Highlights of physics results from ATLAS and CMS

Reinhard Schwienhorst, Michigan State

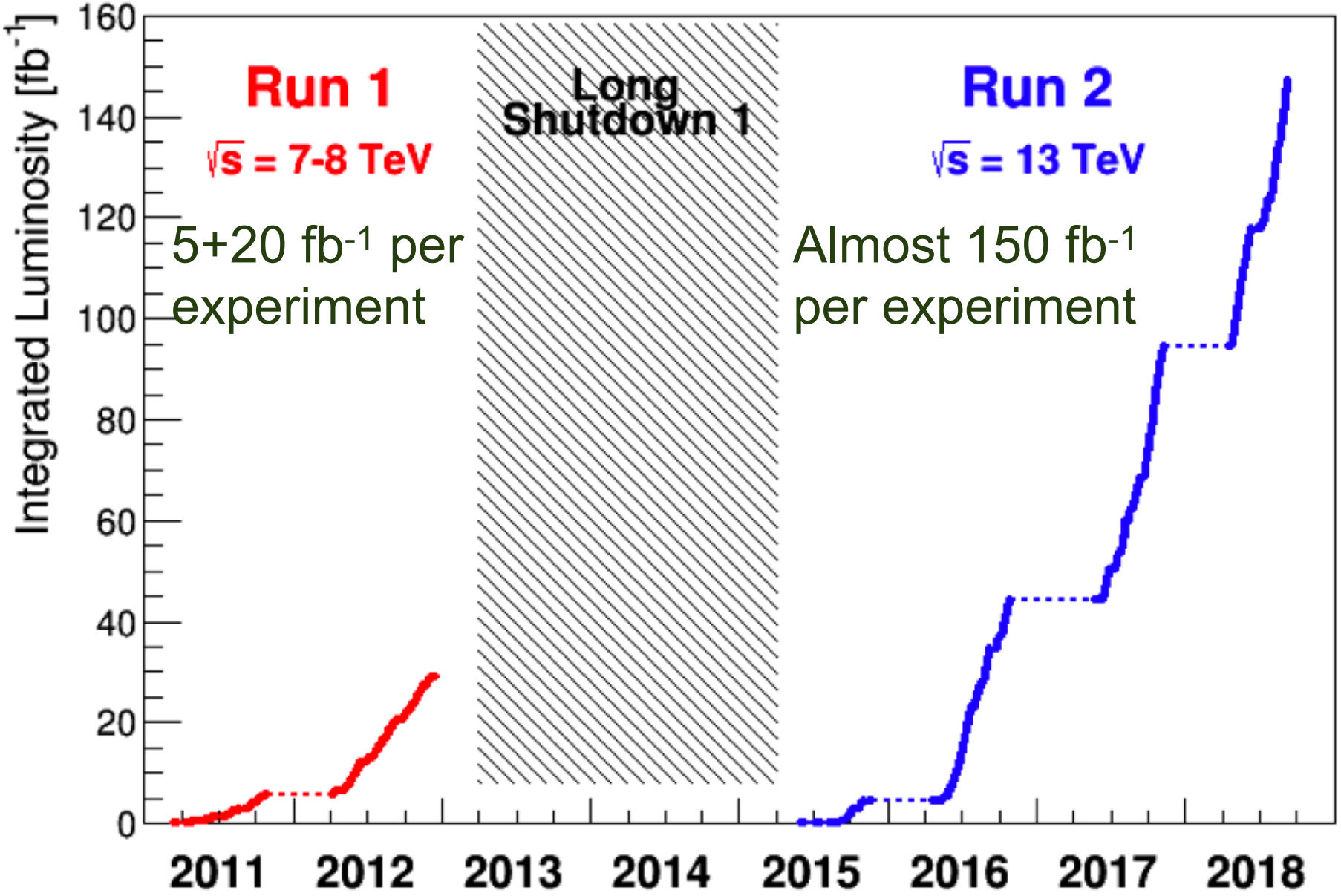
On behalf of the ATLAS and CMS Collaborations

Introduction

- LHC physics program is broad and ambitious
- Determine fundamental parameters of SM very precisely
- Measure rare SM processes for the first time
  - VVV and tttt
- Probe new physics, directly and indirectly
  - Broad exploration of TeV-scale physics
- Measurements from previous *n* years are still valuable
  - Persistence - many measurements will not be updated for a long time
  - Full Run-2 data results will be continue to be published even as Run 3 has started
- Many interesting recent physics results from LHC
  - Selection of ATLAS and CMS results in this talk
- Separate talk on flavor physics and LHCb on Tuesday
- Many more talks in parallel sessions

- Note: This is my first in-person conference since 2019

Lots of LHC collisions: 1 μg protons accelerated so far



- Only place in the world to produce key SM particles: 8M Higgs, 0.1G top, 0.5G W, Z
- Plus many rare processes

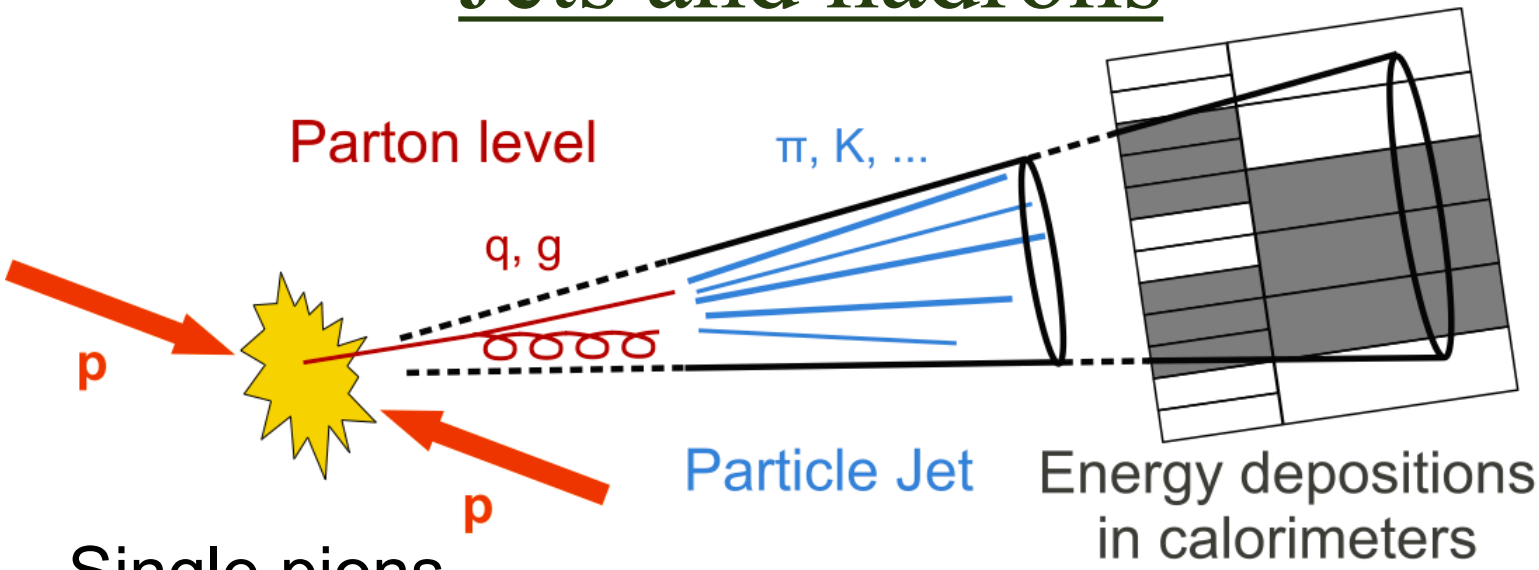
LHC physics program

- Electroweak symmetry breaking
  - Precision Studies of Higgs, top, W/Z
- Origin and fate of the Universe
  - New physics searches at the highest energies
  - Precision measurements of SM processes
- Dark matter
  - Searches for SUSY and other DM candidates
  - Long-lived particle searches
- New physics at high energy scales
  - Explore TeV scale through direct searches
  - Explore higher energy scales indirectly
- Anomalies in leptons and b-physics experiments
  - LHC measurements place strict constrains on new physics explanations
  - Flavor physics talk by Marina Artuso on Tuesday
- Heavy ion physics
  - Not covered here

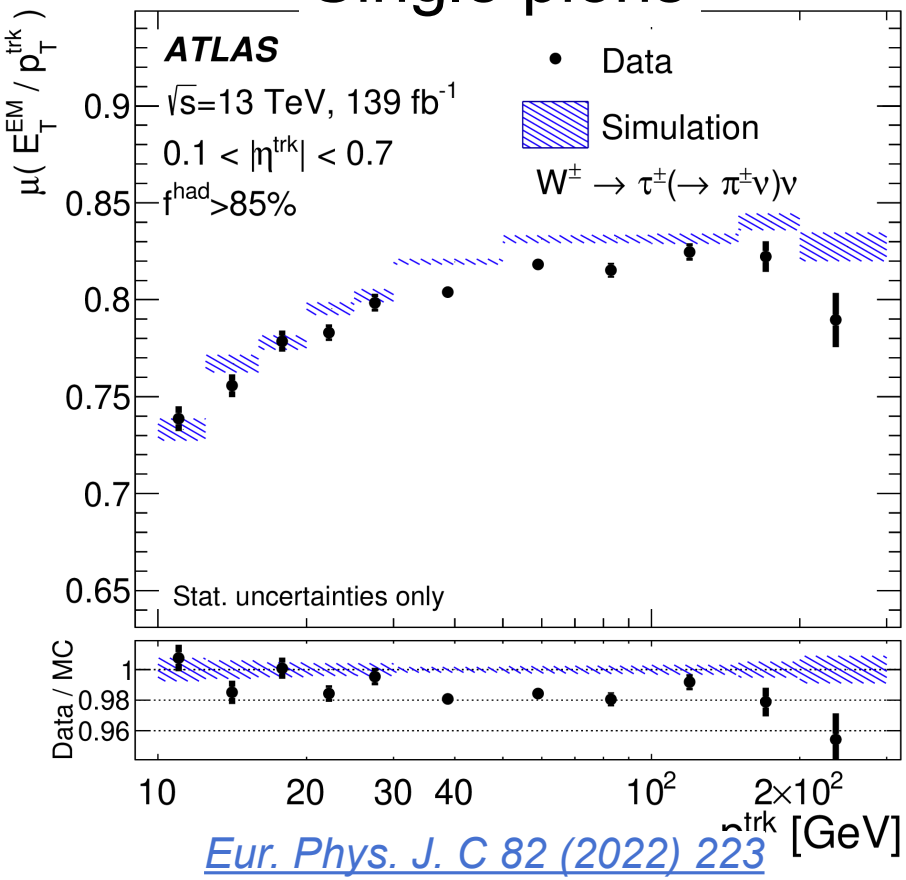
Detailed understanding of detector and backgrounds

- Precision measurements limited by:
  - detector understanding
    - Calibration, systematic uncertainty
  - Modeling of SM backgrounds
    - Parton shower, higher-order corrections
- First SM measurements of rare processes limited by:
  - Modeling of SM backgrounds
    - Parton shower, higher-order corrections, heavy flavor (b, c quarks)
    - Object ID performance
- Searches limited by:
  - Detector understanding
    - Object ID performance, especially for 3rd generation fermions
    - Object ID performance for charm quarks
  - Modeling of SM backgrounds
    - in extreme regions of phase space
- A lot of effort put into improving understanding of detector and simulation

Jets and hadrons

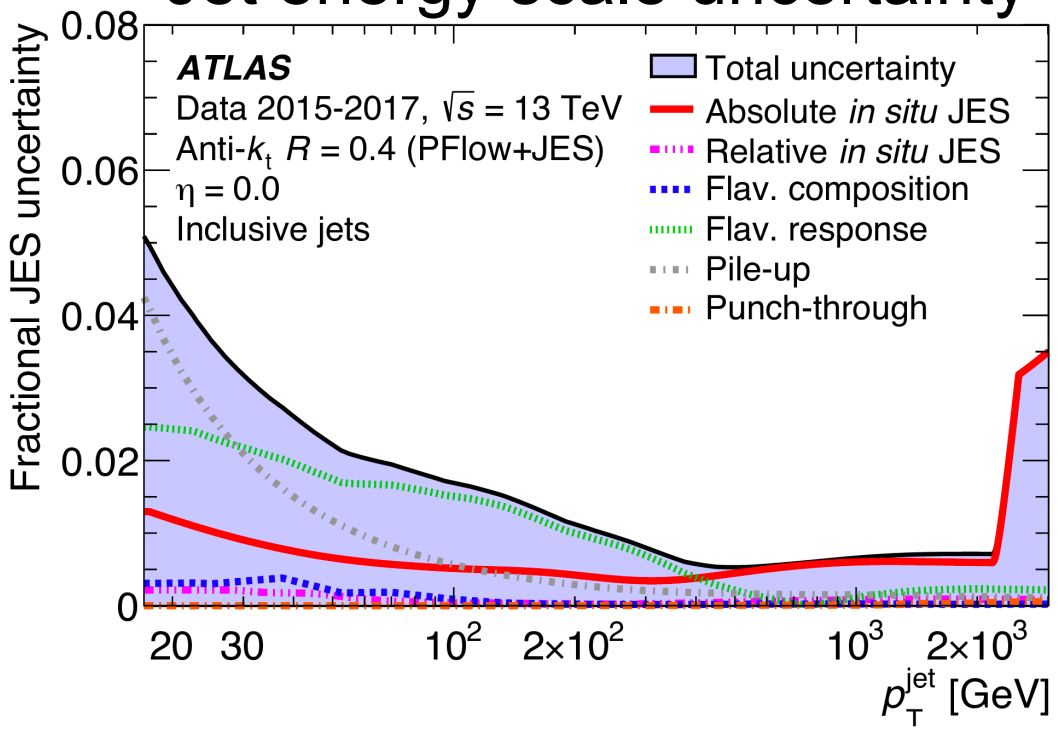


Single pions



Eur. Phys. J. C 82 (2022) 223

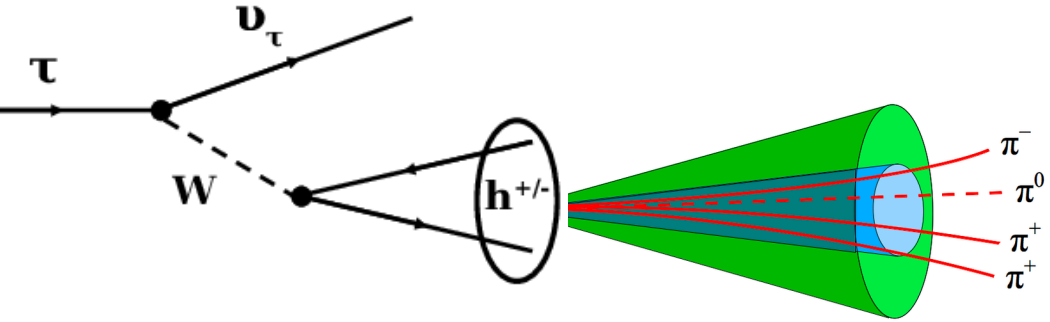
Jet energy scale uncertainty



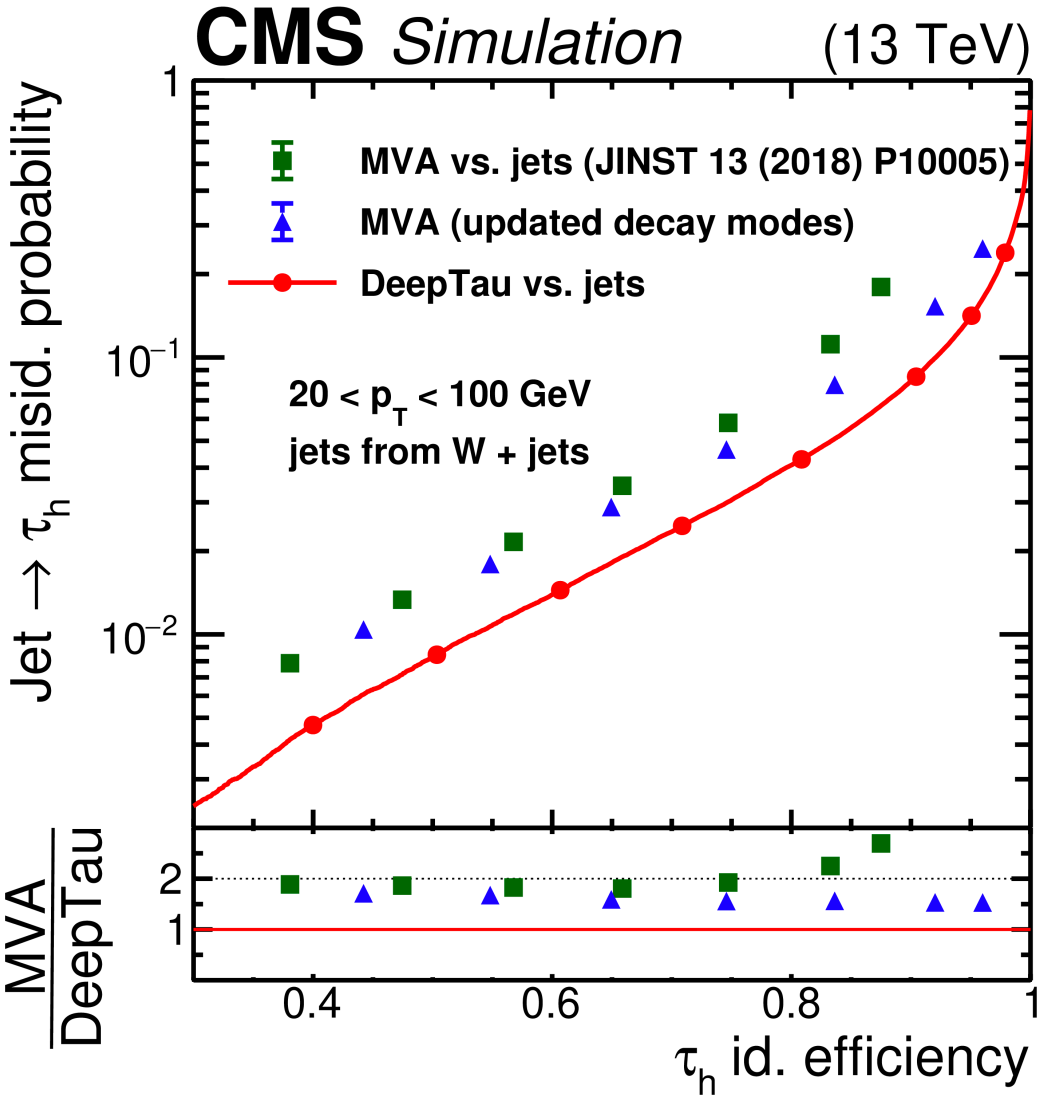
Eur. Phys. J. C 81 (2021) 689

Object reconstruction: tau lepton

- Improved tau ID based on Deep Neural Network



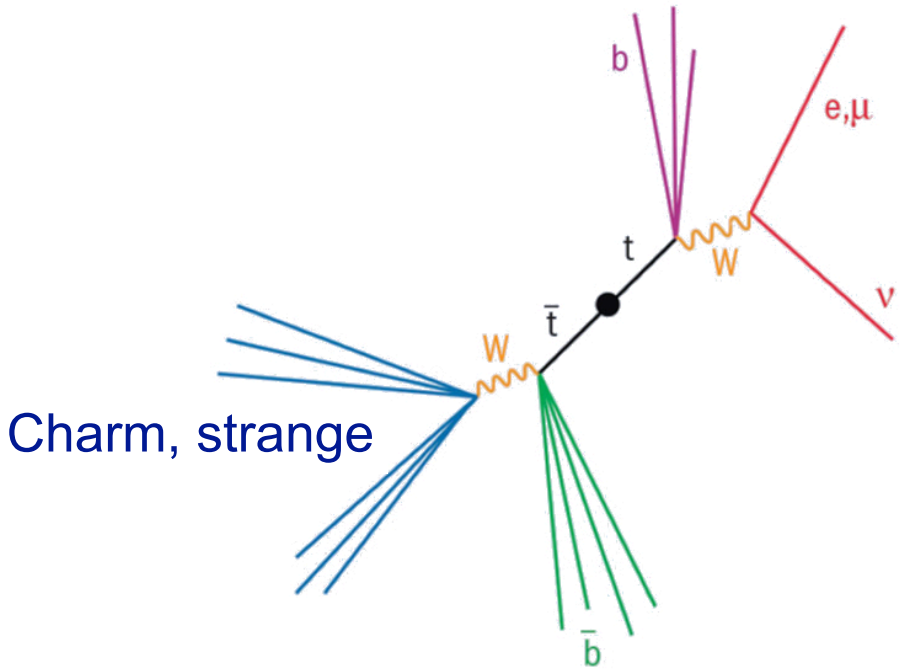
- Large improvement compared to previous MVA from DNN
  - Train against jets, leptons
- And from including information from all tracks surrounding narrow tau cone

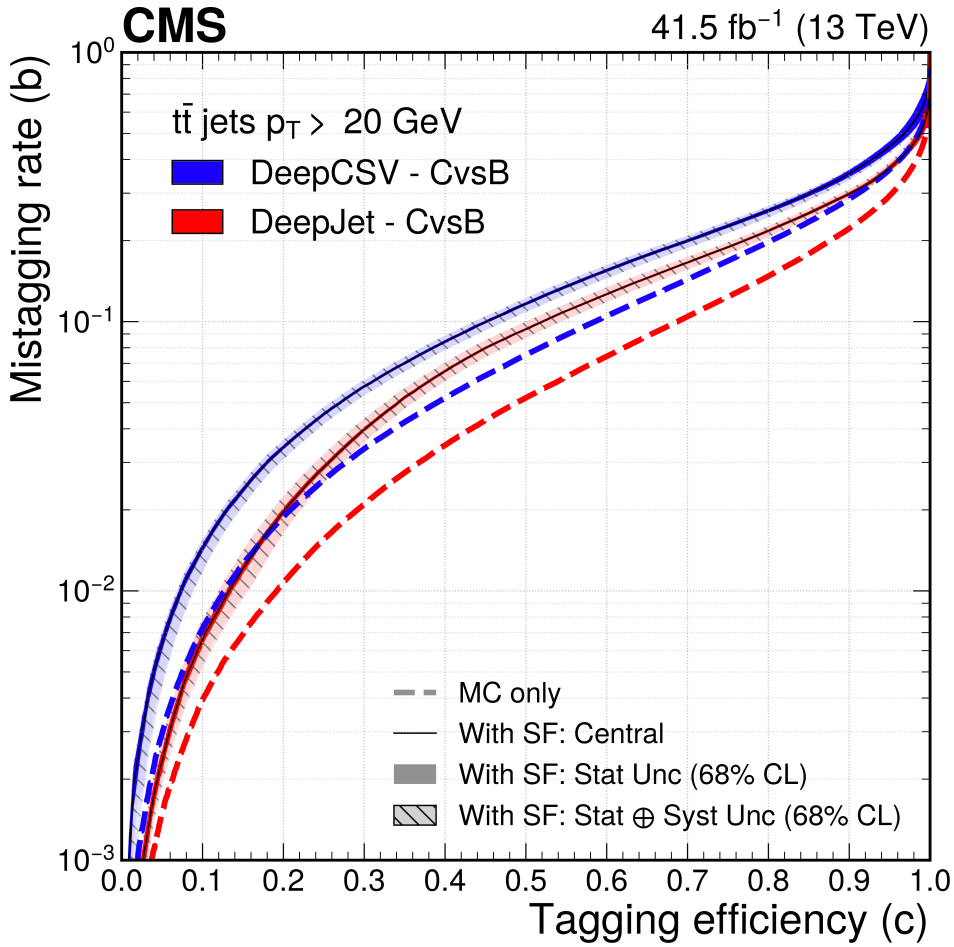


arXiv:2201.08458

Object reconstruction: charm quark

- Charm quark jet ID is key to measurement of Charm Yukawa
- Dedicated charm ID - separation from light quarks and b quarks
- Calibrate using W bosons from top-quark decays

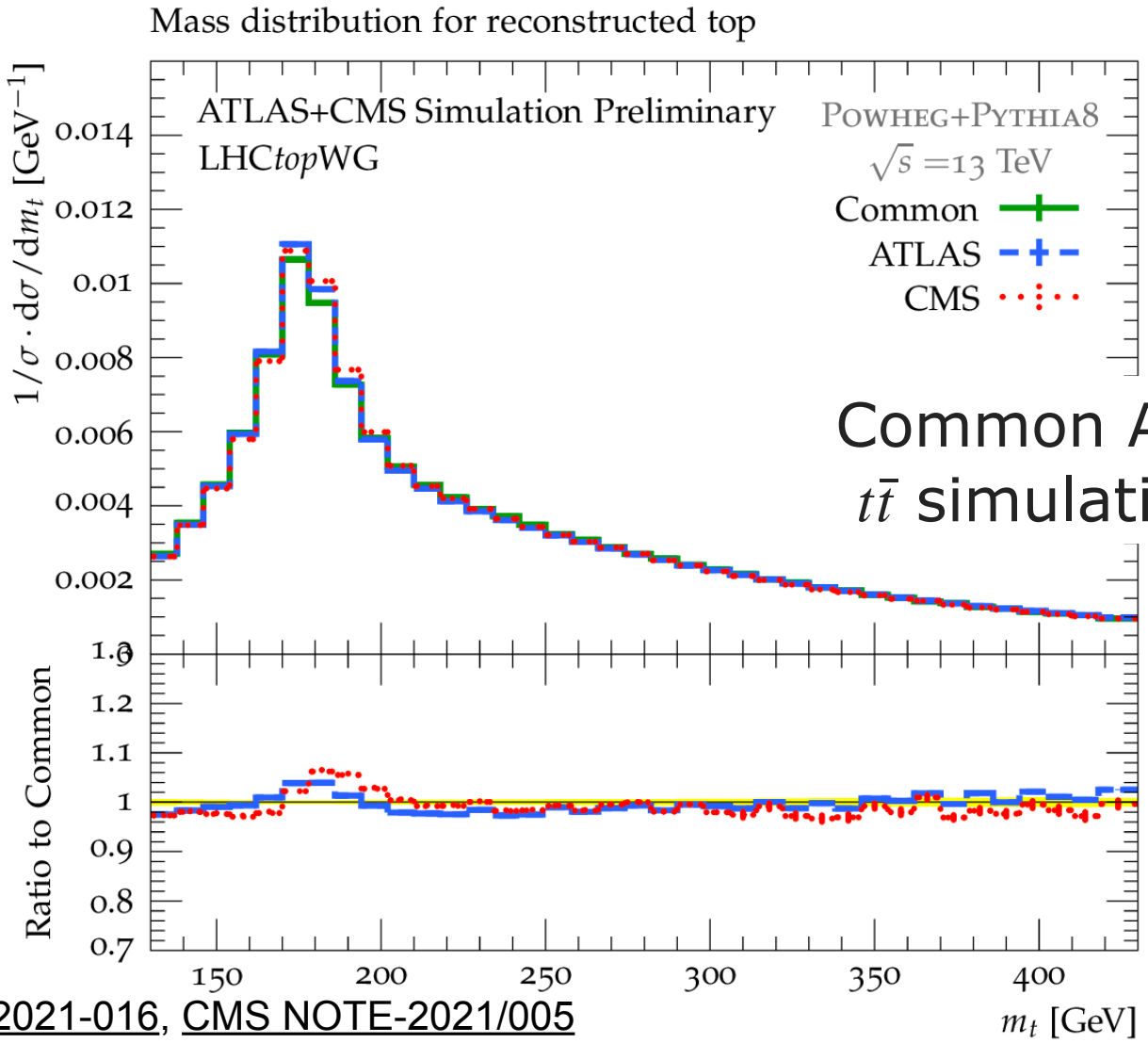




JINST 17 (2022) P03014

Simulation of SM processes

- Improve modeling of SM processes
  - Tuning generators to data
  - NLO generators interfaced to parton shower
  - Compare ATLAS and CMS generator setups



Common ATLAS-CMS $t\bar{t}$ simulation sample

ATL-PHYS-PUB-2021-016, CMS NOTE-2021/005

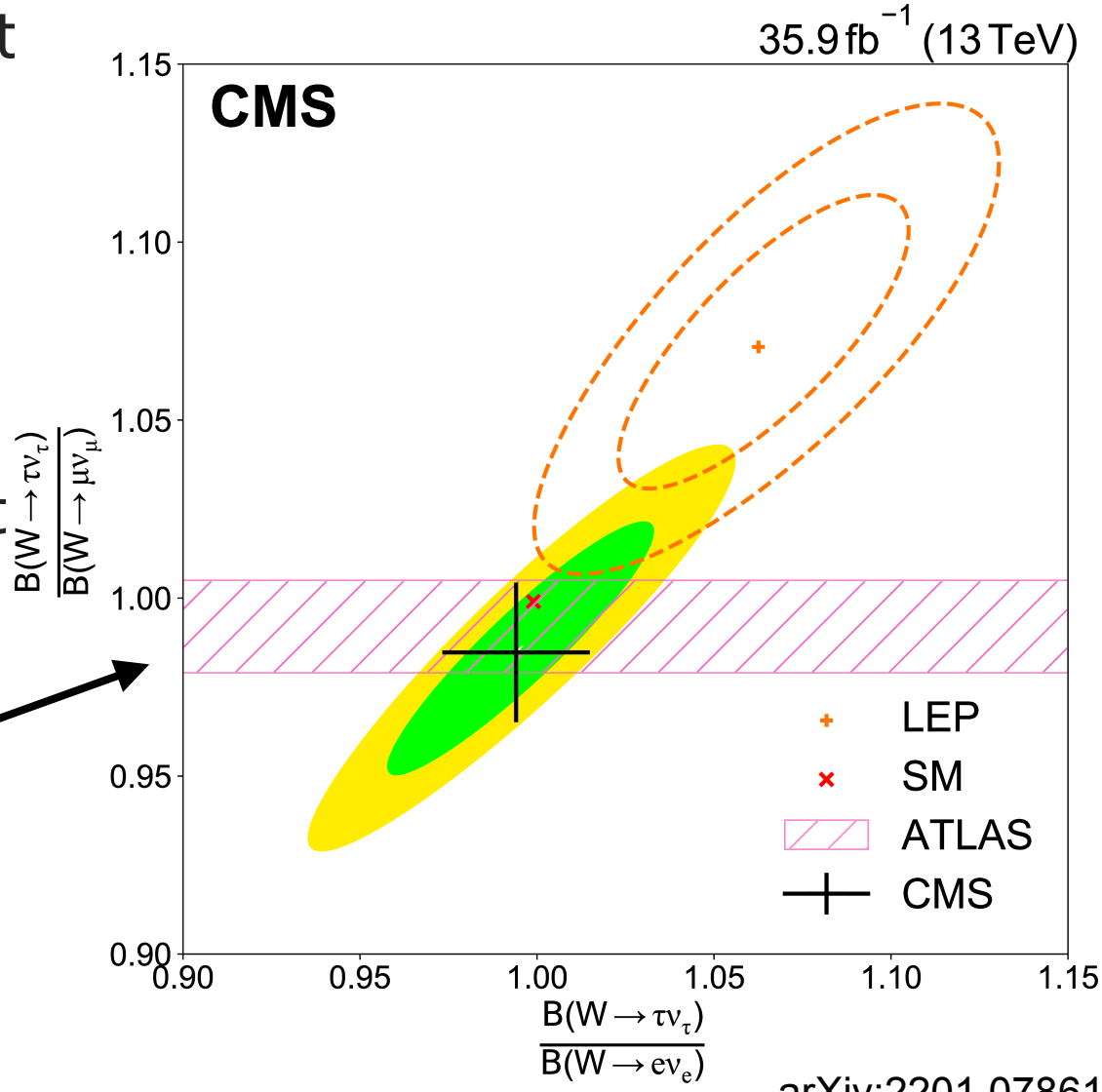
Precision measurements

- Stringent tests of Higgs mechanism
- Measure Yukawa couplings
- Stringent tests of self-consistency of SM

Lepton flavor universality in W decays

- Address long-standing discrepancy from LEP
- Select W bosons primarily from $t\bar{t}$ events
- Separately measure BR for decays to electron, muon, tau, all hadronic decays toget
- Likelihood fit to select clean signals
- Extract CKM matrix elements
  $|V_{cs}| = 0.967 \pm 0.011$ and strong coupling constant
  $\alpha_s(m_W^2) = 0.095 \pm 0.033$

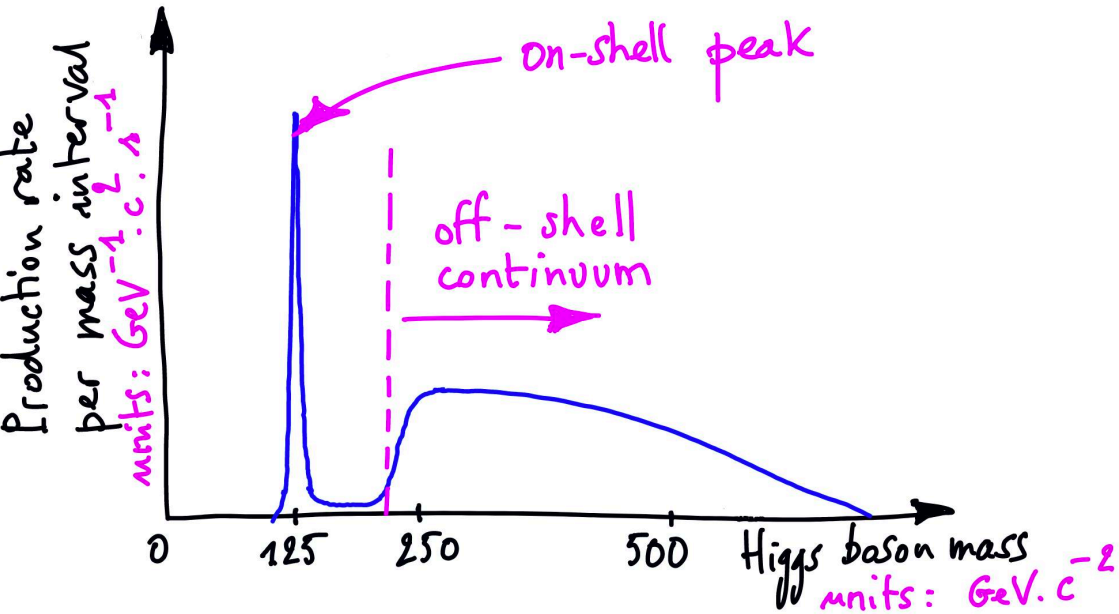
ATLAS result
Nature Phys. (2021)
- Focus on τ



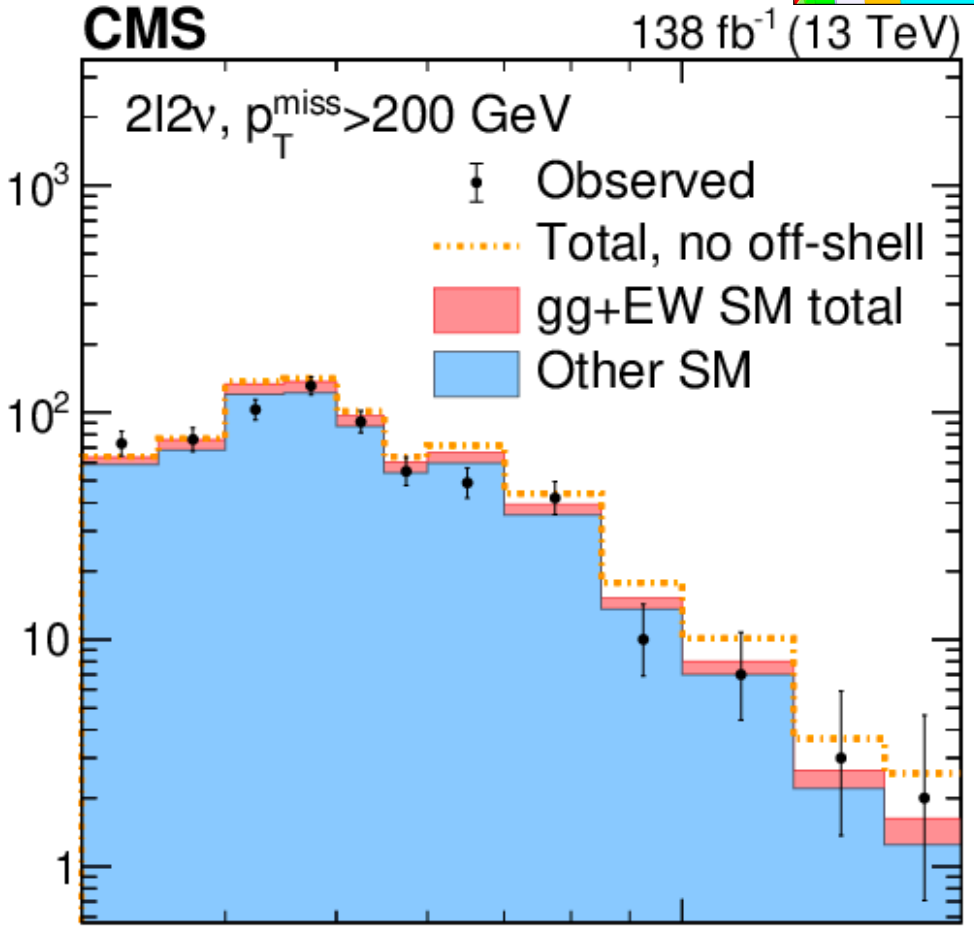
arXiv:2201.07861

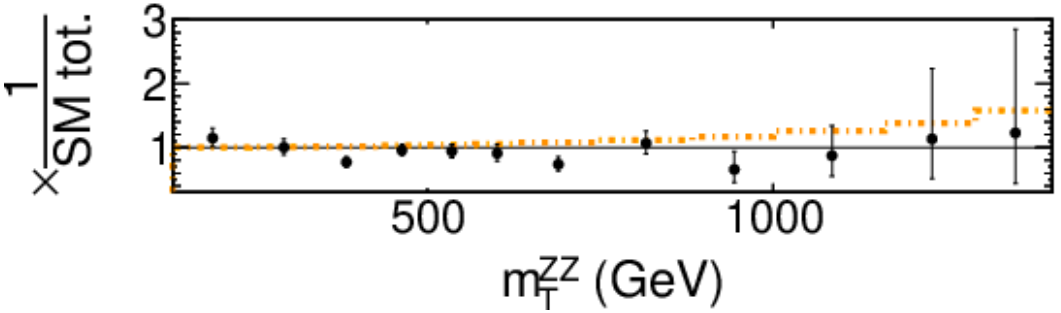
Higgs boson width

- Evidence for off-shell Higgs production



- Events with 2 l, 2 ν
- Extract Higgs width from off-shell production

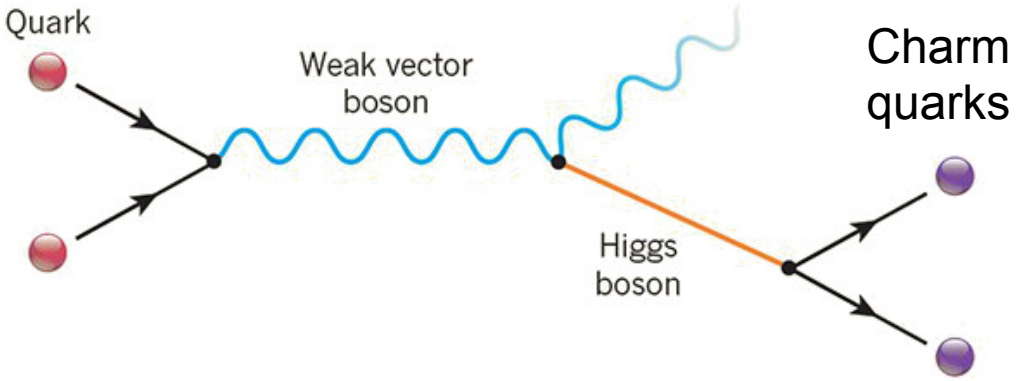




ATLAS limit from early Run 2 data 1808.01191

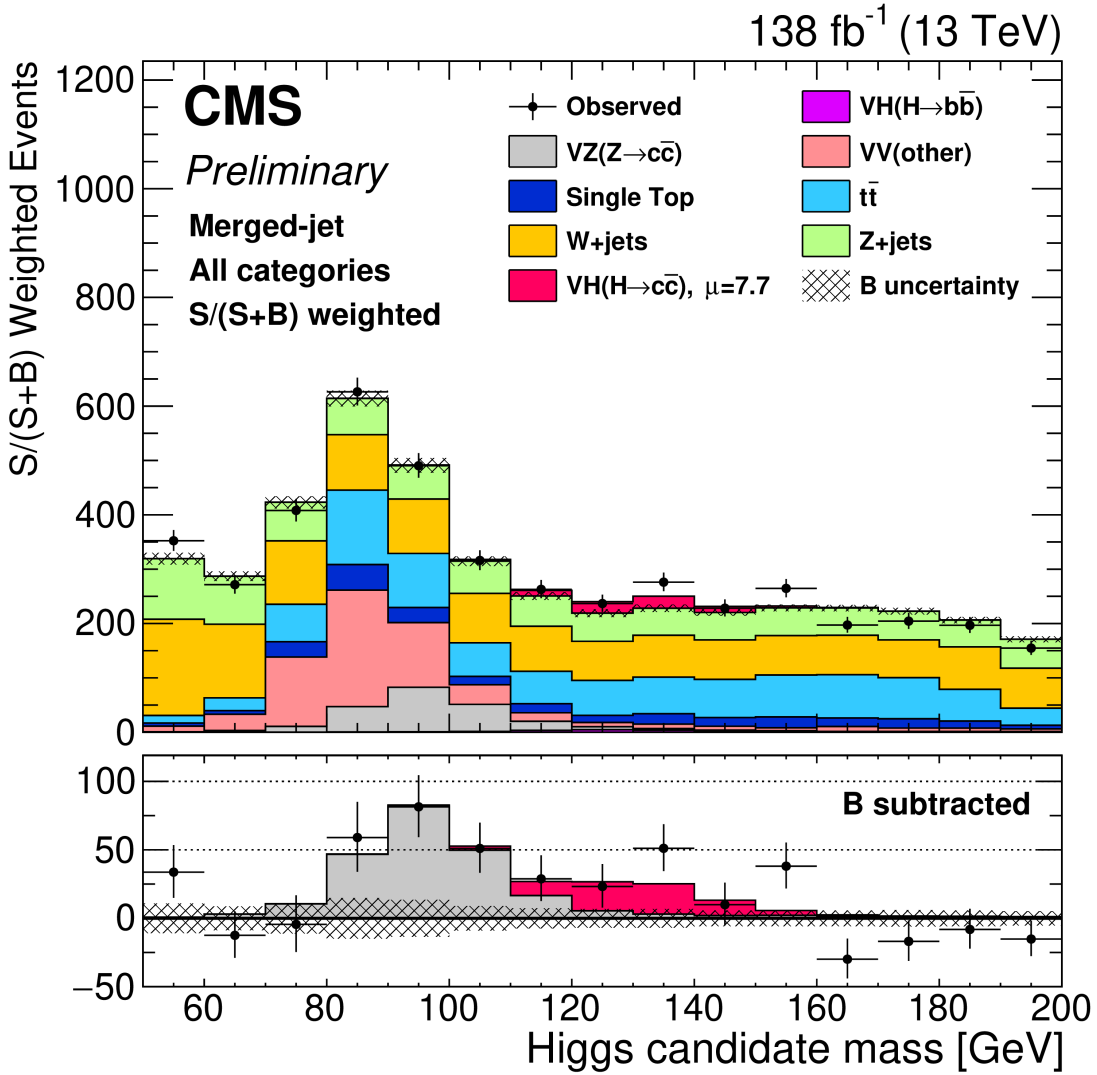
arXiv:2202.06923

Higgs Boson coupling to charm quark



- Search for Higgs decay to charm in VH events
  - Using charm tagger
- Many event categories
  - Including resolved and merged ($c\bar{c}$) jets
- Limit on ratio of Charm Yukawa to prediction

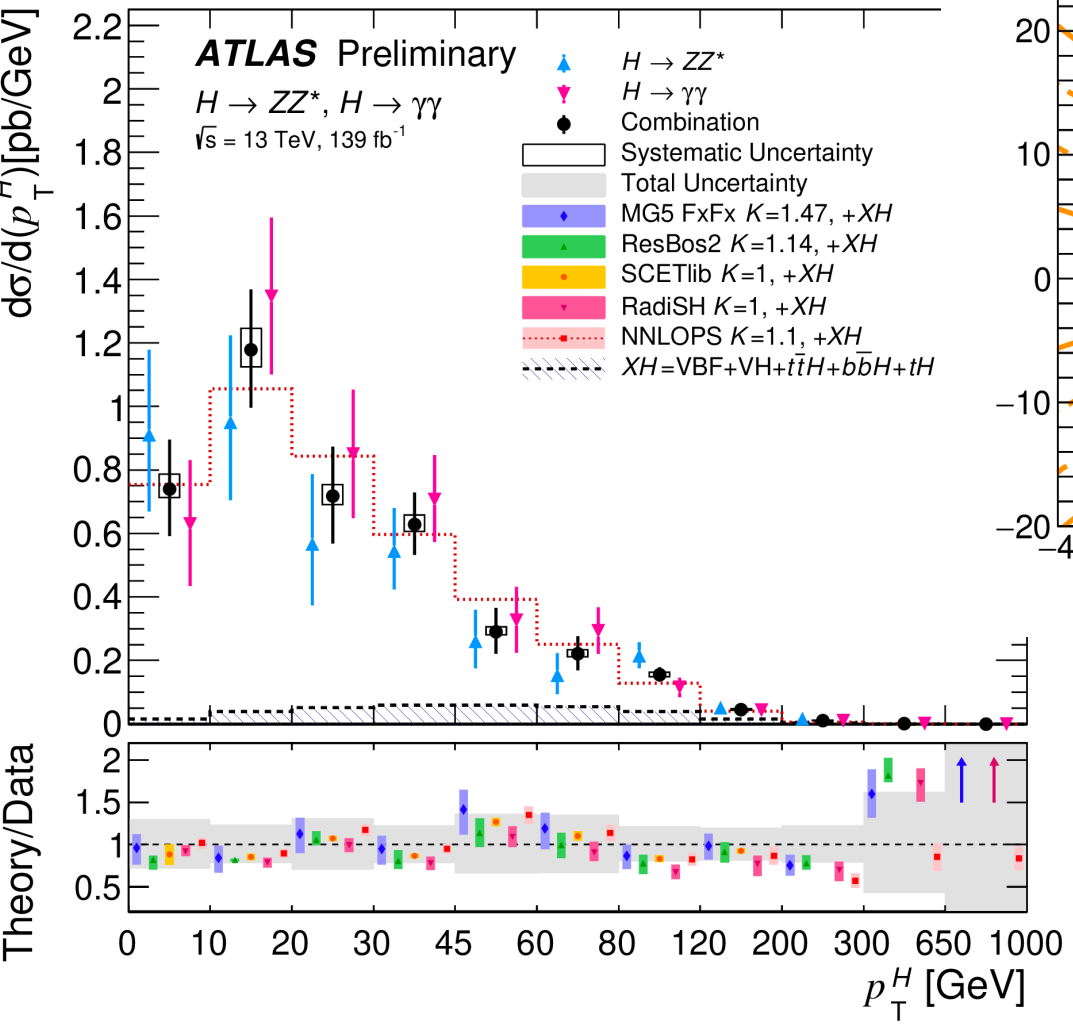
$$1.1 < |\kappa_c| < 5.5$$

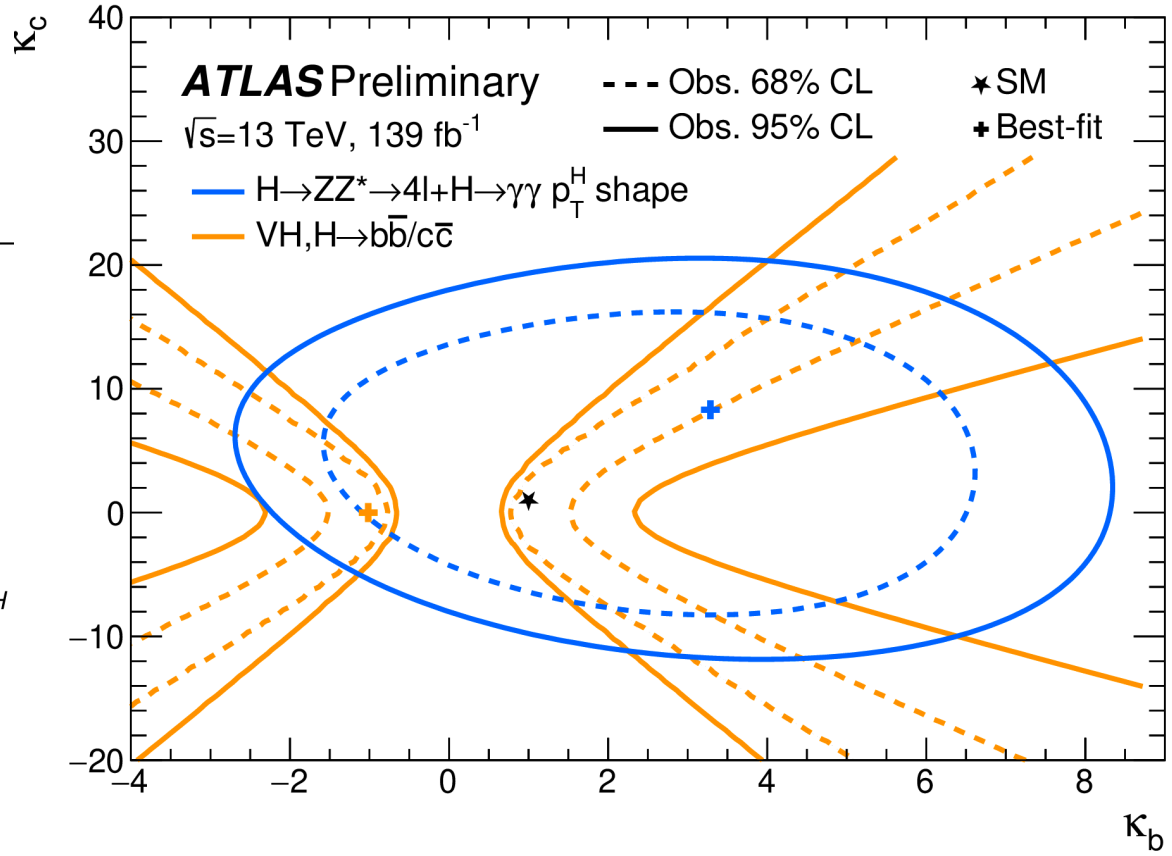


CMS-PAS-HIG-21-008

Higgs Boson couplings

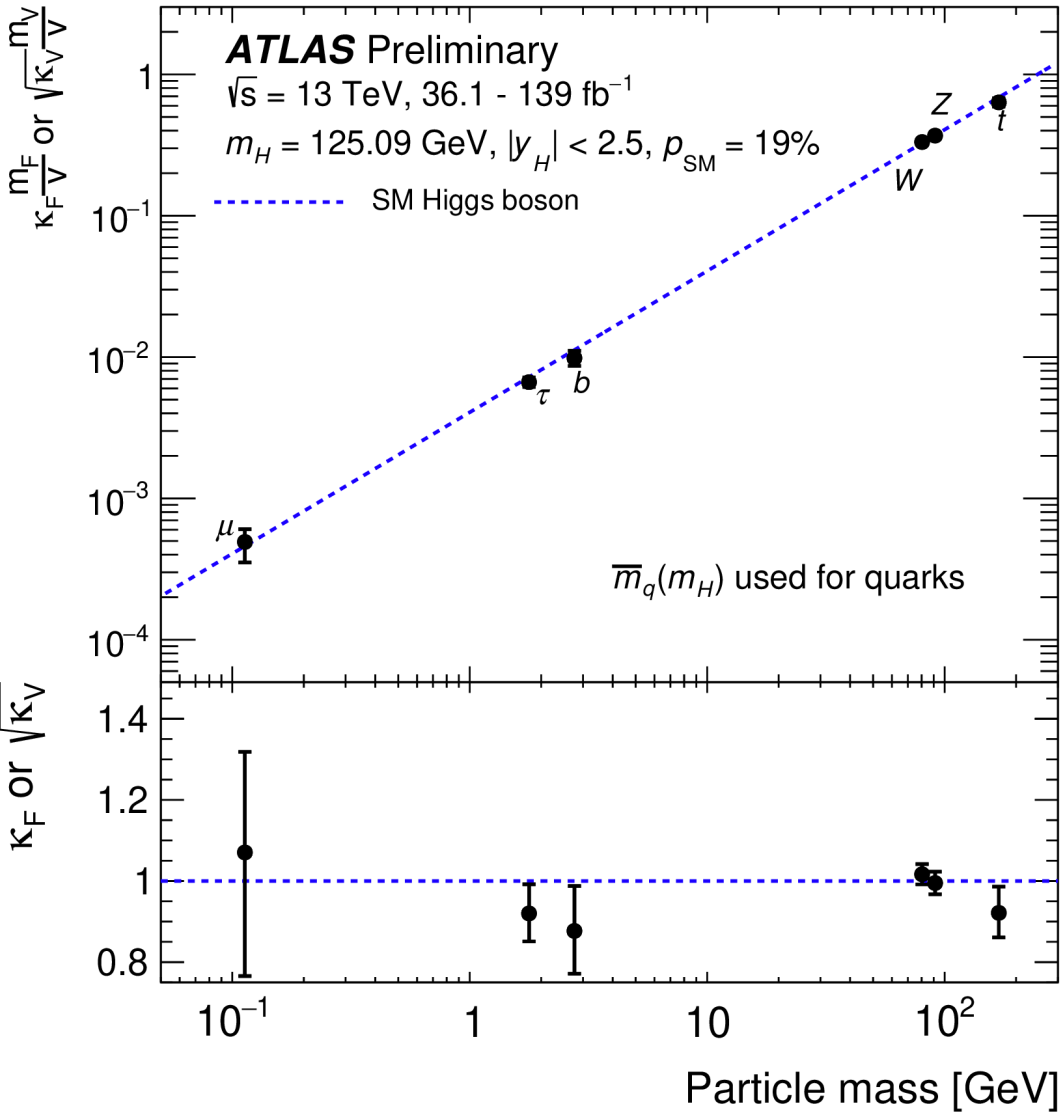
- Constrain Higgs-charm coupling simultaneously with Higgs-bottom coupling



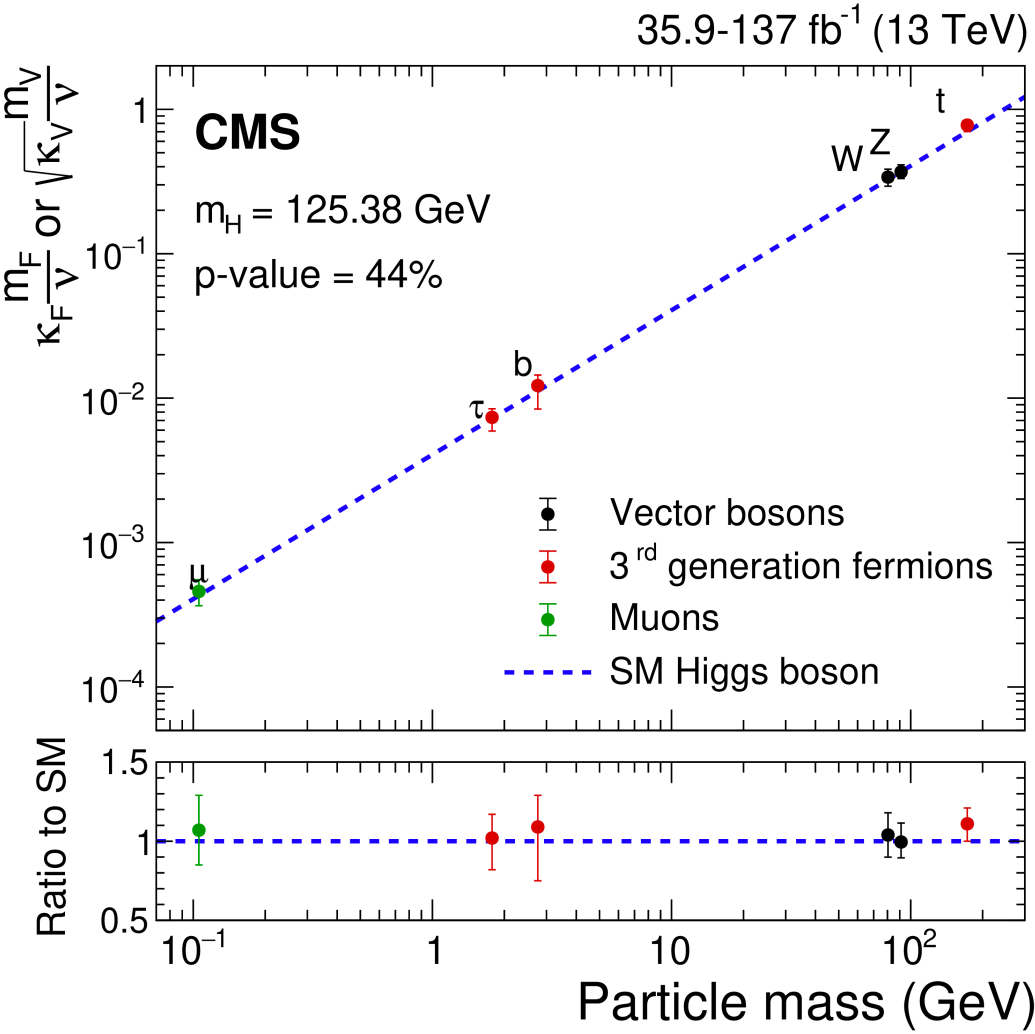


arXiv: 2201.11428, ATLAS-CONF-2022-002

Yukawa coupling summary



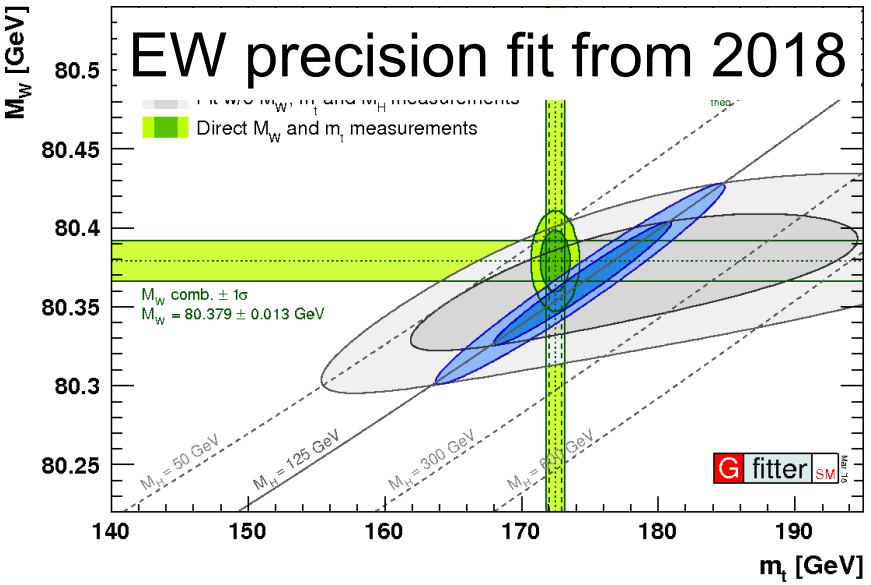
ATLAS-CONF-2021-053

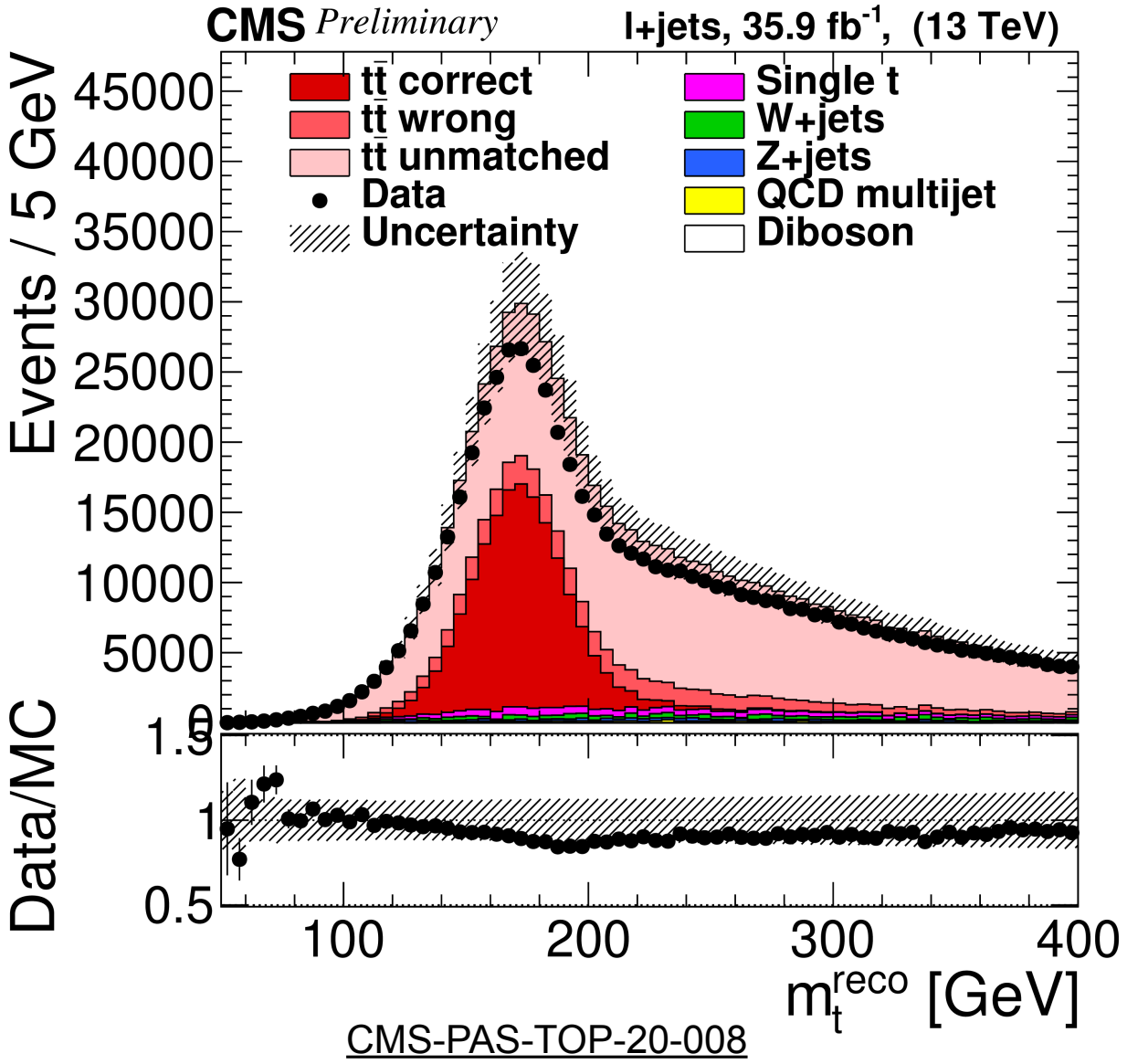


CMS Higgs results

Top quark mass

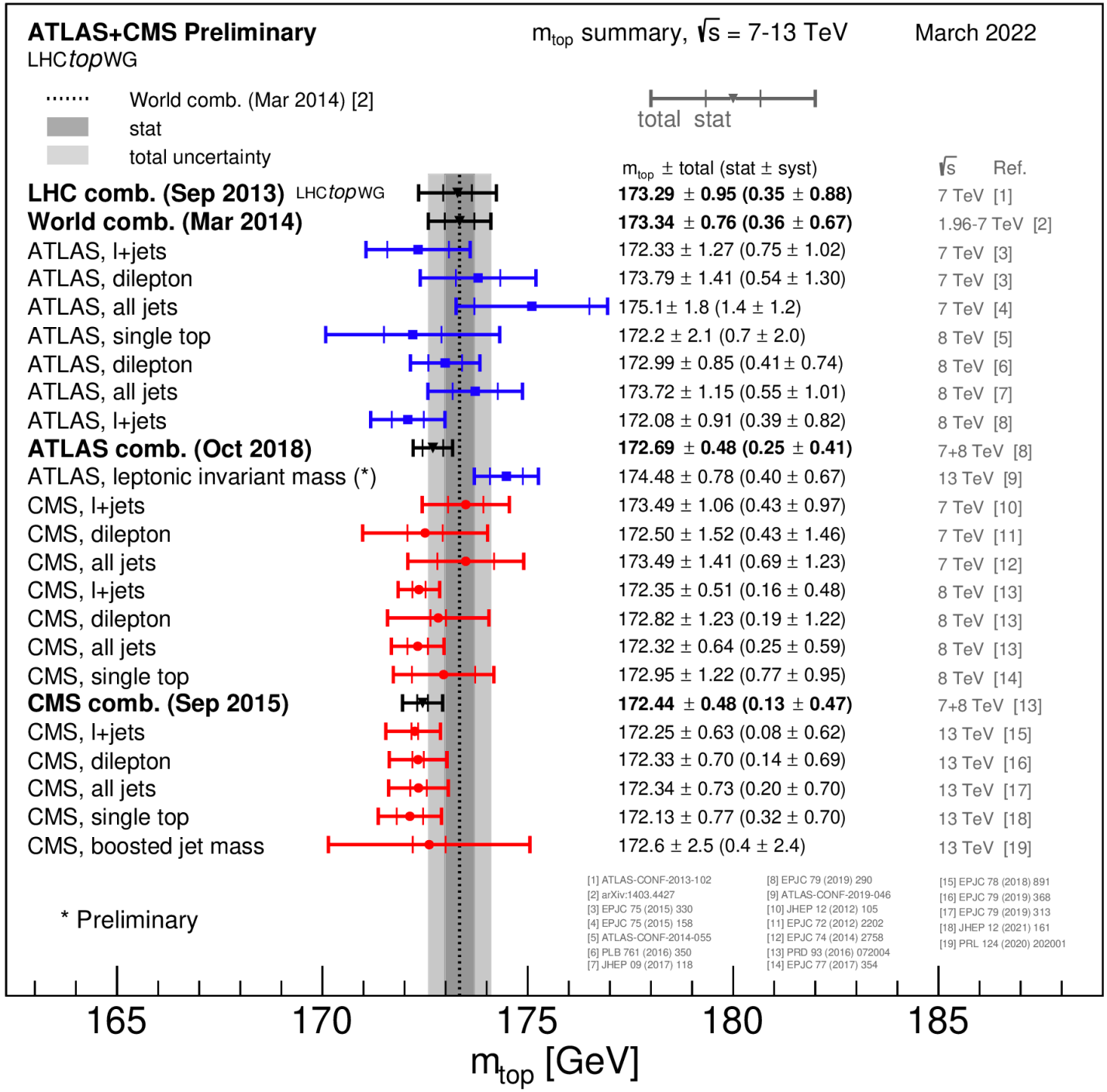
- Key to electroweak precision fits
- Large top mass implies meta-stable universe
- Precision measurements requires
  - Detector understanding
  - Accurate generators
  - Tuned parton shower
  - Statistical methods
- Measured mass
  171.77 ± 0.38 GeV





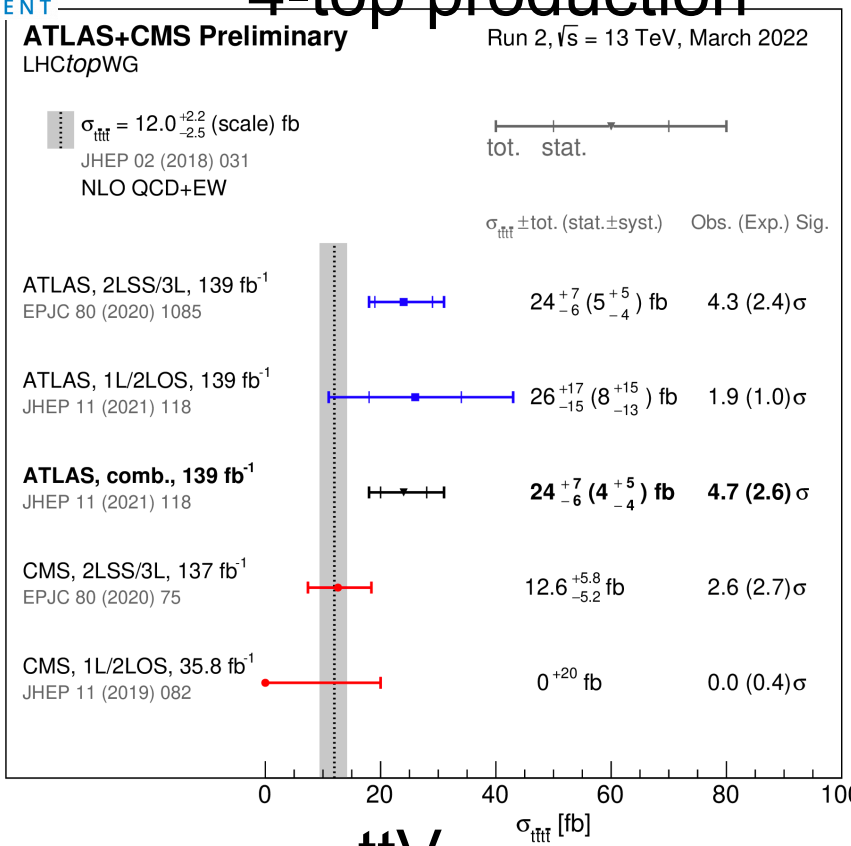
CMS-PAS-TOP-20-008

Many top quark mass measurements

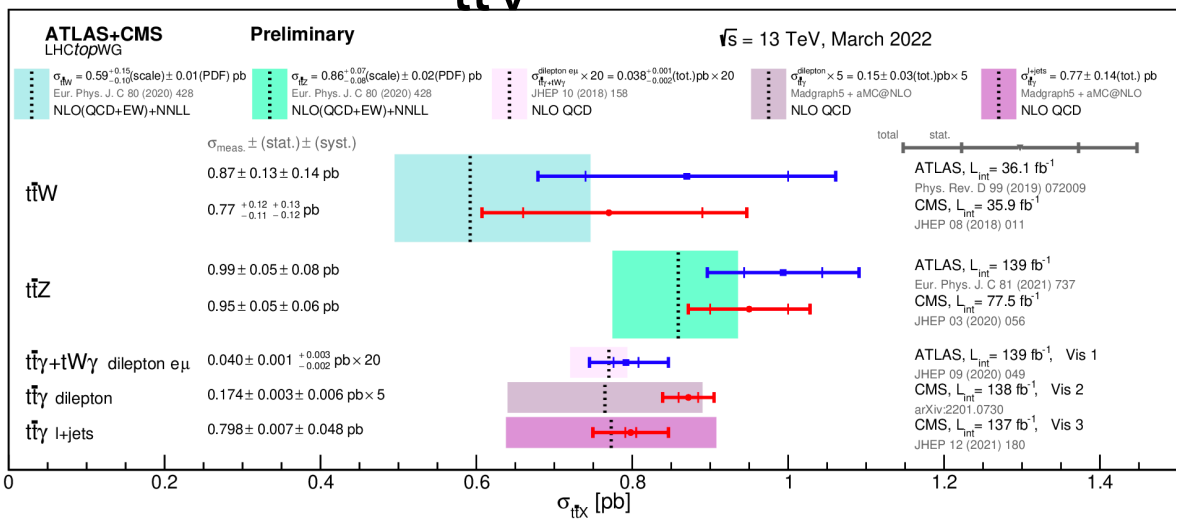


Precision top measurements: LHC*top*WG

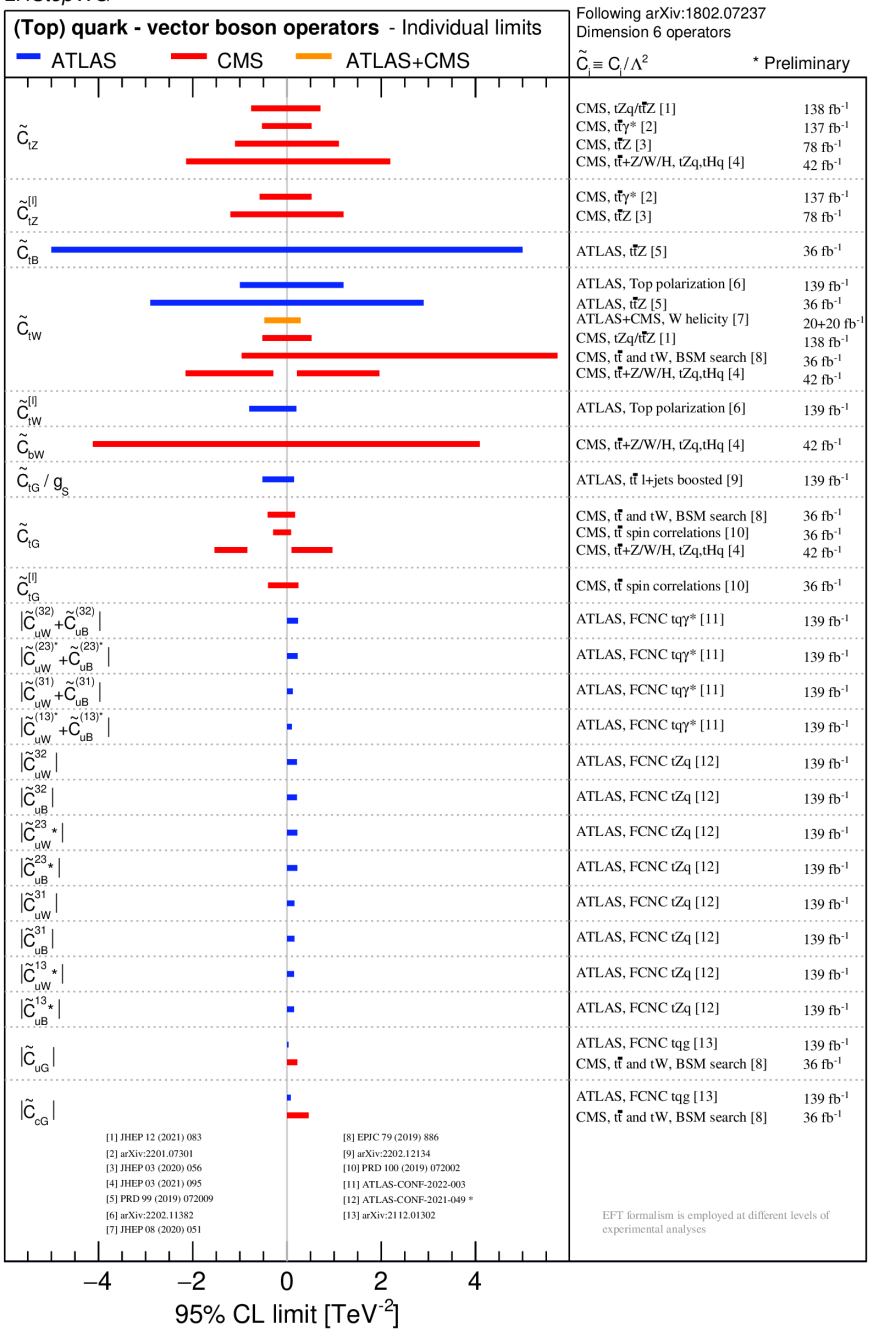
4-top production



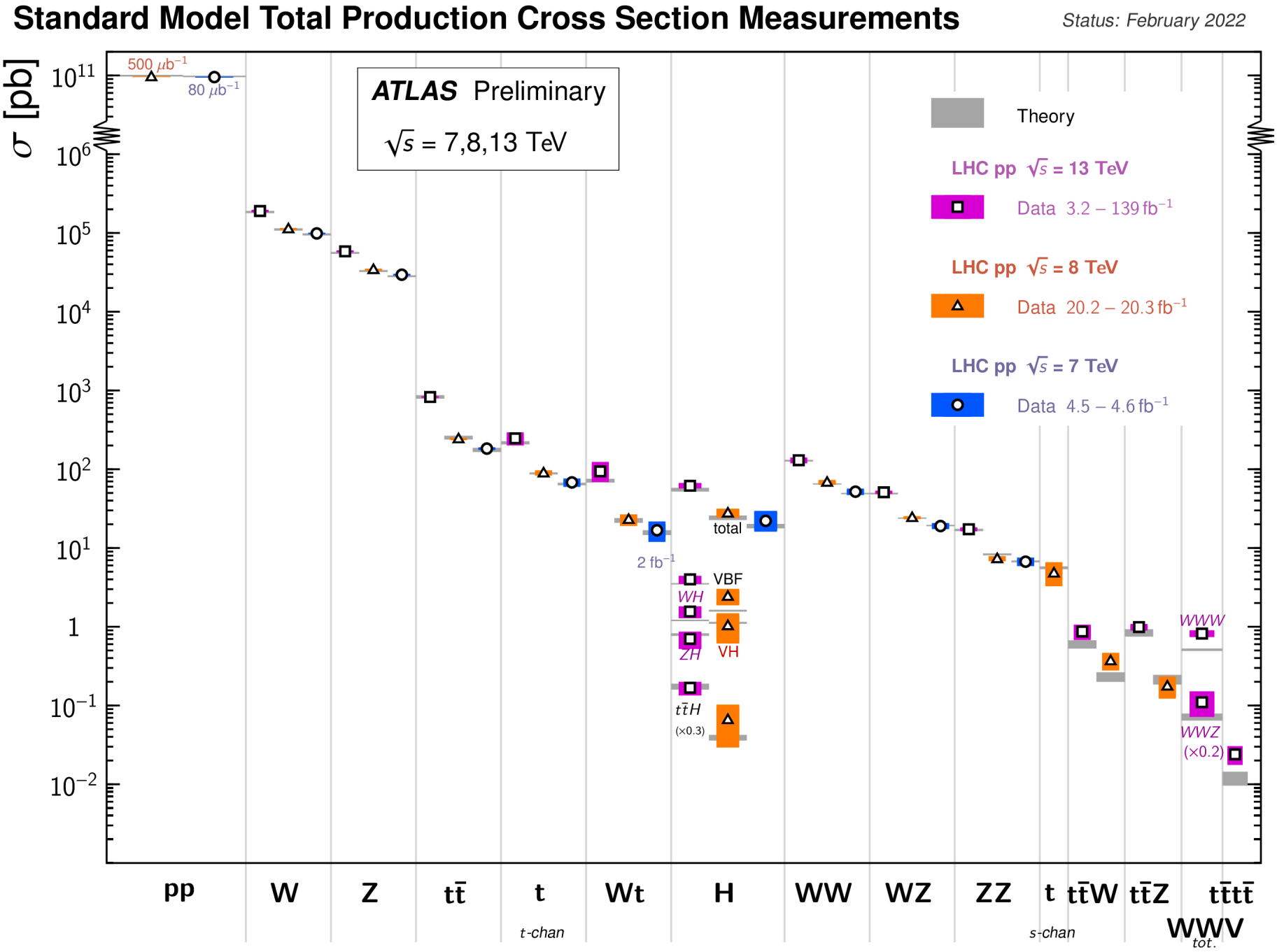
ttV



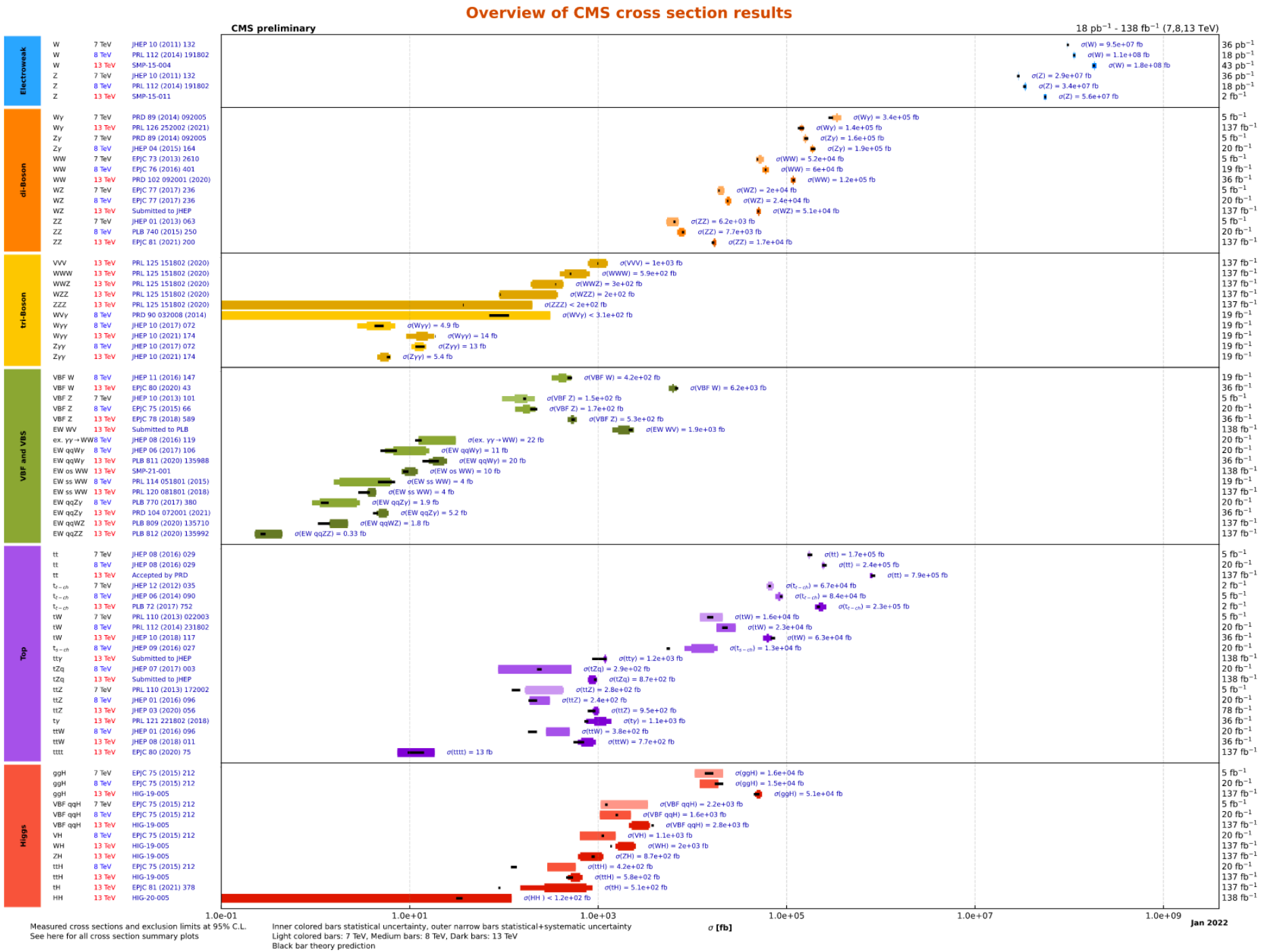
EFT limits



Standard model summary



Cross-section summary

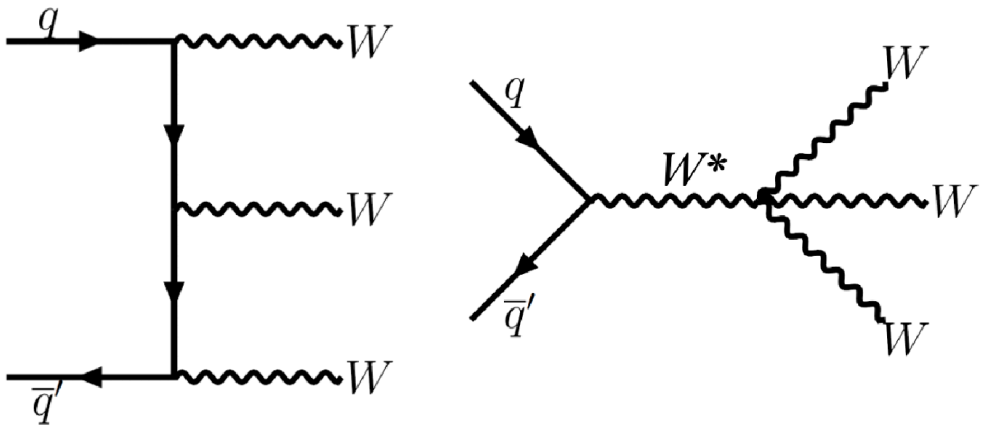


Rare SM processes

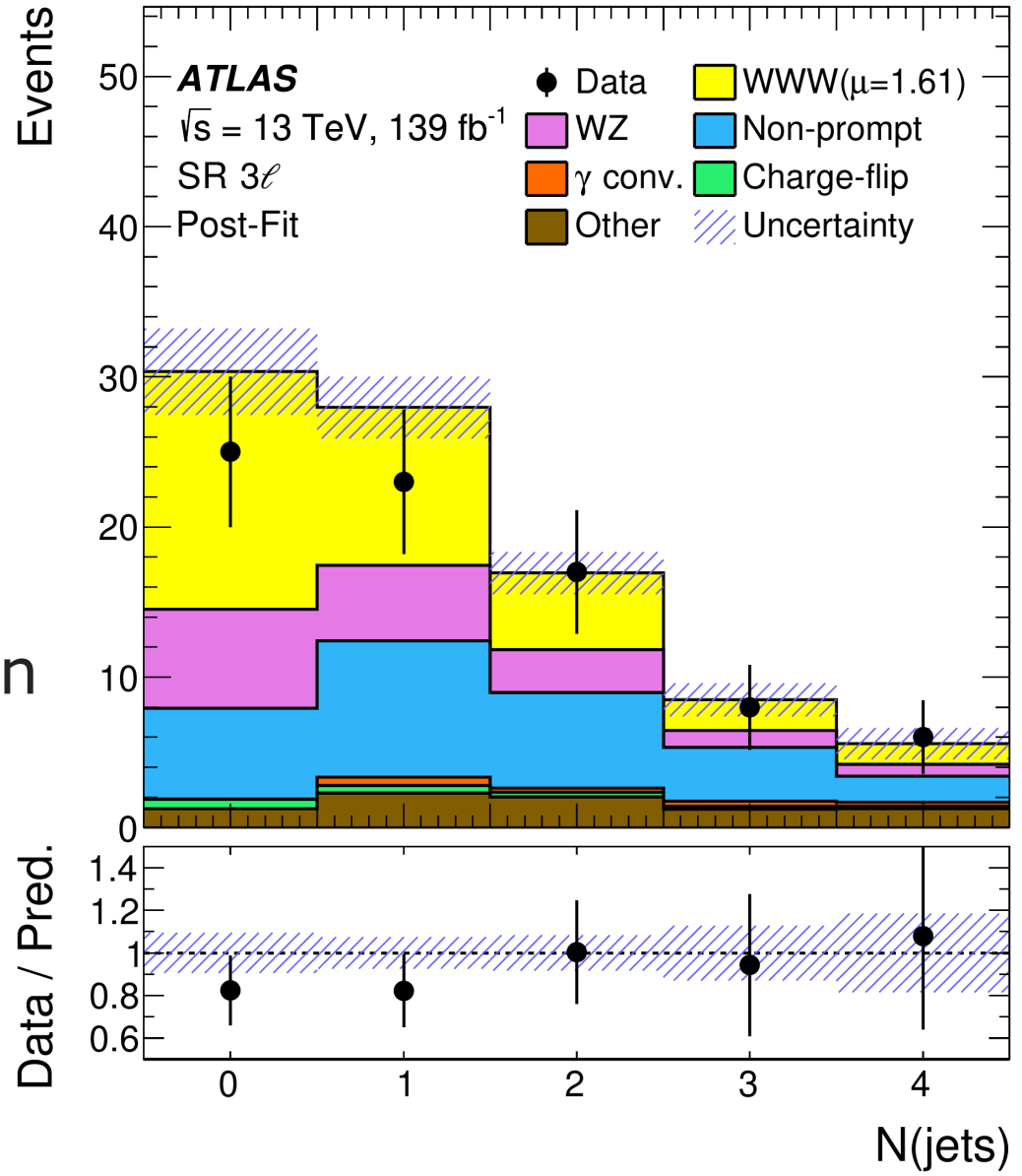
- Measure parameters of EW symmetry breaking
- Sensitive to many models of new physics

Triple and Quartic boson couplings

- First observation of WWW production



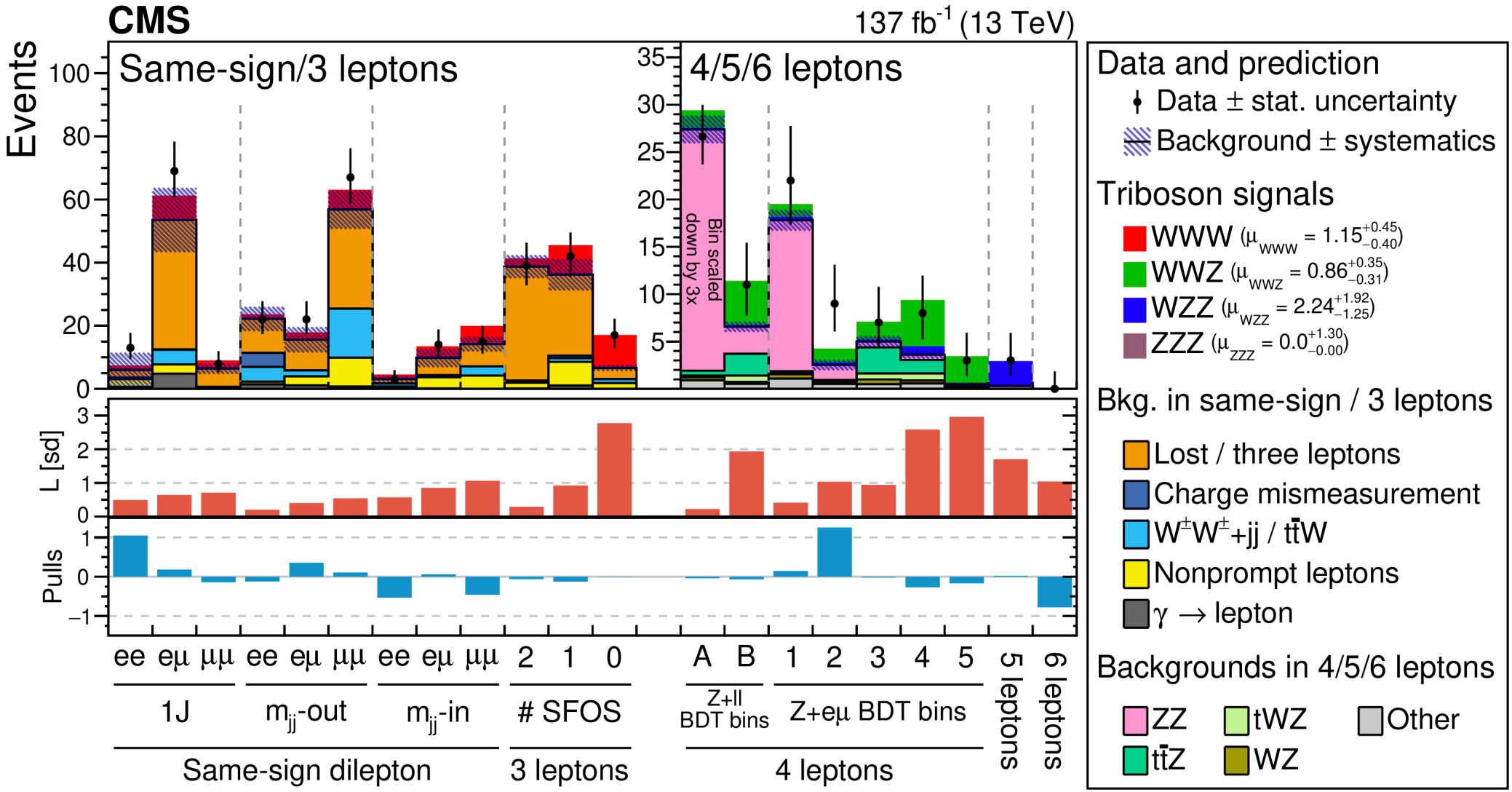
- 2 same-sign or 3 leptons
- BDT in 4 regions
- 8 standard deviation signif.
- Factor 1.6 above SM prediction
- Sensitive to new heavy bosons, extra dimensions
  (see for example Arxiv:1703.06153)



arXiv:2201.13045

Triple and Quartic boson couplings

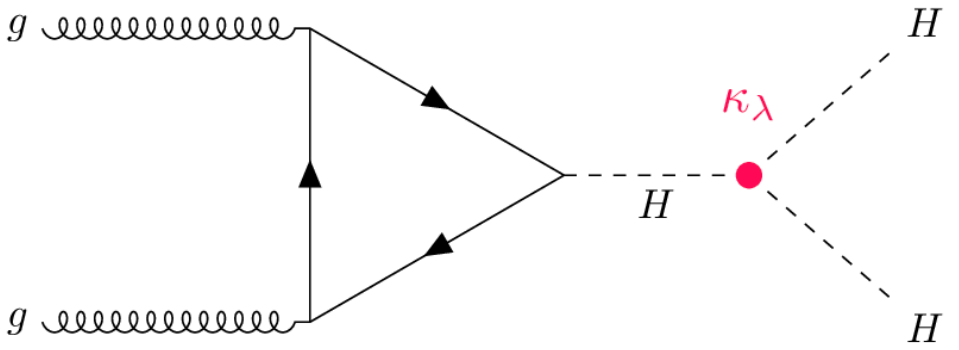
- First observation of VVV production
  - WWW, WWZ, WZZ, ZZZ combined, probe 4-V and 3-V couplings
  - 5.7 sigma for VVV, 3.3 sigma for WWW



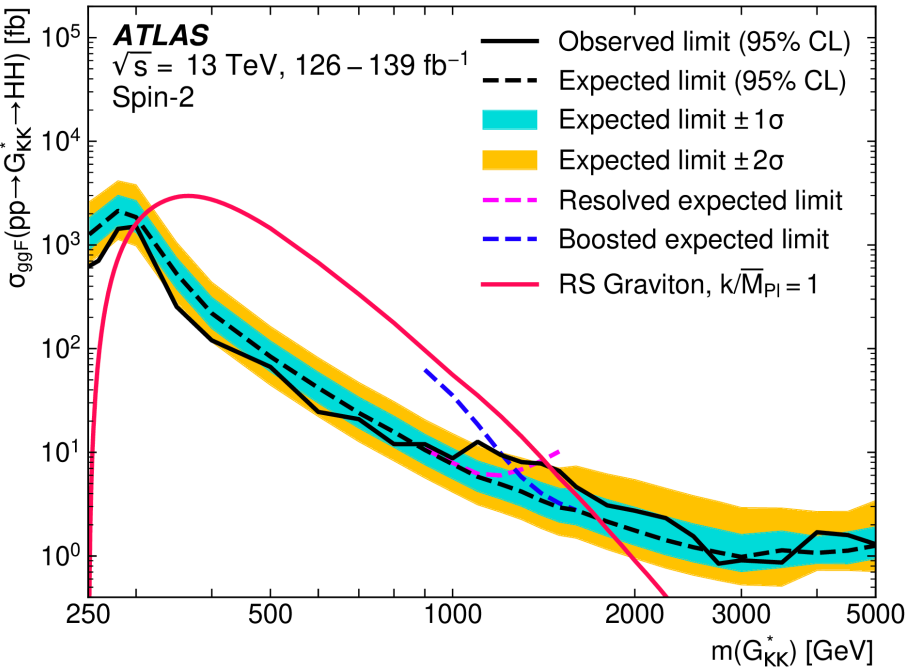
PRL 125 (2020) 151802

Higgs self-coupling

- Searches for di-Higgs production allow to probe the Higgs boson self-coupling as well as new physics e.g. resonances decaying to HH
- Similar CMS recent search (CMS-PAS-B2G-22-003)

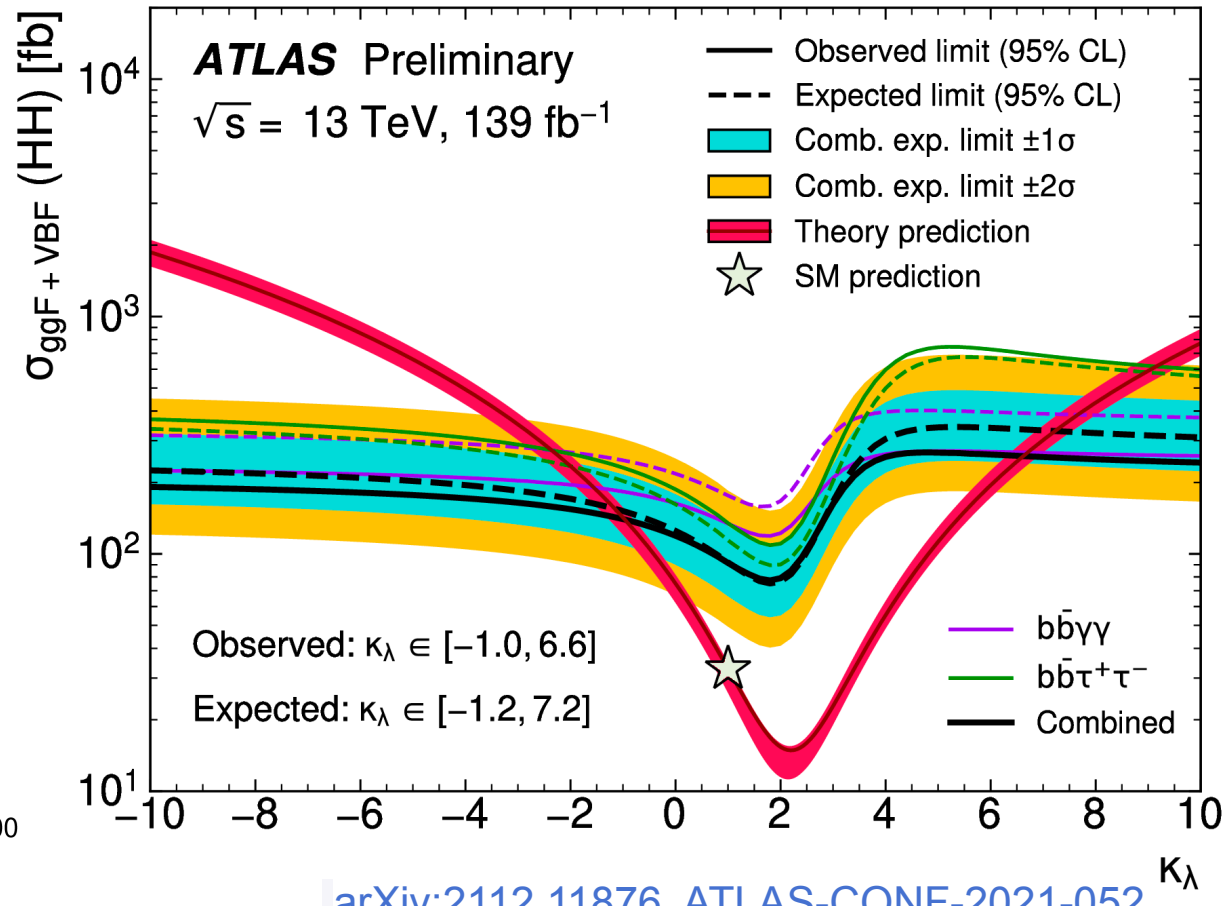


4b, resolved and boosted



arXiv:2202.07288

Combination

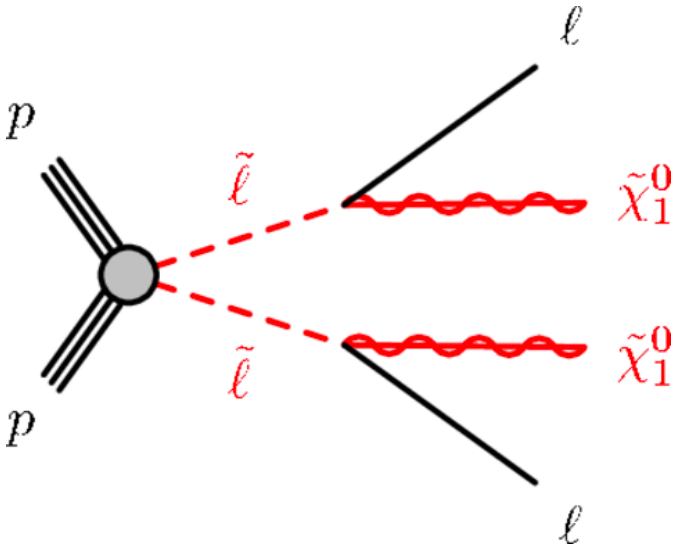


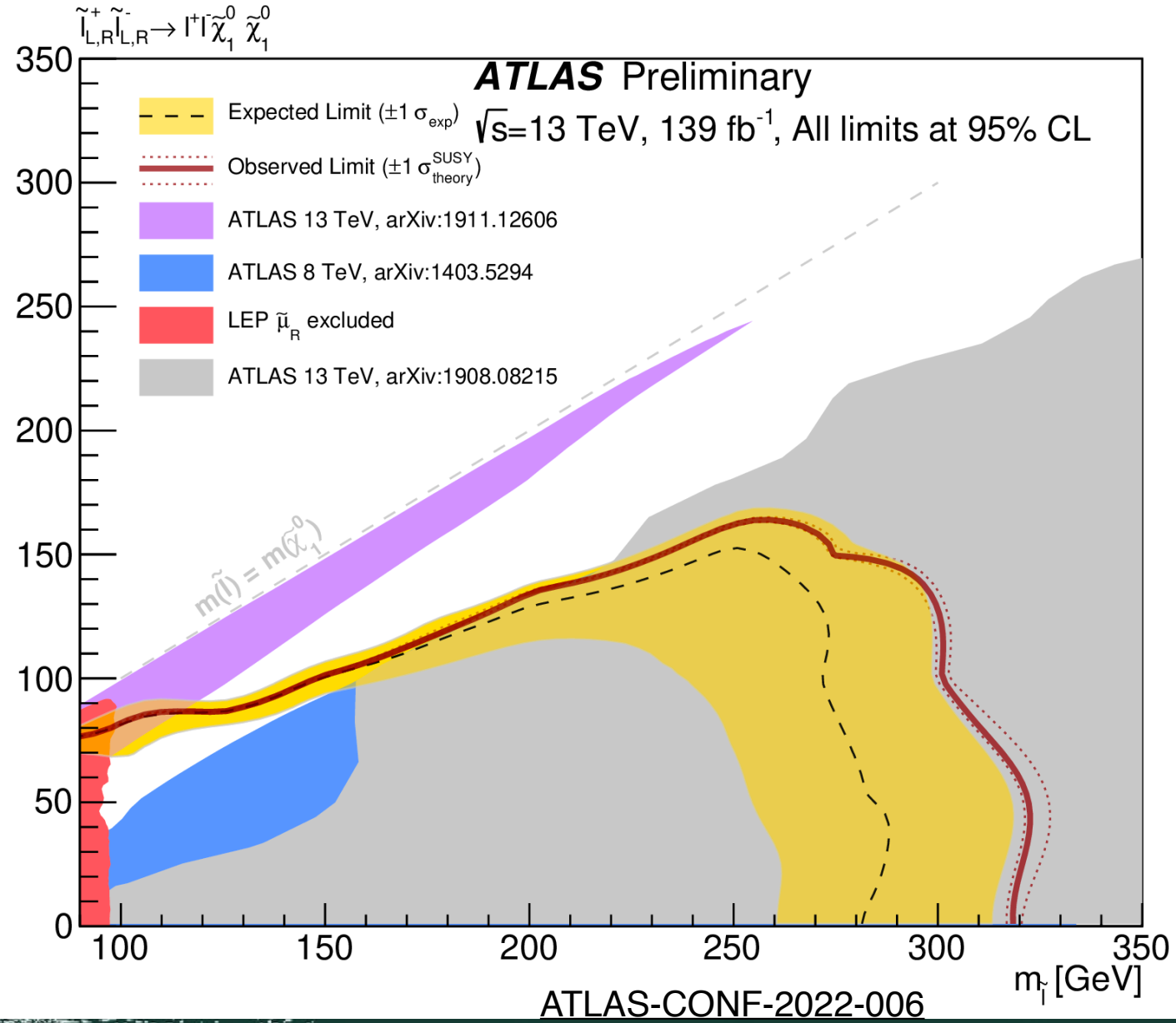
arXiv:2112.11876, ATLAS-CONF-2021-052

Searches for new physics

SUSY search for sleptons

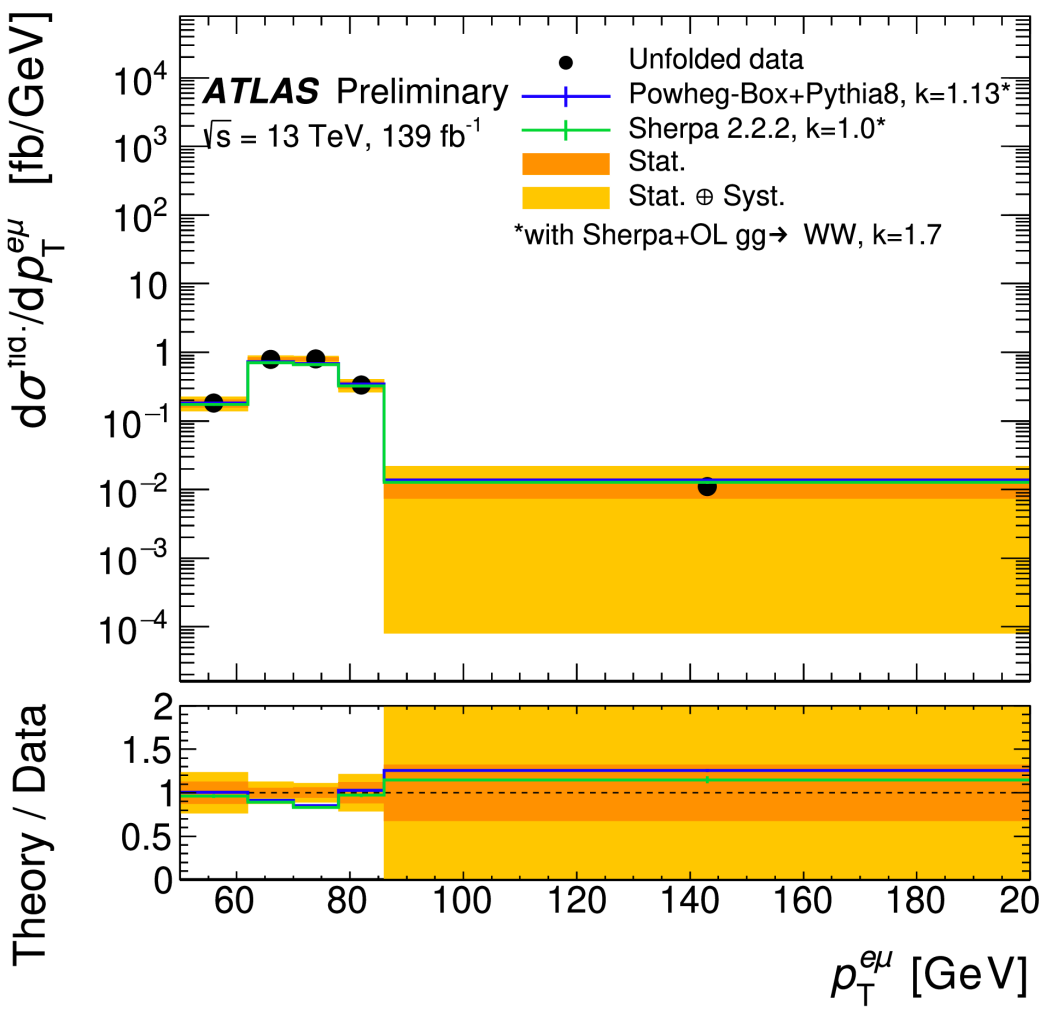
- In the moderately compressed region
  - mass differences of the order of the W boson mass
- Events with 2 l, 2 $\tilde{\chi}^0$

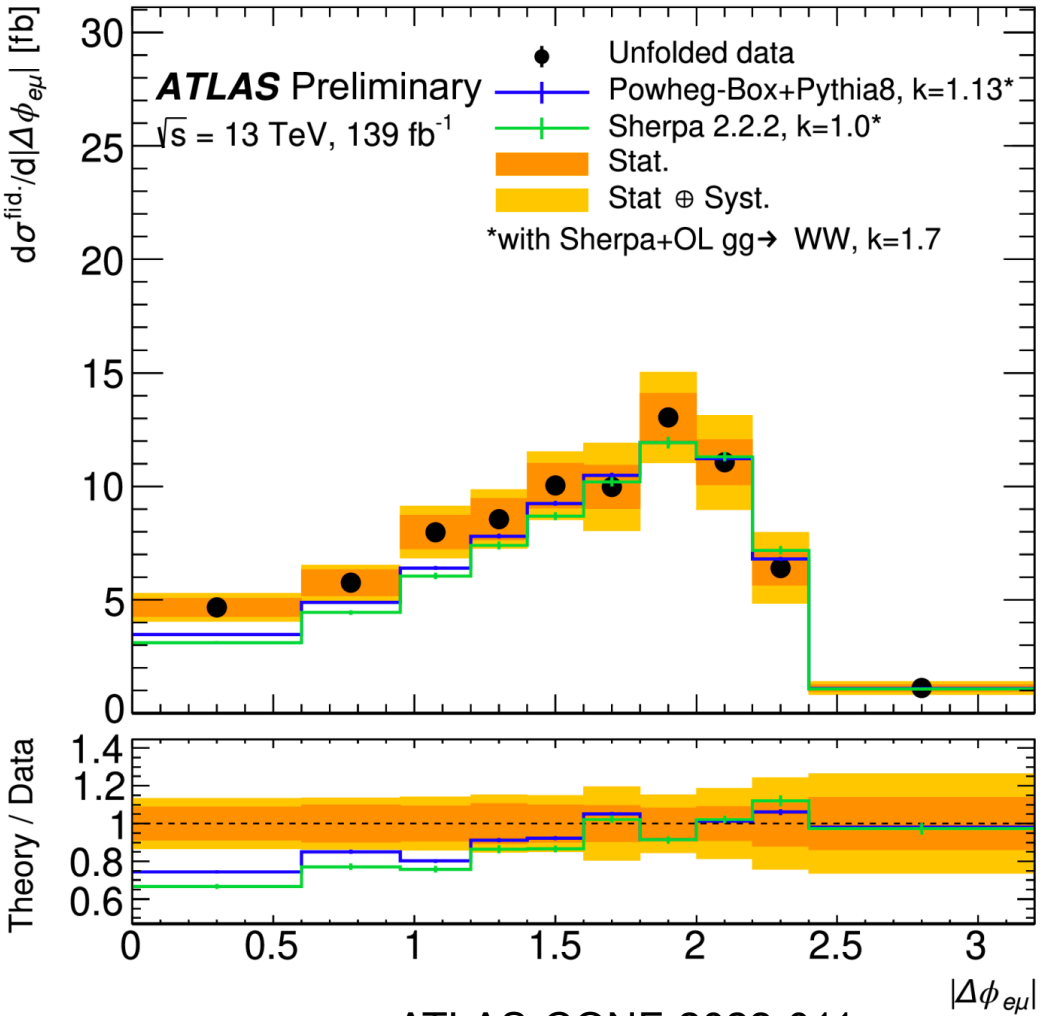




Constraining a key background in SUSY measurements

- Differential WW cross-section measurement
  - Important background in many SUSY searches and many measurements
- Events with 2 l, 2 ν

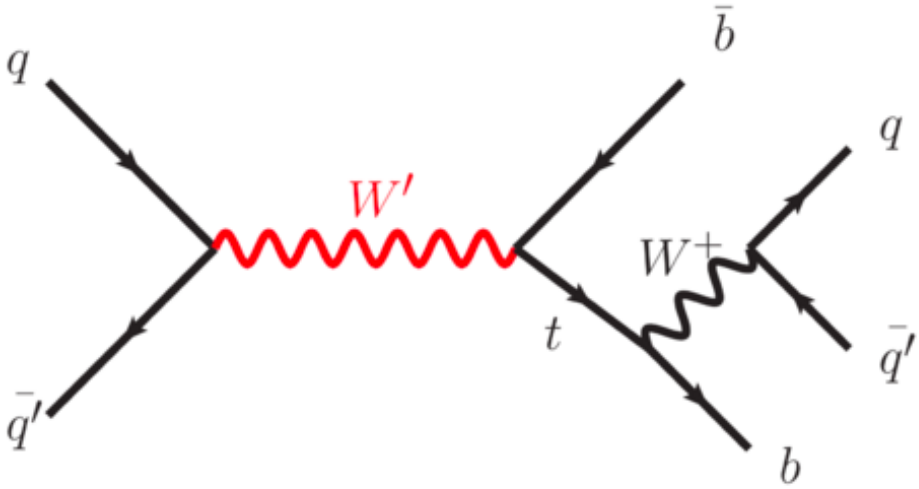


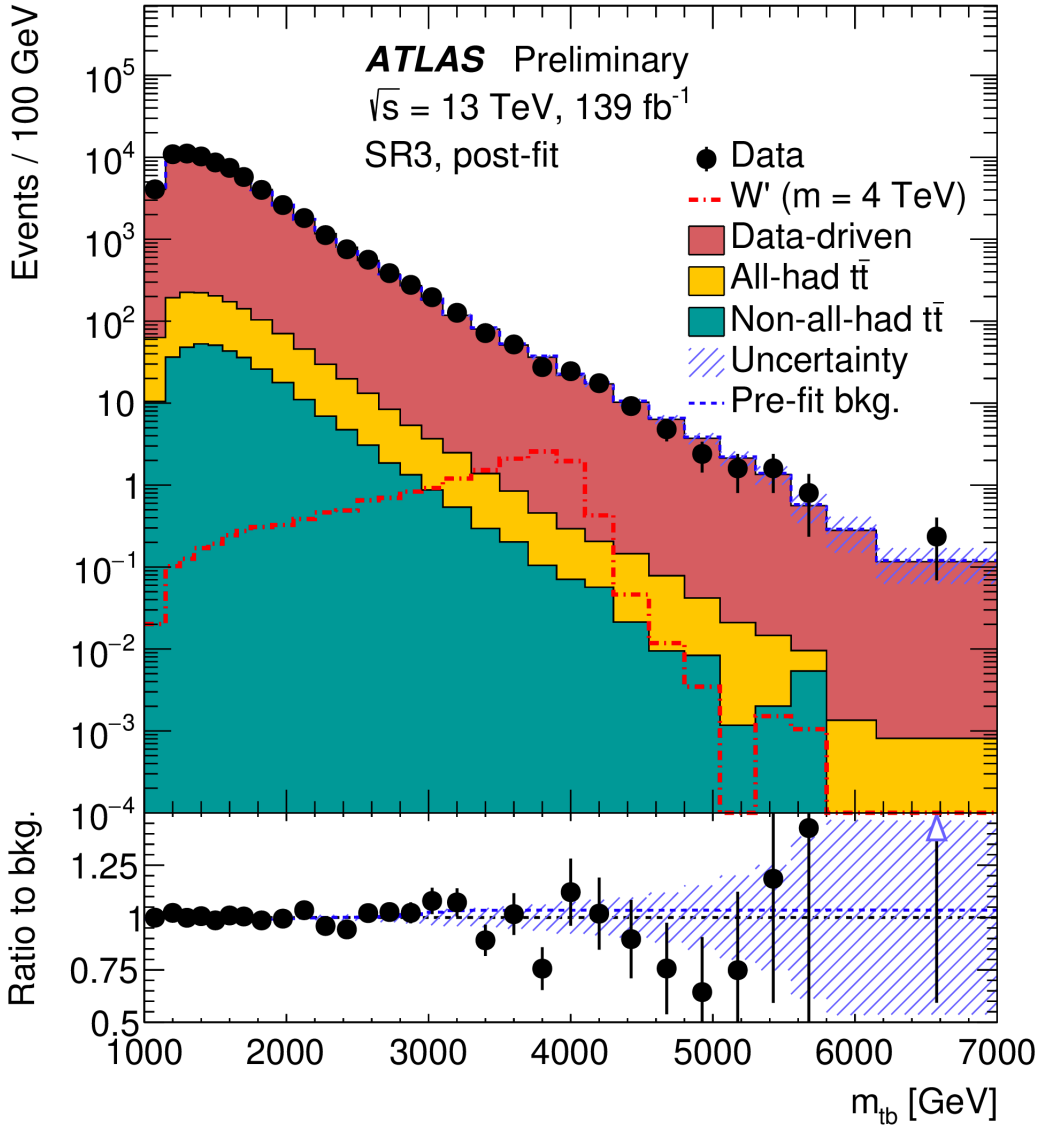


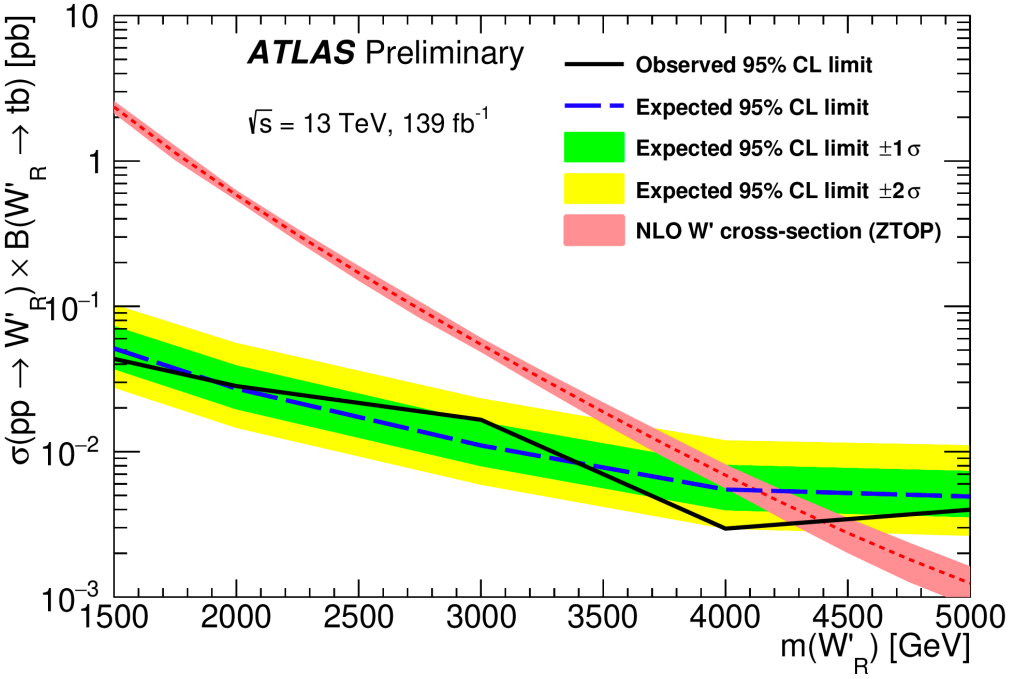
ATLAS-CONF-2022-011

High-mass resonance search

- New heavy boson W′ decays to bottom and boosted top
- Data-driven background est.

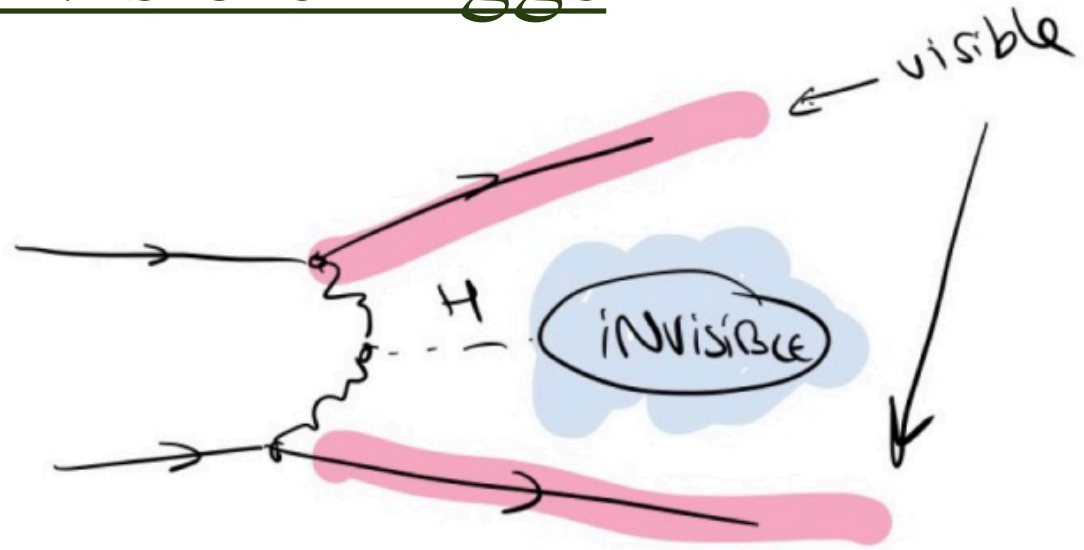


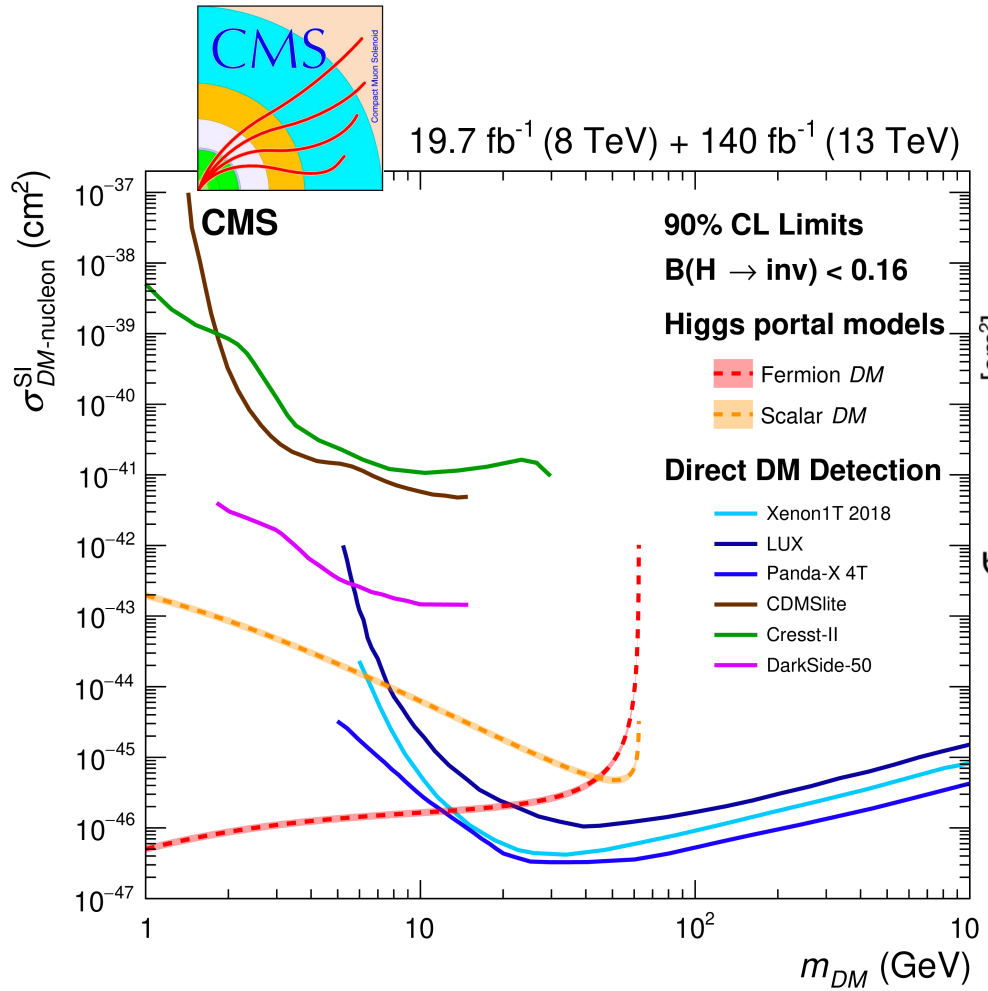




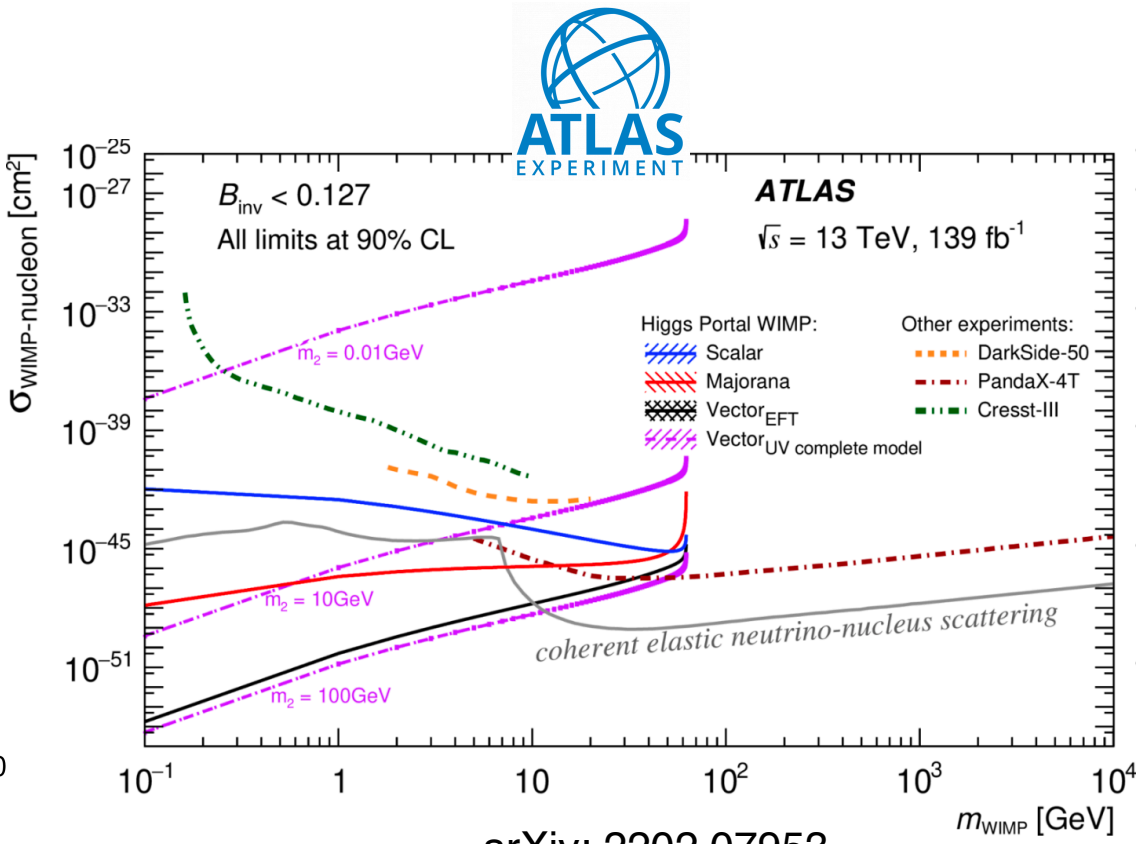
Search for invisible Higgs

- Higgs Boson coupling to dark matter or other non-detectable particles





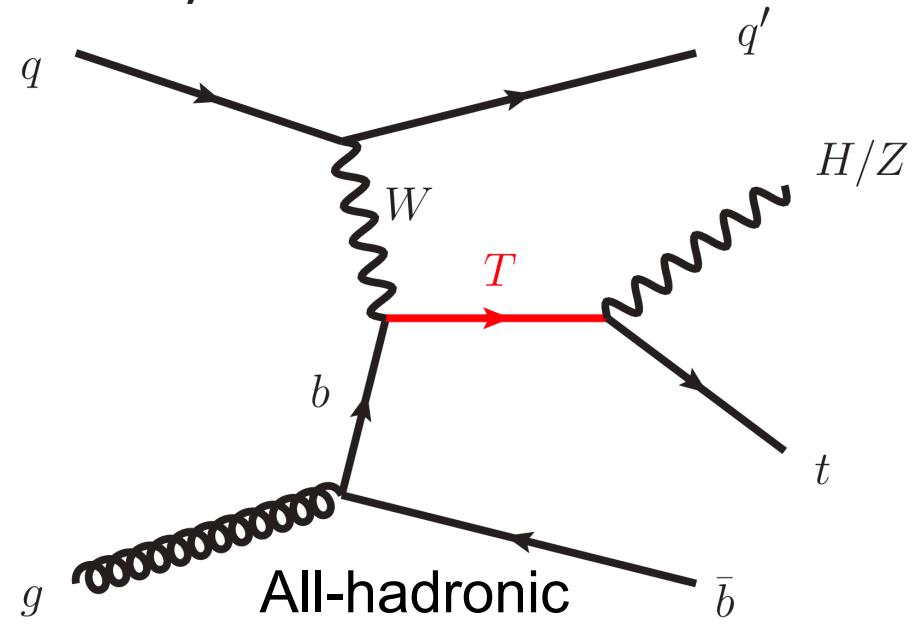
arXiv:2201.11585



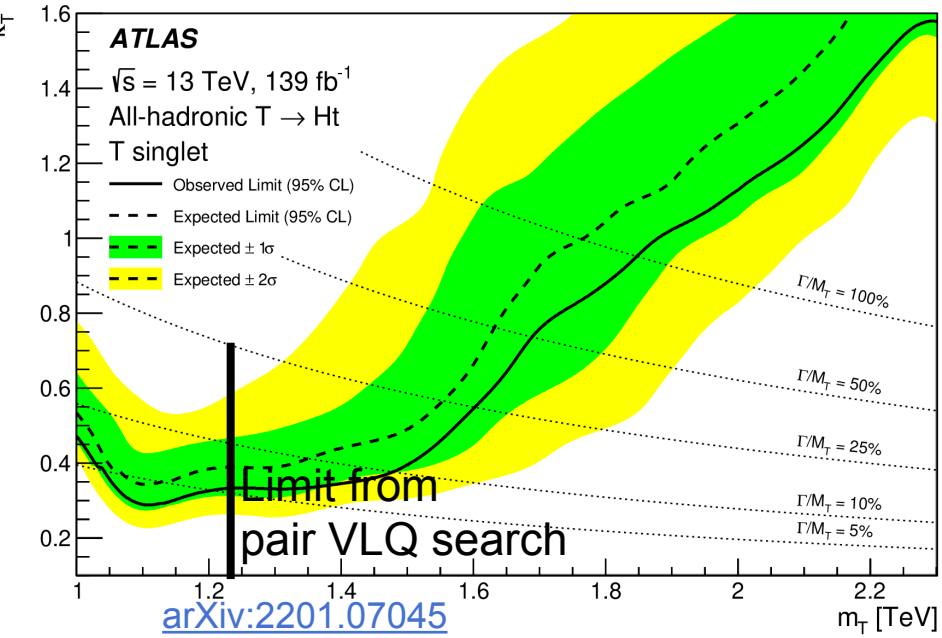
arXiv: 2202.07953

Search for vector-like quarks

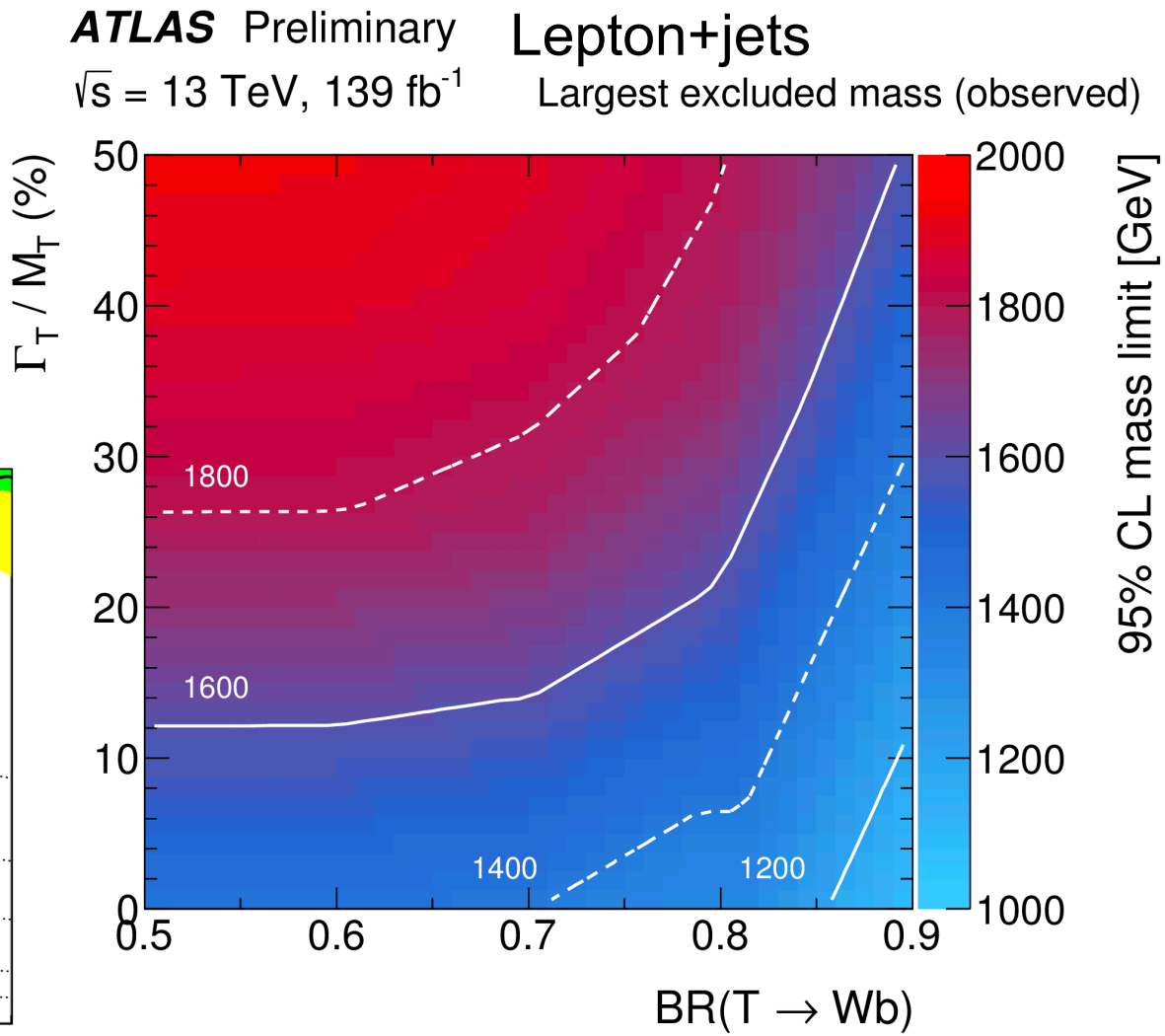
- Single and double (ATLAS-CONF-2021-024) VLQ searches
- tH, tZ final states



All-hadronic



arXiv:2201.07045

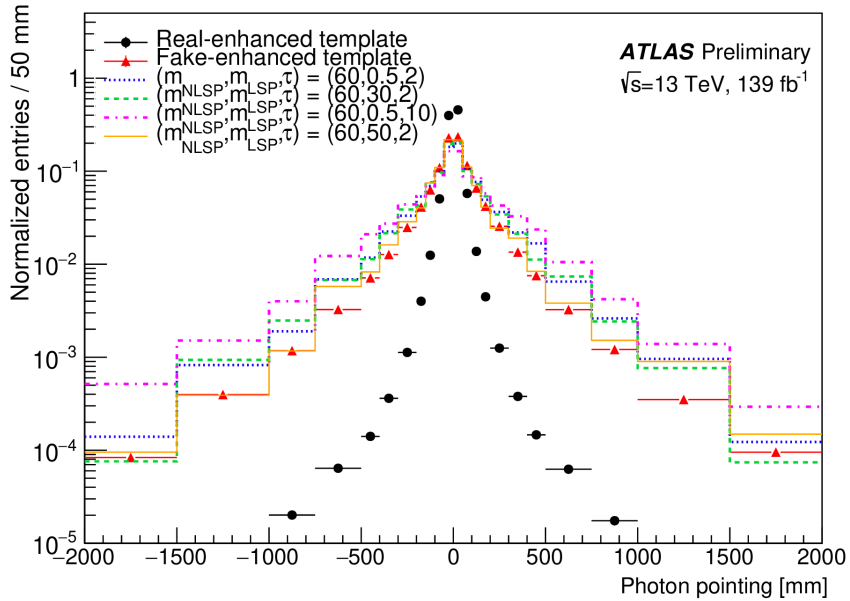


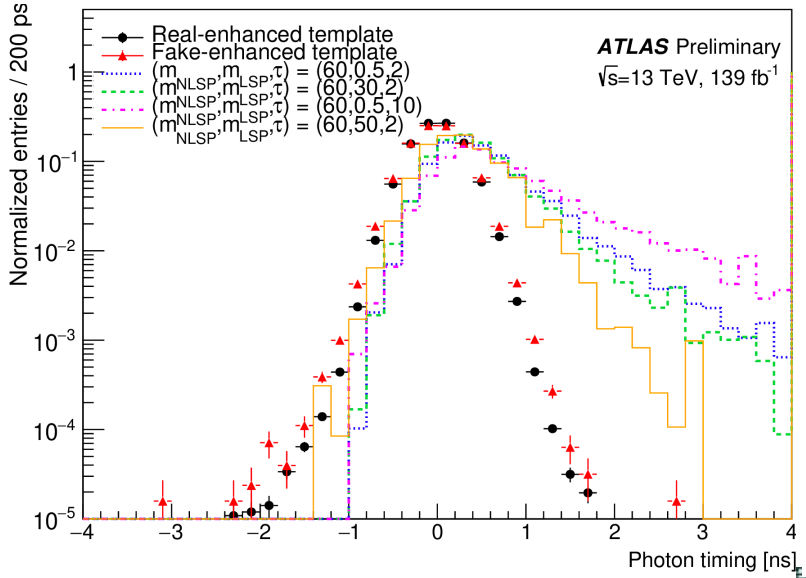
ATLAS-CONF-2021-040

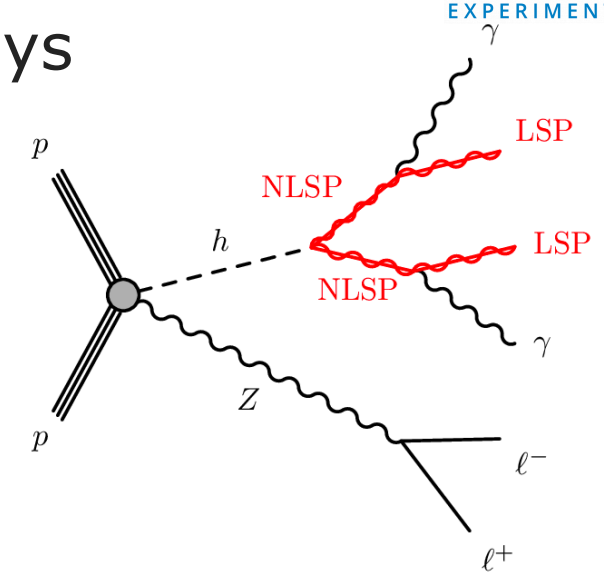
Long-lived particle searches

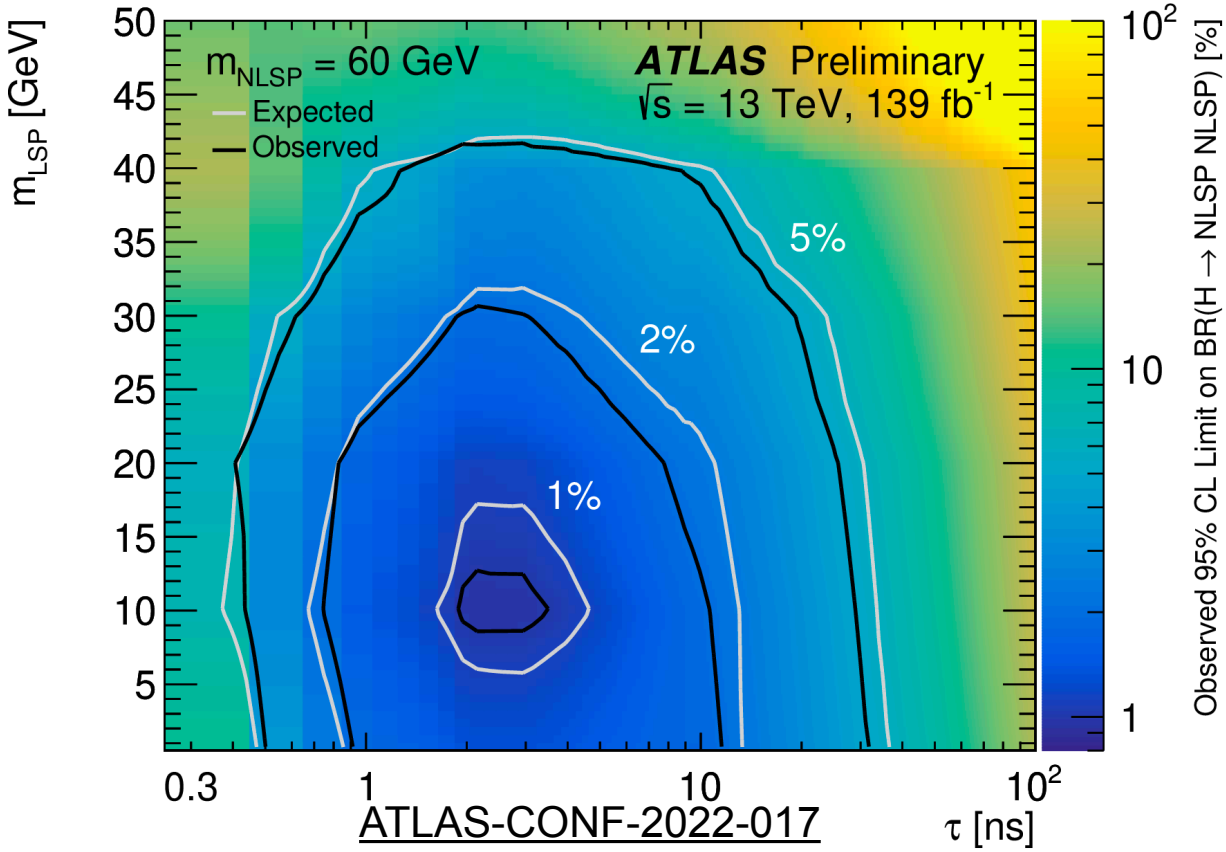
Displaced photon search

- Long-lived (dark) photons from Higgs decays
- Precision photon pointing (mm) and timing (< 1 ns)

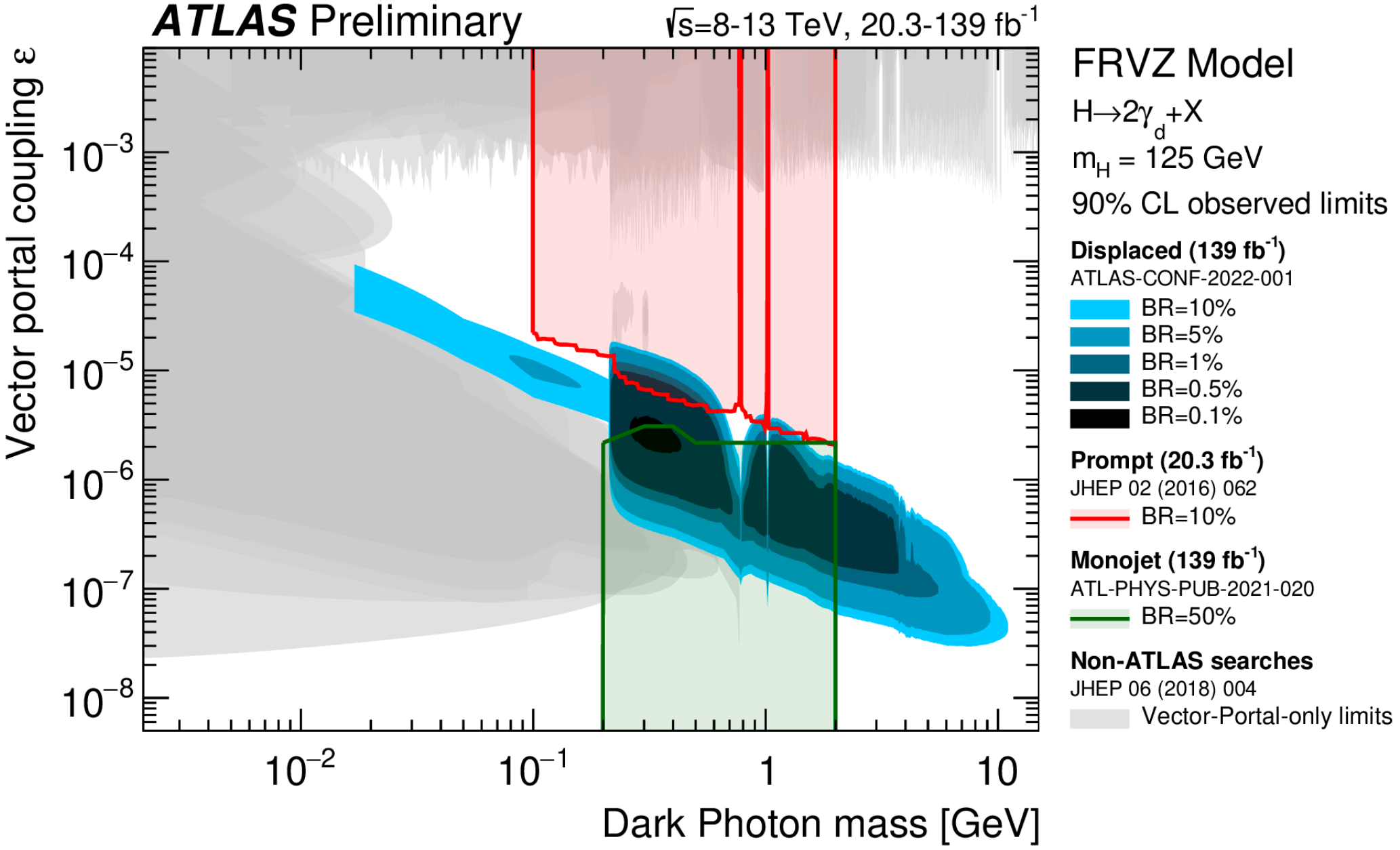






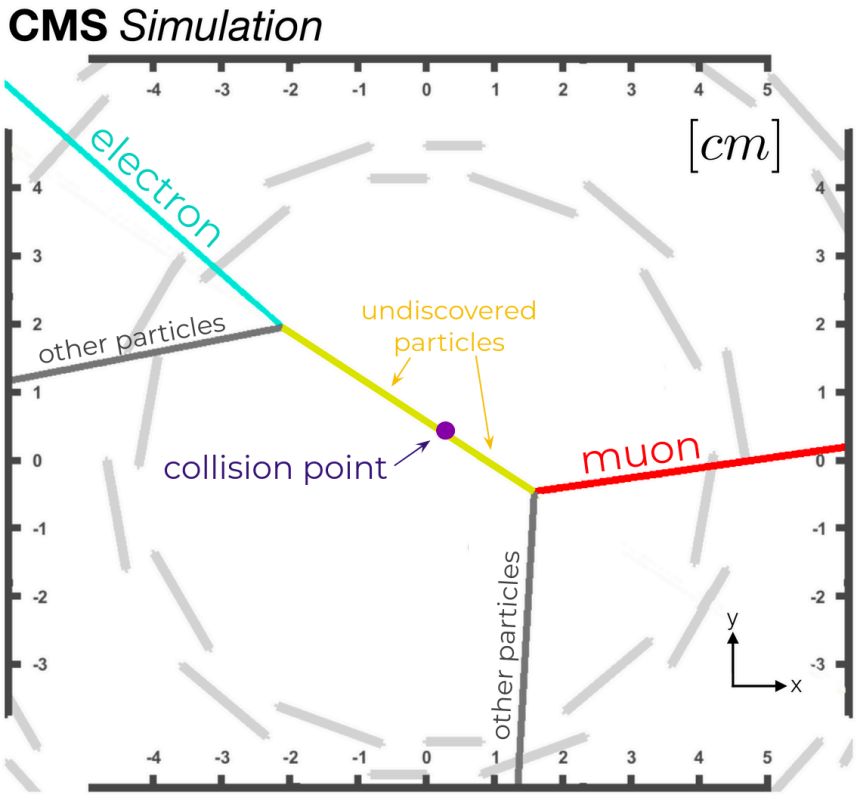


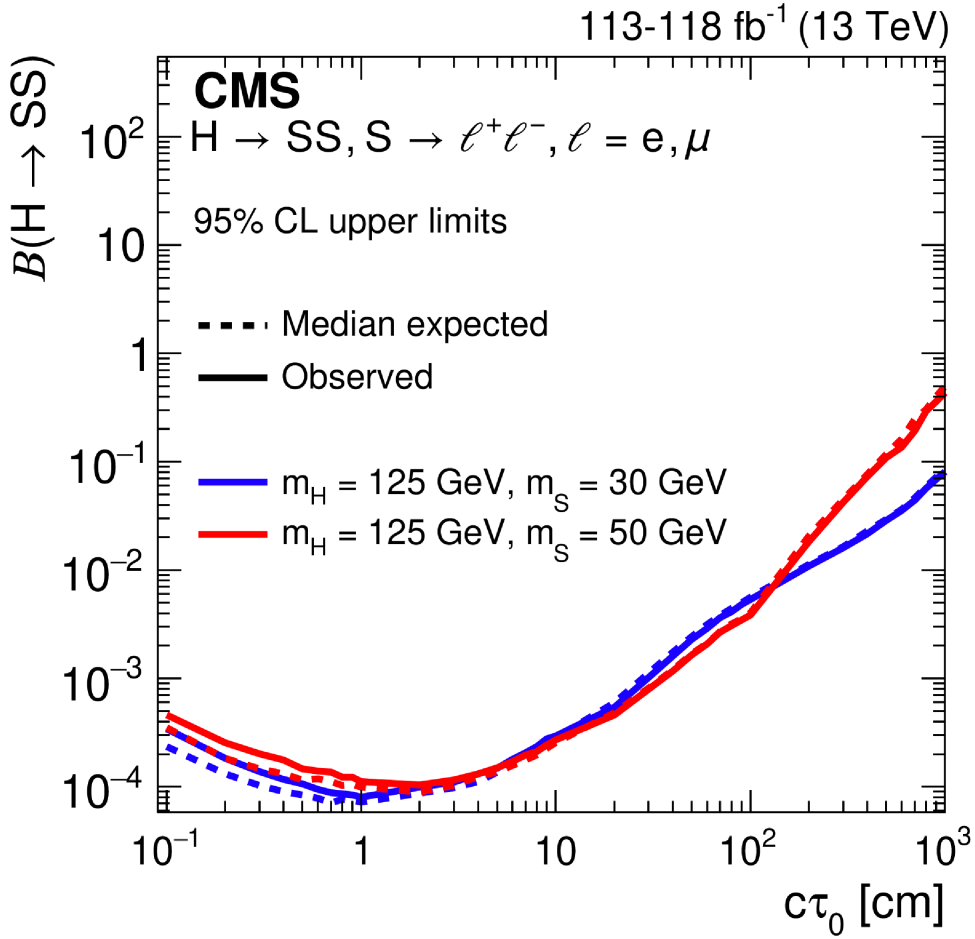
LLP dark photon summary



Displaced lepton search

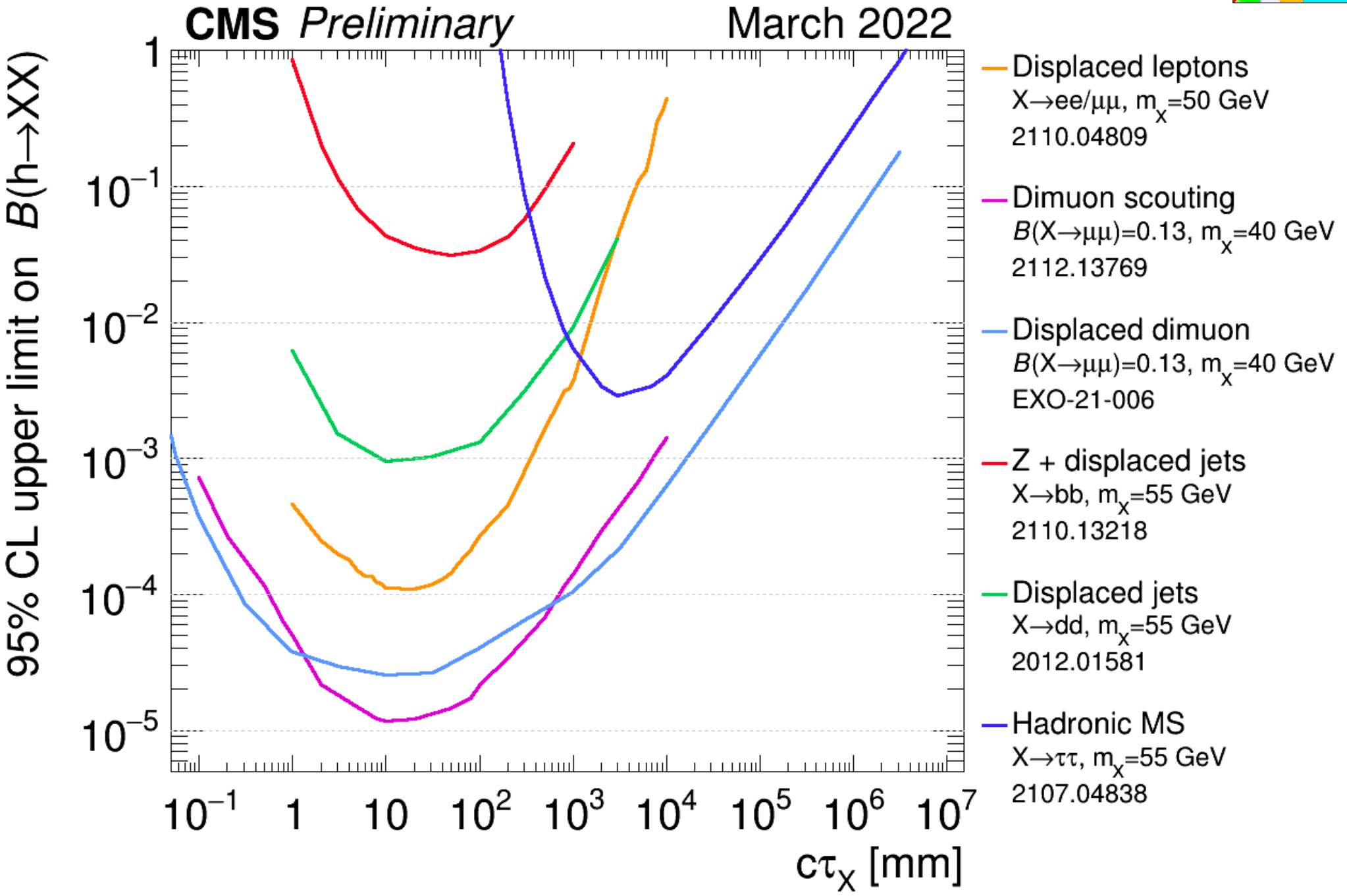
- Two-lepton final states, both leptons have large transverse impact parameter
- Sensitive to many NP models, including RPV SUSY (sleptons), NP Higgs (decaying to two long-lived scalars S)





Eur. Phys. J. C 82 (2022) 153

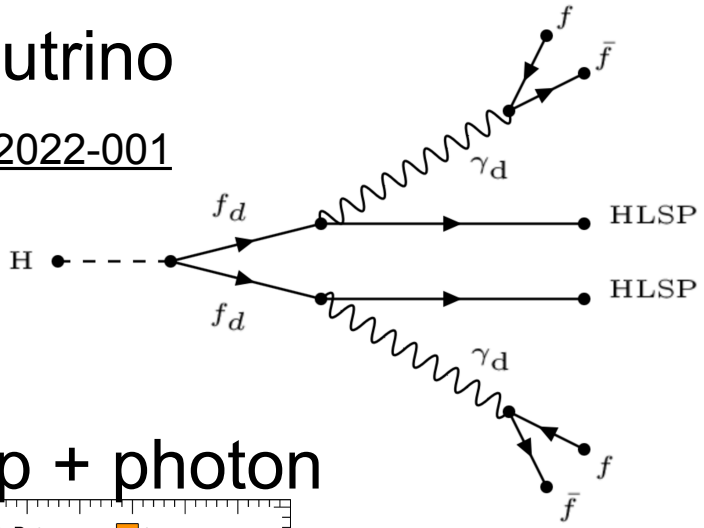
LLP Higgs decay summary



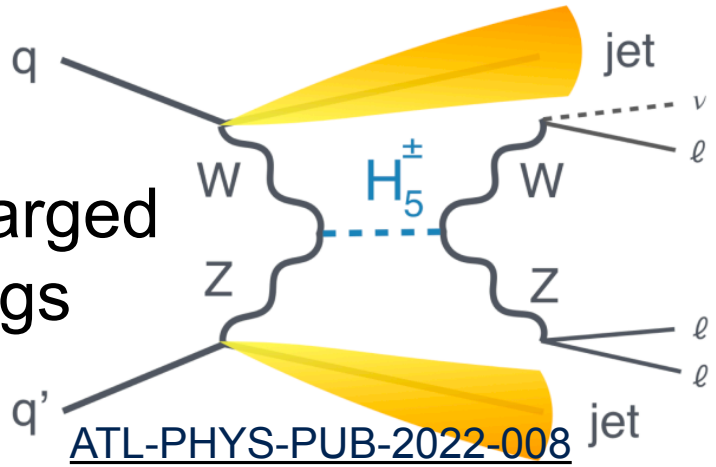
Many more interesting results than I could cover

Heavy neutrino

ATLAS-CONF-2022-001

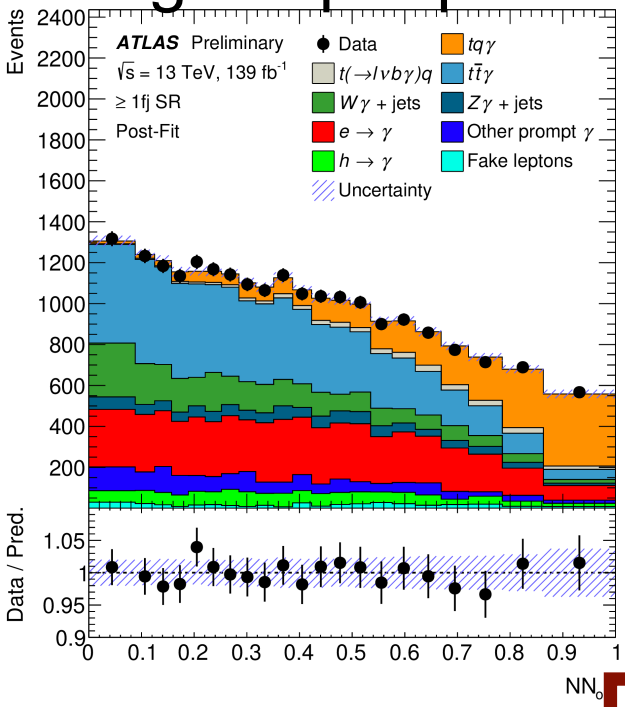


Charged Higgs



ATL-PHYS-PUB-2022-008

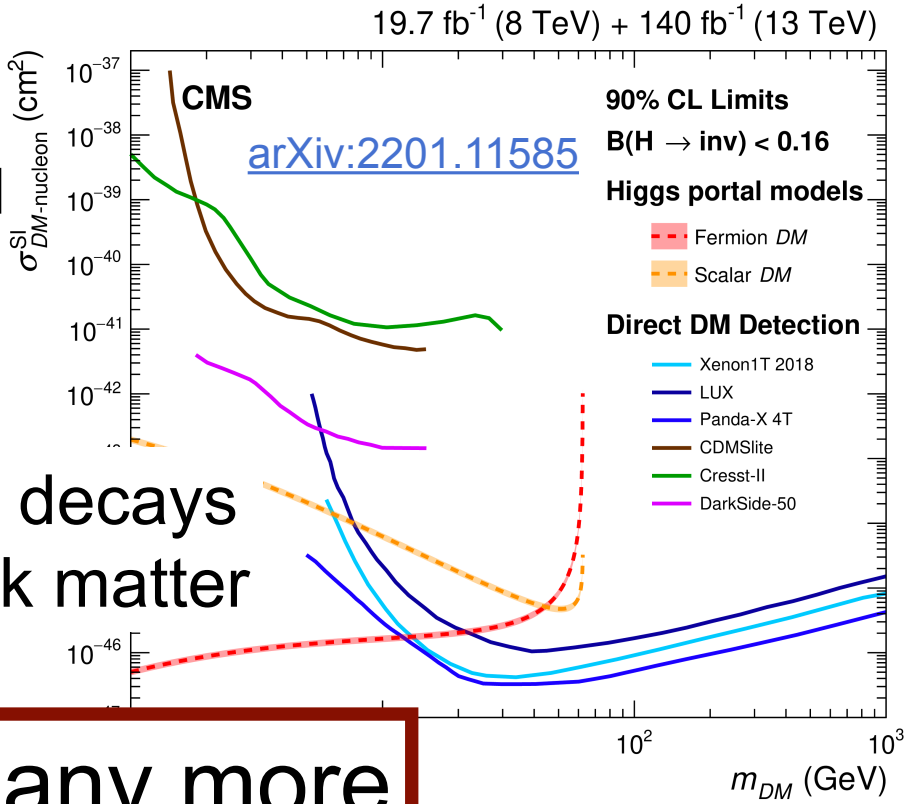
Single top + photon



ATLAS-CONF-2022-013

Drell-Yan forward-backward asymmetry

CMS-SMP-21-002



Higgs decays to dark matter

And many many more

ATLAS talks at Pheno

- Measurements of the CP structure of Higgs-boson couplings with the ATLAS detector, Christian Grefe
- Searches for dark matter with the ATLAS detector, Benjamin Rosser
- Highlights of the ATLAS top quark precision measurements, Pavol Bartos
- Searches for rare top quark production and decay processes with the ATLAS experiment
- Measurement of Z boson production in association with jets at ATLAS, Pierre-Hugues Beauchemin
- Searches for additional Higgs bosons in ATLAS, Luis Dominguez
- Measurement of Higgs boson differential and fiducial cross sections with the ATLAS detector, Benedict Winter
- Searches for electroweak production of supersymmetric particles with the ATLAS detector, Eric Ballabene
- Searches for strong production of supersymmetric particles with the ATLAS detector, Bertrand Dit Latour
- Measurements of the Higgs boson properties and their interpretations with the ATLAS experiment, Carolyn Gee
- Searches for BSM physics using challenging and long-lived signatures with the ATLAS detector, Mason Proffitt
- Probing the nature of electroweak symmetry breaking with Higgs boson pair-production at ATLAS, Iza Veliscek
- Search for rare and exotic decays of the Higgs boson in ATLAS, Jay Chan
- Searches for new phenomena in final states with 3rd generation quarks using the ATLAS detector, Paul Gadow

CMS talks at Pheno

- Search for heavy resonances in diboson final states at CMS, Irene Zoi
- Search for new physics in events with leptons in the final state in CMS, Joseph Reichert
- BSM Higgs decays and extended Higgs sector in CMS, Alp Akpinar
- Dark Matter searches in CMS, Siqi Yuan
- Measurements of Higgs-fermion interactions at CMS, Nick Smith
- Search for supersymmetry in hadronic final states with the CMS experiment, Vinay Hedge
- Search for heavy BSM particles coupling to third generation quarks at CMS, Ia Iashvili
- Higgs Differential and STSX cross-sections in CMS, Roberto Seidita
- Multiboson measurements at CMS, Saptaparna Bhattacharya
- Measurements of V+jets production in CMS, Duong Hai Nguyen

Conclusion

- Continued stream of LHC run 2 publications
- Precise measurements in all areas
  - Including measurements of rare processes and in extreme phase spaces
  - Including heavy flavors (see talk by Marina tomorrow)
  - Including heavy ion collisions
- New physics searches in multi-TeV range
  - And indirect limits from EFT fits
- LHC can probe many of the current puzzles
  - Probe NP related to heavy flavor anomalies
  - Probe NP related to muon g-2
  - Searches for dark matter
- Run 3 will more than double the dataset
  - At 13.6 TeV