Lepton Universality Tests and Searches for Charged Lepton Flavor Violation with the CMS Experiment

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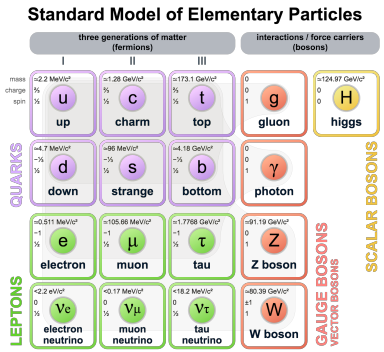
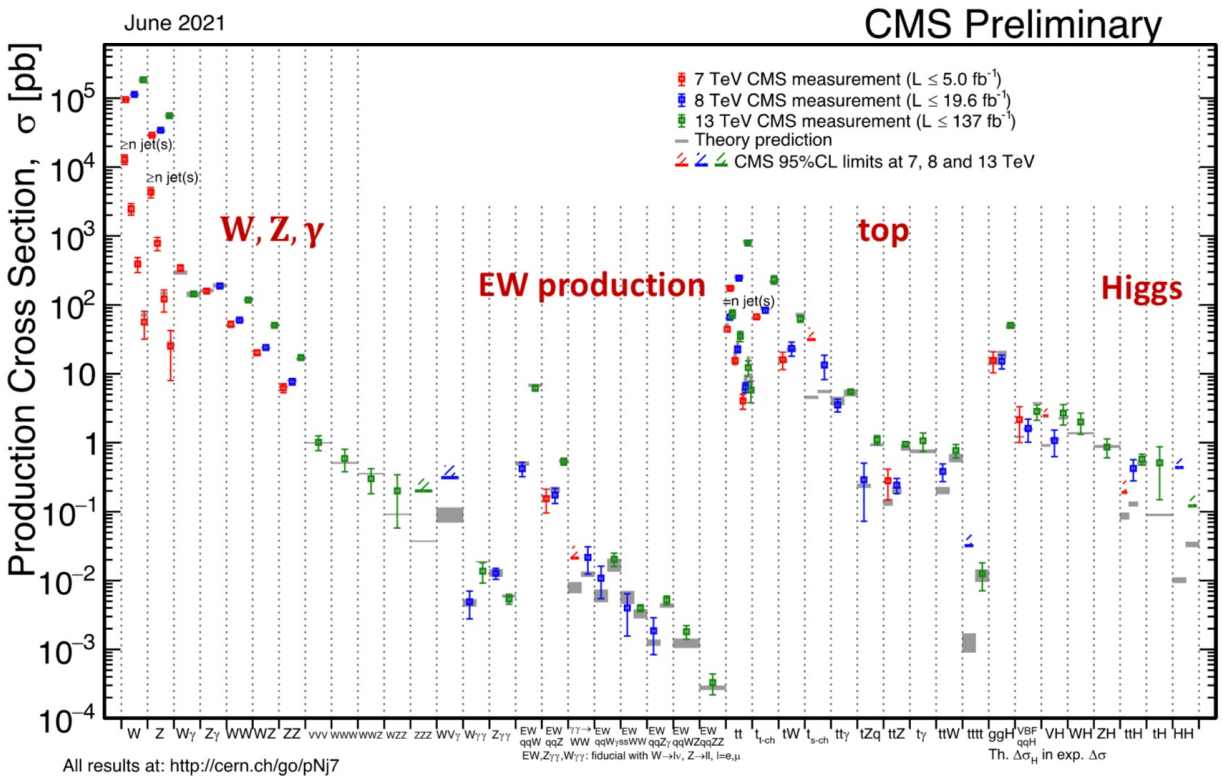
- ✓ Introduction
- ✓ Particle reconstruction and tau leptons
- ✓ SM: W, Top and Higgs boson
- ✓ BSM searches and rare decays

SM confirmed by the data…so far

- Good agreement over 10 orders of magnitude
- Rare processes, EFT interpretations, theory calculations





Despite its success, the SM has unresolved problems (hyerarchy problem, ν masses, DM, dark energy, etc.)

Lepton Flavour Universality

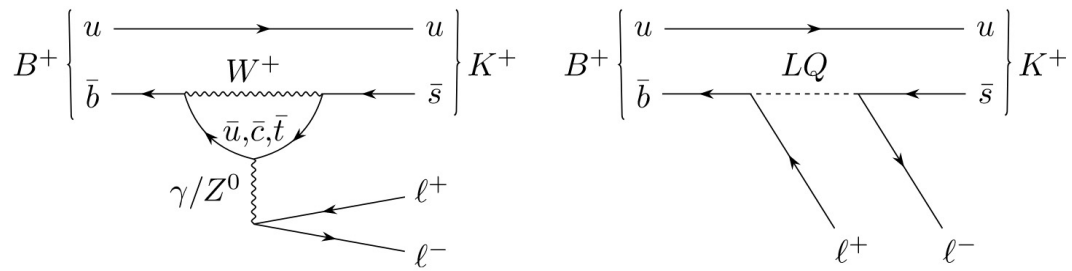
- Theory predicts that the different charged leptons - the electron, muon and tau - have identical electroweak interaction strengths
- Measurements have shown a wide range of particle decays are consistent with lepton universality
- “lepton universality” is a principle taken for granted put under stress by recent measurements
- Very active field in light of flavour anomalies
  - LFU involving e/μ/τ ratios, etc.

Flavor anomalies

arXiv:2103.11769, arXiv:2103.16558, PRL 126(2021)14801

Recent hints for breaking of LFU

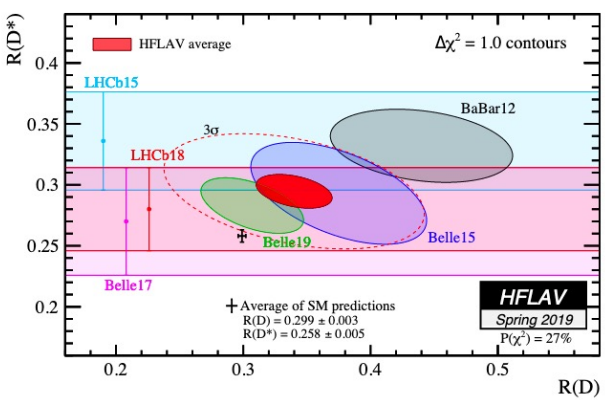
- Both in neutral ($b \longrightarrow s l^+ l^-$) and charged ($b \longrightarrow c\tau\nu$) decays: (3.1 σ)
- $(g\text{-}2)_\mu$: (4.2 σ)

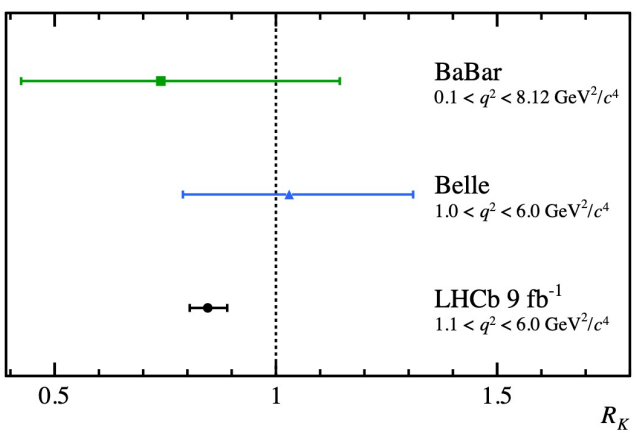


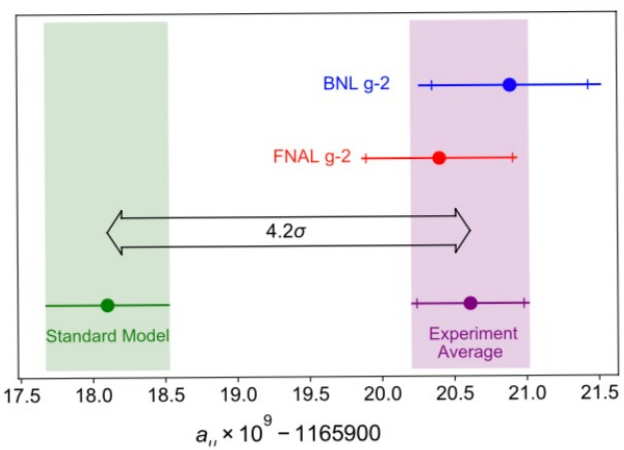
$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\ell\nu)}$$

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

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



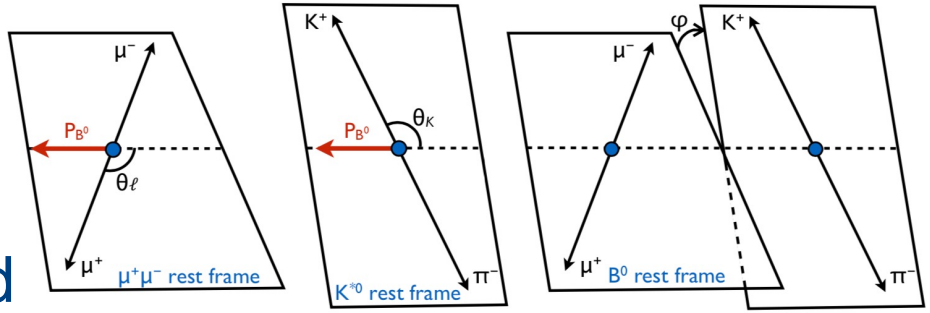


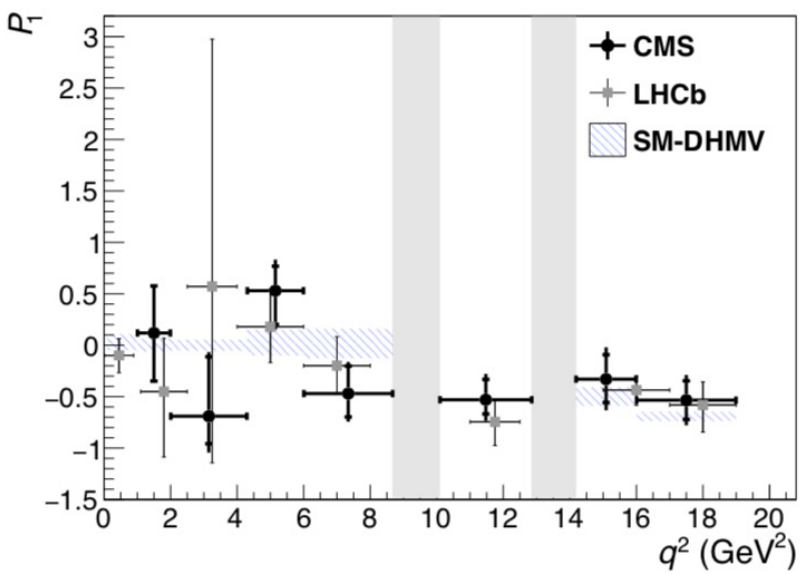


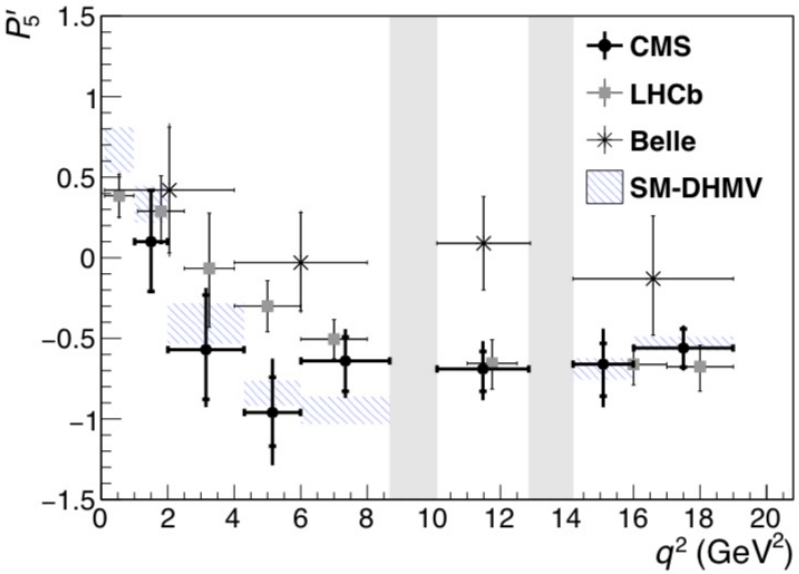
Angular distributions: B^0 decays

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

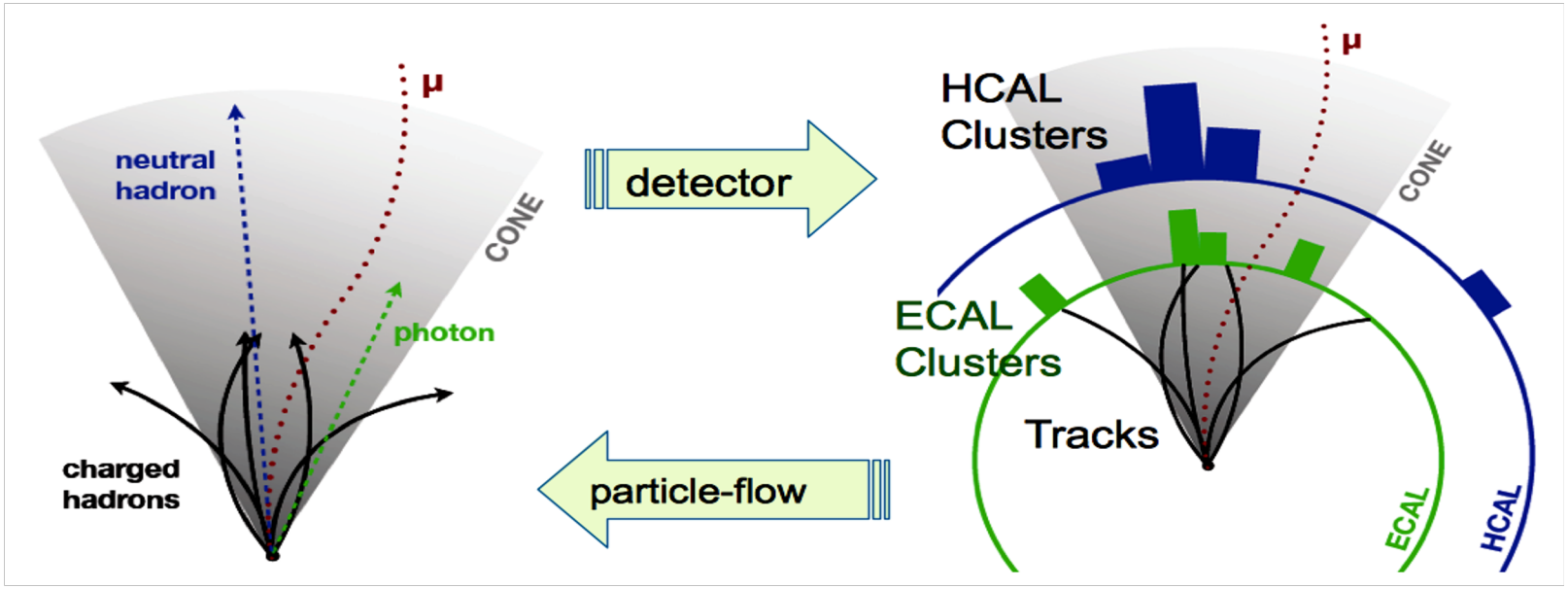






Particle Flow event reconstruction

- 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.

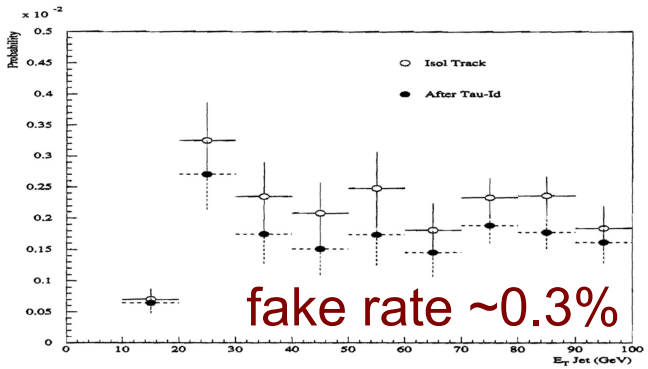


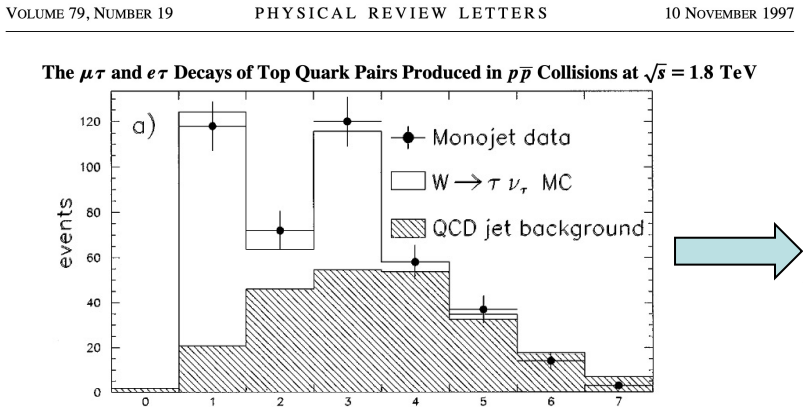
Tau lepton identification

JINST 12(2017)10

From first identification of hadronic tau decays to precise measurements

1997

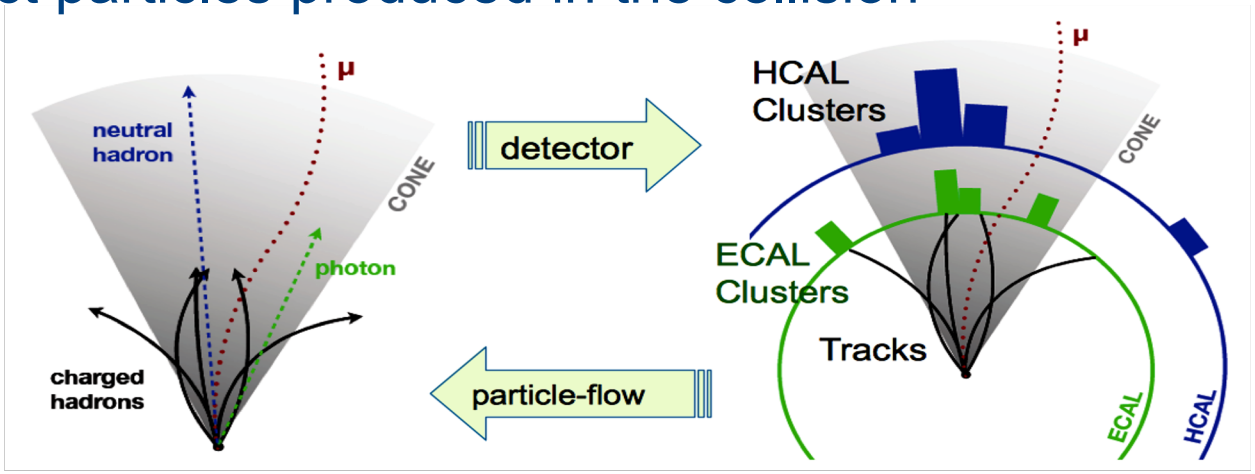




4 ttbar candidate events

2021

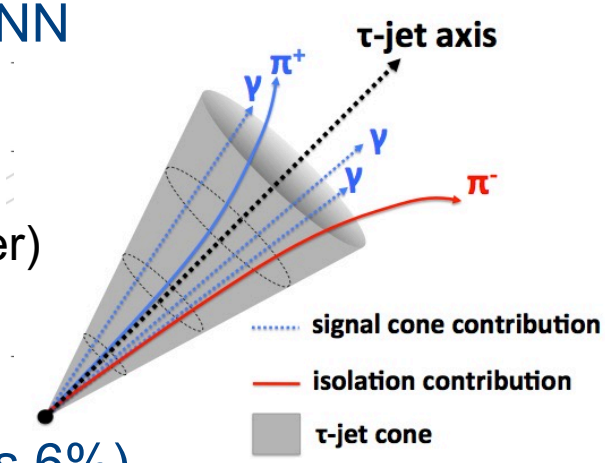
- Particle Flow (PF) combines information from all subdetectors to reconstruct particles produced in the collision

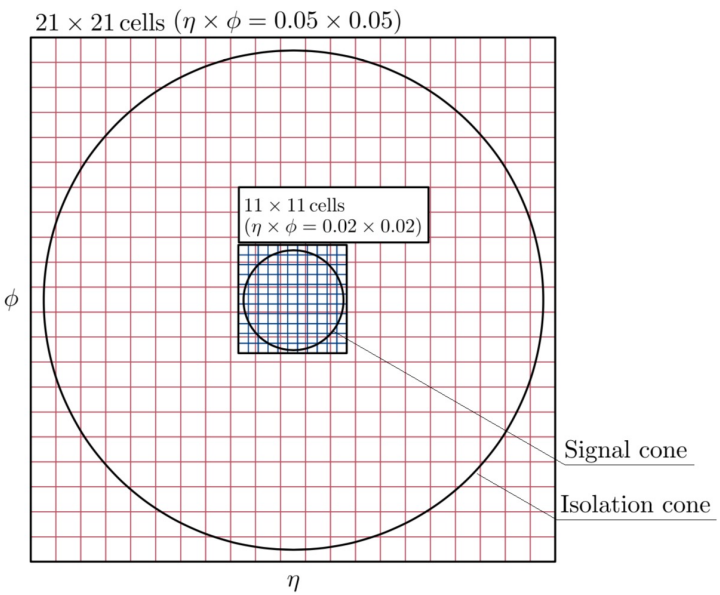


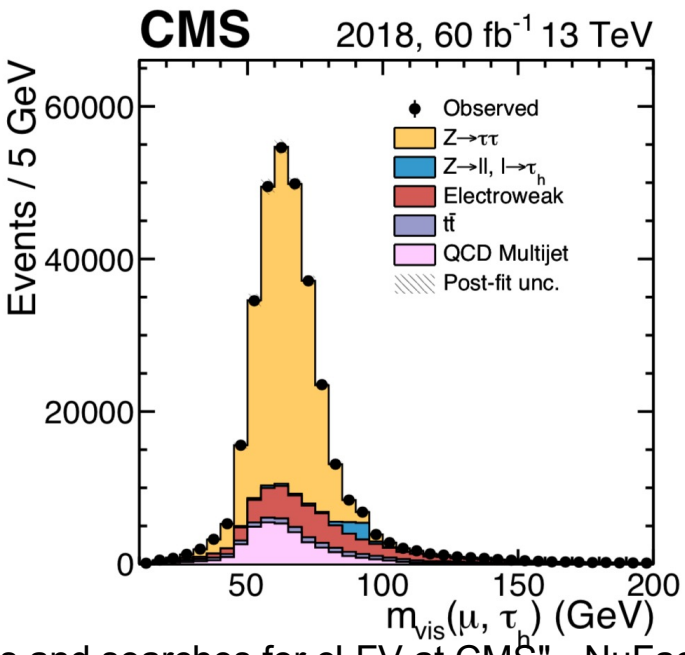
Tau lepton identification (cont.)

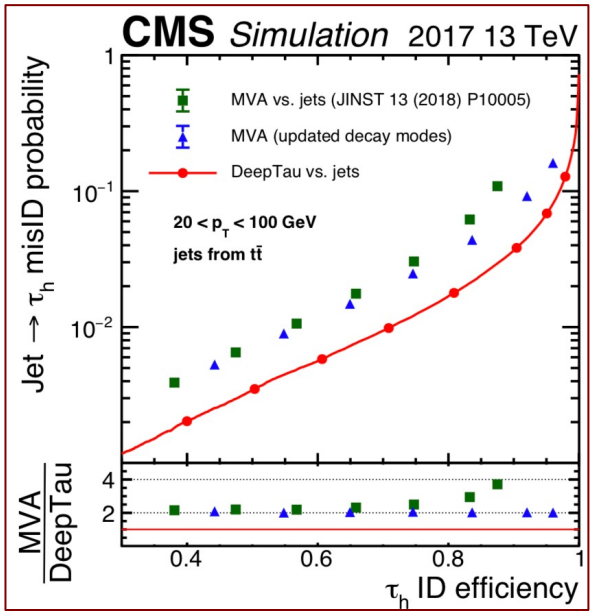
CMS-TAU-20-001

- 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%)





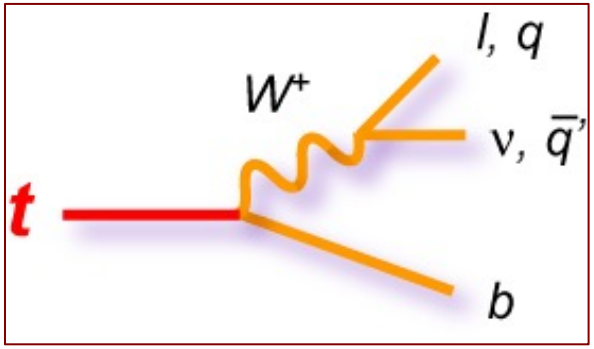




W branching fractions

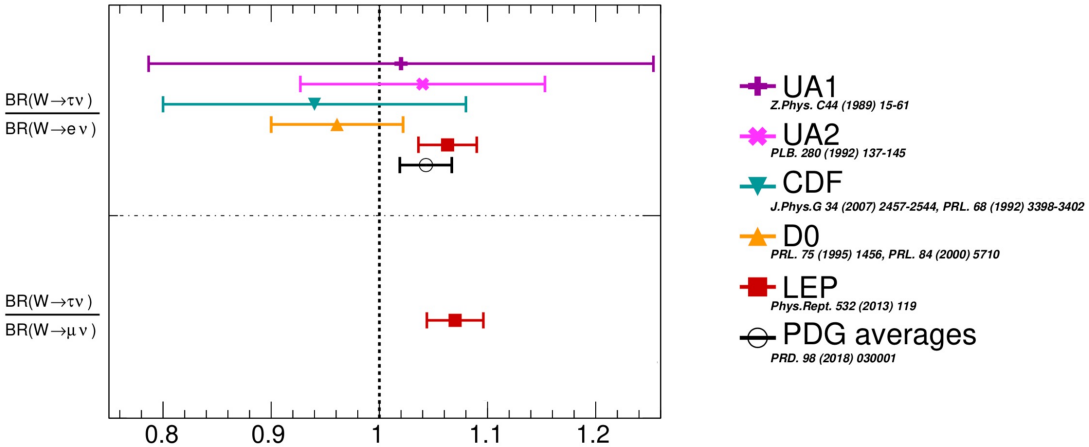
CMS-SMP-18-011

- 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

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

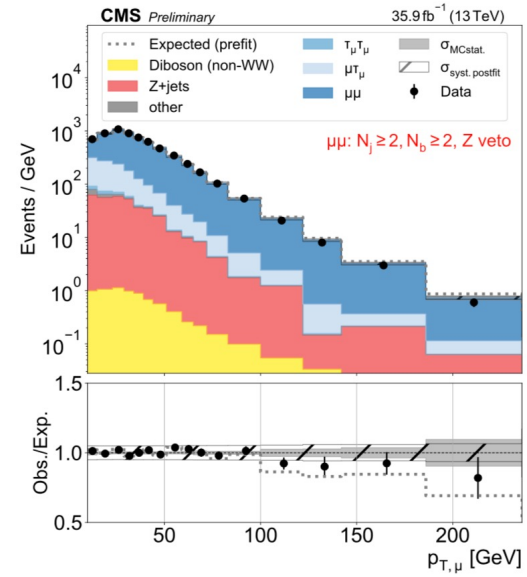


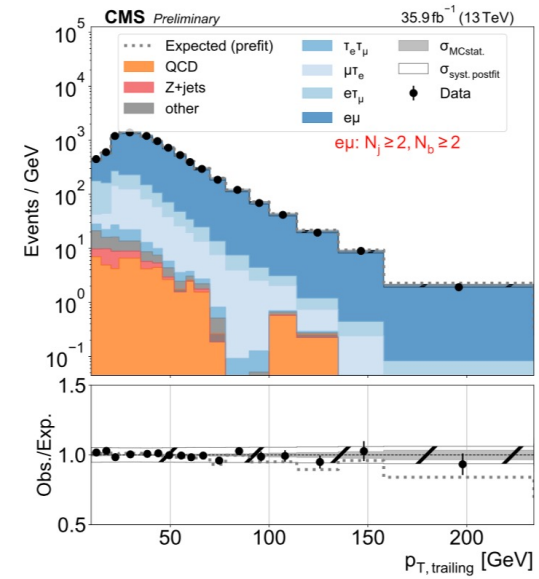
W branching fractions (cont.)

CMS-SMP-18-011

- Precise measurement of the W boson BRs (electrons, muons, taus)
  - use events with WW and W+jets
  - many more Ws than at LEP
  - 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 $\alpha_S(m_W^2)$

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





W branching fractions (cont.)

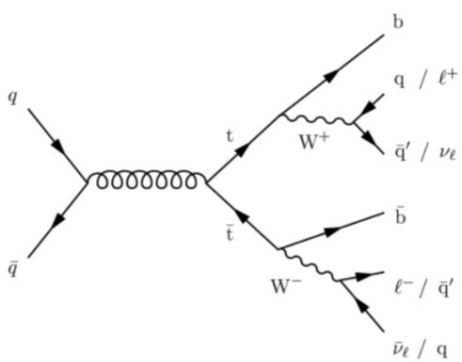
arXiv:2007.14040, CMS-SMP-18-011

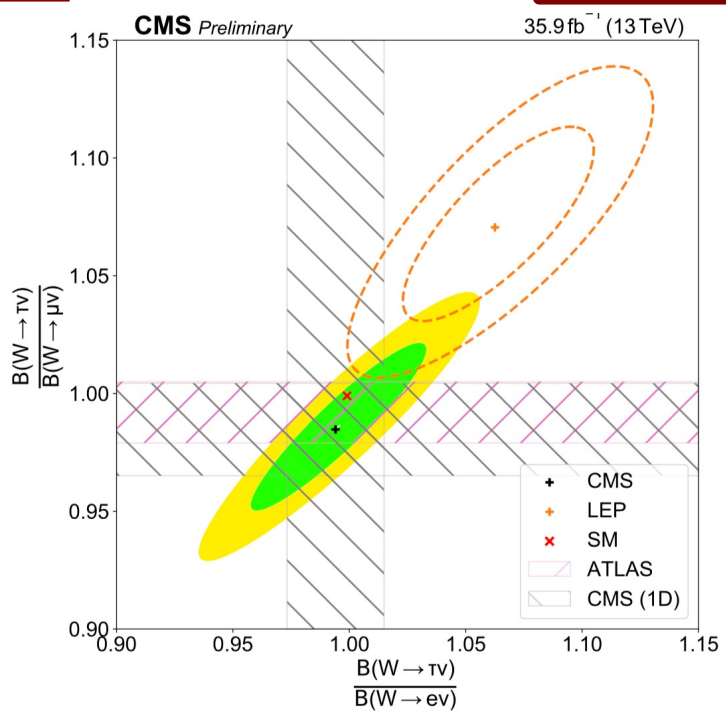
Results consistent with LFU hypothesis

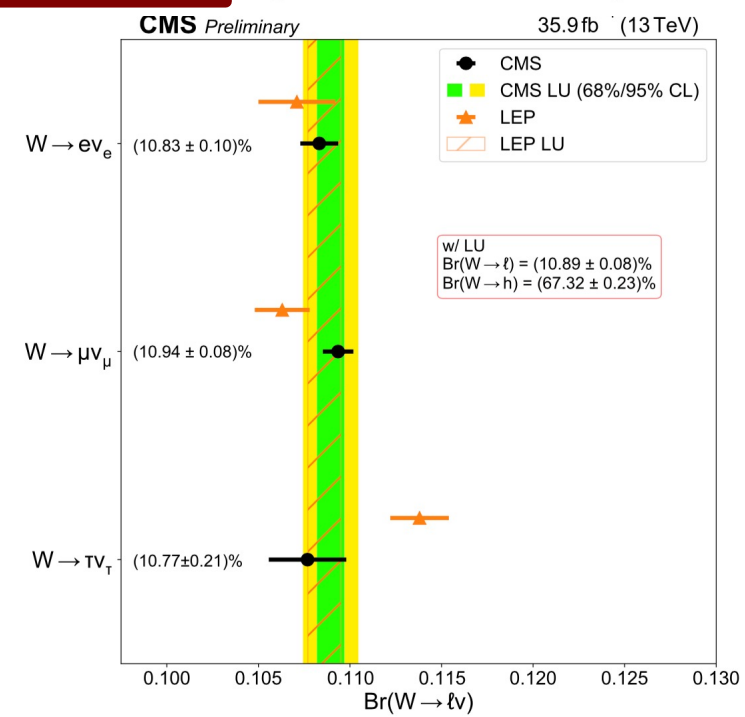
- Extract V_{cs} and $\alpha_S(m_W^2)$

$$|V_{cs}| = 0.969 \pm 0.011$$
$$\alpha_S(m_W^2) = 0.094 \pm 0.033$$

	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		
$\mathcal{B}(W \to \ell\overline{\nu})$	$(10.89 \pm 0.01 \pm 0.08)\%$	$(10.86 \pm 0.06 \pm 0.09)\%$
$\mathcal{B}(W \to h)$	$(67.32 \pm 0.02 \pm 0.23)\%$	$(67.41 \pm 0.18 \pm 0.20)\%$







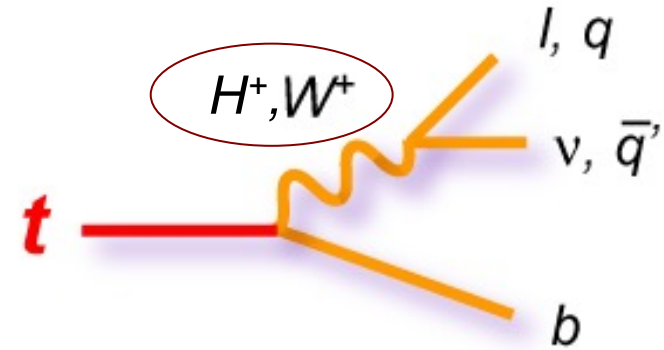
Probing the Wtb vertex

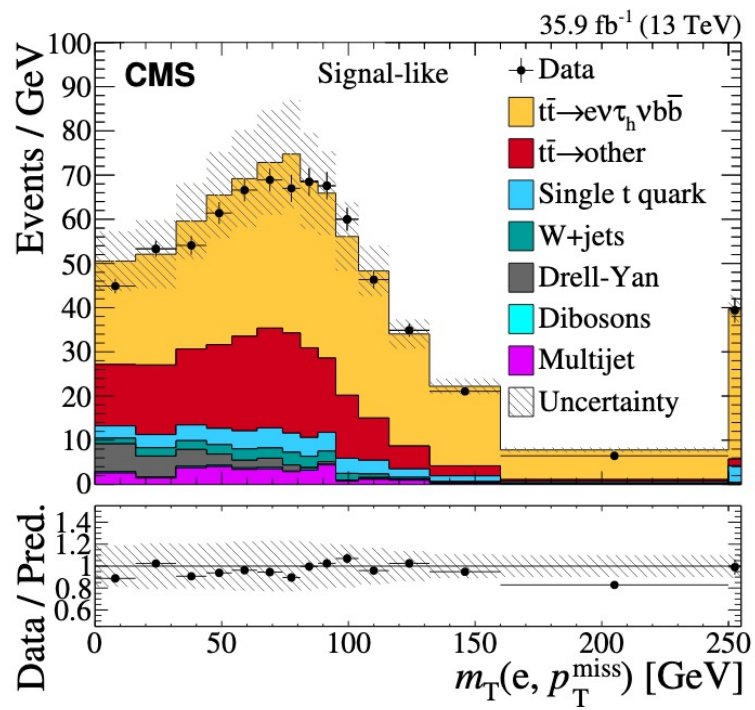
JHEP 02(2020)191

Top quark decays: dileptons with taus

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

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





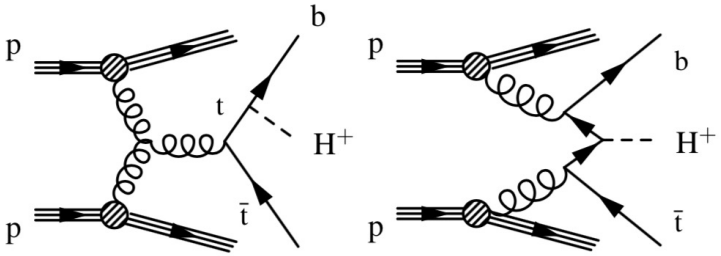
- If top quark plays special role in EWK symmetry breaking, couplings to W may change
- Charged Higgs may alter coupling to W

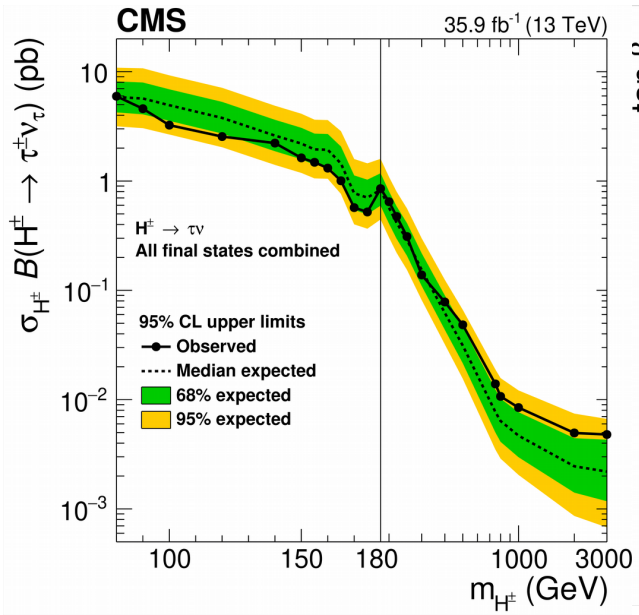
Charged Higgs: $H^+ \to \tau\nu$

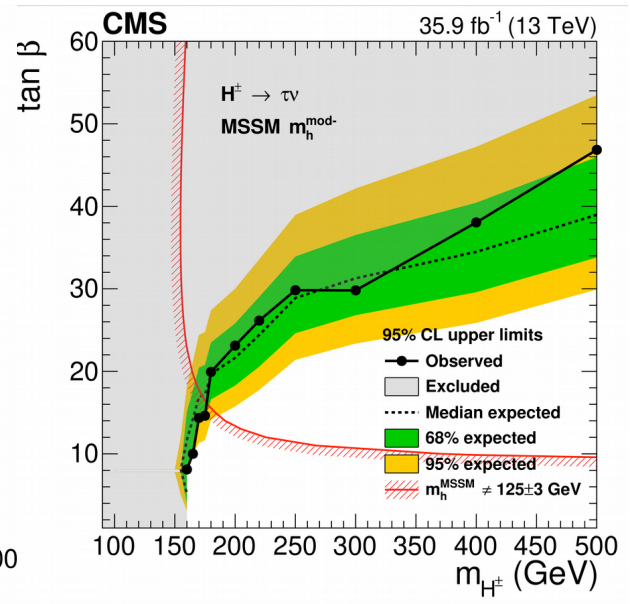
arXiv:1903.04560

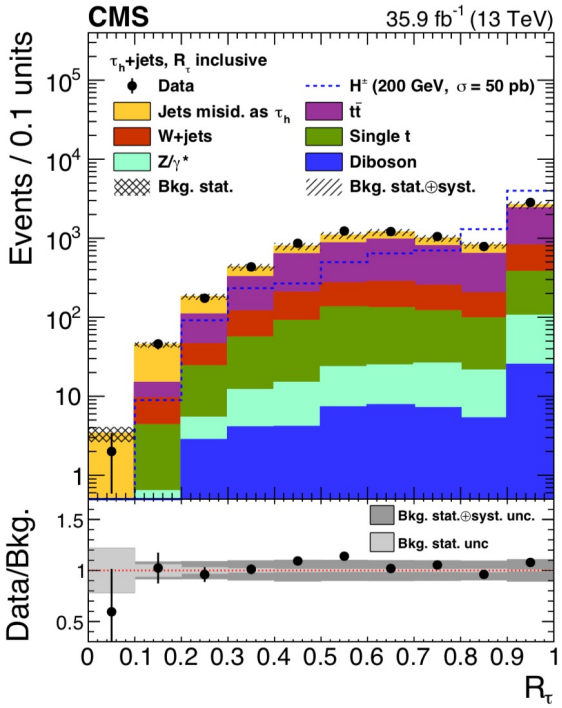
MSSM: coupling to taus large for high tanβ

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





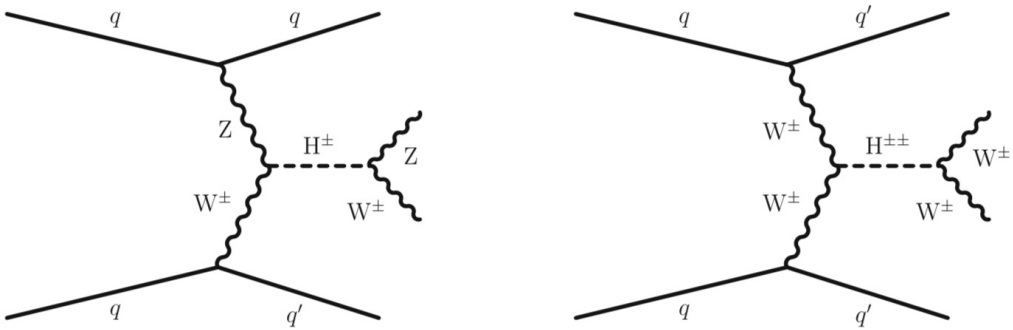


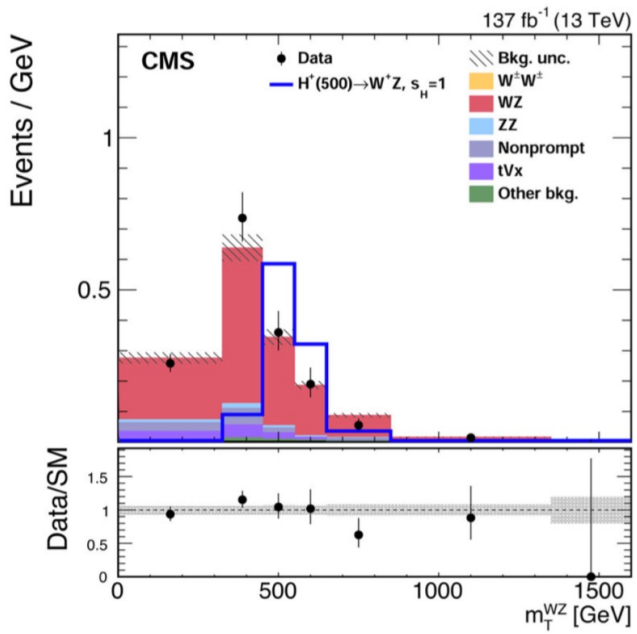


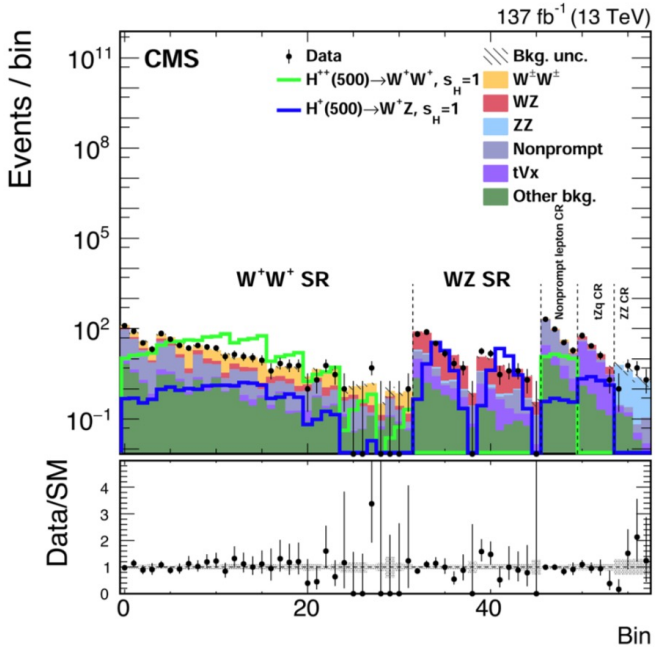
Charged Higgs: VBF

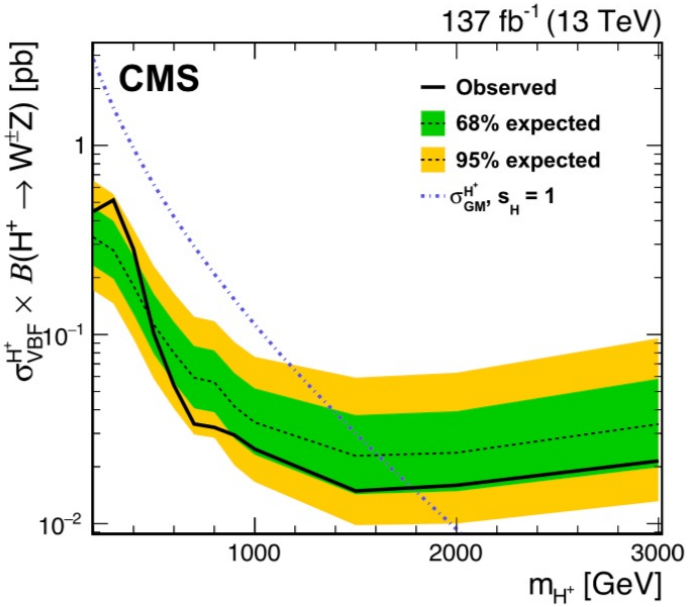
EPJC 81(2021)723

- 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^+ and H^{++} production









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

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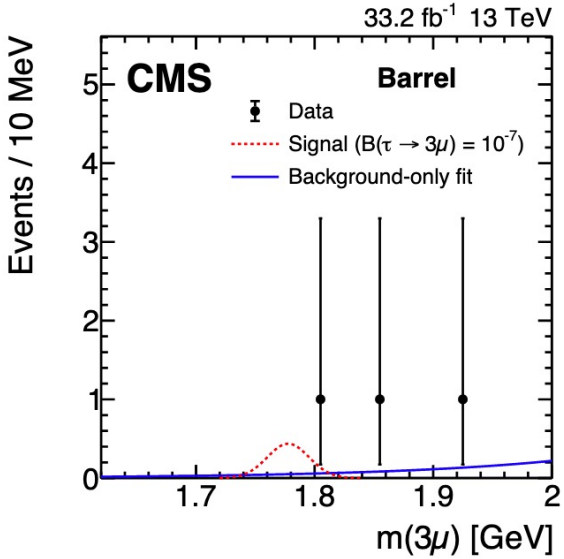
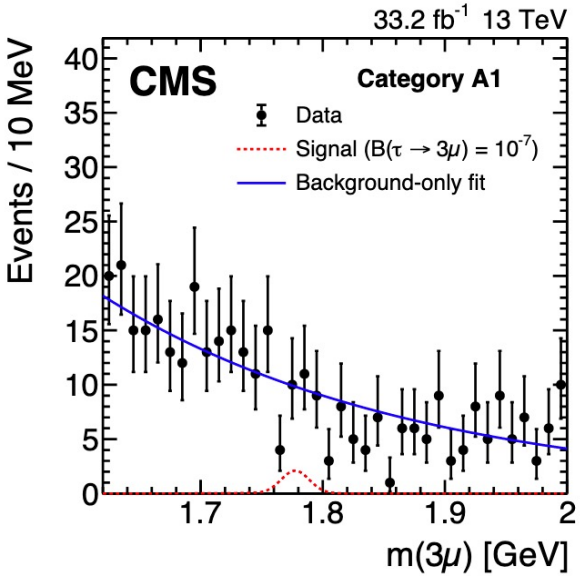
- LFV processes can occur via neutrino mixing
- Lepton flavour violating decay: $\tau \to 3\mu$
  - Very rare process, BR~10^{-10}–10^{-8}
  - World's best limit: 2.1×10^{-8} (Belle)
- Search performed in 2016 data
  - Tau leptons produced in W and HF hadron decays
  - 2/3 low-p_T muons trigger
  - Select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

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

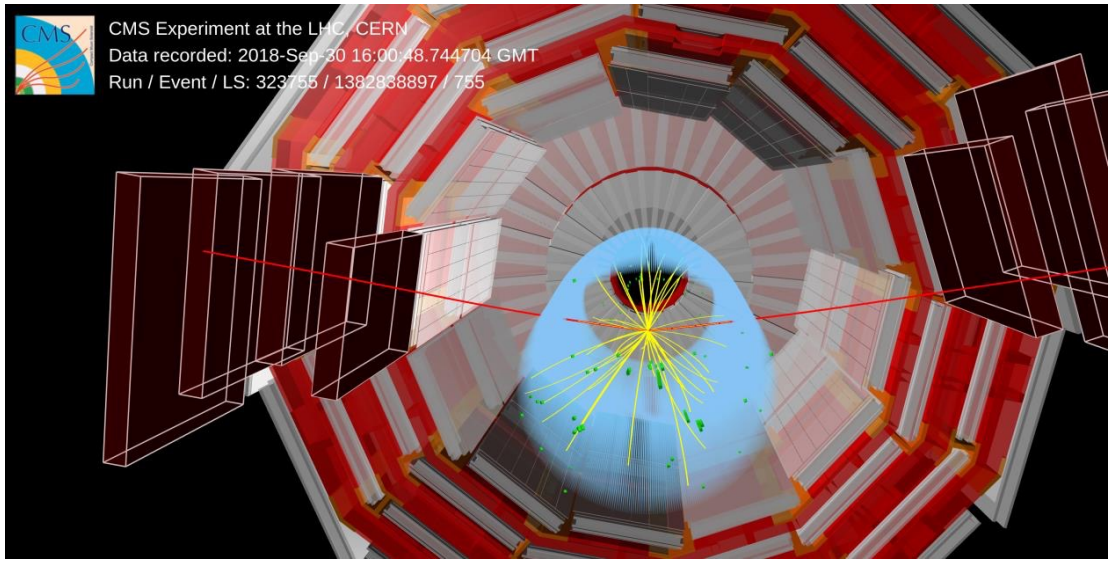


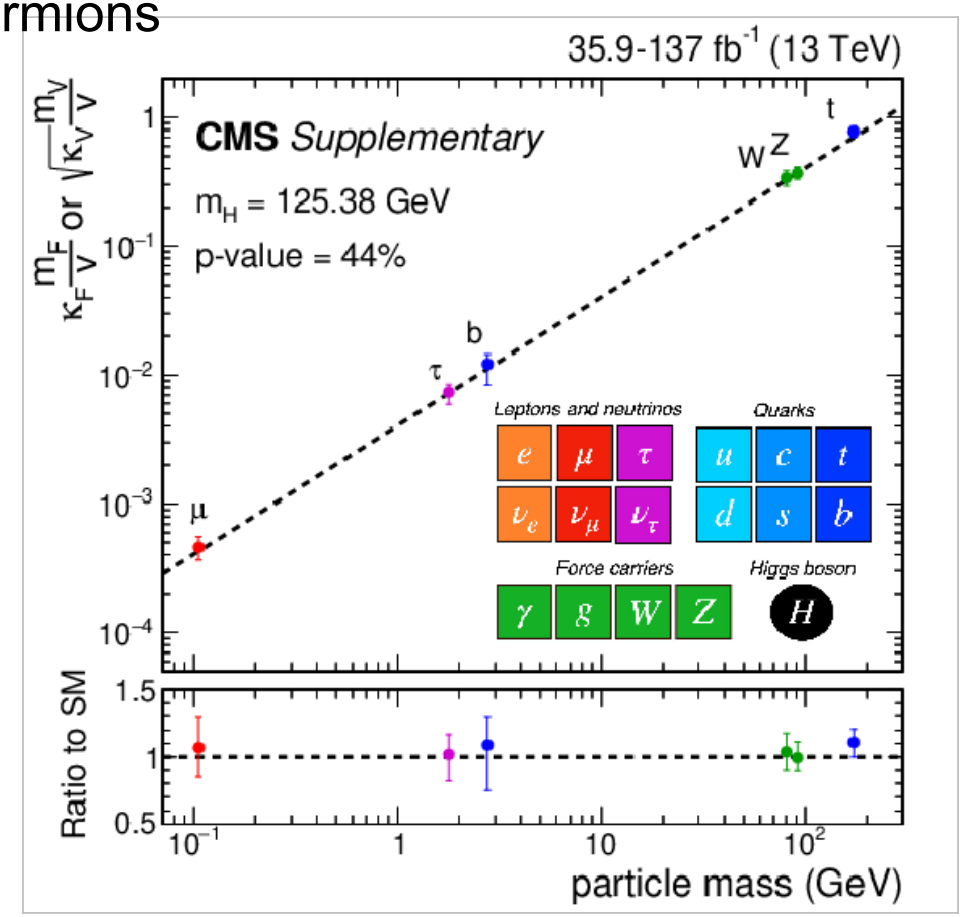


Higgs boson couplings

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

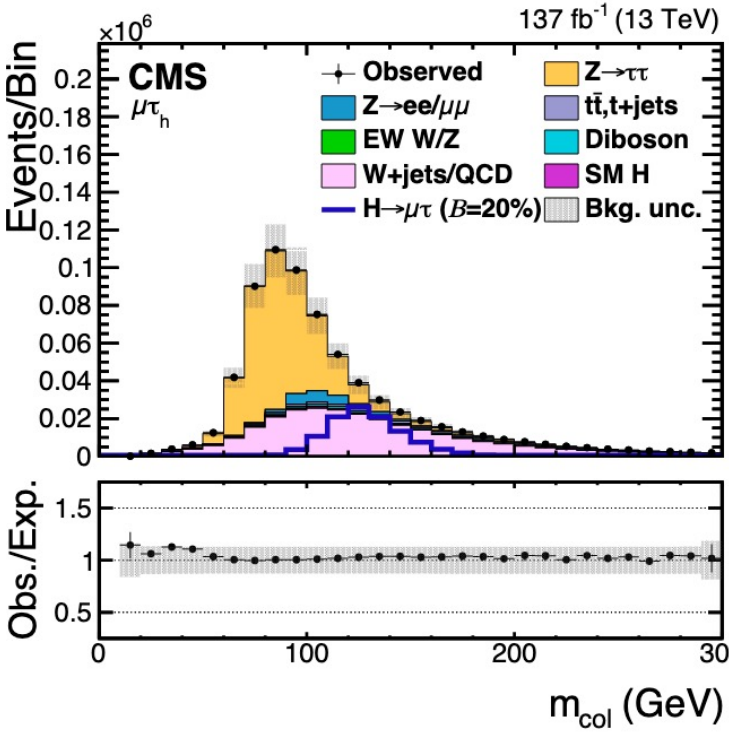
LFV in Higgs decays

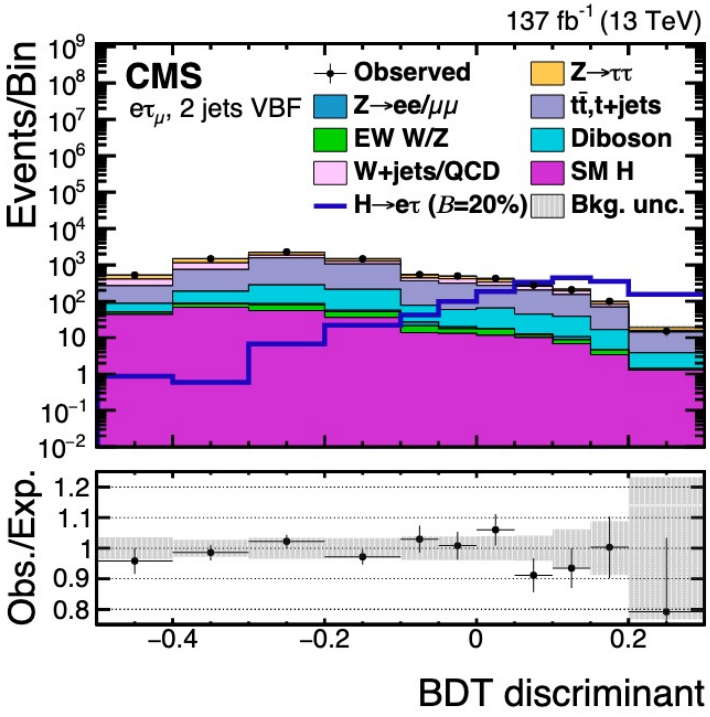
arXiv:1911.10267, arXiv:2105.03007

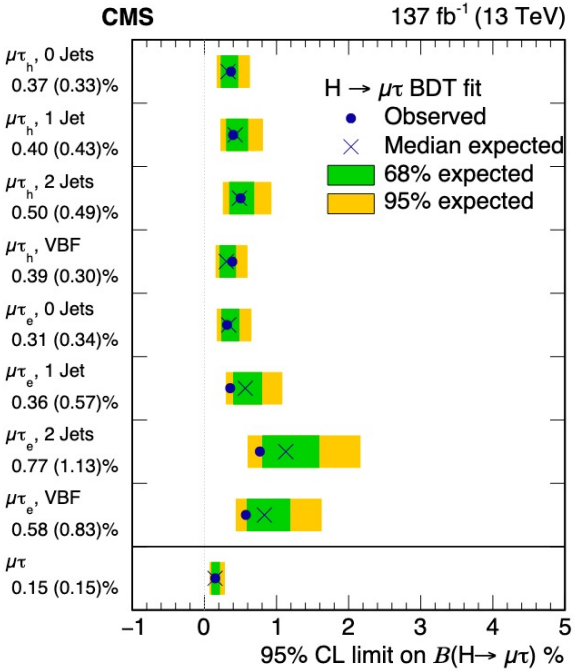
- Some BSM models allow for LFV Higgs decays
- Search for H→eτ, eμ, μτ final states
  - N_{jet} to target ggH and VBF production
  - Categories: N_{jet}, lepton kinematics
- Main background from DY, ttbar, WW

	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



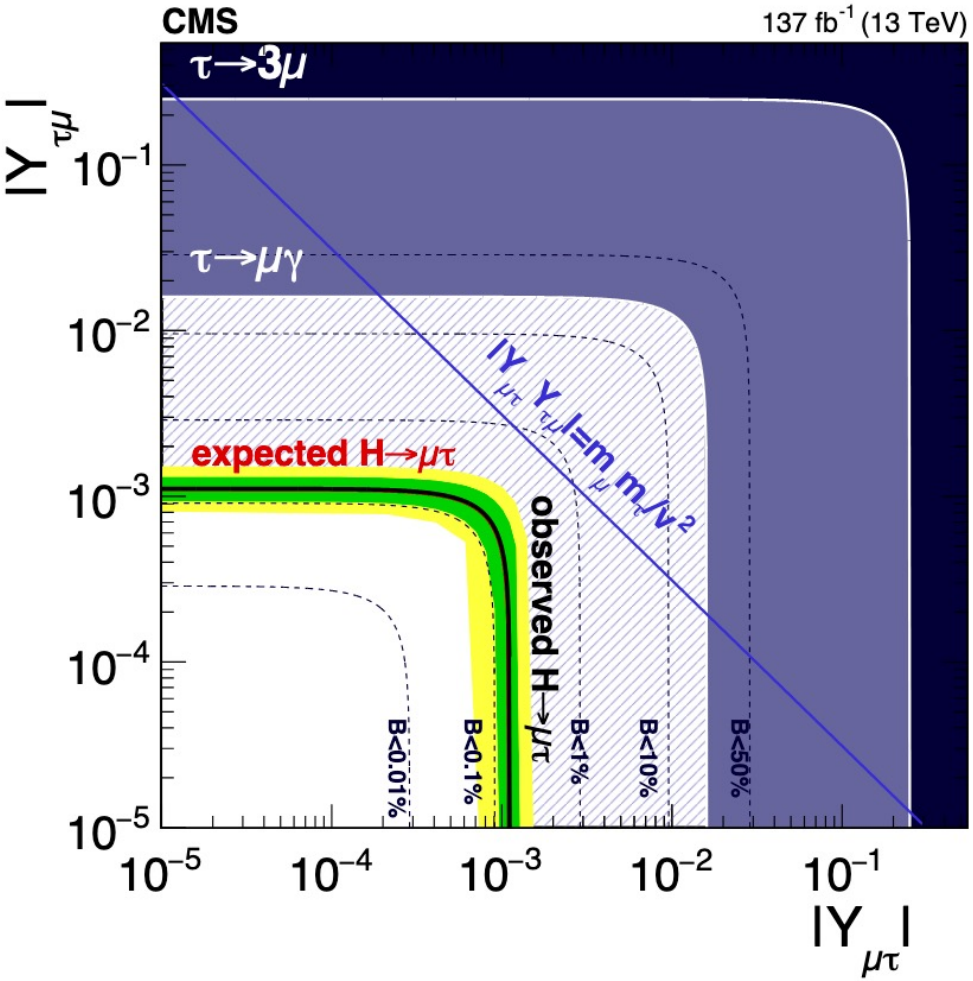


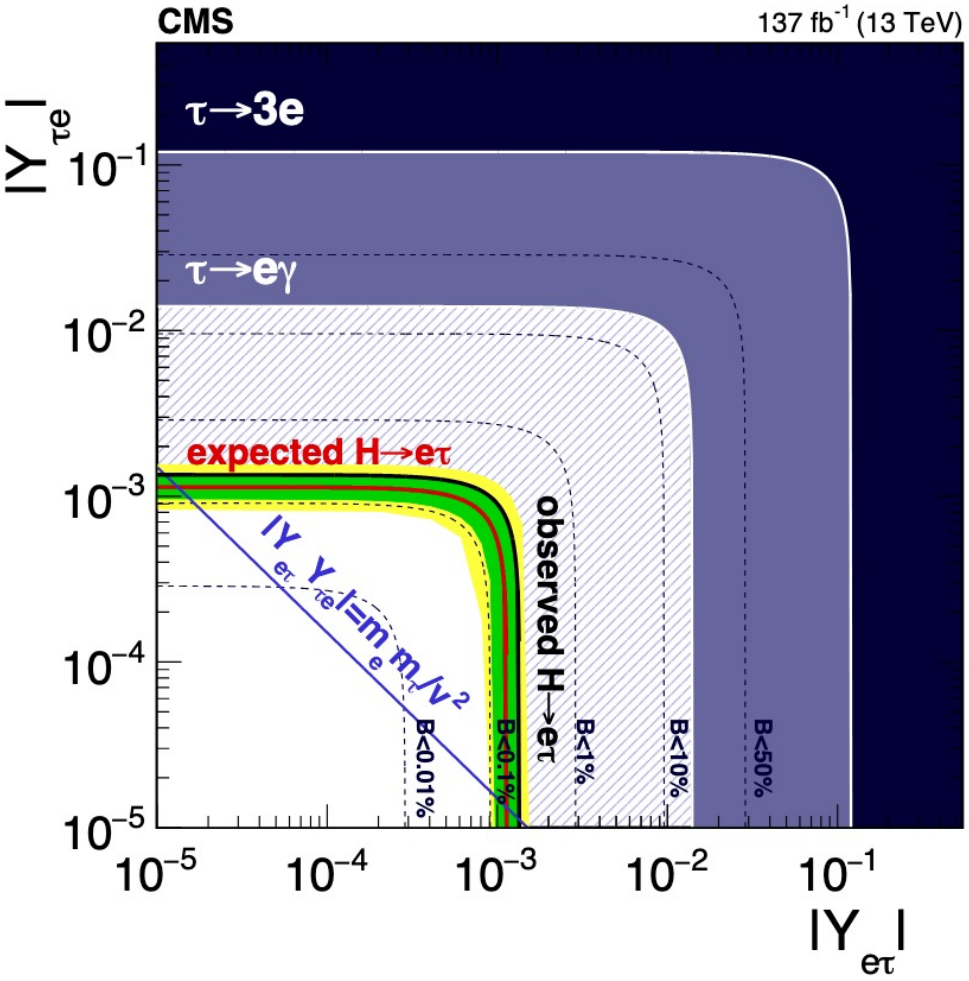


LFV decays - constraints

arXiv:1911.10267, arXiv:2105.03007

Limits set on off-diagonal Yukawa coupling terms, Y





SUSY

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

Several tests in SUSY related searches

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

Search for chargino-neutralino production

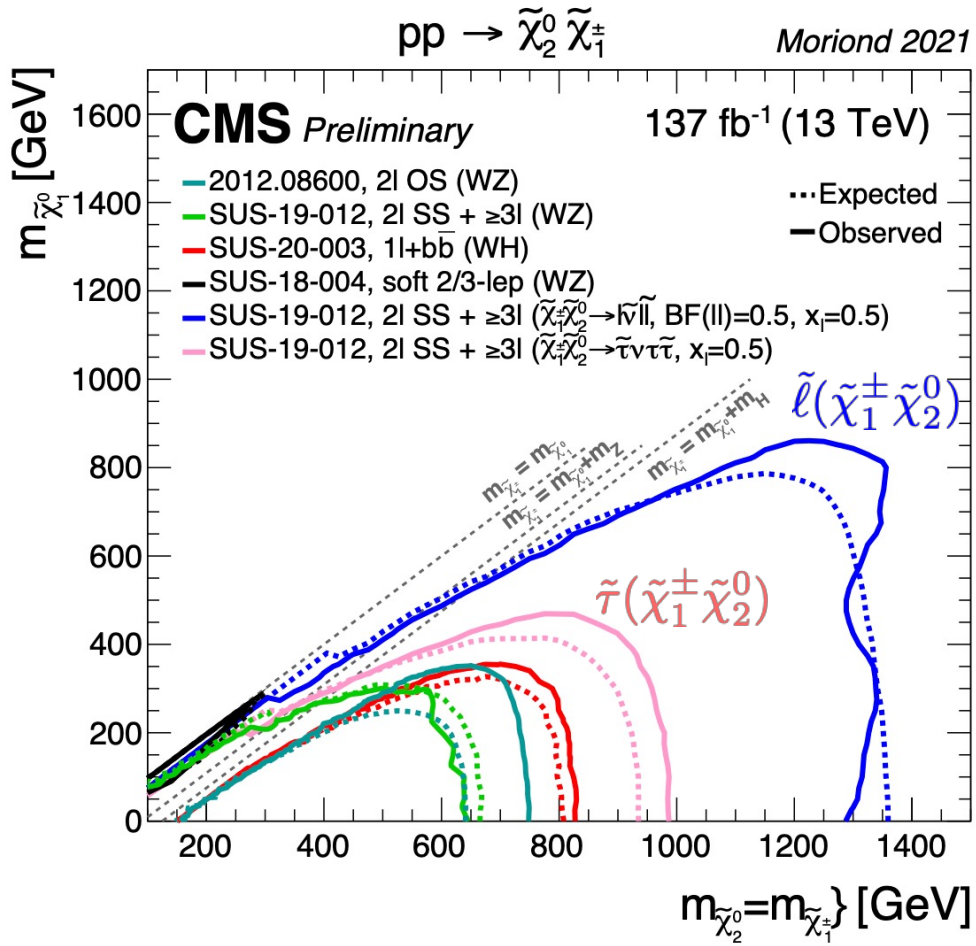
- Flavour-democratic scenario: chargino-neutralino decays mediated by LH-sleptons
- τ-enriched-scenario: chargino couples to RH sleptons, neutralino to LH sleptons

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 search in ditau final state

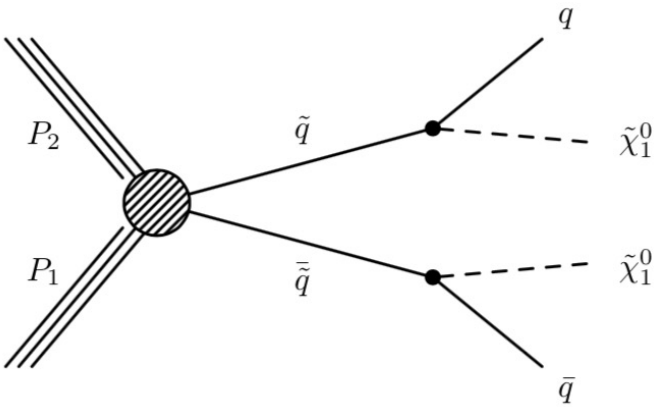
- High-tanβ and higgsino-like scenario, the chargino mostly decays to τ leptons

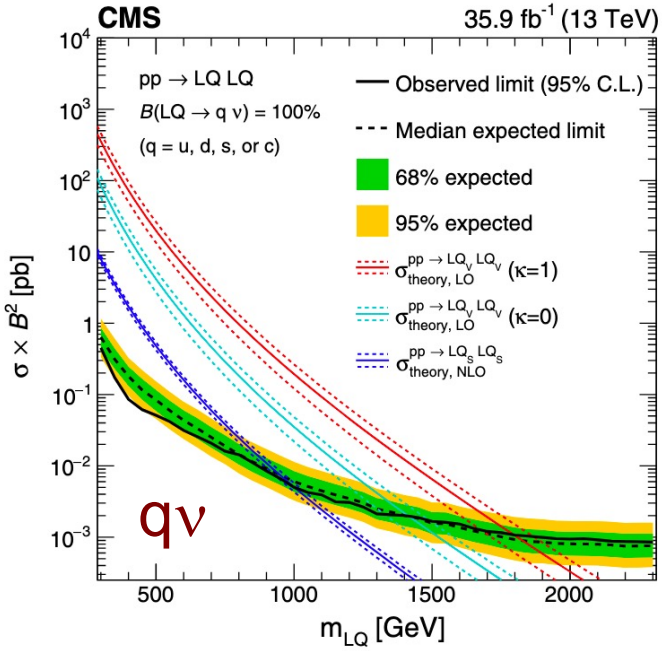


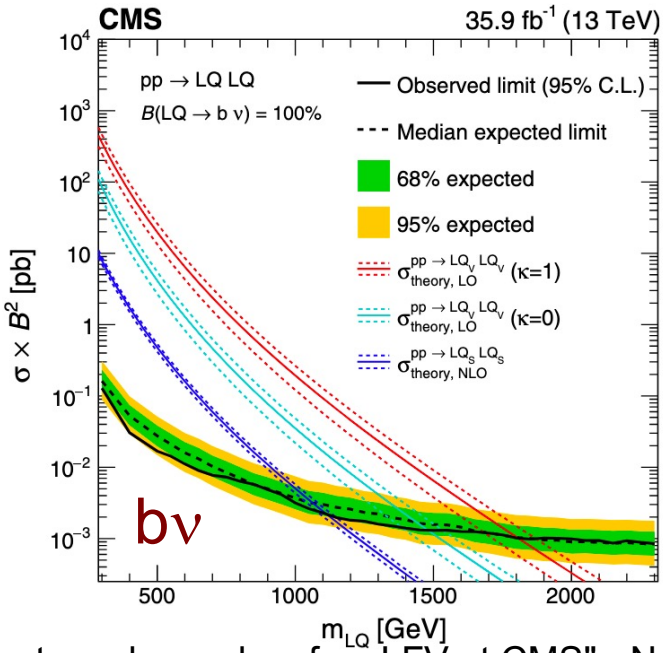
SUSY: LQ pair

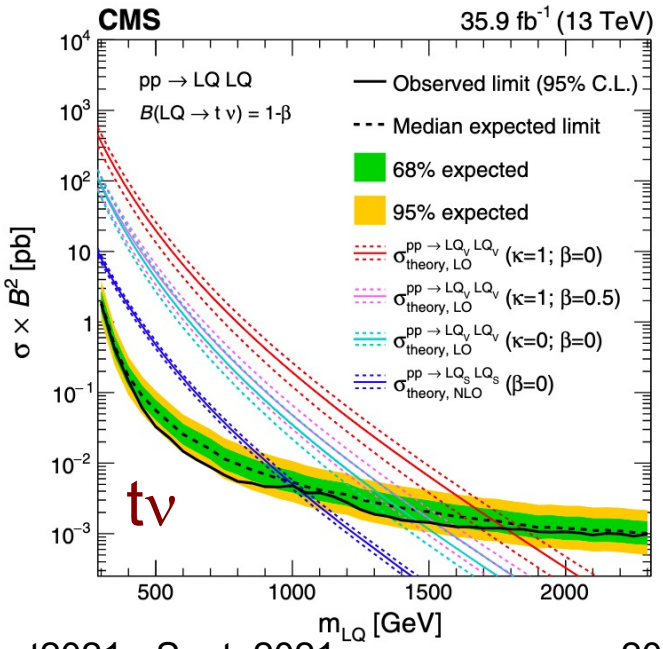
PRD 98(2018)032005

- SUSY searches for pair produced squarks
  - For M(χ)=0: same final state as LQ⟶ qν
- Reinterpretation in LQ models
- Signal acceptance is similar
- Interpretation in scalar and vector scenarios
  - Exclude M_{LQ}<1TeV(scalar) and <1.8 TeV (vector)





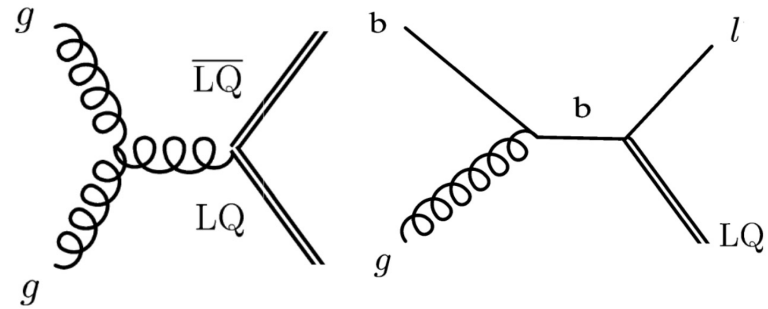


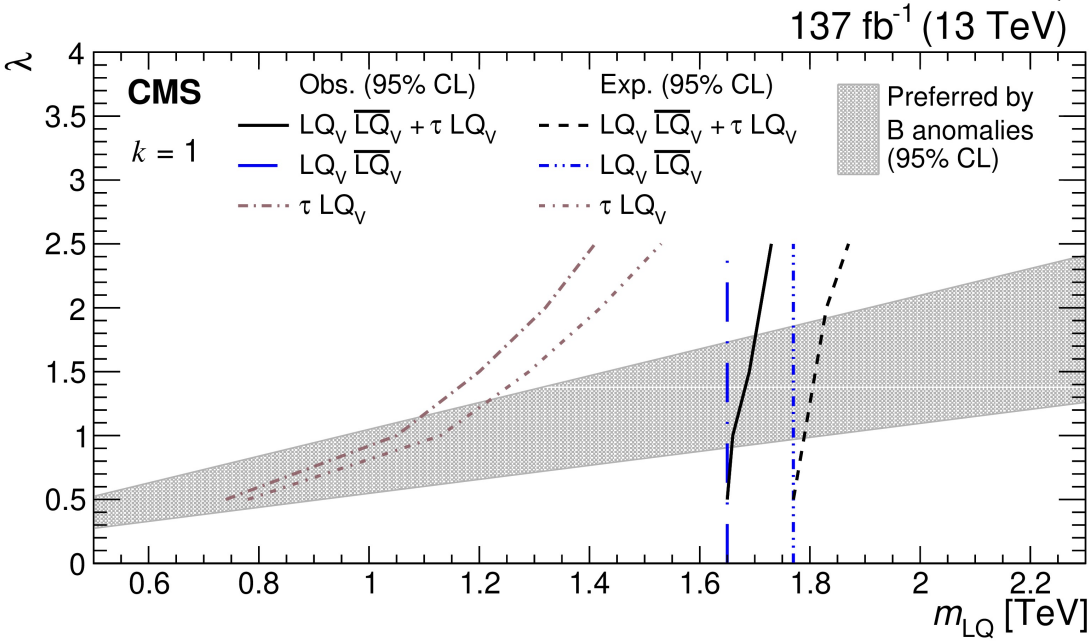


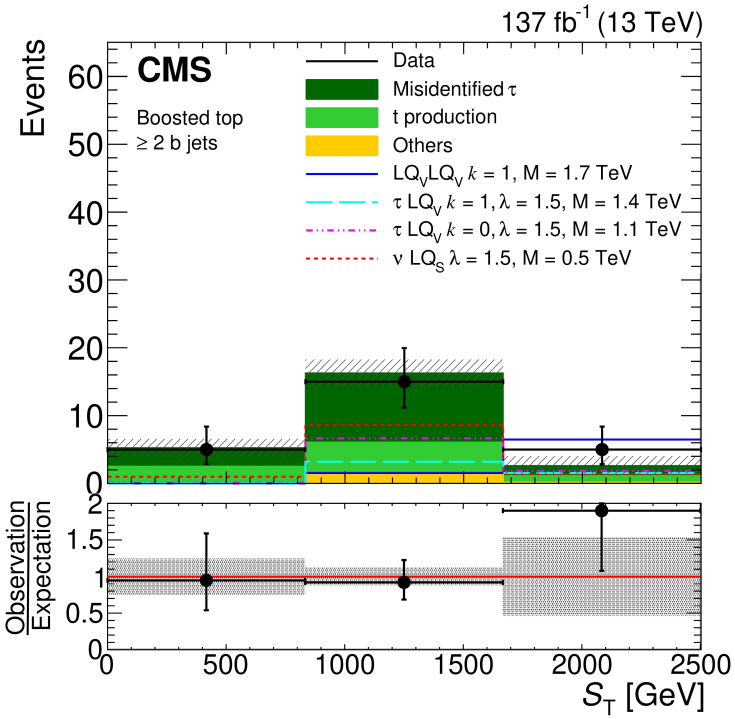
Leptoquarks

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
- Search for LQ coupled to 3rd gen fermions
  - consider LQs: LQ→tτ (tν) or LQ→bν (bτ)
  - Fully hadronic final state: top (resolved or boosted), τ_h, b
- Set limits on lepton-quark coupling λ vs M_{LQ}





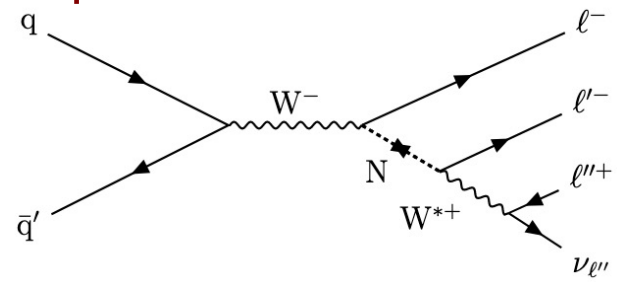


Long-lived heavy neutral leptons

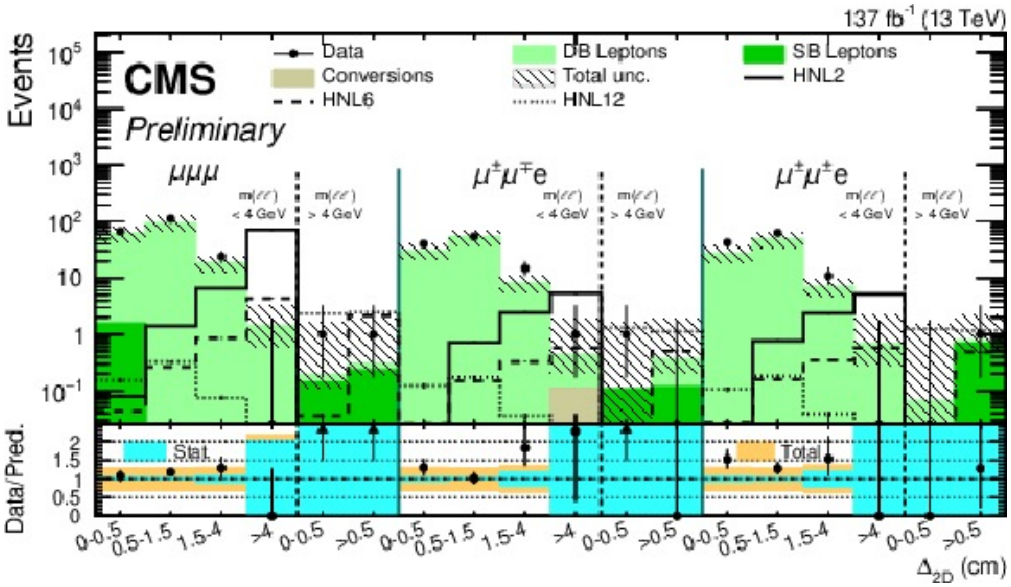
CMS-EXO-20-009

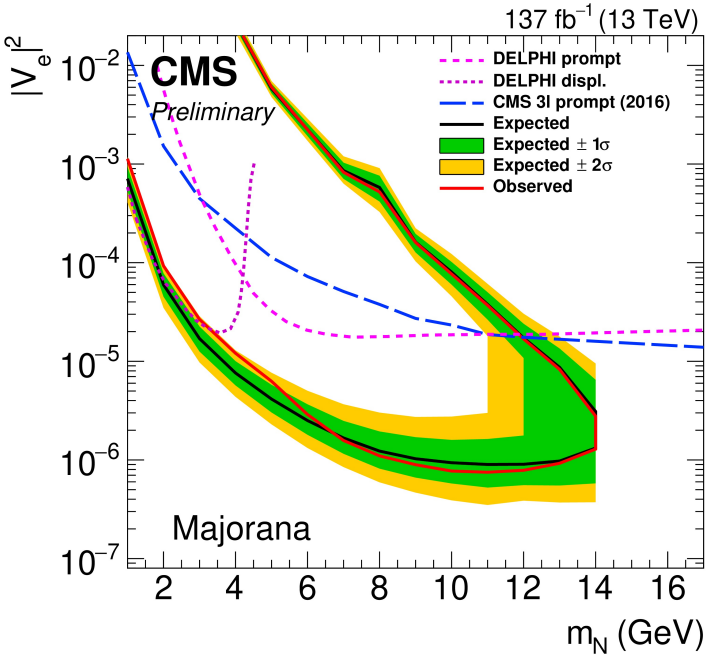
- HNL can be produced through mixing with SM νs
  - HNLs could explain small neutrino masses or be DM cand.
- HNL may be long-lived
  - for small values of HNL mass (<20 GeV) and HNL-SM neutrino mixing parameter
- Search for 3-lepton events (e, μ)
  - 2 with displaced vertex+1 prompt

Lepton Flavor Violation?



Dirac vs Majorana particles



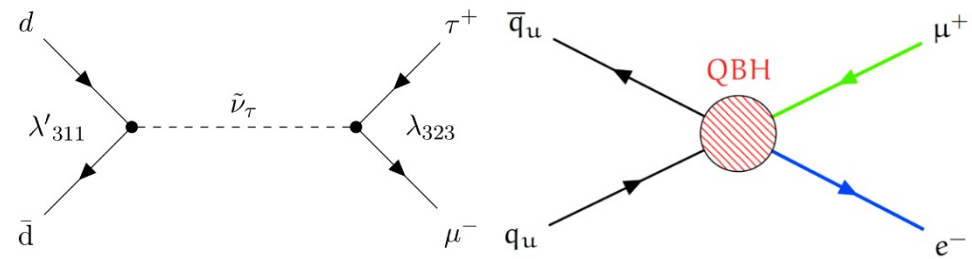


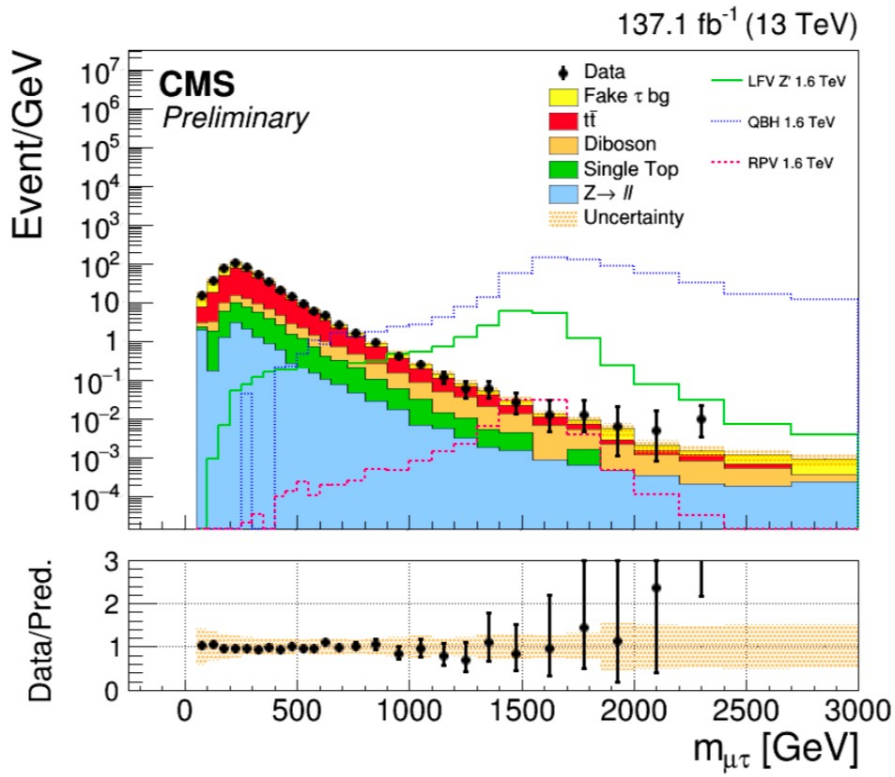
Mixing vs HNL mass

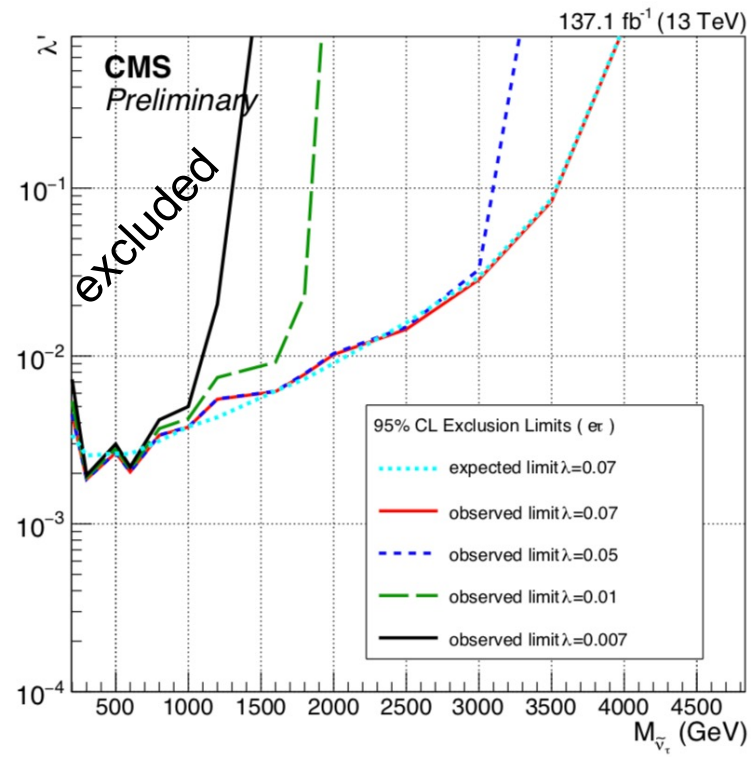
Heavy resonances & QBHs

CMS-EXO-19-014

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







Summary

- Lepton Flavour Universality measurements in tension with SM
- Current results at CMS indicate LFU holds within uncertainties
  - rare decays, W boson, Top quark, Higgs boson, BSM searches, etc

- Towards precise measurements and rare processes
- Plenty of data: 137 fb^{-1} → 300 fb^{-1} → 3000 fb^{-1}
- LHC Run3 is about to start (2022+)
- HL-LHC a few years away (2027+) with improved detectors

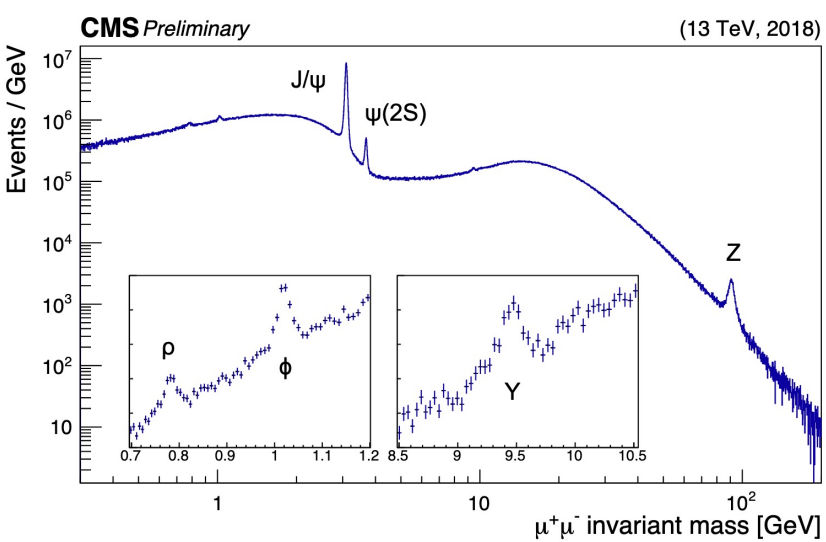
Thank you!

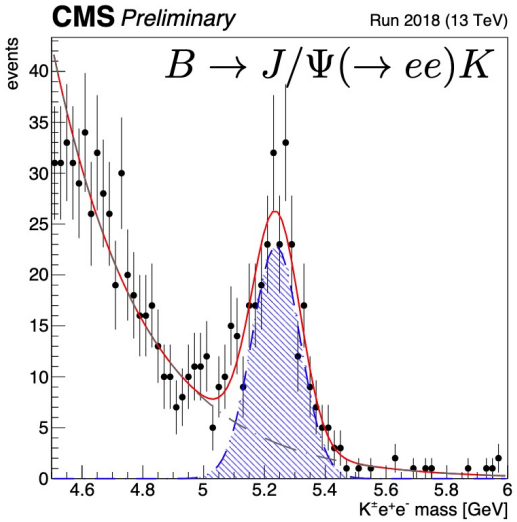
Simplicity if the essence of universality – M. Gandhi

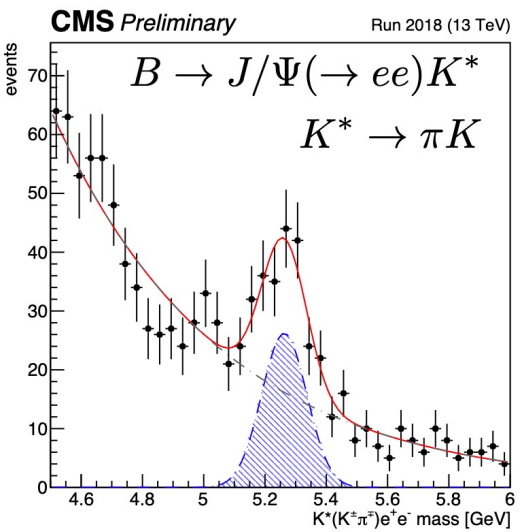
backup

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

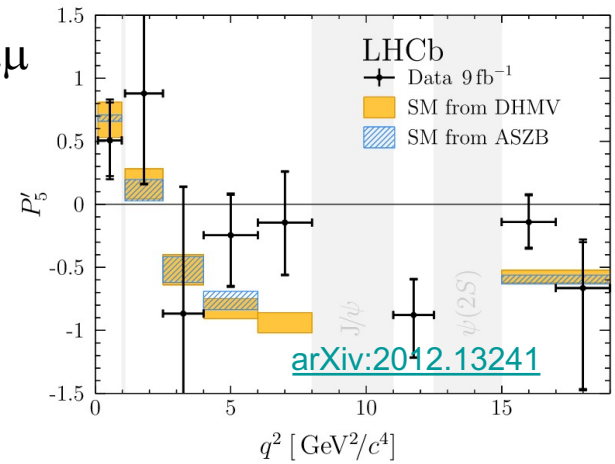


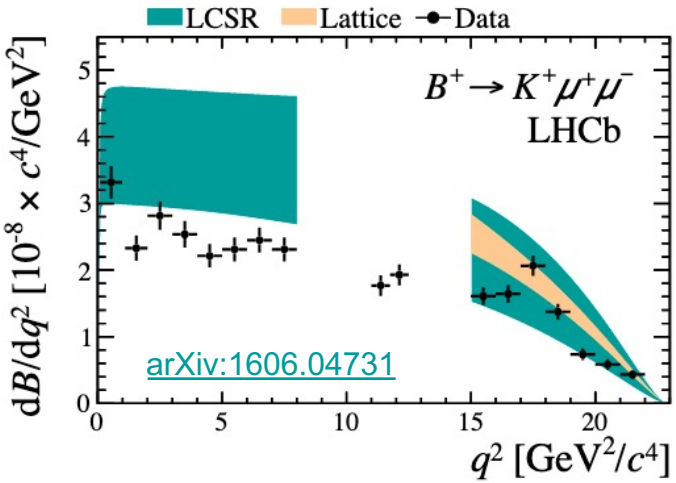


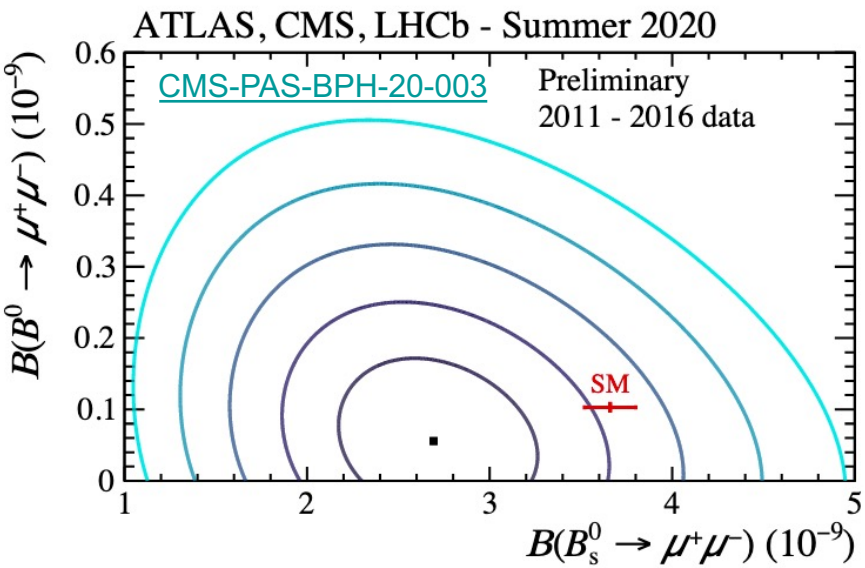


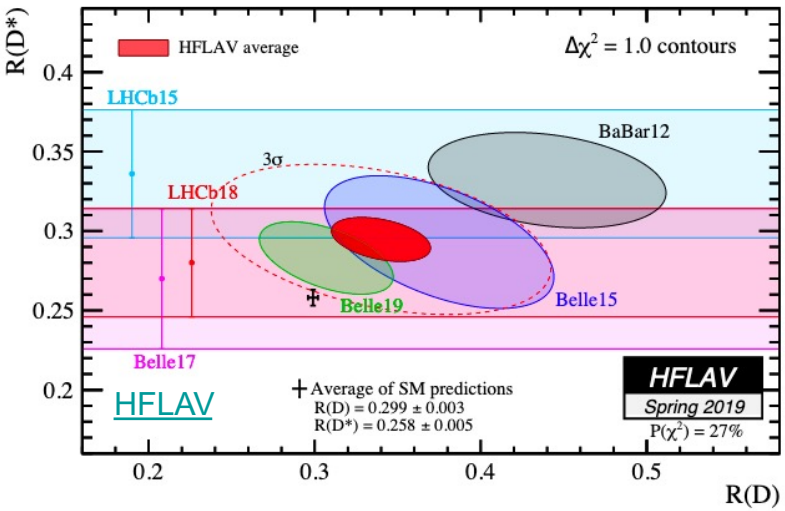
Flavour anomalies

- 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 (2.3σ)









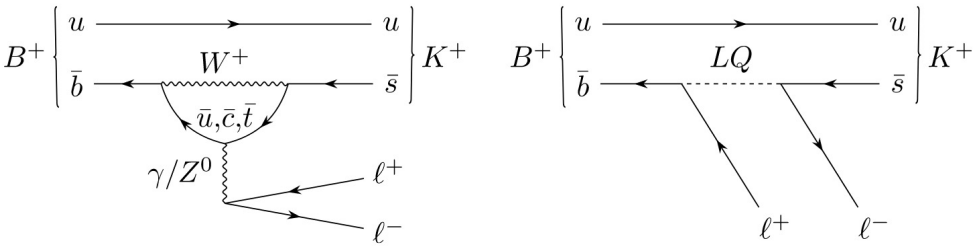
$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\ell\nu)}$$

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

LFU: anomalies

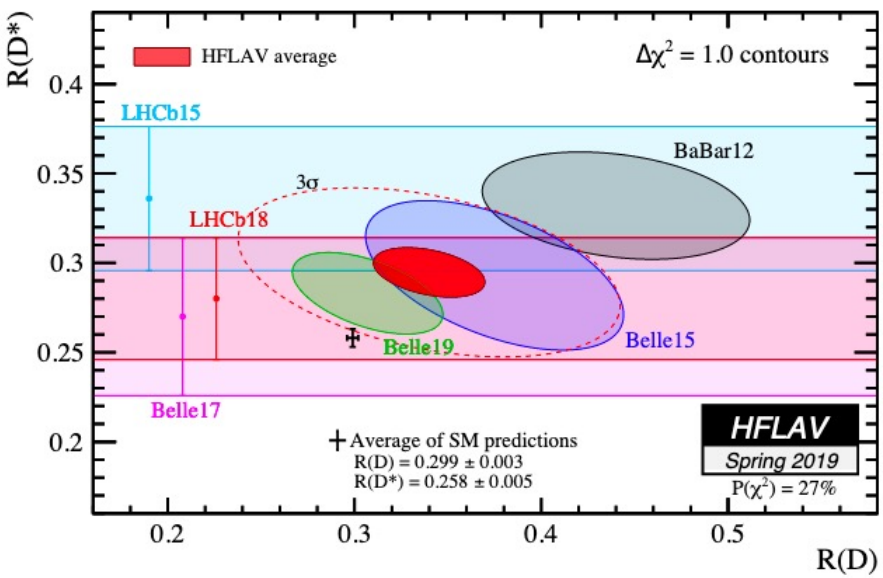
arXiv:2103.11769, arXiv:2103.16558

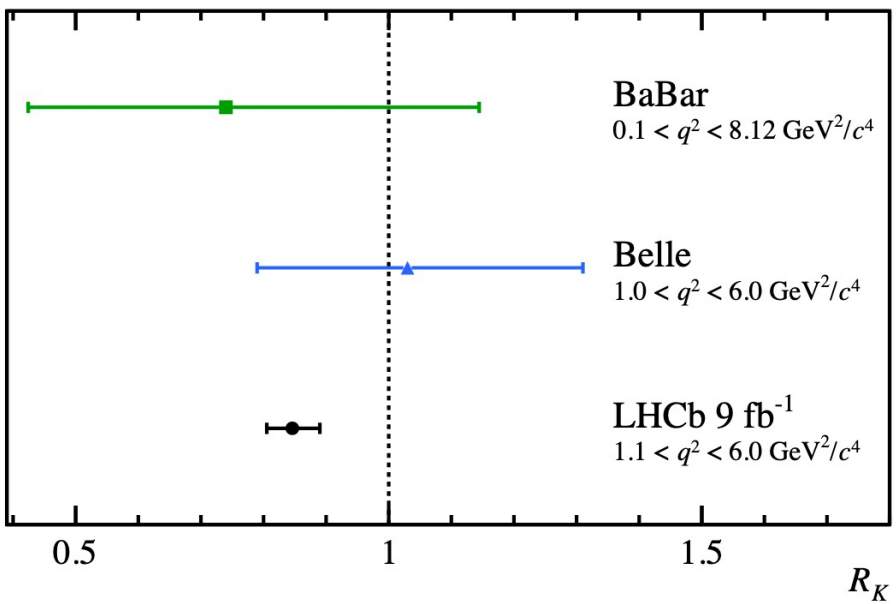
- Recent LHCb results indicate evidence for breaking of LFU in b-quark decays (3.1 σ)
- Both in neutral ($b \to s l^+ l^-$) and charged ($b \to c \tau \nu$) decays



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

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



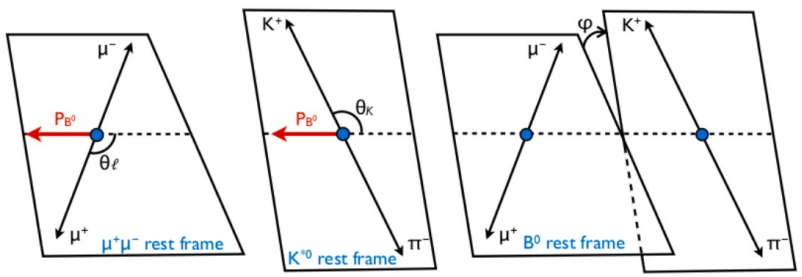


Angular distributions

Angular variables

- The $B^0 \to K^{*0}(K^+\pi^-)\ \mu^+\mu^-$ decay has a 4-particle final state which can be full described by a set of 4 kinematic variables: $q^2, \theta_l, \theta_K, \phi$

- q^2 is the **dimuon invariant mass** squared and:



$B^0 \to K^{*0}\mu^+\mu^-$ CP averaged decay rate

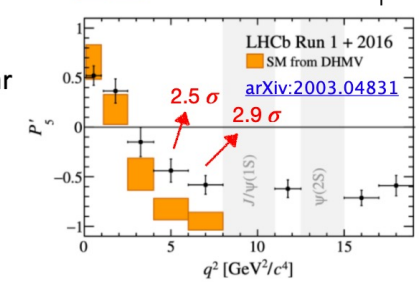
$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{dq^2 d\cos\theta_l d\cos\theta_K d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}F_T \sin\theta_K{}^2 + F_L\cos\theta_K{}^2$$
$$+ (\frac{1}{4}F_T\sin\theta_K{}^2 - F_L\cos\theta_K{}^2)\cos 2\theta_l$$
$$+ \frac{1}{2}P_1 F_T \sin\theta_K{}^2 \sin\theta_l{}^2 \cos 2\phi$$
$$+ \sqrt{F_T F_L}(\frac{1}{2}P_4' \sin 2\theta_K \sin 2\theta_l \cos\phi + P_5' \sin 2\theta_K \sin\theta_l \cos\phi)$$
$$\sqrt{F_T F_L}(P_6' \sin 2\theta_K \sin\theta_l \sin\phi - \frac{1}{2}P_8' \sin 2\theta_K \sin 2\theta_l \sin\phi)$$
$$+ 2P_2 F_T \sin\theta_K{}^2 \cos\theta_l - P_3 F_T \sin\theta_K{}^2 \sin\theta_l{}^2 \sin 2\phi\Big].$$

K^{*0} **transverse / longitudinal polarisation**
(prone to hadronic uncertainties coming from form factor calculations)

$P_i^{(\prime)}$ **basis**
(form factor independent; theoretically clean)

- New physics can alter the value of the angular parameters wrt to their SM predictions

- Some tensions were already detected in P_5' :



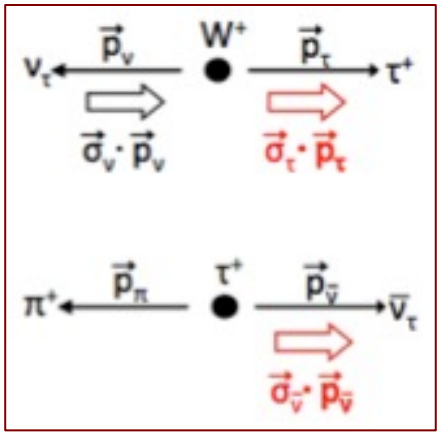
Looking at tau decays

arXiv:1903.04560

Low H^+ mass:

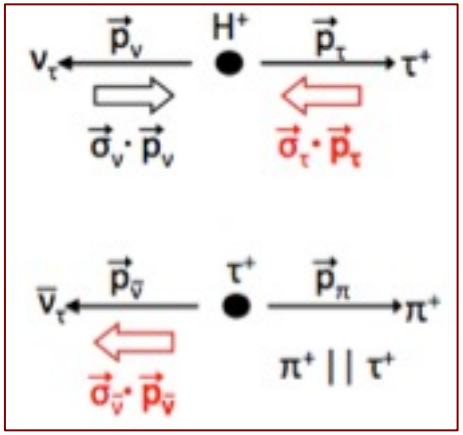
- Use R variable in the limit extraction: binned maximum-likelihood fit
- Tau fake component is data-driven, includes uncertainties

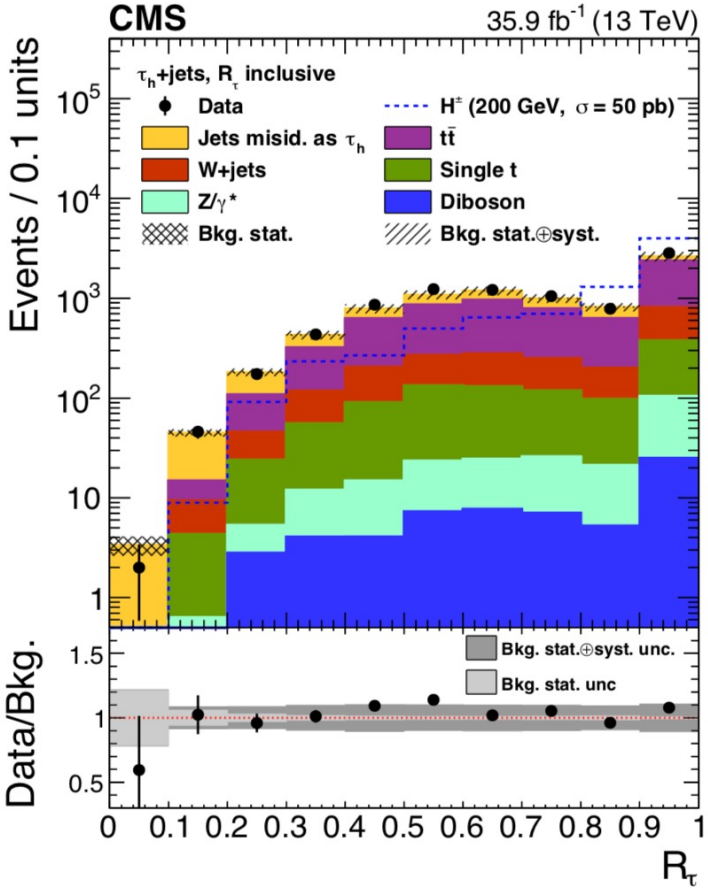
SM



vs

BSM

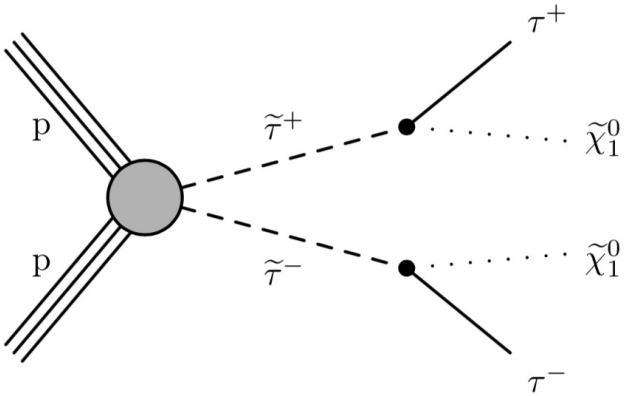


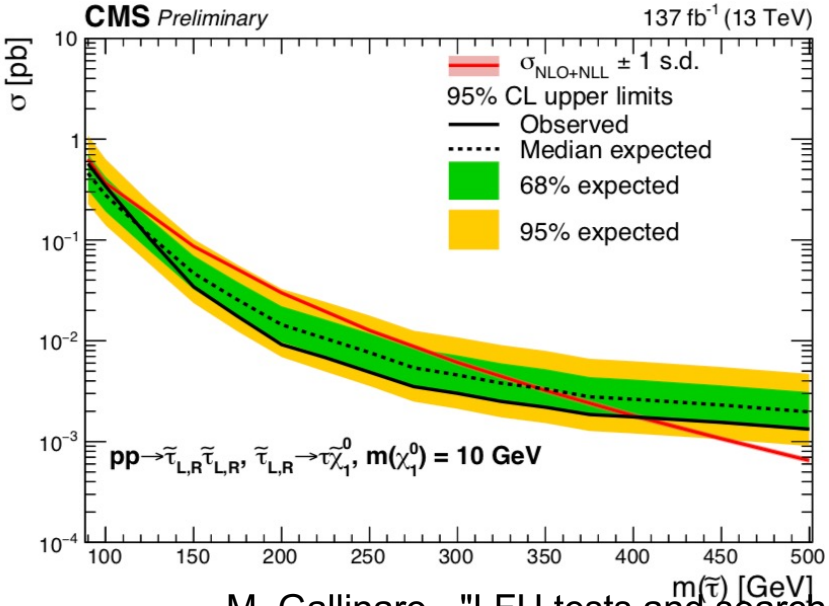


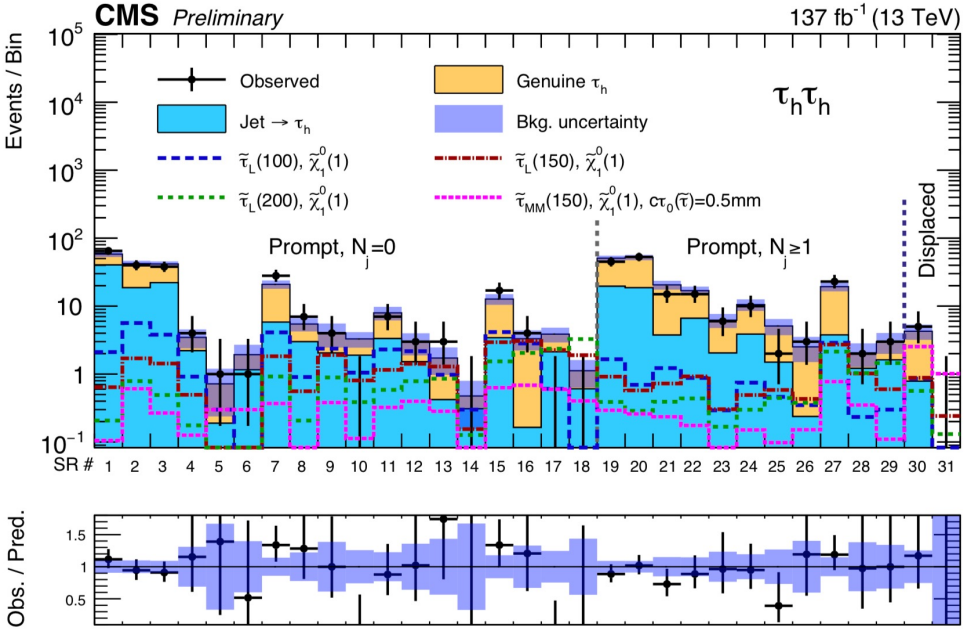
SUSY: staus

CMS-SUS-21-001

- Direct production of τ slepton pairs
- τ neutralino coannihilation models provide a mechanism that can explain the observed DM relic density
- Prompt and long-lived tau pairs
  - 2 tau- or MET- triggers
  - simultaneous maximum likelihood fit of data in 31 SRs
  - Σ*m*T, the sum of the transverse masses (*m*T) calculated for each τ with *MET*
- Bkg: DY, W+jets, ttbar, VV, QCD







W BRs: Event selection

CMS-SMP-18-011

- Use inclusive lepton triggers
- Events are characterized based on jet and b-tag multiplicities
  - Improve sensitivity to specific BRs and constrain systematics
- For each category, events are binned based on a kinematic observable

<table>
<tr><th></th><th>$N_j = 0$</th><th>$N_j = 1$</th><th>$N_j = 2$</th><th>$N_j = 3$</th><th>$N_j \geq 4$</th></tr>
<tr><td rowspan="2">$N_b = 0$</td><td>$e\tau, \mu\tau,$</td><td>$e\tau, \mu\tau,$</td><td colspan="3">$e\tau, \mu\tau$</td></tr>
<tr><td>$e\mu$</td><td>$e\mu$</td><td colspan="3">$ee, \mu\mu, e\mu$</td></tr>
<tr><td rowspan="3">$N_b = 1$</td><td rowspan="3"></td><td rowspan="2">$e\tau, \mu\tau, e\mu$</td><td>$e\tau, \mu\tau$</td><td colspan="2">$e\tau, \mu\tau$</td></tr>
<tr><td colspan="3">$ee, \mu\mu, e\mu$</td></tr>
<tr><td colspan="3"></td><td>$eh, \mu h$</td></tr>
<tr><td rowspan="3">$N_b \geq 2$</td><td rowspan="3"></td><td rowspan="3"></td><td>$e\tau, \mu\tau$</td><td colspan="2">$e\tau, \mu\tau$</td></tr>
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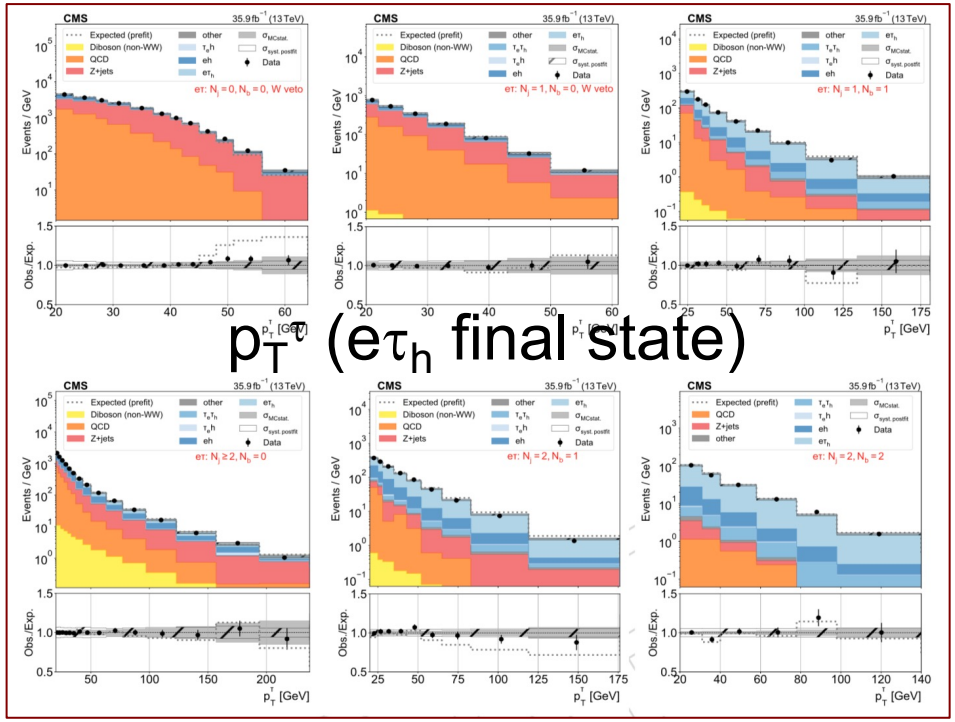
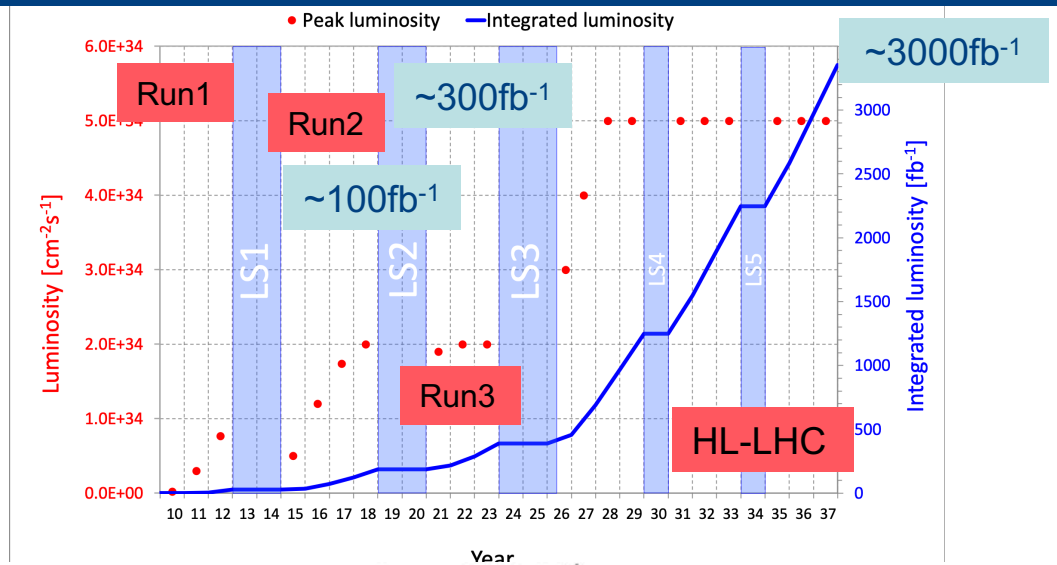
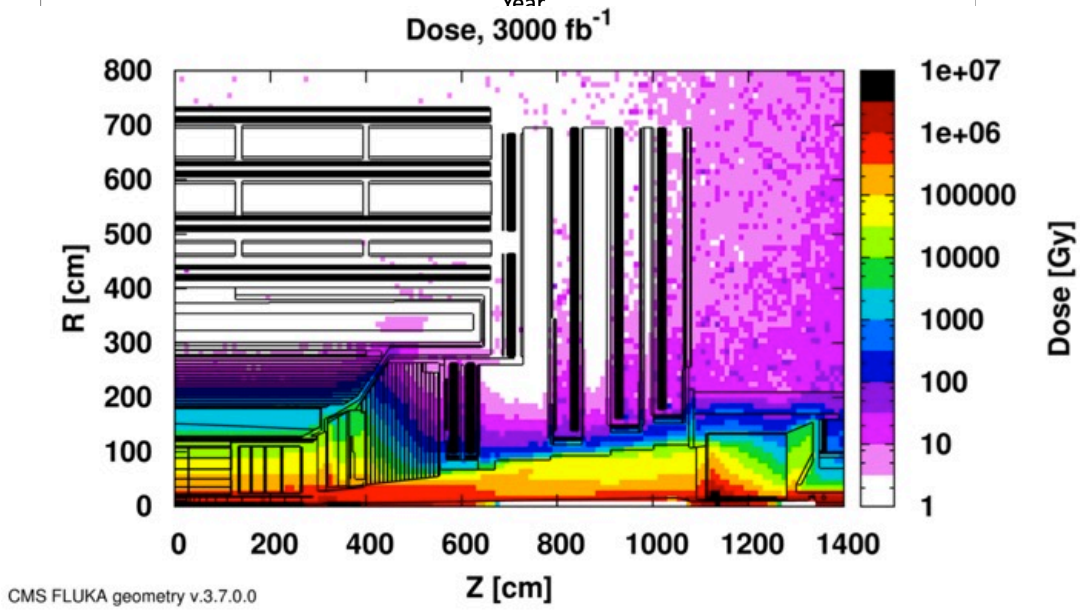


Prospects for Run3 and beyond

- More luminosity in a more challenging environment
- Will enhance the mass reach in the search for new particles
- Need to meet experimental challenges
  - Aging of detector, improve/adapt capability
  - Integrated luminosity: 300-3000/fb
  - peak luminosity of $2x10^{35}cm^{-2}s^{-1}$
  - pileup will be ~150 or higher (Phase2)
  - large radiation doses

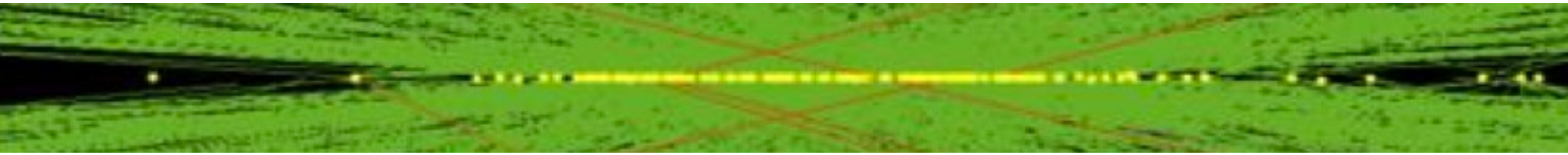




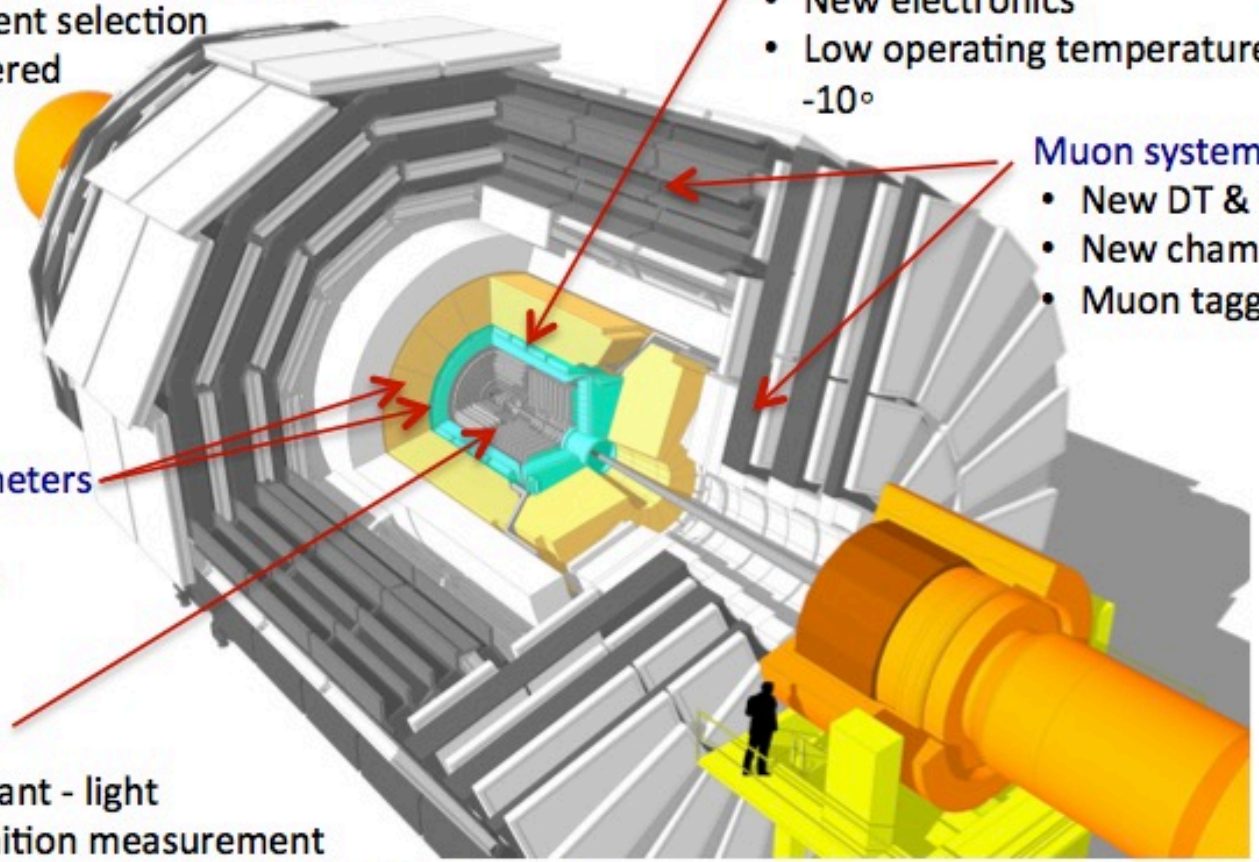
HL-LHC upgrades

Luminosity of ~3000 fb^{-1} expected for HL-LHC

- Tracking information in "L1 track-trigger"
  - Tracker designed to enable finding all tracks w/p_T>2GeV in <4μs
- Tracker is all silicon but with much higher granularity, up to $|\eta|$=4
  - >2billion pixels and strips
- High Granularity Endcap Calorimeters
  - Sampling of EM showers: every ~1λ (28 samples) w/pixels, and every ~0.35λ (24 samples) with pixels+scintillator to map 3D shower development
  - ~6M channels in all
- Precision timing to add a 4th dimension to object reconstruction



Future: HL-LHC upgrades



Trigger/HLT/DAQ
- Track information in hardware event selection
- 750 kHz hardware event selection
- 7.5 kHz events registered

Barrel EM calorimeter
- New electronics
- Low operating temperature ≃ -10°

Muon systems
- New DT & CSC electronics
- New chambers $1.6 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$

New Endcap Calorimeters
- Rad. Tolerant
- 5D measurement

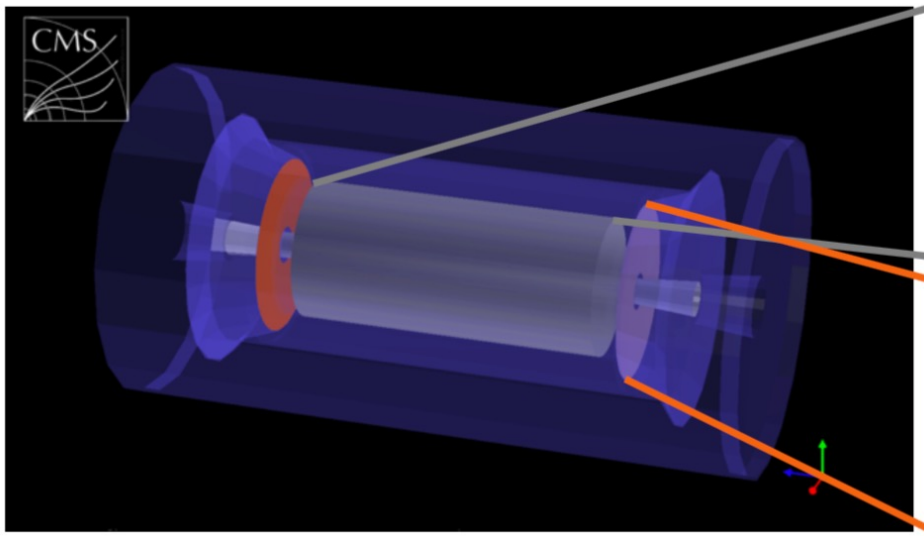
New Tracker
- Rad. Tolerant - light
- High Definition measurement
- 40 MHz selective readout for hardware trigger
- Extended Pixel coverage to $\eta \simeq 3.8$

Beam radiation and luminosity
Common systems and infrastructure

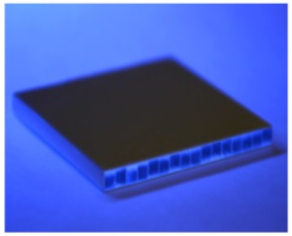
MIP Timing Detector @CMS

CERN-LHCC-2019-003

- High precision time measurement of MIPs
  - 30-40 ps at start, degrading to <60ps at 3000 fb^{-1}
  - Provide track-vertex association
  - Improve sensitivity to slow particles, add particle ID capabilities, etc.



BTL: LYSO bars + SiPM read-out
- ▹ TK / ECAL interface ~ 45 mm thick
- ▹ $|\eta| < 1.45$ and $p_T > 0.7$ GeV
- ▹ Active area ~ 38 m^2 ; 332k channels
- ▹ Fluence at 3 ab^{-1}: 2×10^{14} n_{eq}/cm^2



ETL: Si with internal gain (LGAD)
- ▹ On the HGC nose ~ 65 mm thick
- ▹ $1.6 < |\eta| < 3.0$
- ▹ Active area ~ 14 m^2; ~ 8.5M channels
- ▹ Fluence at 3 ab^{-1}: up to 2×10^{15} n_{eq}/cm^2