The Flavor of Higgs

ZPW2015: The flavor of new physics

University of Zurich
7 January 2015

Yossi Nir (*Weizmann Institute of Science*)

Plan of Talk

1. Introduction
   Flavor@LHC YN, Phys. Scripta T158 (2013) 014005

2. $h \to \ell_i \ell_j$:
   Theory Dery, Efrati, Hochberg, YN, JHEP 1305 (2013) 039 [1302.3229]

3. $t \to hq,\ h \to \tau\ell$:
   Model building Dery, Efrati, YN, Soreq, Susič, PRD 90 (2014) 115022 [1408.1371]

4. $h \to \tau\ell$:
   Experiment Bressler, Dery, Efrati, PRD 90 (2014) 015025 [1405.3229]

Introduction

Questions for the LHC

- What is the mechanism of electroweak symmetry breaking?
- What separates the electroweak scale from the Planck scale?
- What happened at the electroweak phase transition?
- How was the baryon asymmetry generated?
- What are the dark matter particles?
- What is the solution of the flavor puzzles?

Questions for the LHC

- What is the mechanism of electroweak symmetry breaking?
  The BEH mechanism; a VEV of a doublet scalar field
- What separates the electroweak scale from the Planck scale?
- What happened at the electroweak phase transition?
- How was the baryon asymmetry generated?
- What are the dark matter particles?
- What is the solution of the flavor puzzles?

Questions for the LHC

- What is the mechanism of electroweak symmetry breaking?
  The BEH mechanism; a VEV of a doublet scalar field
- What separates the electroweak scale from the Planck scale?
  No idea. No signs of supersymmetry, composite Higgs...
- What happened at the electroweak phase transition?
- How was the baryon asymmetry generated?
- What are the dark matter particles?
- What is the solution of the flavor puzzles?

Questions for the LHC

- What is the mechanism of electroweak symmetry breaking?
  The BEH mechanism; a VEV of a doublet scalar field
- What separates the electroweak scale from the Planck scale?
  No idea. No signs of supersymmetry, composite Higgs...
- What happened at the electroweak phase transition
  $gg \to h$, $h \to \gamma\gamma$ exclude many possibilities for 1st order PT
- How was the baryon asymmetry generated?
- What are the dark matter particles?
- What is the solution of the flavor puzzles?

Questions for the LHC

- What is the mechanism of electroweak symmetry breaking?
  The BEH mechanism; a VEV of a doublet scalar field
- What separates the electroweak scale from the Planck scale?
  No idea. No signs of supersymmetry, composite Higgs...
- What happened at the electroweak phase transition
  $gg \to h$, $h \to \gamma\gamma$ exclude many possibilities for 1st order PT
- How was the baryon asymmetry generated?
  If not 1st order PT – not electroweak baryogenesis
- What are the dark matter particles?
- What is the solution of the flavor puzzles?

Questions for the LHC

- What is the mechanism of electroweak symmetry breaking?
  The BEH mechanism; a VEV of a doublet scalar field
- What separates the electroweak scale from the Planck scale?
  No idea. No signs of supersymmetry, composite Higgs...
- What happened at the electroweak phase transition
  $gg \to h$, $h \to \gamma\gamma$ exclude many possibilities for 1st order PT
- How was the baryon asymmetry generated?
  If not 1st order PT – not electroweak baryogenesis
- What are the dark matter particles?
  No idea. No signs of missing energy events BSM
- What is the solution of the flavor puzzles?

Questions for the LHC

- What is the mechanism of electroweak symmetry breaking?
  The BEH mechanism; a VEV of a doublet scalar field
- What separates the electroweak scale from the Planck scale?
  No idea. No signs of supersymmetry, composite Higgs...
- What happened at the electroweak phase transition
  $gg \to h$, $h \to \gamma\gamma$ exclude many possibilities for 1st order PT
- How was the baryon asymmetry generated?
  If not 1st order PT – not electroweak baryogenesis
- What are the dark matter particles?
  No idea. No signs of missing energy events BSM
- What is the solution of the flavor puzzles?
  The topic of this talk

The flavor puzzles

- The SM flavor puzzle:
  Why is there structure in the charged fermion flavor parameters?
  Smallness and hierarchy

- The SM flavor puzzle extended:
  Why is the neutrino flavor structure different?
  Neither smallness nor hierarchy

- The NP flavor puzzle:
  If there is TeV-scale NP, why doesn't it affect FCNC?
  Degeneracy and alignment

Can we make progress?

- NP that couples to quarks/leptons $\Longrightarrow$ New flavor parameters (spectrum, flavor decomposition) that can be measured
- The NP flavor structure could be:
  - MFV
  - Related but not identical to SM
  - Unrelated to SM or even anarchical
- The NP flavor puzzle:
  With ATLAS/CMS we are likely to understand how it is solved
- The SM flavor puzzle:
  Progress possible if structure not MFV but related to SM

Can we make progress?

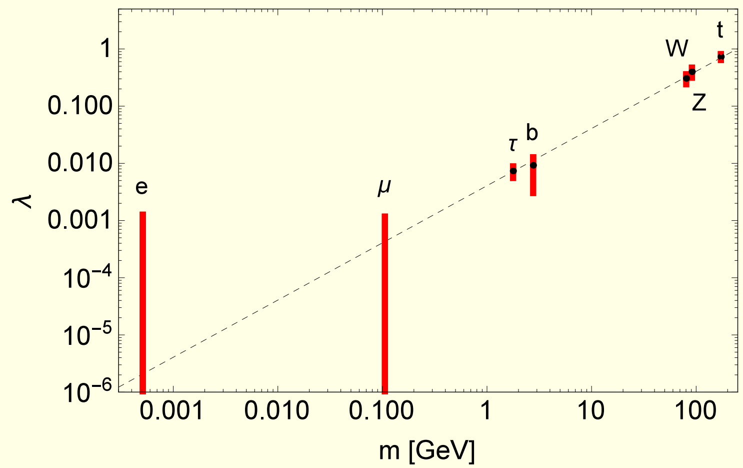
- NP that couples to quarks/leptons $\Longrightarrow$ New flavor parameters (spectrum, flavor decomposition) that can be measured
- The NP flavor structure could be:
  - MFV
  - Related but not identical to SM
  - Unrelated to SM or even anarchical
- The NP flavor puzzle:
  With ATLAS/CMS we are likely to understand how it is solved
- The SM flavor puzzle:
  Progress possible if structure not MFV but related to SM
- $\boxed{h}$ $\Longrightarrow$ The "NP" is already here!
  $Y_{\bar{f}_i f_j}$ are new flavor parameters that can be measured

Relevant data

Observable	Experiment
$R_{\gamma\gamma}$	1.15 ± 0.18
R_{ZZ^*}	1.2 ± 0.2
R_{WW^*}	0.9 ± 0.2
$R_{b\bar{b}}$	0.7 ± 0.3
$R_{\tau\tau}$	1.04 ± 0.23
$R_{\mu\mu}$	< 7
R_{ee}	$< 4 \times 10^5$

- $R_f = \frac{\sigma_{\rm prod}{\rm BR}(h\to f)}{[\sigma_{\rm prod}{\rm BR}(h\to f)]^{\rm SM}}$

$Y_f \propto m_f$?



A. Efrati

- Indication that Y_t, Y_b, Y_τ not far from SM
- The beginning of Higgs flavor physics

Y_{ij}: Theory

Avital Dery, Aielet Efrati, Yonit Hochberg, YN, JHEP1305,039 [arXiv:1302.3229]

Avital Dery, Aielet Efrati, Gudrun Hiller, Yonit Hochberg, YN, JHEP1308,006 [arXiv:1304.6727]

Recent related work

- Blankenburg, Ellis, Isidori, Phys. Lett. B712, 386 (2012)
- Bhattacharyya, Leser, Pas, Phys. Rev D86, 036009 (2012)
- Harnik, Kopp, Zupan, JHEP 1303, 026 (2013)
- Davidson, Verdier, Phys. Rev. D80, 111701 (2012)
- Celis, Cirigliano, Passemar, Phys. Rev. D89, 013008 (2014)
- Falkowski, Straub, Vicente, JHEP 1405, 092 (2014)
- Delaunay *et al.*, Phys. Rev. D89, 033014 (2014)
- Gorbahn, Haisch, JHEP 1406, 033 (2014)
- Kagan *et al.*, arXiv:1406.1722
- Crivellin, D'Ambrosio, Heeck, arXiv: 1501.00993

Natural Flavor Conservation (NFC)

- A solution to the 2HDM flavor puzzle
- NFC $\equiv$ Each fermion sector (U, D, E) couples to a single Higgs doublet
- Type II: $\overline{Q}Y^U U\phi_2 + \overline{Q}Y^D D\phi_1 + \overline{L}Y^E E\phi_1$

- Y^F diagonal in the F mass basis
- $Y^F \propto M_F$
- No Higgs-mediated FCNC at tree level

Minimal Flavor Violation (MFV)

- A solution to the NP flavor puzzle
- SM: When $Y^F = 0 \Longrightarrow$ A large global symmetry
  $SU(3)_Q \times SU(3)_U \times SU(3)_D \times SU(3)_L \times SU(3)_E$
- MFV $\equiv$ The only NP breaking of the $SU(3)^5$ symmetry:
  $Y^U(3,\bar{3},0,0,0),\ Y^D(3,0,\bar{3},0,0),\ Y^E(0,0,0,3,\bar{3})$
- Example: Gauge mediated supersymmetry breaking
- FV suppressed by small fermion masses and CKM angles

The Froggatt-Nielsen mechanism (FN)

- A solution to both the SM and the NP flavor puzzles
- A $U(1)_H$ symmetry broken by a small spurion $\epsilon_H(-1) \ll 1$
- Different generations carry different H-charges
- Selection rules suppress FV parameters by powers of ϵ_H

  Example: $Y^U_{12} = \mathcal{O}(1) \times \epsilon_H^{H(\bar{Q}_1)+H(U_2)+H(\phi)}$
- Can solve also the ν flavor puzzle

Leptonic observables

Observable ($\ell = e, \mu$)	SM
$R_{\tau^+\tau^-}$	1
$X_{\ell\ell} = \frac{\text{BR}(h\to\ell^+\ell^-)}{\text{BR}(h\to\tau^+\tau^-)}$	$(m_\ell/m_\tau)^2$
$X_{\ell\tau} = \frac{\text{BR}(h\to\ell^\pm\tau^\mp)}{\text{BR}(h\to\tau^+\tau^-)}$	0

- What can we learn from $R_{\tau\tau},\ X_{\ell\ell},\ X_{\tau\ell}$?

Leptonic observables

Observable ($\ell = e, \mu$)	SM
$R_{\tau^+\tau^-}$	1
$X_{\ell\ell} = \frac{\text{BR}(h\to\ell^+\ell^-)}{\text{BR}(h\to\tau^+\tau^-)}$	$(m_\ell/m_\tau)^2$
$X_{\ell\tau} = \frac{\text{BR}(h\to\ell^\pm\tau^\mp)}{\text{BR}(h\to\tau^+\tau^-)}$	0

- What can we learn from $R_{\tau\tau},\ X_{\ell\ell},\ X_{\tau\ell}$?
- ATLAS/CMS:
  - $R_{\tau\tau} = 1.04 \pm 0.23$
  - $X_{\mu\mu} < 15(m_\mu/m_\tau)^2 \sim 0.05, \quad X_{ee} < 8\times10^5(m_e/m_\tau)^2 \sim 0.07$
  - $\text{BR}_{\tau\mu} = 0.009 \pm 0.004 \implies X_{\mu\tau} = 0.14 \pm 0.06 < 0.3$

Flavor models

- 2HDM with Type II NFC
  - Universal correction to the diagonal couplings
- 1HDM with MFV
  - Non-universal correction to the diagonal couplings
- 1HDM with FN
  - Non-universal correction to the diagonal couplings + Off-diagonal couplings

Higgs Physics = new flavor arena

Model	$Y_\tau^2/(2m_\tau^2/v^2)$	$(Y_\mu^2/Y_\tau^2)/(m_\mu^2/m_\tau^2)$	$Y_{\mu\tau}^2/Y_\tau^2$
SM	1	1	0
NFC	$(V_{h\ell}v/v_\ell)^2$	1	0
MSSM	$(\sin\alpha/\cos\beta)^2$	1	0
MFV	$1+2av^2/\Lambda^2$	$1-4bm_\tau^2/\Lambda^2$	0
FN	$1+\mathcal{O}(v^2/\Lambda^2)$	$1+\mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}(\|U_{23}\|^2v^4/\Lambda^4)$
GL	9	$25/9$	$\mathcal{O}(10^{-2})$

Higgs Physics = new flavor arena

Model	$Y_\tau^2/(2m_\tau^2/v^2)$	$(Y_\mu^2/Y_\tau^2)/(m_\mu^2/m_\tau^2)$	$Y_{\mu\tau}^2/Y_\tau^2$
SM	1	1	0
NFC	$(V_{h\ell}v/v_\ell)^2$	1	0
MSSM	$(\sin\alpha/\cos\beta)^2$	1	0
MFV	$1+2av^2/\Lambda^2$	$1-4bm_\tau^2/\Lambda^2$	0
FN	$1+\mathcal{O}(v^2/\Lambda^2)$	$1+\mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}(\|U_{23}\|^2v^4/\Lambda^4)$
GL	9	$25/9$	$\mathcal{O}(10^{-2})$

Measuring Y_{ij} can probe flavor models

Y_{ij}: Model Building

Avital Dery, Aielet Efrati, Gudrun Hiller, YN, Yotam Soreq, Vasja Susič, PRD 90, 115022 (2014)

[arXiv:1408.1371]

The question

- Experimentally, the best direct probes of FC Higgs couplings:
  - $t \to hq$ $(q = c, u)$
  - $h \to \tau\ell$ $(\ell = \mu, e)$
- Are there viable and natural flavor models that have
  - $Y_{qt} \sim 0.17$ but $Y_{uc} \lesssim 10^{-4}$?
  - $Y_{\ell\tau} \sim 0.02$ but $Y_{e\mu} \lesssim 10^{-6}$?

$Y_{tq}, Y_{\tau\ell}$ in flavor models

- NFC
  - Impossible ($Y_{qt} = Y_{\ell\tau} = 0$)
- MQFV
  - Impossible ($Y_{ct} \lesssim V_{cb} \sim 0.04$)
- MLFV
  - Possible only with full seesaw (Y^E, Y^N, M^N) and accidental cancelations
- FN:
  - Possible only with supersymmetry and holomorphic zeros

Summary: $Y_{tq}, Y_{\tau\ell}$ in flavor models

- The upper bounds on Y_{tc} and $Y_{\tau\mu}$ can be saturated within viable and natural flavor models
- The models are not generic and need to be carefully selected
- If $t \to hq$ or $h \to \tau\ell$ is observed in experiments, it will challenge present explanations of the flavor puzzles

$Y_{\tau\ell}$: Experiment

Shikma Bressler, Avital Dery, Aielet Efrati, PRD 90 (2014) 015025 [1405.3229]

The background

- Consider the following signal processes:
  - $h \to \tau^\pm \mu^\mp$ followed by $\tau^\pm \to e^\pm \nu \bar{\nu}$
  - $h \to \tau^\pm e^\mp$ followed by $\tau^\pm \to \mu^\pm \nu \bar{\nu}$
- SM background:

  (i) $Z \to \tau^+ \tau^- \to \mu^\pm e^\mp \not{E}_T$

  (ii) $W^+ W^- \to \mu^\pm e^\mp \not{E}_T$
- Problem: signal lies in transitional region between (i) and (ii)
- Extrapolations from outside Higgs window inadequate; Monte-Carlo uncertain
- But: SM processes approximately symmetric under $e \leftrightarrow \mu$; $\text{BR}(h \to \tau\mu) \neq \text{BR}(h \to \tau e)$ breaks this symmetry

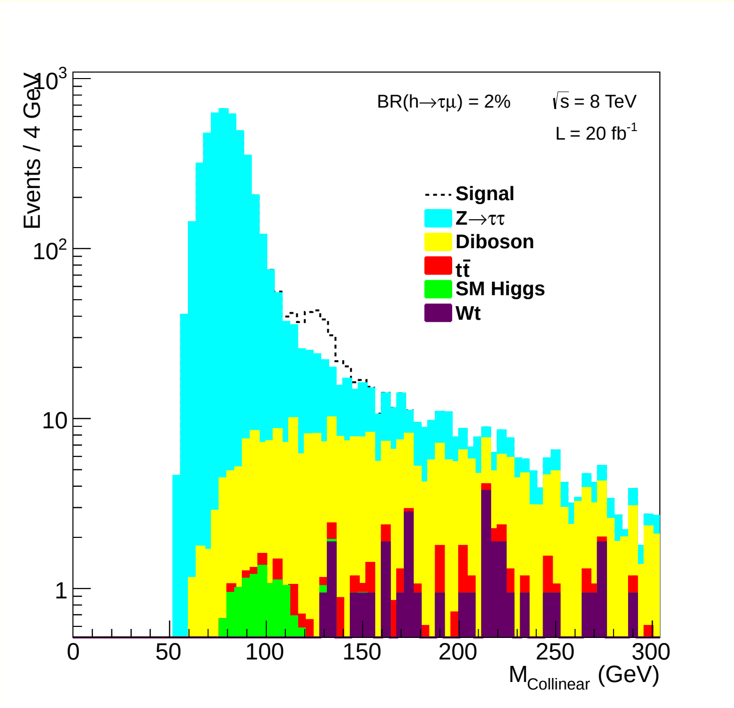
The method

- Divide the data to two mutually exclusive samples:
  - μe data sample: $p_T^\mu > p_T^e$
  - $e\mu$ data sample: $p_T^e > p_T^\mu$
- SM background: divided equally between the two samples
- $h \to \tau^\pm \mu^\mp$ events are mostly in the μe sample;
  $h \to \tau^\pm e^\mp$ events are mostly in the $e\mu$ sample
- Subtracting $(\mu e) - (e\mu)$ provides a measurement of
  $\mathrm{BR}_{\tau\mu} - \mathrm{BR}_{\tau e}$

The method

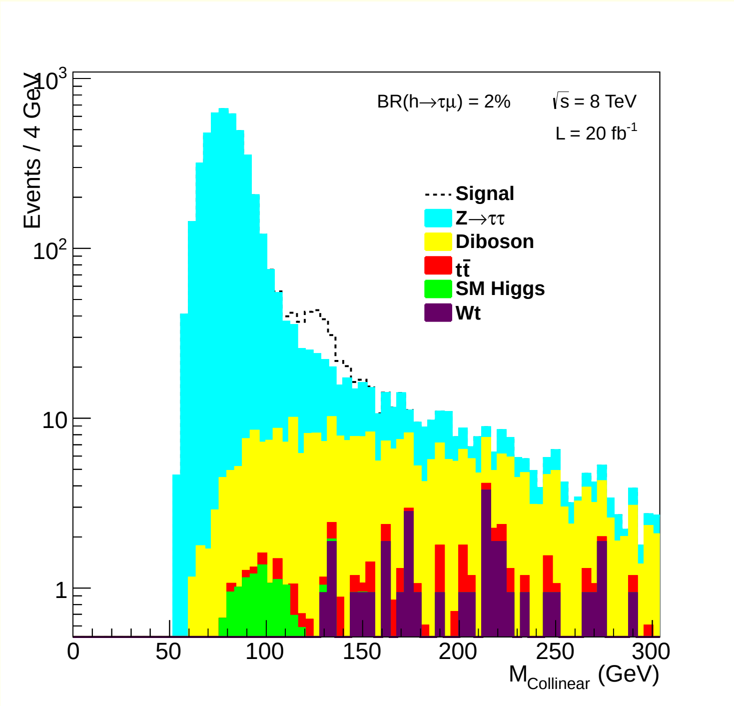
- Divide the data to two mutually exclusive samples:
  - μe data sample: $p_T^\mu > p_T^e$
  - $e\mu$ data sample: $p_T^e > p_T^\mu$
- SM background: divided equally between the two samples
- $h \to \tau^\pm \mu^\mp$ events are mostly in the μe sample;
  $h \to \tau^\pm e^\mp$ events are mostly in the $e\mu$ sample
- Subtracting $(\mu e) - (e\mu)$ provides a measurement of
  $\mathrm{BR}_{\tau\mu} - \mathrm{BR}_{\tau e}$
- The bounds from $\mu \to e\gamma$ imply that $\mathrm{BR}_{\tau\mu}$ and $\mathrm{BR}_{\tau e}$ cannot be simultaneously close to the respective upper bounds
- For $\mathrm{BR}_{\tau e} = 0$, the $e\mu$ sample provides the SM background

Data driven background estimate

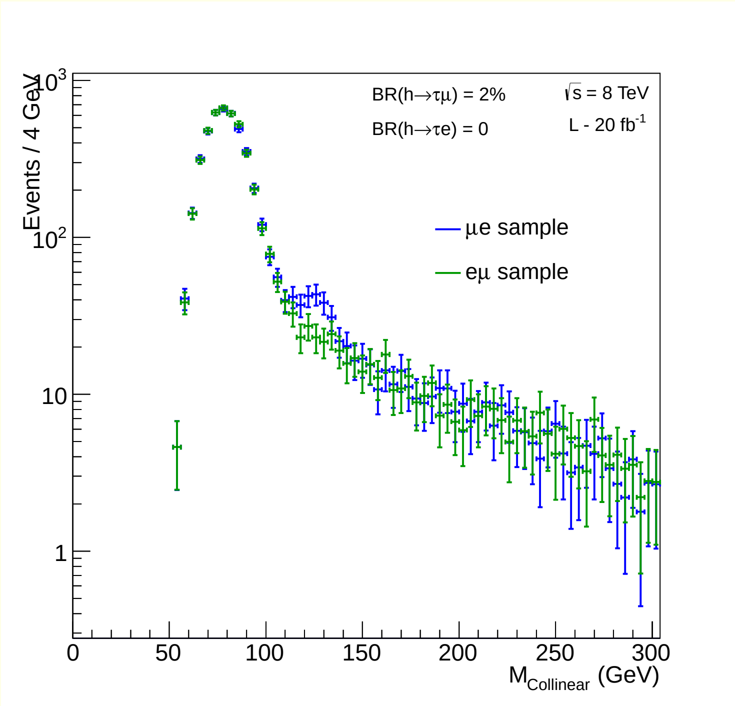


Simulated background+signal

Data driven background estimate



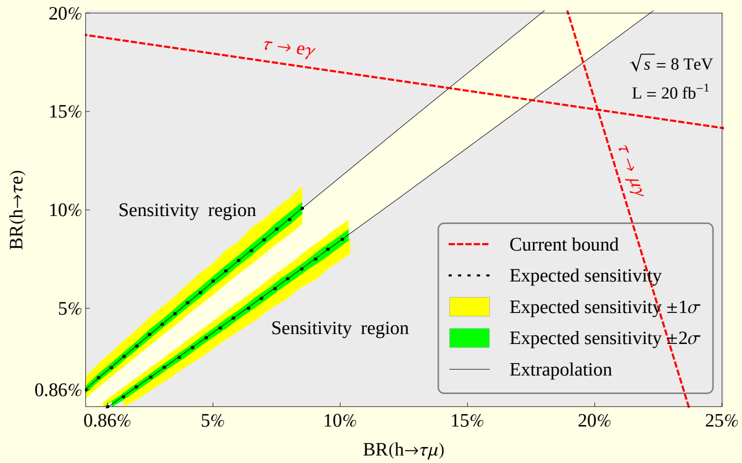
Simulated background+signal

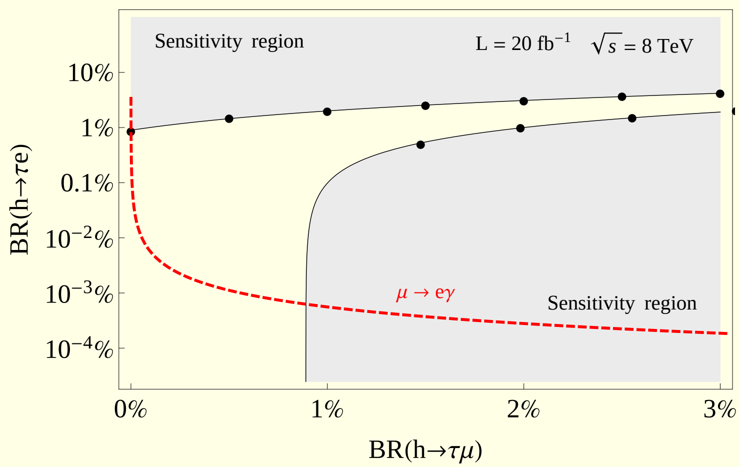


μe and $e\mu$ distributions

[Bressler, Dery, Efrati, 1405.4545]

The sensitivity





1405.4545

- With one rate negligibly small, and with 20 fb^{-1} of collected data: 3σ sensitivity for discovering $\mathrm{BR}_{\tau\mu}$ (or $\mathrm{BR}_{\tau e}$) $\simeq 0.9\%$.

Conclusions

h Physics = New Flavor Arena

Measure:

- Third generation couplings: Y_t, Y_b, Y_τ
- Second generation couplings: Y_c, Y_s, Y_μ
- Flavor violating couplings: $Y_{\mu\tau}$, $Y_{e\tau}$, Y_{ct}, Y_{ut}

Test:

- MFV
- FN
- NFC
- ...