Efforts in ATLAS and CMS on Flavor Anomalies

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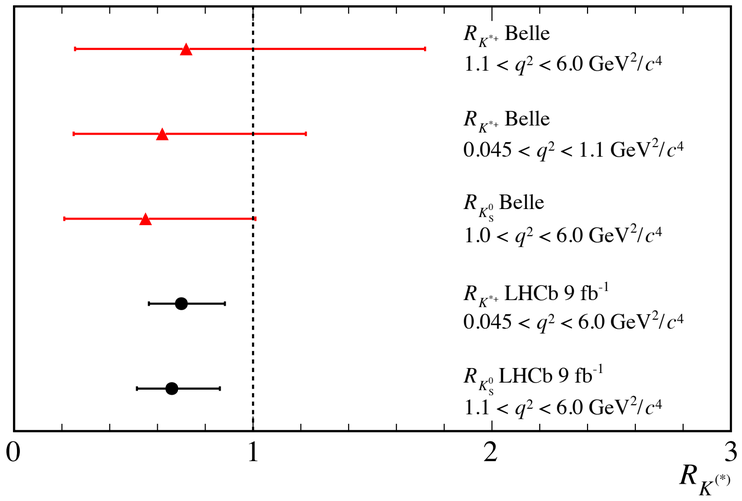
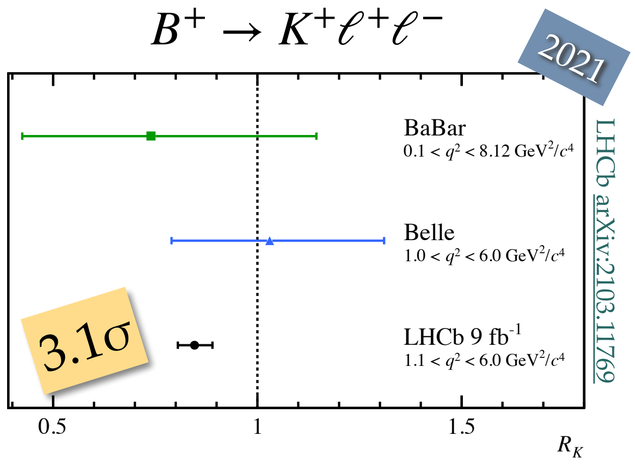
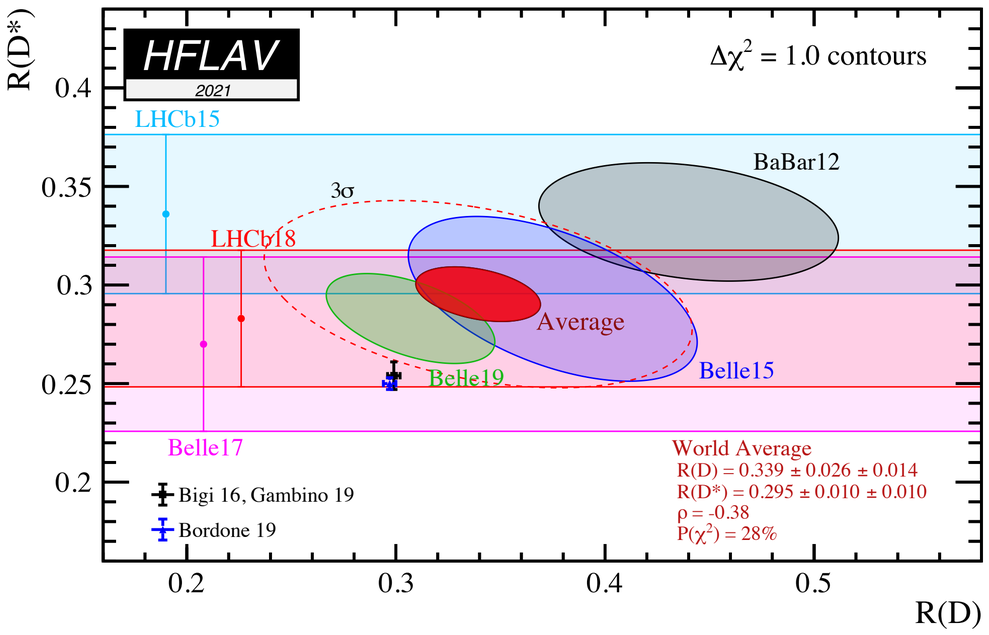
CERN

A two-front mission

- Flavor physics
  - We have hints of discrepancies, but not an established breaking of SM expectation
    - R(D),R(D*) pull is driven by BaBar
    - R(K) and R(K*) are driven by LHCb
    - Independent checks by other experiments are welcome. Waiting for Belle II, CMS and ATLAS are doing something about it

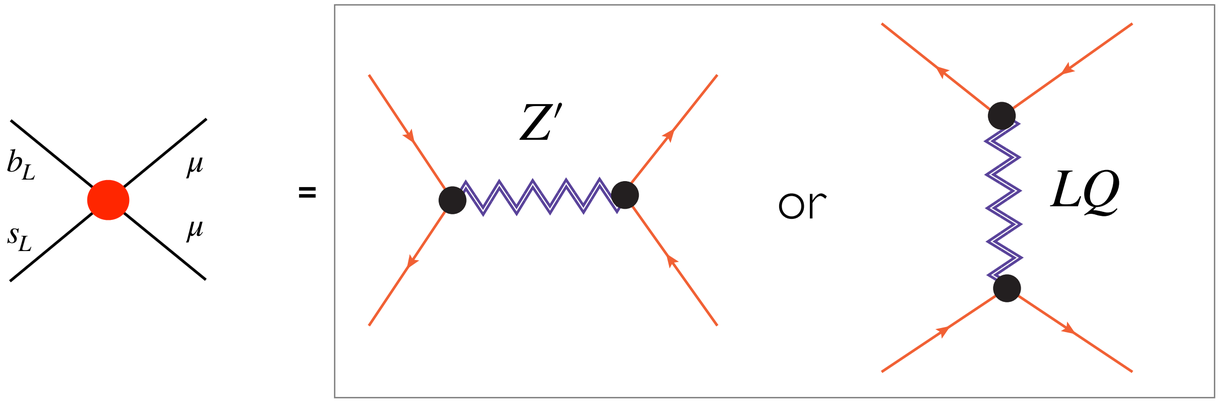




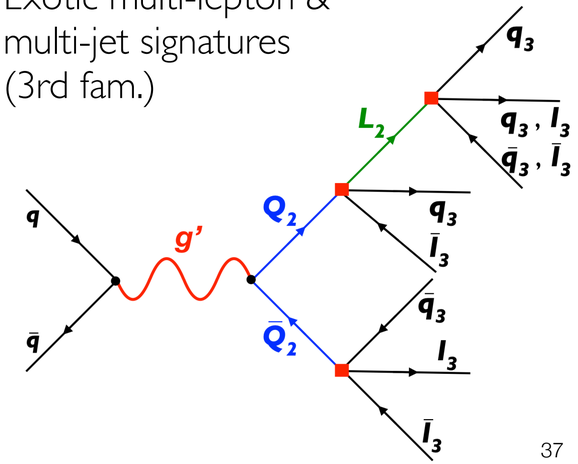


A two-front mission

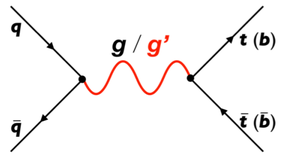
- *High-pT searches*
  - *Z' and LQ searches are the main explanations for what is seen in B decays. Searching for Z' and LQs are part of our physics program since Run I*
  - *In this context, additional features (e.g., associated b-jet, 3rd-generation dominance etc.) can be exploited to improve sensitivity*
  - *More complete New Physics models open the possibility to apply SUSY-like methods (e.g., long-chain decays vs. reconstructing the LQ particles)*
  - *New opportunities (e.g., t-channel mediation)*
  - *See this talk at the CERN Flavor Anomalies workshop from October 2021*



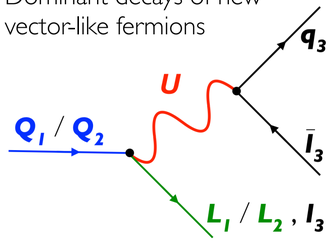
Exotic multi-lepton & multi-jet signatures (3rd fam.)



Third-generation high-p_T signatures

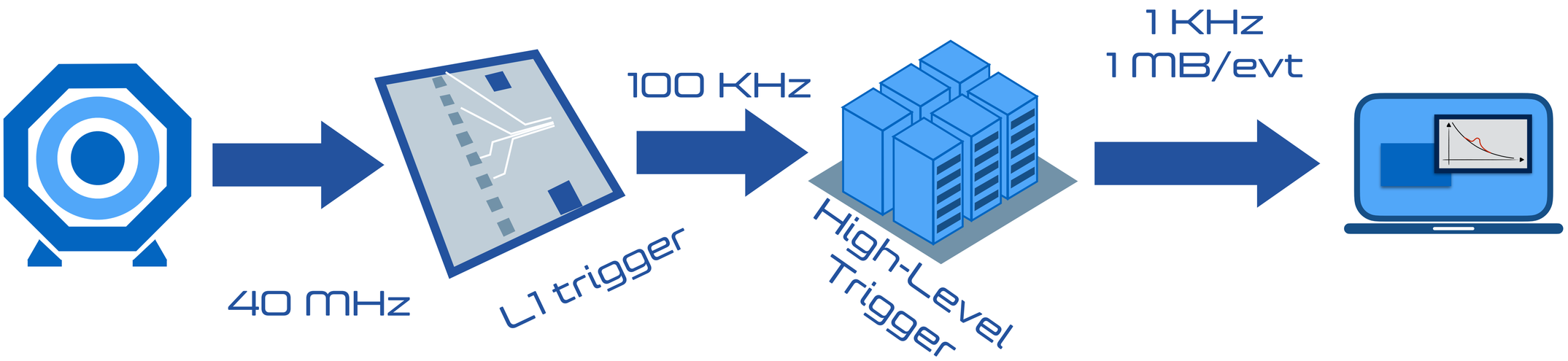


Dominant decays of new vector-like fermions



Flavor Physics

B physics in a non-dedicated experiment

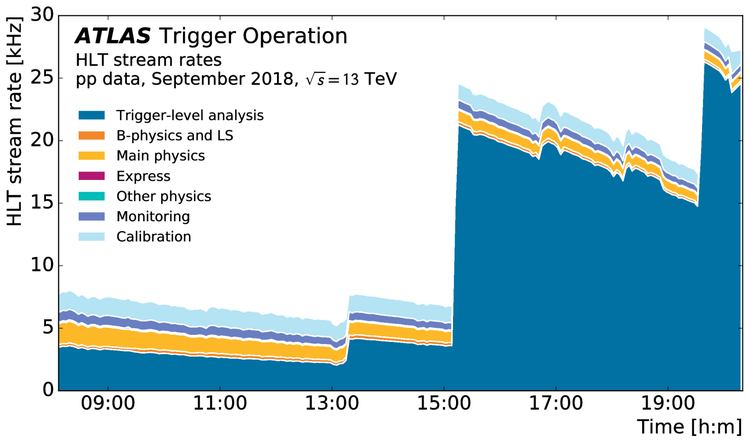


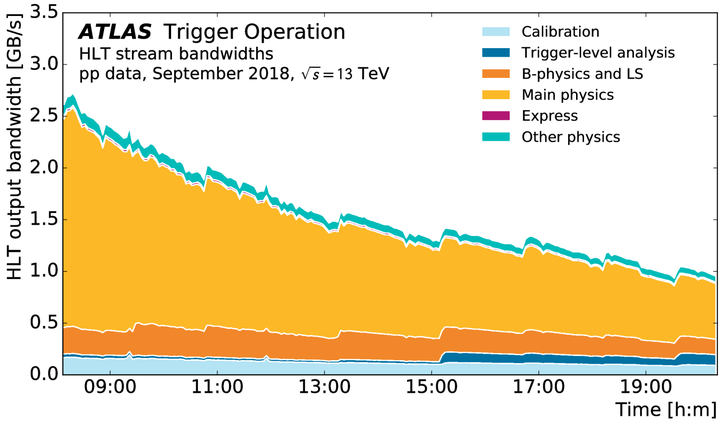
- *We are budgeted for ~1000 evt/sec (we could take more, but we run in troubles with offline resources)*
  - *Experiments dedicate ~ 10% of their resources to B physics*
  - *In special conditions, we can go beyond that (e.g., with B-parking)*

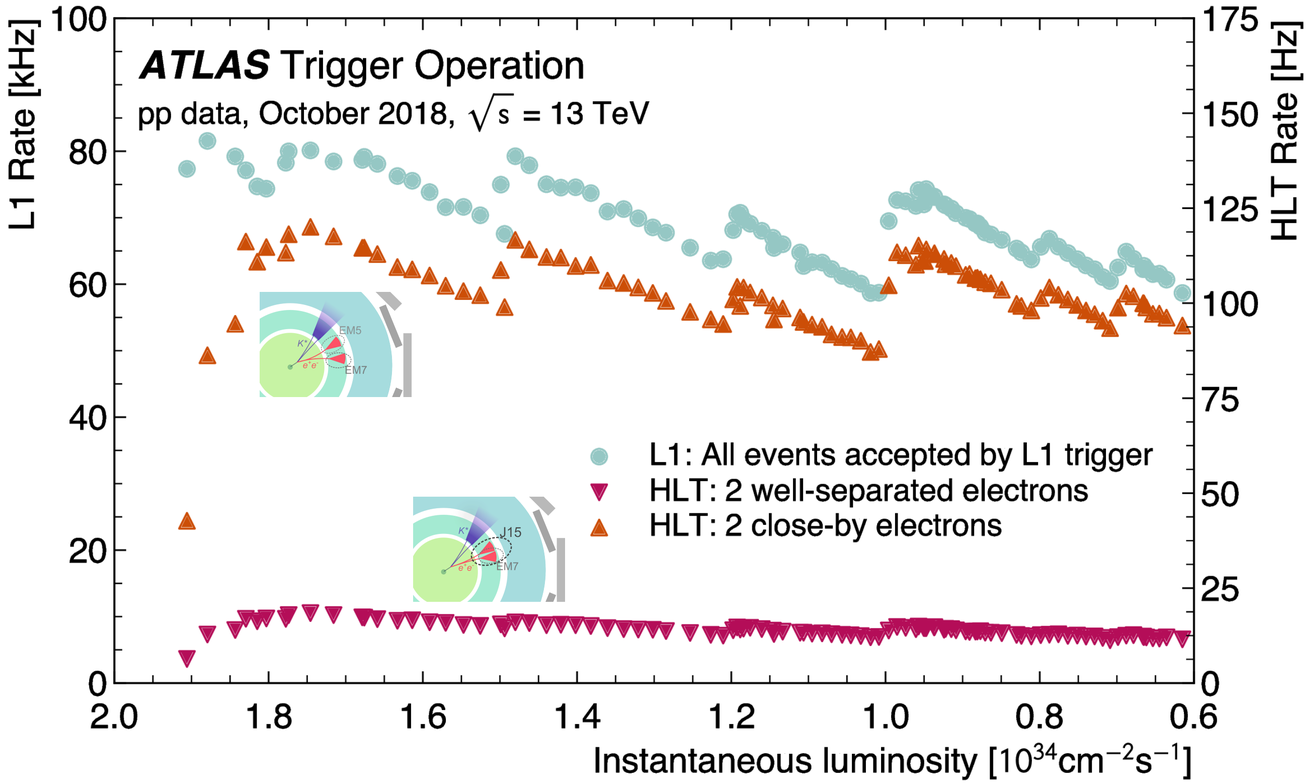
B physics in a non-dedicated experiment

- *The biggest challenge is to trigger on soft particles*
- *Electrons are particularly challenging*
- *ATLAS and CMS are investing resources on this*
  - *ATLAS successfully deployed dielectron triggers (merged and resolved) taking ~ 100 Hz by themselves*

ATLAS-DAQ-PUB-2019-001/

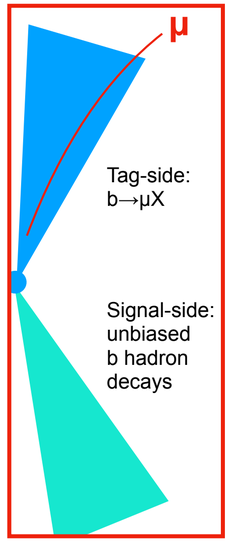


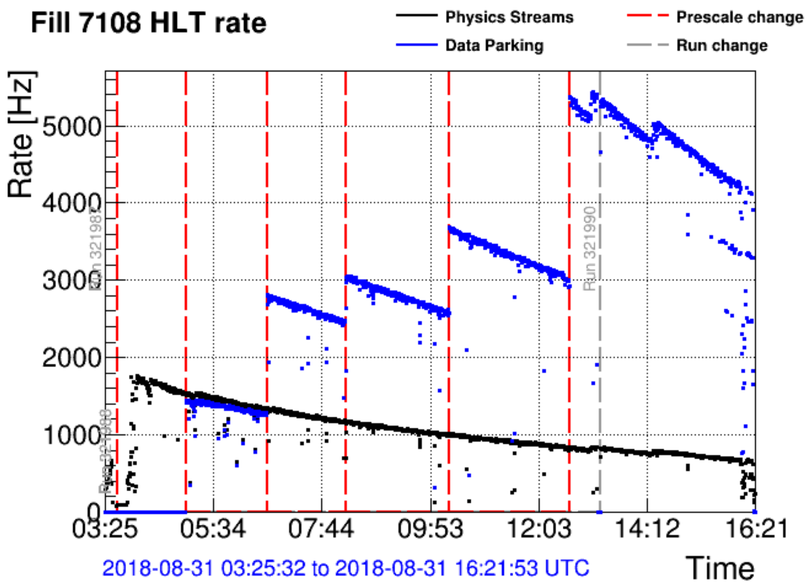


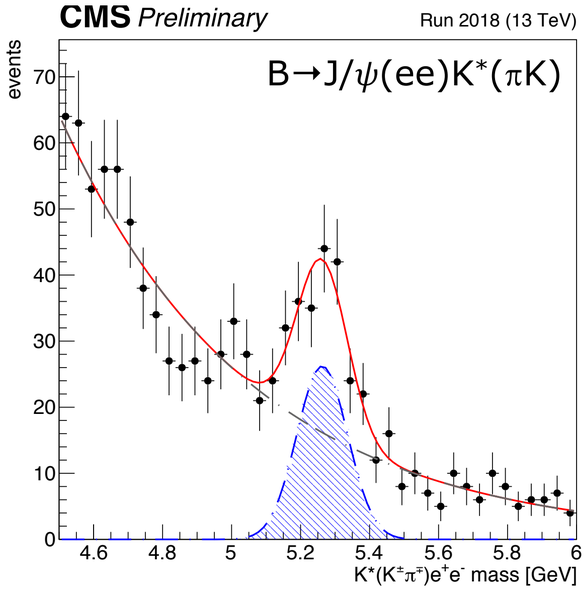


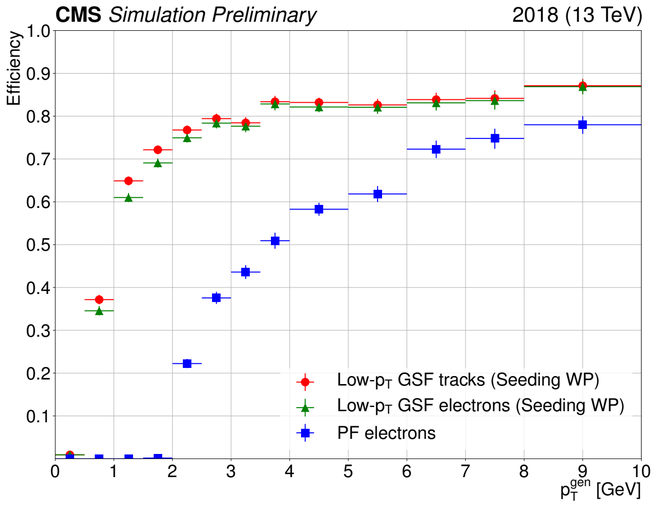
B physics in a non-dedicated experiment

- CMS took data in 2018 at the end of the fill, when luminosity goes down and the other triggers take less resources
- Trigger strategy based on one displaced muon
- These data were parked since no CPU resources to process them promptly
- They were processed in 2019 and we are now analysing them
- Early studies showed the capability of seeing soft electrons, thanks to a custom electron ID





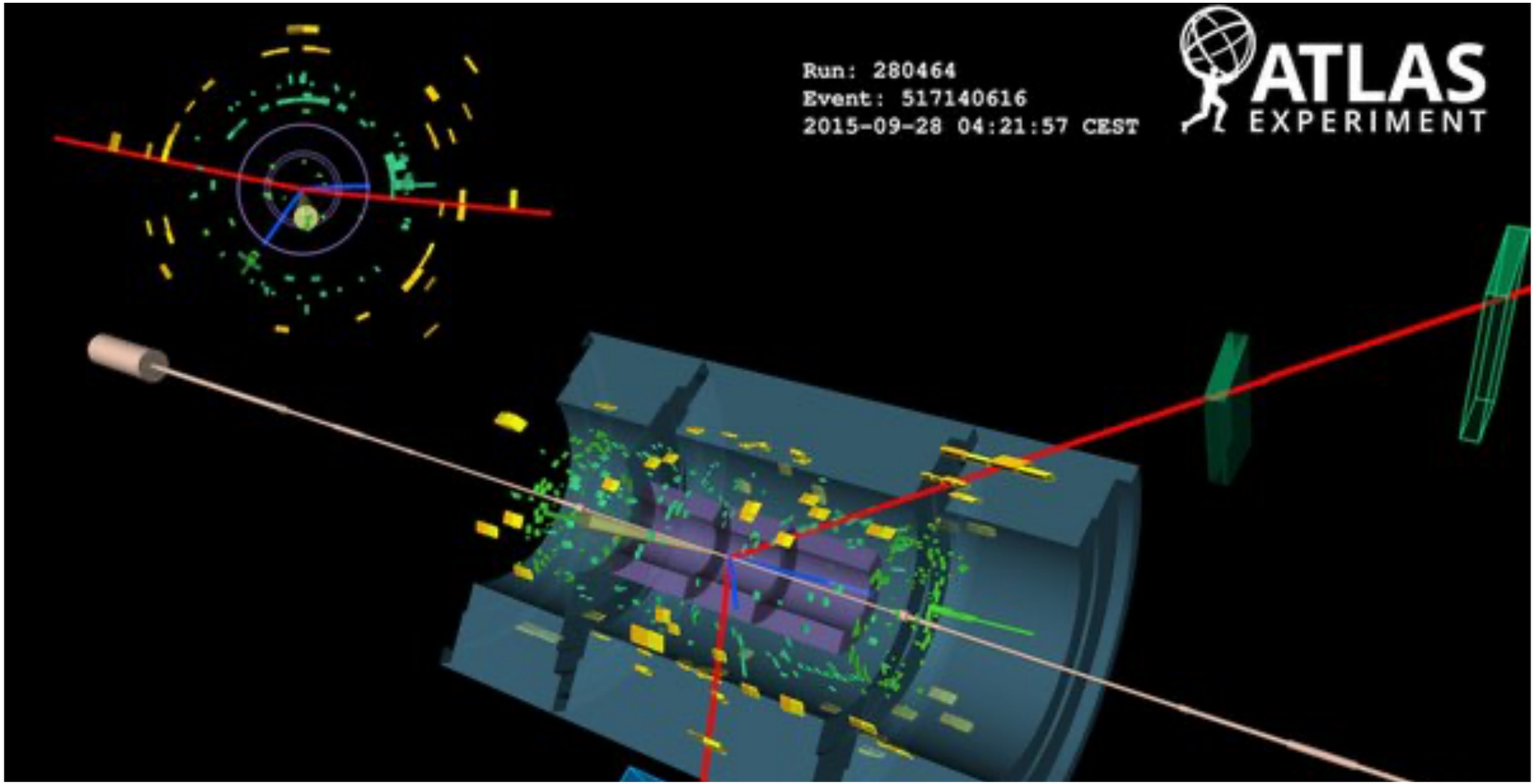




CMS-DP-2019-043

Plans for Run3

- *Both experiments learned from what was done in Run2*
  - *Trigger and analysis strategy improved*
  - *Aiming at producing results during Run3*
- *We hope that this will help to clarify the situation*


Run: 280464
Event: 517140616
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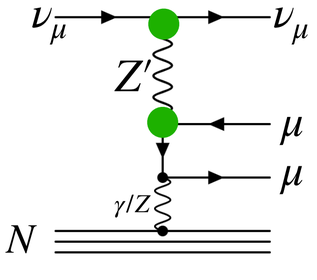
ATLAS
EXPERIMENT

Z' searches

Allowed mass range

- A Z' could be anywhere between a few GeV and O(10) TeV
- Since Run1, we are searching for it on the whole mass range accessible at the LHC

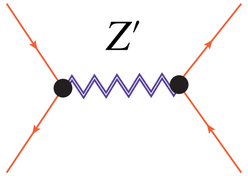


[Altmannshofer, Gori, Pospelov, Yavin 2014]

Neutrino trident production

(production of muon pairs when muon neutrinos scatter off a nucleus)

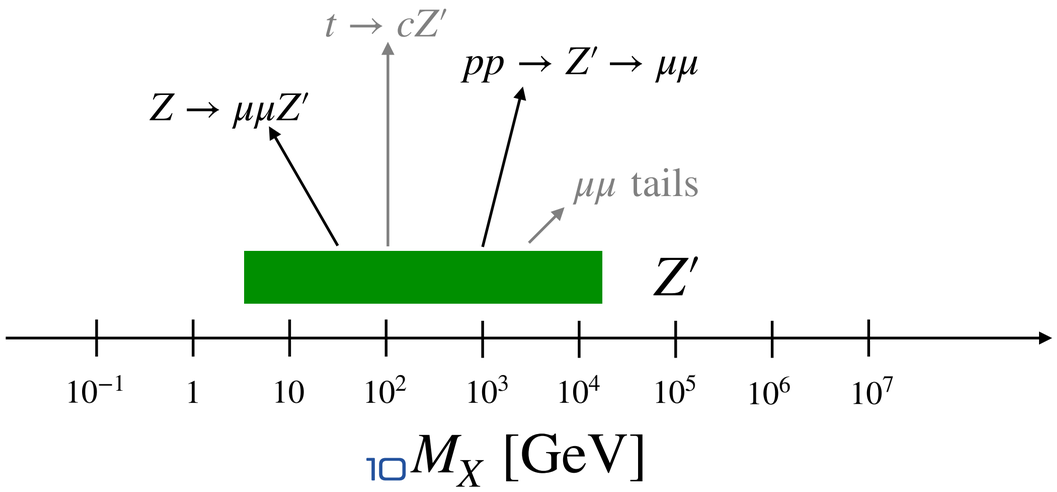
Can be evaded if Z' is not too light



- Tree-level $b \to s\ell\ell$ $\frac{1}{(40\,\text{TeV})^2} = \frac{g_{bs}g_{\mu\mu}}{M_{Z'}^2}$
- Tree-level $B_s - \bar{B}_s$ oscillations $\propto \frac{g_{bs}^2}{M_{Z'}^2}$

$$\Longrightarrow \sqrt{4\pi} \gtrsim g_{\mu\mu} > \frac{M_{Z'}}{5\,\text{TeV}}$$

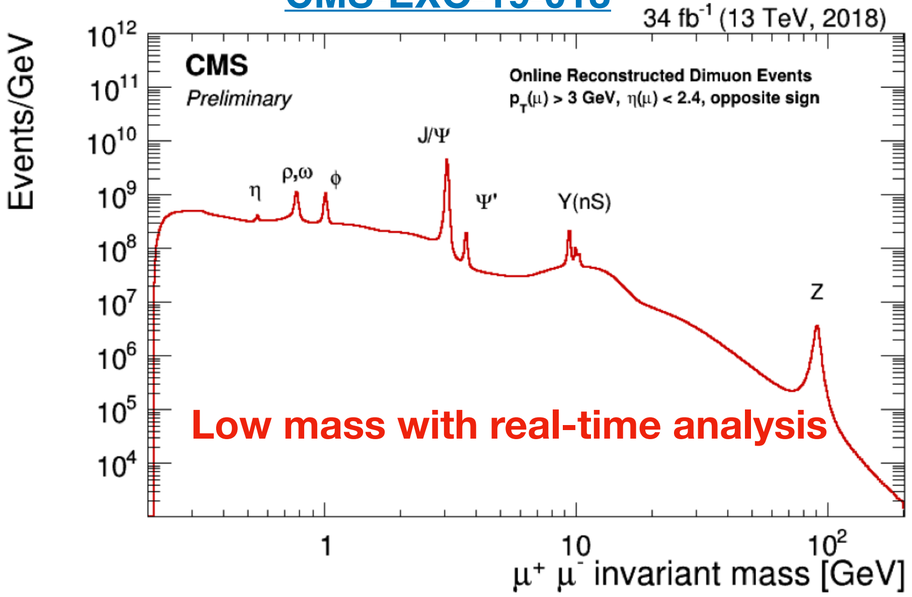
~ Mass Lower Limit

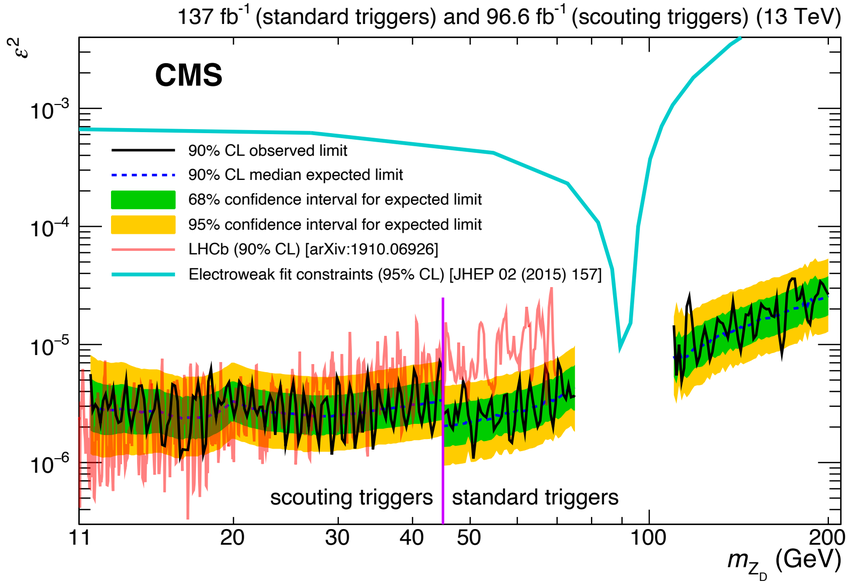


~ Mass Upper Limit

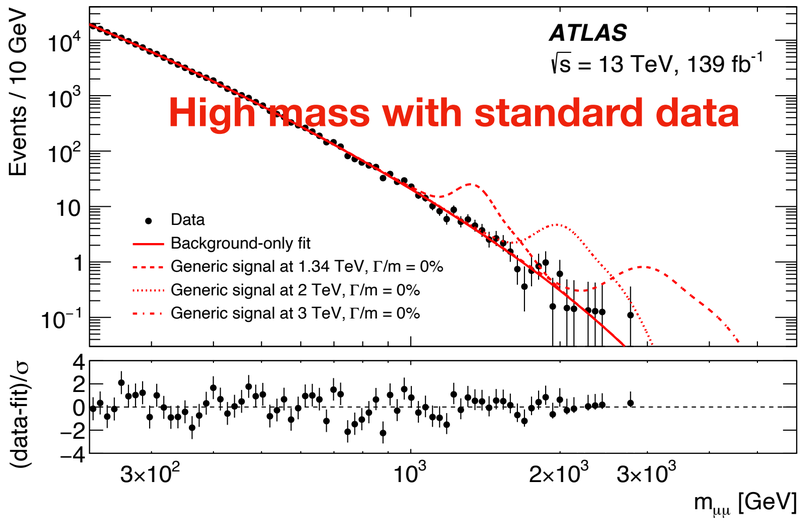
Z' searches

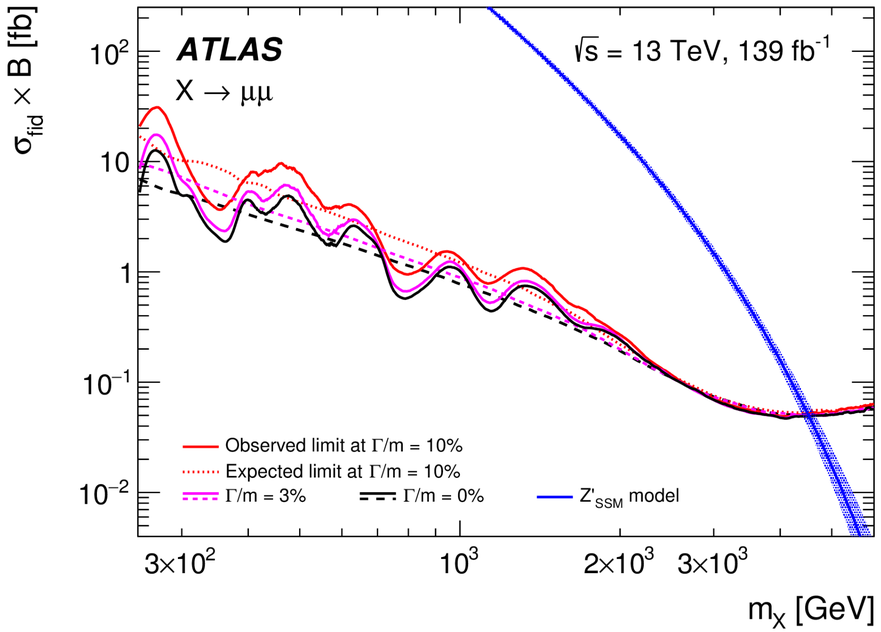
CMS-EXO-19-018





ATLAS-EXOT-2018-08





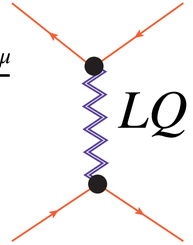
“front” “back”

Leptoquark

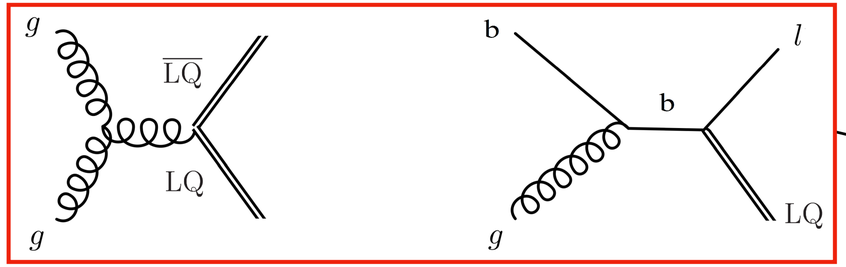
Mass ranges

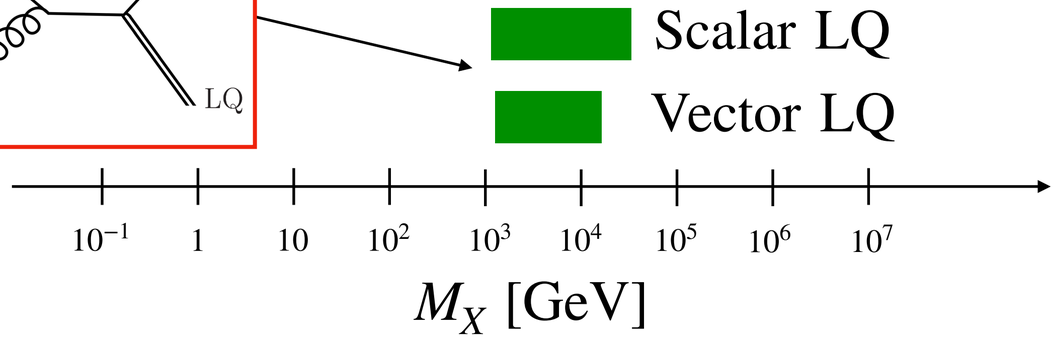
- *Also LQ bounded from above (at ~ 10 TeV)*
- *Lower bound from searches at the LHC (single and pair production)*

- Tree-level $b \to s\ell\ell$ $\quad \frac{1}{(40\,\mathrm{TeV})^2} = \frac{g_{b\mu} g_{s\mu}}{M_{Z'}^2}$
- One-loop $B_s - \bar{B}_s$ oscillations. Vector LQ comes with the Z'.



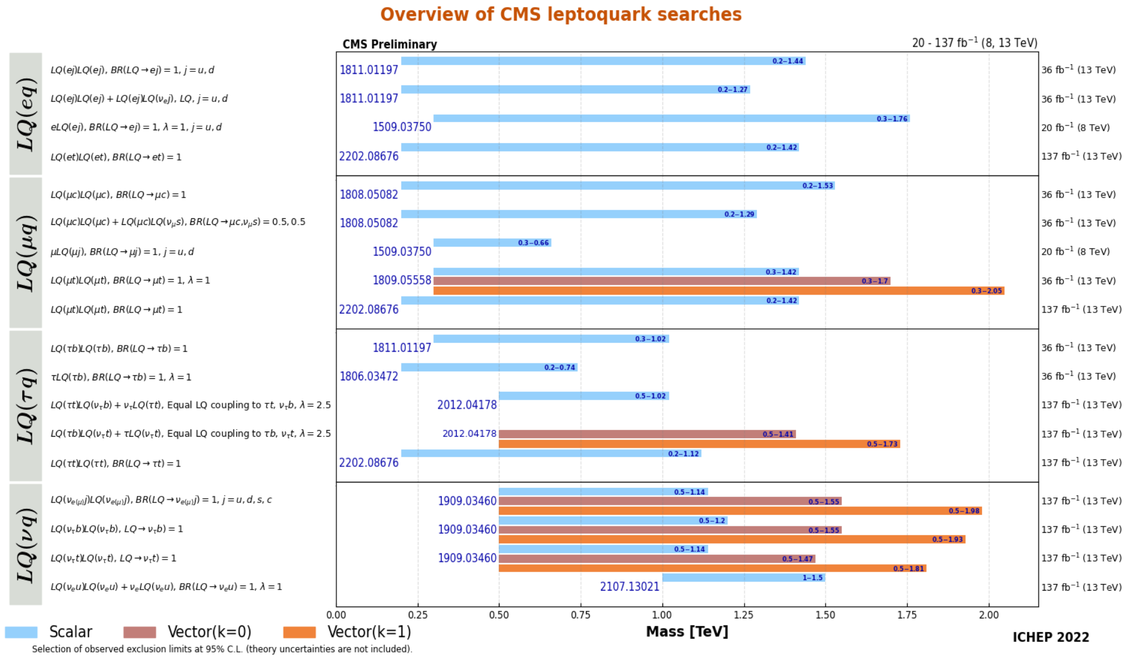
- LHC bounds: LQ pair production $m_{LQ} \gtrsim 1\,\mathrm{TeV}$



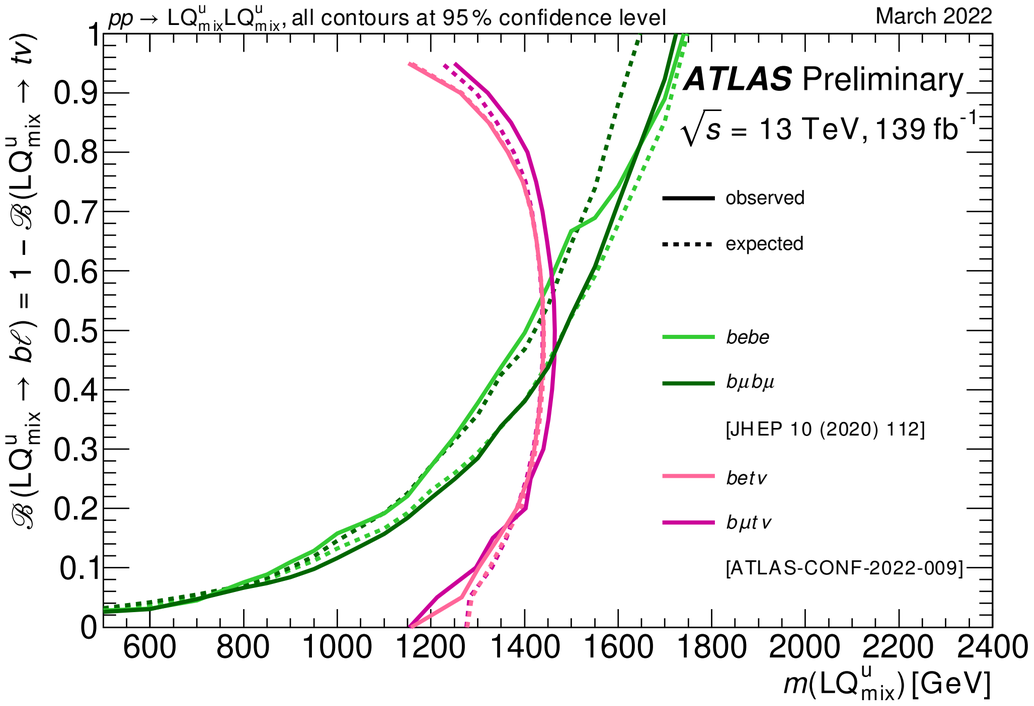


We Search for Any LQ

- *Double and single production, more recently) t-channel*
- *For LFUV, 2nd & 3rd generation LQs are more relevant (bτ, bμ, etc)*



[CMS-SummaryPlots-EXO13TeV#Leptoquark]

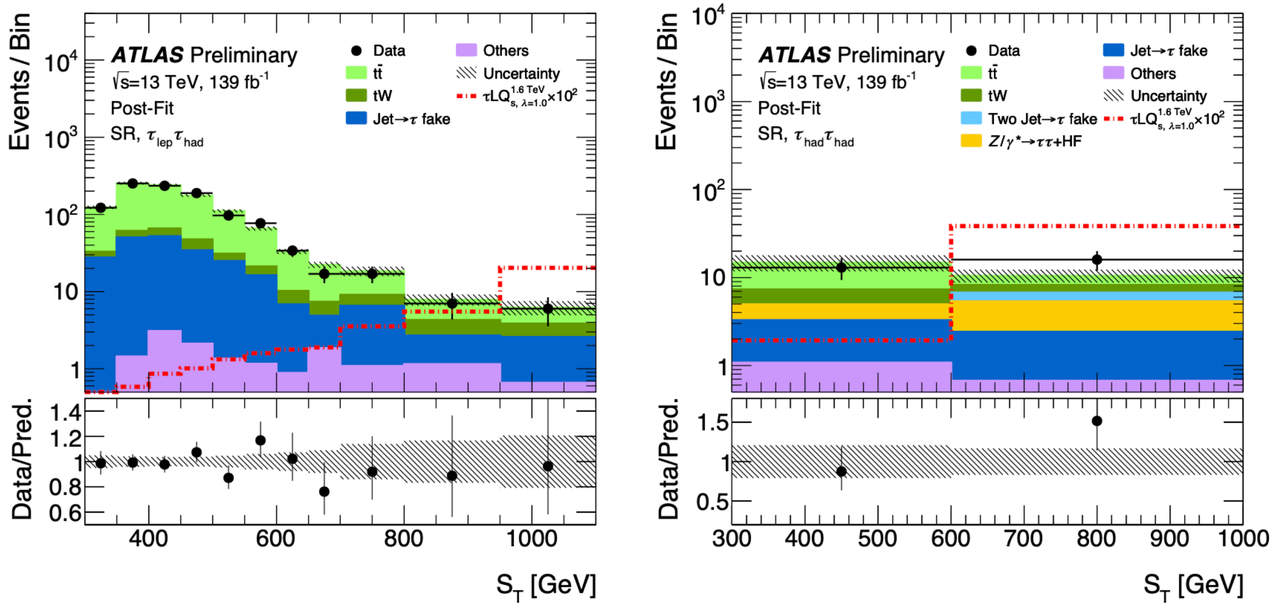


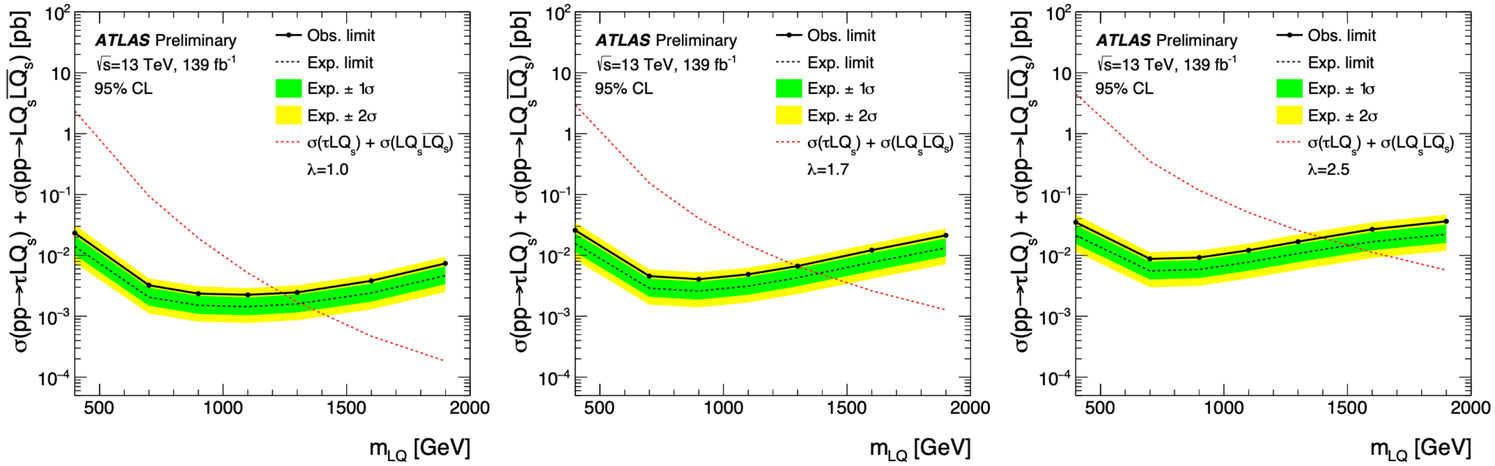
[ATL-PHYS-PUB-2022-012]

Strategy and Results

- Searches carried on in a similar way that an inclusive SUSY search
  - Selection of final-state objects (leptons and jets)
  - Events separated in various categories, matching different topologies)
  - Background measured in control regions and scaled to signal
  - Signal probed through the distribution of an inclusive kinematic quantity (S_T) of functions of them (ML classifiers)
- Often sensitive to multiple production mechanisms

ATLAS-CONF-2022-037



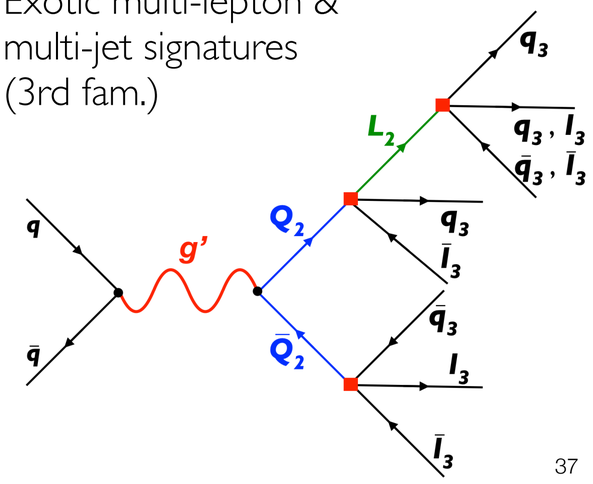


Other Searches

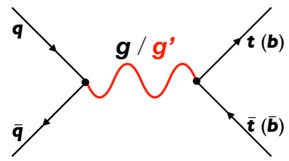
Beyond single-particle searches

- *A structured explanation of the anomalies (e.g., 4321 model) imply a SUSY-like scenario*
  - *production of heavy colored particles*
  - *cascade decays to lighter states*
  - *multi-body final states with quarks and leptons*
  - *expected third-generation dominance*

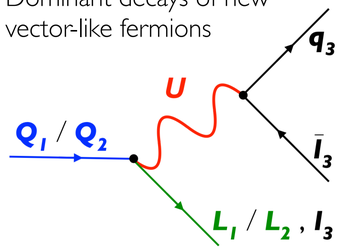
Exotic multi-lepton & multi-jet signatures (3rd fam.)



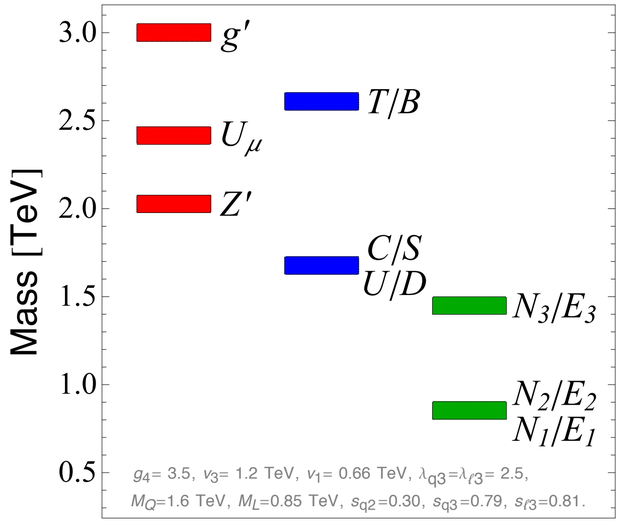
Third-generation high-p_T signatures



Dominant decays of new vector-like fermions



Benchmark spectrum



Di Luzio, Fuentes-Martin, AG, Nardecchia, Renner; 1808.00942

Beyond single-particle searches

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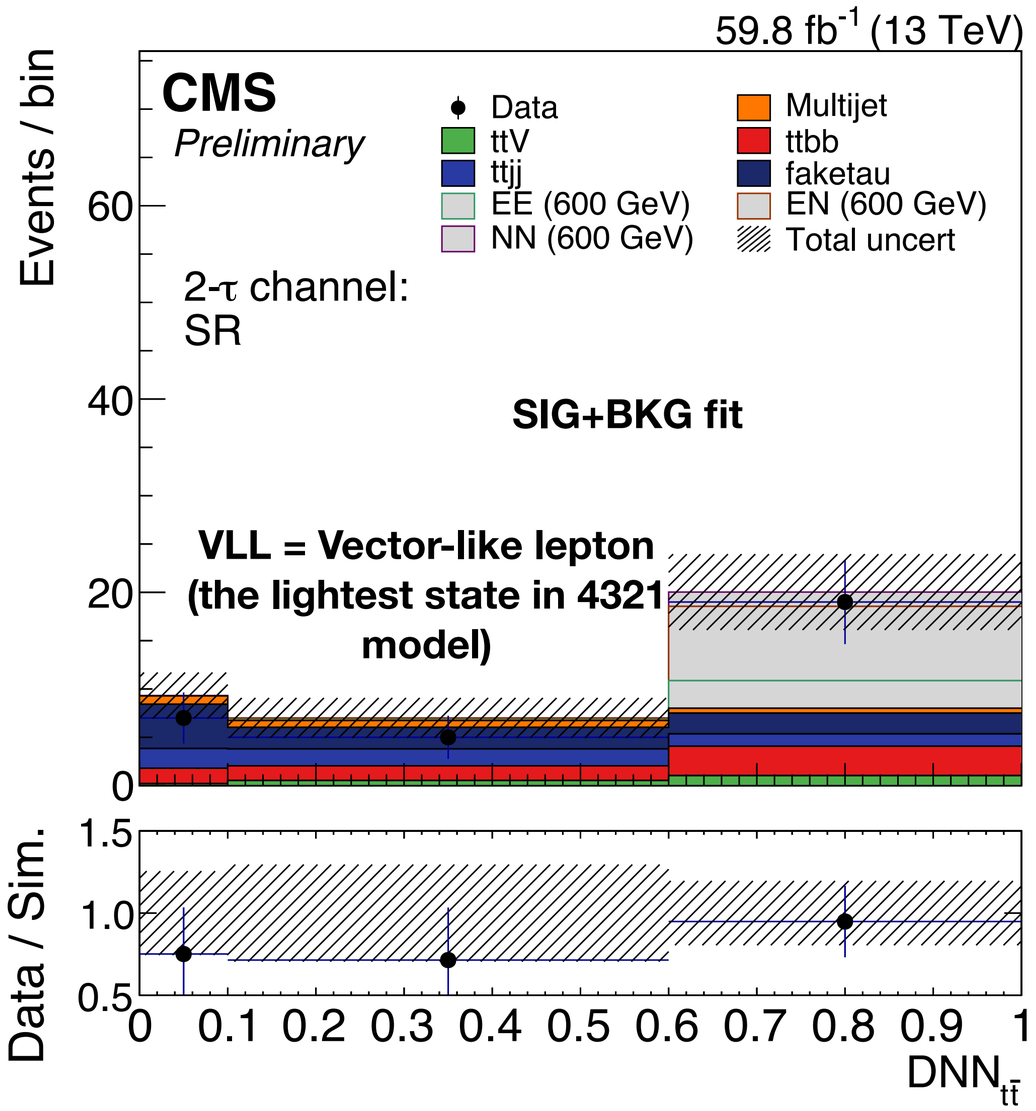

CMS-B2G-21-004

Beyond single-particle searches

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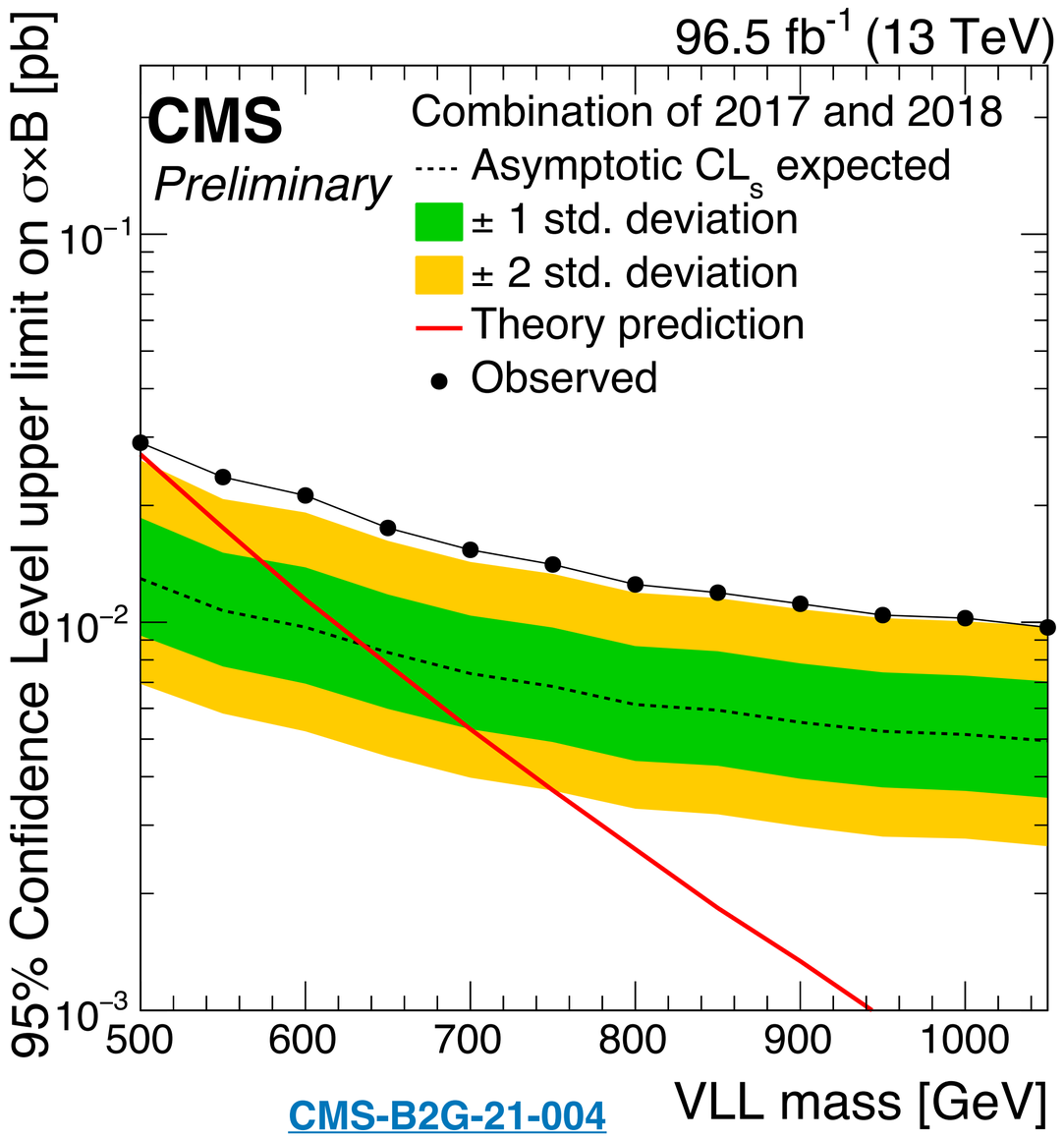
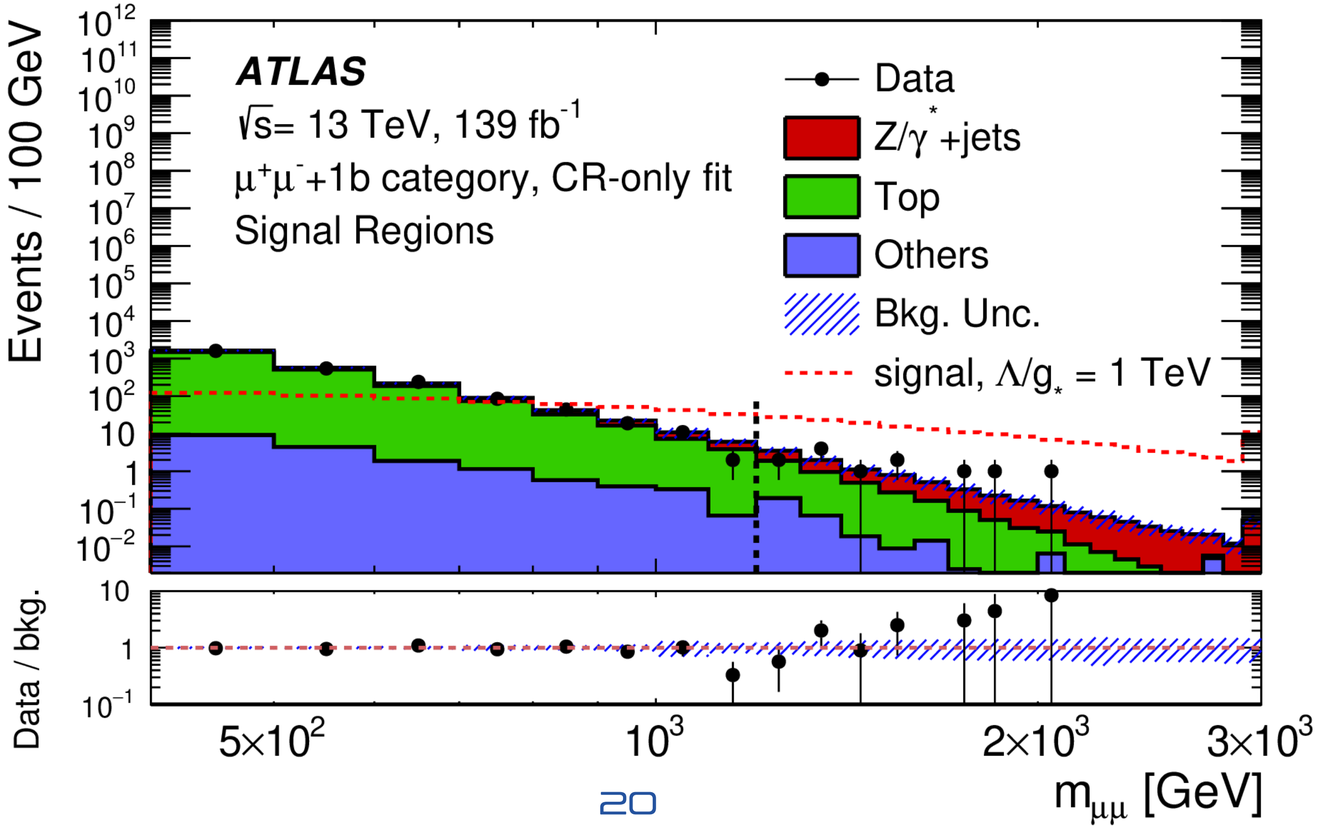


CMS-B2G-21-004

Contact interactions

- *In the limit of large masses for new particles, the NP effect becomes a bsμμ contact interaction*

- *ATLAS searches for it in the dimuon spectrum*



ATLAS-EXOT-2018-16

Contact interactions

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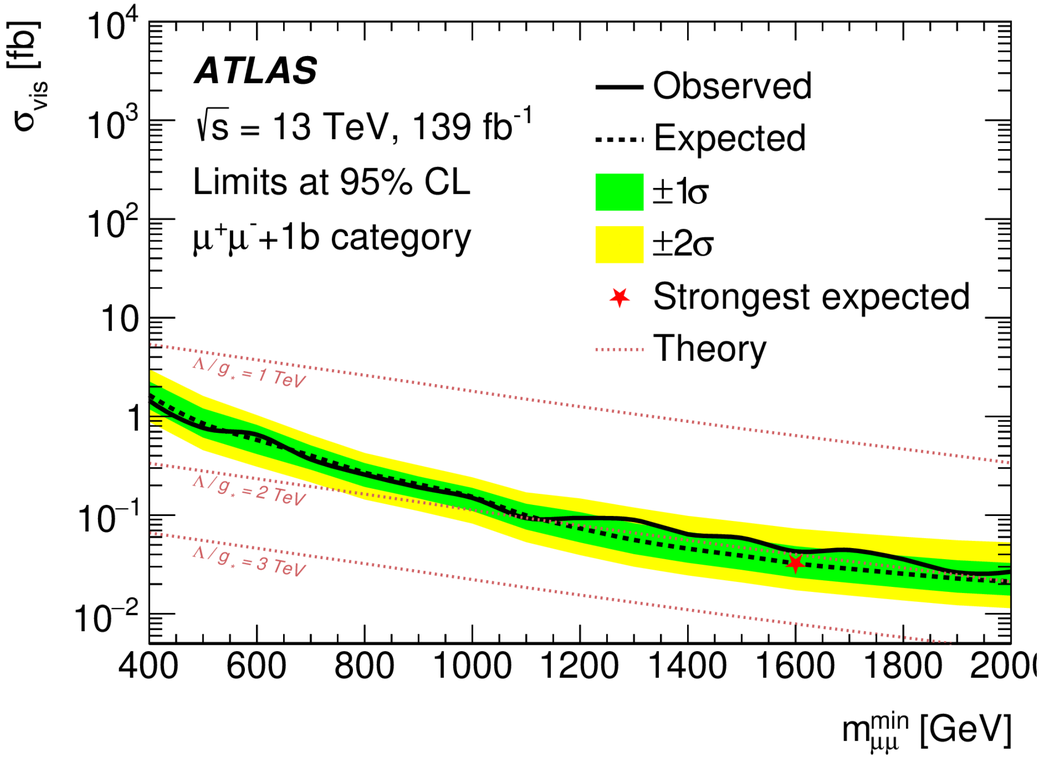
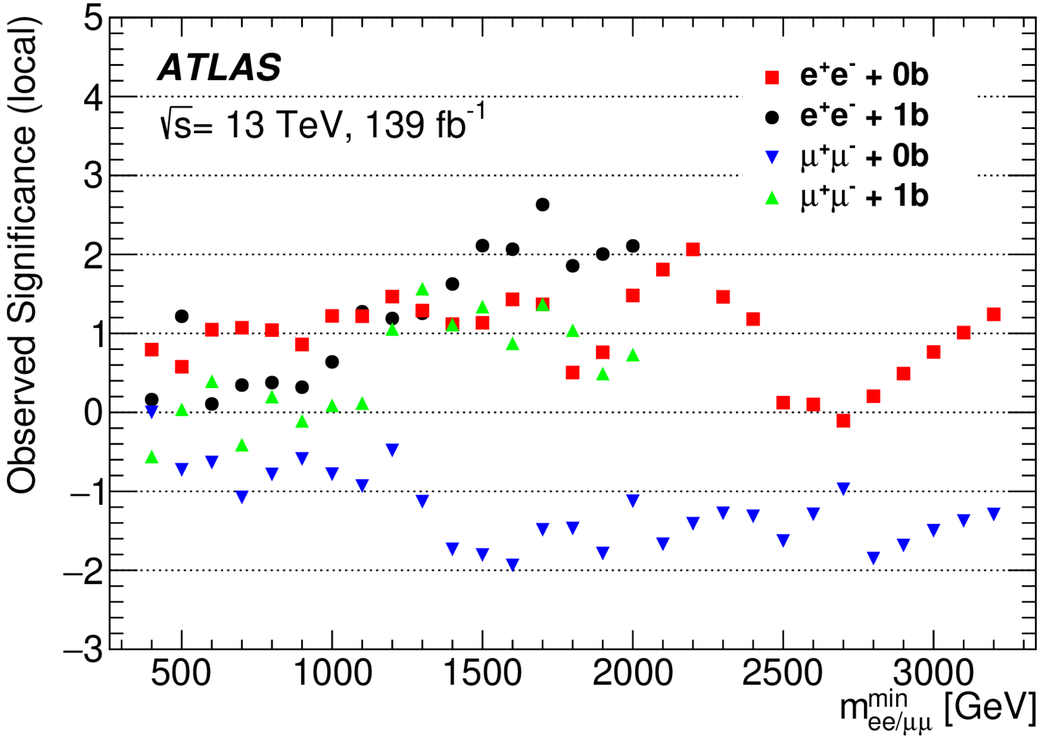
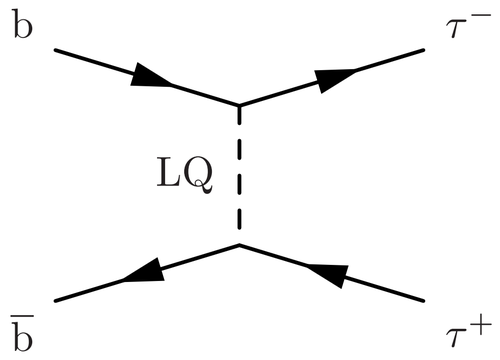


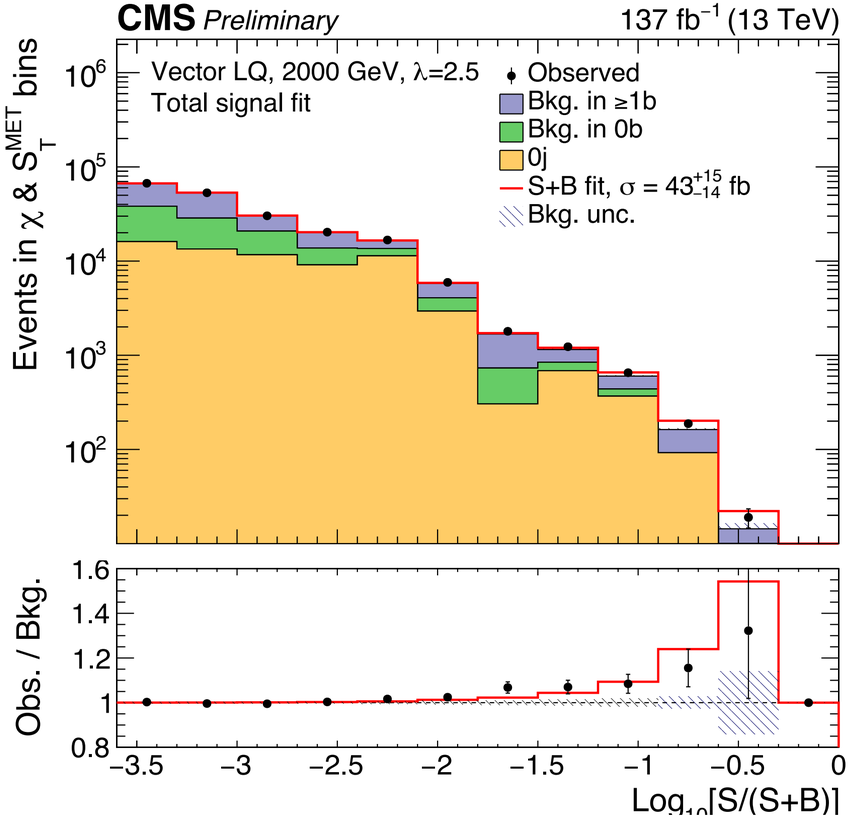


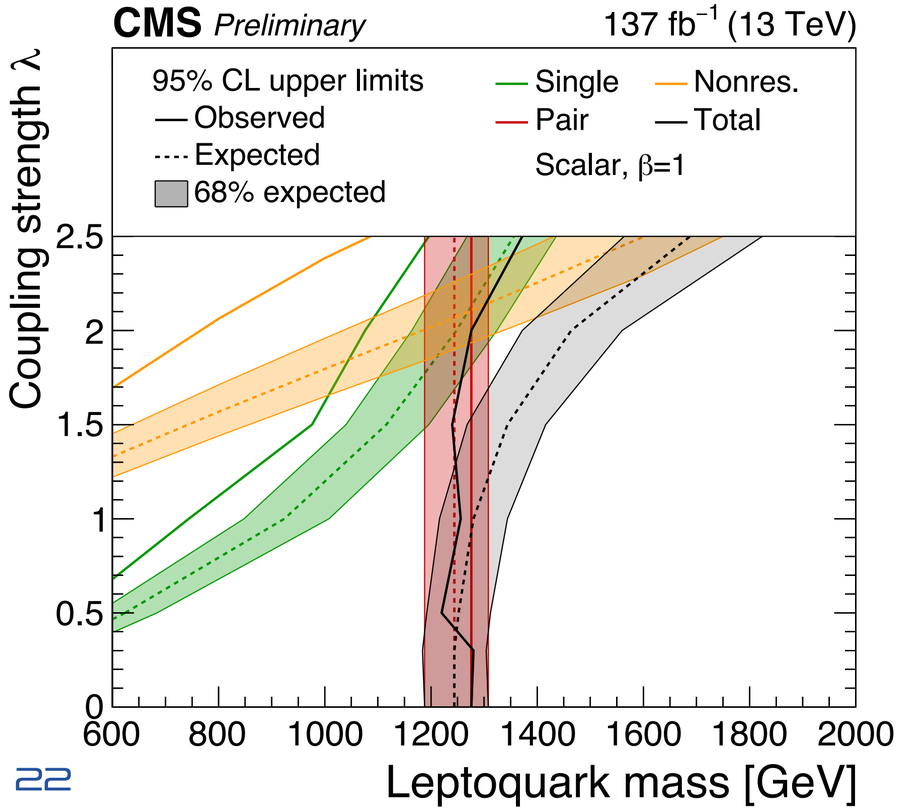
ATLAS-EXOT-2018-16

t-channel production

- CMS searches for LQ->bτ production, tuning the search to be sensitive also to t-channel production
- An excess is observed, which corresponds to 3.4 significance under the t-channel hypothesis (less with single and double resonant production)







CMS-EXO-19-016

Conclusions

- *LFV anomalies are certainly intriguing but still far from being an established experimental fact*
  - *It is our duty to join LHCb in the effort of establishing the presence of these anomalies*
  - *Certainly our detectors are not designed to do so, but they are robust enough to be pushed there*
  - *A lot of work happened towards this (e.g., di-electron trigger) in view of Run3.*
- *At the same time, we should keep pushing high-pT exploration*
  - *If within LHC reach, LQs and Z' will be found*
  - *By tuning searches to specific models, we are pushing sensitivity improvement beyond sqrt(L)*

Recent relevant ATLAS searches

- LQLQ -> tl tl: ATLAS-CONF-2022-052
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2022-052/

- LQ -> btau tau: ATLAS-CONF-2022-037
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2022-037/

- VLL taus: ATLAS-CONF-2022-044
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2022-044/

- LQLQ->bv ttau / btau tv: SUSY-2019-18
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2019-18/

- LQLQ->bv tl / bl tv: CONF-EXOT-2022-09
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2022-009/

- LQ summary plots: ATL-PHYS-PUB-2022-012
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-012/

- bsll contact interactions: EXOT-2018-16
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2018-16/

- W'->tb: CONF-EXOT-2018-50
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2021-043/

- ttZ'->4-tops: CONF-EXOT-2018-44
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2021-048/

- Heavy resonance combination: ATLAS-CONF-2022-028
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2022-028/

For a complete list of public results see:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

Recent relevant CMS searches

Z' to μμ:
- CMS-EXO-18-008 (https://arxiv.org/abs/1808.03684)
- CMS-EXO-19-018 (https://arxiv.org/abs/1912.04776)
- CMS-EXO-19-019 (https://arxiv.org/abs/2103.02708)
- CMS-EXO-20-014 (https://arxiv.org/abs/2112.13769)
- CMS-EXO-21-018 (PAS)

LQ (ele q):

Scalar:
- CMS-EXO-17-009 (https://arxiv.org/abs/1811.01197),
- CMS-EXO-21-001 (https://arxiv.org/abs/2202.08676),

LQ (muon q)

Scalar:
- CMS-EXO-17-003 (https://arxiv.org/abs/1808.05082),
- CMS-EXO-21-001 (https://arxiv.org/abs/2202.08676),

Vector:
- CMS-B2G-16-027 (https://arxiv.org/abs/1809.05558)

DM (1μ, 1j, met):
- CMS-EXO-17-015 (https://arxiv.org/abs/1811.10151)

LQ(τq)
- CMS-EXO-17-009 (https://arxiv.org/abs/1811.01197),
- CMS-EXO-19-015 (https://arxiv.org/abs/2012.04178)
- CMS-EXO-19-016 (PAS)
- CMS-EXO-21-001 (https://arxiv.org/abs/2202.08676),

LQ (νq)
- CMS-EXO-20-004 (https://arxiv.org/abs/2107.13021),
- CMS-SUS-19-005 (https://arxiv.org/abs/1909.03460)

For a complete list of public results see:
http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/index.html