Exotic searches by ATLAS and CMS

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(on behalf of ATLAS and CMS collaborations)

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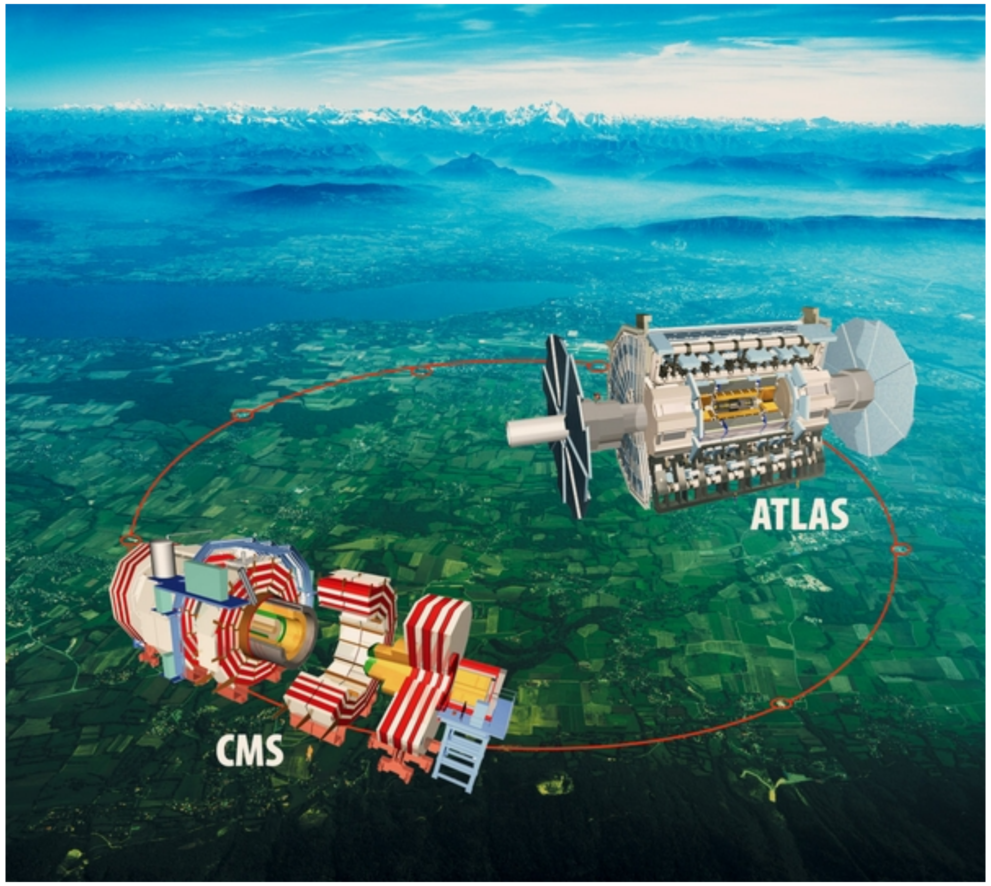
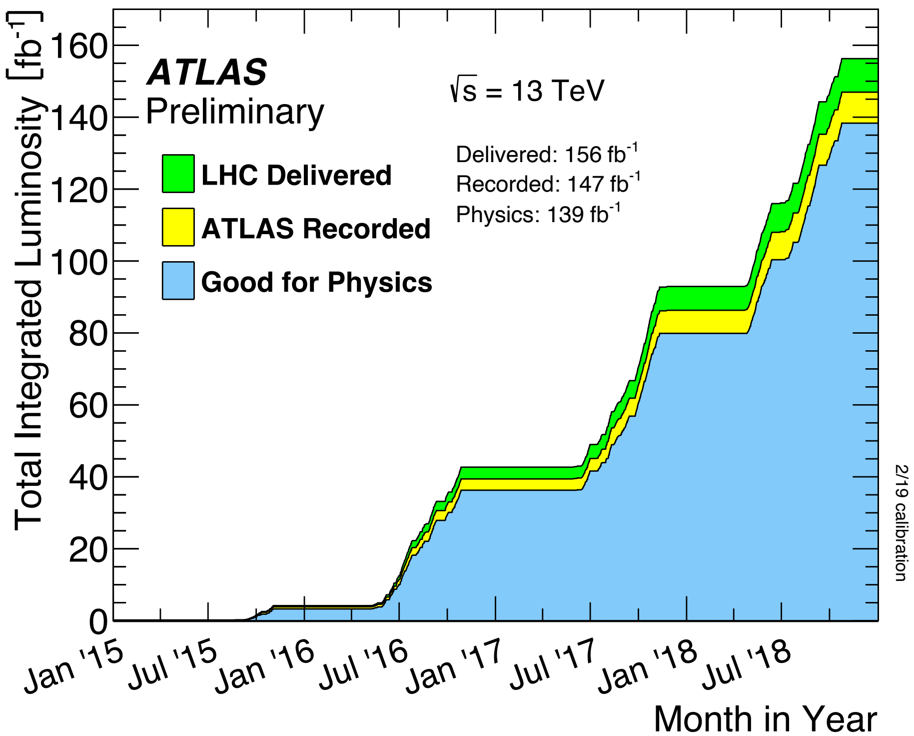
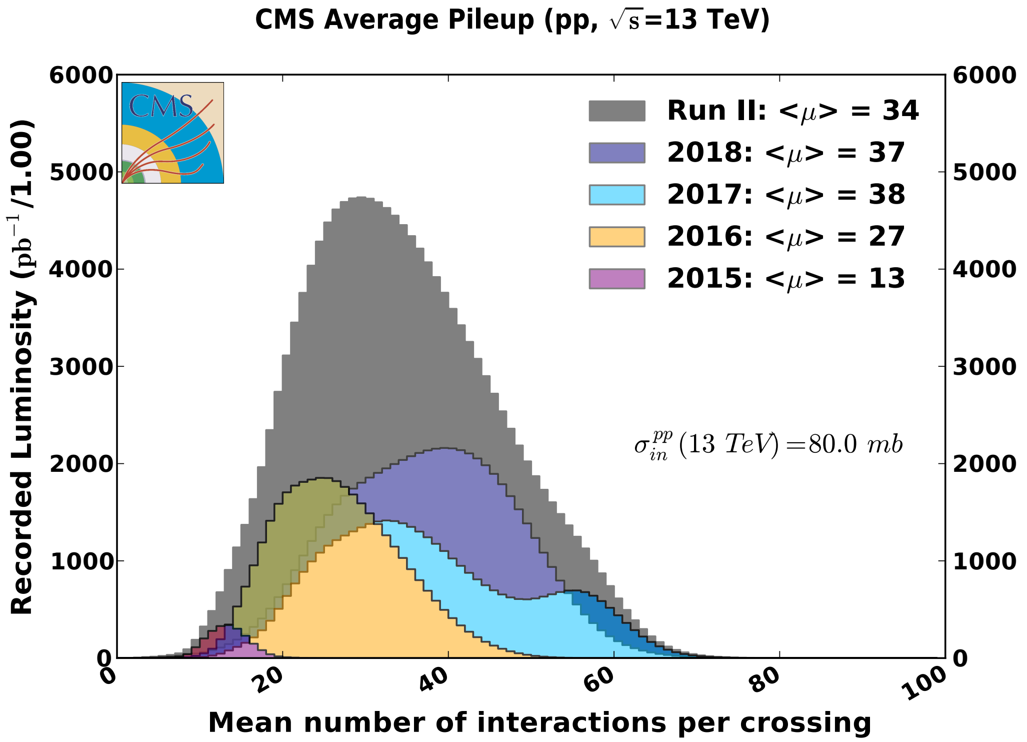
Introduction

- ATLAS and CMS are two multipurpose detectors at the LHC ring resulted in the discovery of Higgs Boson in 2012
- With successful data taking during Run-II and having several upgrades for implementing fast electronics, ATLAS and CMS has recorded up to ~139 fb^{-1} of data at 13 TeV
- This would help in looking at several model predictions falling in beyond standard model sector
- Will answer many unanswered questions like matter-antimatter asymmetry, existence of dark matter and so on....

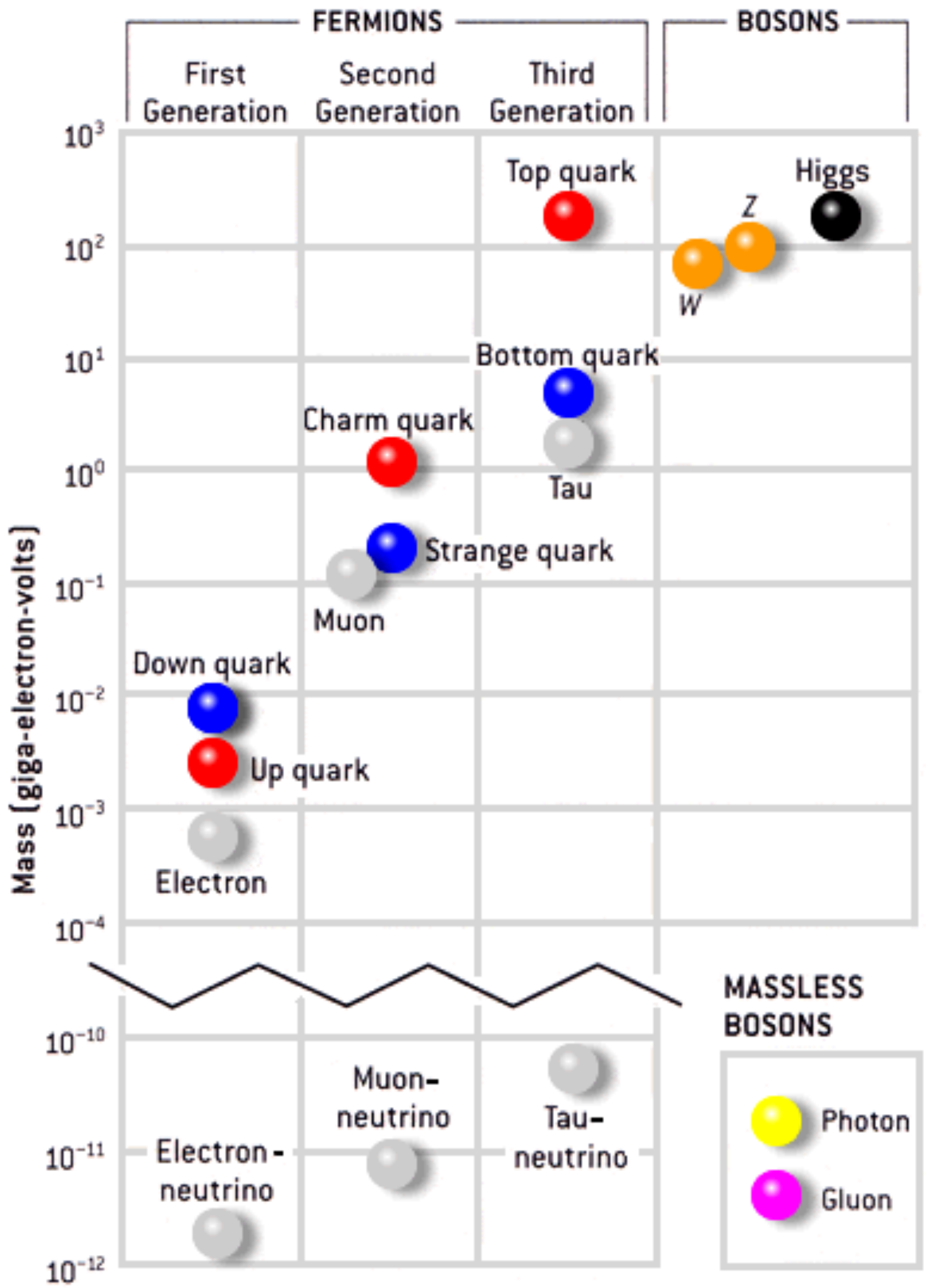






Why do we need to look Beyond Standard Model?

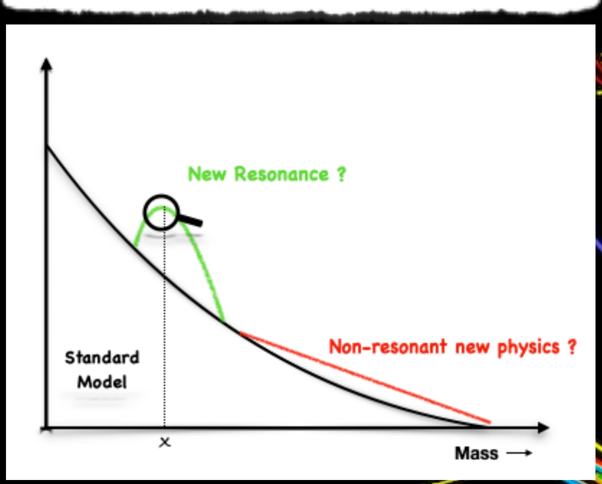
- Standard model successfully explains the structure of matter and the forces acting between them. Still, it fails to answer many important questions:
    - Inclusion of the forth fundamental force i.e gravitational force
    - Why only 5% of matter made of ordinary SM particles?
    - Why there are only three families of quarks and leptons?
    - Is there a more fundamental theory of which the Standard Model is a low energy approximation?



To answer such questions , new models beyond standard model have evolved with time and predicts "new phenomena" at the "TeV" scale

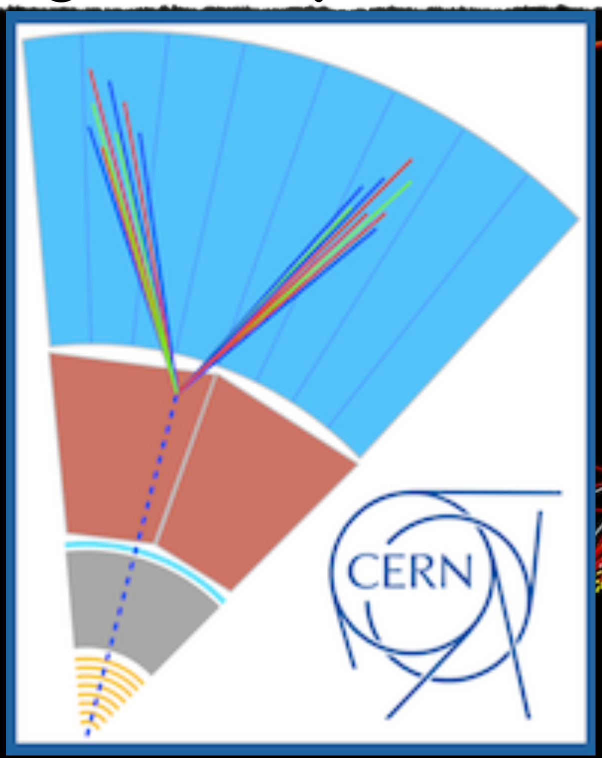
What do we expect Beyond Standard Model ?

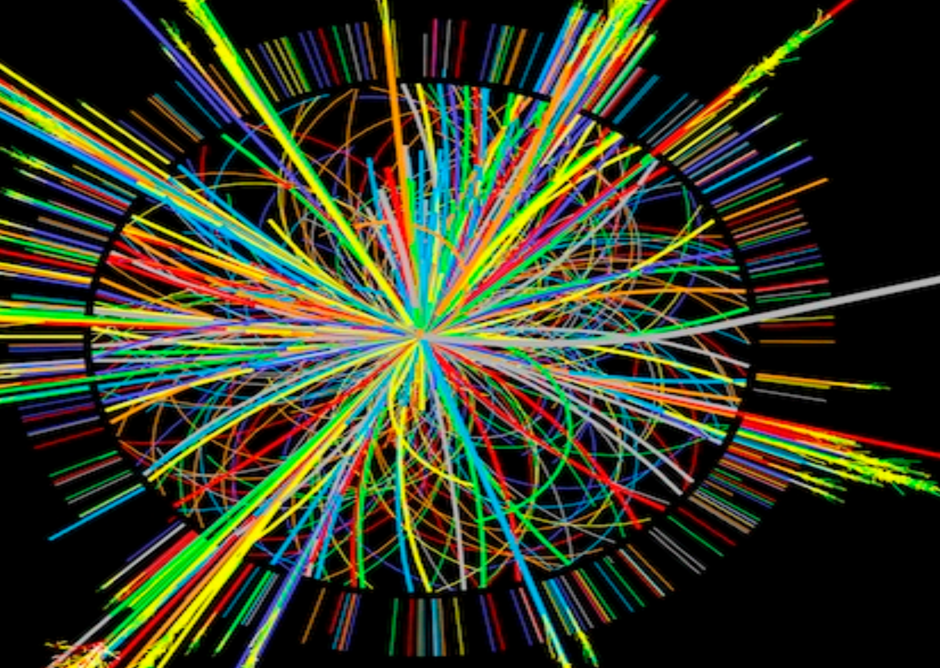
New resonance ?



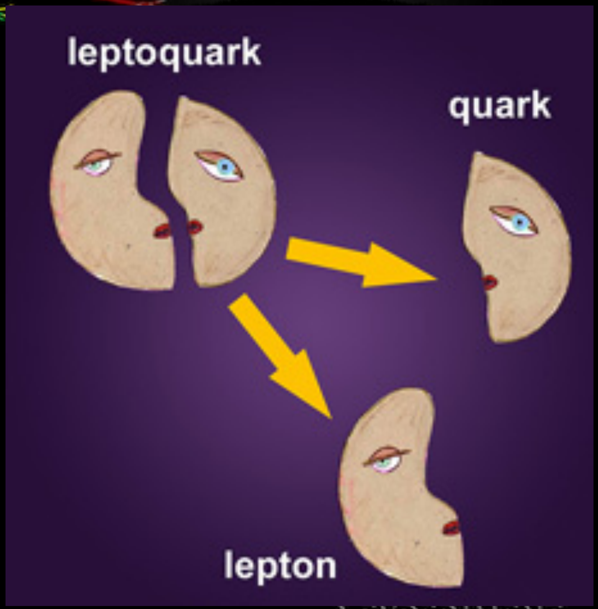
Dark matter ?

Long lived particles ?



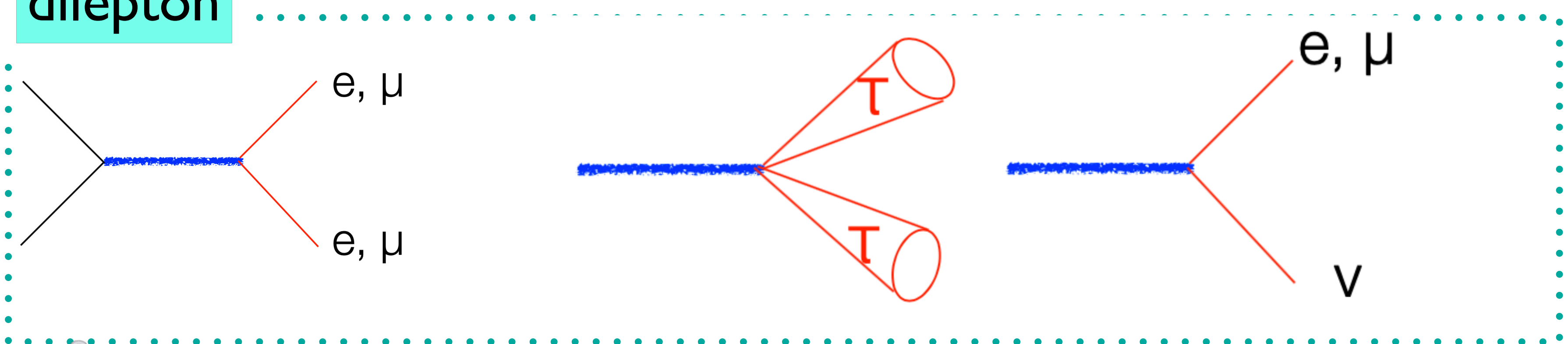


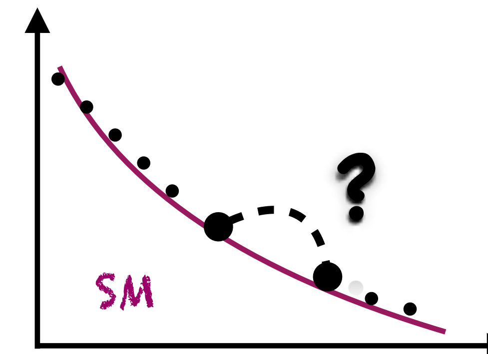
New quarks?



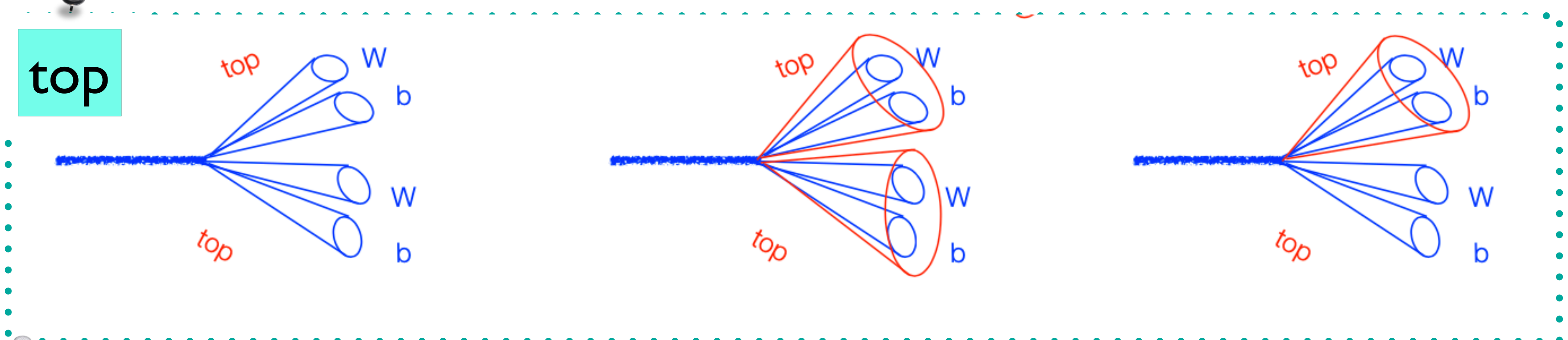
Resonances

dilepton

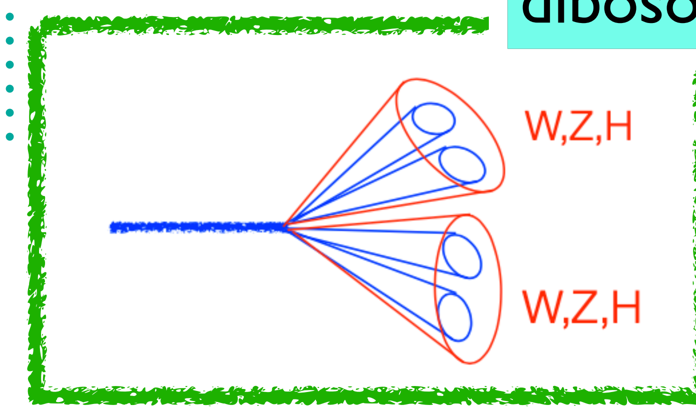




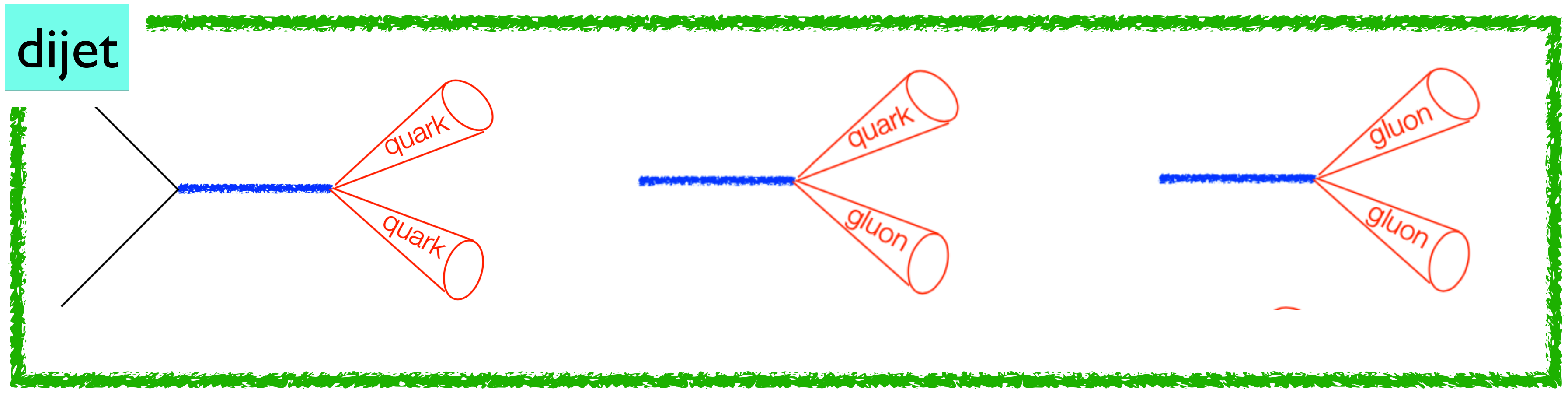
top



diboson



dijet



Parallel talk by:
Venugopal Ellajosyula [Link]
Andrea Piccinelli [Link]

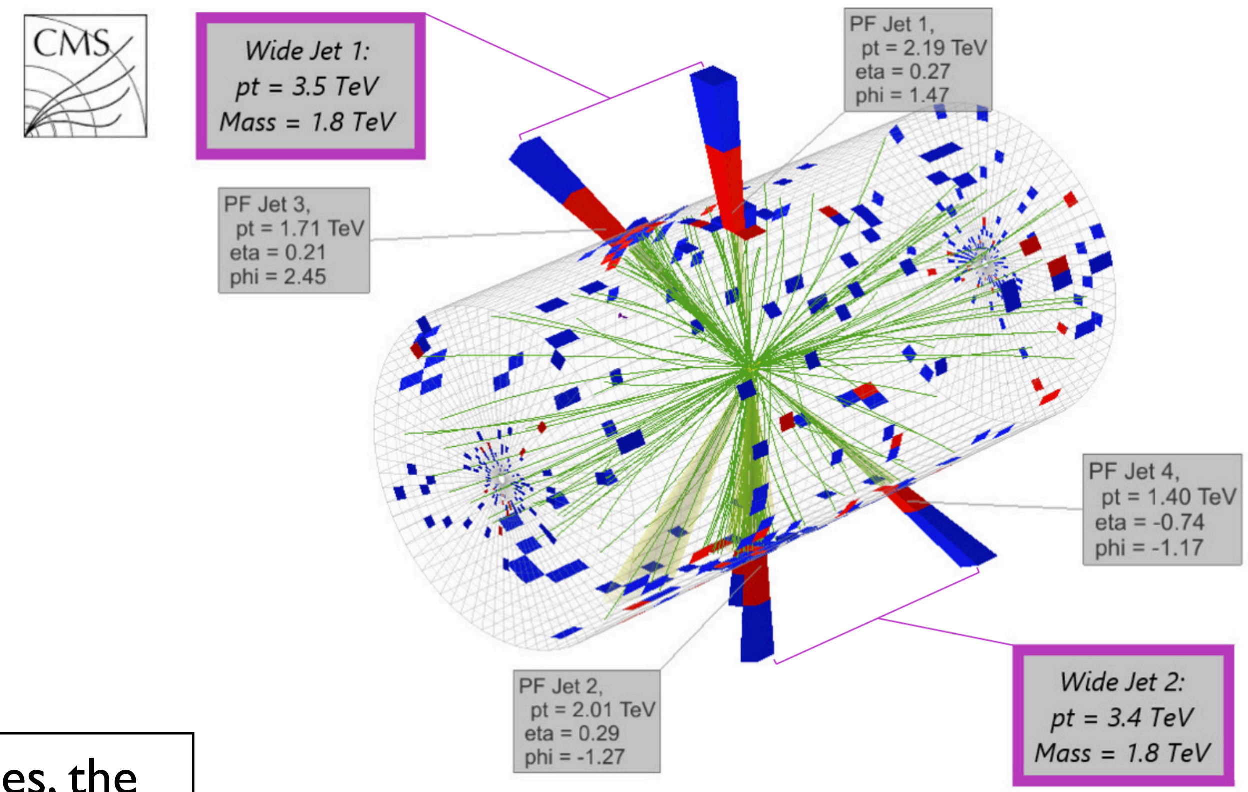
Focus on very recent or brand new results!

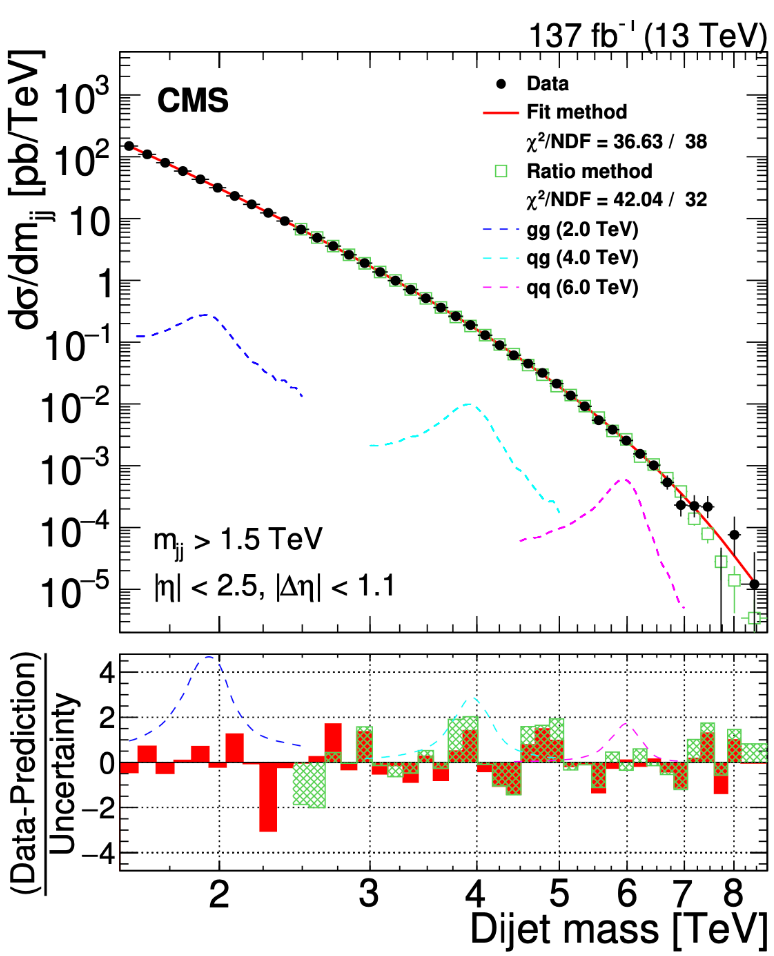
Di-Jet resonance search

CMS : arXiv:1911.03947

Full Run 2 dataset

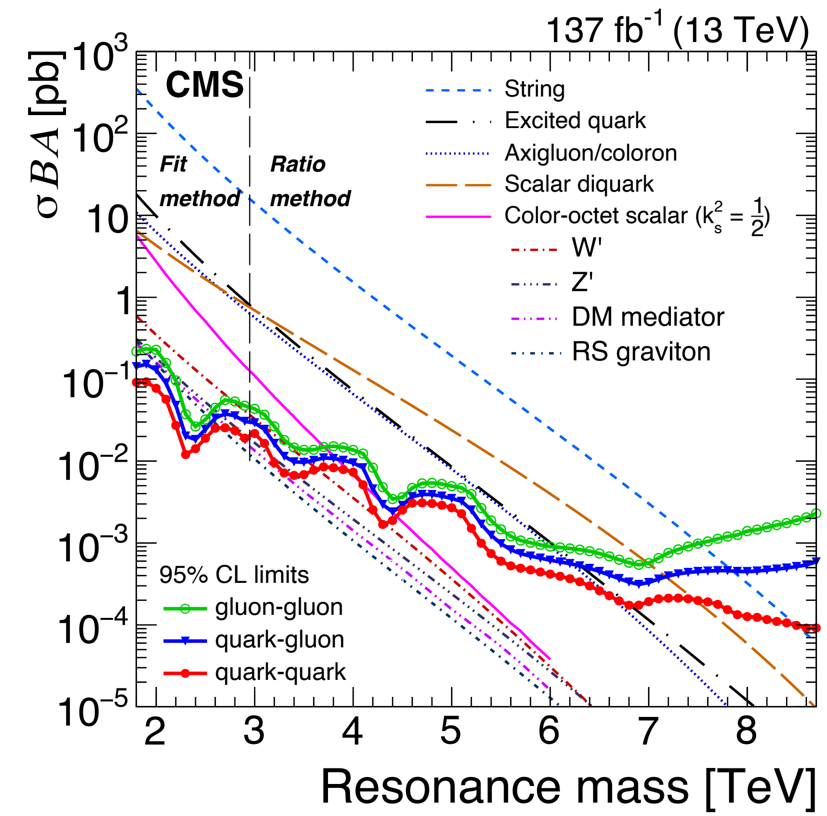
- Considered "wide" jets to combine close-by jets: reduce analysis sensitivity to final state radiation
- Parametric fit to signal region data for 1.5 $< m_{jj} <$ 2.4 TeV
- New "ratio method" for $m_{jj} >$ 2.4 TeV : using control regions with larger $\Delta\eta$ values and MC-to-data transfer factors





For broad resonances, the ratio method provides significantly enhanced sensitivity compared to the fit method

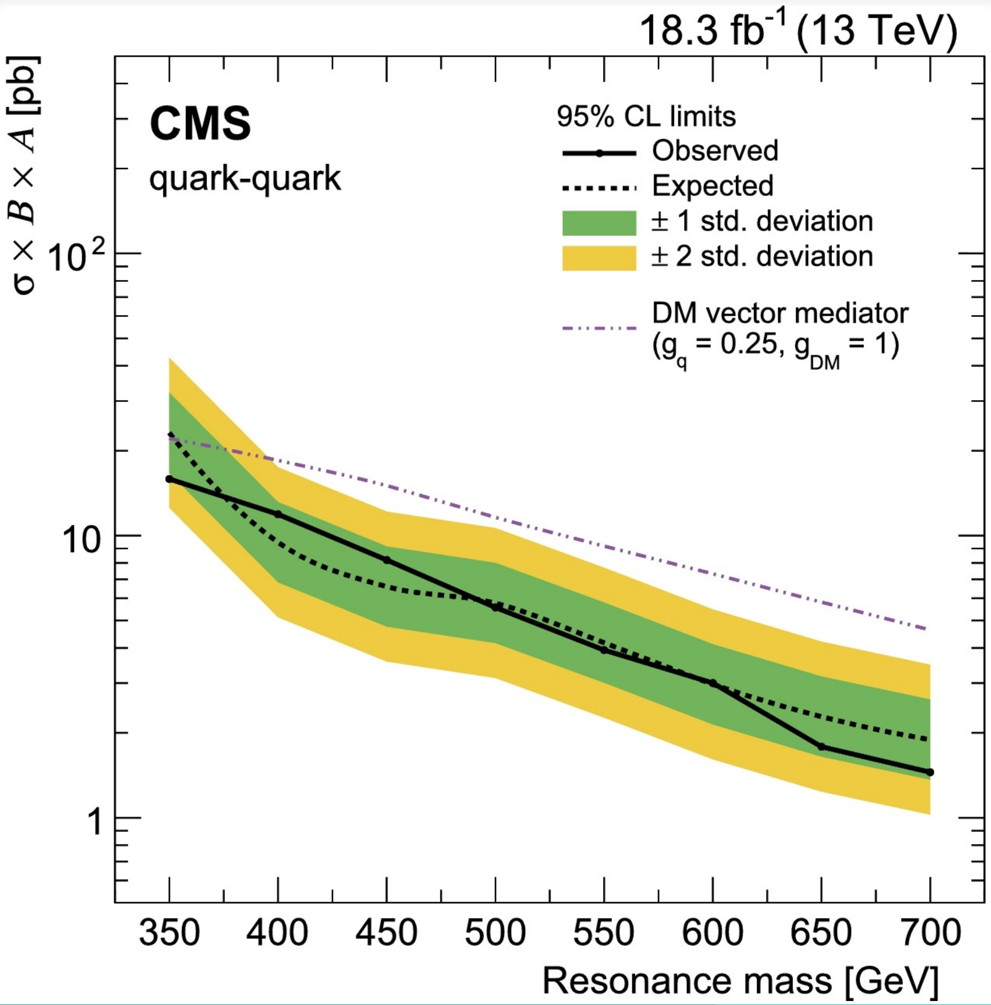
Limits set for qq, qg and gg final states, with narrow and broad widths (up to 30% of resonance mass).

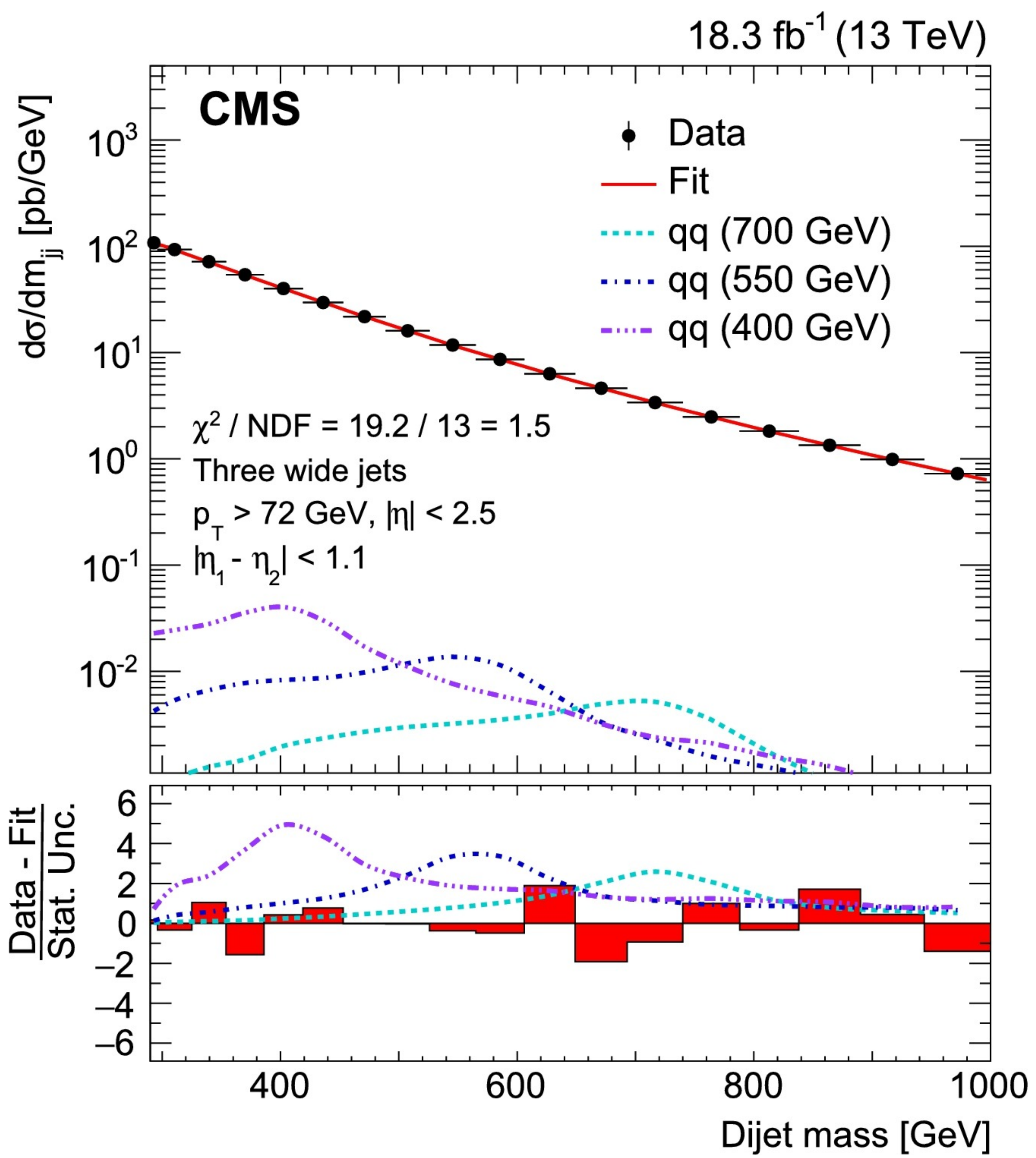


Di-Jet resonance search

CMS : PhysLettB(2020)135448

- To get sensitivity at low masses :
  - Data collected with different technique known as "Data scouting" is analyzed
- 3-jet events are recorded and reconstructed using only calorimeter-based information with lower p_T thresholds
- Backgrounds estimated using parametric fit to data



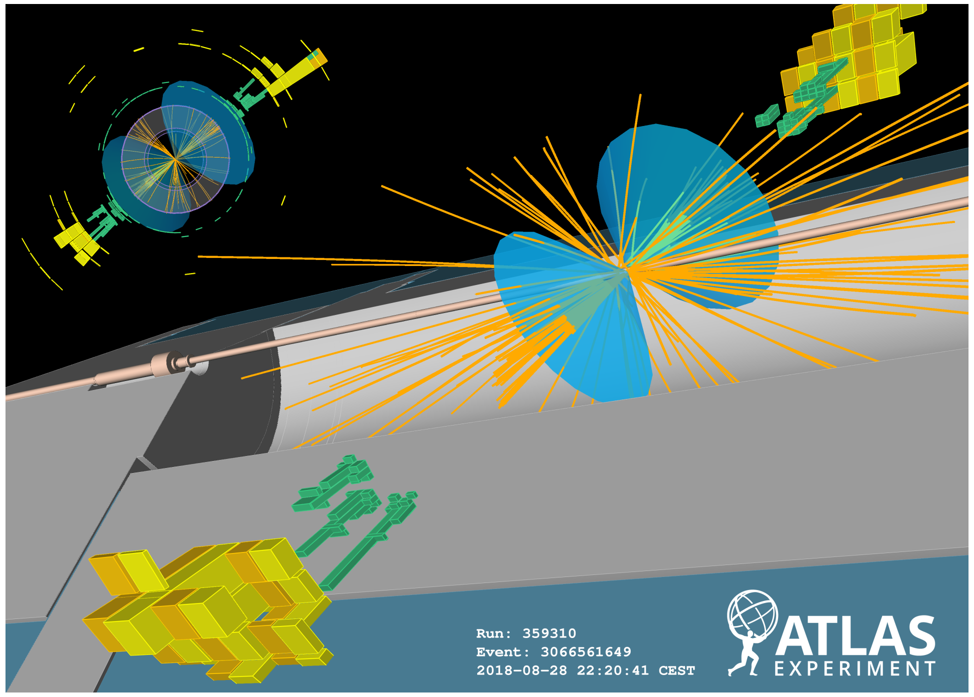


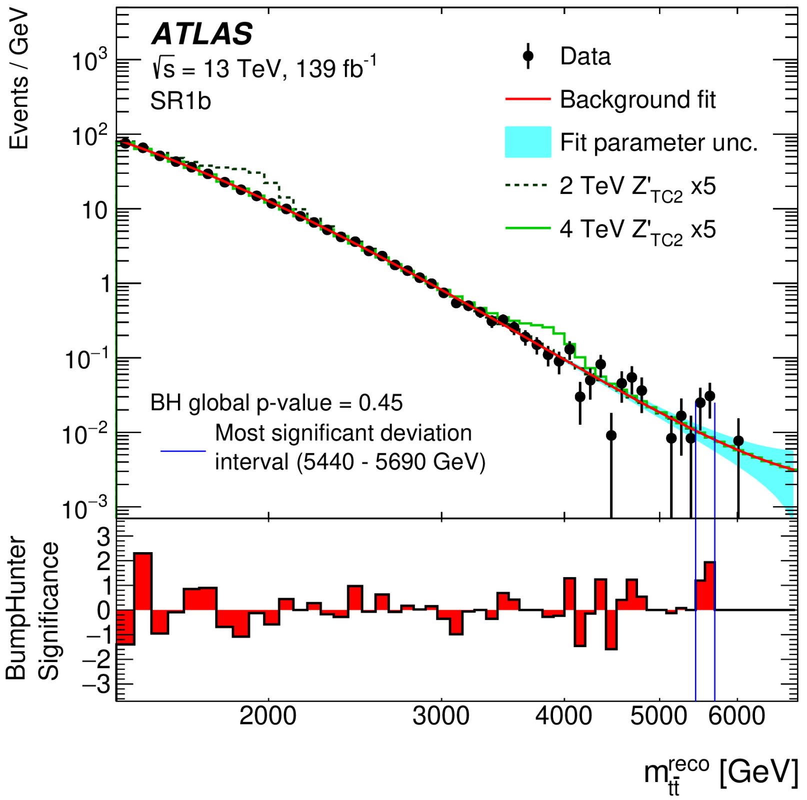
Fully-hadronic top-pair resonances

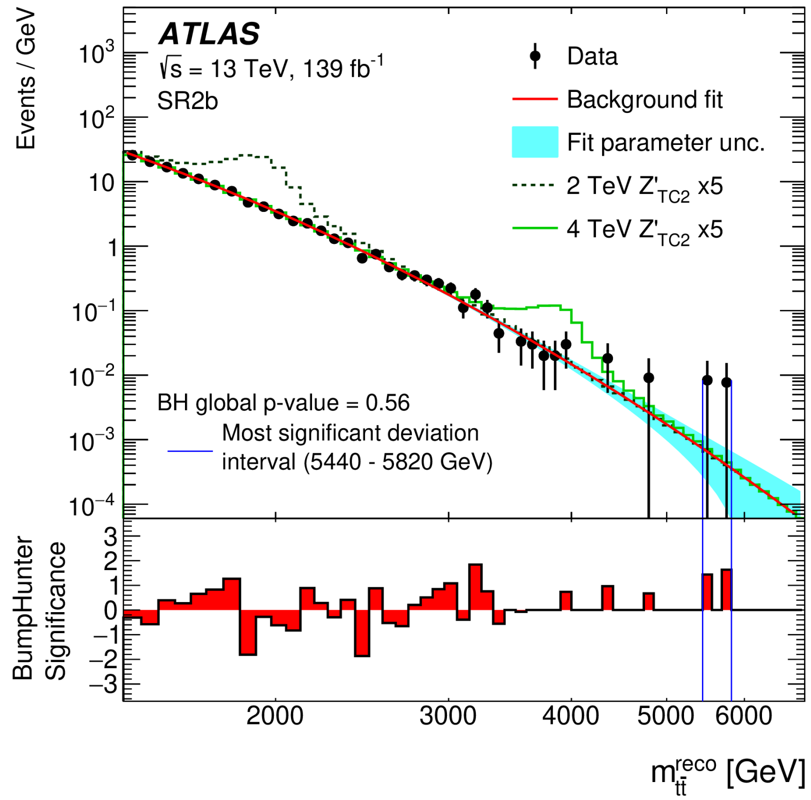
ATLAS : arXiv:2005.05138

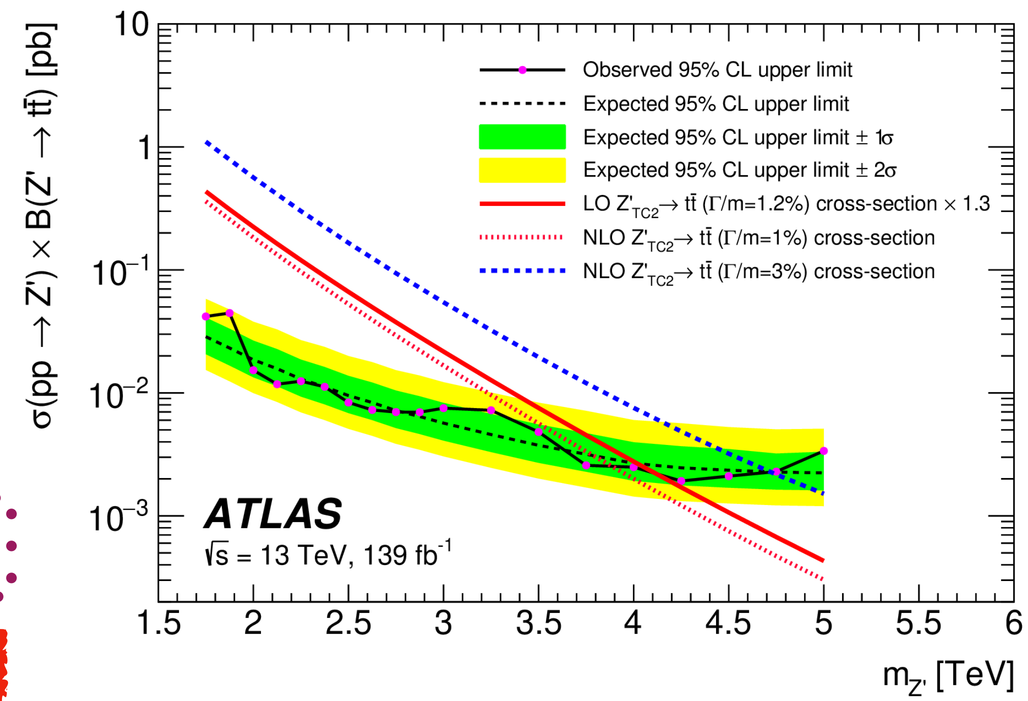
Full Run 2 dataset

- Fully hadronic top decaying to large-radius jets (R = 1.0)
- Jets are DNN top-tagged
- b-tagging using variable-radius track-jets : two signal regions with 1 or 2 b-tagged jets









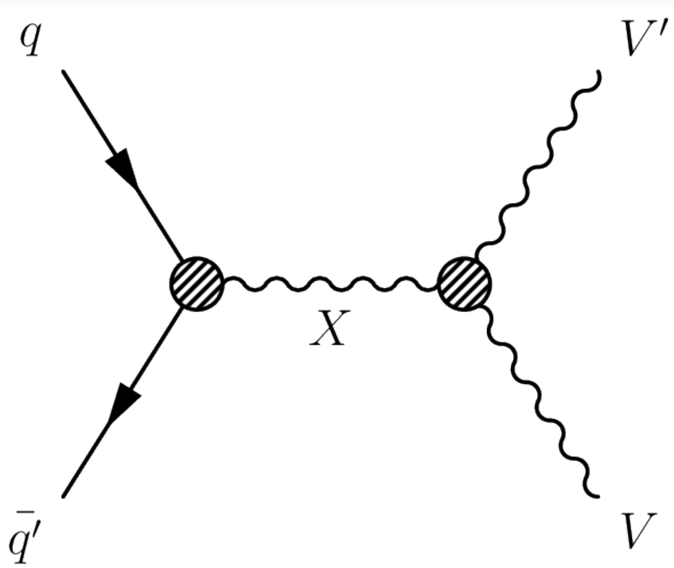
No significant deviation from the background prediction is observed

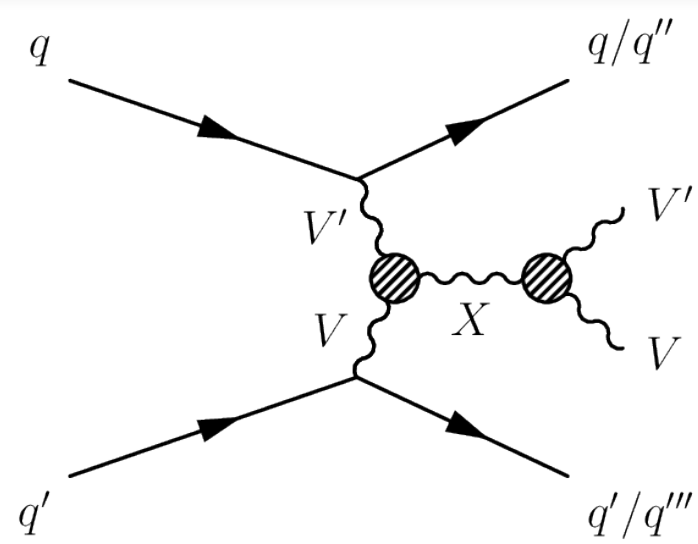
Thr Z' boson masses below 3.9 and 4.7 TeV are excluded at 95% confidence level for the decay widths of 1% and 3% respectively

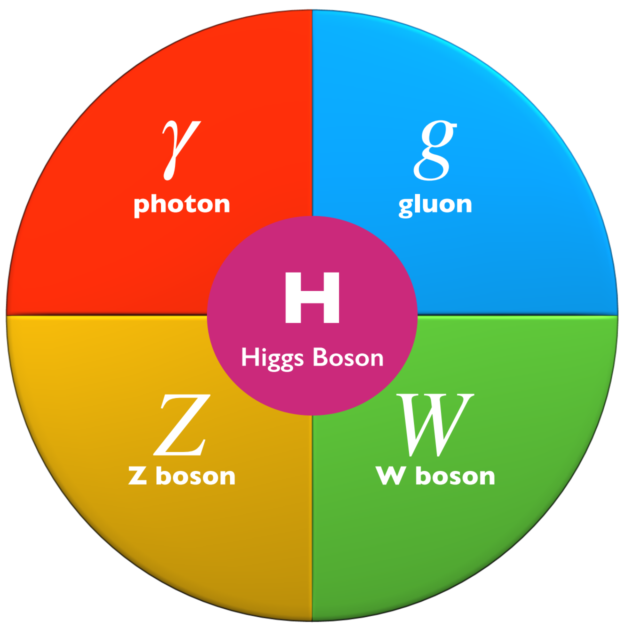
Improved analysis techniques lead to 65% improvement in exp. limits at 4 TeV

diboson resonance search

- Targeting O(100 GeV) to multi-TeV resonances (radions, gravitons, new vector bosons, extended Higgs sector) in different BSM scenarios :
- Warped extra-dimensions, composite Higgs, technicolor, …

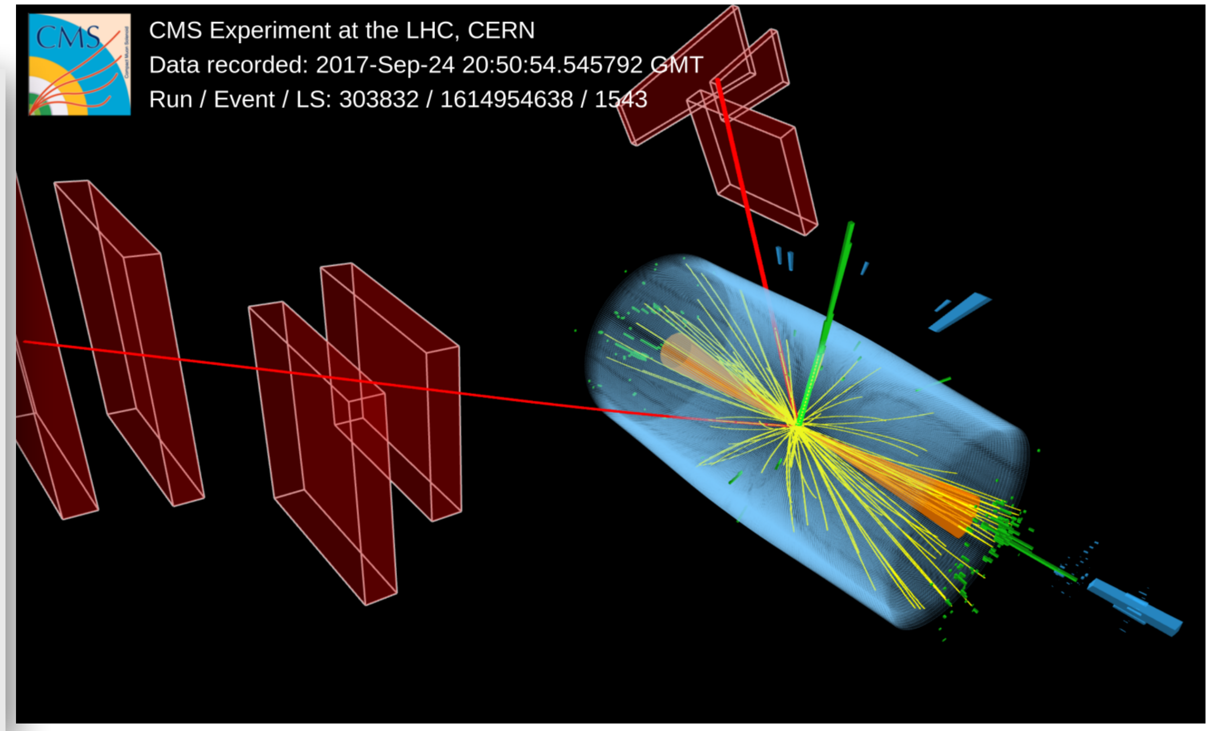






Highlights

- All possible production modes are targeted
- Improved tagging algorithms for high p_T $V \rightarrow qq, H \rightarrow bb,\ H \rightarrow \tau\tau$ decays :
  - Dense environment : critical to combine calorimeter with superior angular resolution of trackers
  - Novel analysis methods: 3D likelihood fits and anomaly detection techniques for broadening scope of the searches

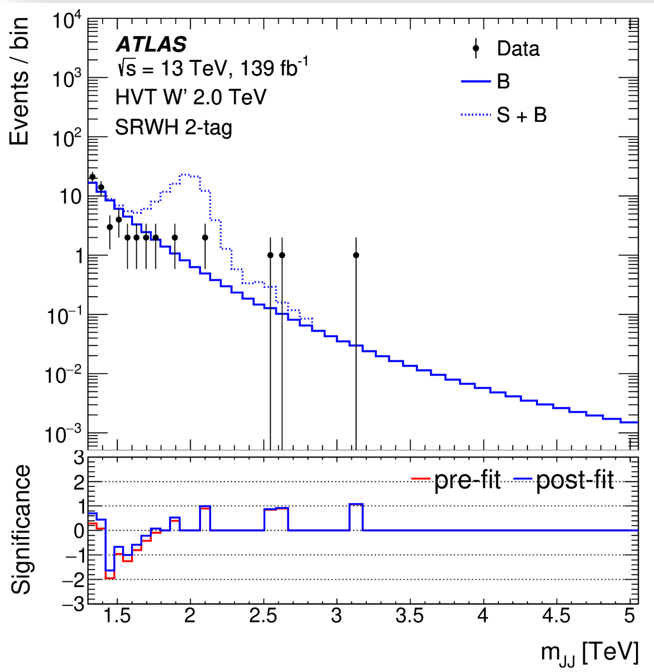


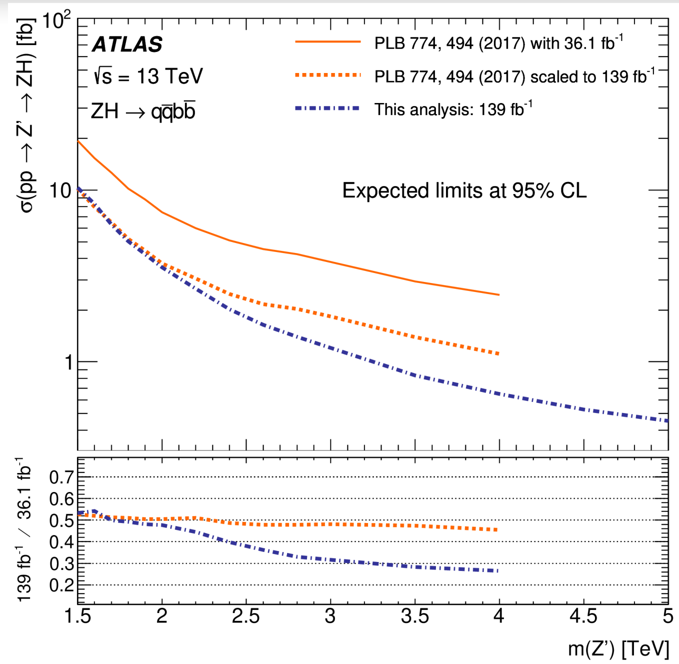
VH resonances

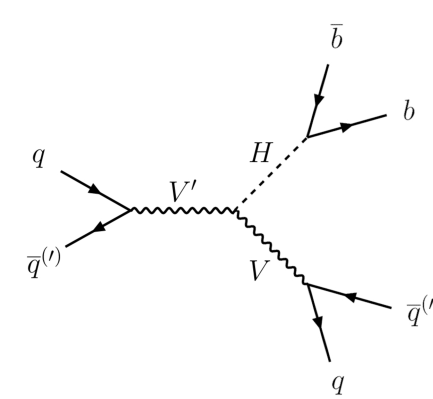
ATLAS : ATLAS-CONF-2020-043

HDBS-2018-11 **Full Run 2 dataset**

- **Fully-hadronic final state:** two large-radius jets, jet substructure, track multiplicity and b-tagging to identify H->bb and V-> qq candidates



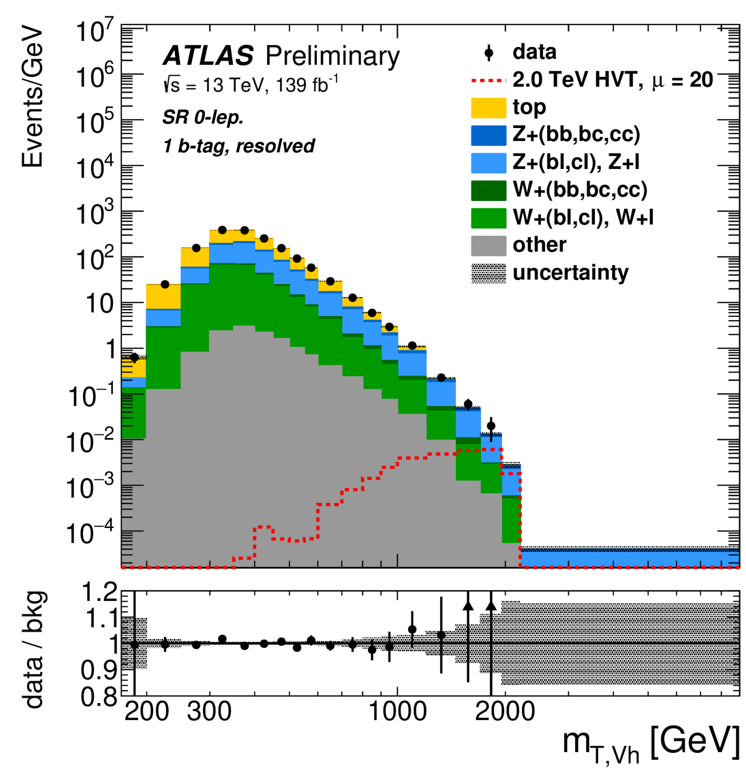


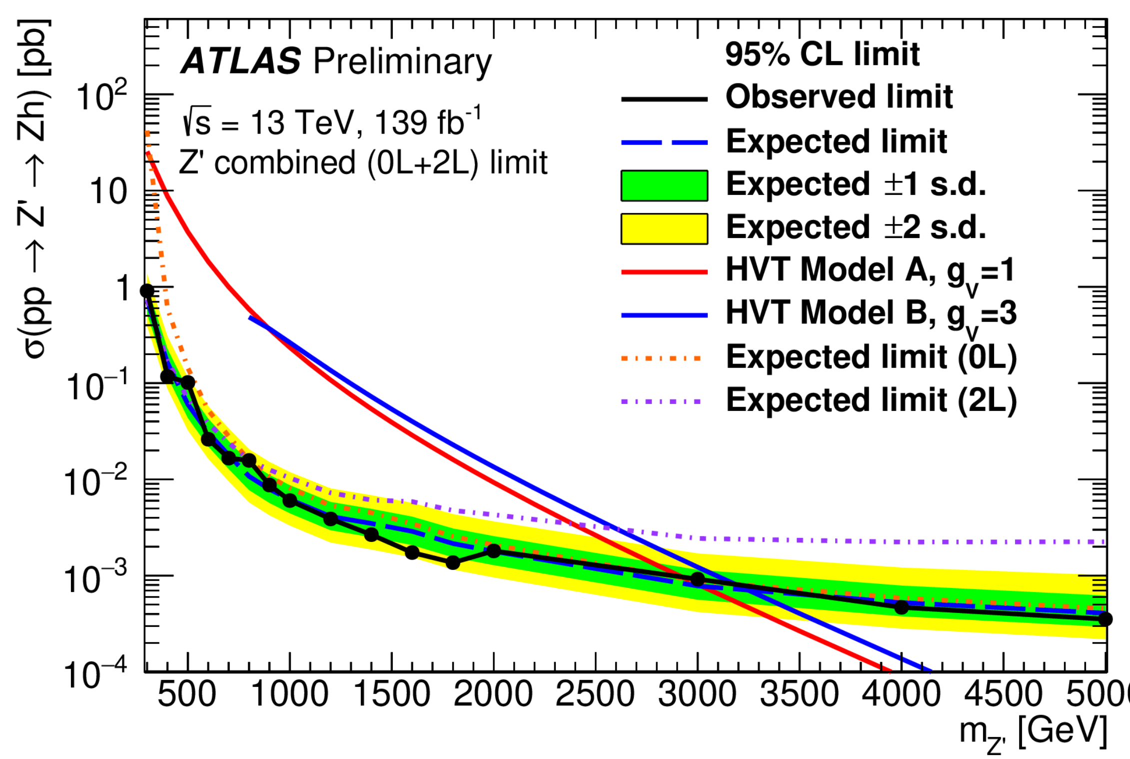


New: Variable-radius track-jets for b-tagging: pT-dependent radius to resolve highly boosted bb pairs from Higgs boson decay

Multijet Background estimated from region with 0-tag: BDT trained on control region data to estimate extrapolation corrections to 1 and 2-tag

- **Semi-leptonic final state: 0 lepton and 2 lepton channels considered**
  - Resolved: 2 small-R(0.4) calo jets
  - Marged: 1 large-R TCC calo jet with at least 1 associated b-tagged VR track jet

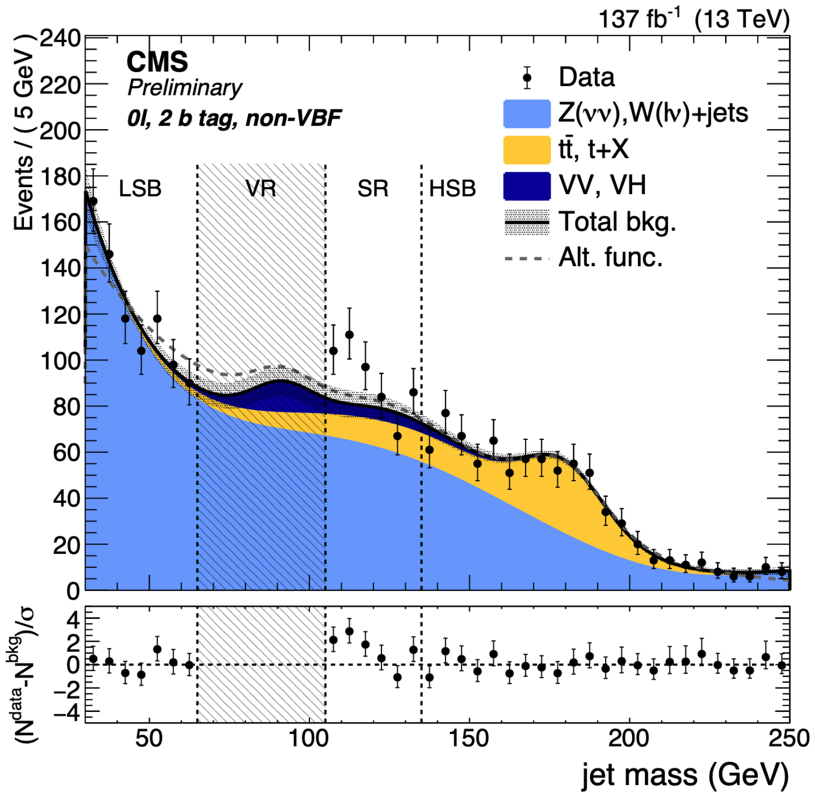




ZH resonances

Full Run 2 dataset

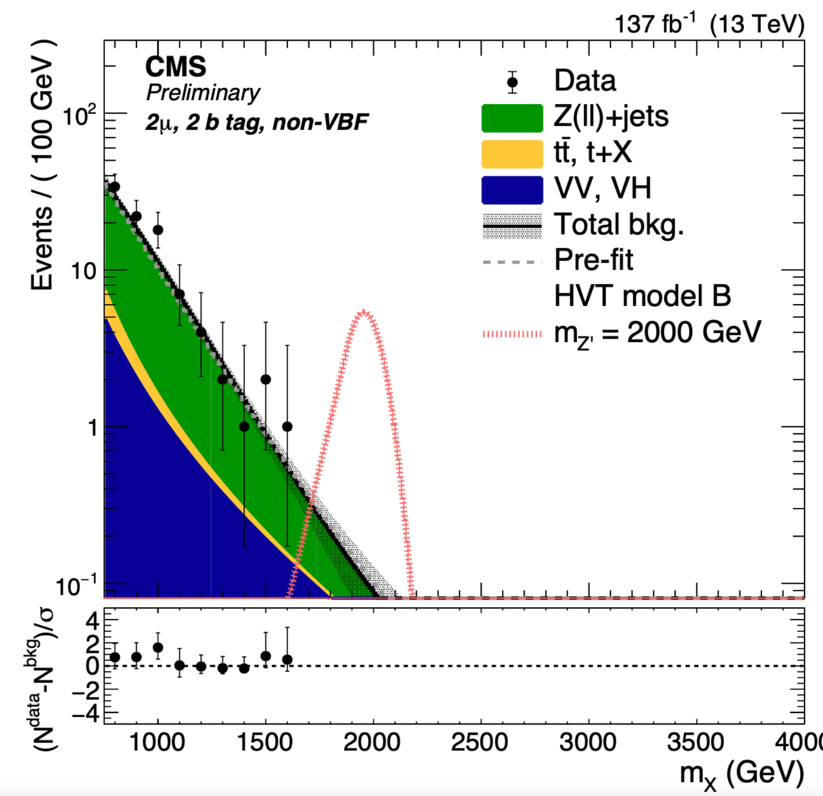
- Search for spin 1 resonances in the boosted regime for $m_X >$ 800 GeV
  - => 0 lepton (large pT_{miss}) and 2 lepton channels considered
    - Including VBF production for the first time!
- Major backgrounds V+jets, ttbar and VV



$$\alpha(m_X) = \frac{N_{SR}^{Vjet}(m_X)}{N_{SB}^{Vjet}(m_X)},$$

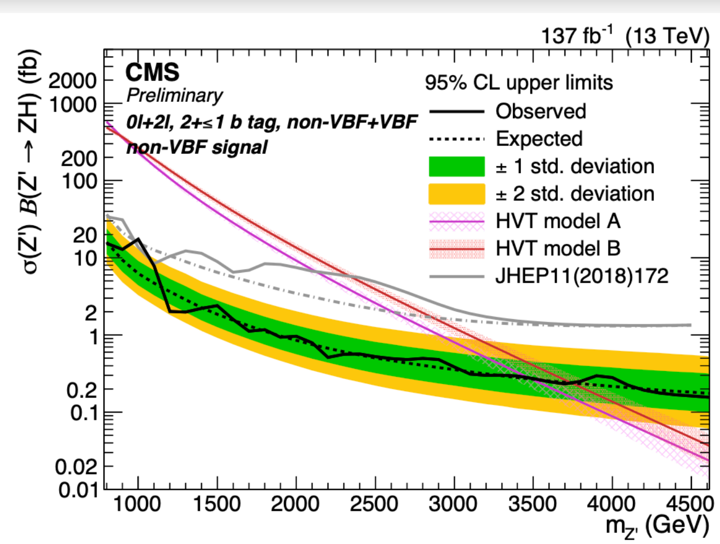
$$N_{SR}^{Vjet}(m_X) = \left[N_{SB}^{data}(m_X) - N_{SB}^{top}(m_X) - N_{SB}^{VV}(m_X)\right] \times \alpha(m_X).$$

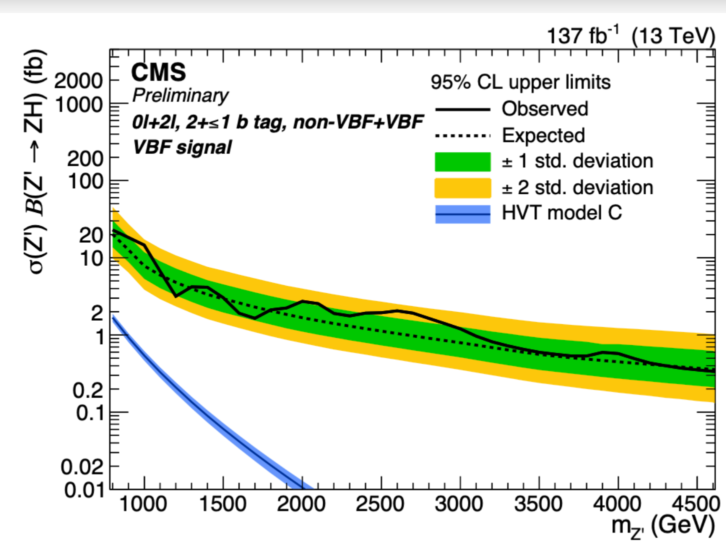
$$N_{SR}^{bkg}(m_X) = N_{SR}^{Vjet}(m_X) + N_{SR}^{top}(m_X) + N_{SR}^{VV}(m_X)$$



- The m_X (or m_{TX}) distributions are estimated using the data in the jet mass sidebands
- A function is defined as the ratio of the two functions describing the m_X shape in the signal and sideband range of the V+jets background

Z' with mass below 3.5 TeV and 3.7 TeV is excluded

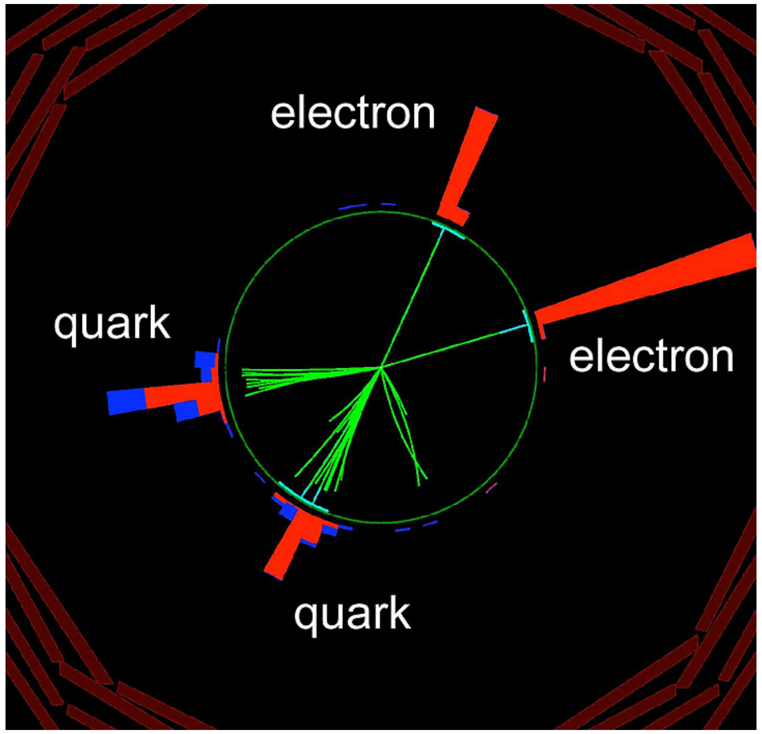




Leptoquarks and vector like-quarks

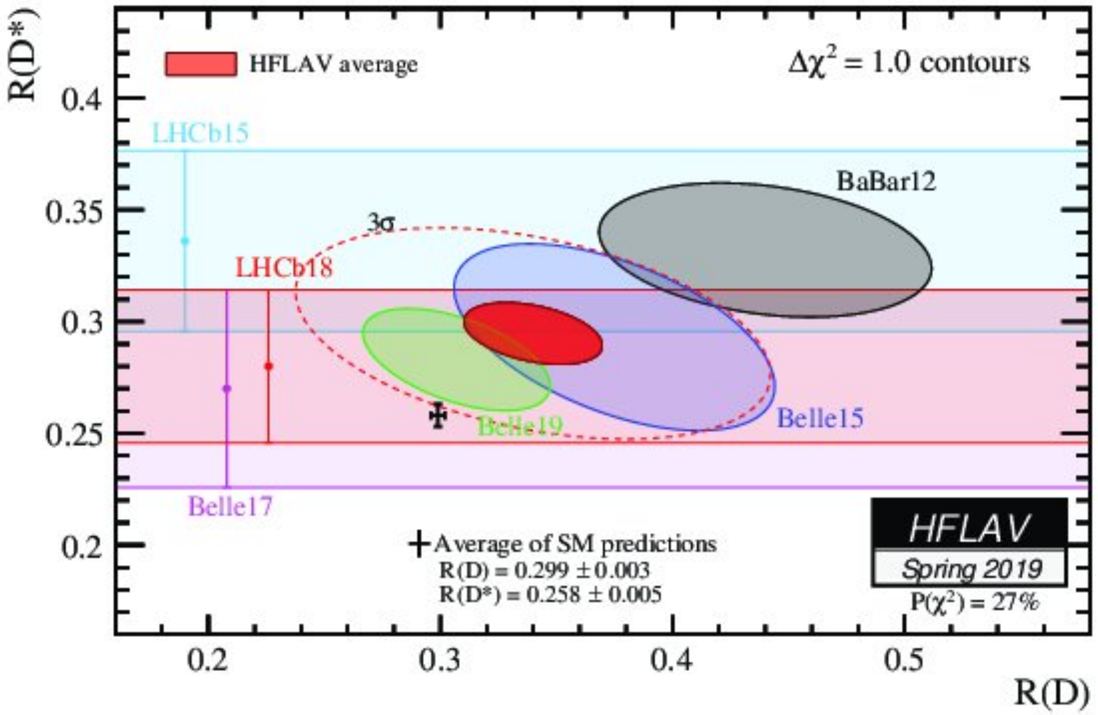
Parallel talk by:
Andrej Gorisek [Link]

- LQ appears in many BSM models to answer the question: **Why same number of generation for leptons and quarks**
- leptoquarks carry both lepton and baryon number
  - decay in lepton-jet
- Motivated by models such as grand unified theories, technicolor models, compositeness scenario and R-parity violating supersymmetry



Vector -like quarks

- Heavy quarks for which left- and right- handed chirality components transform the same under SU(2)
- Predicted in many theories (extra- dimensions, Higgs compositeness, ….) to solve hierarchy problem
- Strong production of pairs, electroweak single production



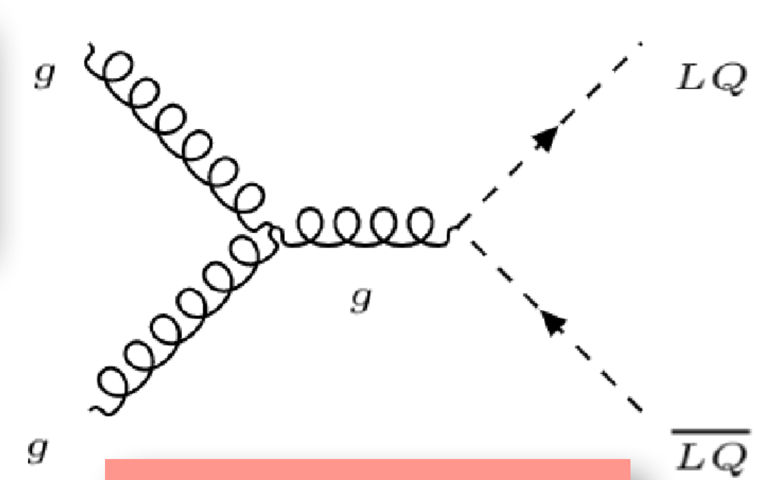
Search for leptoquarks

NEW

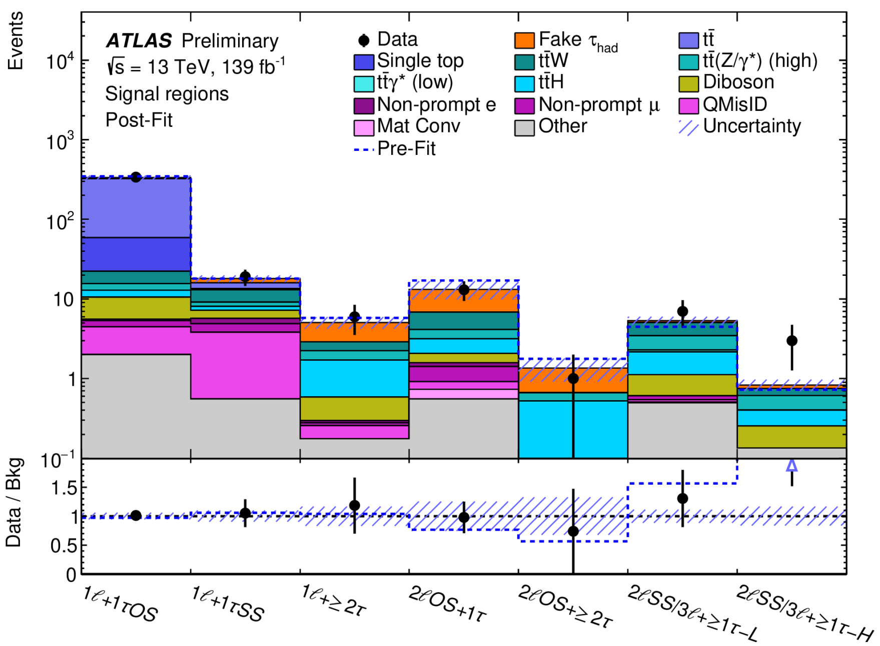
ATLAS : ATLAS-CONF-2020-029

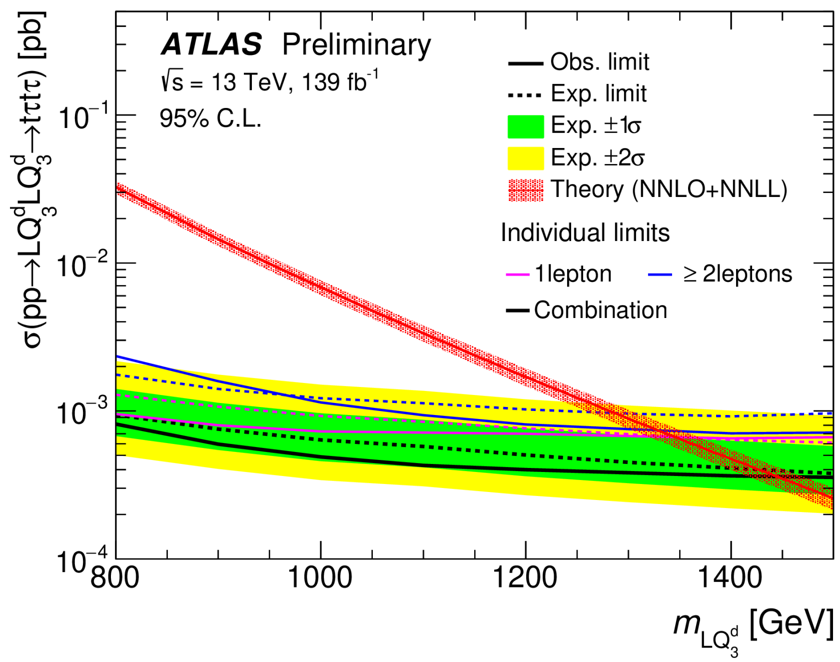
ATLAS : ATLAS-CONF-2020-033

- Events having one light lepton and at least one τ_h, or at least two light lepton with two or more jets with at least one to be arising from the fragmentation of b-hadron



Full Run 2 dataset

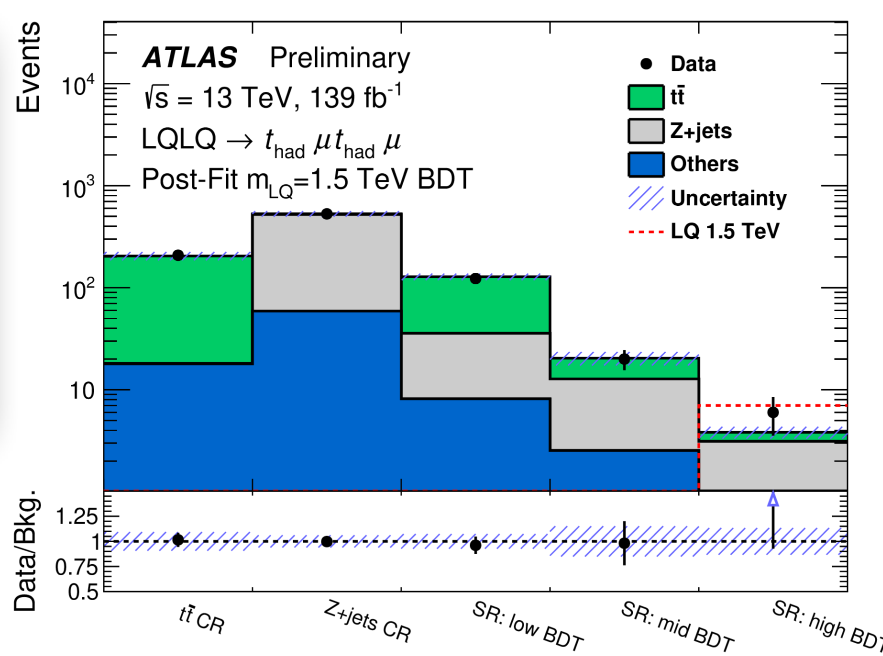


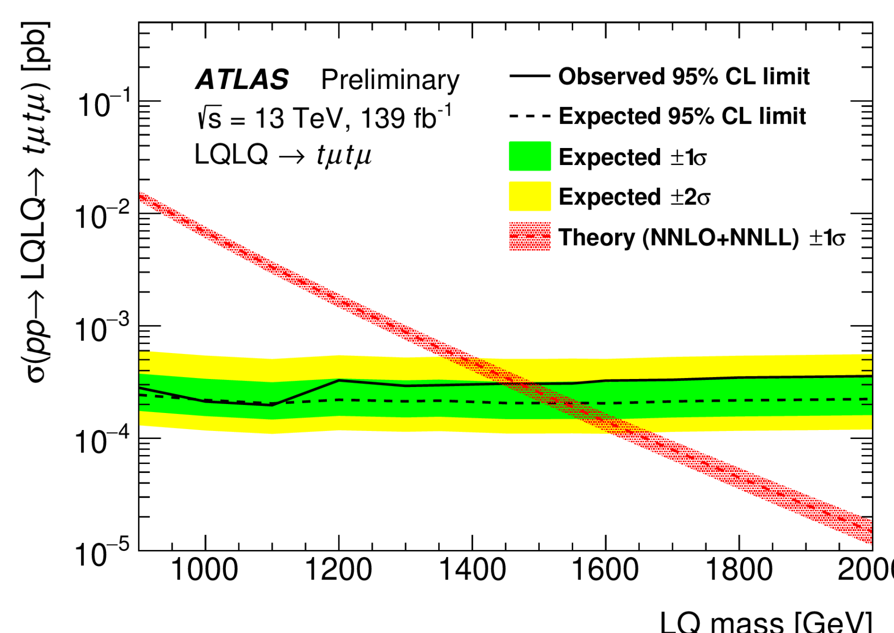


Scalar leptoquarks decaying exclusively into $t\tau$ are excluded up to masses of 1.43 TeV

- Events having a top quark and either an electron or a muon
- targets heavy leptoquarks having top quark decaying to single high p_T wide jet

limits are set at 1.48 TeV and 1.47 TeV for the e and μ channels

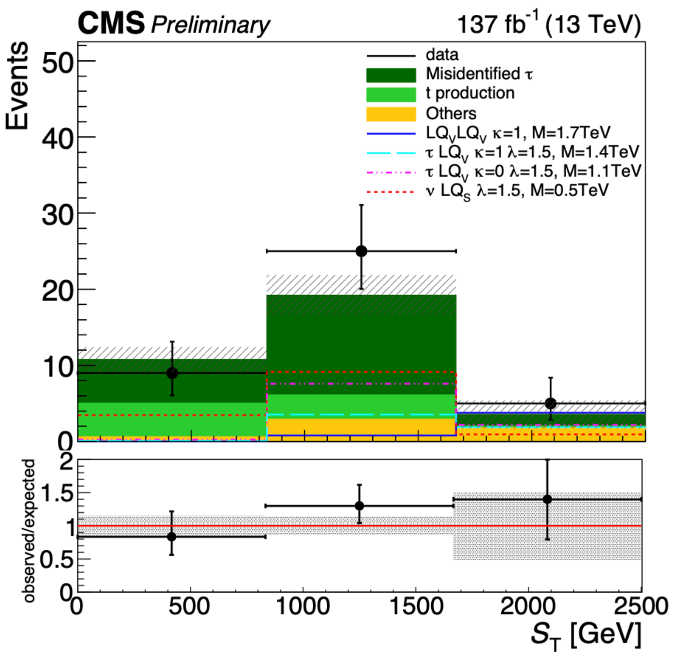




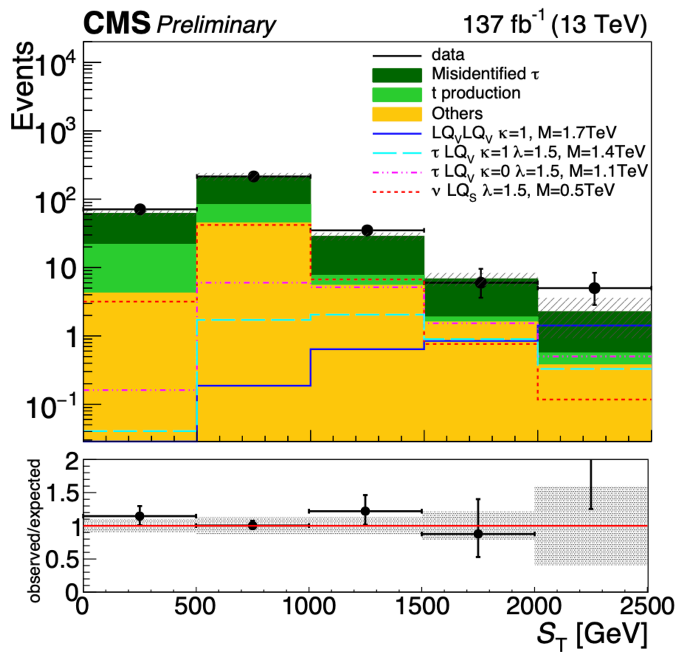
Search for leptoquarks

Full Run 2 dataset

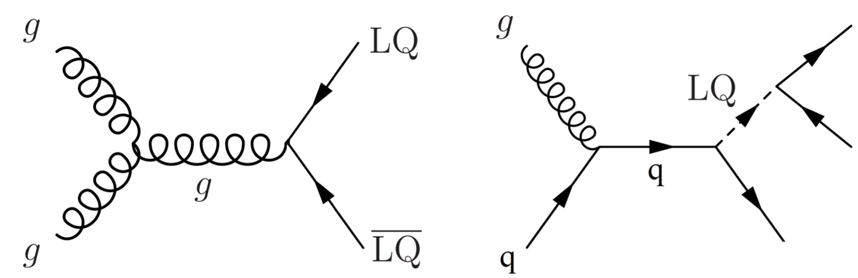
- The leptoquark (LQ) may couple to a top quark plus a τ lepton ($t\tau$) or a bottom quark plus a neutrino ($b\nu$, scalar LQ), or else to $t\nu$ or $b\tau$ (vector LQ), leading to the final states $t\tau\nu b$ and $t\tau\nu$
  - high p_T^{miss}, high H_T, one hadronic top candidate and one hadronic τ



hadronically decaying top quark reconstructed in the merged topology

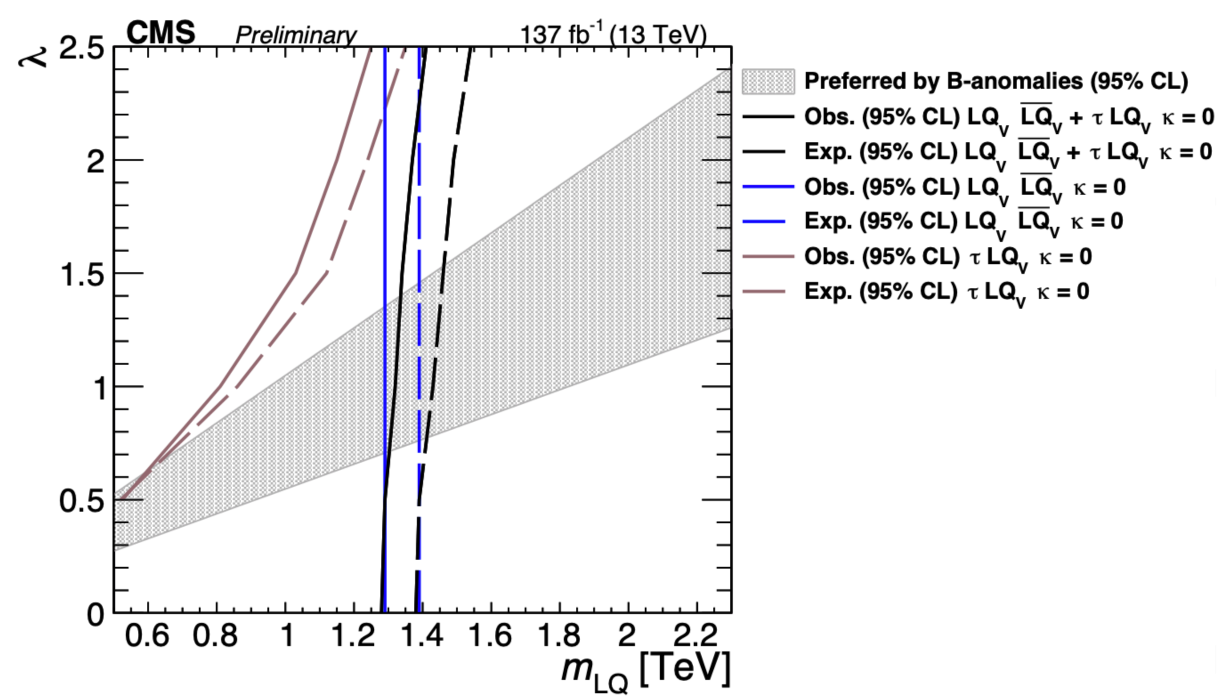


hadronically decaying top quark reconstructed in the resolved topology



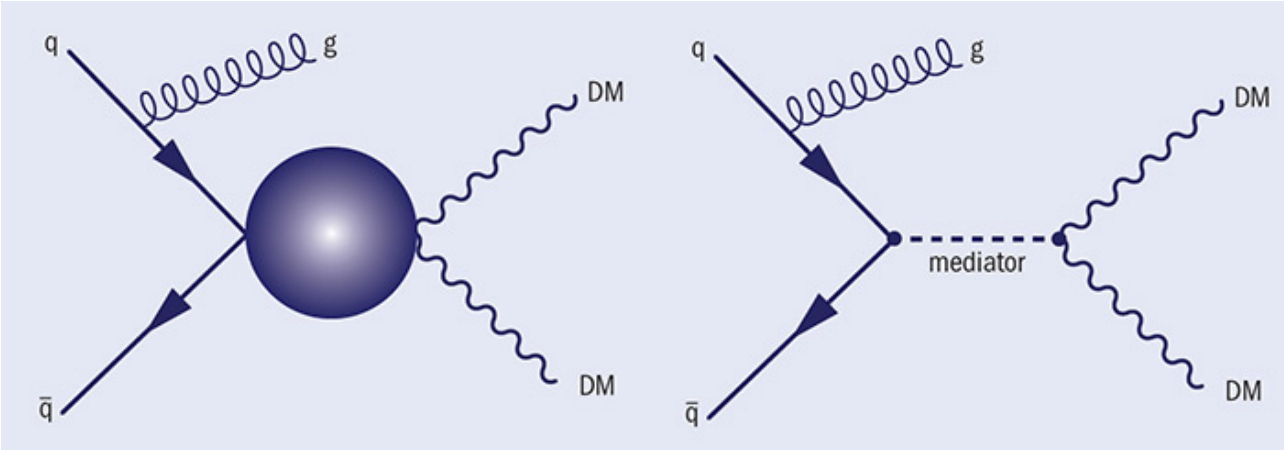
- Major backgrounds: real top production checked in control region and backgrounds from misidentified τ from data

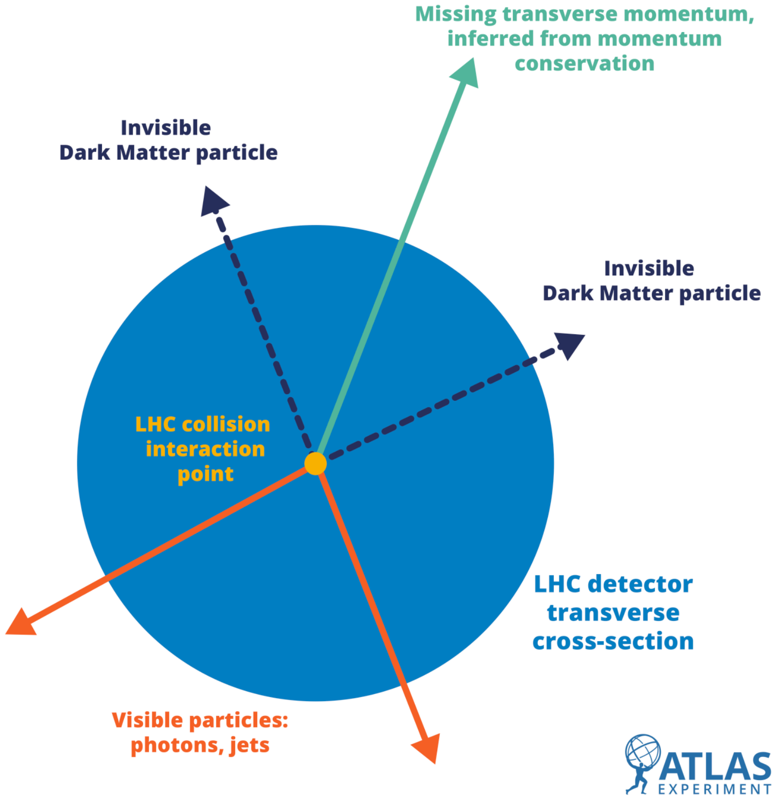
Lower limits at 95% CL are set on the LQ mass in the range 0.98-1.73 TeV, depending on the LQ spin and the LQ-lepton-quark vertex coupling λ, and assuming equal branching fractions for the two LQ decay modes considered



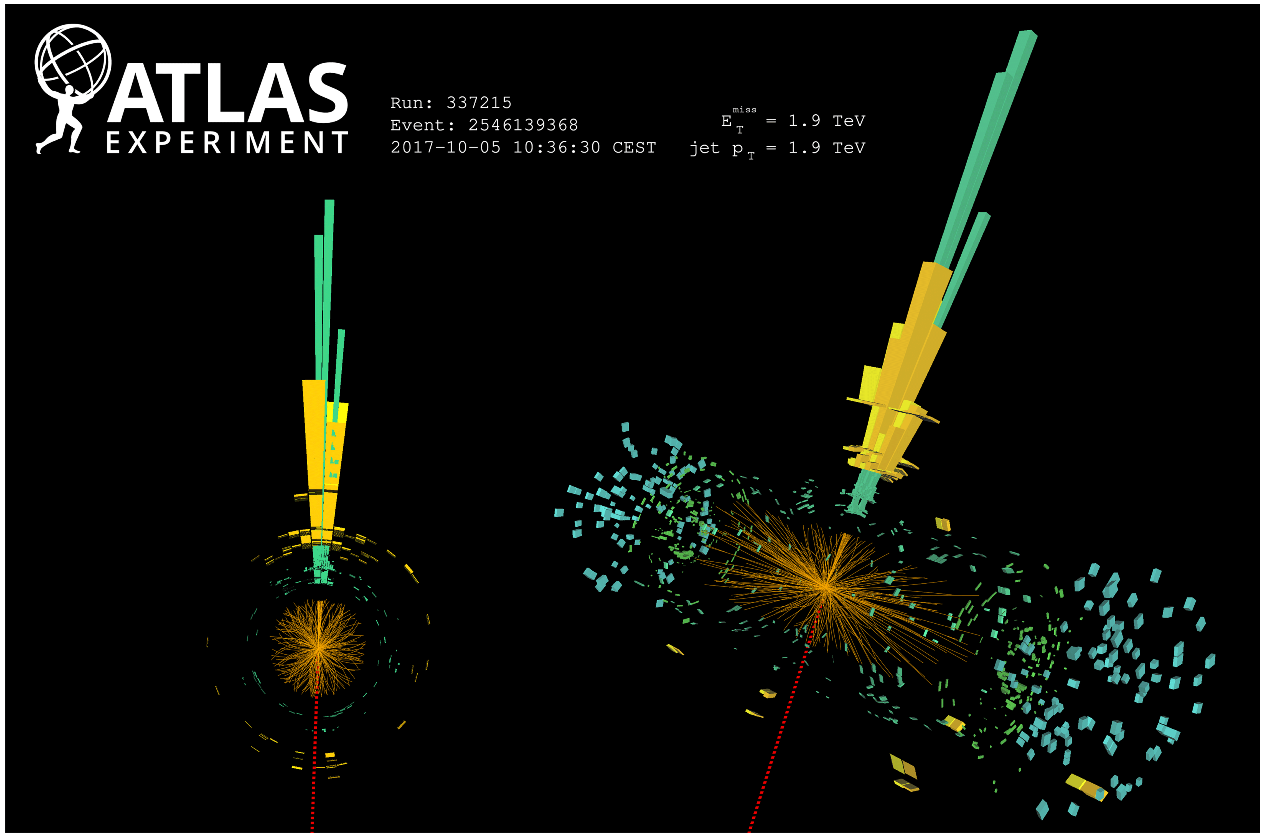
Dark matter

- Pair production at LHC
  - DM candidates escape the detector (weakly interacting)
- Large missing energy distribution is the key variable





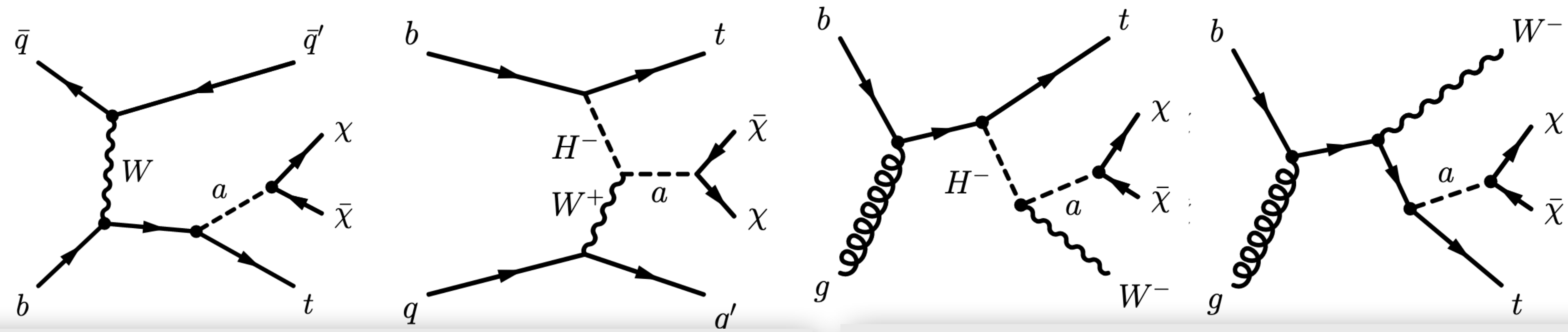
- Simplified S-channel model : **Mediator that couples to SM and to Dark Sector particles**
- **low mass mediator searches:** triggering on an associated object or performing analysis at the "trigger level"



- More complete models:
- 2HDM + a:
  - Mediator that couples to Higgs, SM and Dark Sector → typically: mediator + 2HDM in alignment limit
  - Higgs coupling to new particles

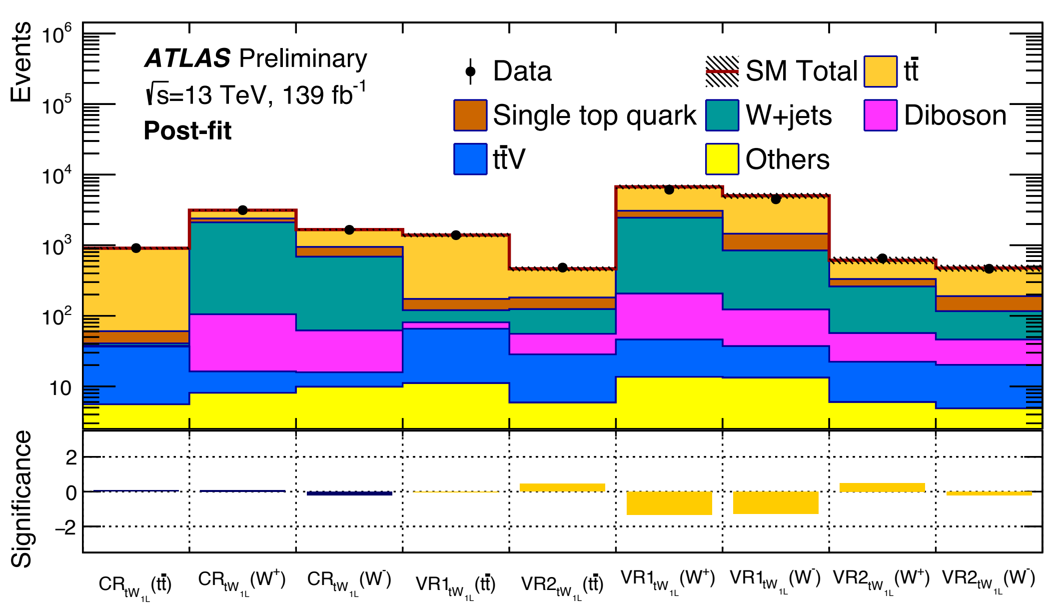
Search for Dark matter

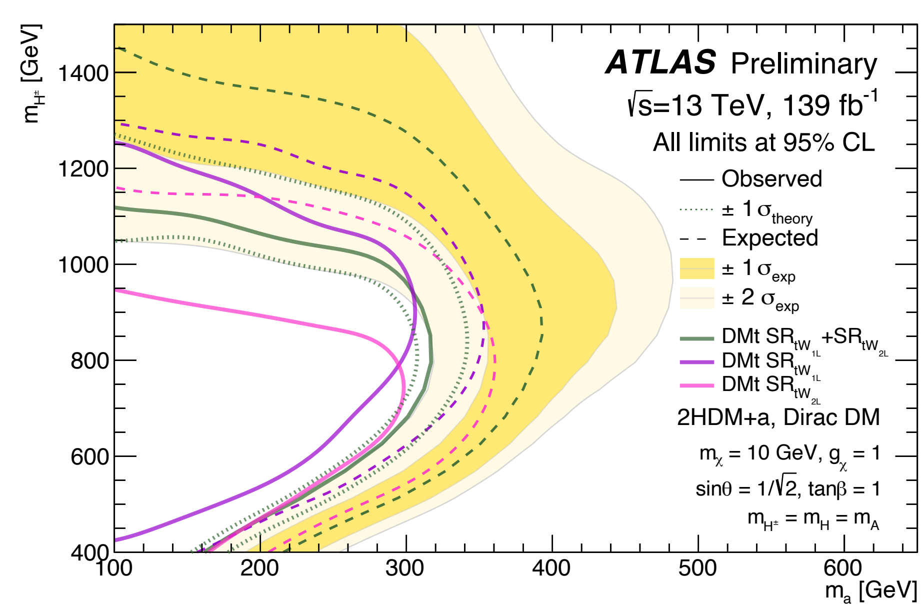
Full Run 2 dataset



- On-shell production of charged Higgs boson leads to a resonance enhancement of tW + MET signal
  - **tW + MET 1L:** shape fit on E_T^{miss}, **tW+MET 2L :** single-bin SR
  - Major backgrounds: ttbar and W+jets (normalized in CRs)

- Cross-section increases with the mass of the charged Higgs
  - **tj+MET 1L:** shape fit on BDT score using E_T^{miss} transverse mass m_T^{lep}, number of forward jets, $\Delta\phi$(le1, bjet1)
  - Major backgrounds: ttbar and W+jets (normalized in CRs)





No significant excess is found with respect to Standard Model predictions

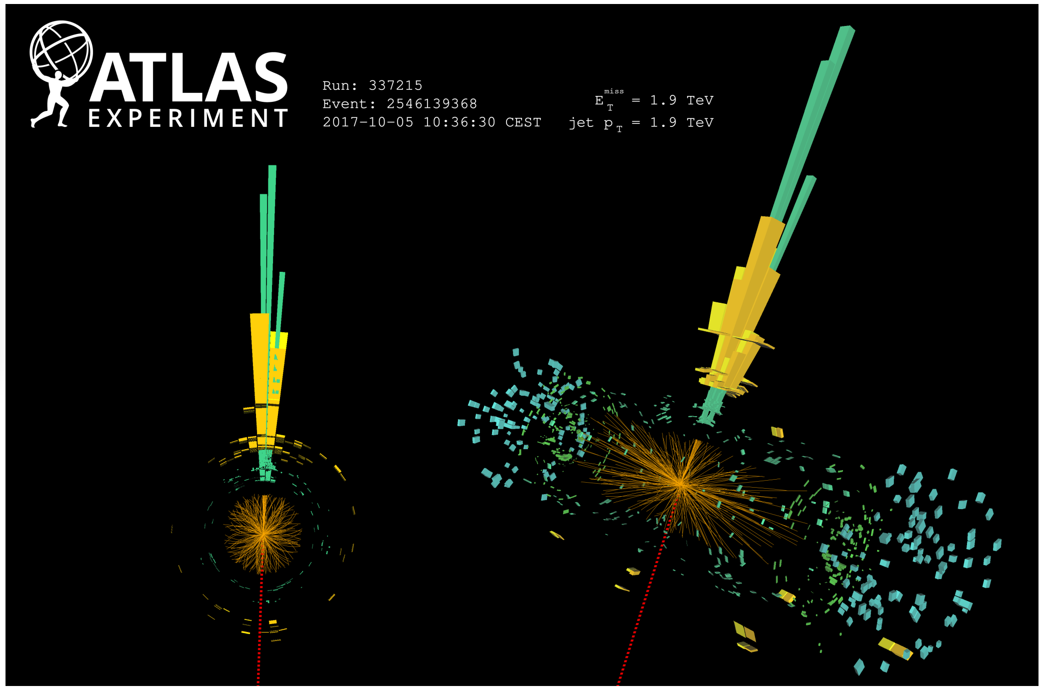
Search for Dark matter

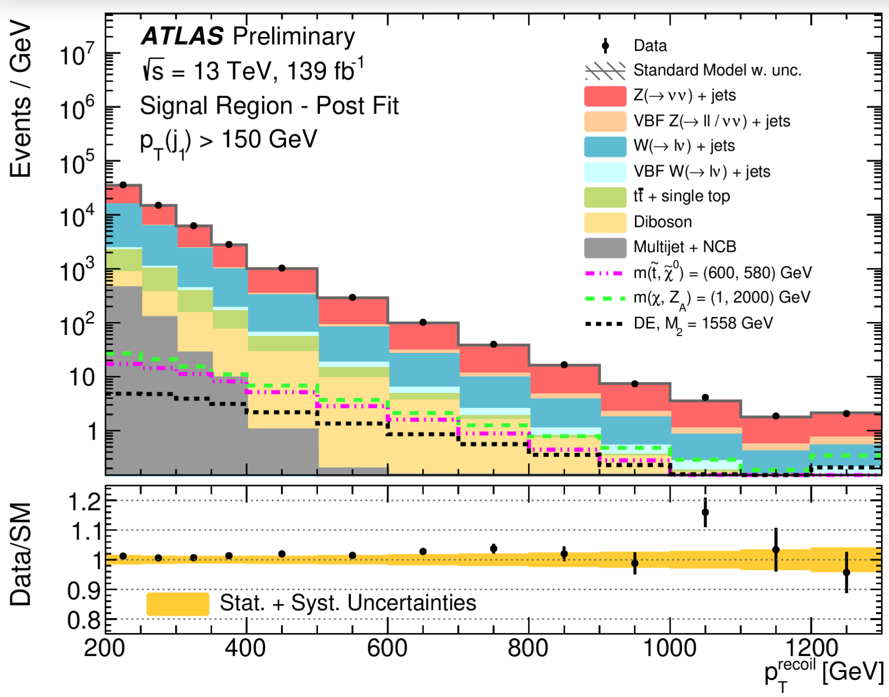
NEW

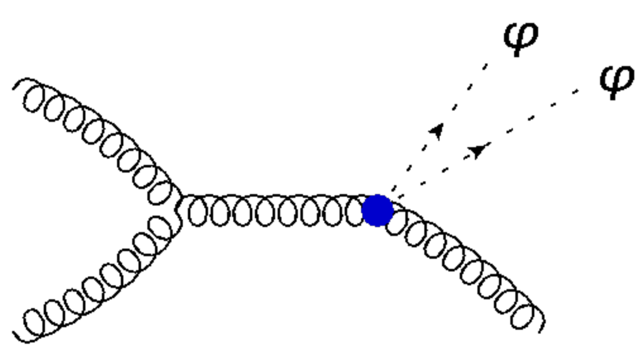
ATLAS : ATLAS-CONF-2020-048

Full Run 2 dataset

- Events having jets and large missing transverse energy
- Considered models : pair-produced weakly interacting dark-matter candidates, large extra spatial dimensions, supersymmetric particles, axion-like particles, and new scalar particles in dark-energy inspired models

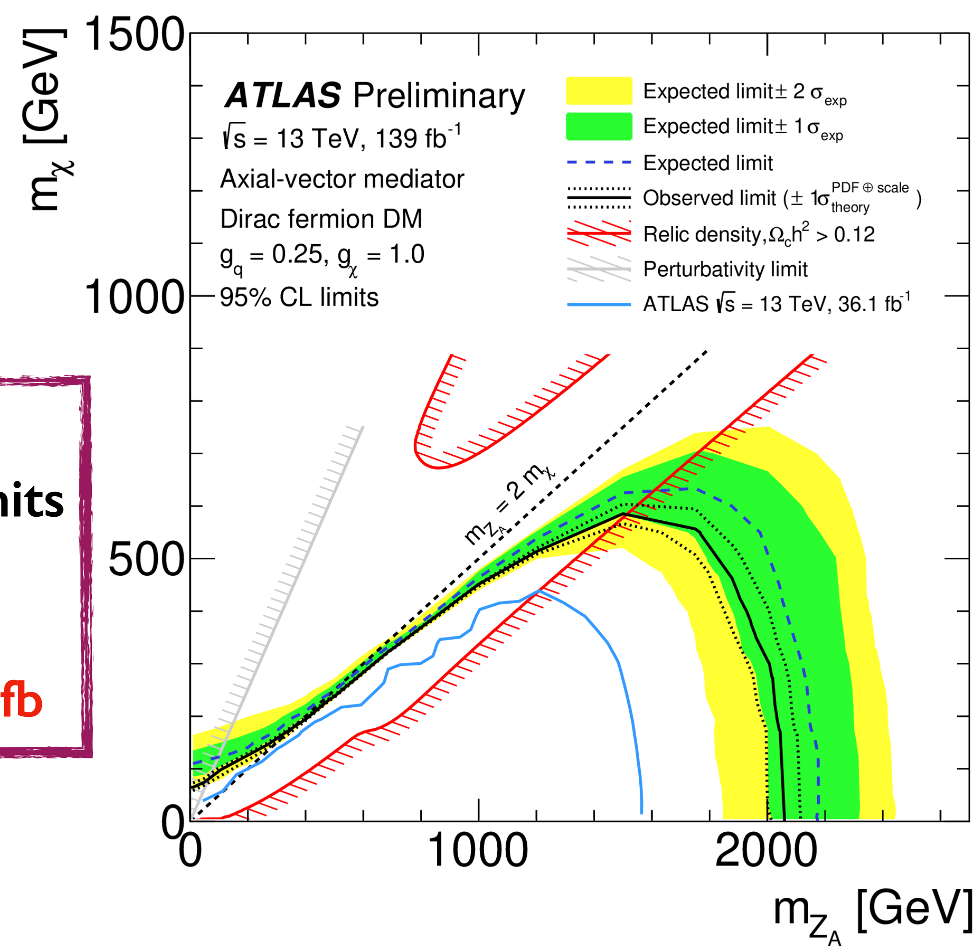






Selection	$\langle\sigma\rangle^{95}_{obs}$ [fb]	S^{95}_{obs}	S^{95}_{exp}
p_T^{recoil} > 200 GeV	861	119653	86000^{+27000}_{-24000}
p_T^{recoil} > 250 GeV	350	48636	35600^{+12700}_{-10000}
p_T^{recoil} > 300 GeV	156	21624	15500^{+6000}_{-4300}
p_T^{recoil} > 350 GeV	87	12066	8200^{+3100}_{-2300}
p_T^{recoil} > 400 GeV	52	7285	4700^{+1800}_{-1300}
p_T^{recoil} > 500 GeV	21	2903	1910^{+720}_{-530}
p_T^{recoil} > 600 GeV	10	1421	930^{+350}_{-260}
p_T^{recoil} > 700 GeV	4.2	578	480^{+180}_{-130}
p_T^{recoil} > 800 GeV	2.1	296	267^{+100}_{-75}
p_T^{recoil} > 900 GeV	1.2	165	161^{+62}_{-45}
p_T^{recoil} > 1000 GeV	1.3	189	113^{+43}_{-31}
p_T^{recoil} > 1100 GeV	0.5	73	71^{+27}_{-20}
p_T^{recoil} > 1200 GeV	0.3	39	47^{+19}_{-13}

Model-independent 95% confidence level limits on visible cross sections obtained in the range between 861 fb and 0.3 fb

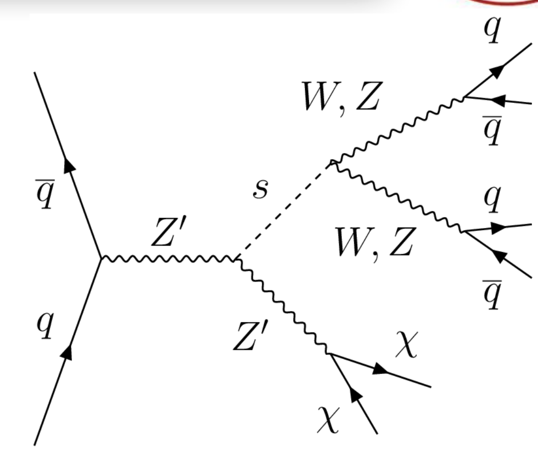


Search for Dark matter

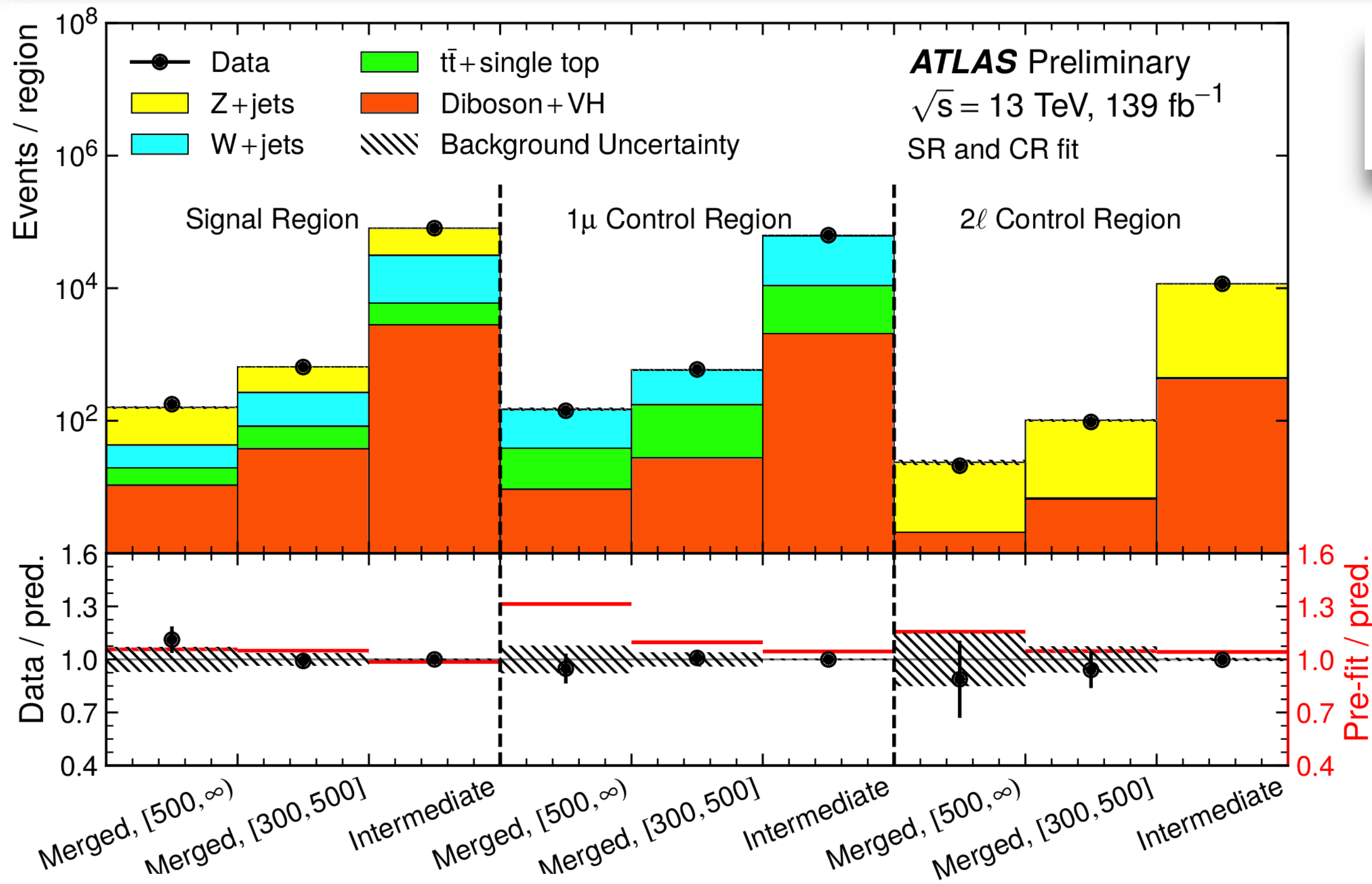
NEW

Full Run 2 dataset

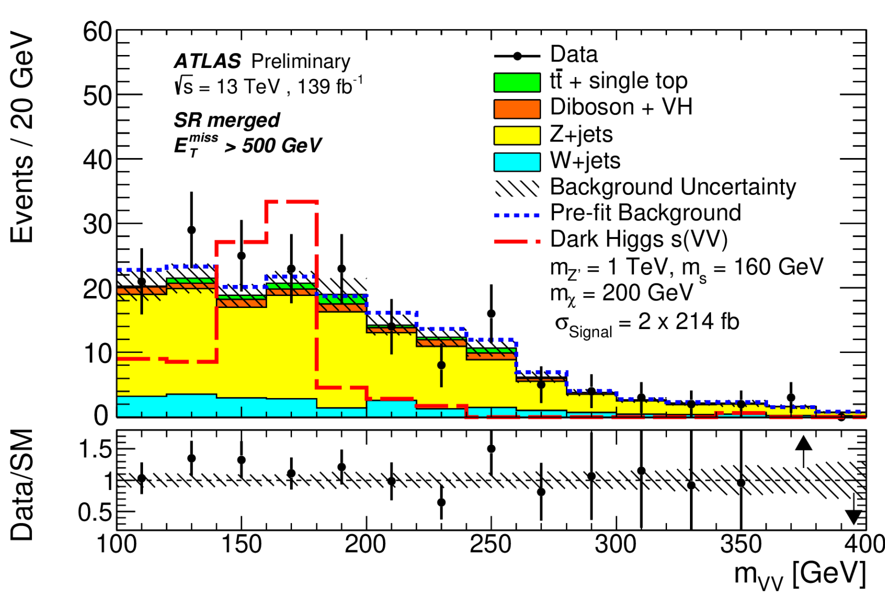
- Search is performed for DM particles produced in association with a Dark Higgs boson 's' decaying to VV where $VV = W^{\pm}, Z$



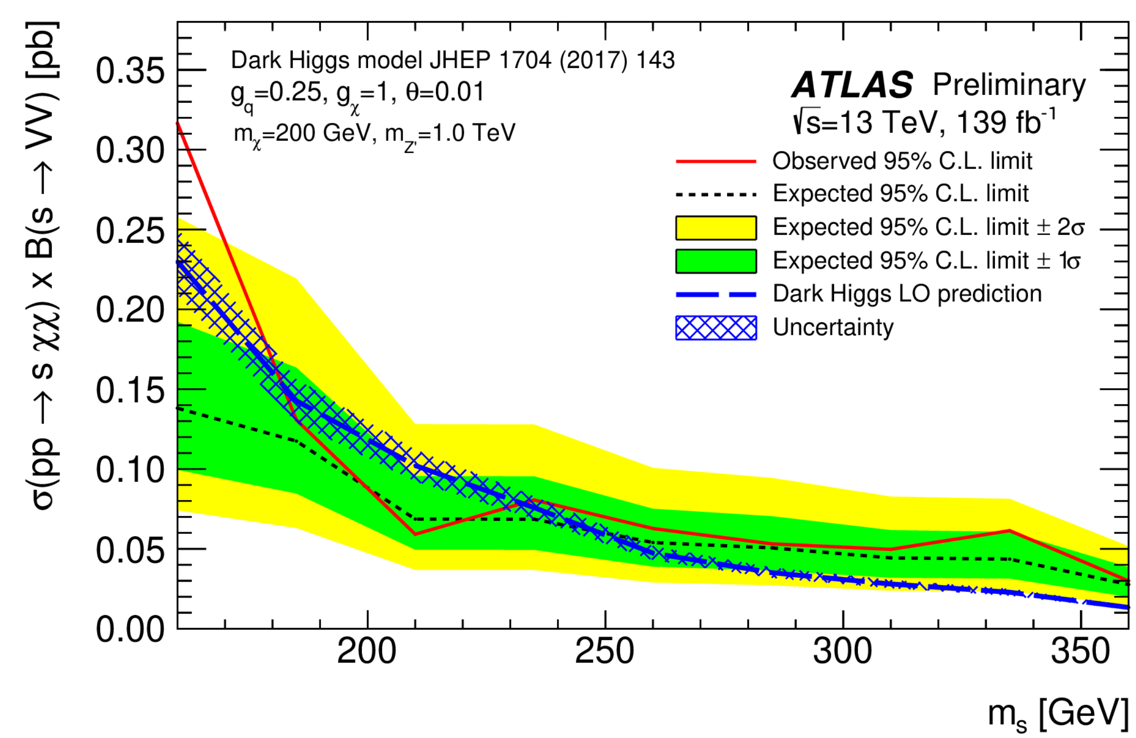
FIRST RESULTS!



$S \to V(q\bar{q})V(q\bar{q})$ **decays are reconstructed with 'Track Assisted Reclustered' (TAR) jets technique using reclustered jets with a cone parameter R=0.8 based on R=0.4 calorimeter jets and tracking information**



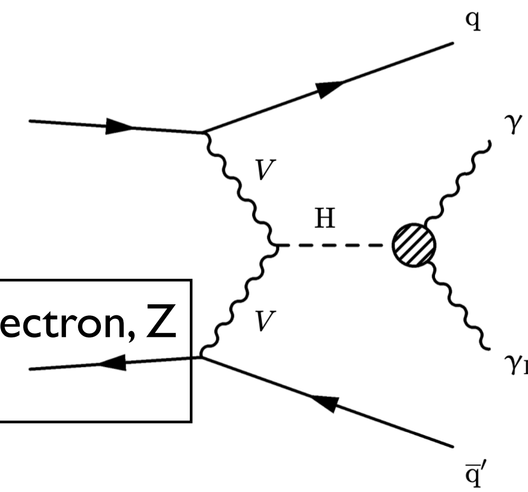
No significant excess over the predicted background is found and sets exclusion for m_s > 160 GeV

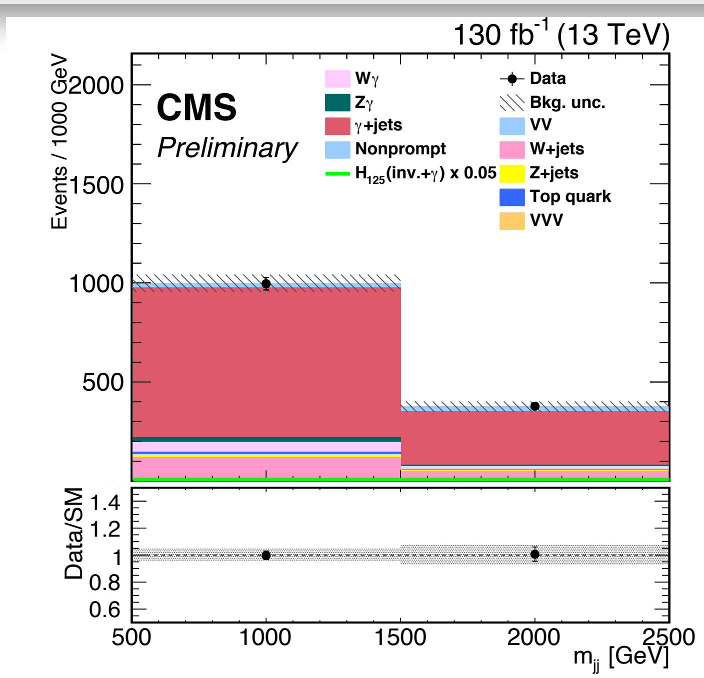


Search for Dark matter

Full Run 2 dataset

- The signal topology consists of two forward high-p_T jets consistent with VBF production (large $\Delta\eta$ and m_{jj} > 500 GeV), large p_T^{miss} and an isolated high p_T photon

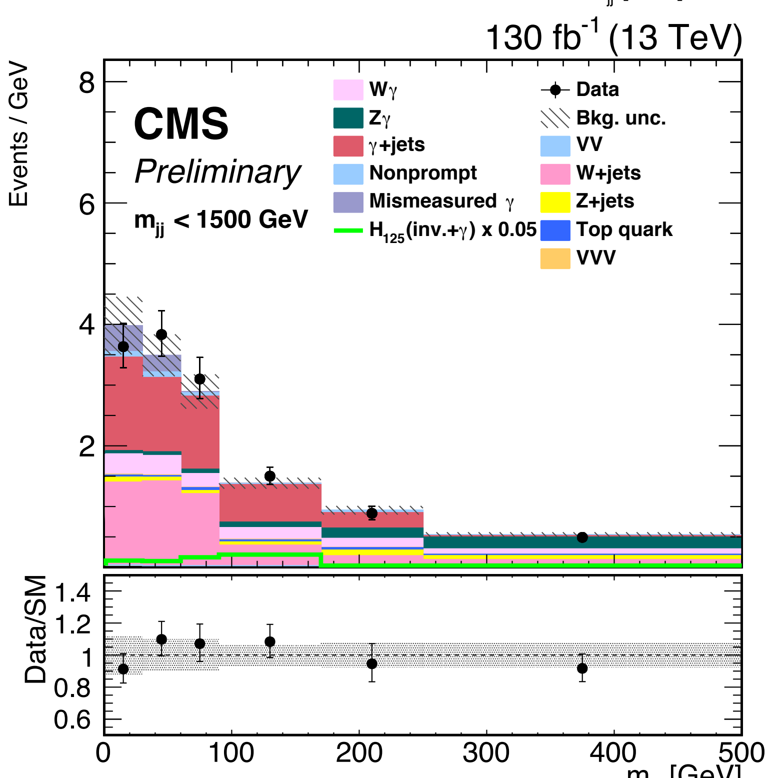


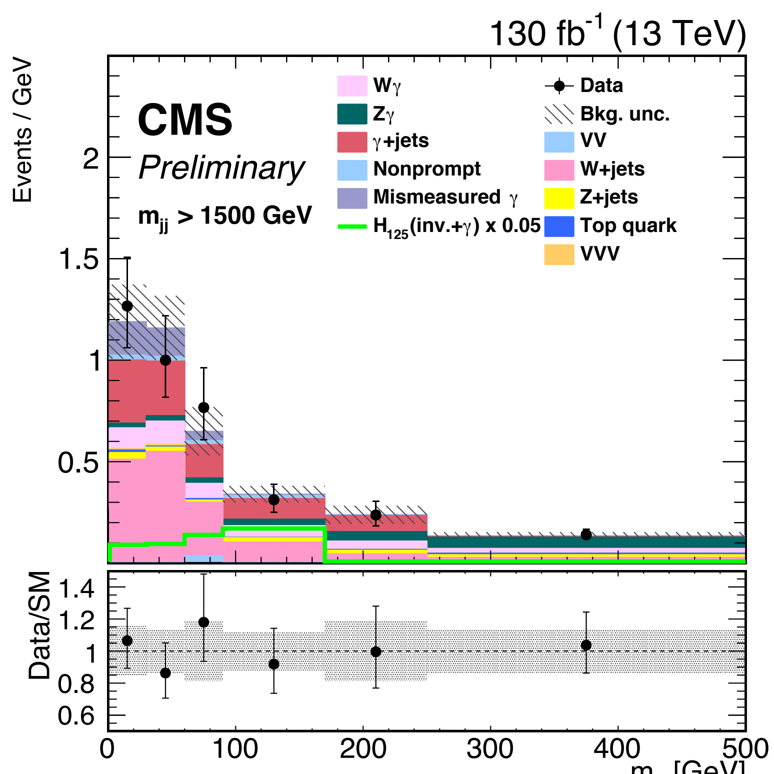


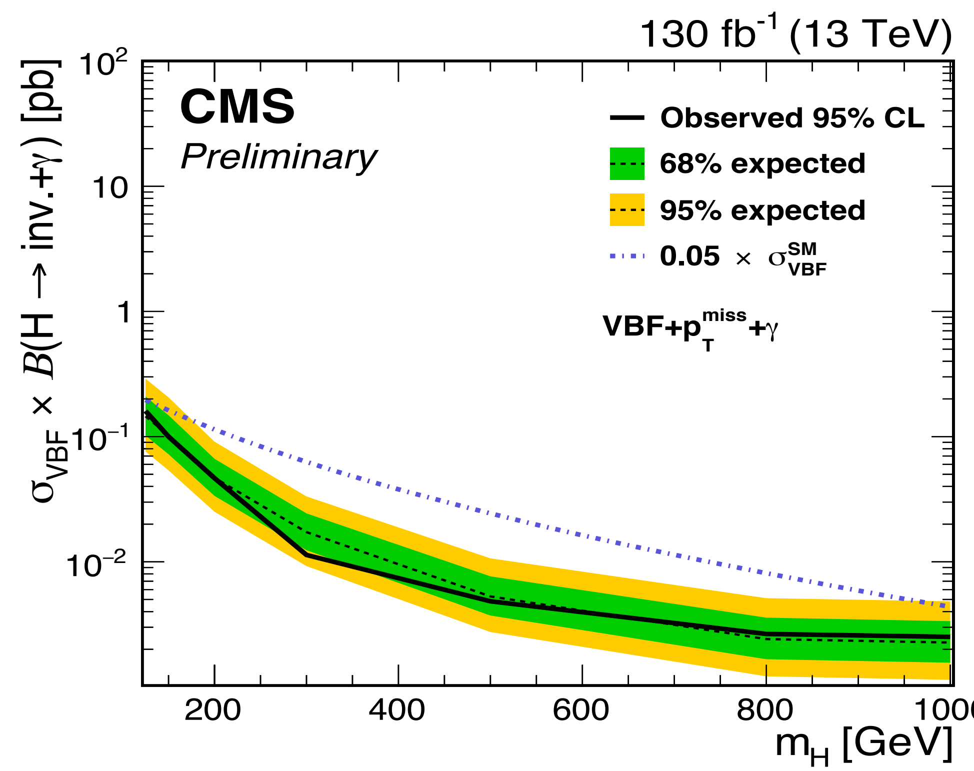
- Dominant background : W+Jets where photon is misidentified electron, Z $\rightarrow \nu\nu + \gamma$, and W→l$\nu + \gamma$ and γ + jets with mis-measured p_T^{miss}

Fit to the mT distribution (p_T^{miss} + photon)

Combining with similar CMS ZH search the observed (expected) upper limits at 95% confidence level at mH = 125 GeV on B(H $\rightarrow$ invisible + γ) is 2.9 (2.1) %



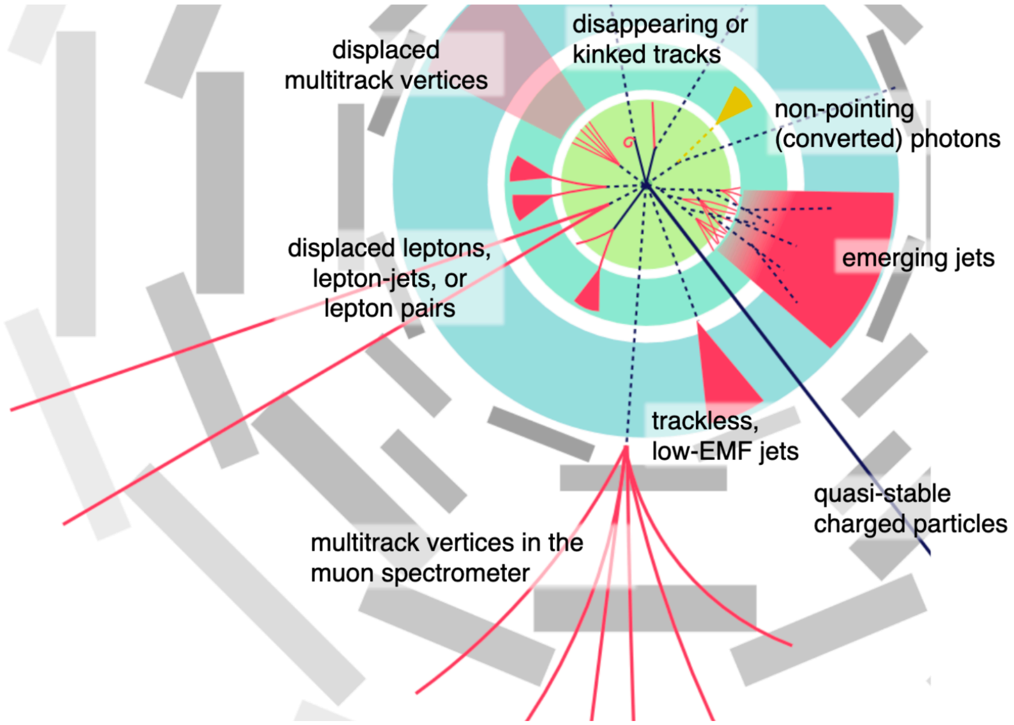




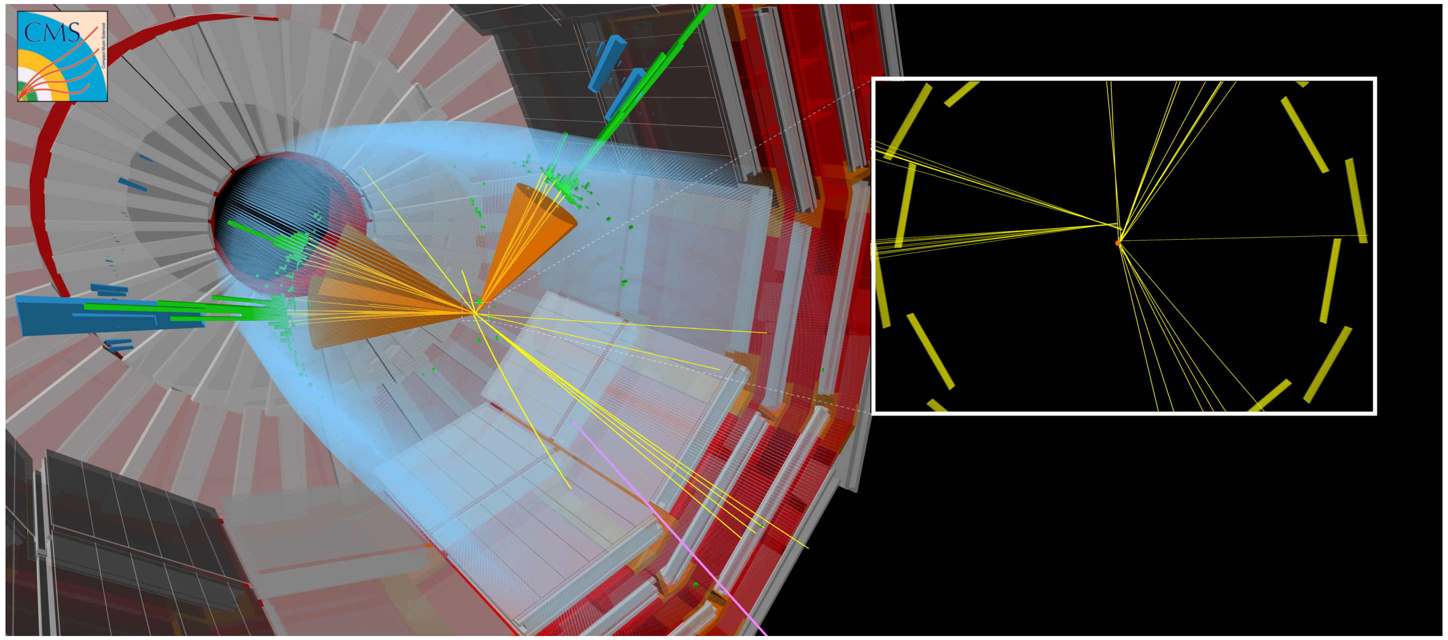
Search for long lived particles

Parallel talk by:
Lesya Horyn [Link]

- **Long-lived and unconventional exotic particles** with striking signatures **predicted by many extensions of the SM**



- Examples:
  - Heavy, long-lived, charged particles (R-hadrons, Sleptons) Particles can decay in the detector after few cm
    - neutralinos in GMSB, mass-degenerate gauginos, particles of an Hidden sector



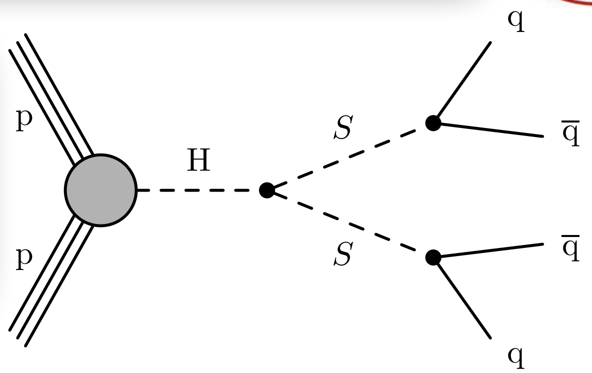
Challenging from the experimental point of view:
- Non-standard reconstruction
- Displacements, timing and ionization
  - Dedicated triggers
- Non-standard background is a challenge
  - Detector noise, cosmic rays, reconstruction failures
  - Usually estimated from data

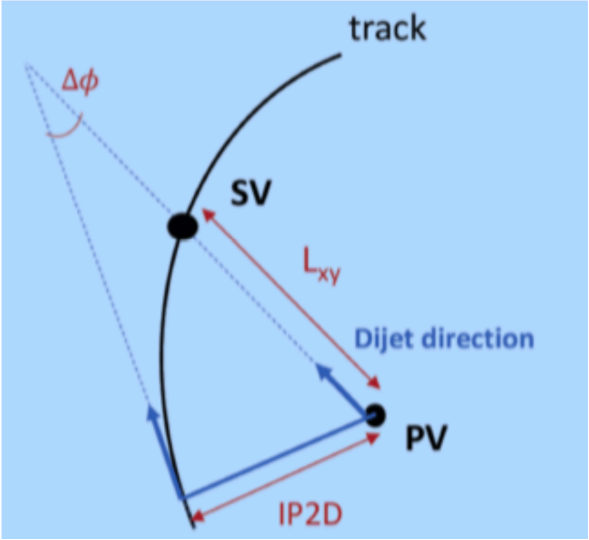
Search for long lived particles

CMS : CMS-PAS-EXO-19-021

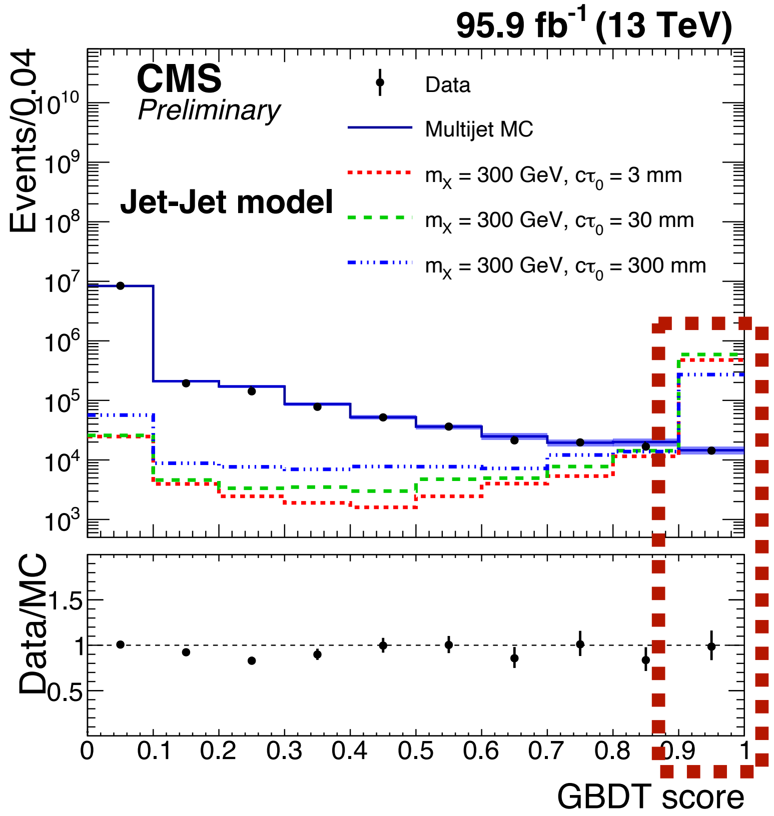
Full Run 2 dataset

- Distinctive topology: pair of jets originating at a secondary vertex
- Models targeted : LLP decaying to q-qbar, Exotic decays of Higgs: gg→H→2S, S→qq ($c\tau \sim 1$mm to 3mm)

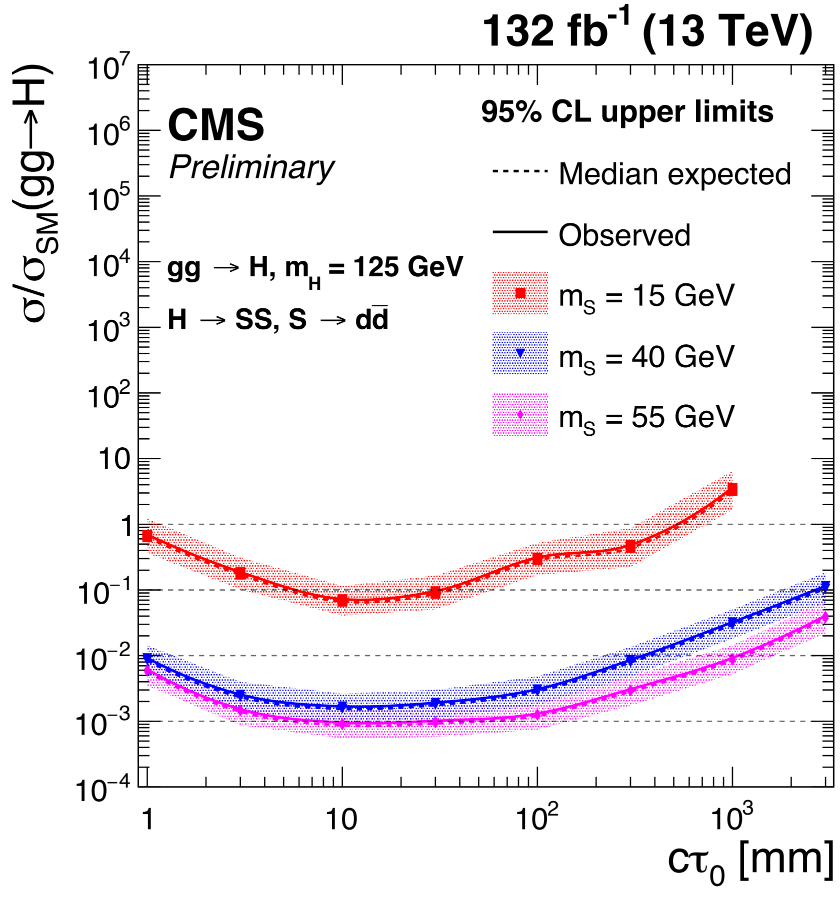




- A dedicated secondary vertex reconstruction is performed
- Dominant background : QCD multijet
- Gradient Boosted decision tree (GBDT) which includes variables like vertex track multiplicity, signed IP2D and Lxy



CMS excludes top squark masses up to 1.6 TeV for $c\tau$ between 3 and 340 mm



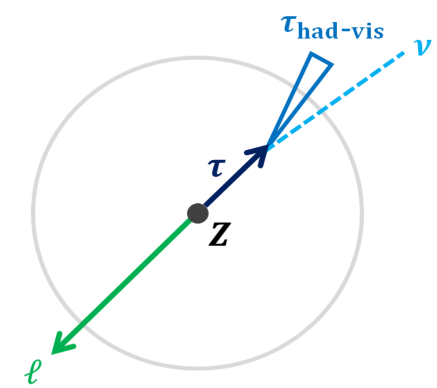
Search for LFV Z

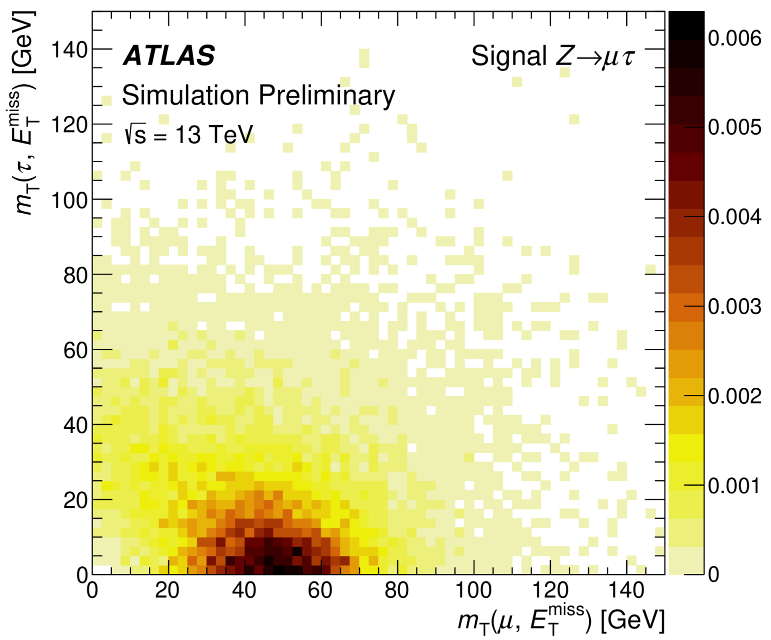
NEW

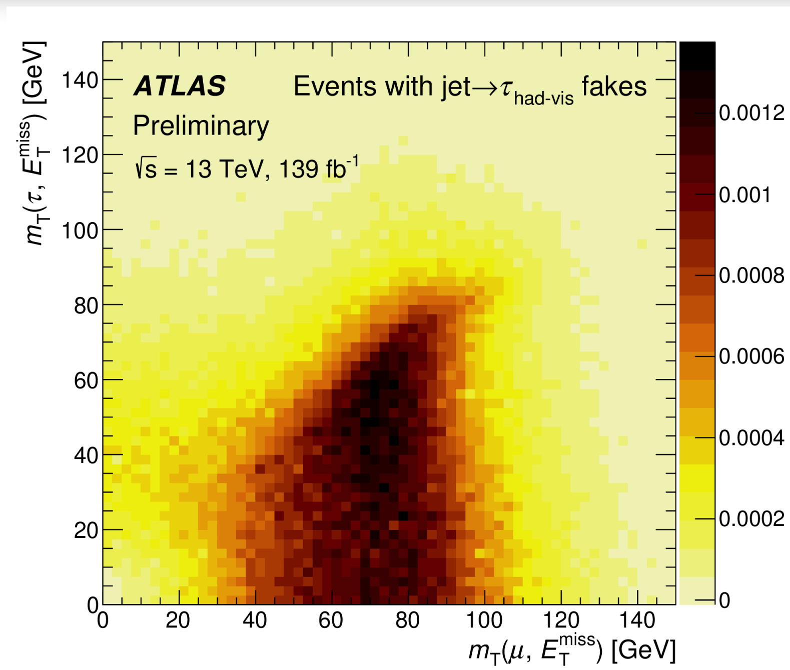
ATLAS : ATLAS-CONF-2020-035

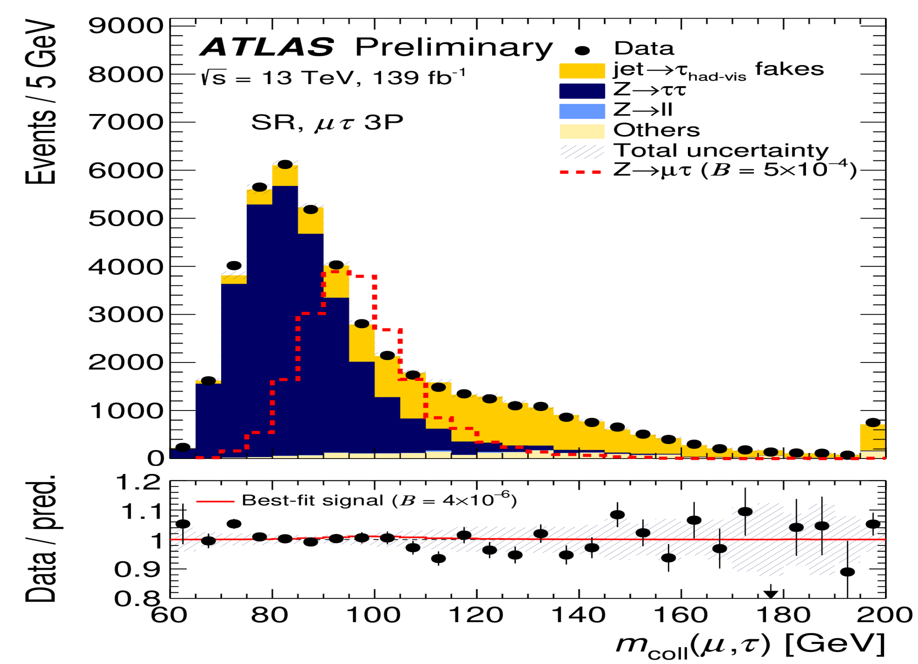
Full Run 2 dataset

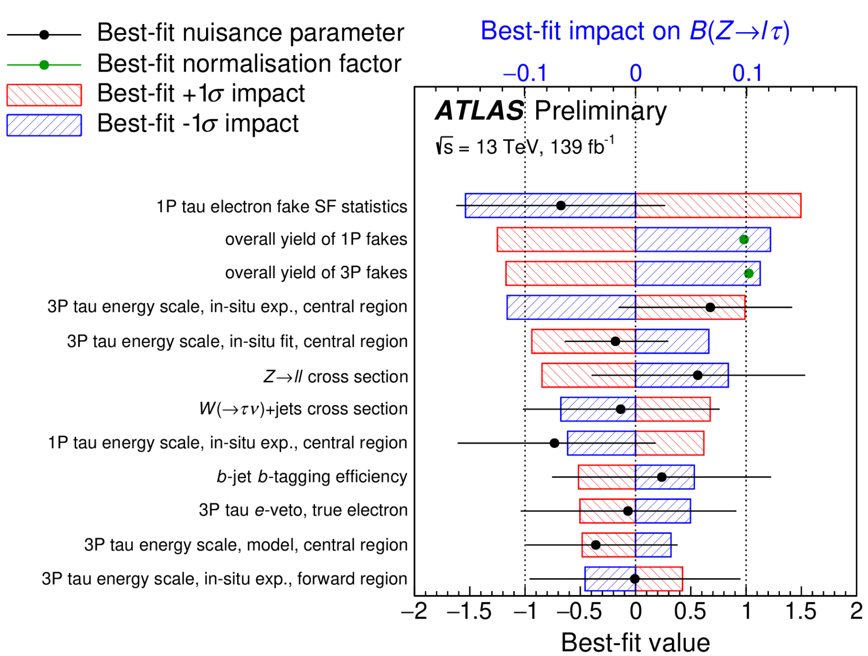
- Neutrino oscillations experiments have demonstrated that Lepton Flavour Conservation is violated in nature
- Searching Z boson decaying into a τ- lepton and another lepton of different flavour (e or μ) with opposite charge









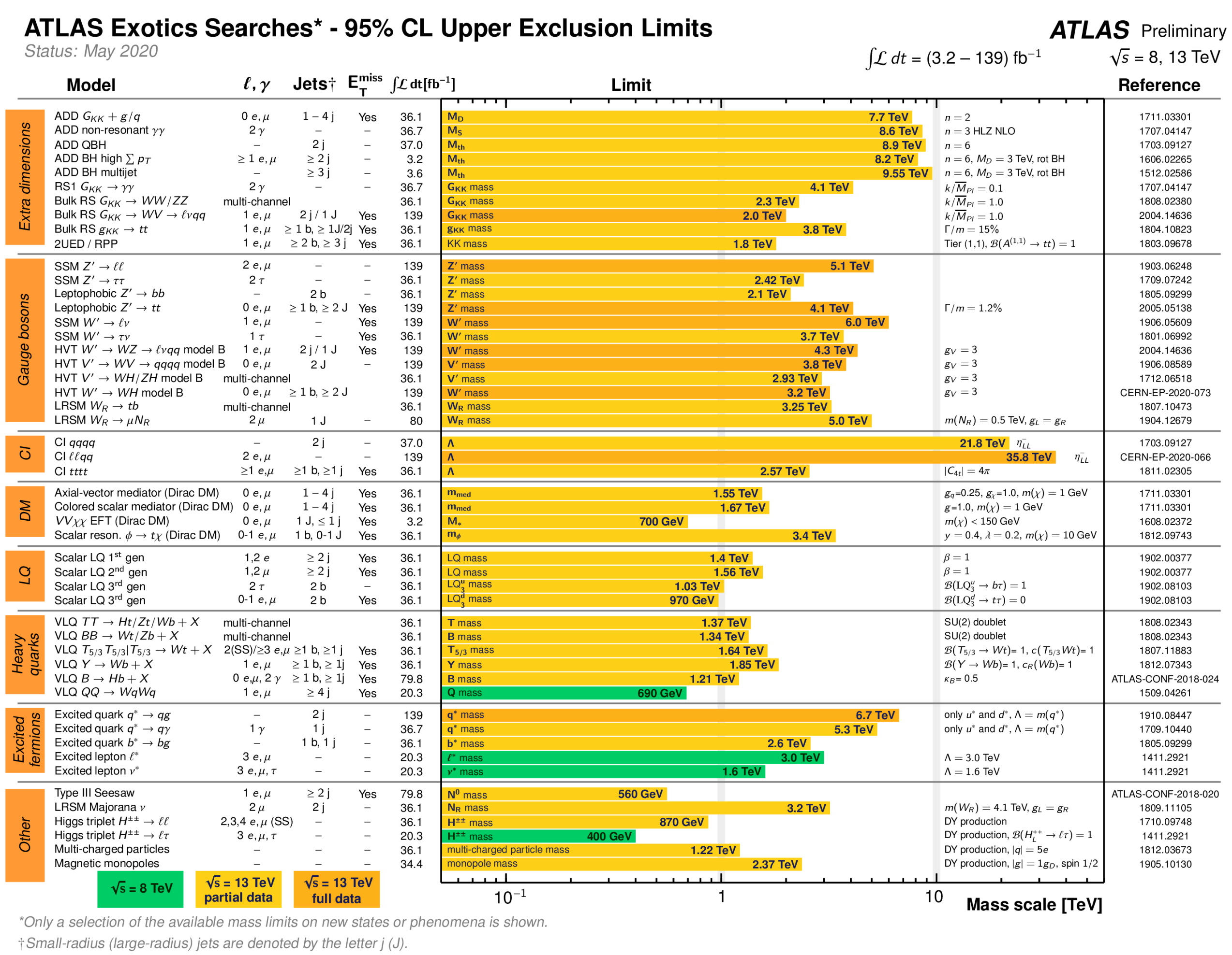


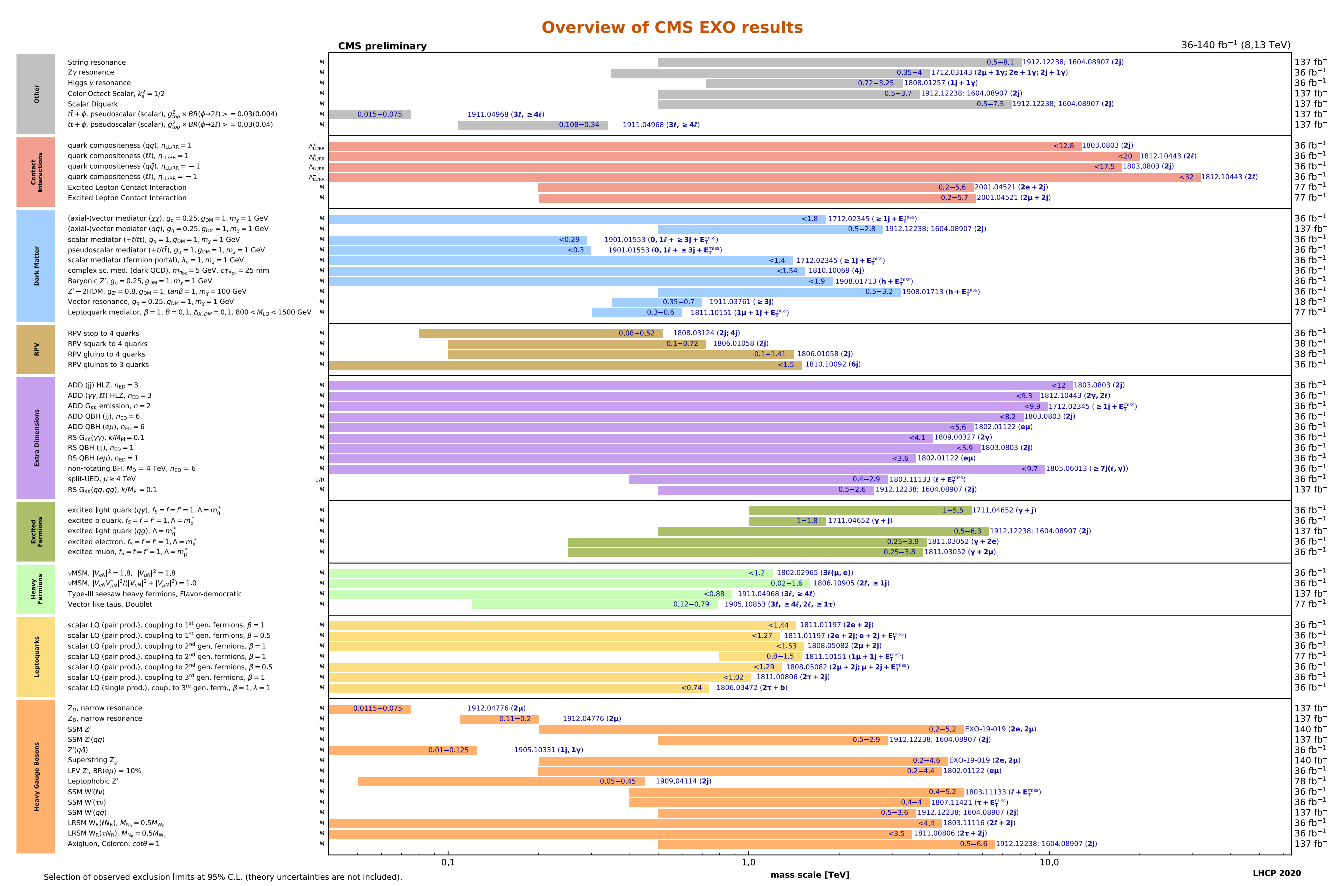
superseding the otherwise best limits set by the LEP experiments

Experiment, polarisation assumption	Observed (expected) upper limit on $\mathcal{B}(Z\rightarrow\ell\tau)$ [$\times10^{-6}$] $e\tau$	$\mu\tau$
ATLAS Run 2, unpolarised τ	8.1 (8.1)	9.9 (6.3)
ATLAS Run 2, left-handed τ	8.2 (8.6)	9.5 (6.7)
ATLAS Run 2, right-handed τ	7.8 (7.6)	10 (5.8)
ATLAS Run 1, unpolarised τ [53]		17 (26)
ATLAS Run 1 and Run 2, unpolarised τ		9.5 (6.1)
LEP OPAL, unpolarised τ [10]	9.8	17
LEP DELPHI, unpolarised τ [11]	22	12

Conclusion

- Searching for exotics is both challenging and exciting, with developing new techniques and considering possible final states
- With increasing efficiency with using increased analysis techniques and improved object performance, sensitivity is increased leading to improved exclusion limits
- Many full run-2 results are still to come. Stay tuned!





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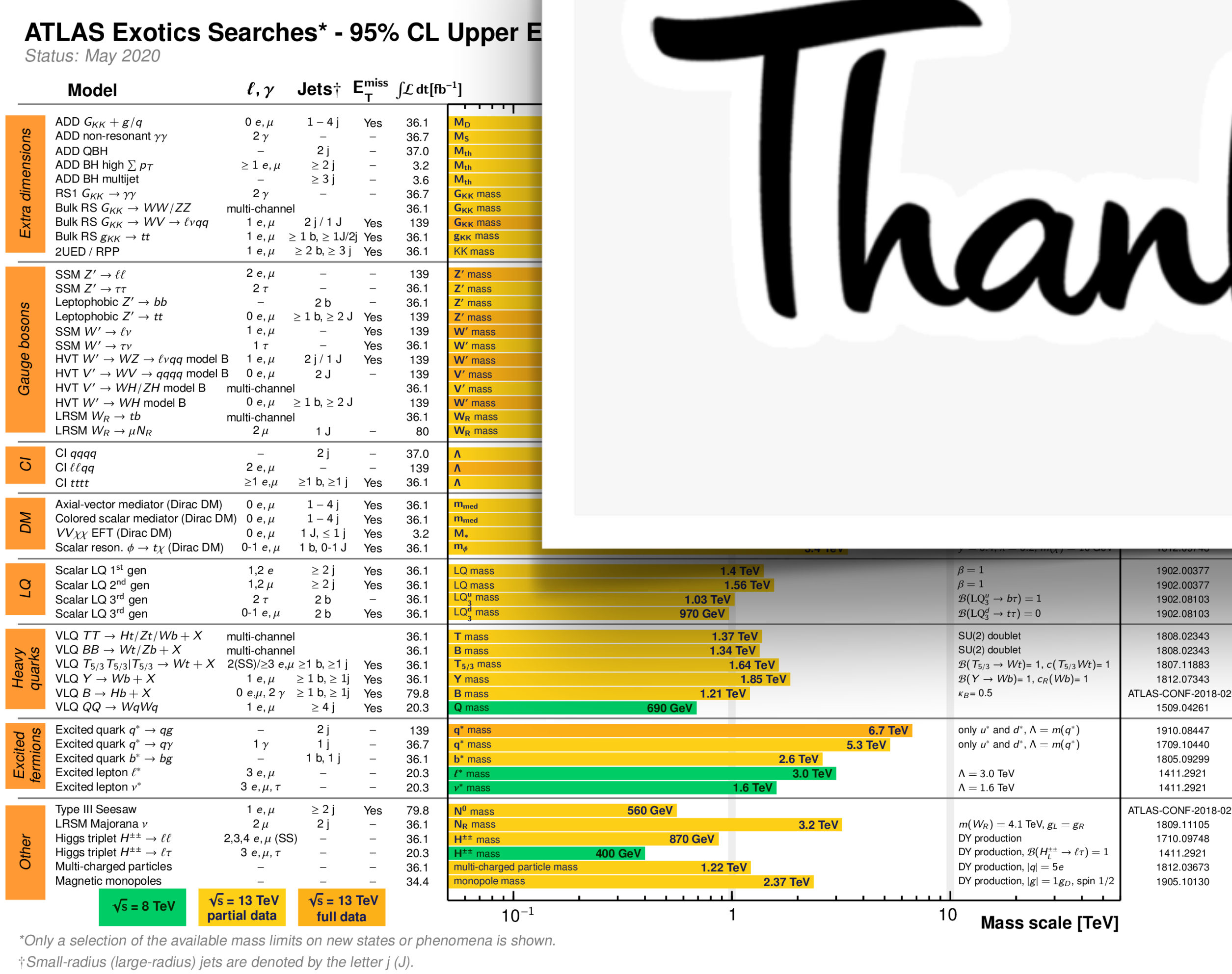
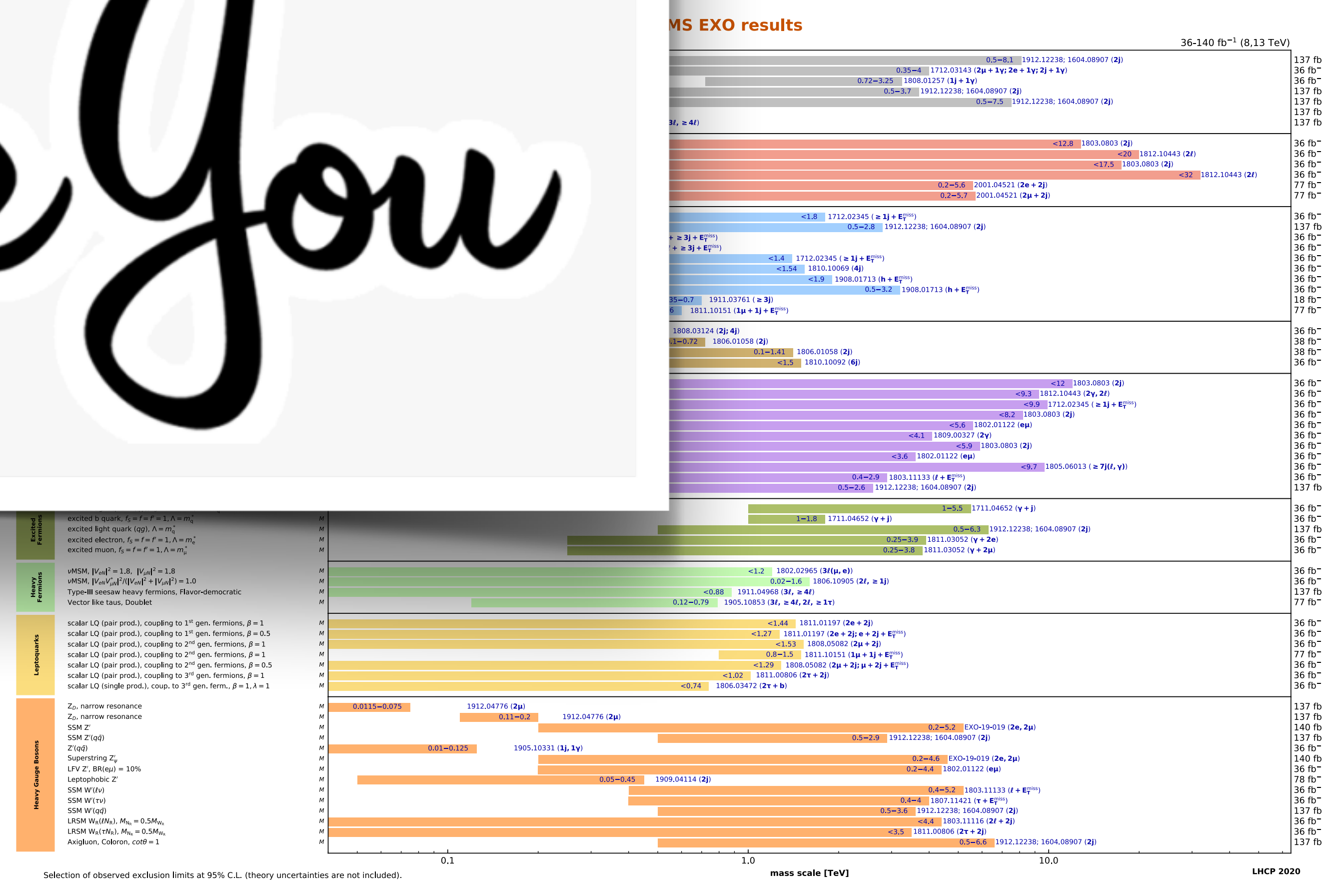
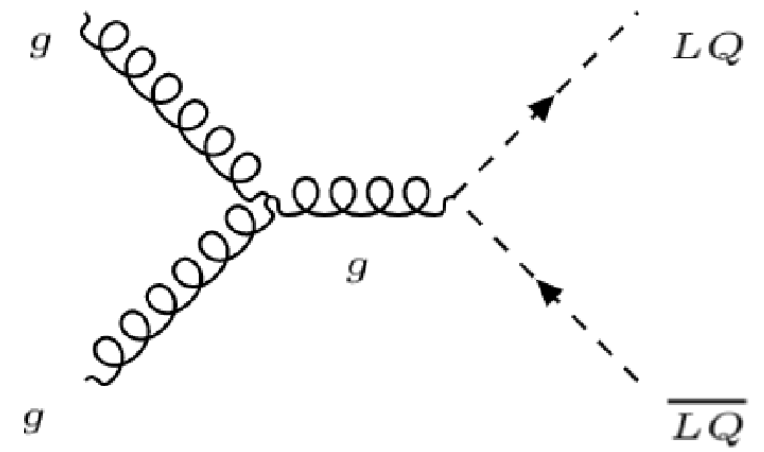


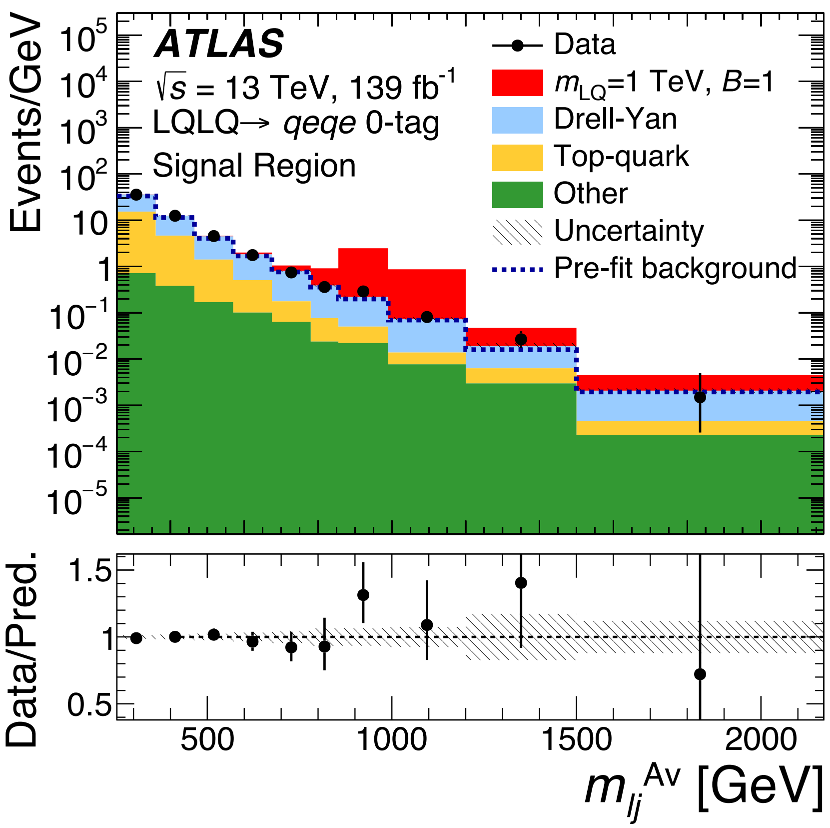


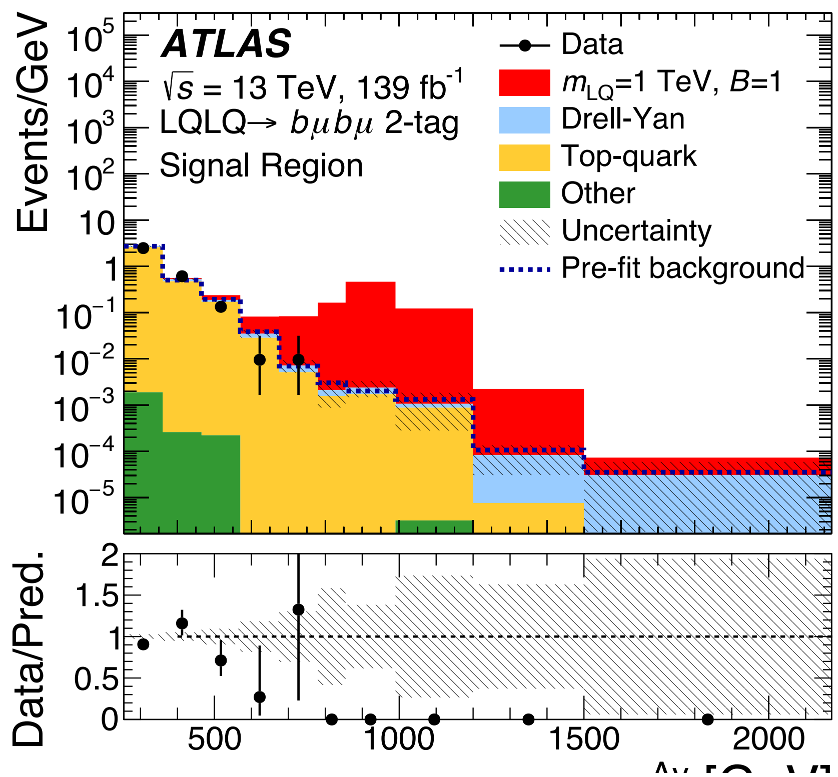
Additional Slides

Search for leptoquarks

- events with two electrons or two muons and two or more jets, including jets identified as arising from the fragmentation of c - or b-quarks

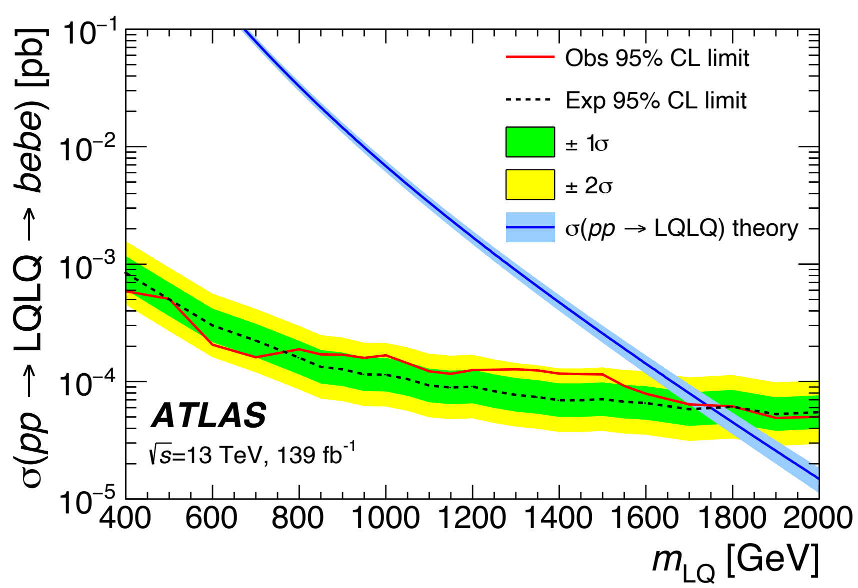


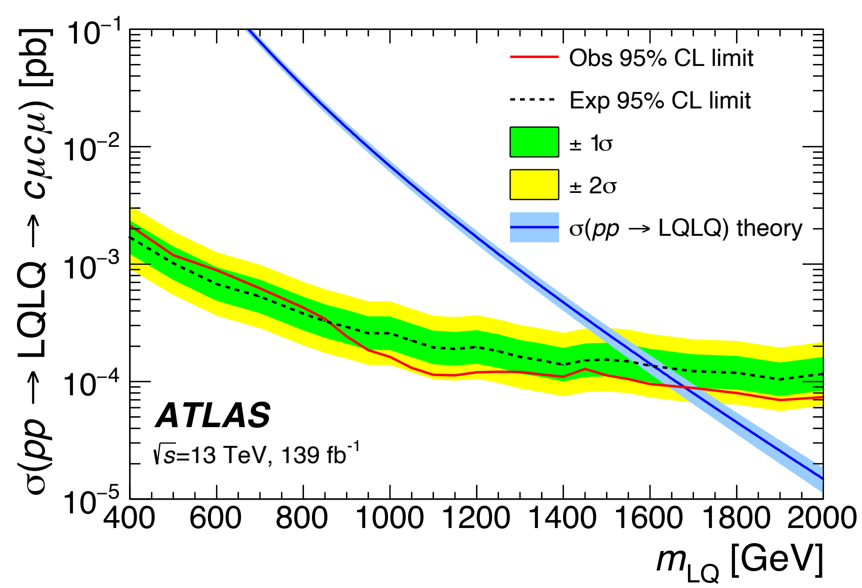




A branching ratio into a charged lepton and a quark is assumed to be 100%, with minimal dependence on the quark flavor

Leptoquarks with masses below 1.8 TeV and 1.7 TeV are excluded in the electron and muon channels





Di-Jet resonance search

ATLAS : JHEP03(2020)145

Full Run 2 dataset

- Inclusive result with events with 1 or 2 b-jets
- Jets close in Δy (to reject background)
- Background from sliding-window fit to data
- Exclusions on several benchmarks: e.g. excited quarks, chiral excitation of the W, leptophobic Z' DM mediator
- For reinterpretation: 95% CL cross-section limits on gaussian-shaped signals of various widths (up to 15%) as a function of the mass