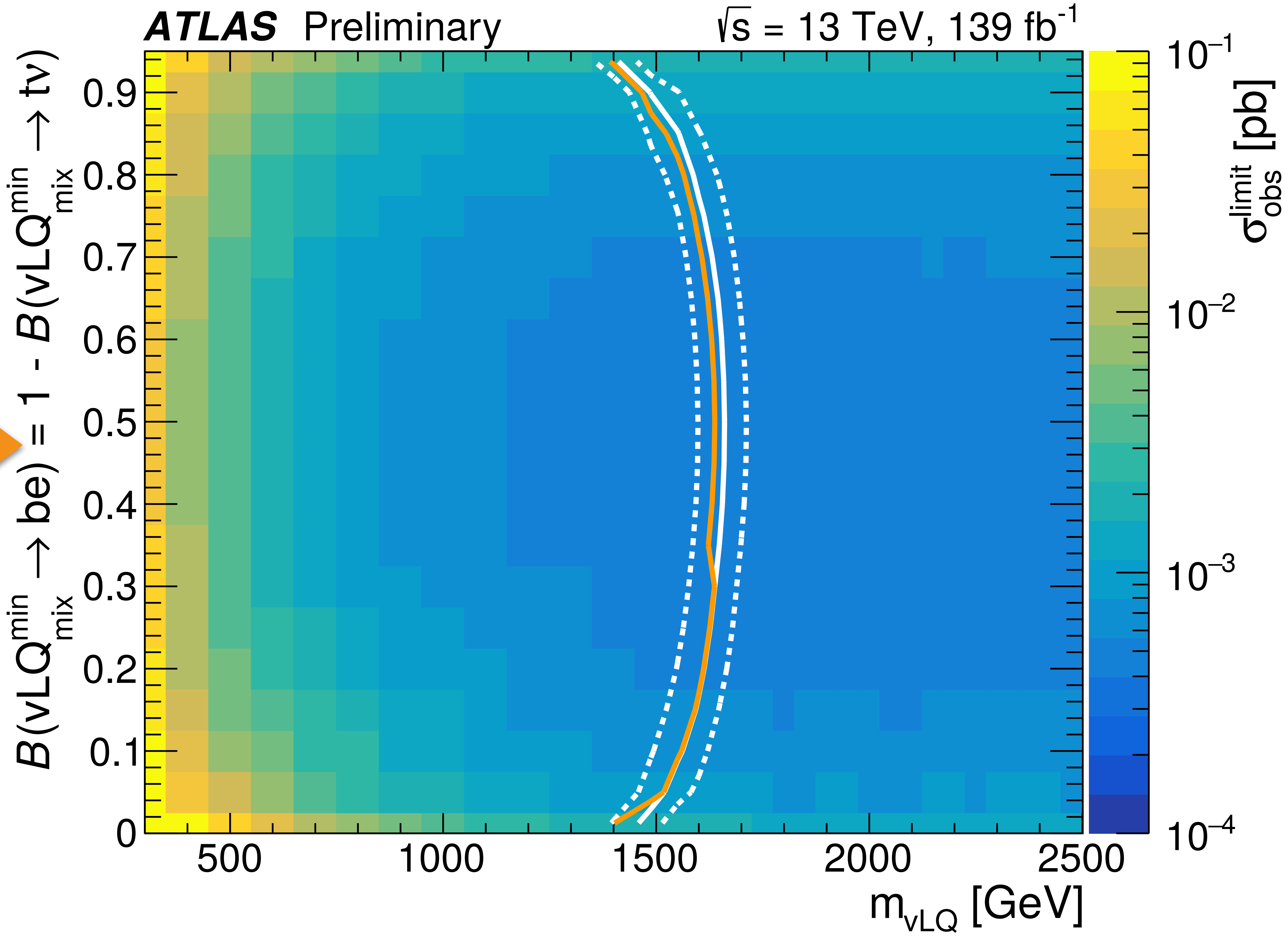


$LQ\ LQ \to bl + t\nu$

rules out a large number of possible LQ scenarios
coupling to light leptons and 3rd-generation quarks

ATLAS-CONF-2022-009;
arxiv 2201.07861



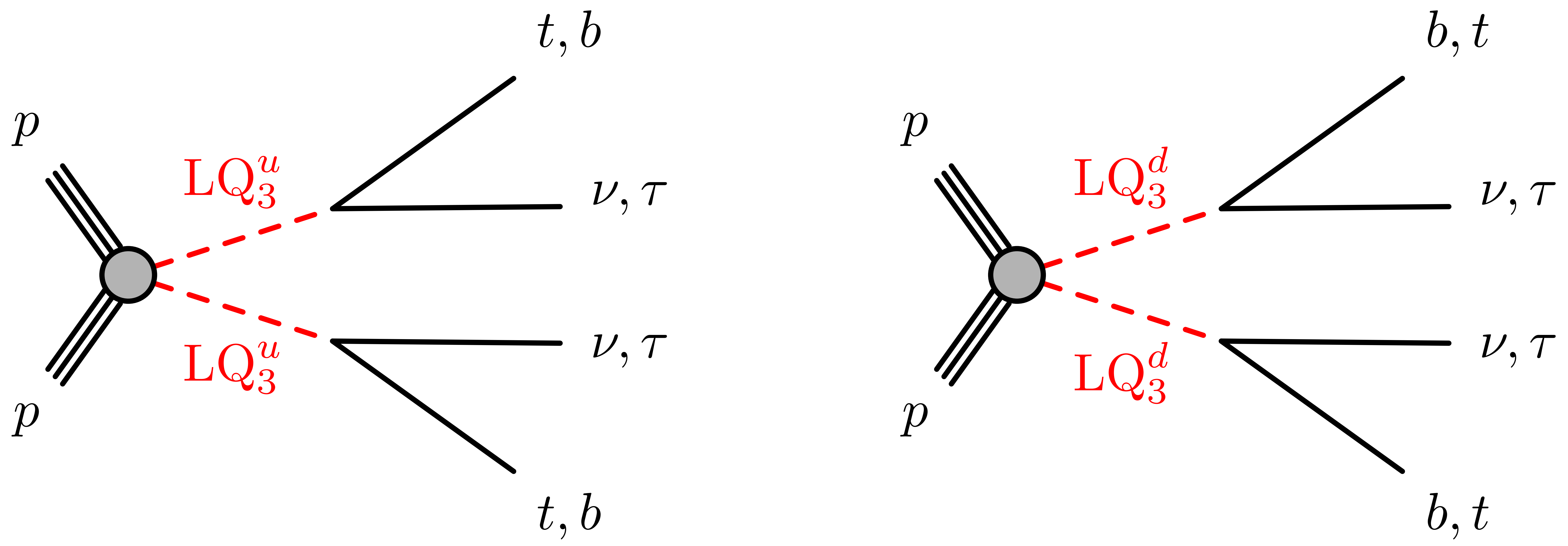


$LQ\ LQ \to b\tau + t\nu$

SUSY-2019-18; arxiv 2108.07665

this analysis targets final states
with strong third-generation couplings,

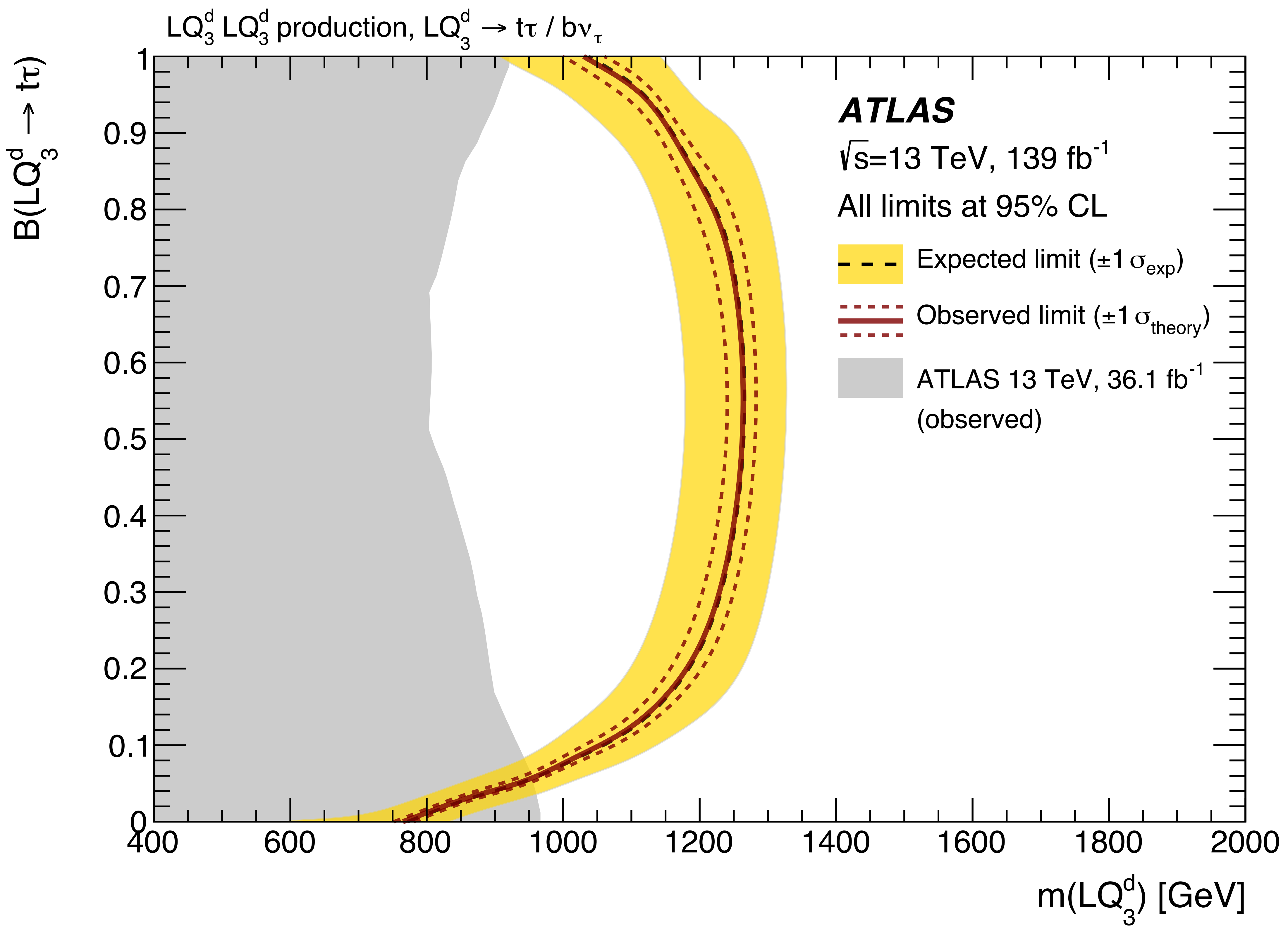
searching rather inclusively in $\tau\tau b + E_T^{miss}$

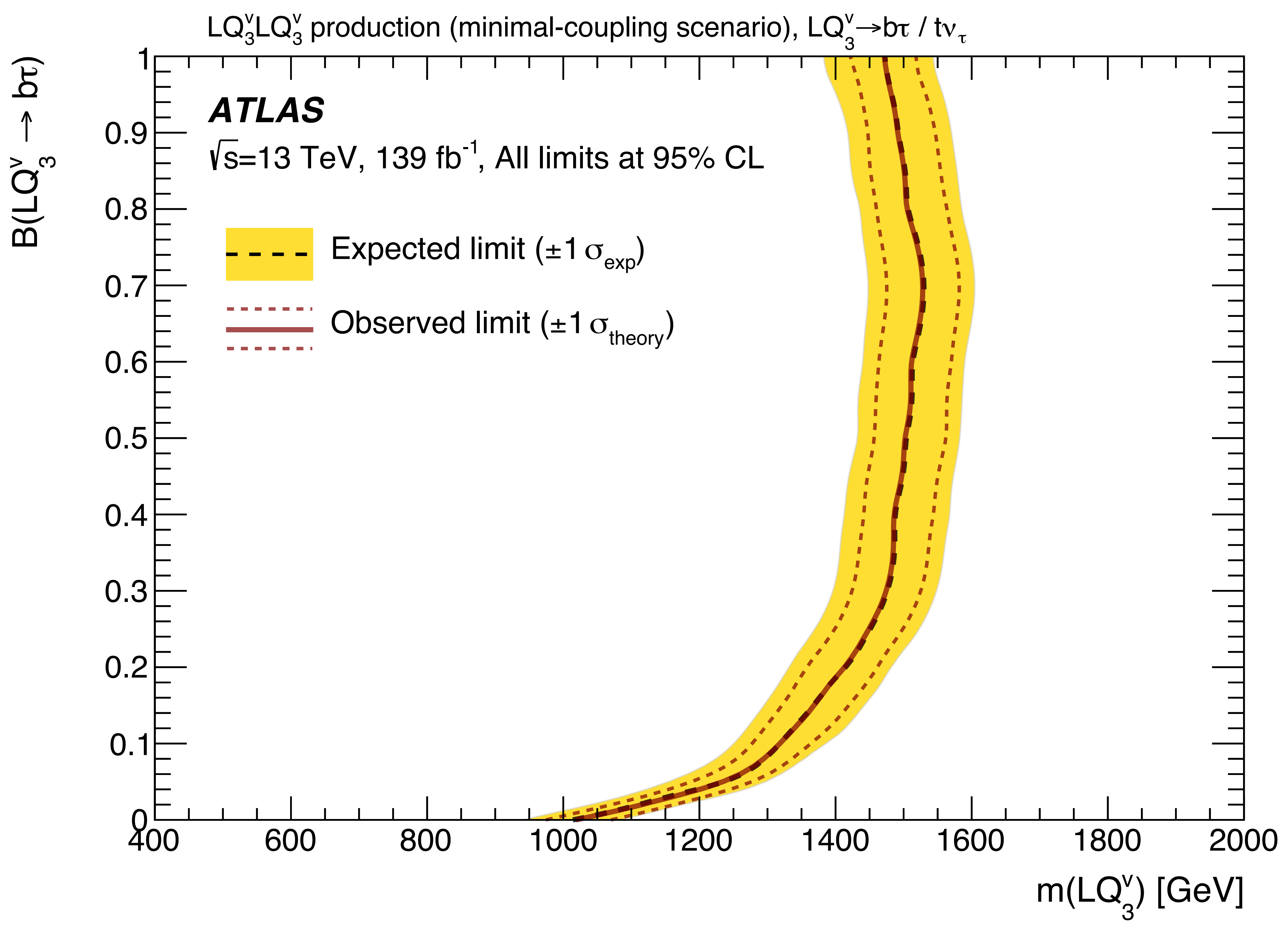


$LQ\ LQ \rightarrow b\tau + t\nu$

SUSY-2019-18; arxiv 2108.07665

rules out a large number of possible LQ scenarios coupling to 3rd-generation leptons and quarks

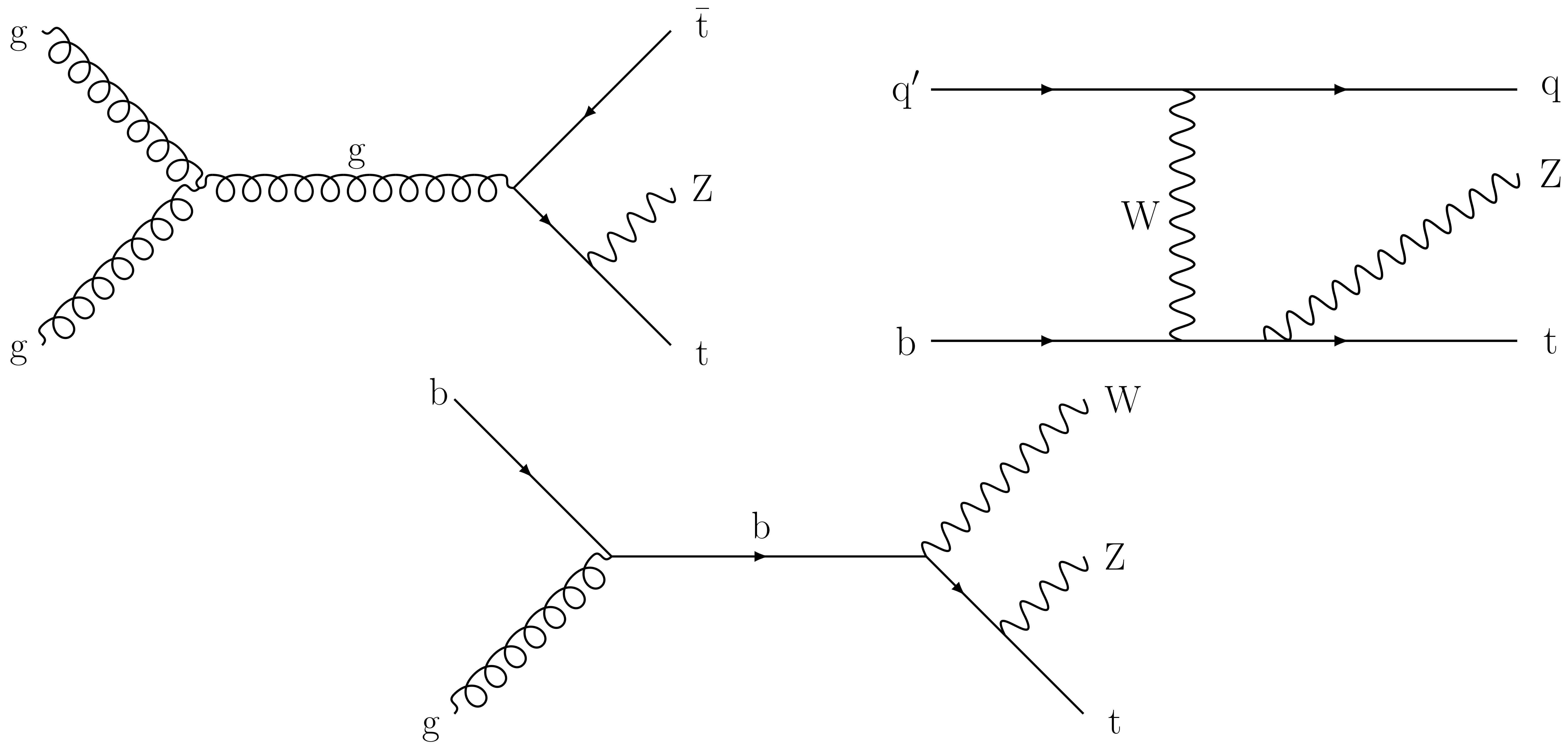




probing the $t \leftrightarrow Z$ coupling

TOP-21-001; arxiv 2107.13896

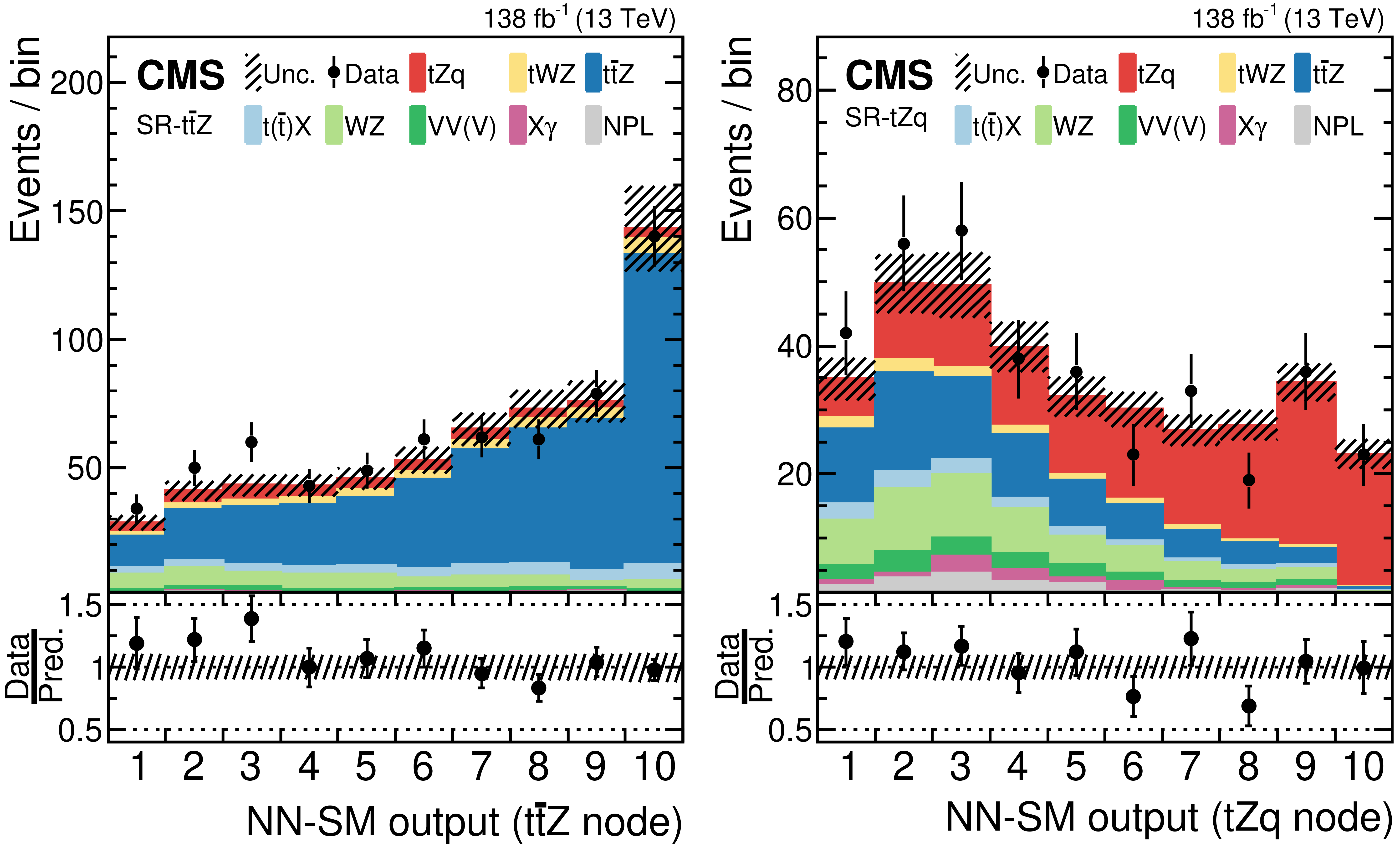
additional vector bosons with flavor-dependent coupling
can alter *apparent* ttZ cross sections and $t \to Zq$ branching fractions



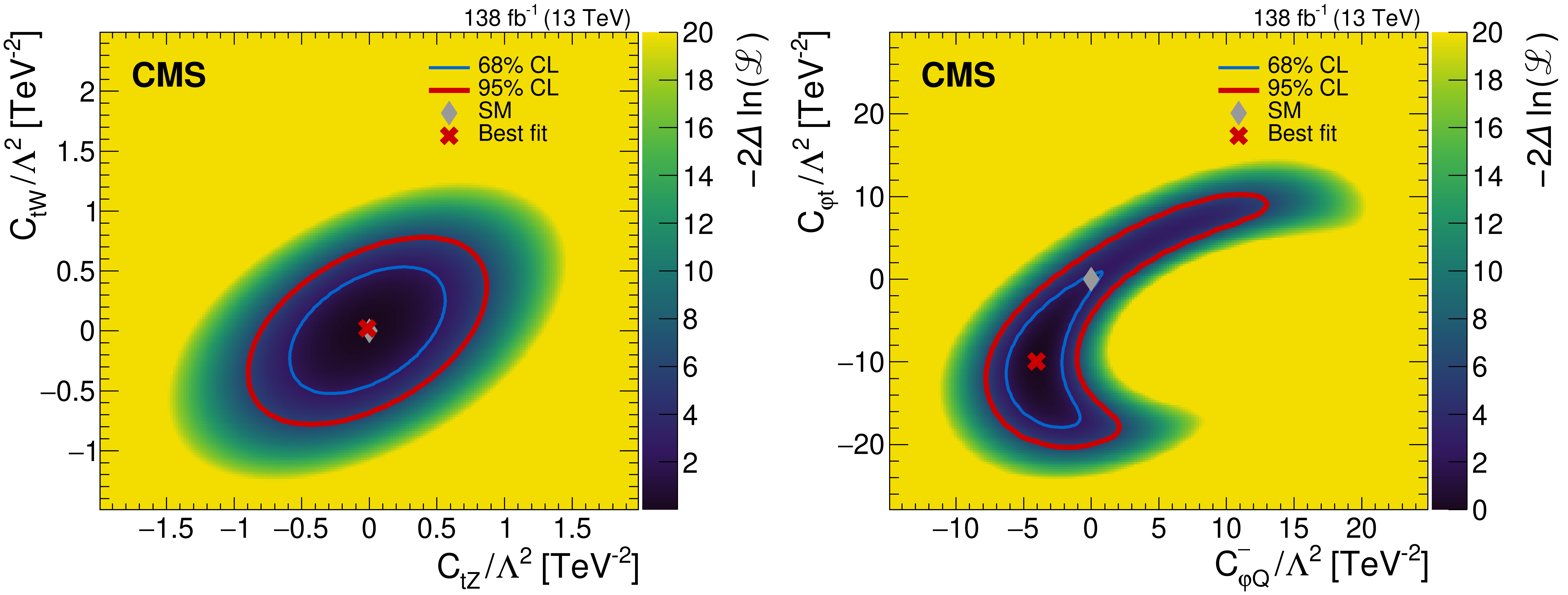
probing the $t \leftrightarrow Z$ coupling

TOP-21-001; arxiv 2107.13896

CMS have recently taken a very careful look at both processes coherently.



probing the $t \leftrightarrow Z$ coupling



new, stringent limits on tW, tZ, etc anomalous effective couplings.
could we search for for tZ' in the same way (particularly for light Z')?

multi-top final states

recall the very strong coupling to top-quarks
predicted by fits to the b-anomalies
+ other precision experimental data

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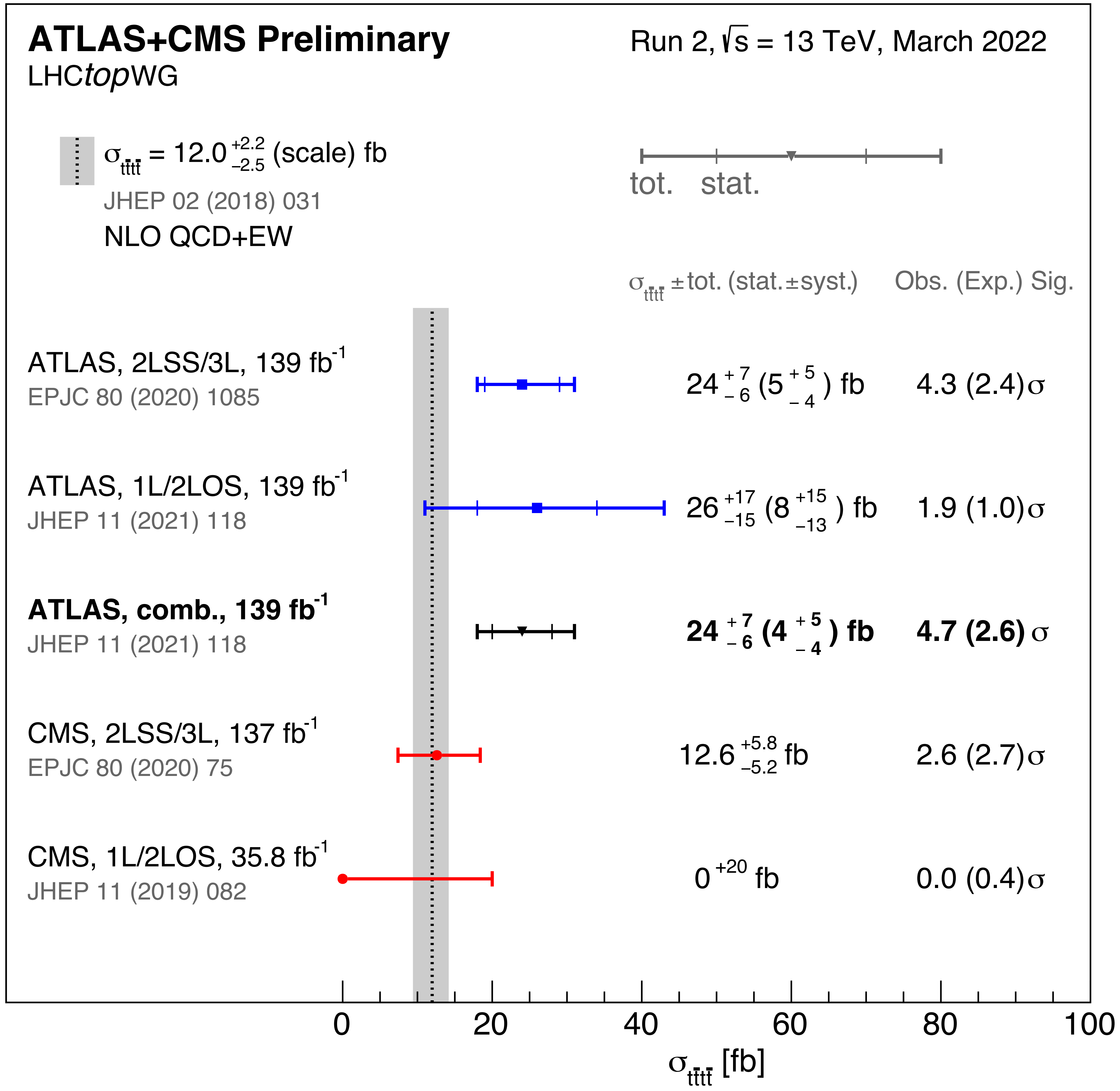
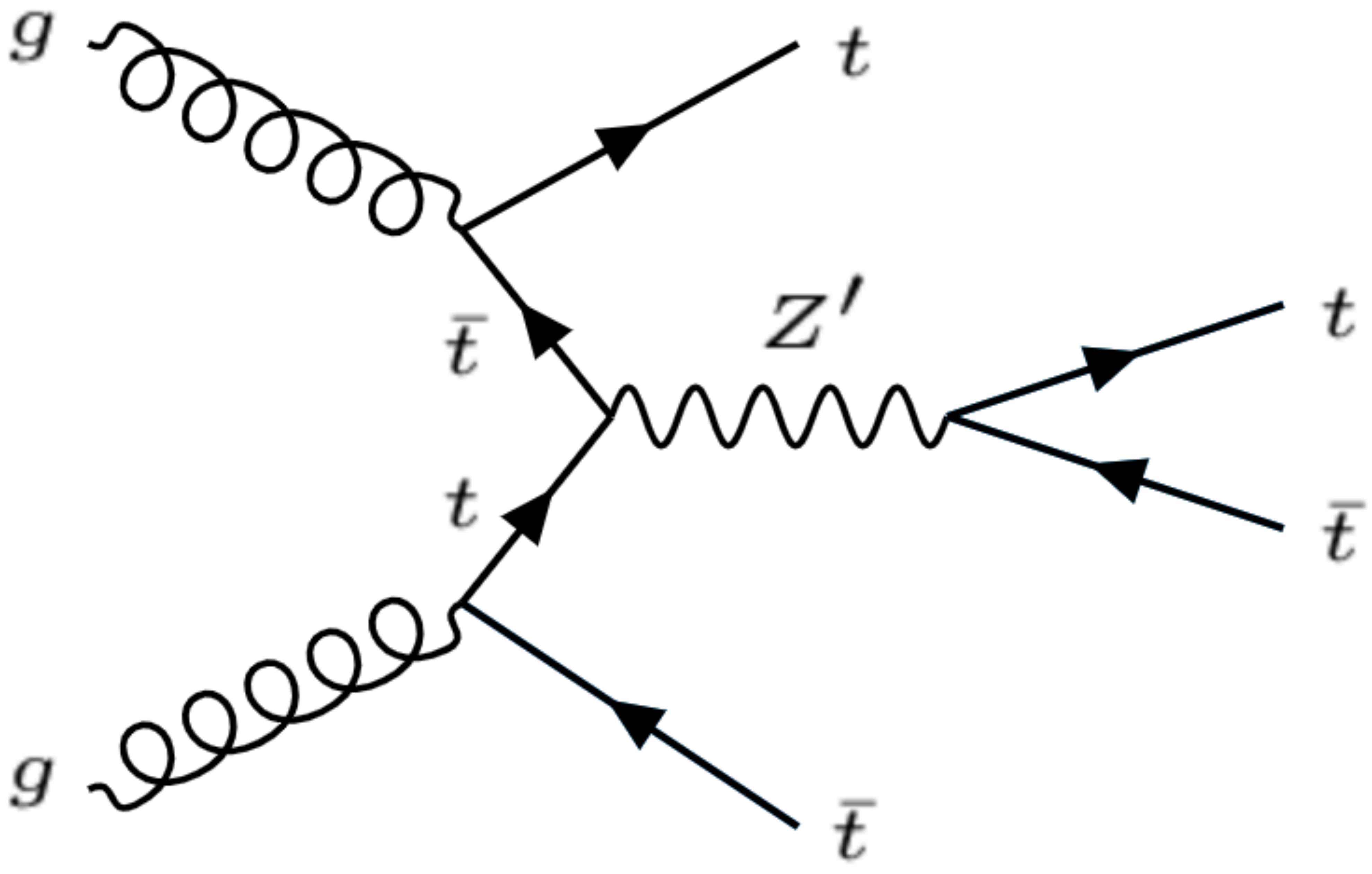
new top-philic vector bosons are in vogue!
remember that $gg \to Z' \to t\bar{t}$ is OZI suppressed.

multi-top final states

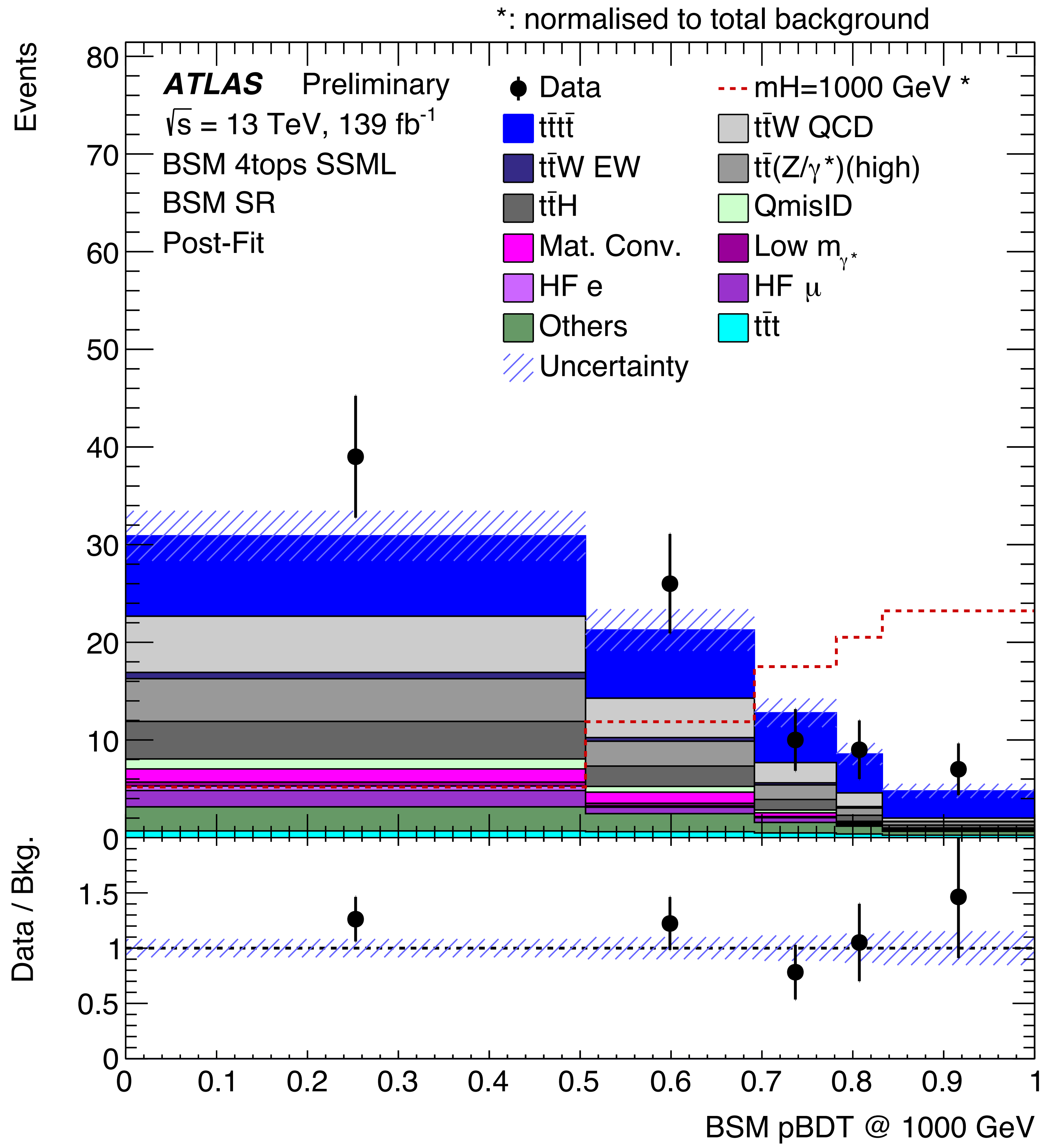


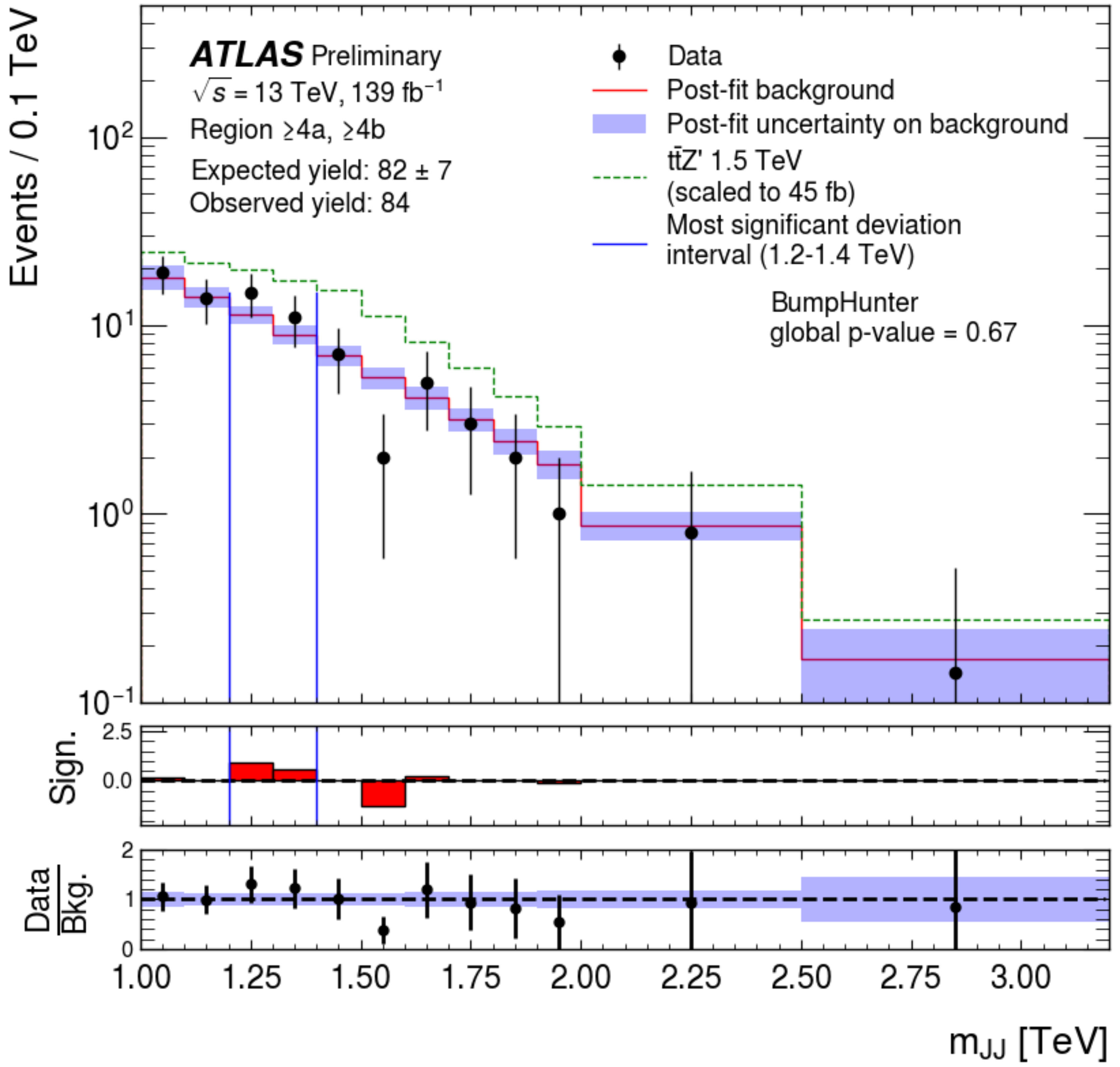


"top fusion" or "associated production" is critical to access some kinds of new physics.

multi-top final states

four-top analyses will be covered in detail by Mathis





this very well may be the best way for us to see new (flavor) physics in the top sector.

$ttbb$ and $bb\tau\tau$ also highly motivated!

are they covered?

summary

- *many* stones still left un-turned: a lot to do yet in Run 2 and 3 on this topic!
  - huge number of models with rich phenomenology to cover.
  - will be fascinating to see how high-mass, non-resonant analyses alter the picture.
- this summary is ***far from exhaustive*** in covering experimental probes of the b-anomalies…
- the top quark certainly has a part to play in unraveling observations in B-physics.
  - via W decays, b decays, or direct couplings.

bonus

useful (theory) references

- flavor anomalies workshop: https://indico.cern.ch/event/1055780/timetable/
- B Allanach: https://conference.ippp.dur.ac.uk/event/1030/contributions/5287/attachments/4329/5252/manifesto.pdf
- A Crivellin: https://conference.ippp.dur.ac.uk/event/1030/contributions/5288/
- reading footprints in the anomalies: https://arxiv.org/pdf/2103.16558.pdf
- LQ solutions to $B_s \to \ell\ell$: https://arxiv.org/pdf/2103.12504.pdf
- EFT for $B_s \to \ell\ell$: https://arxiv.org/pdf/2110.09882.pdf

CMS dilepton A_{FB}

SMP-21-002; arxiv 2202.12327

2.4σ discrepancy with lepton universality in ΔA_{FB}