Flavour Anomalies and BSM searches

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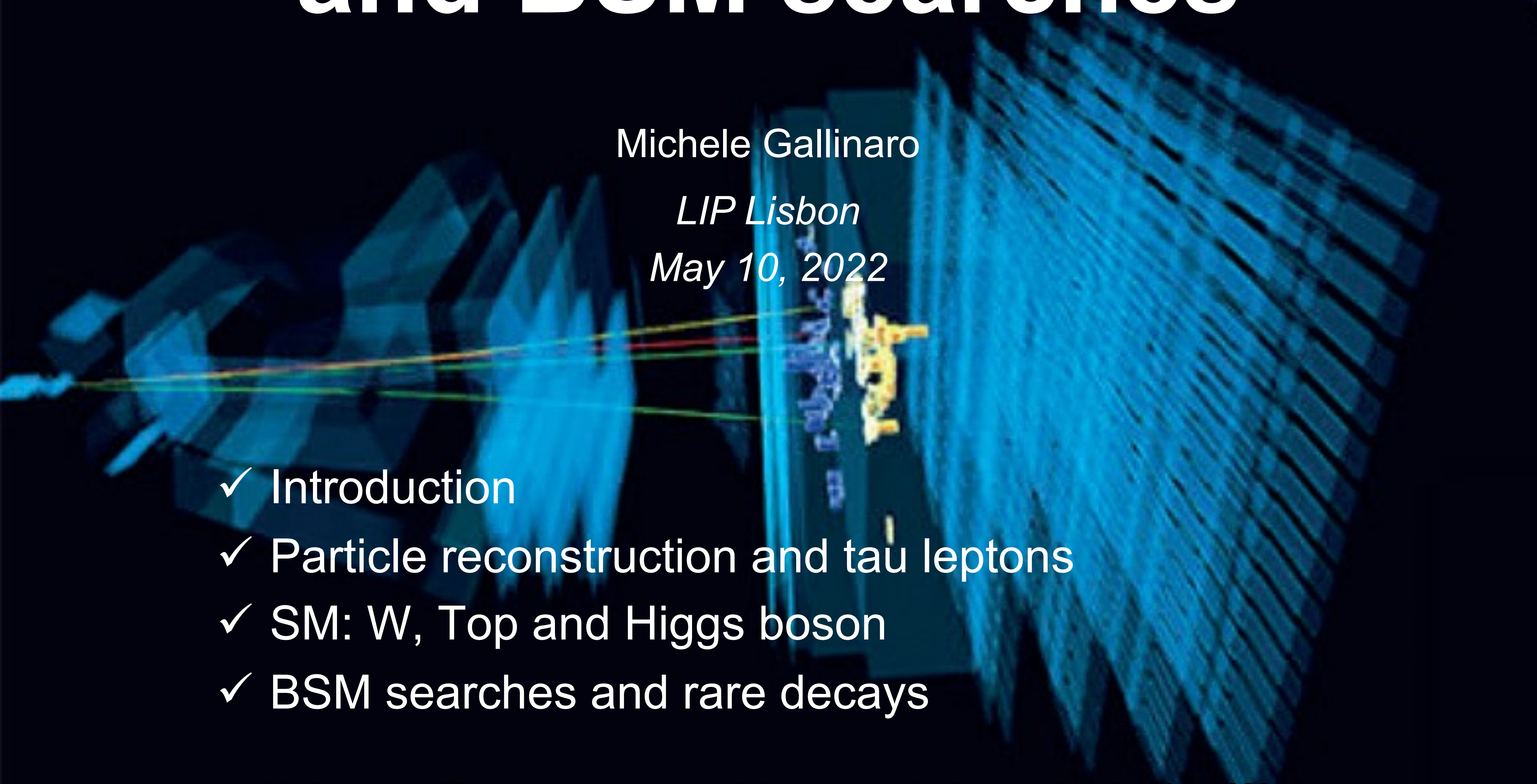
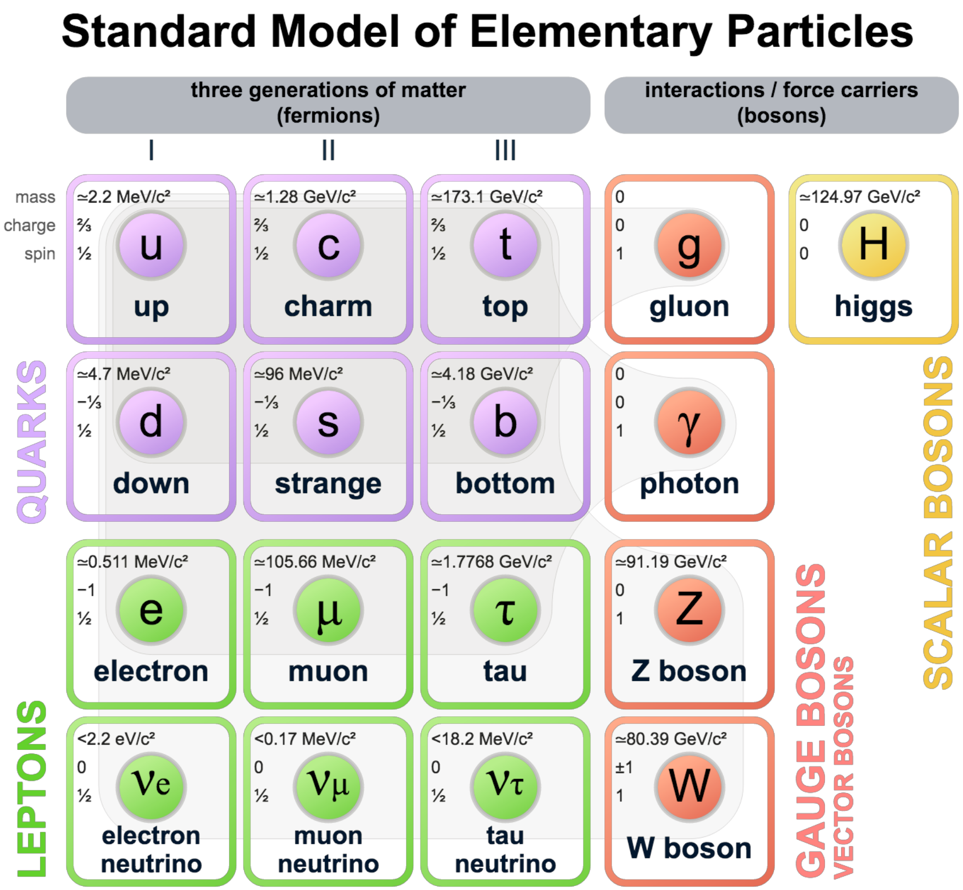
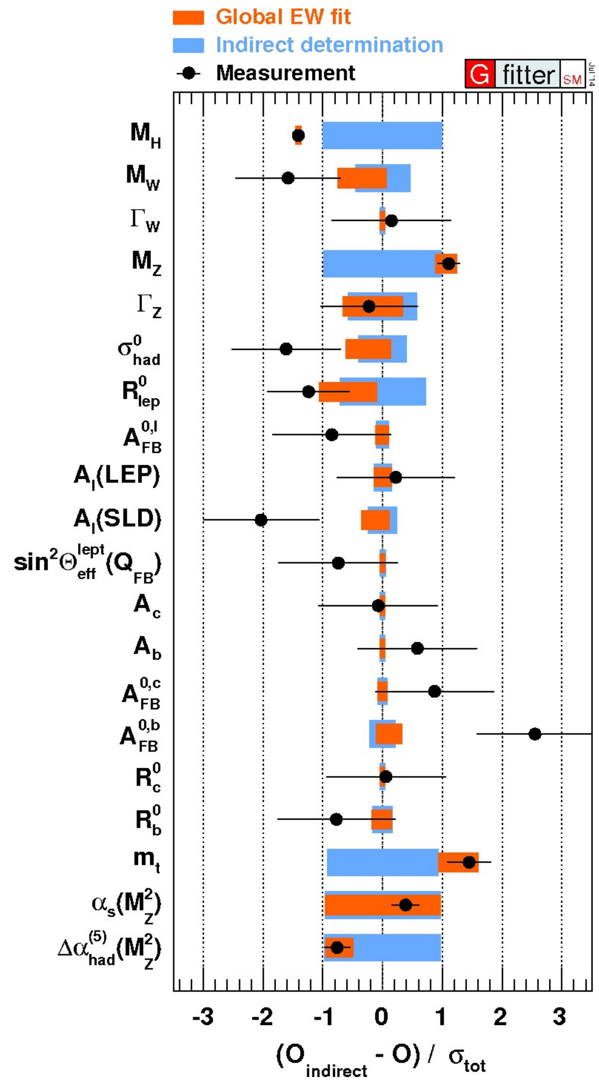


- ✓ Introduction
- ✓ Particle reconstruction and tau leptons
- ✓ SM: W, Top and Higgs boson
- ✓ BSM searches and rare decays

SM confirmed by the data



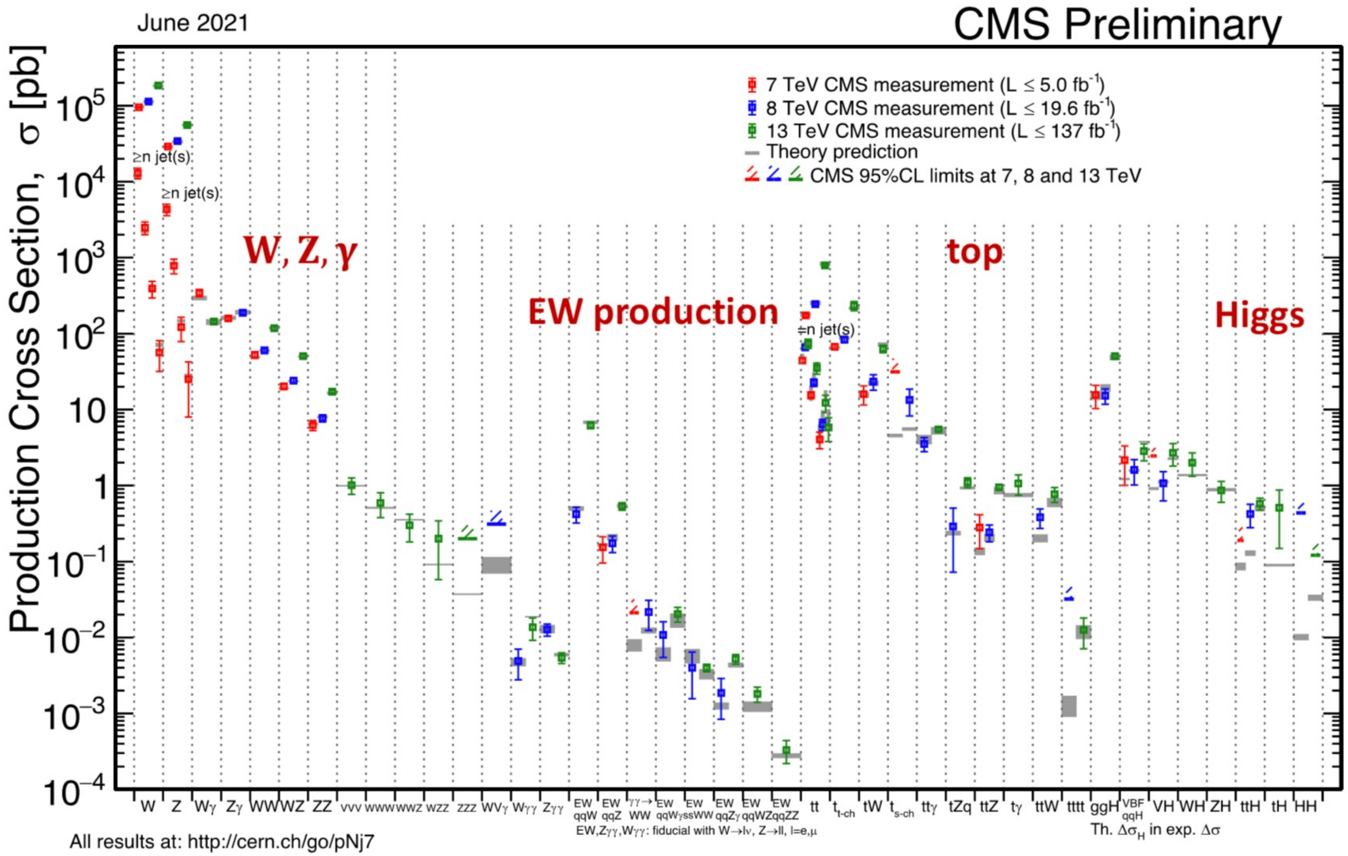


Excellent agreement with all experimental results

Experimental measurements

Measurements of different processes

- Rare processes, EFT interpretations, theory calculations
- Deviations may indicate NP



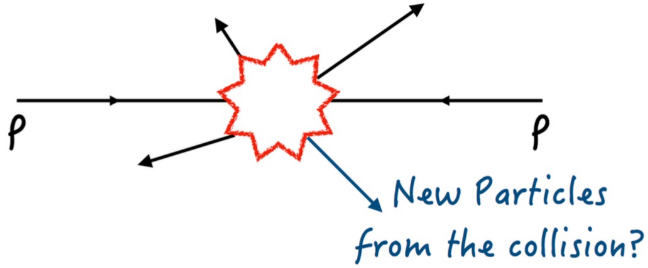
Search for new phenomena

…How?

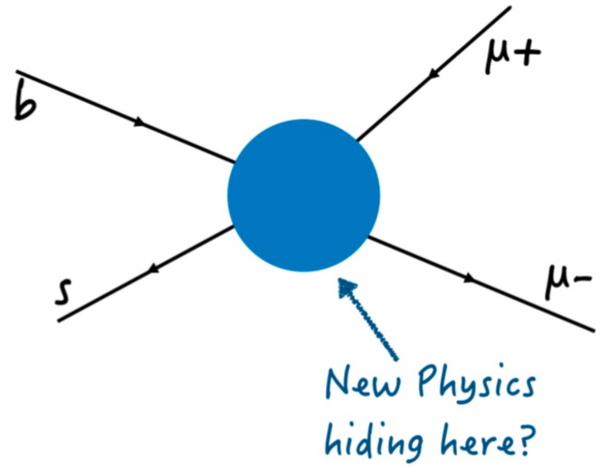
- Indirect searches
  - precision measurements, event properties, etc.
- Direct searches
  - resonances, specific final states, model-(in)dependent searches, etc.
- Production and decay rates, event characteristics, advanced tools

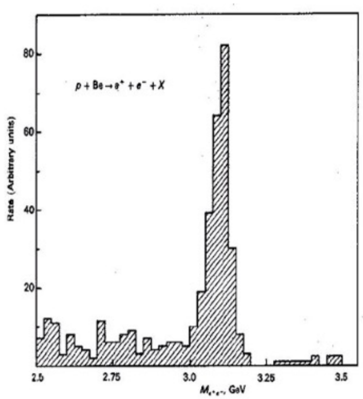
Search for New Physics

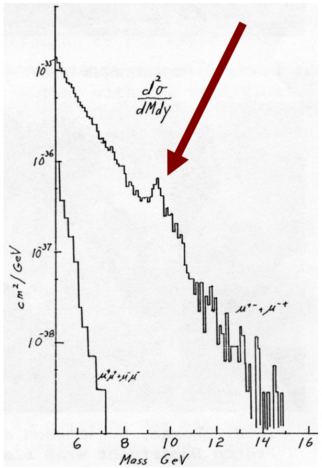
direct searches



indirect searches







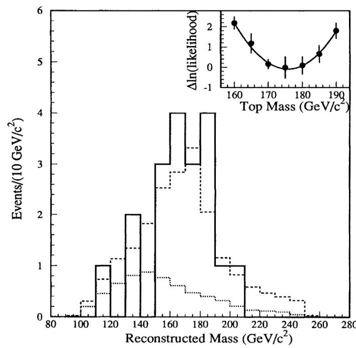
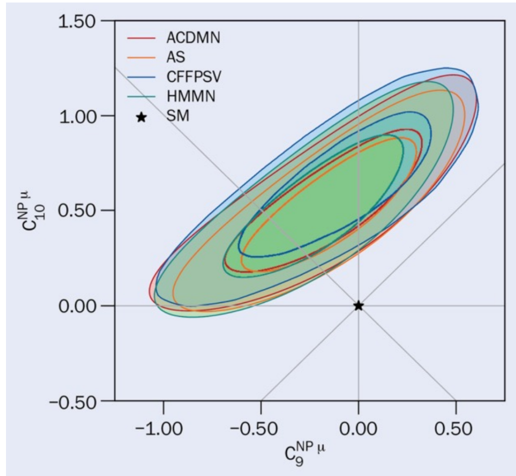
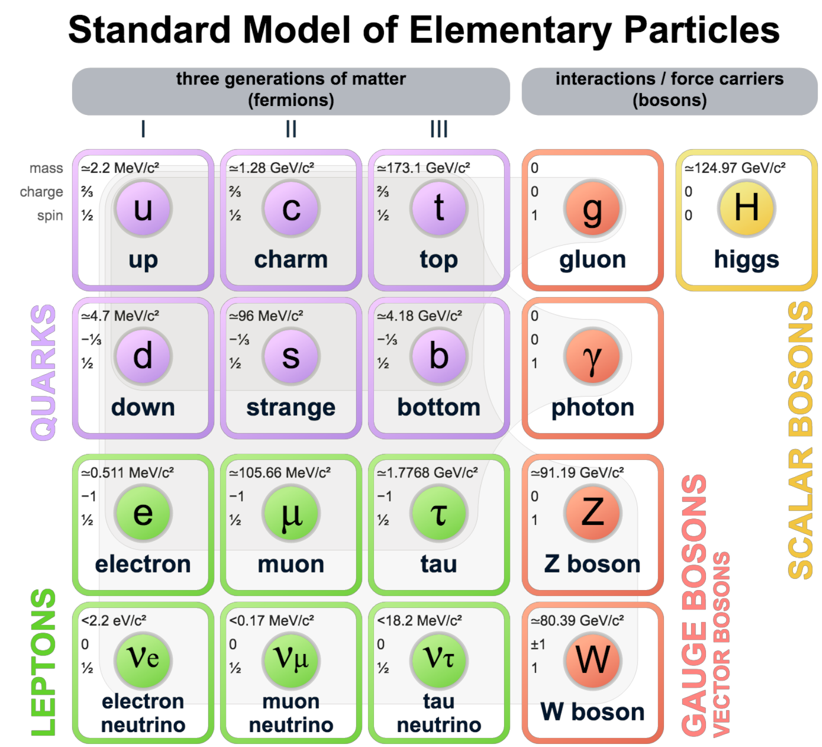


FIG. 3. Reconstructed mass distribution for the b-tagged $W+\geq4$-jet events (solid). Also shown are the background shape (dotted) and the sum of background plus $t\bar{t}$ Monte Carlo simulations for $M_{top} = 175$ GeV/c^2 (dashed), with the background constrained to the calculated value, $6.9^{+2.5}_{-1.9}$ events. The inset shows the likelihood fit used to determine the top mass.



Flavours

- 6 quarks and 6 leptons arranged in 3 families
  - get their masses through interaction with Higgs boson
- Families are identical except for their masses
  - same interaction with gauge bosons
- "flavour" refers to type of quark/lepton
- Why are there 3 families?
- Processes where 3 generations interact differently would be a sign of NP

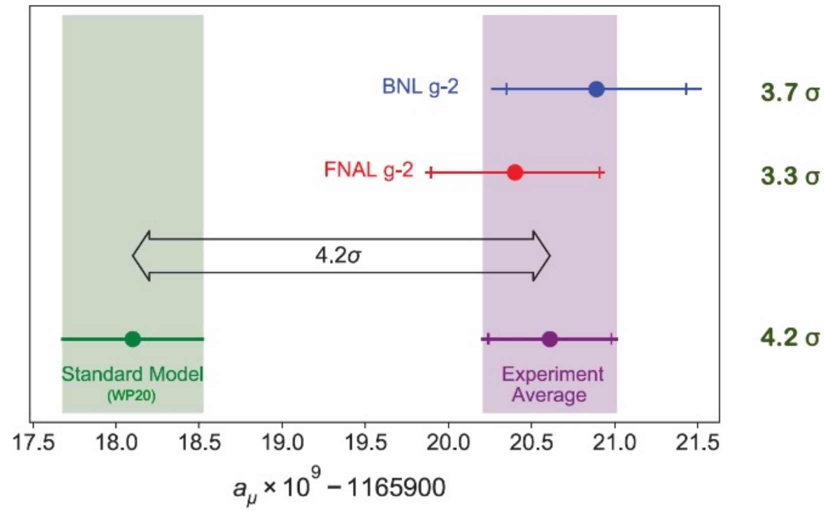


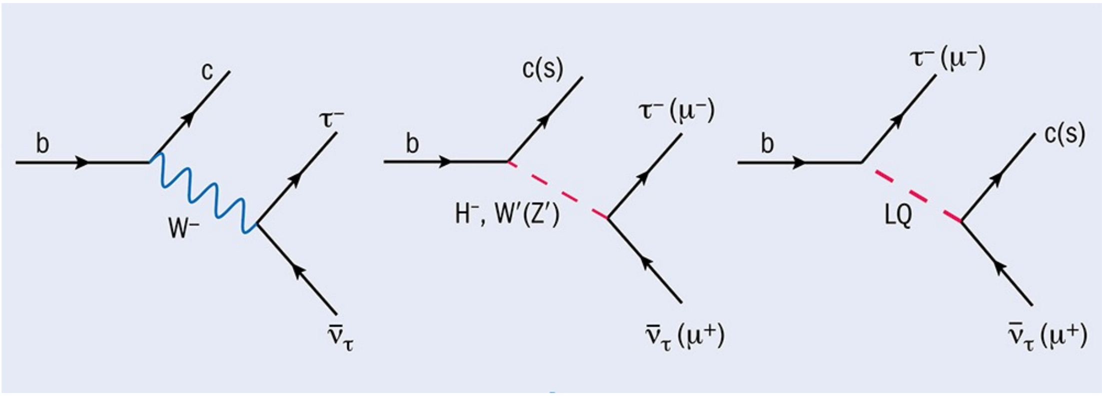
Lepton Flavour Universality

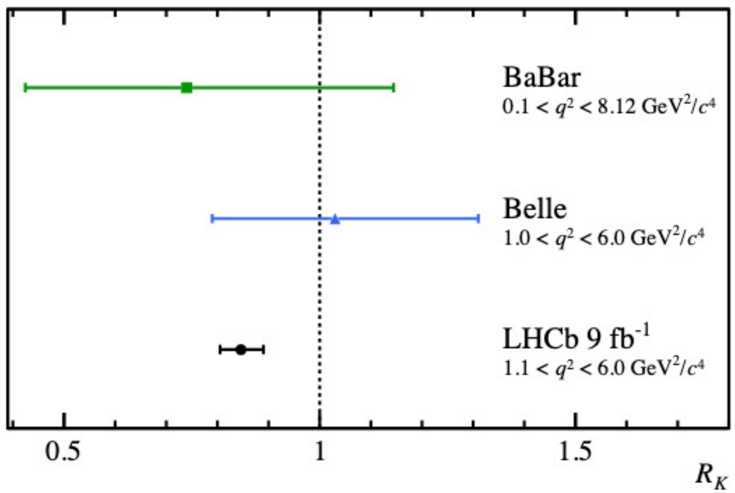
- Theory predicts that the different charged leptons - the electron, muon and tau - have identical electroweak interaction strengths
- Measurements have shown a wide range of particle decays are consistent with the lepton flavour universality (LFU) principle
- "lepton universality" is a principle taken for granted put under stress by recent measurements
- Very active field in light of flavour anomalies
  - Look for violation of LFU
  - LFU involving $e/\mu/\tau$ ratios

Recent measurements

- Recently there have been measurements related to lepton flavour (LF) that show tension with SM expectations
- Anomalies:
  - For ex. $(g\text{-}2)_\mu$, and more
  - R_K and R_{K^*} @LHCb

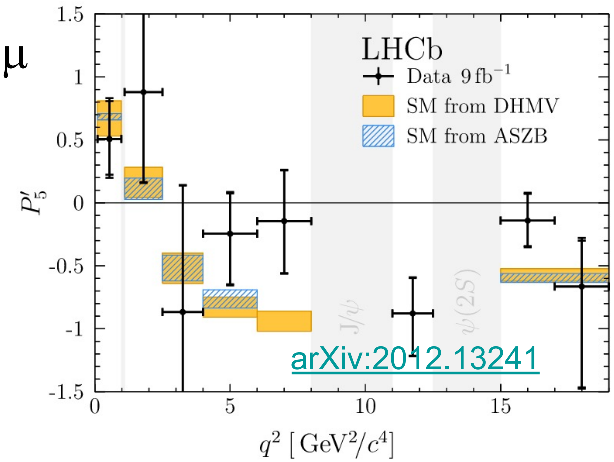


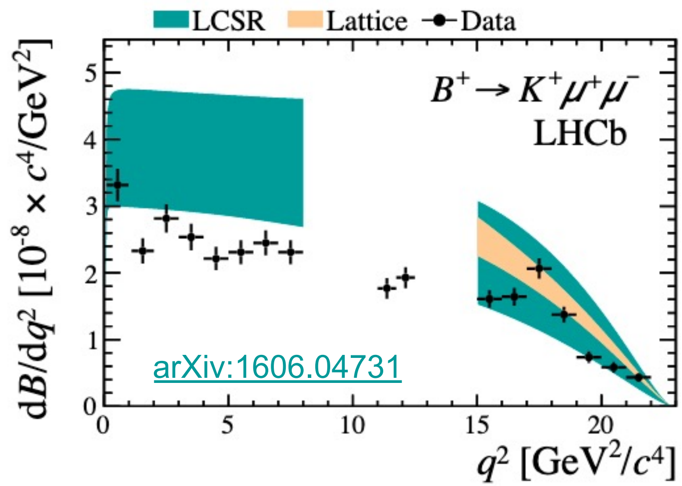


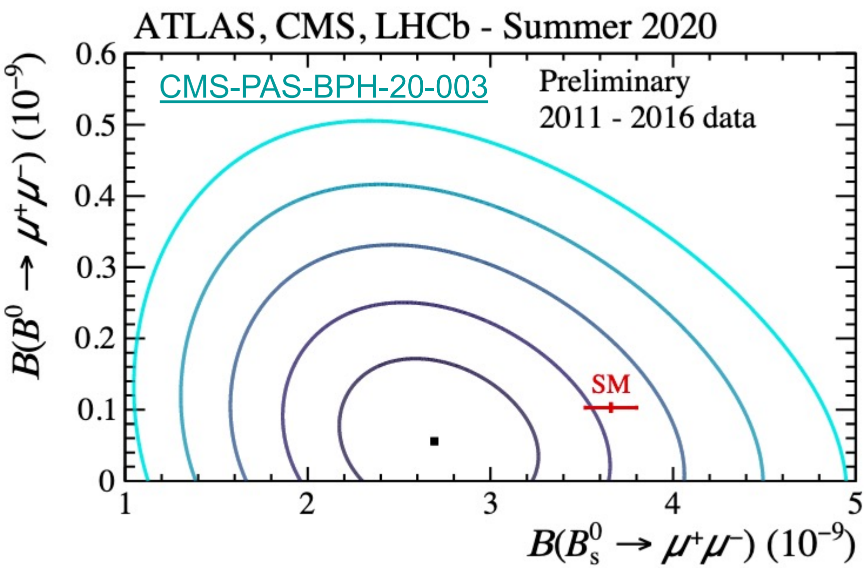


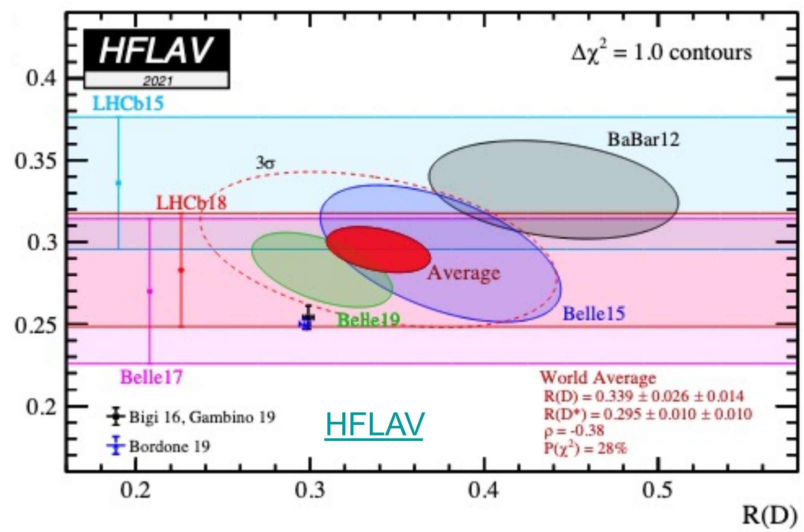
Flavour anomalies

- Several measurements deviate from SM predictions
  - –Angular observables in B ⟶K*μμ
  - –Branching ratios
  - –R_D ratios show combined deviation from SM by 3-4σ
  - –Combination of B_s⟶μμ measurements (2.1σ)









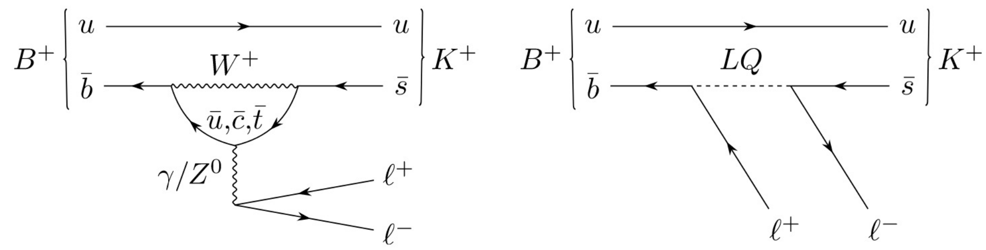
$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\ell\nu)}$$

$$\ell \in \{e, \mu\}$$

LFU: anomalies

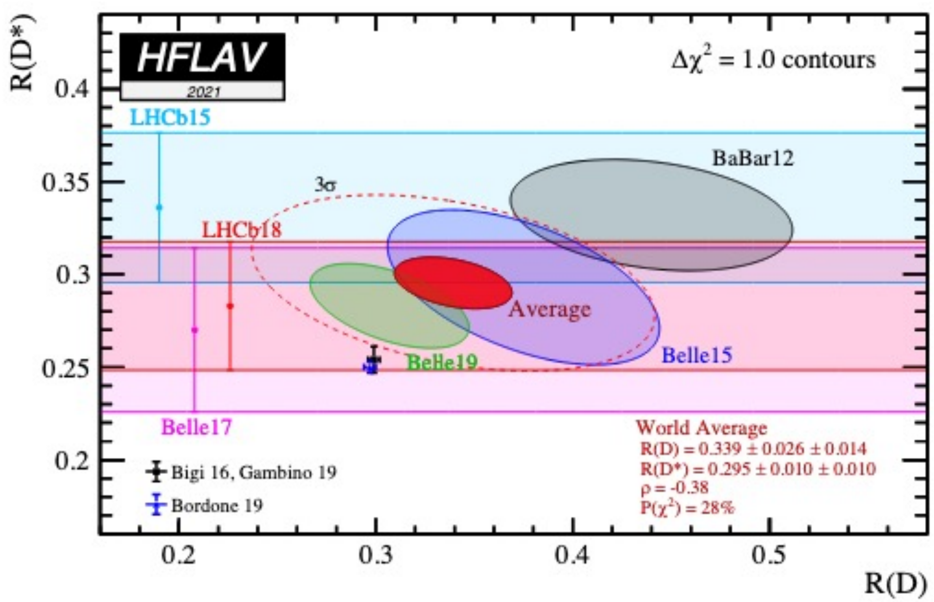
arXiv:2103.11769

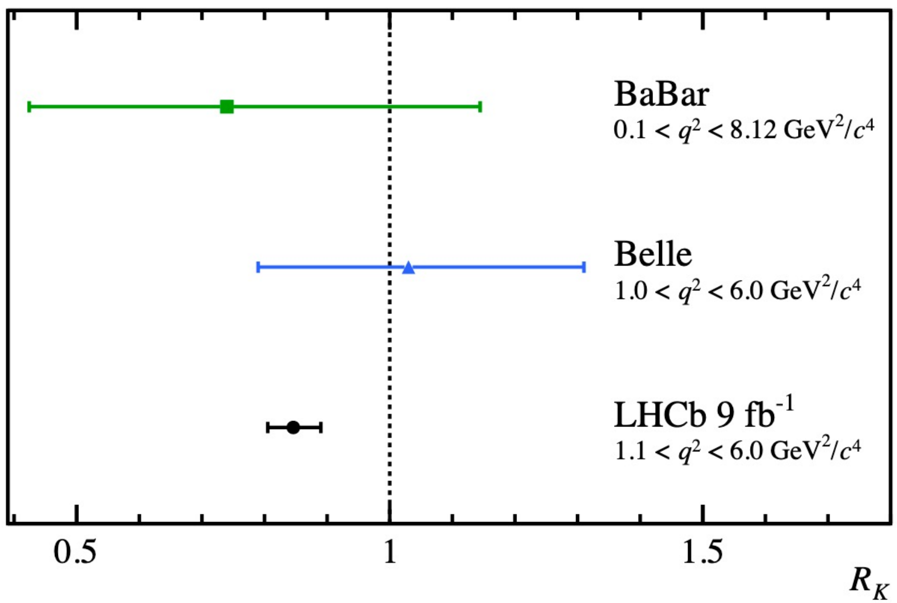
- Recent LHCb results indicate evidence for breaking of LFU in b-quark decays (3.1 σ)
- Both in neutral ($b \to s\ell^+\ell^-$) and charged ($b \to c\tau\nu$) decays



$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\ell\nu)} \qquad \ell \in \{e, \mu\}$$

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))}$$





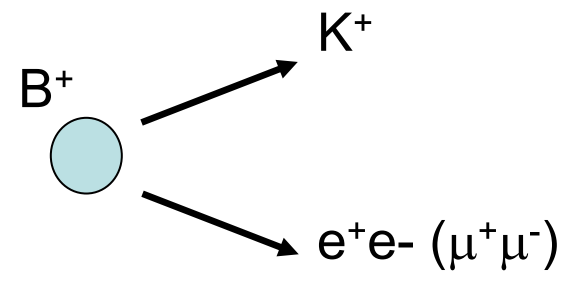
Anomaly: R_K measurement

arXiv:2103.11769

Test of μ/e universality

- In SM, $B^+ \to K^+ee$ and $B^+ \to K^+\mu\mu$ should happen at the same rate
  - Rare process in SM
  - BSM effects can be large
  - Without errors, ratio is 1
  - Differences in detecting electrons and muons
- Common systematics cancel in double ratio
  - similar final state as reference

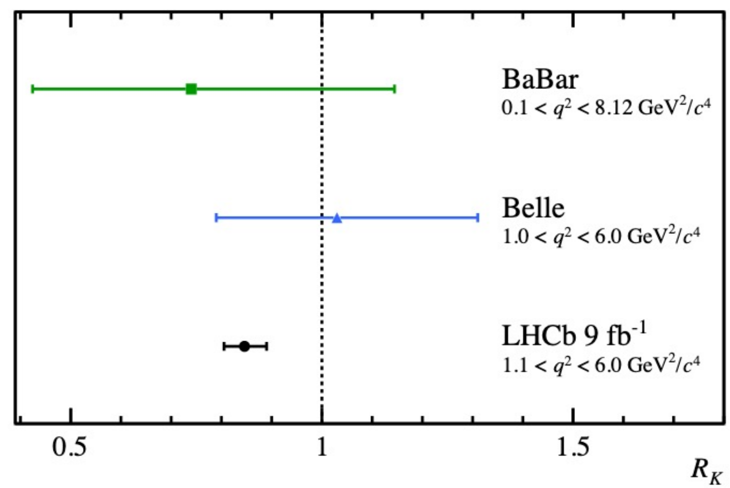
$$b \to s\ell^+\ell^-$$



(3.1 σ)

Observable	Experiment	SM
$R_{K^*}^{[0.045,1.1]}$	$0.66^{+0.11}_{-0.07} \pm 0.03$ [3]	0.906 ± 0.028 [55]
$R_{K^*}^{[1.1,6.0]}$	$0.69^{+0.11}_{-0.07} \pm 0.05$ [3]	1.00 ± 0.01 [55]
$R_{K}^{[1.1,6.0]}$	$0.846^{+0.042+0.013}_{-0.039-0.012}$ [1]	1.00 ± 0.01 [55]
$\mathcal{B}(B_s \to \mu^+\mu^-)$	$(2.85^{+0.32}_{-0.31}) \times 10^{-9}$ [56–58]	$(3.66 \pm 0.14) \times 10^{-9}$ [59]

$$R_K = \frac{\dfrac{B(B^+ \to K^+\mu^+\mu^-)}{B(B^+ \to K^+e^+e^-)}}{\dfrac{B(B^+ \to K^+J/\psi(\to\mu^+\mu^-))}{B(B^+ \to K^+J/\psi(\to e^+e^-))}}$$



R_D measurement

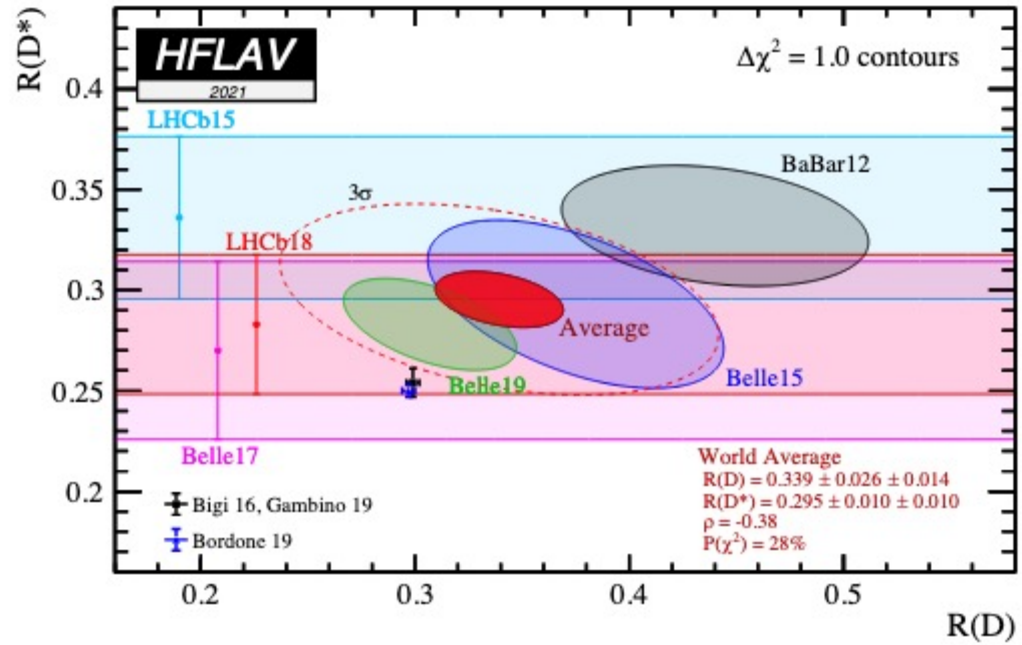
arXiv:1708.08856, arXiv:1711.02505, arXiv:1910.05864

$$b \to c\tau\nu$$

Test of τ/μ (τ/e) universality

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$

⇒ τ decays rates provide a powerful test of LFU



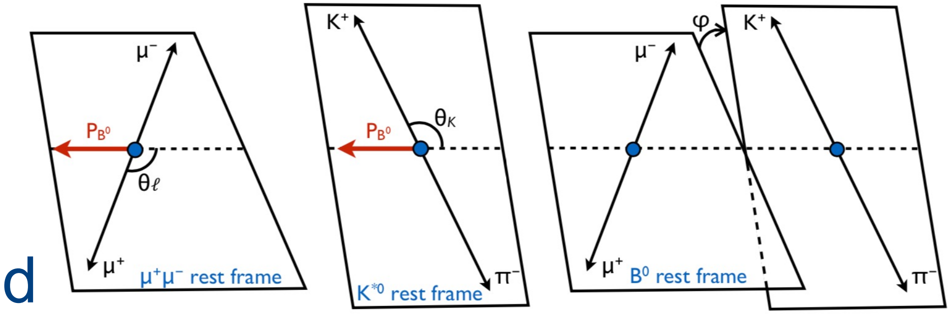
Observable	Experiment	SM
$\{R_D, R_{D^*}\}$	$\{0.337(30), 0.298(14)\}$ $\rho = -0.42$ [77]	$\{0.299(3), 0.258(5)\}$ [78]
$\mathcal{B}(B^- \to \tau\bar{\nu})$	$1.09(24) \times 10^{-4}$ [79]	$0.812(54) \times 10^{-4}$ [80]

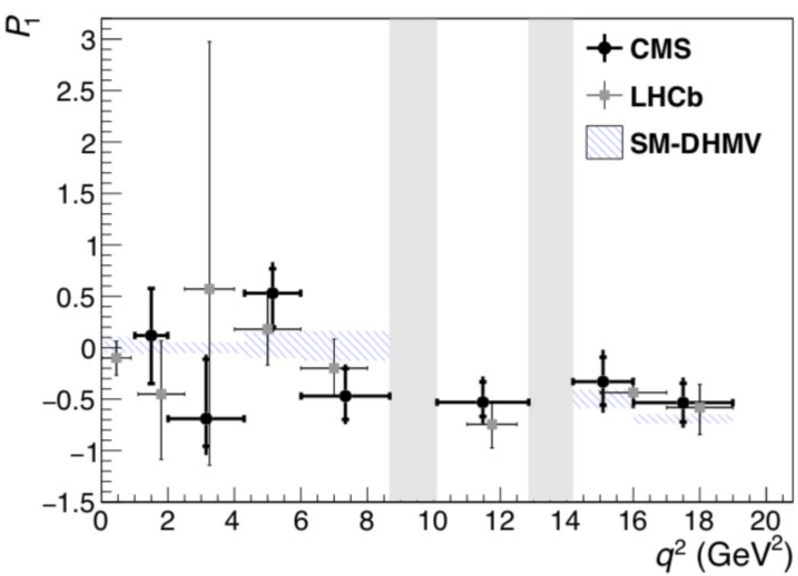
⇒ earlier measurements had a 4.1σ discrepancy. With the inclusion of new data, discrepancy comes down to 3.1σ

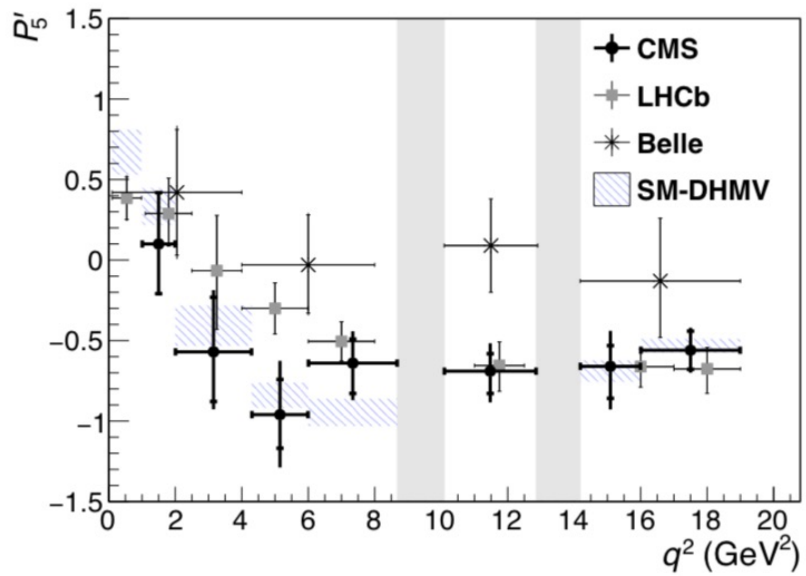
Angular distributions: B^0 decays

arXiv:1710.02846

- $B^0 \longrightarrow K^*\mu\mu$ decay as FCNC process
  - highly suppressed in SM
  - small theoretical uncertainties
- Angular analysis to determine P_1 and P'_5 parameters vs $\mu\mu$ invariant mass
- BSM effects may modify decay properties

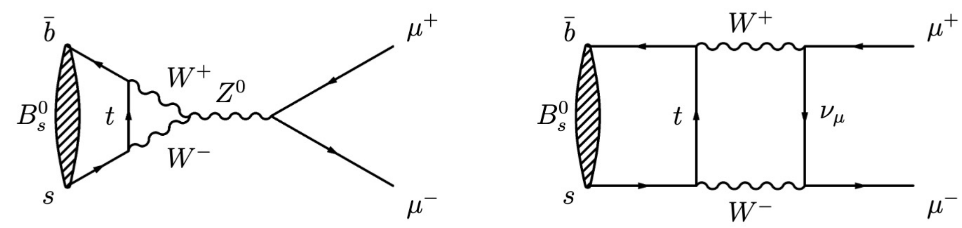






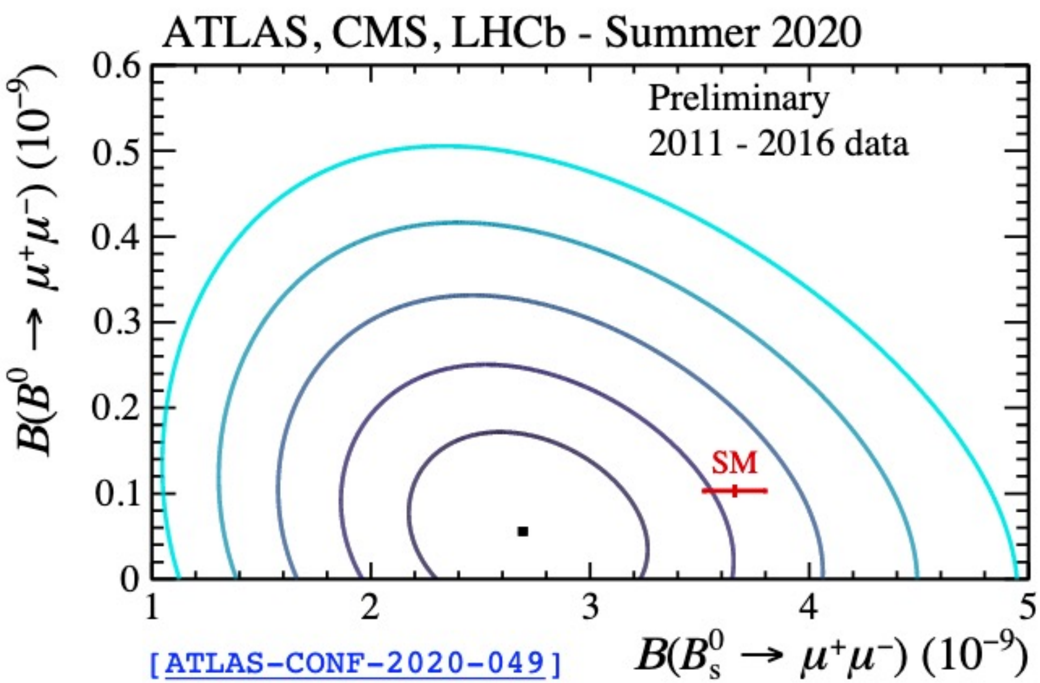
$B_s \longrightarrow \mu\mu$: experimental measurements

- SM predicts $B^0 \longrightarrow \mu\mu$ decays are very rare
- Differences wrt expectations could indicate NP



Combination of ATLAS, CMS and LHCb results

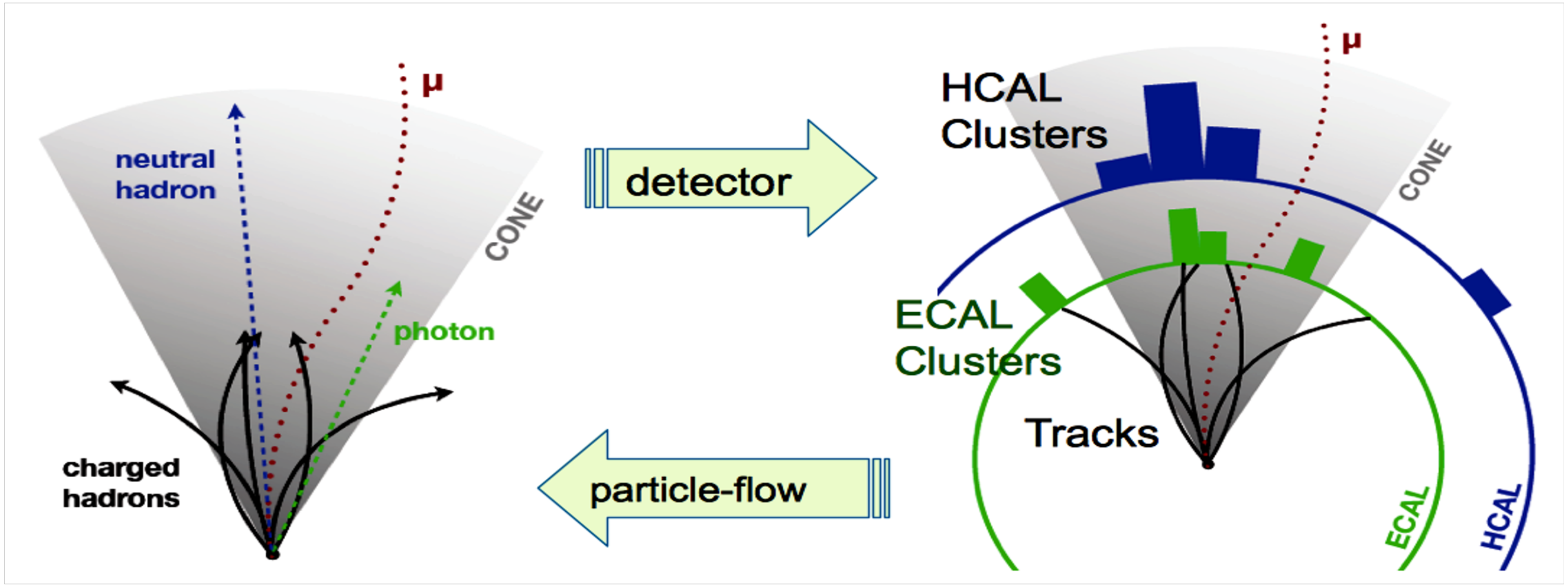
- $\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (2.69^{+0.37}_{-0.35}) \times 10^{-9}$
- 2.1σ away from the SM
- $\tau_{\mu^+\mu^-} = 1.91^{+0.37}_{-0.35}$ ps
- $\mathscr{B}(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10}$ (95 % CL



[ATLAS-CONF-2020-049]

Particle Flow event reconstruction

- Particle Flow (PF) combines information from all subdetectors to reconstruct particles produced in the collision
  - charged hadrons, neutral hadrons, photons, muons, electrons
  - use complementary info. from separate detectors to improve performance
  - tracks to improve calorimeter measurements
- From list of particles, can construct higher-level objects
  - Jets, b-jets, taus, isolated leptons and photons, MET, etc.

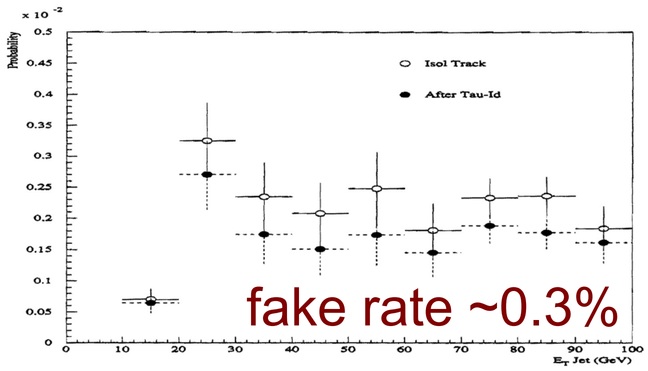


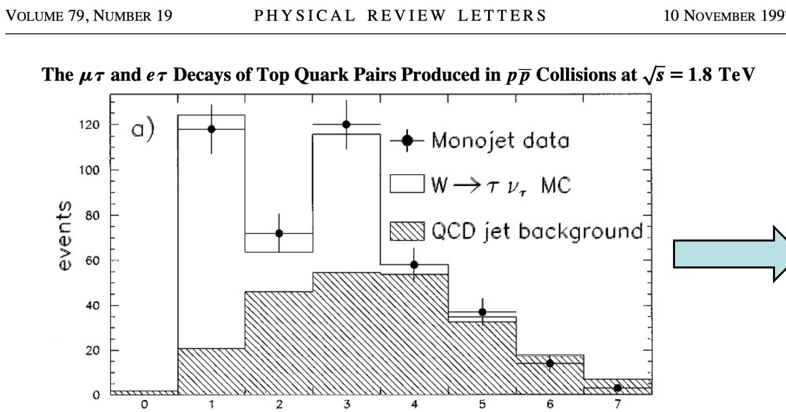
Tau lepton identification

JINST 12(2017)10

From first identification of hadronic tau decays to precise measurements

1997

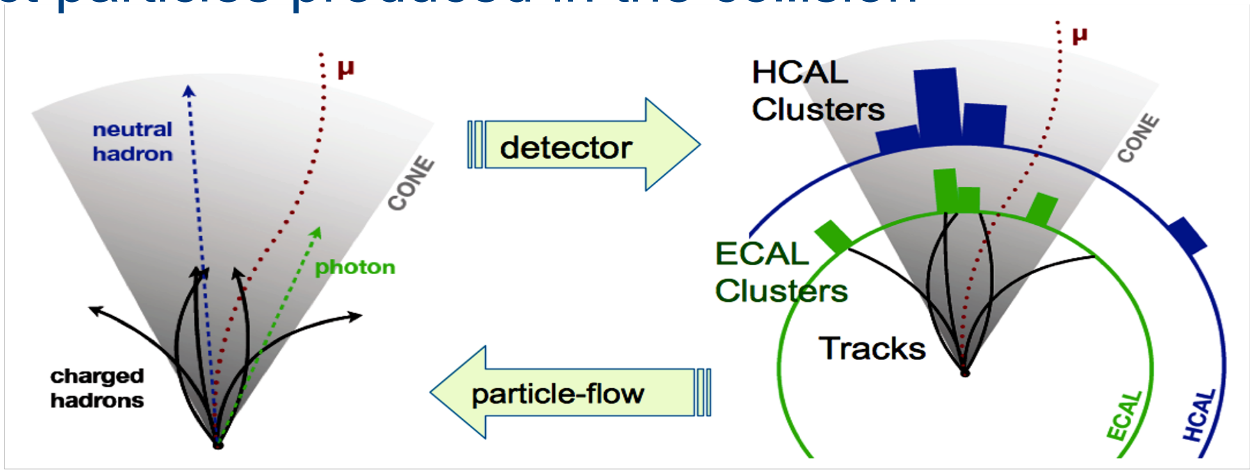




4 ttbar candidate events

2021

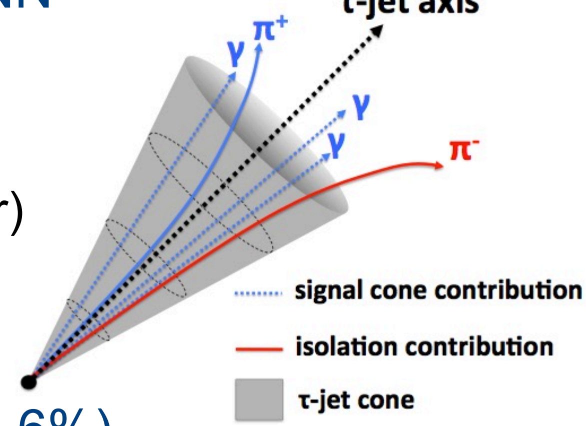
- Particle Flow (PF) combines information from all subdetectors to reconstruct particles produced in the collision

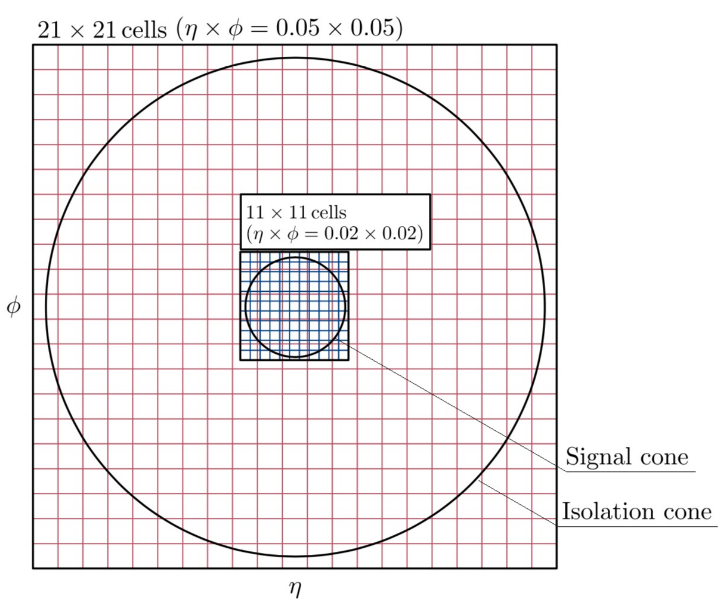


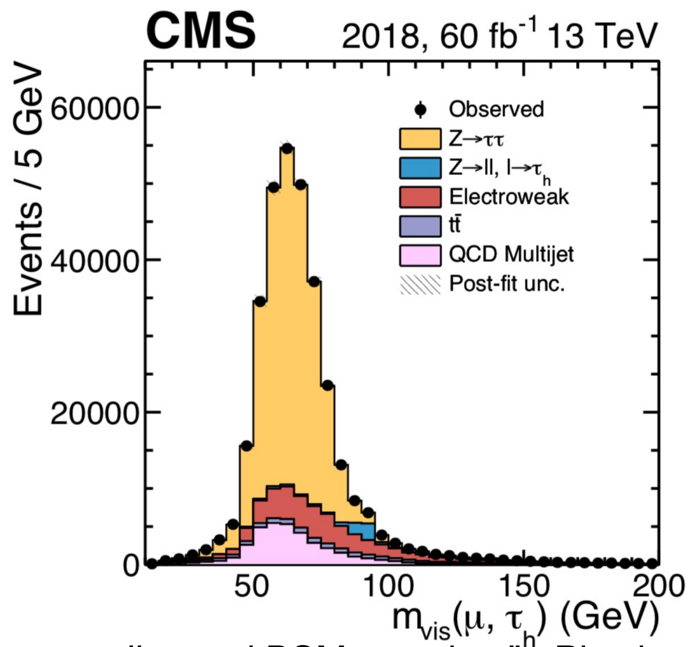
Tau lepton identification (cont.)

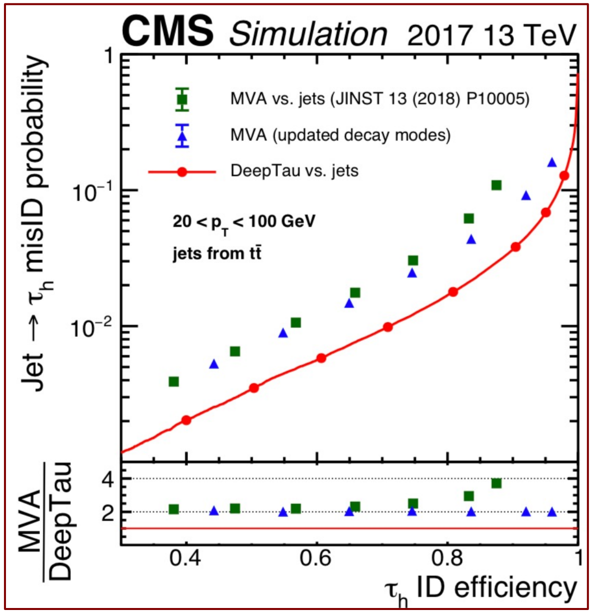
CMS-TAU-20-001

- Hadronic tau (τ_h) reconstruction and identification using a DNN
- Isolation cone and signal cone
  - narrow jet with few tracks
  - leptonic tau decays similar to prompt leptons (lepton p_T is softer)
  - inputs from all reconstructed particles near the tau candidate
- Validated with data
- The combined scale factor uncertainty amounts to ≈2% (was 6%)





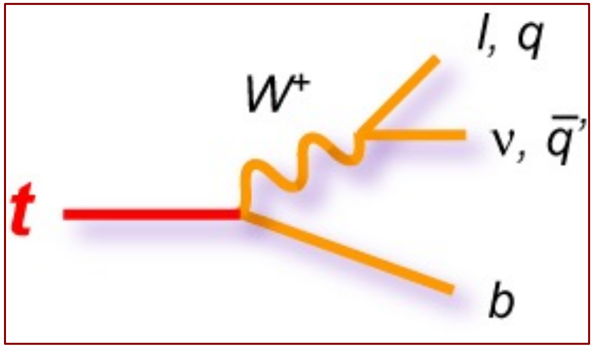




W branching fractions

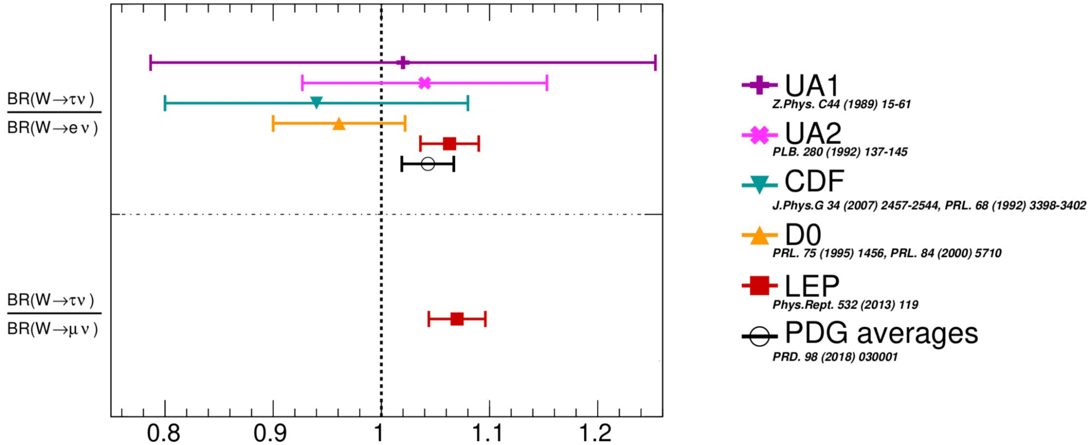
arXiv:2201.07861

- Precise measurement of the W boson BRs (electrons, muons, taus)



- Most precise determination of B(W⟶lν) from LEP has 2.6σ deviation from LFU

$$R_{\tau/\ell} = \frac{2\,\mathcal{B}(\mathrm{W} \to \tau\overline{\nu}_\tau)}{\mathcal{B}(\mathrm{W} \to \mathrm{e}\overline{\nu}_\mathrm{e}) + \mathcal{B}(\mathrm{W} \to \mu\overline{\nu}_\mu)} = 1.066 \pm 0.025$$

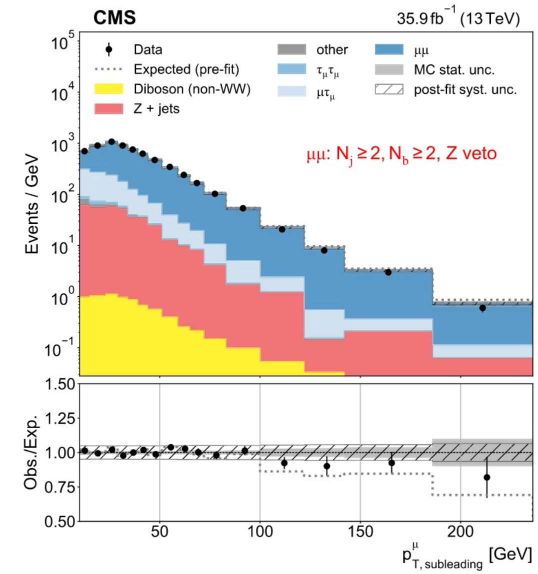


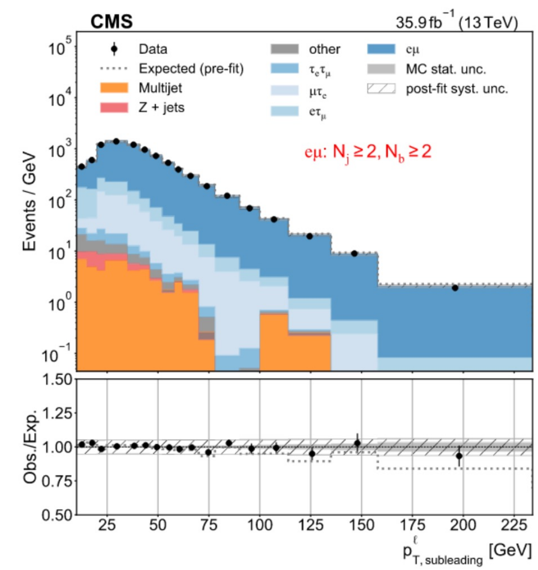
W branching fractions (cont.)

arXiv:2007.14040, arXiv:2201.07861

- Precise measurement of the W boson BRs (electrons, muons, taus)
  - use events with WW and W+jets
  - exploit p_T to distinguish prompt leptons and leptons from τ decays
  - Maximum likelihood simultaneous fitting of templates to data in several categories
- Hadronic width of the W boson depends on several free parameters
- Extract V_{cs} and $\alpha_S(m_W^2)$

$$\frac{\mathcal{B}(\mathrm{W} \to \mathrm{h})}{1 - \mathcal{B}(\mathrm{W} \to \mathrm{h})} = \left(1 + \frac{\alpha_S(m_W^2)}{\pi}\right) \sum_{\substack{i=(u,c),\\ j=(d,s,b)}} |V_{ij}{}^2| = 2.060 \pm 0.021$$





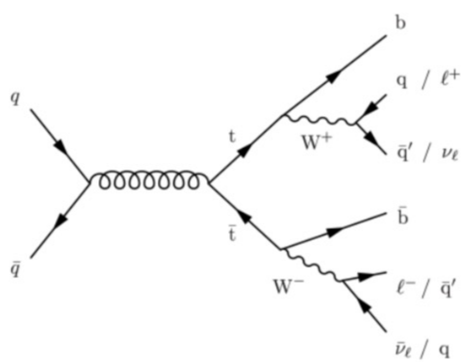
W branching fractions (cont.)

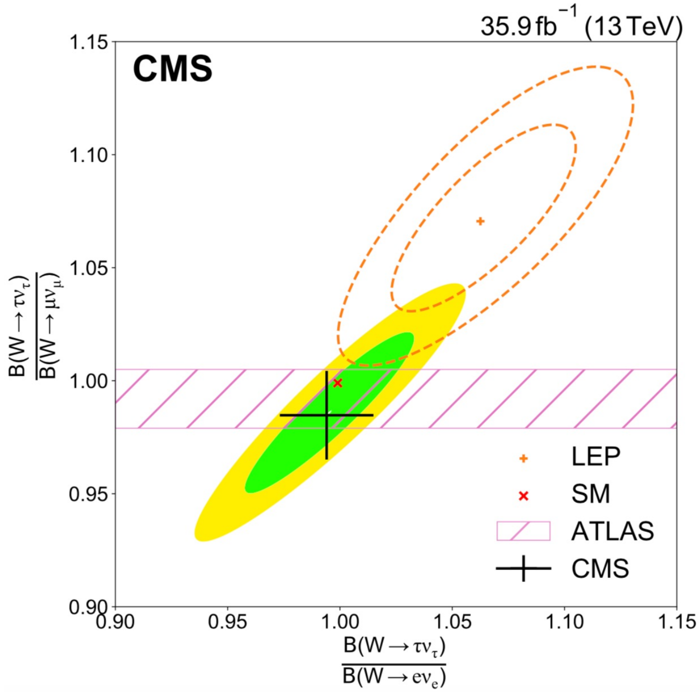
arXiv:2007.14040, CMS-SMP-18-011

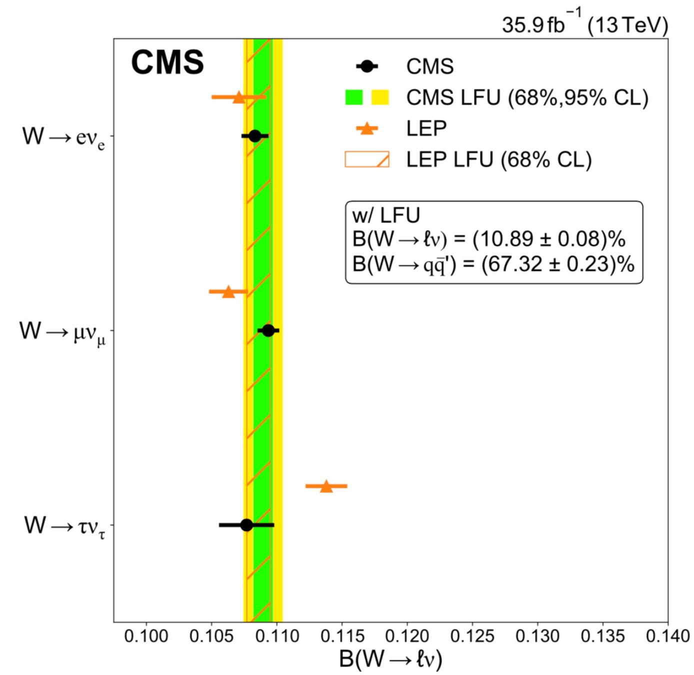
Resolving an old discrepancy from LEP

- Many more Ws than at LEP
- Extract V_{cs} and $\alpha_S(m_W^2)$

	CMS	LEP
$\mathcal{B}(W \to e\overline{\nu}_e)$	$(10.83 \pm 0.01 \pm 0.10)\%$	$(10.71 \pm 0.14 \pm 0.07)\ \%$
$\mathcal{B}(W \to \mu\overline{\nu}_\mu)$	$(10.94 \pm 0.01 \pm 0.08)\%$	$(10.63 \pm 0.13 \pm 0.07)\ \%$
$\mathcal{B}(W \to \tau\overline{\nu}_\tau)$	$(10.77 \pm 0.05 \pm 0.21)\%$	$(11.38 \pm 0.17 \pm 0.11)\ \%$
$\mathcal{B}(W \to h)$	$(67.46 \pm 0.04 \pm 0.28)\%$	–
with LU		
$\mathcal{B}(W \to \ell\overline{\nu})$	$(10.89 \pm 0.01 \pm 0.08)\%$	$(10.86 \pm 0.06 \pm 0.09)\%$
$\mathcal{B}(W \to h)$	$(67.32 \pm 0.02 \pm 0.23)\%$	$(67.41 \pm 0.18 \pm 0.20)\%$







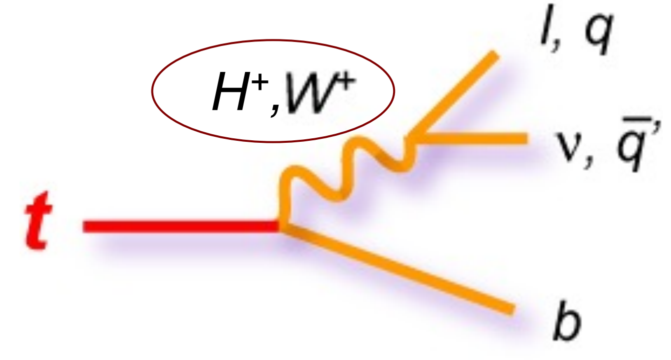
Probing the Wtb vertex

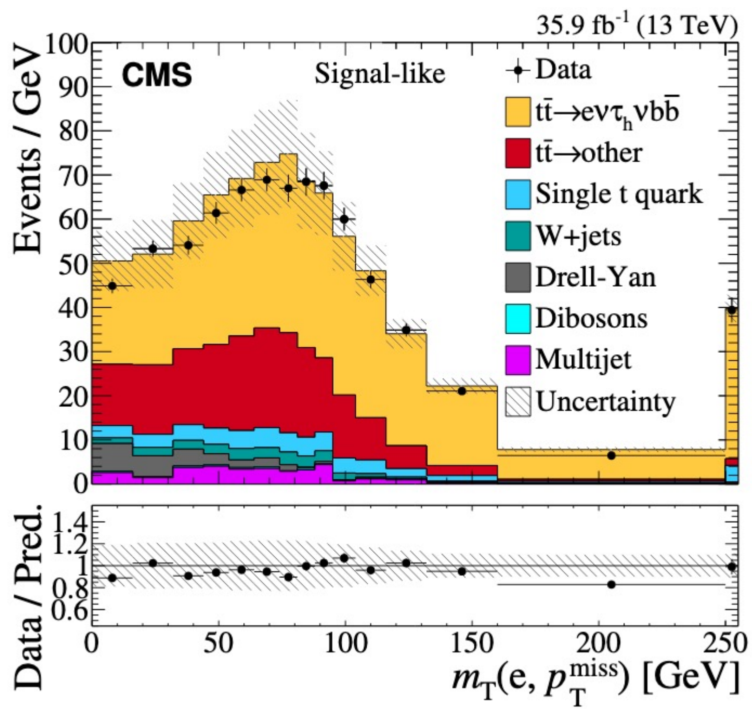
JHEP 02(2020)191

Dileptons with taus

- cross section measurement including τs
- Includes only 3[rd] generation quarks/leptons
- Syst unc: tauId, fakes

Channel	Signature	BR
Dilepton(e/μ)	$ee,\mu\mu,e\mu$ + 2b-jets	4/81
Single lepton	e,μ + jets + 2b-jets	24/81
All-hadronic	jets + 2b-jets	36/81
Tau dilepton	$e\tau$, $\mu\tau$ +2 b-jets	4/81
Tau+jets	τ + jets + 2b-jets	12/81





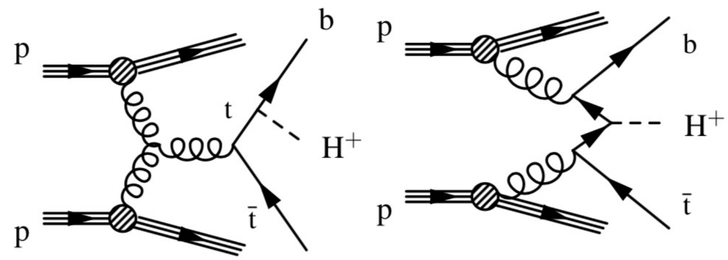
- If top quark plays special role in EWK symmetry breaking, couplings to W may change
- Charged Higgs may alter coupling to W
- Search for final states with taus: charged Higgs

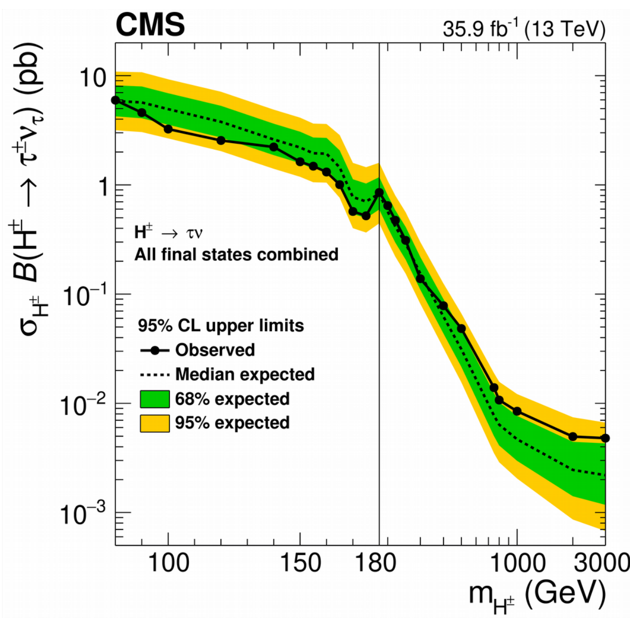
Charged Higgs: $H^+ \to \tau\nu$

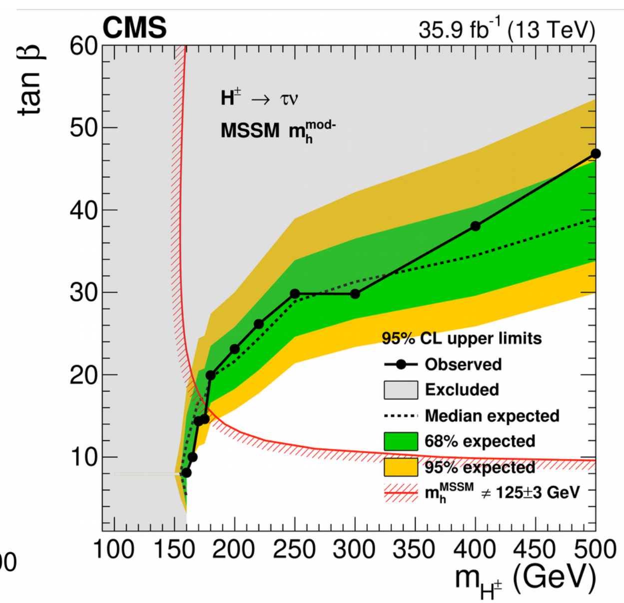
arXiv:1903.04560

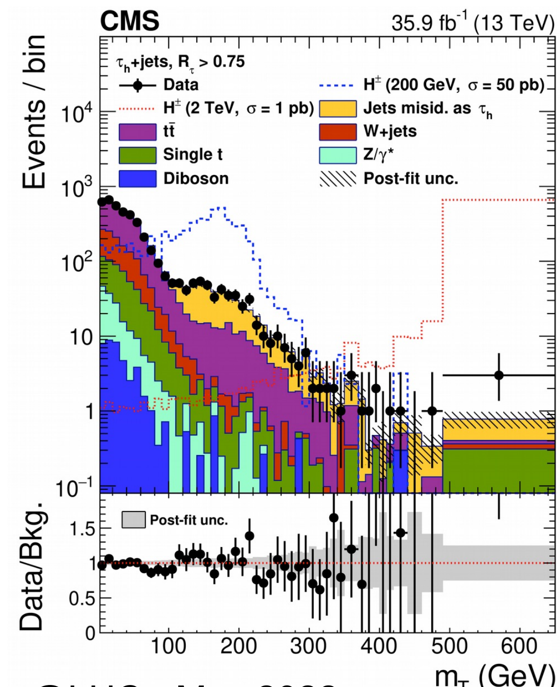
MSSM: coupling to taus large for high tanβ

- Production mechanism depends on H^+ mass
  - Final states: τ+jets, ℓ+τ, ℓ+0τ
  - 36 categories: incl. #jets, polarization $R = p_T(\mathrm{tk})/p_T(\mathrm{tau})$
- Cross section limits: 6pb to 5fb (80-3000 GeV)





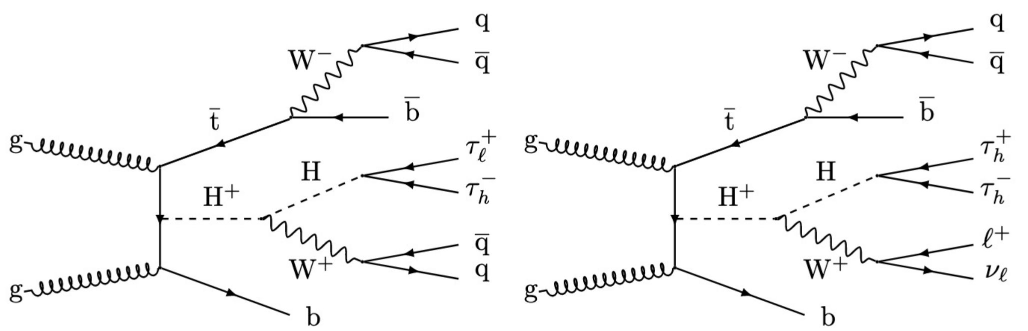


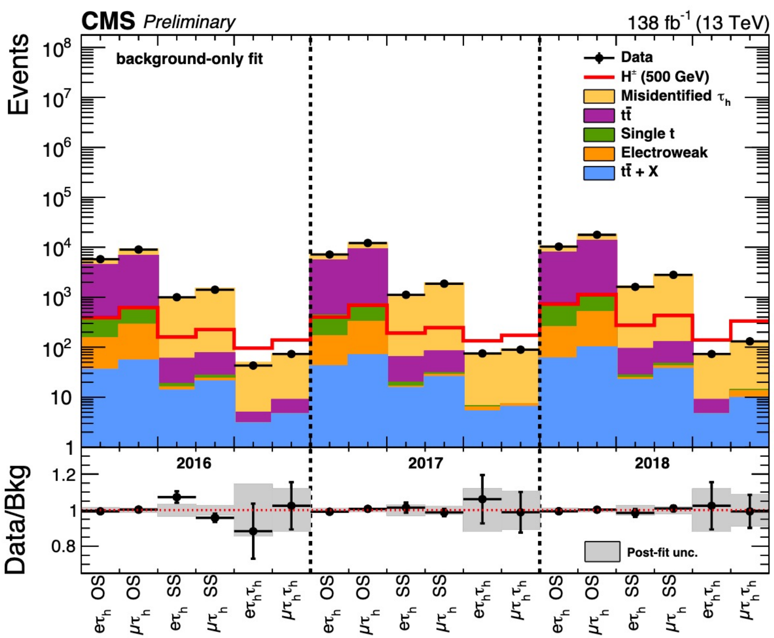


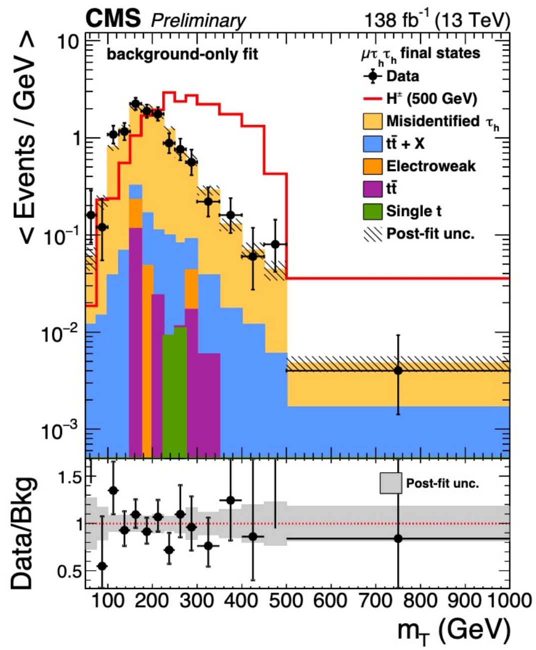
Charged Higgs: $H^+ \to tb$ (cont.)

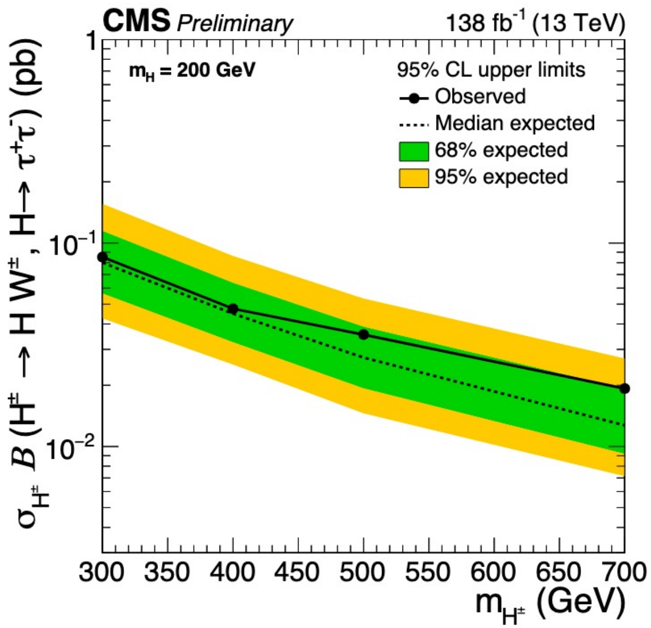
CMS-HIG-21-010

- Search for a $H^\pm$ decaying to a heavy neutral Higgs boson H and a W
- data consistent with SM expectations
- Set limits:
  - $H^\pm$ in the mass range 300-700GeV, assuming m_H=200 GeV
  - Cross-section limit from 0.08pb@300GeV to 0.013pb @700GeV





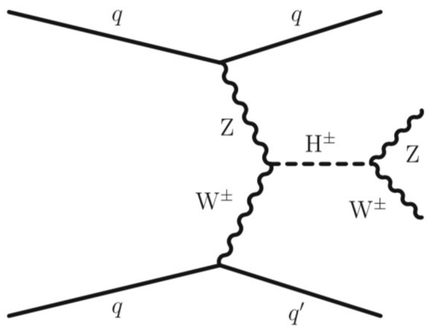


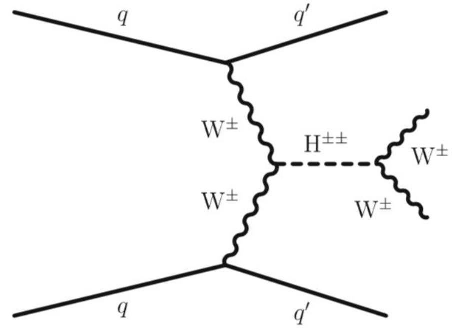


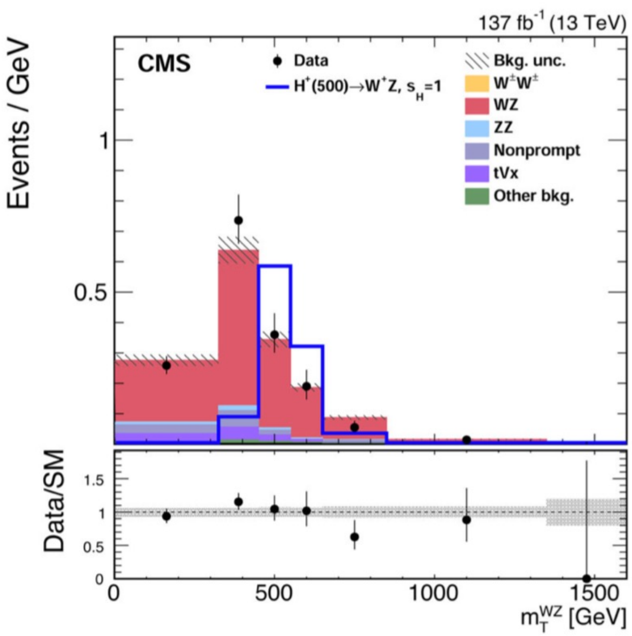
Charged Higgs: VBF

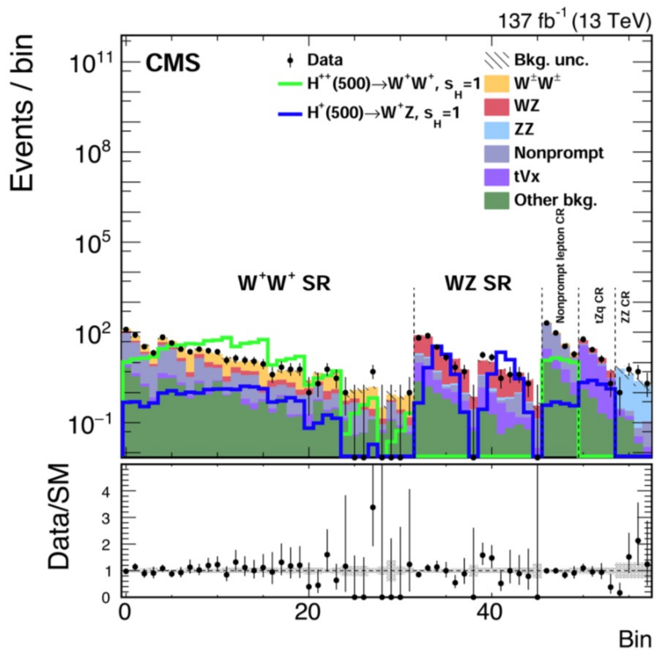
EPJC 81(2021)723

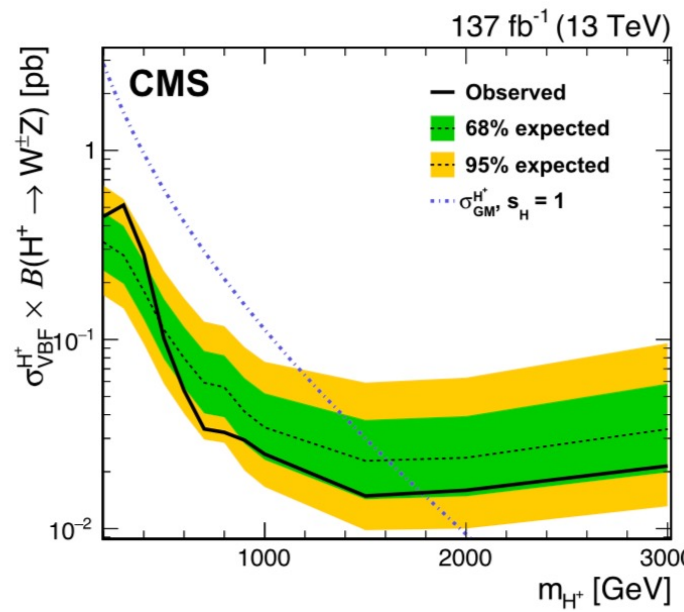
- Search for H^+ bosons produced in VBF processes
- Use leptonic final states (e,μ)
- Combination of methods based on simulation and CRs in data used to estimate backgrounds
- Set constraints on $H^{\pm}$ and H^{++} production









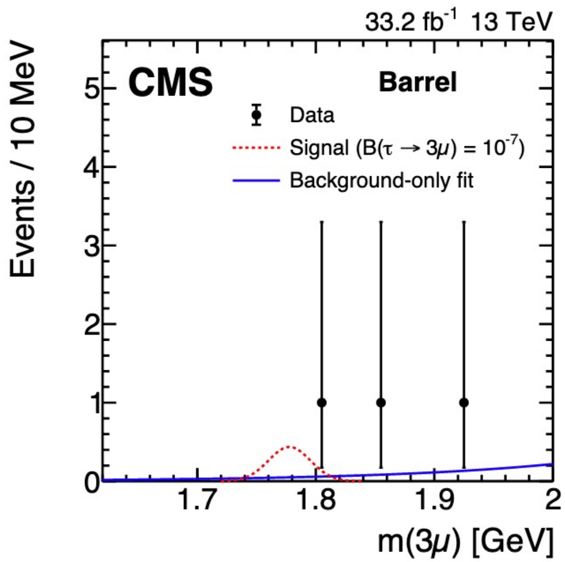


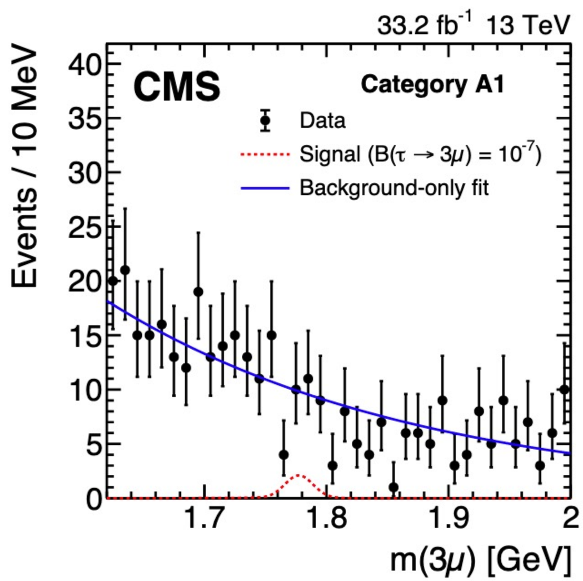
Rare decays: $\tau \to 3\mu$

JHEP 01(2021)163

- LFV processes can occur via neutrino mixing
- Lepton flavour violating decay: $\tau \to 3\mu$
  - Very rare process, BR~10^{-10}–10^{-8}
  - World's best limit: 2.1×10^{-8} (Belle)
- Search performed in 2016 data
  - Tau leptons produced in W and HF hadron decays
  - 2/3 low-p_T muons trigger
  - Select 3μ candidates
  - BDT for signal (MC) & bkg (sidebands) separation
- No evidence for a $\tau \to 3\mu$ decay signal found
- Set upper limit:

$$\boxed{\mathcal{B}(\tau \to 3\mu) < 8.0(6.9) \times 10^{-8}}$$

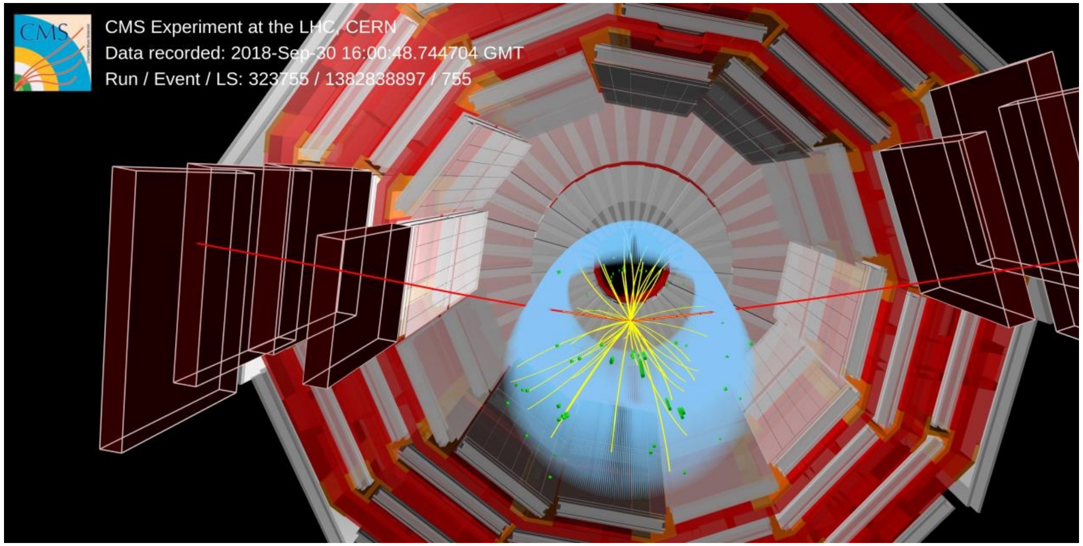


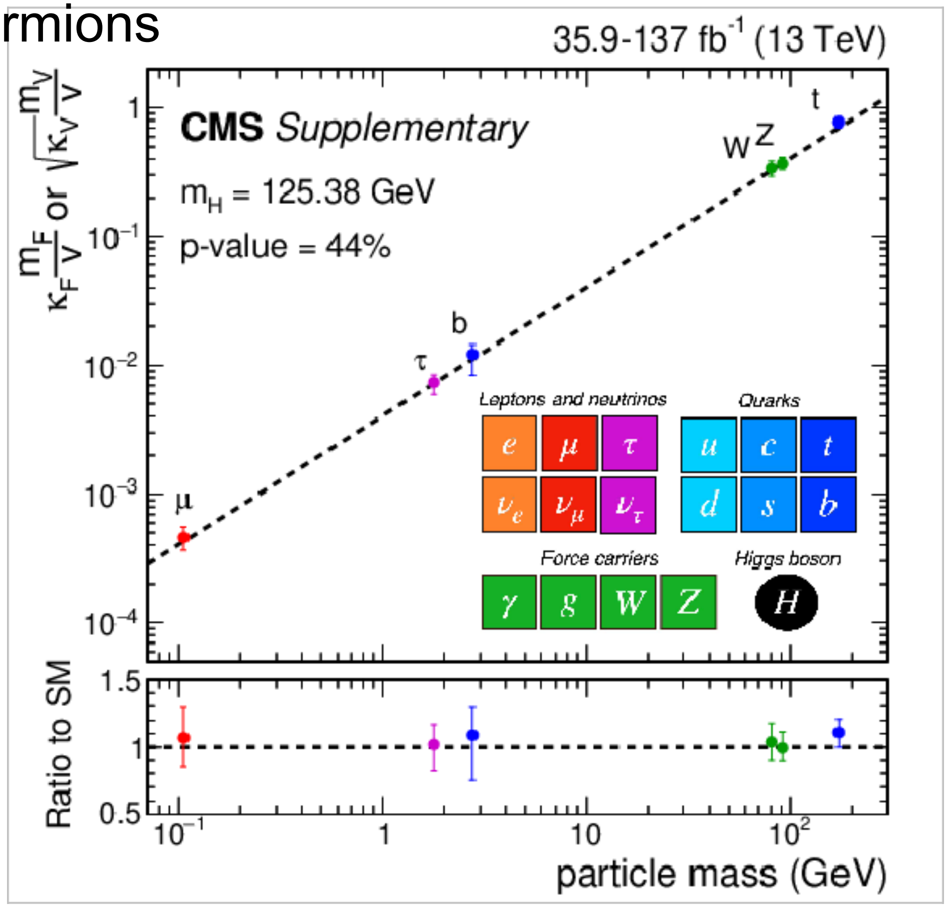


Higgs boson couplings

JHEP 01(2021)148

- Higgs boson coupling to fermions and quarks
  - First evidence of coupling to 2nd gen fermions





- Signal strength wrt SM:

$$\hat{\mu} = 1.19\ ^{+0.41}_{-0.40}\ (\text{stat})^{+0.17}_{-0.16}\ (\text{syst})$$

- obs.(exp.) significance: 3.0(2.5)σ

⇒ couplings in agreement w/SM

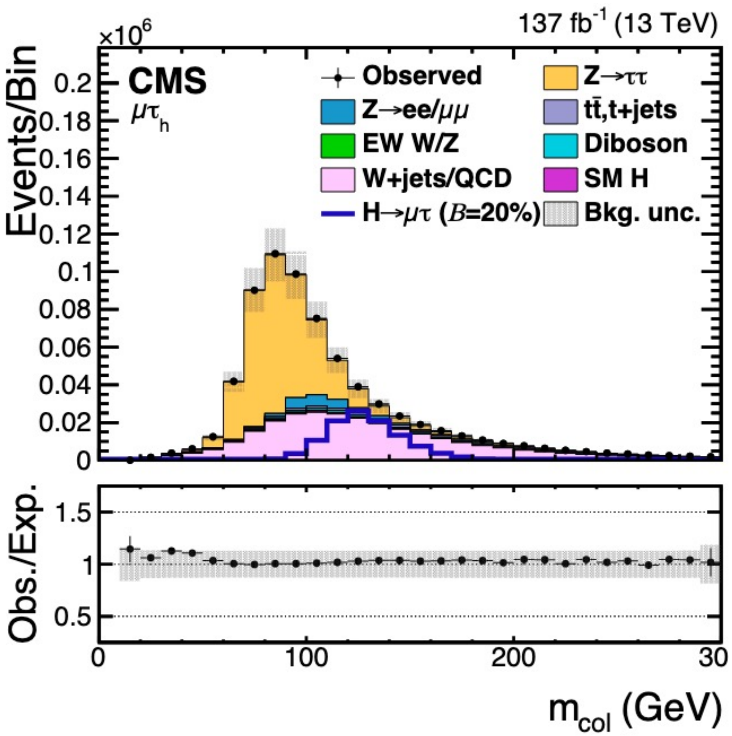
LFV in Higgs decays

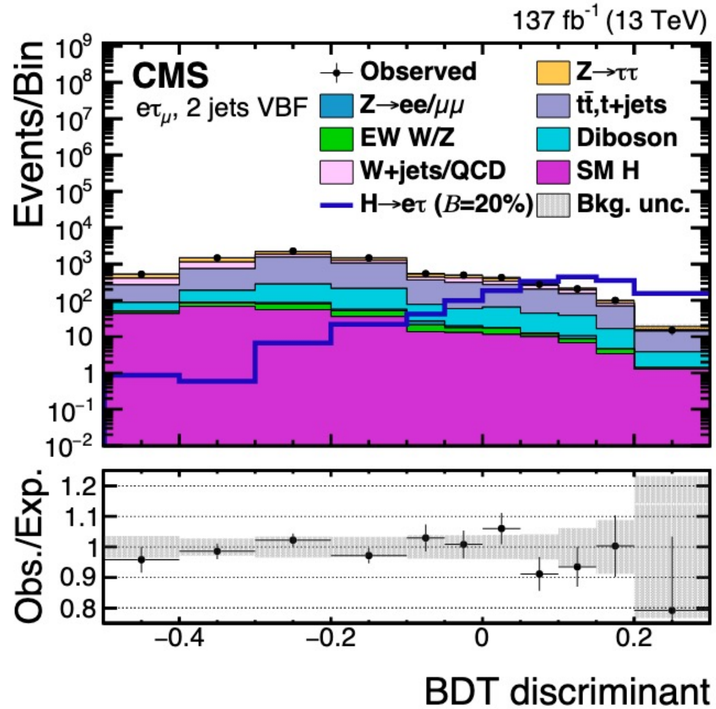
arXiv:1911.10267, arXiv:2105.03007

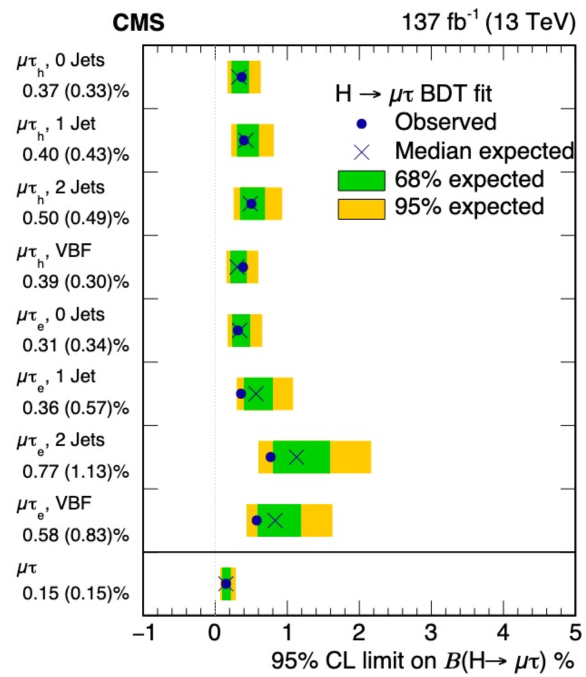
- Some BSM models allow for LFV Higgs decays
- Search for H→eτ, eμ, μτ final states
- Categories: N_{jet}, lepton kinematics
  - N_{jet} to target ggH and VBF production
- Main background from DY, ttbar, WW

	Observed (expected) upper limits (%)	Best fit branching fractions (%)	Yukawa coupling constraints
$H \to \mu\tau$	<0.15 (0.15)	0.00 ± 0.07	$< 1.11\,(1.10) \times 10^{-3}$
$H \to e\tau$	<0.22 (0.16)	0.08 ± 0.08	$< 1.35\,(1.14) \times 10^{-3}$

⇒ No significant deviation found



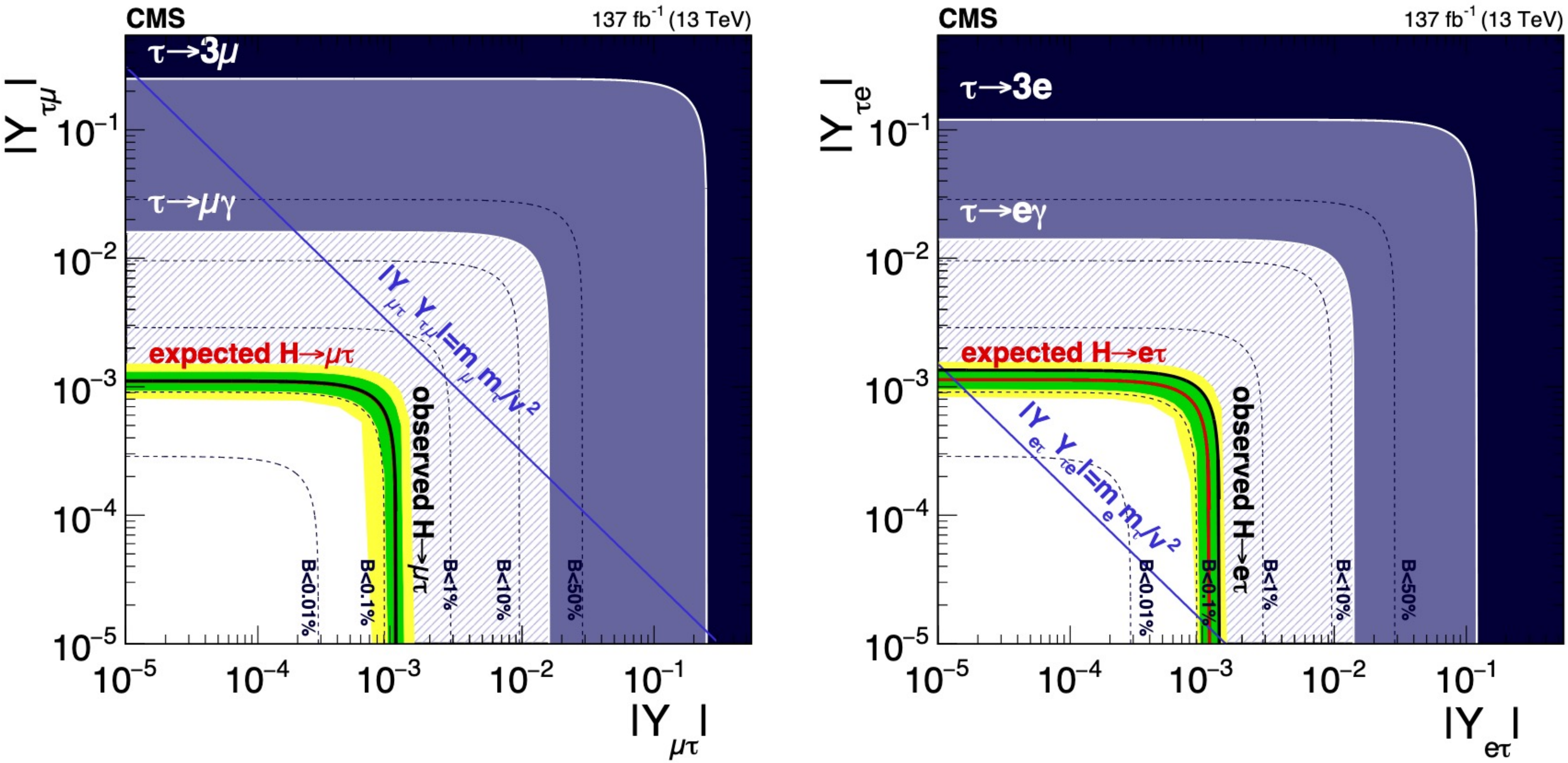




LFV decays - constraints

arXiv:1911.10267, arXiv:2105.03007

Limits set on off-diagonal Yukawa coupling terms



SUSY ?

arXiv:2106.14246, CMS-SUS-21-001, JHEP02(2020)015

Several tests in SUSY related searches

- Study final states with leptons in final states
- Different couplings may enhance specific flavour production

Search for chargino-neutralino production

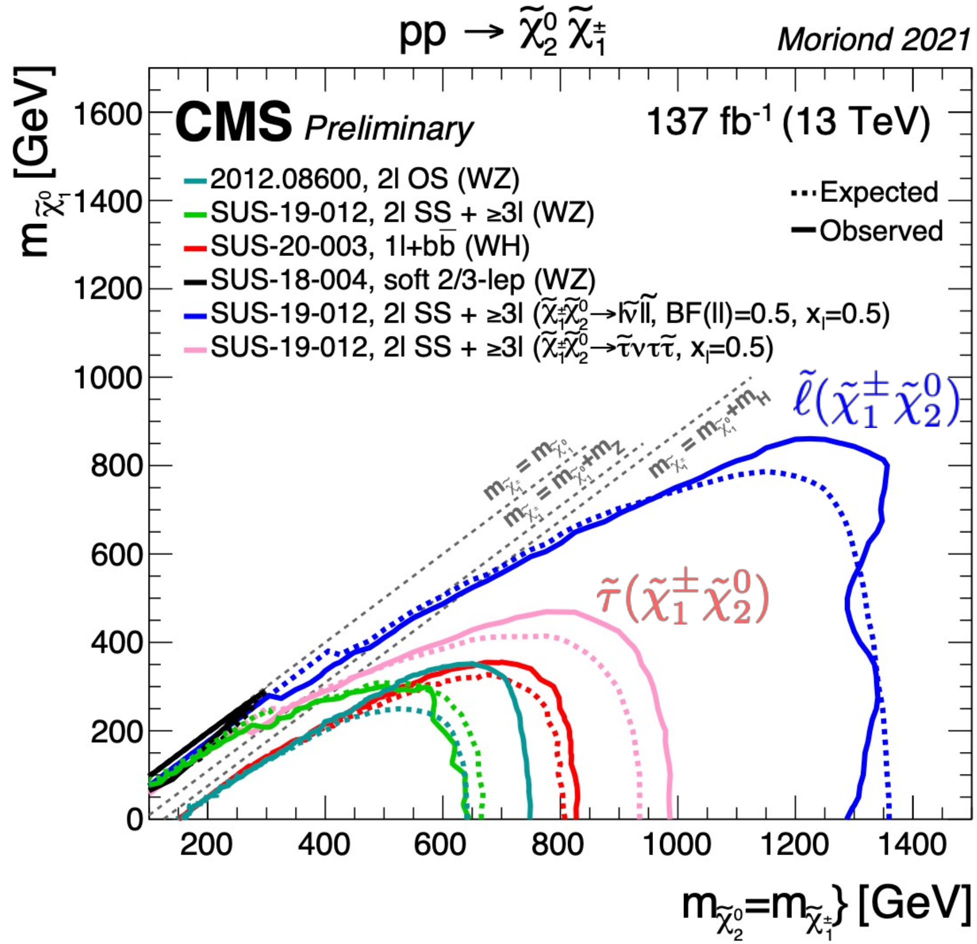
- Flavour-democratic scenario: chargino-neutralino mediated by LH-sleptons
- τ-enriched-scenario: chargino couples to RH sleptons, neutralino to LH sleptons

Stau lepton

- Early universe stau-neutralino coannihilation provides mechanism explaining DM relic density motivates stau as NLSP leading enhancement of τ leptons in final state

Top squark in ditau final state

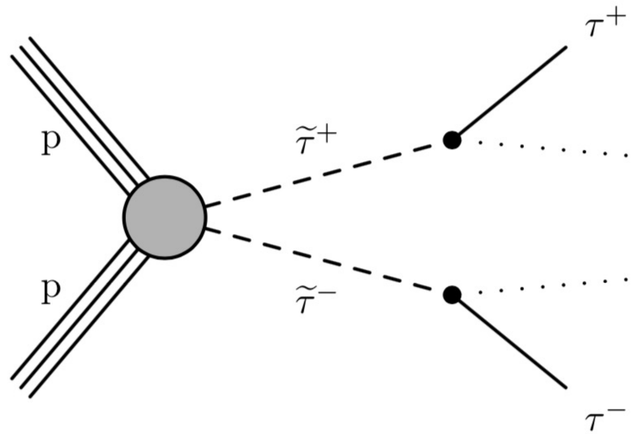
- High-tanβ and higgsino-like scenario, the chargino mostly decays to τ leptons

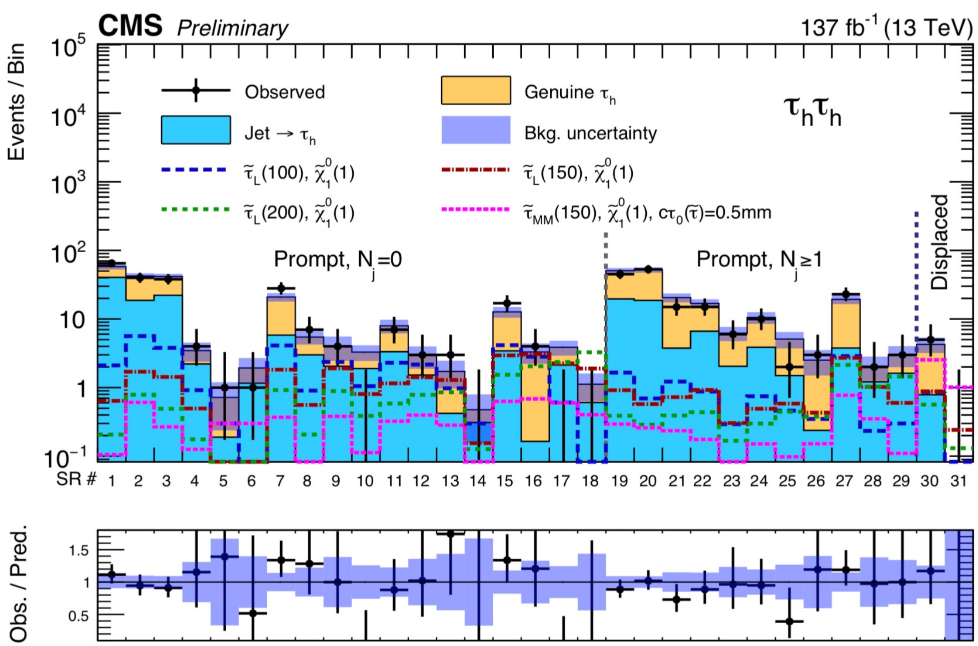


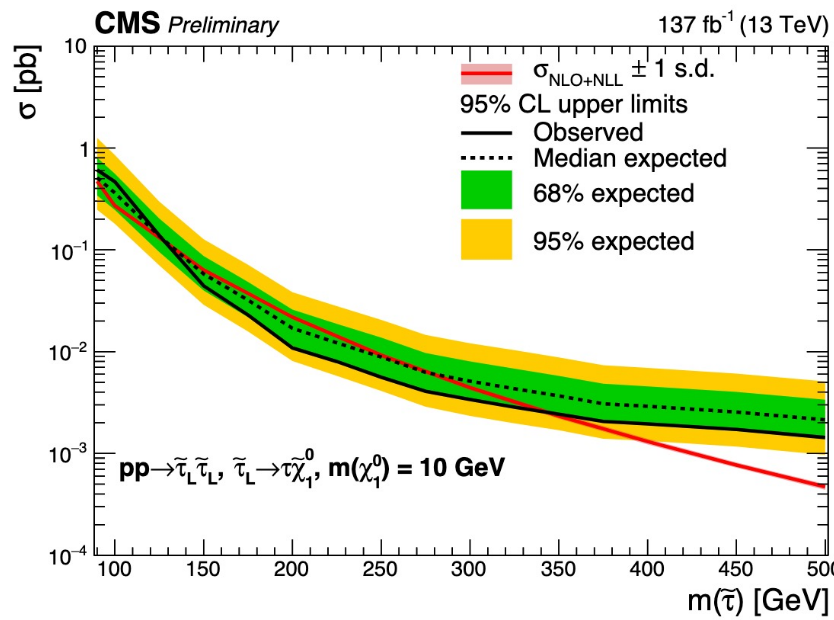
RPV SUSY

CMS-SUS-21-001

- Direct production of τ slepton pairs
- Prompt and long-lived tau pairs



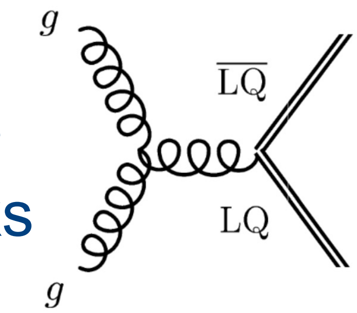


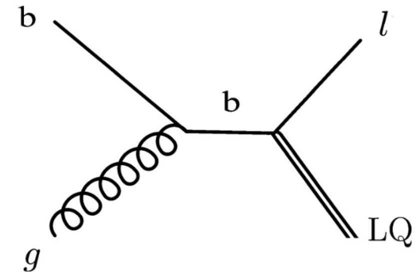


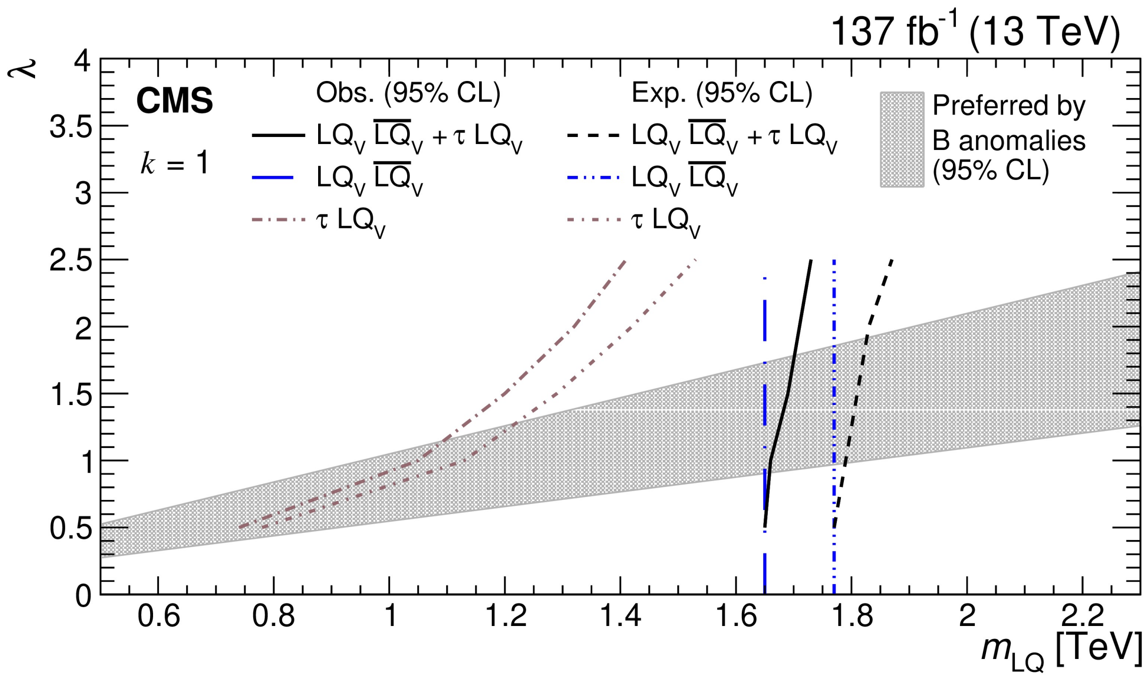
Leptoquarks

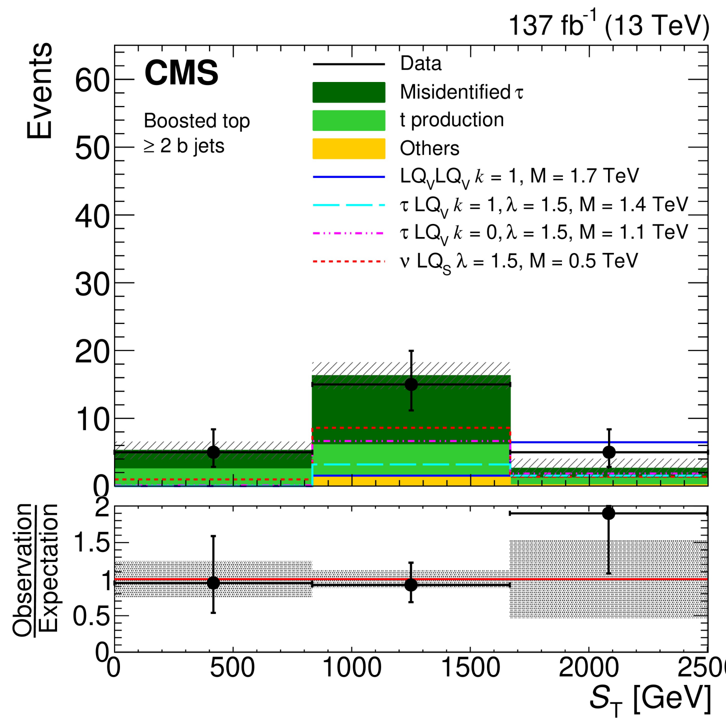
PLB 819(2020)136446

- Why are matter particles separated?
- LQs possible explanation to LU anomalies
- LQs as missing link btw leptons and quarks
- LQs favor couplings to heavy fermions







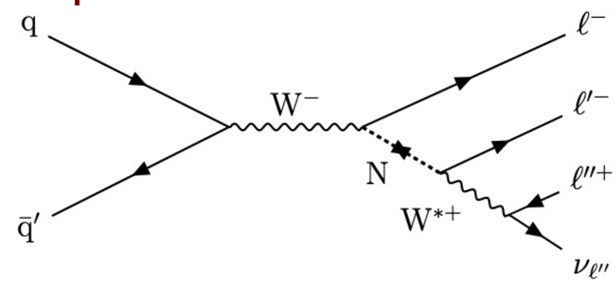


Long-lived heavy neutral leptons

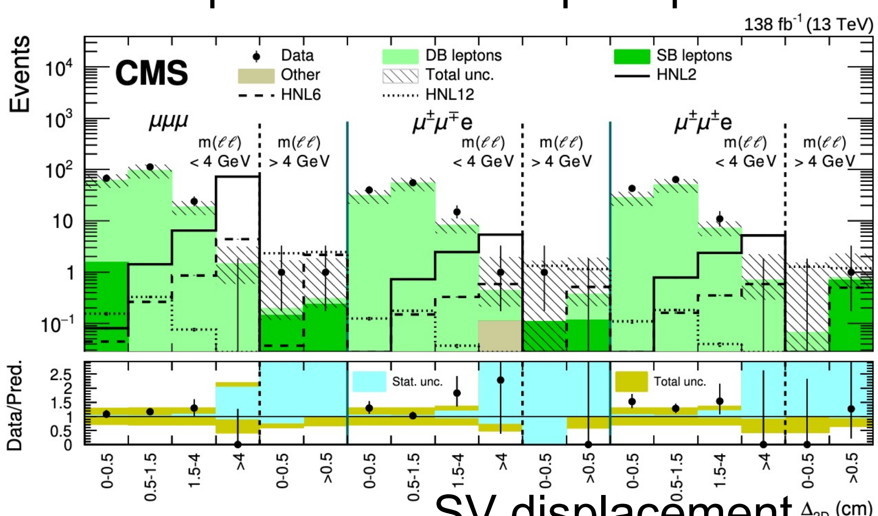
arXiv:2201.05578, CMS-EXO-21-003

- Neutrino masses are small wrt SM fermions
  - HNL produced through mixing with SM neutrinos
- Stable HNLs could be DM candidates
  - Produced in mixing of SM (e,μ,τ) neutrinos
- HNL may be long-lived
  - for small values of HNL mass (<20 GeV) and HNL-SM neutrino mixing parameter
- Search for 3-lepton events (e, μ)
  - 2 with displaced vertex+1 prompt

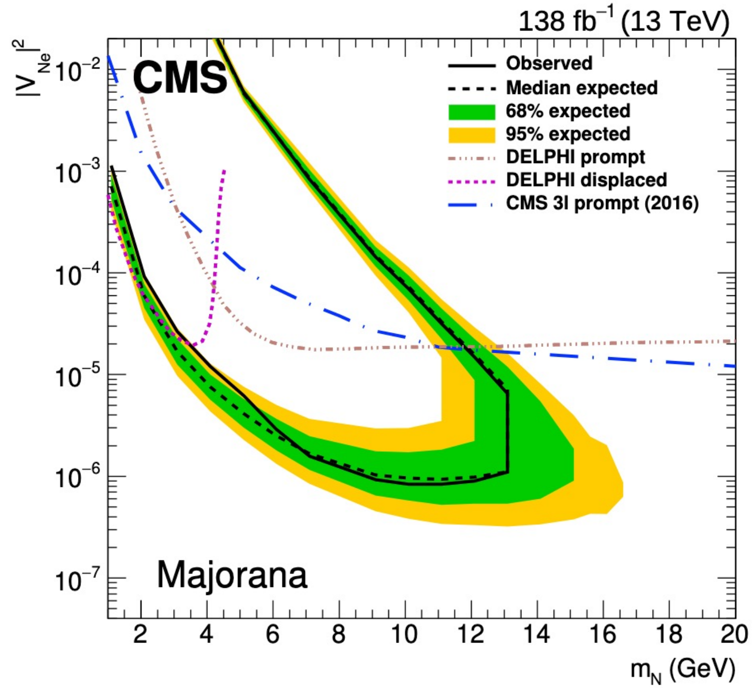
Lepton Flavor Violation?



Dirac vs Majorana particles



SV displacement

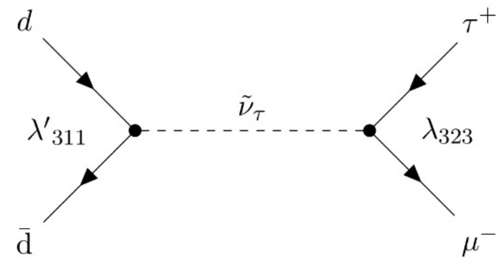


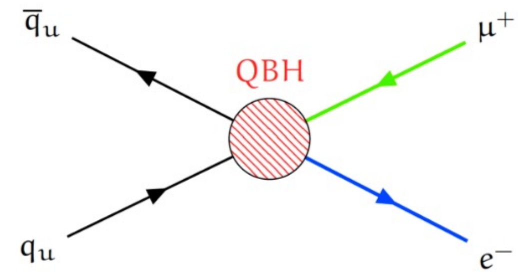
Mixing vs HNL mass

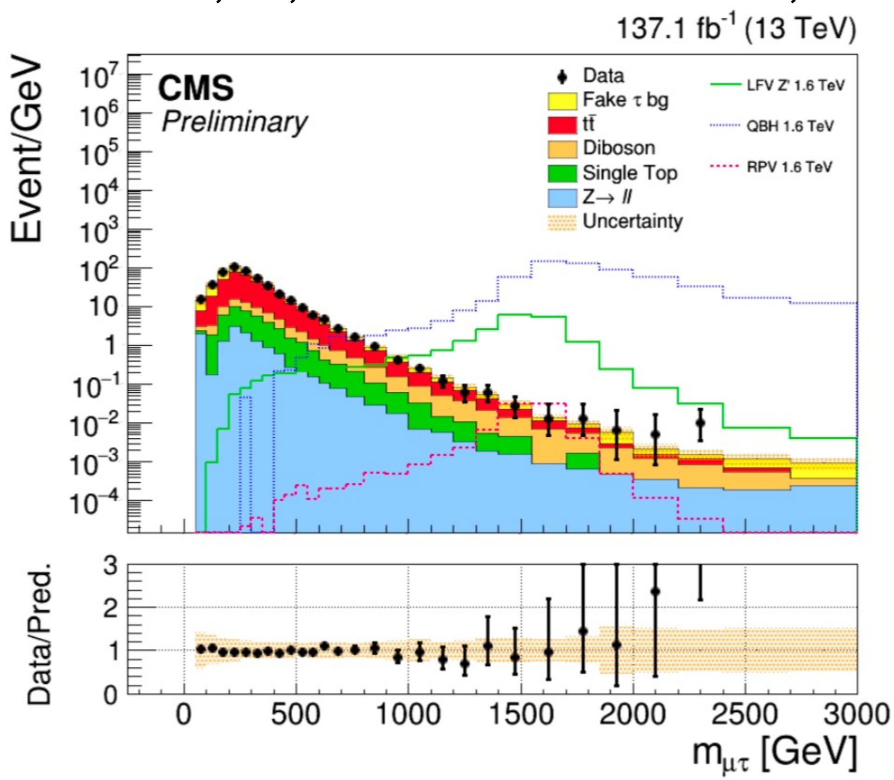
Heavy resonances & QBHs

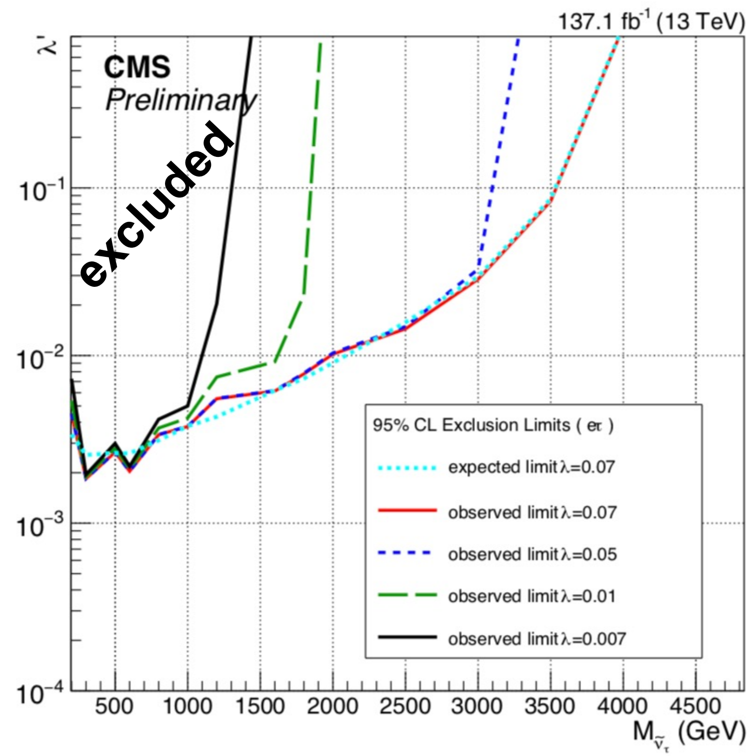
CMS-EXO-19-014

- Search for resonances and quantum black holes
  - Decays: eμ, eτ, μτ
  - Different models include RPV SUSY, Z', non-resonant QBHs, etc.









Summary

- Lepton Flavour Universality principle can be probed at LHC
- Several tests performed: rare decays, W boson, Top quark, Higgs boson, BSM searches, etc
- Current results indicate tension of LFU with SM

- Improvements towards precision measurements
- Plenty of data: 137 $fb^{-1} \rightarrow$ 300 $fb^{-1} \rightarrow$ 3000 fb^{-1}
- LHC Run3 is about to start soon (2022+)
- HL-LHC a few years away (2029+) with improved detectors

Simplicity if the essence of universality – M. Gandhi

backup

B-physics parked data sample

- As luminosity drops, turn on various seeds to keep L1 rate constant, increase HLT rate towards end of fill, tune thresholds
- Stored ~10^{10} Bs on disk in 2018
- Trigger strategy optimized to maximize # of B hadrons
- Significantly enhances B-physics potential in CMS and be competitive in several measurements not possible before
- Unique opportunity to test several flavour anomalies