Flavourful Directions towards Unravelling New Physics

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Setting the stage and why to care about flavour.

Three possible paths ahead:

NP close to threshold of Run 2

- ➜ Quick discovery via $\sqrt{s}$ increase
- ➜ Spectacular signals
- ➜ How is this compatible with precision Flavour?

Possible window for understanding aspects of the Flavour puzzle

NP heavier or weakly interacting

- ➜ Luminosity / **time** needed for discovery
- ➜ First signals may come from indirect searches

Flavour may point to scale/interaction strength we should focus on

NP inaccessible at the LHC

- ➜ LHC provide invaluable SM understanding for next-gen. experiments

Flavour & other indirect searches our only access to NP

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Flavour: why we care less

$$\mathcal{L}_{\text{SM-Yukawa}} \supset \overline{Q}_i H \, \mathbf{Y^u_{ij}} \, u_j + \overline{Q}_i \, \tilde{H} \, \mathbf{Y^d_{ij}} \, d_j$$

$$\begin{pmatrix} u & c & t \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Large Hierarchies ➜ SM Flavour Puzzle
Yukawas dimensionless ➜ Hierarchies technically natural, i.e.

$$\boldsymbol{Y} \propto \frac{\langle \Phi \rangle}{\Lambda}$$

Λ not fixed by Naturalness

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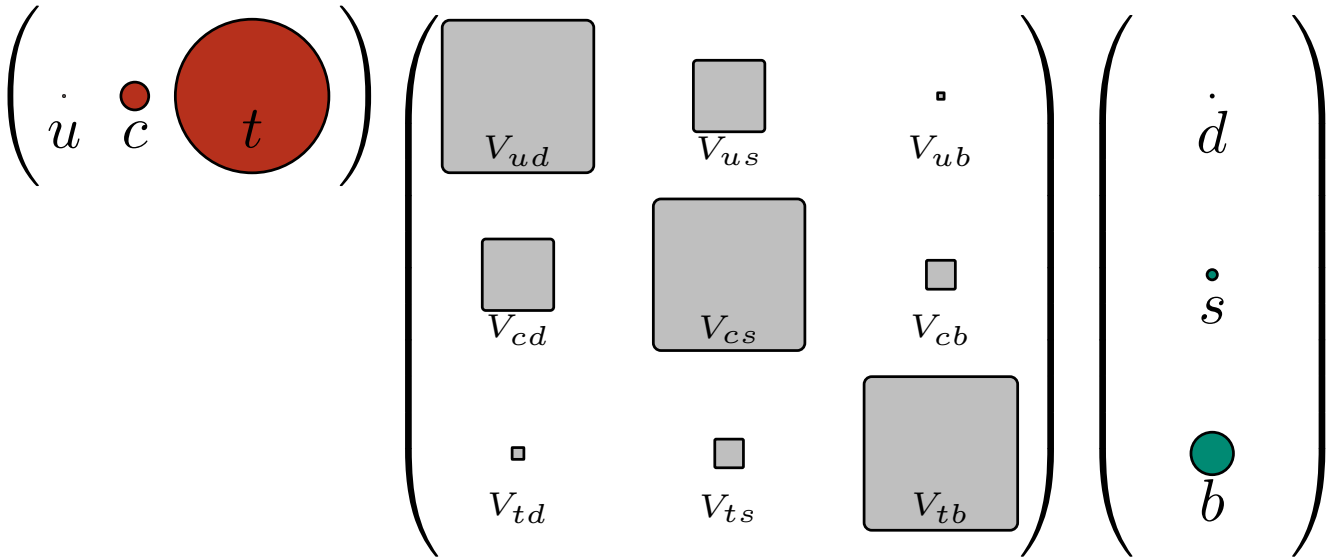

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Flavour: from a puzzle to a problem

- Generic TeV-scale NP typically introduce extra flavour violation

  e.g. squark masses m_{ij}^{LL}, partial-compositeness mixings, Δ_{ij}^{LL}

- FCNCS ➜ TeV-scale NP flavour violation must be tiny

New Physics Flavour Problem

- some sort of alignment with SM flavour violation necessary

  e.g. MFV, Wavefunction Suppression, Flavour Symmetries

- Apart from stringent constraints on NP this suggests an *opportunity*

Relation between NP Flavour Problem and SM Flavour Puzzle?

SUSY may be the mediator of Flavour dynamics to low scales, see next talk by Y. Shadmi

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Outline

"Traditional" Flavour: FCNCs

- $B_{s,d} \to \mu^+\mu^-$, $K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$,
- tensions in $B \to K^{(*)}\ell^+\ell^-$
  violation of lepton-flavour universality
- reverse logic: m_t from Flavour data

Higgs Flavour: the new Flavour arena

- a new "unitarity triangle"
- measuring the charm Yukawa
- directions for measuring light Yukawas

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“Traditional” Flavour

rare decays, FCNCS,. . .

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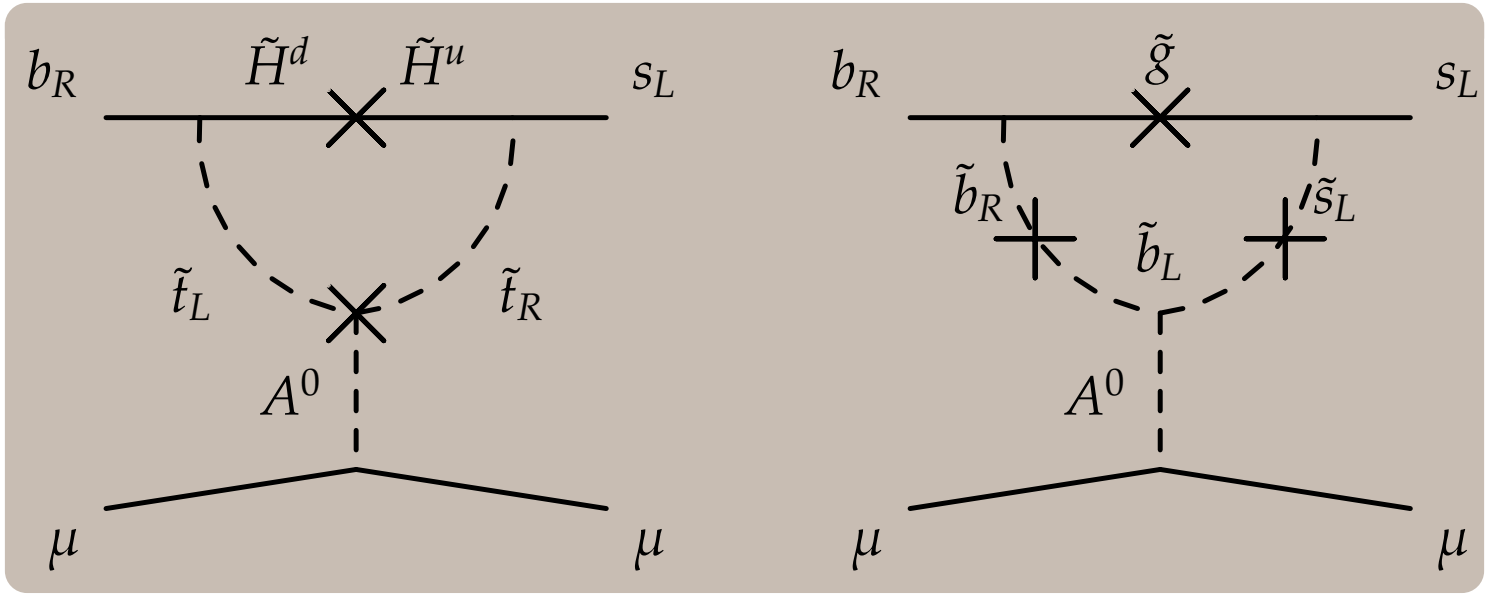
Rare decays: $B_{s,d} \to \mu^+\mu^-$

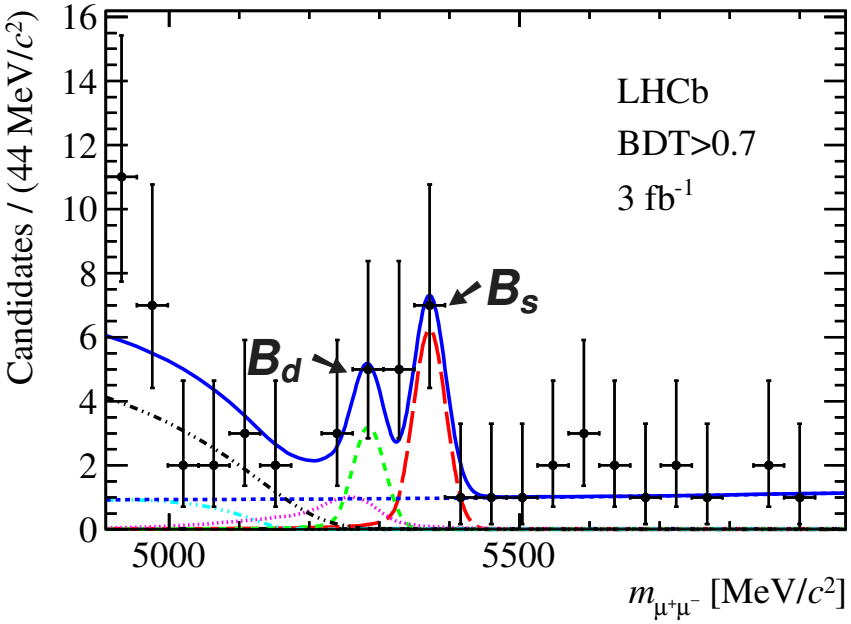
SM: loop-, CKM , and helicity suppressed + clean
SUSY: discovery channel



- SUSY generates **scalar pseudo-scalar operators**
- **BR** $\propto$ **tan**$^6\,\beta$, compensating helicity-suppression
- present even for **flavour-blind SUSY**
- decouples with $1/M_A^2$ **not with** $1/M^2_{\mathrm{SUSY}}$

Nevertheless,. . .

Rare decays: $B_{s,d} \to \mu^+\mu^-$



- Good agreement with SM expectations
- 2.3σ tension in Ratio

  [talk by Mimura]

LHCb+CMS

$$BR(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7)\times 10^{-9}$$
$$BR(B_d \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4})\times 10^{-10}$$

[CMS-PAS-BPH-13-007 ; LHCb-CONF-2013-012]

SM

$$BR(B_s \to \mu^+\mu^-) = (3.65 \pm 0.23)\times 10^{-9}$$
$$BR(B_d \to \mu^+\mu^-) = (1.06 \pm 0.09)\times 10^{-10}$$

[Bobeth et al 13]

Rare decays: $K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$

Why Kaons if we have Bottoms?

➜ CKM counting of GIM-breaking top contribution ($\lambda \simeq 0.23$)

$$\mathcal{A}_{b\to s} \propto \lambda^2$$
$$\mathcal{A}_{b\to d} \propto \lambda^3$$
$$\mathcal{A}_{s\to d} \propto \lambda^5$$

➜ more suppressed, more sensitive MFV-violating effects

➜ $K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$ extremely clean, $\approx \mathcal{O}(5\%)$ uncertainty

[Misiak et al, 99; Buchalla et al, 99; Buras et al, 06; Brod et al, 08; Mescia et al 07; Brod et al, 10]

$K^+ \to \pi^+\nu\bar{\nu}$ CP-conserving, NA62@CERN

Physics run began, final precision $\sim 10\%$ [see talk by Biino]

$K_L \to \pi^0\nu\bar{\nu}$ CP-violating, KOTO@JPARC

First 100h physics run, next run in 2015?, final precision $\sim 10\%$

Correlation of the two can disentangle NP effects.

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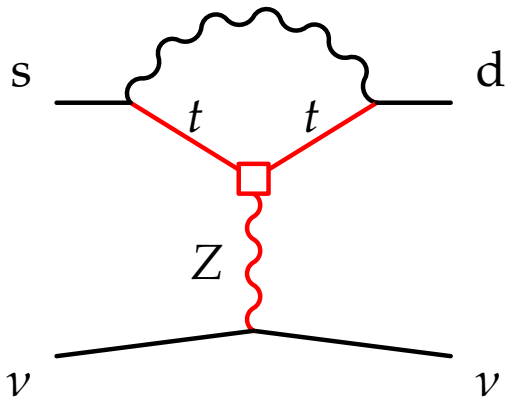
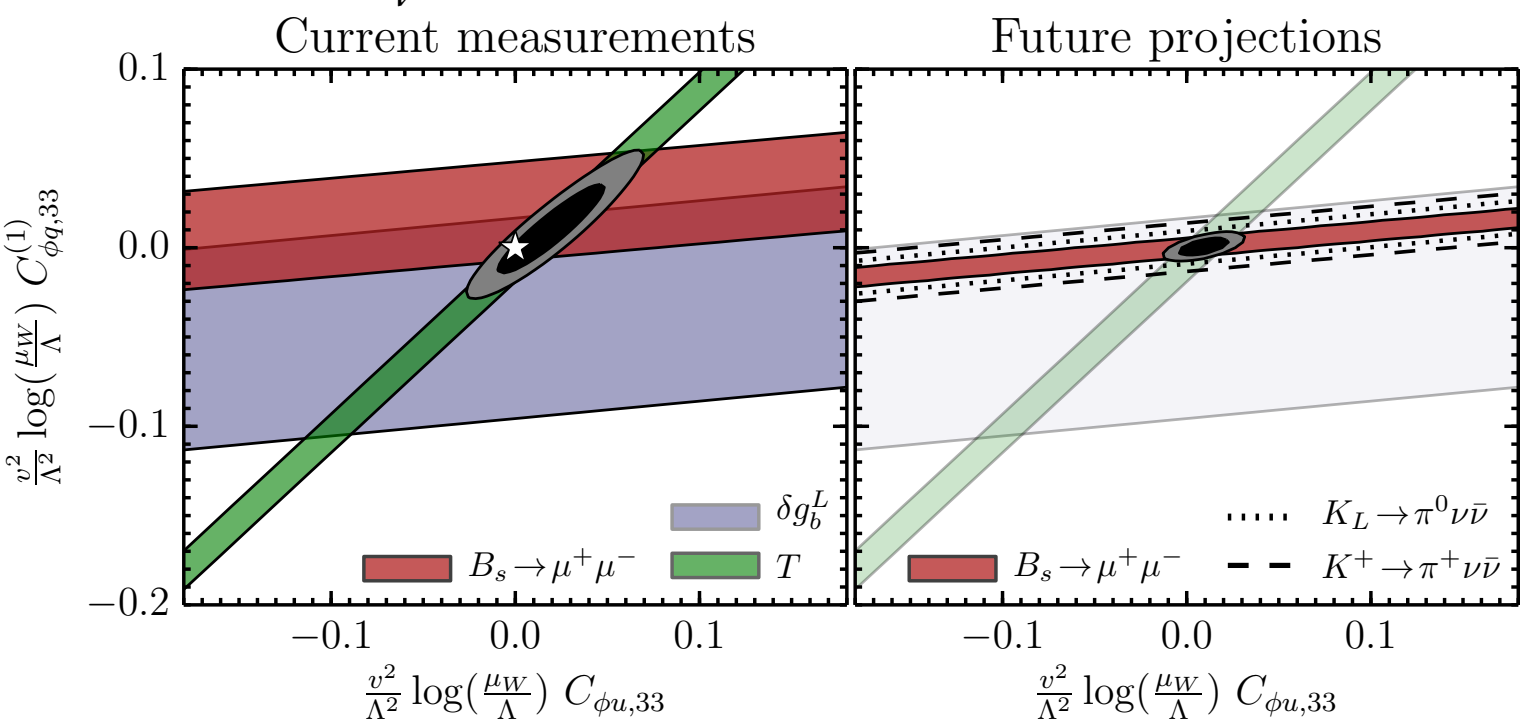
Rare decays: NP sensitivity and Collider Interplay

An example: anomalous *ttZ* couplings



- Prospects 20–30% uncertainty at HL-LHC [Röntsch et al, 14]
- EW+Rare decays ~ few % uncertainty [Brod et al, 14]



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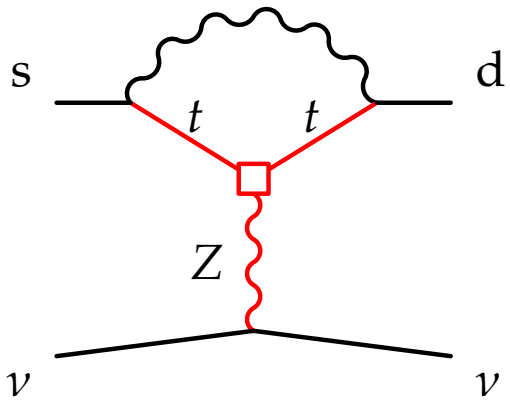


- Prospects 20–30% uncertainty at HL-LHC [Röntsch et al, 14]
- EW+Rare decays ∼ few % uncertainty [Brod et al, 14]

Similarly:

- FCNC Z couplings [Li et al, 11; Gong et al, 13]
- Anomalous W couplings [Drobnak et al, 11]
- Triple Gauge Couplings [Bobeth et al, 15]

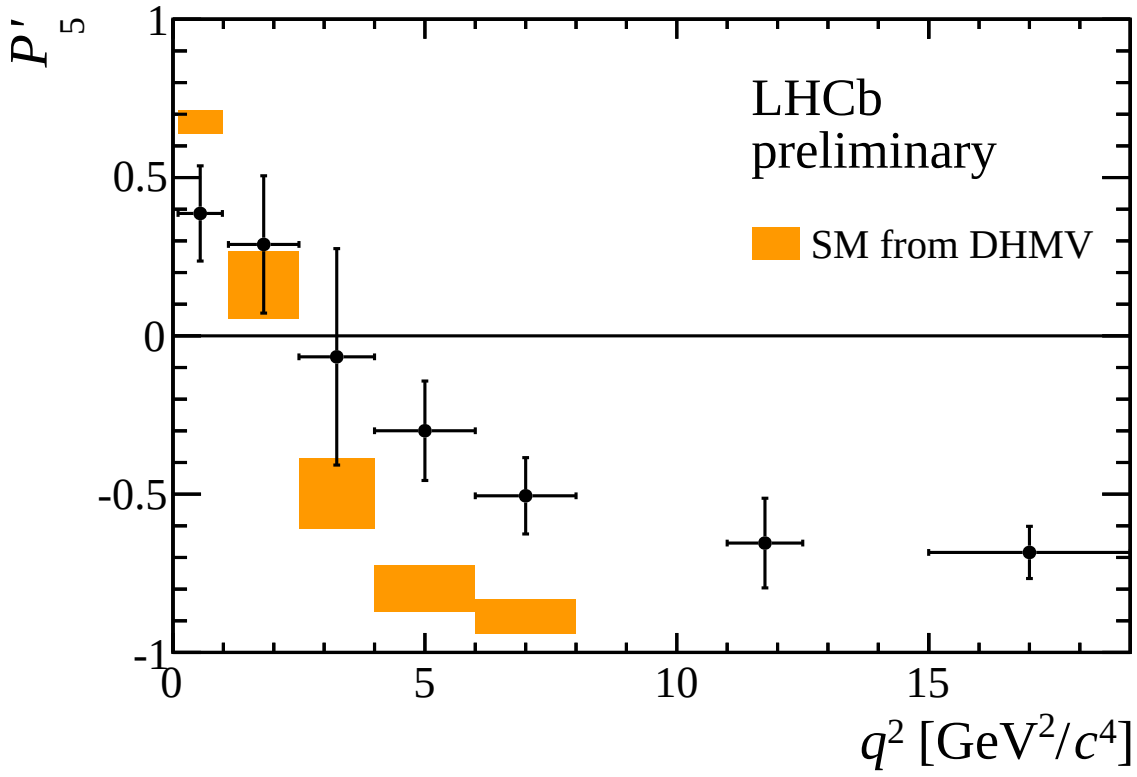
Message:

Flavour is constraining collider observables

But: correlations come with assumptions, e.g. SM-EFT

Tensions in $B \to K^*(\to K\pi)\mu^+\mu^-$, R_K

Difficult, difficult story. . . The first question is.
Is it: a)

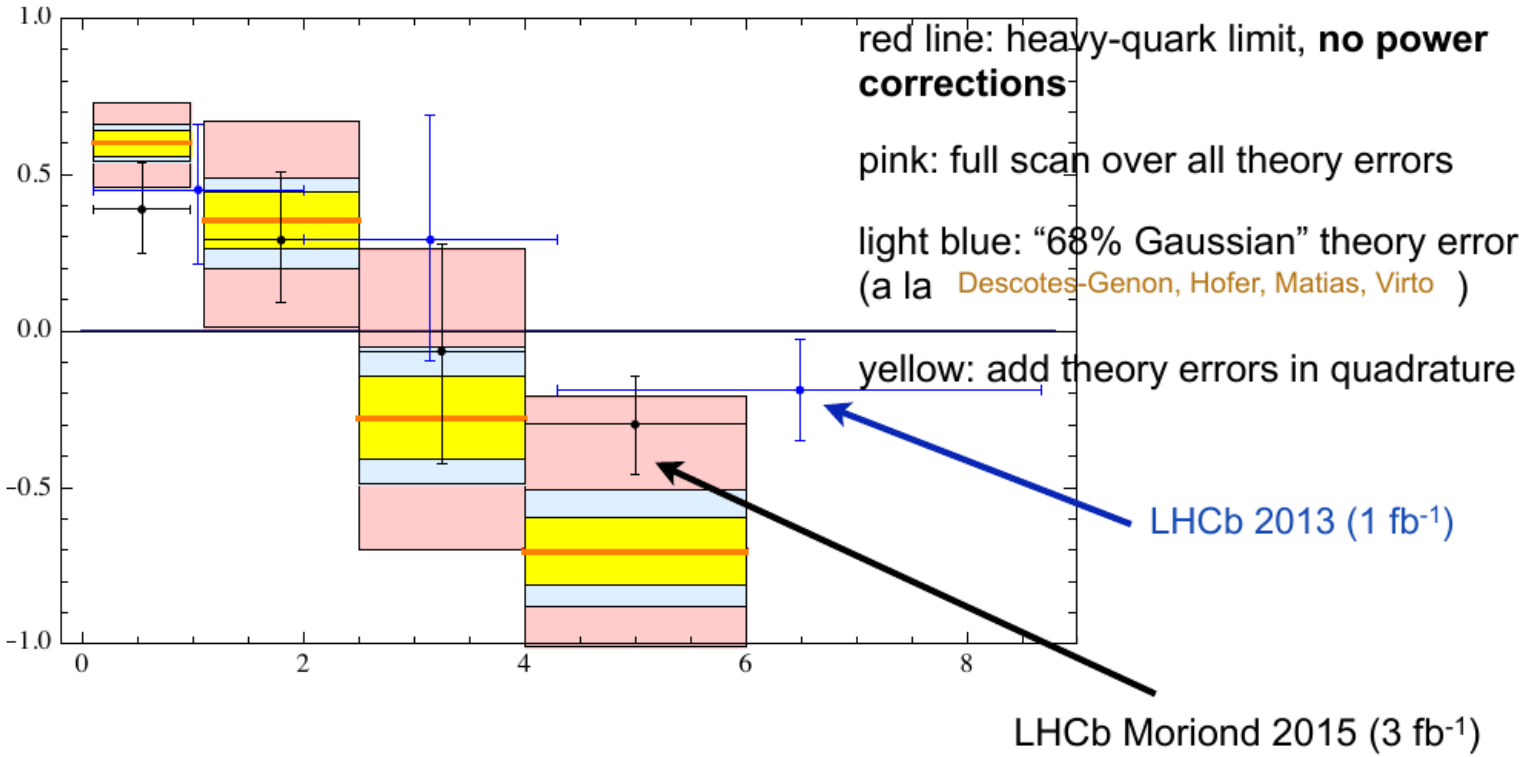


➜ **3.7σ anomaly**

[LHCb-CONF-2015-002, Descotes-Genon et al 14]

Tensions in $B \to K^*(\to K\pi)\mu^+\mu^-$, R_K

Difficult, difficult story. . . The first question is.
Is it: b)



➜ **no anomaly**, single-bin analysis

[Jaeger@Portoroz2015, Jaeger, Camalich, 12, 14]

support from global fit

[talk by Valli, HEPfit in preparation]

Tensions in $B \to K^*(\to K\pi)\mu^+\mu^-$, R_K

Difficult, difficult story. . . The first question is.

What is P_5'?

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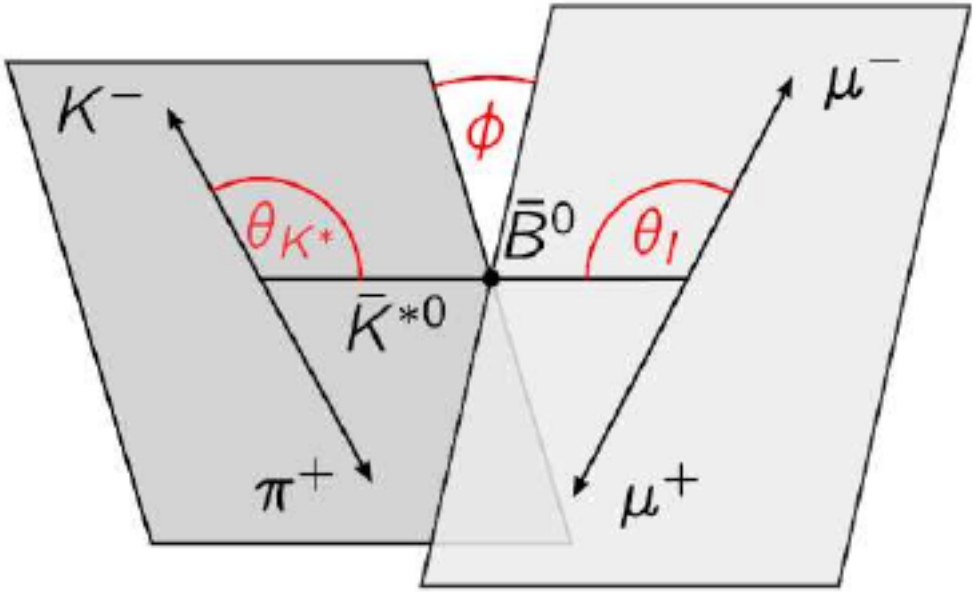
P_5' tensions in $B \to K^*(\to K\pi)\mu^+\mu^-$

- $B \to K^*(\to K\pi)\mu^+\mu^-$ is a 4-body decay, kinematics described by 4 variables



- Many, differential in q, observables accessible from angular distribution
  - Differential decay width
  - Lepton Forward-Backward Asymmetry, A_{FB}
  - Longitudinal polarisation fraction of the K^*, F_L
  - CP-Asymmetries, A_i^a [Kruger et al, 99; Bobeth et al, 08]
  - CP-averaged angular coefficients, $S_i^{(a)}$ [Altmannshofer et al, 08; Bharucha et al, 15]
  - **Optimized Observables** (P_i')

    [Matias et al, 12; Descotes-G et al, 13; Bobeth et al, 10, 11, 12; Becirevic et al, 11...]

Optimized variables

e.g.

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

- Designed to cancel all form-factor dependence **in $m_b \to \infty$ limit**
- Nevertheless, subject to factorizable and **non-factorizable power corrections** [Jäger et al, 12 14; Descotes-G et al 14, . . .]

$$P_5' = \underbrace{\mathcal{F}(\text{Wilson Coefficients}, q^2)}_{\text{clean}} + \underbrace{\text{power corrections}}_{\text{non-perturbative}}$$

- treatment of power corrections can inflate / inflates errors

[see talk by Valli]

SUSY 2015, so what NP can it be?

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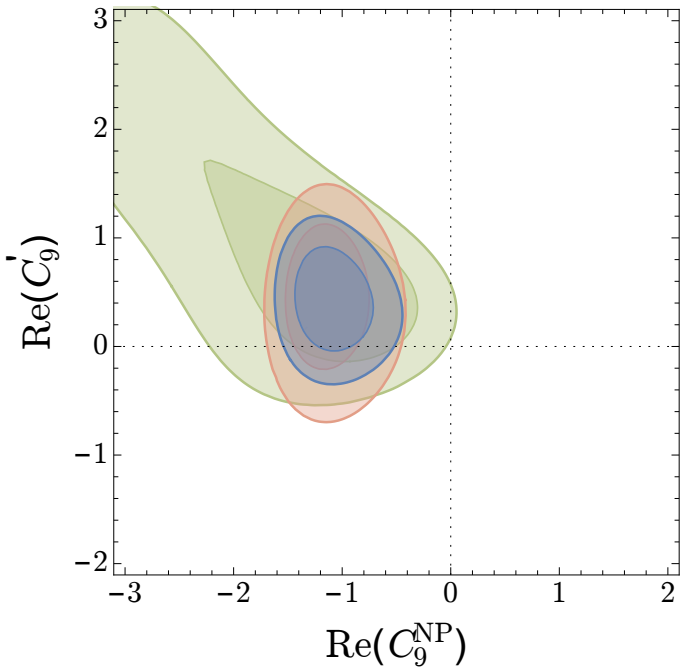
NP in $B \to K^* \mu^+ \mu^-$

- **Global Fits** including many processes and processes required
  [Altmannshofer et al 11 12 13 14; Bobeth et al 11, Beaujean et al, 12, 13; Descotes-Genon 13 14; Hurth et al 13 14; Ghosh et al 14, Jäger 14,...]
- Fit relevant Wilson Coefficients $\underbrace{C_7^{(\prime)}}_{B \to X_s \gamma}, C_9^{(\prime)}, \underbrace{C_{10}^{(\prime)}}_{B_s \to \mu^+\mu^-}, \qquad \prime \equiv L \to R$
- Neglect tensor-operators and scalar, pseudo-scalar operator
  (constrained by $B_s \to \mu^+\mu^-$)



a) Best Fit: muonic vector current

$$Q_9 = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}\gamma^\mu \mu)$$
$$Q_9' = (\bar{s}_R \gamma_\mu b_R)(\bar{\mu}\gamma^\mu \mu)$$

$$C_9^{\mathrm{NP}} = -1.1 \pm 0.3 \qquad C_9' = +0.5 \pm 0.4$$

Results from Altmannshofer et al, 15

Tensions prefers negative shift in C_9.

NP in $B \to K^* \mu^+ \mu^-$

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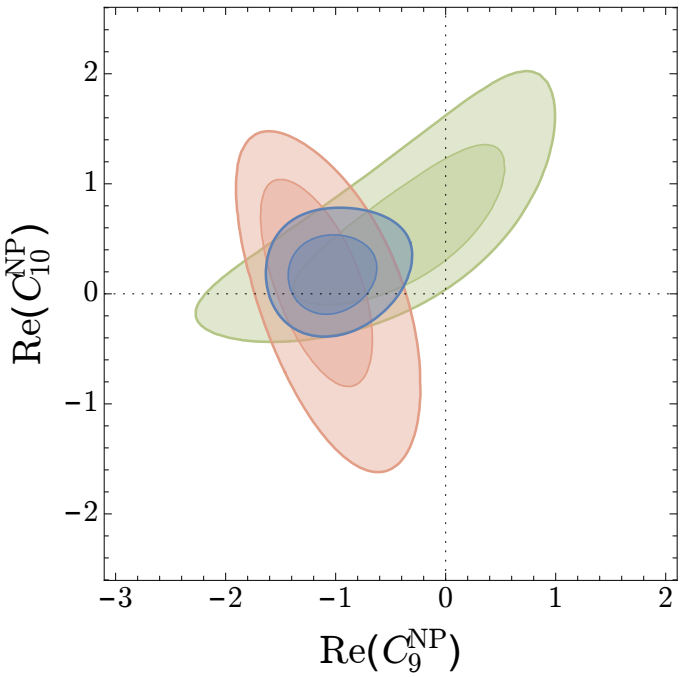

b) Best Fit: SM-like current

$Q_9 = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}\gamma^\mu \mu)$

$Q_{10} = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$

$C_9^{\mathrm{NP}} = -1.1 \pm 0.3 \qquad C_{10} = +0.2 \pm 0.3$

Results from Altmannshofer et al, 15

Tensions prefers negative shift in C_9.

R_K: Violation of Lepton-Flavour Universality

$$R_K \equiv \frac{BR(B \to K\mu^+\mu^-)_{[1,6]\mathrm{GeV}^2}}{BR(B \to Ke^+e^-)_{[1,6]\mathrm{GeV}^2}}$$

[Hiller et al, 04]

LHCb measurement

$$R_K^{\mathrm{exp}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

[LHCb 1406.6482]

Clean SM prediction

$$R_K^{\mathrm{SM}} = 1.0003 \pm 0.0001$$

[Bobeth et al, 07]

2.6σ tension ➜ Flavour Non-Universal NP?

Is this compatible with the related $B \to K^*\mu\mu$ "anomaly"?

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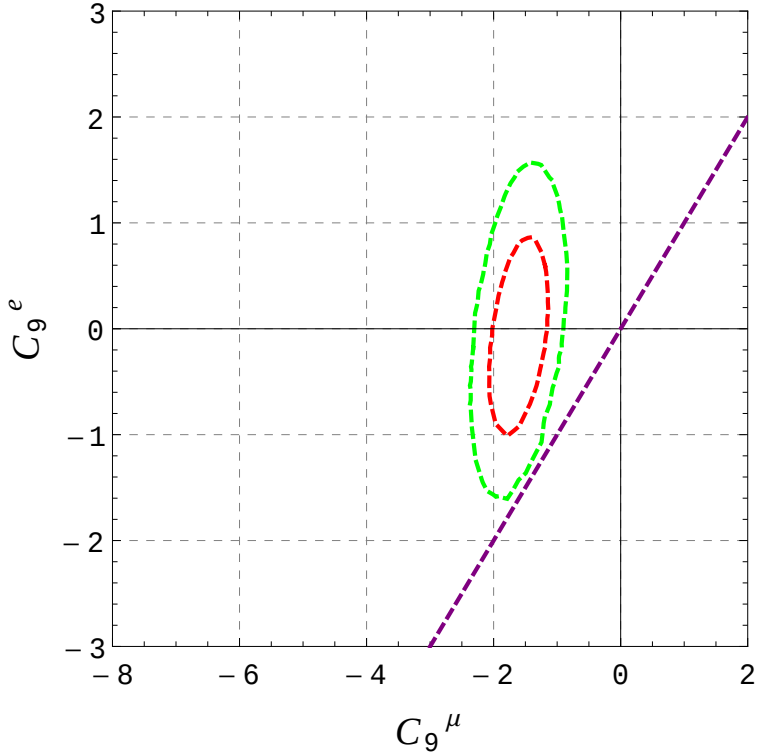
R_K: Violation of Lepton-Flavour Universality

- Most combinations of Wilson coefficients fail [Hiller et al, 14]
- Q_9^e, Q_9^μ give the only good fit. [Ghosh et al, 14]



➜R_K **and** $B \to K^* \mu^+ \mu^-$ **compatible**

➜**no NP necessary in** e**-mode** [Ghosh et al, 14]

Does any NP model emerge naturally?

One model for the $B \to K^* \mu^+ \mu^-$ and R_K tension

- various proposals, most with Z''s
- one predicted R_K

"Recipe":

➜ gauge $L_\tau - L_\mu$ get flavour non-universal Z'

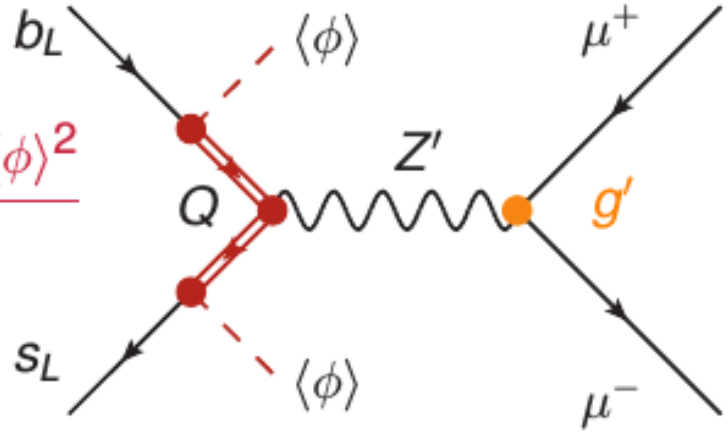
➜ couple Z' via mixing of vector-like fermions to b, s

➜ fix couplings from $B \to K^* \mu^+ \mu^-$

➜ check constraints and R_K

[Altmannshofer et al, 14]

$$\frac{g' Y_{Qb} Y^*_{Qs} \langle\phi\rangle^2}{2 m_Q^2}$$



- constraints $\bar{B}_s - B_s$, LEP, ... satisfied
- $R_K \simeq 0.82 \pm 0.11$ ✓

➜ not SUSY but it works! ←

Summary of "Traditional Flavour"

- No sign of NP in "golden" SUSY channel $B_s \to \mu^+\mu^-$
- Run 2 LHC ➜$B_d \to \mu^+\mu^-$
- NA62 and KOTO ➜$K \to \pi\nu\bar{\nu}$
- Tensions in $B \to K^*\mu^+\mu^-$, R_K
  power corrections? statistical fluctuations?
  NP with very special structure?

Current Flavour data do not favour SUSY signals

Important things I did not cover:

- **Fist lattice results for** ϵ' matrix-elements
  [RBC-UKQCD arXiv:1502.00263]
  ➜ 3σ tension with data [Buras et al, 15]
- **New results on** $B \to D^*\tau\nu$ from Belle and LHCb
  [Belle arXiv:1507.03233; LHCb arXiv:1506.08614]
  ➜ 4σ tension with data [Freytsis et al, 15]

one very last slide on "traditional" Flavour

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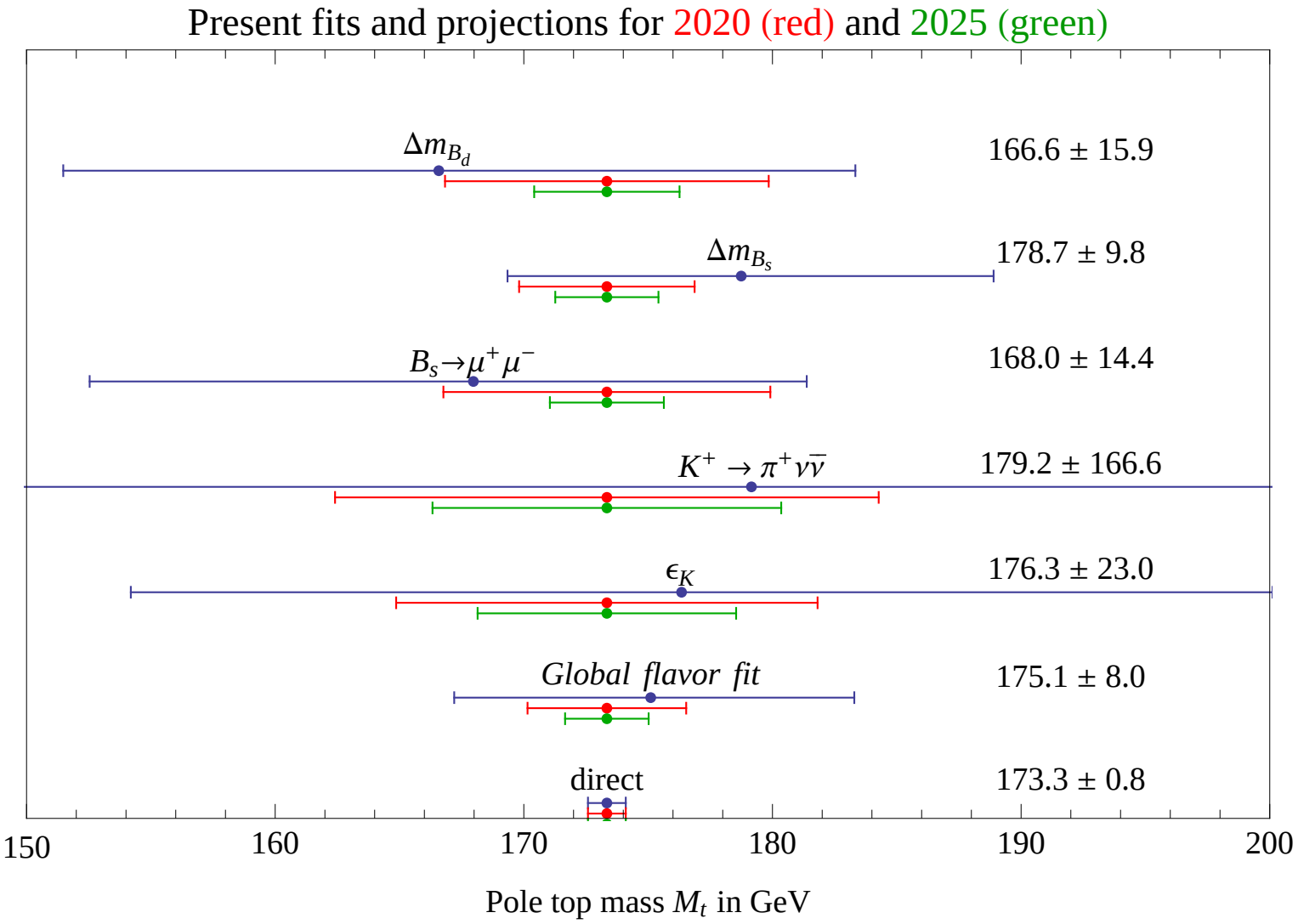
If everything else fails: m_t from Flavour



[From 2 days ago Giudice et al, 15, see also Haisch talk at Top@20]

Higgs Flavour

the new Flavour arena

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Which is the only flavour-dependent interaction in the SM?

➜ Higgs-field interaction ➜

- Goldstone bosons / W bosons ➜ flavour violation
  Precision Flavour observables, FCNCs, indirect searches for NP

  "Traditional" Flavour

- Higgs particle ➜ interaction strength $\propto$ mass
  New source of flavour data at LHC/future colliders, more room for NP

  Higgs Flavour

- masses ✚ fermion Higgs couplings ➜ new "unitarity triangle"
  EWSB $\equiv$ fermion masses only for SM, small deviations $\rightarrow$ large effects

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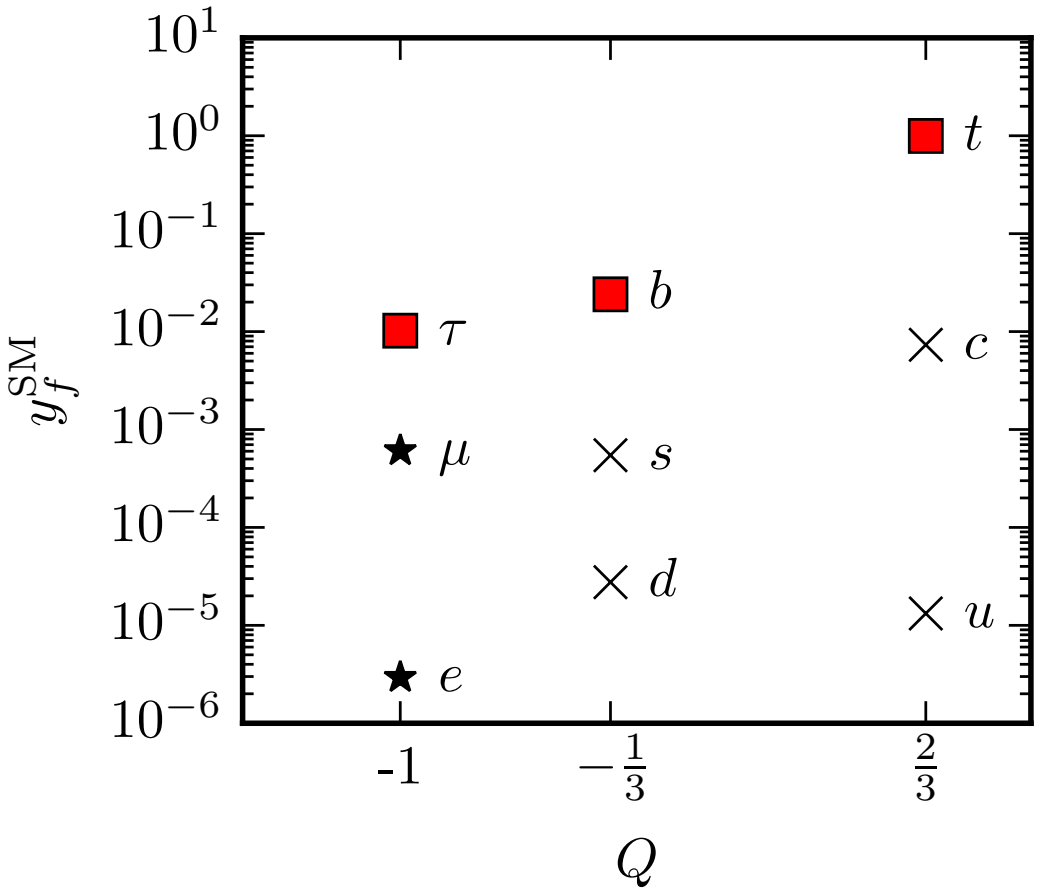
Direct observations for fermionic higgs couplings

- higgs couples to t, b, and τ ✓



- upper bound on higgs to e, μ
- nothing for light quarks

Signal strenth

$$\mu \simeq \frac{\sigma}{\sigma^{\rm SM}} \frac{\mathcal{BR}}{\mathcal{BR}^{\rm SM}}$$

- $\mu_\tau = 0.98 \pm 0.22$
- $\mu_b = 0.71 \pm 0.31$
- $\mu_{tth} = 2.41 \pm 0.81$

  [naive ATLAS, CMS averages]
- $\mu_\mu < 7$ @95 CL
- $\mu_e < 3.7 \cdot 10^5$ @95 CL

  [ATLAS, arXiv:1406.7663]

  [CMS, arXiv:1410.6679]

$\frac{\mu_\mu}{\mu_\tau} \sim 280$ for $y_\mu = y_\tau$ but observation $\frac{\mu_\mu}{\mu_\tau} < 15$

➜ higgs couples non-universally to leptons

What about quarks?

$h \to$ light-quark light-quark

Challenges

- SM-higgs branching ratios tiny
- huge QCD background
- need some sort of flavour tagging

(c-tag seems possible at the LHC)

Directions

- **Be exclusive**
  - $h \to M\,\gamma$ as a flavour proxy (M vector meson)
  - possible for u, d, s, c

  [Bodwin et al, 13; Kagan et al, 14; Bodwin et al, 14; König et al 15, Perez et al 15; **ATLAS: 1501.03276**]

- **Be inclusive**
  - limited by b- and c-tag
  - higher statistics

  [Delaunay et al 13; Perez et al 15, 15; Brivio et al, 15; **ATLAS arXiv:1501.01325, ATLAS-CONF-2013-063**]

Impressive progress in c-tag in ATLAS used already in SUSY searches:

$$\epsilon_c = 19\% \qquad \epsilon_b = 12\%$$

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y_c from mistagging, recasting 8 TeV data

Charm-Yukawa

special case ✚ a buried jewel in Vh data

Simple Idea: [Perez et al, 15]

i) ATLAS+CMS observed $h \to b\bar{b}$ in ***Vh*** production

ii) some b-jets came from c-quarks

iii) what is the *bound* on charm-Yukawa *from mistagging*?

➜**essential point 1)** use different tagging working points

otherwise cannot distinguish c's from b's

➜**essential point 2)** production modified by y_c

otherwise no bound

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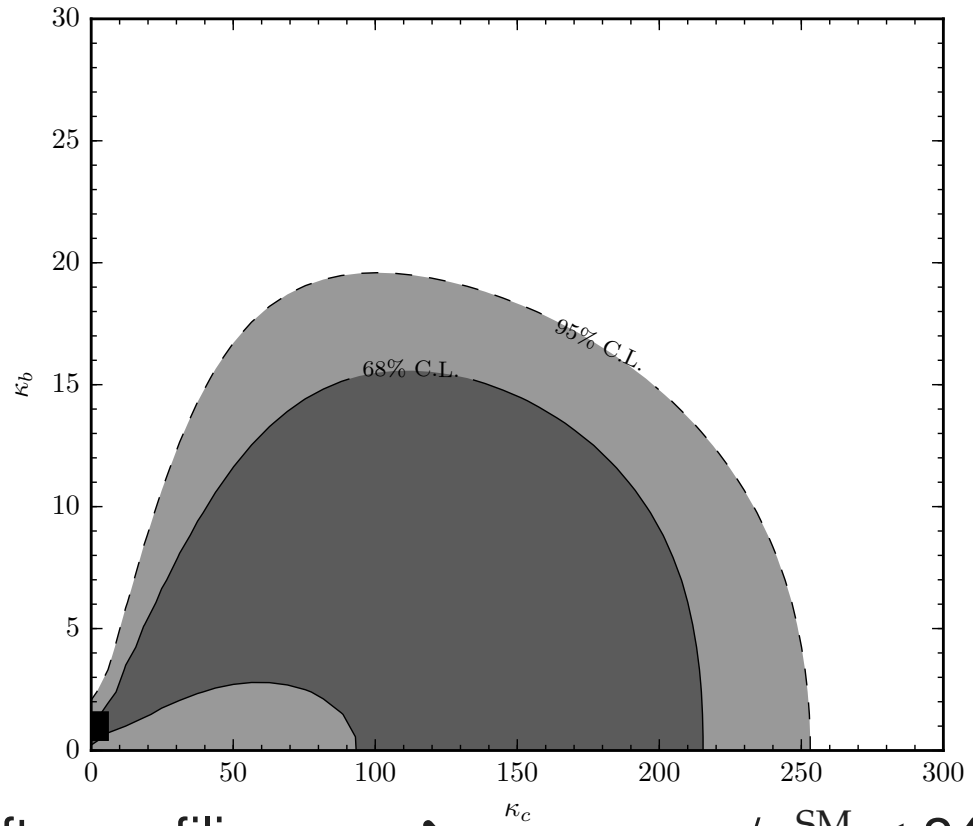


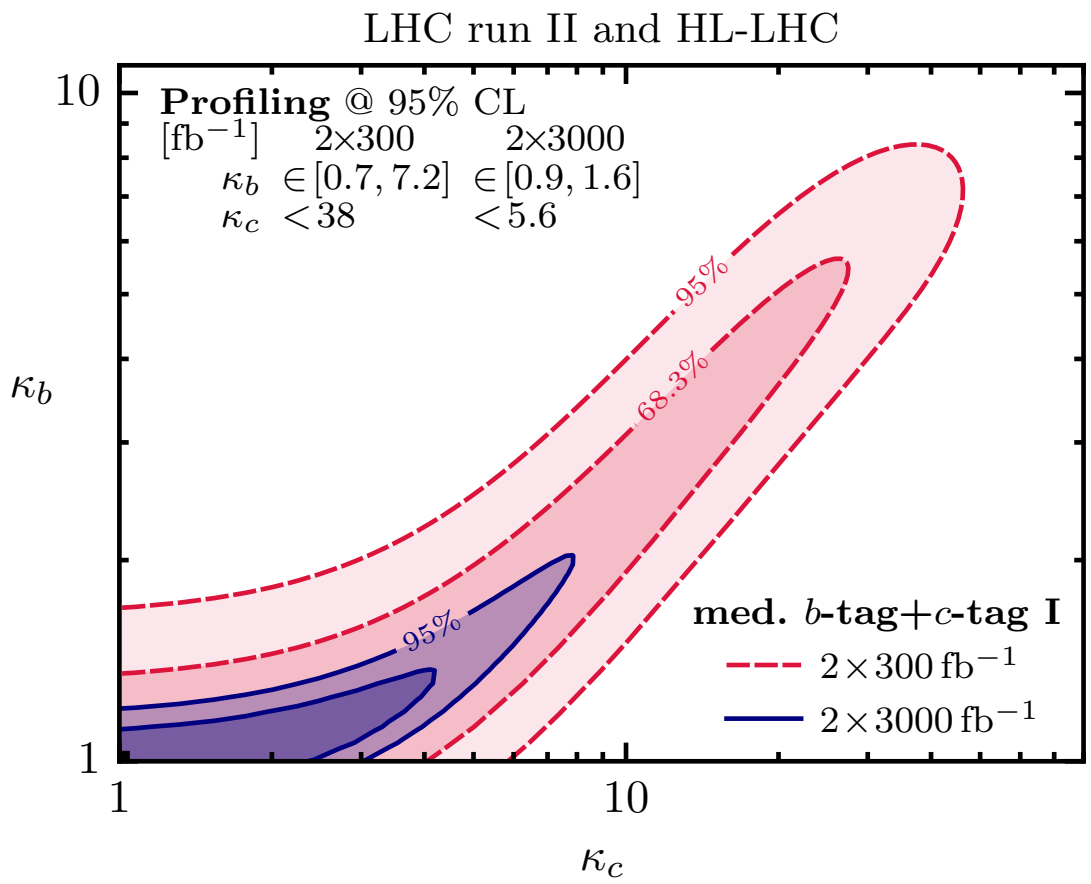
a) Sufficient to exclude Higgs-quark universality

a) Excellent prospects for improvement

After profiling ➜ $\kappa_c = y_c/y_c^{\rm SM} \lesssim 245$

κ_c prospects at LHC14 2×300 **fb**$^{-1}$ 2×3000 **fb**$^{-1}$

c-tagging I : $\epsilon_c = 19\%$ $\epsilon_b = 13\%$



[Perez et al, 15]

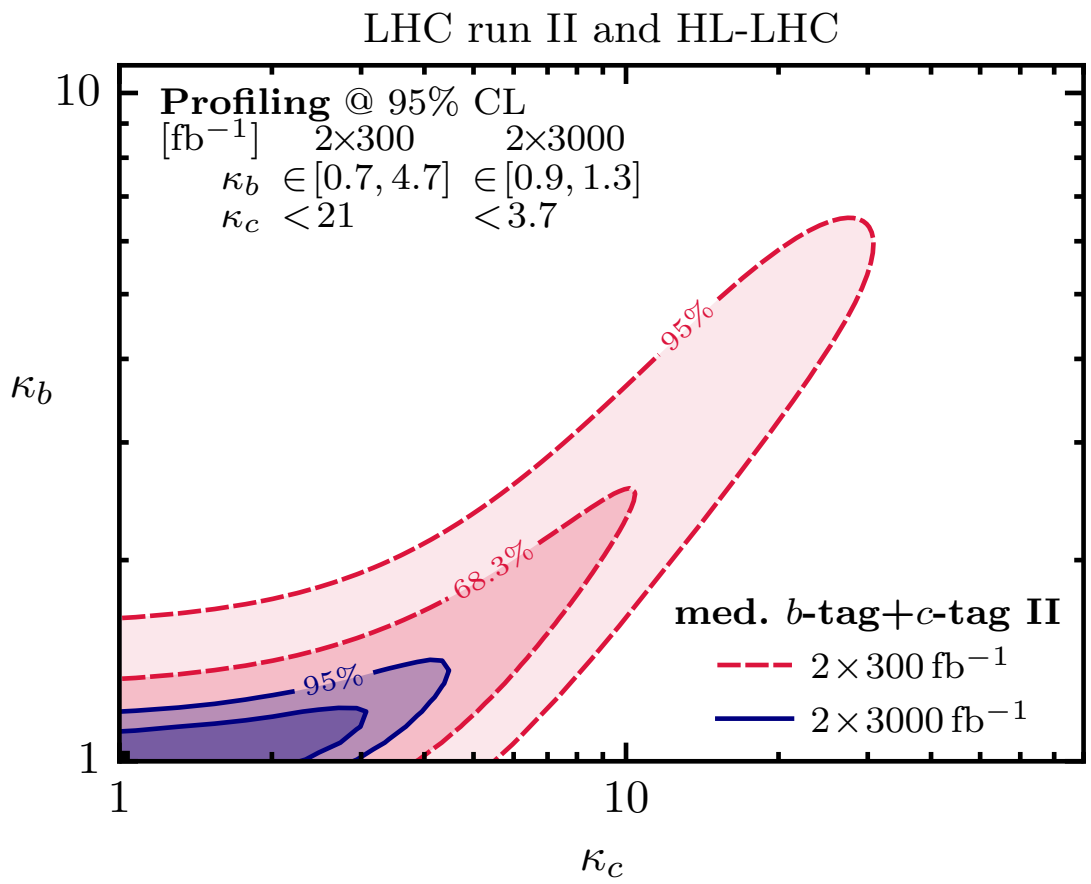
@95% CL **$|\kappa_c| < \pm38$, ± 5.6** at Run 2, HL-LHC

Similar sensitivity in $pp \to hc$ **mode seems possible.**

[Brivio et al, 15]

κ_c prospects at LHC14 2×300 **fb**$^{-1}$ 2×3000 **fb**$^{-1}$

c-tagging II : $\epsilon_c = 30\%$ $\epsilon_b = 20\%$



[Perez et al, 15]

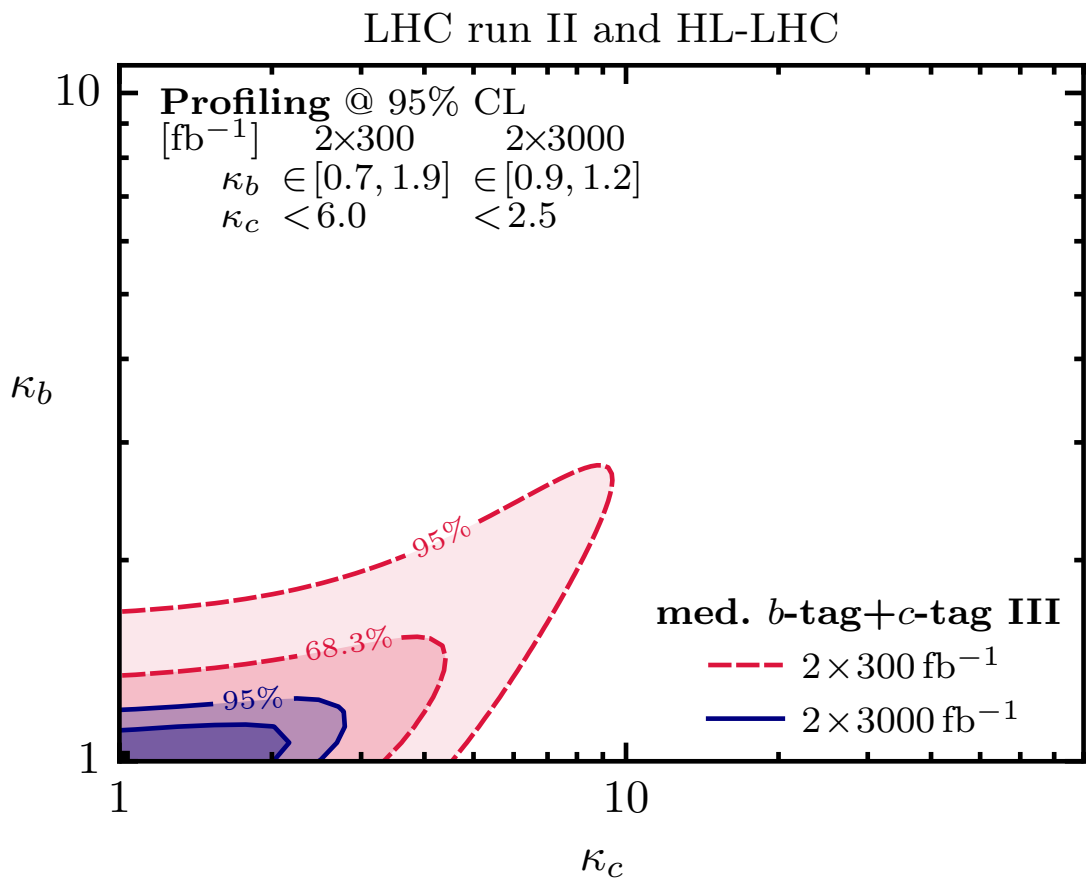
@95% CL $|\kappa_c| <$ **±21, ± 3.7** at Run 2, HL-LHC

Similar sensitivity in $pp \to hc$ **mode seems possible.**

[Brivio et al, 15]

κ_c prospects at LHC14 2×300 **fb**$^{-1}$ 2×3000 **fb**$^{-1}$

***c*-tagging III :** $\epsilon_c = 50\%$ $\epsilon_b = 20\%$



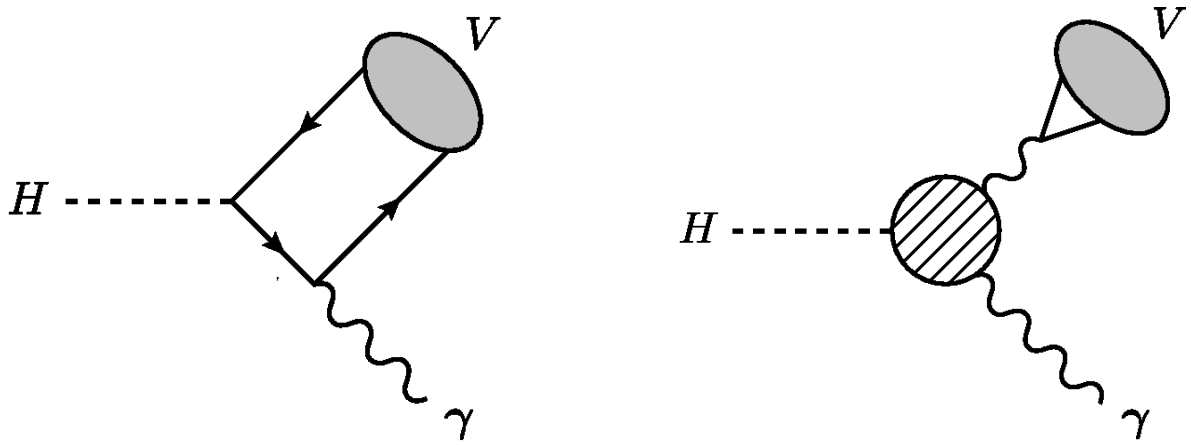
[Perez et al, 15]

@95% CL **$|\kappa_c| < \pm6.0$, ± 2.5** at Run 2, HL-LHC

Similar sensitivity in *pp* → *hc* mode seems possible.

[Brivio et al, 15]

Exclusive approach: $h \to J/\psi\,\gamma$



$$\Gamma_{h\to J/\psi\,\gamma} = |(11.9 \pm 0.2)\kappa_\gamma - (1.04 \pm 0.14)\kappa_c|^2 \cdot 10^{-10}\ \text{GeV}$$

[Bodwin et al, 13; Bodwin et al, 14]

[**Improved prediction:** König et al, 15]

Highlights

- tagging via the flavour of the meson
- two contributions direct (κ_c) and indirect (κ_γ)
- main effect from interference
- **generalisable to** *s*, *u*, *d* **quarks!** [Kagan et al, 14]

➜only known direct way to access *s*, *u*, *d* Yukawas

Exclusive approach: $h \to J/\psi\,\gamma$ new results

ATLAS $\sigma \cdot \mathcal{BR}(h \to J/\psi\,\gamma) < 33\text{fb}$ at 95% CL

[ATLAS 1501.03276]

Important for 2 reasons:

- translates to a weak $|\kappa_c| < 220$ bound

  (after normalising to $h \to ZZ^*$, and assuming κ_V, κ_γ like in SM) [Perez et al, 15]

- **first measurement of a tough QCD background**

  ➜ QCD+real photon and QCD with jet mistagged as a γ

  $$P(j \to \gamma) \simeq 2.9 \cdot 10^{-2}$$

  [ATL-COM-PHYS-2010-1051]

  ➜ expect similar background for other modes

  ➜ use new data to project sensitivy in ϕ mode

  ➜ use new data to project sensitivy in Run-2/HL-LHC

  [Perez et al, 15]

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Exclusive projection for y_c and y_s

Assumptions for extrapolation: $S_E/\sqrt{B_E} \sim S_8/\sqrt{B_E}$, unchanged signal efficiencies, $S_E/\sqrt{B_E}$ same in J/ψ and ϕ mode, PYTHIA simulation to rescale B

Results for charm-Yukawa

$|\kappa_c| < 91,\ 56,\ 33$

at LHC run 2, HL LHC, and a 100 TeV with $2\times3000\,\text{fb}^{-1}$

Results for strange-Yukawa

$|\kappa_s| < 3300,\ 2000,\ 1200$

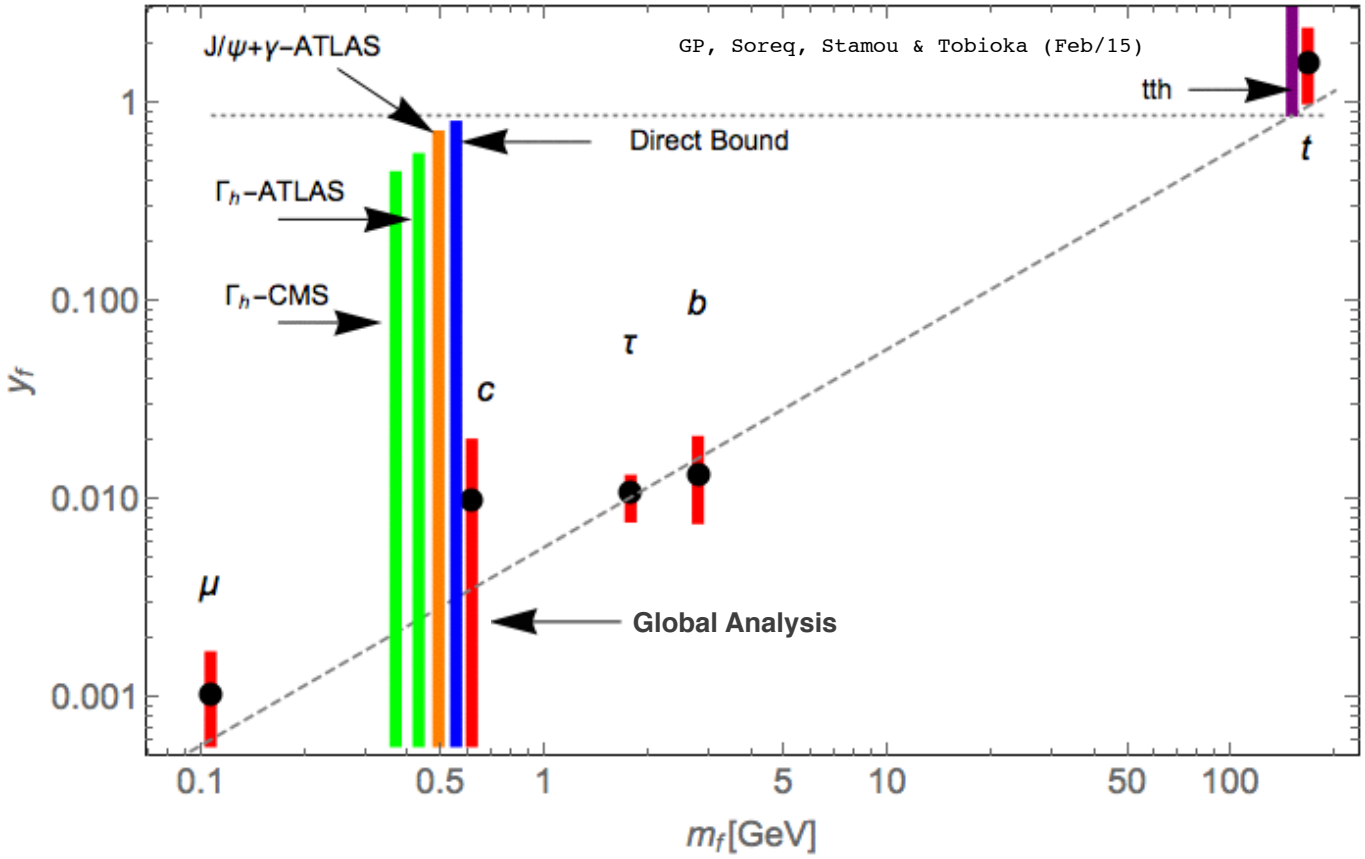
at LHC run 2, HL LHC, and a 100 TeV with $2\times3000\,\text{fb}^{-1}$

➜ exclusive approach struggles with QCD background ←

possible to reduce in other production modes? $Vh, VBF, t\bar{t}h$**?**

[Perez et al, 15]

Status of fermionic Higgs couplings before Run 2



Fit dominated by untagged Higgs decay driven by VBF production.

$$\mu_{\mathrm{VBF}\to h\to WW^*} = \kappa_V^2 \times \frac{\kappa_V^2}{\Gamma_{\mathrm{tot}}/\Gamma_{\mathrm{tot}}^{\mathrm{SM}}} \quad \rightarrow \quad \Gamma_{\mathrm{tot}} < 4\Gamma_{\mathrm{tot}}^{\mathrm{SM}}$$

Robust as long as there is no new VBF production channel.

Summary & Conclusions

"Traditional" Flavour

- no clear indication for NP (no large effects in $B_s \to \mu^+\mu^-$)
- flavour constraints ➜collider constraints
- semi-incoherent pattern of tensions (Z's, gauged $L_\mu - L_\tau$,lepto-quarks,...)
- new data and new experiments on the way, clarify situation?

Higgs Flavour

- large NP effects possible
- impressive theoretical and experimental progress last 2 years
- complementary approaches possible (inclusive/exclusive)
- prospects for future and unexplored channels/directions

Run 2 will be inevitably interesting for "Flavour"

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