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

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LIP Lisbon
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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, $\nu$ masses, DM, dark energy, etc.)

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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 $e/\mu/\tau$ ratios, etc.
Recent hints for breaking of LFU

- Both in neutral \((b \rightarrow s \ell^+ \ell^-)\) and charged \((b \rightarrow c \tau \nu)\) decays: \((3.1 \sigma)\)
- \((g-2)_{\mu} : (4.2 \sigma)\)

\[
R_{D^+} = \frac{BR(B \rightarrow D^{(*)} \tau \nu)}{BR(B \rightarrow D^{(*)} \ell \nu)}
\]

\[
R_K = \frac{BR(B^+ \rightarrow K^+ \mu^+ \mu^-)/BR(B^+ \rightarrow K^+ J/\psi (\mu^+ \mu^-))}{BR(B^+ \rightarrow K^+ e^+ e^-)/BR(B^+ \rightarrow K^+ J/\psi (e^+ e^-))}
\]

\[\ell \in \{e, \mu\}\]
Angular distributions: $B^0$ decays

- $B^0 \rightarrow K^* \mu\mu$ 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

From first identification of hadronic tau decays to precise measurements

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1997
fake rate ~0.3%

2021

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

4 ttbar candidate events
Tau lepton identification (cont.)

CMS-TAU-20-001

• Hadronic tau ($\tau_h$) 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 $\approx 2\%$ (was 6%)
W branching fractions

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

- Most precise determination of $B(W \rightarrow l\nu)$ from LEP has 2.6σ deviation from LFU

$$R_\tau/\ell = \frac{2 B(W \rightarrow \tau \bar{\nu}_\tau)}{B(W \rightarrow e\bar{\nu}_e) + B(W \rightarrow \mu \bar{\nu}_\mu)} = 1.066 \pm 0.025$$
W branching fractions (cont.)

- 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 $\tau$ 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 $\alpha_S(m_W^2)$

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

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

$$|V_{cs}| = 0.969 \pm 0.011$$

$$\alpha_S(m_W^2) = 0.094 \pm 0.033$$

<table>
<thead>
<tr>
<th></th>
<th>CMS</th>
<th>LEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B(W \to e\bar{\nu}_e)$</td>
<td>$(10.83 \pm 0.01 \pm 0.10)%$</td>
<td>$(10.71 \pm 0.14 \pm 0.07)%$</td>
</tr>
<tr>
<td>$B(W \to \mu\bar{\nu}_\mu)$</td>
<td>$(10.94 \pm 0.01 \pm 0.08)%$</td>
<td>$(10.63 \pm 0.13 \pm 0.07)%$</td>
</tr>
<tr>
<td>$B(W \to \tau\bar{\nu}_\tau)$</td>
<td>$(10.77 \pm 0.05 \pm 0.21)%$</td>
<td>$(11.38 \pm 0.17 \pm 0.11)%$</td>
</tr>
<tr>
<td>$B(W \to h)$</td>
<td>$(67.46 \pm 0.04 \pm 0.28)%$</td>
<td>$(67.41 \pm 0.18 \pm 0.20)%$</td>
</tr>
</tbody>
</table>

with LU

<table>
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<tr>
<td>$B(W \to \ell\bar{\nu})$</td>
<td>$(10.89 \pm 0.01 \pm 0.08)%$</td>
<td>$(10.86 \pm 0.06 \pm 0.09)%$</td>
</tr>
<tr>
<td>$B(W \to h)$</td>
<td>$(67.32 \pm 0.02 \pm 0.23)%$</td>
<td>$(67.41 \pm 0.18 \pm 0.20)%$</td>
</tr>
</tbody>
</table>
Probing the Wtb vertex

Top quark decays: dileptons with taus

- cross section measurement including $\tau$s
- Includes only 3rd generation quarks/leptons
- Syst unc: taud, fakes

<table>
<thead>
<tr>
<th>Channel</th>
<th>Signature</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dilepton(e/\mu)</td>
<td>$ee, \mu\mu, e\mu + 2b$-jets</td>
<td>4/81</td>
</tr>
<tr>
<td>Single lepton</td>
<td>$e, \mu +$ jets + 2$bb$-jets</td>
<td>24/81</td>
</tr>
<tr>
<td>All-hadronic</td>
<td>jets + 2$bb$-jets</td>
<td>36/81</td>
</tr>
<tr>
<td>Tau dilepton</td>
<td>$e\tau, \mu\tau$ + 2 $b$-jets</td>
<td>4/81</td>
</tr>
<tr>
<td>Tau+jets</td>
<td>$\tau$ + jets + 2$bb$-jets</td>
<td>12/81</td>
</tr>
</tbody>
</table>

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

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MSSM: coupling to taus large for high $\tan\beta$

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

- Search for $H^+$ bosons produced in VBF processes
- Use leptonic final states ($e, \mu$)
- Combination of methods based on simulation and CRs in data used to estimate backgrounds
- Set constraints on $H^+$ and $H^{++}$ production
Rare decays: $\tau \rightarrow 3\mu$

- LFV processes can occur via neutrino mixing

- Lepton flavour violating decay: $\tau \rightarrow 3\mu$
  - Very rare process, $\text{BR} \sim 10^{-10} - 10^{-8}$
  - World’s best limit: $2.1 \times 10^{-8}$ (Belle)

- Search performed in 2016 data
  - Tau leptons produced in $W$ and HF hadron decays
  - $2/3$ low-$p_T$ muons trigger
  - Select $3\mu$ candidates
  - BDT for signal (MC) & bkg (sidebands) separation

- No evidence for a $\tau \rightarrow 3\mu$ decay signal found

- Set upper limit:

$$\mathcal{B}(\tau \rightarrow 3\mu) < 8.0(6.9) \times 10^{-8}$$
Higgs boson couplings

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

• Signal strength wrt SM:

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

• obs.(exp.) significance: $3.0(2.5)\sigma$

⇒ couplings in agreement w/SM

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Some BSM models allow for LFV Higgs decays

- Search for $H \rightarrow \tau \tau$, $e \mu$, $\mu \tau$ final states
  - $N_{\text{jet}}$ to target ggH and VBF production
  - Categories: $N_{\text{jet}}$, lepton kinematics

Main background from DY, ttbar, WW

⇒ No significant deviation found
Limits set on off-diagonal Yukawa coupling terms, $Y$

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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
- $\tau$-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 $\tau$ leptons in final state

Top squark search in ditau final state

- High-$\tan\beta$ and higgsino-like scenario, the chargino mostly decays to $\tau$ leptons

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SUSY: LQ pair

- SUSY searches for pair produced squarks
  - For $M(\chi)=0$: same final state as $LQ \rightarrow q\nu$
- Reinterpretation in LQ models
- Signal acceptance is similar
- Interpretation in scalar and vector scenarios
  - Exclude $M_{LQ}<1$ TeV (scalar) and $<1.8$ TeV (vector)
• 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 (tv) or LQ→bν (bτ)
  – Fully hadronic final state: top (resolved or boosted), τh, b

• Set limits on lepton-quark coupling λ vs M_{LQ}

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PLB 819(2020)136446
Long-lived heavy neutral leptons

- HNL can be produced through mixing with SM vs
  - 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
Heavy resonances & QBHs

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

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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
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 $\sim 10^{10}$ 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

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Flavour anomalies

- Several measurements deviate from SM predictions
  - Angular observables in $B \rightarrow K^* \mu\mu$
  - Branching ratios
  - $R_D$ ratios show combined deviation from SM by 3-4σ
  - Combination of $B_s \rightarrow \mu\mu$ measurements (2.3σ)
**LFU: anomalies**

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

\[
R_{D(*)} = \frac{BR(B \rightarrow D^{(*)\tau\nu})}{BR(B \rightarrow D^{(*)\ell\nu})} \quad \ell \in \{e, \mu\}
\]

\[
R_K = \frac{B(B^+ \rightarrow K^+\mu^+\mu^-)}{B(B^+ \rightarrow K^+J/\psi(\mu^+\mu^-))} / \frac{B(B^+ \rightarrow K^+e^+e^-)}{B(B^+ \rightarrow K^+J/\psi(e^+e^-))}
\]

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Angular distributions

Angular variables

- The \( B^0 \rightarrow K^{*0}(K^+\pi^-) \mu^+\mu^- \) 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:

\[
B^0 \rightarrow K^{*0} \mu^+\mu^- \text{ CP averaged decay rate} \]

\[
\frac{1}{d\Gamma} \frac{d^4\Gamma}{dq^2 dq^2 d\cos \theta_d d\phi} = \frac{3}{16\pi} \left[ \frac{3}{4} F_T \sin \theta_K^2 + F_L \cos \theta_K^2 \\
+ \left( \frac{1}{4} F_T \sin \theta_K^2 - F_L \cos \theta_K^2 \right) \cos 2\theta_l \\
+ \frac{1}{2} P_T F_T \sin \theta_K^2 \sin \theta_l^2 \cos 2\phi \\
+ \sqrt{F_T F_L} \left( \frac{1}{2} P_T \sin 2\theta_K \sin 2\theta_l \cos \phi + P_L \sin 2\theta_K \sin \theta_l \cos \phi \right) \\
\sqrt{F_T F_L} \left( P_T \sin 2\theta_K \sin \theta_l \sin \phi - \frac{1}{2} P_L \sin 2\theta_K \sin 2\theta_l \sin \phi \right) \\
+ 2 P_T F_T \sin \theta_K^2 \cos \theta_l - P_L F_T \cos \theta_K^2 \sin \theta_l^2 \sin 2\phi \right].
\]

- 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

Low H\(^+\) mass:

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

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SUSY: staus

- Direct production of $\tau$ slepton pairs
- $\tau$ 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
  - $\Sigma mT$, the sum of the transverse masses ($mT$) calculated for each $\tau$ with MET
- Bkg: DY, W+jets, ttbar, VV, QCD
W BRs: Event selection

- 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>
<thead>
<tr>
<th>$N_j$</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>
</thead>
<tbody>
<tr>
<td>$N_b = 0$</td>
<td>$e\tau, \mu\tau, e\mu$</td>
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<td>$ee, \mu\mu, e\mu$</td>
<td>$ee, \mu\mu, e\mu$</td>
</tr>
<tr>
<td>$N_b = 1$</td>
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<td>$e\tau, \mu\tau$</td>
<td>$ee, \mu\mu, e\mu$</td>
<td>$eh, \mu h$</td>
</tr>
<tr>
<td>$N_b \geq 2$</td>
<td>$e\tau, \mu\tau$</td>
<td>$e\tau, \mu\tau$</td>
<td>$ee, \mu\mu, e\mu$</td>
<td>$eh, \mu h$</td>
<td>$eh, \mu h$</td>
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</table>

$\mathbf{p_T^{\ell \tau}}$ (e$\tau_h$ final state)
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 $2 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}$
  – pileup will be $\sim$150 or higher (Phase2)
  – large radiation doses

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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 \(p_T > 2\text{GeV}\) in <4\(\mu\text{s}\)
- **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 \(\sim 1\lambda\) (28 samples) w/pixels, and every \(\sim 0.35\lambda\) (24 samples) with pixels+scintillator to map 3D shower development
  - ~6M channels in all
- **Precision timing to add a 4\(^{\text{th}}\) 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 \(\approx -10^\circ\)

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 \(\eta = 3.8\)
High precision time measurement of MIPs

- 30-40 ps at start, degrading to <60 ps at 3000 fb⁻¹
- Provide track-vertex association
- Improve sensitivity to slow particles, add particle ID capabilities, etc.