LEPTON FLAVOR UNIVERSALITY VIOLATION IN TOP DECAYS

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OUTLINE

- Motivations: why LFUV? why in tops?
- Current bounds on LFUV in tops and assumptions behind the measurement
- New technique: using the shapes. Motivations for 100 TeV machine
- Conclusions and outlook

MOTIVATION

Top production cross sections in hadron colliders:

$$\sigma(t\bar{t}) = 0.82 \text{ nb} \qquad \text{at} \qquad \sqrt{s} = 13 \text{ TeV}$$

$$\sigma(t\bar{t}) = 0.97 \text{ nb} \qquad \text{at} \qquad \sqrt{s} = 14 \text{ TeV}$$

$$\sigma(t\bar{t}) \approx 32 \text{ nb} \qquad \text{at} \qquad \sqrt{s} = 100 \text{ TeV}$$

We expect to have 2.5×10^9 top pairs by the end of the HL LHC run. By the end of the FCC-pp run we can produce as many as 10^{12} top quark pairs.

What can be the interesting physics questions we might address with this amount of top quarks? What are the new precision measurement which can be performed?

WHAT DO WE KNOW ABOUT TOP QUARK DECAYS NOW?

By the end of 8 TeV LHC run the constraints on the rare processes in the top sector are still very mild, much weaker than most of the theoretical predictions.

- $BR(t \to ch) < 0.46\%$
- $BR(t \to uh) < 0.45\%$
- $BR(t \to qZ) < 0.08\%$

What about exotic top decays via charged currents?

The only obvious candidate which was considered is $t \to bh^{\pm}$ decay mode. See the discussion later…

ARE TOP DECAYS LEPTON-FLAVOR UNIVERSAL?

Until now this question was addressed via direct measurements of the top production cross sections in different modes. LHC measurements of total cross sections:

$$\begin{aligned} BR(t \to e\; b\; \not{E}_T) &= 13.3\% \pm 0.4\% \pm 0.4\% \\ BR(t \to \mu\; b\; \not{E}_T) &= 13.4\% \pm 0.3\% \pm 0.5\% \\ BR(t \to \tau_h\; b\; \not{E}_T) &= 7.0\% \pm 0.3\% \pm 0.5\% \end{aligned}$$

Leptonic taus are included into the leptonic modes count

All these measurements are in agreement with the SM-predicted LFU. By solving the system of coupled equations we conclude that LFU between the light flavors has been measured with 5%-10% uncertainty and between the tau and the light flavors with 15%-20% uncertainty. Can we do better? Do these bounds always apply?

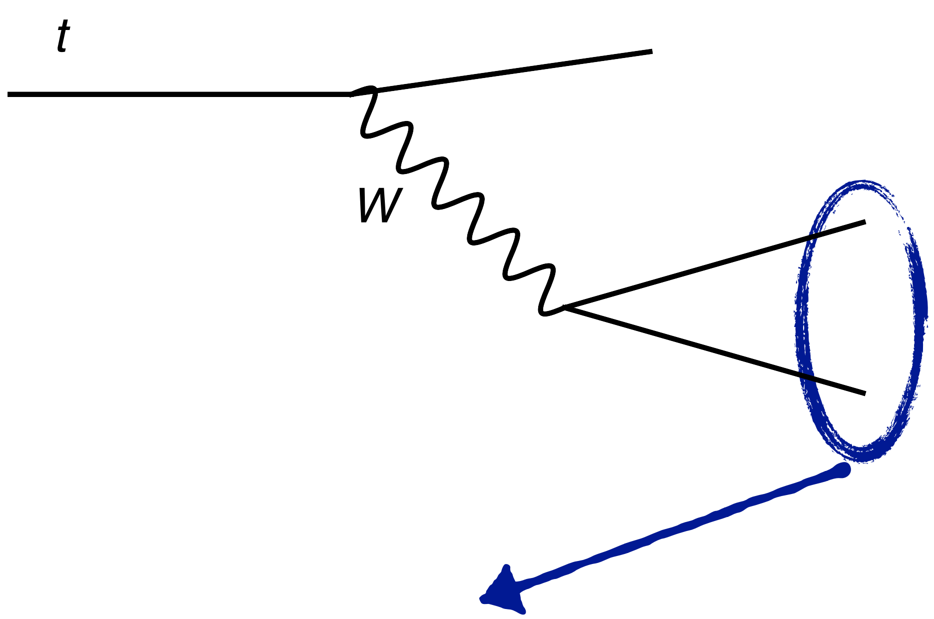
LEPTON FLAVOR UNIVERSALITY AND TOP DECAYS

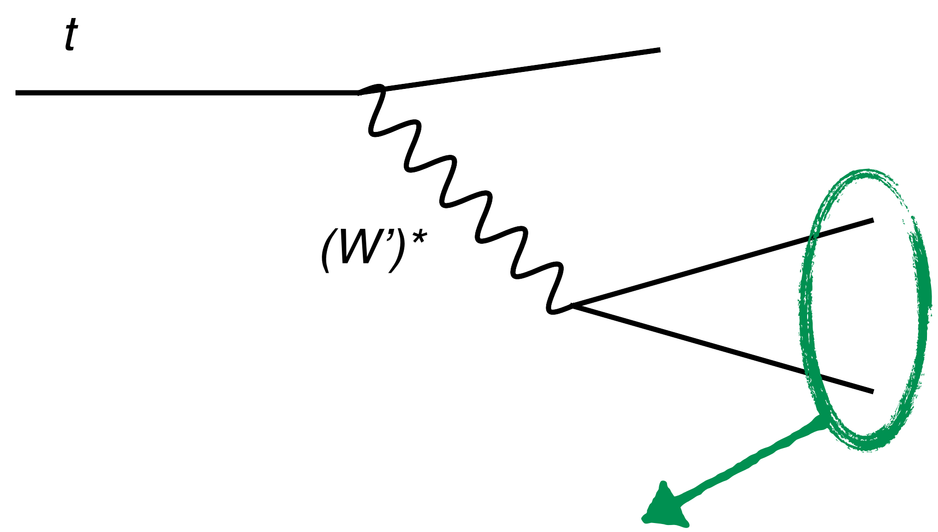
Have we ever seen breakdown of lepton flavor universality?
Not really, but maybe:

- Enhanced $B \to D^* \tau \nu$ compared to the light flavors (R_{D^*} parameter) — **charged current**
- Deficit of $B \to K\mu\mu$ compared to $B \to Kee$ events at the LHCB — R_K parameter. This parameter is predicted to be 1 in the SM and the measurement is in 2.6σ tension with the SM

Both observations are not at the level of discovery, and might be explained by statistical fluctuations and / or systematic uncertainties which were not properly taken into account. However, it might be interesting to consider LFUV via BSM particles. If these are the effects of the BSM physics , it is plausible that these new particles couple to the top, and possibly mediate LFUV in top decays. What can we measure and how?

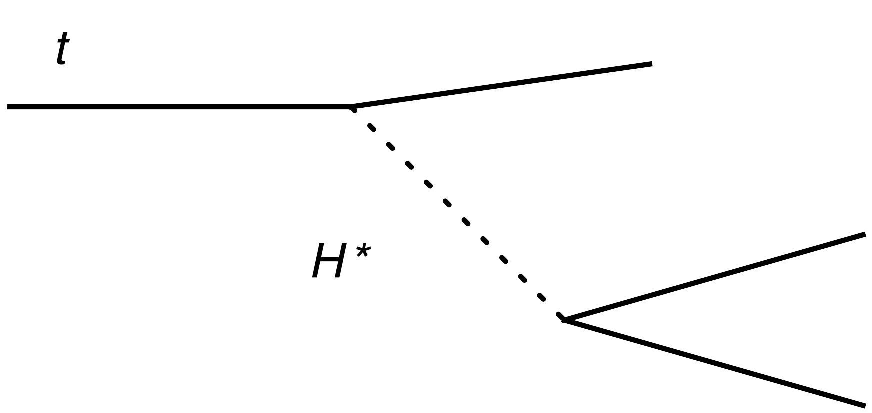
(HIGHLY) OFF SHELL TOP DECAYS





As flavor universal as W decays are, LEP still gives the best bounds.

If there is a W' in the spectrum, we do not have good prediction about its decay modes. They can be flavor non-universal



Decays via charged higgses are always flavor non-universal

The decays via new off shell particles are small. Even if they are strongly tilted to the third generation, the effect is small (and the effects of interference cannot be neglected).
Can we use kinematics to increase the sensitivity?

SIMPLIFIED MODELS OF LFUV IN TOPS

Operators which can contribute to the top LFUV in the EFT language

$$\mathcal{O}^q_{VL} = (\bar{q}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)\,, \qquad \mathcal{O}^q_{SL} = (\bar{q}P_L b)(\bar{\tau}P_L\nu_\tau),$$
$$\mathcal{O}^q_{TL} = (\bar{q}\sigma_{\mu\nu} P_L b)(\bar{\tau}\sigma^{\mu\nu} P_L \nu_\tau)\,, \quad \mathcal{O}^q_{SR} = (\bar{q}P_R b)(\bar{\tau}P_L\nu_\tau)\,,$$

A. Charged massive vector boson which couples to the 3rd generation — "ρ - mesons".

$$\mathcal{L}^{(a)} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{4}R^+_{\mu\nu}R^{-\mu\nu} - m_\rho^2 \rho^+_\mu \rho^{-\mu}$$
$$+ [g_b \sum_q V_{qb}\bar{q}\not{\rho}^+ P_L b + g_\tau \bar{\tau}\not{\rho}^- P_L \nu_\tau + \mathrm{h.c.}]\,,$$

maps onto EFT vector contraction

B. Charged scalars — "heavy higgses".

$$\mathcal{L}^{(b)} = \mathcal{L}_{\mathrm{SM}} + \partial_\mu\phi^+\partial^\mu\phi^- - m_\phi^2\phi^+\phi^-$$
$$+ [\sum_q V_{qb}\phi^+(y^L_\phi \bar{q}P_L b + y^R_\phi \bar{q}P_R b) + y^\tau_\phi \phi^- \bar{\tau}P_L\nu_\tau + \mathrm{h.c.}]\,,$$

maps onto EFT scalar contractions

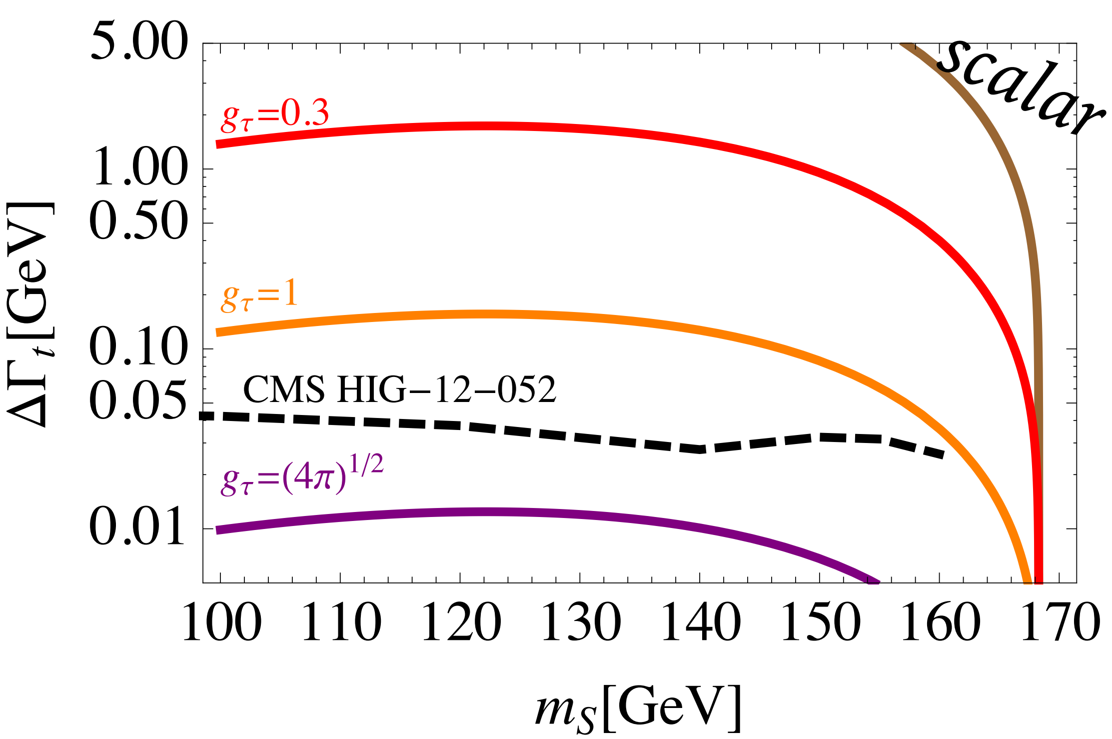
C. Leptoquarks — matches onto the tensor and the scalar operators.

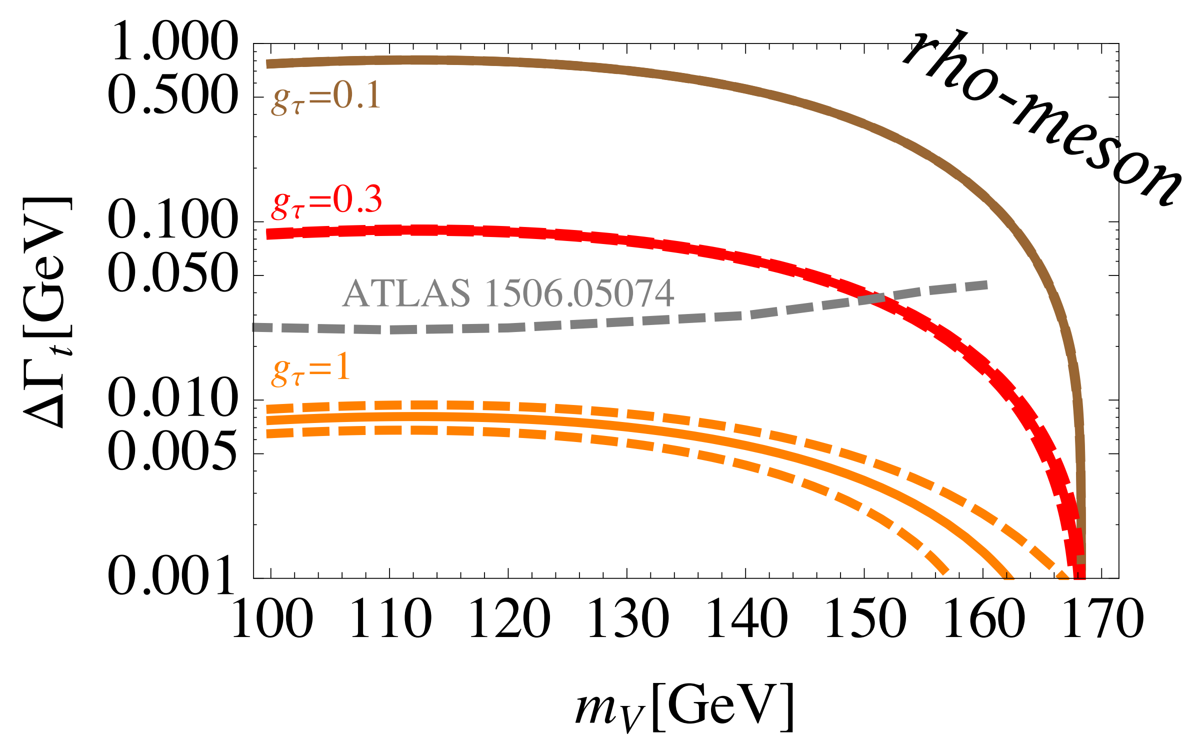
EXISTING CONSTRAINTS ON THE SIMPLIFIED MODELS

Existing measurements established LFU between the light quarks to the level of 5%-10% and between the tau and the light quarks at the level of 15%-20%.

Different kinematics $\Rightarrow$ *Acceptances can vary*

Corrections to the acceptances are around 10% for the m_ρ = 100 GeV and grow to ~50% around 160 GeV





Fix the product $g_\tau g_b$ to match the B-physics results (charged current).

GOING BEYOND 10%

$$BR(t \to e\; b\; \not{E}_T) = 13.3\% \pm 0.4\% \pm 0.4\%$$
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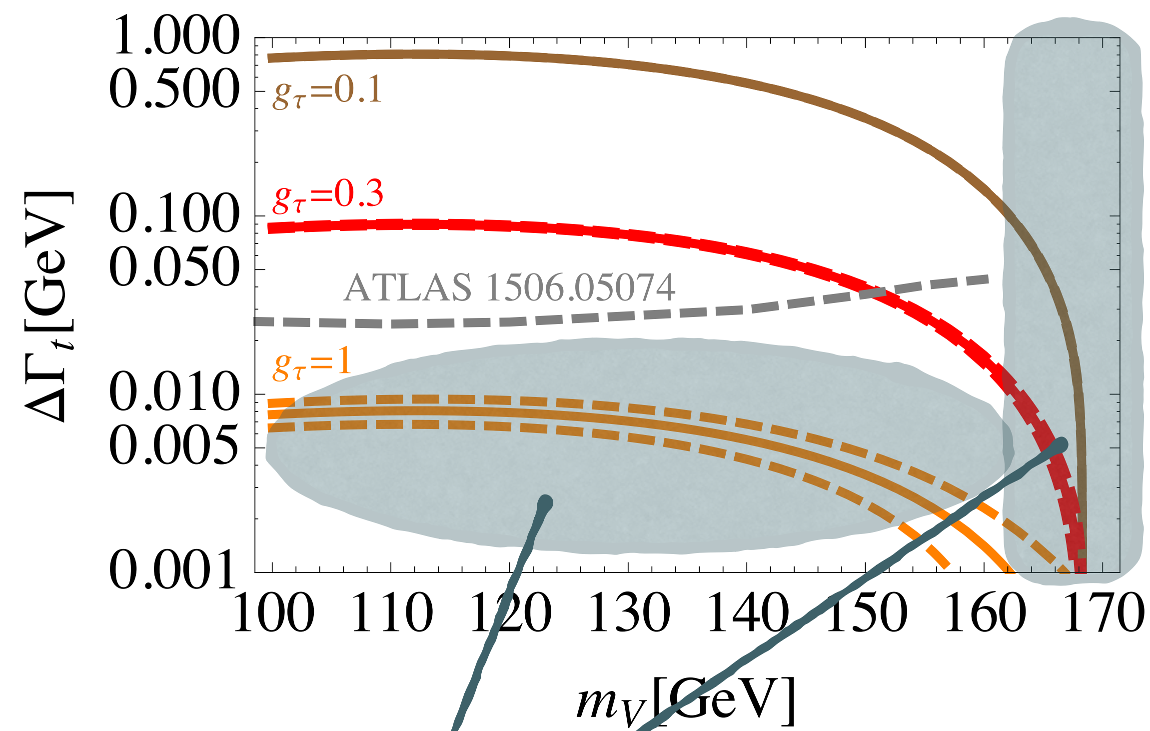


Systematic errors are already comparable to the statistics. Any significant progress is unlikely already after 8 TeV!

This regions are unlikely to be covered if we do not adopt different techniques

Need techniques to go beyond 10%. In fact if we take off shell region seriously, we might need sensitivity beyond 1%

SHAPES IN THE SM TOP DECAYS

Agashe, Franceschini, Kim; 2012

A-priori we do not know whether a particle, which contributes to the LFUV is produced on-shell in the top decay or not. However, there is very little room left for new particles below the 170 GeV mass which couples sufficiently strongly to the top.

Is there anything special in distributions of 2-body decay products?

In 2-body decay B→Aa (with a massless particle a): $$E^* = \frac{m_B^2 - m_A^2}{2m_B} \,.$$

in the B rest frame

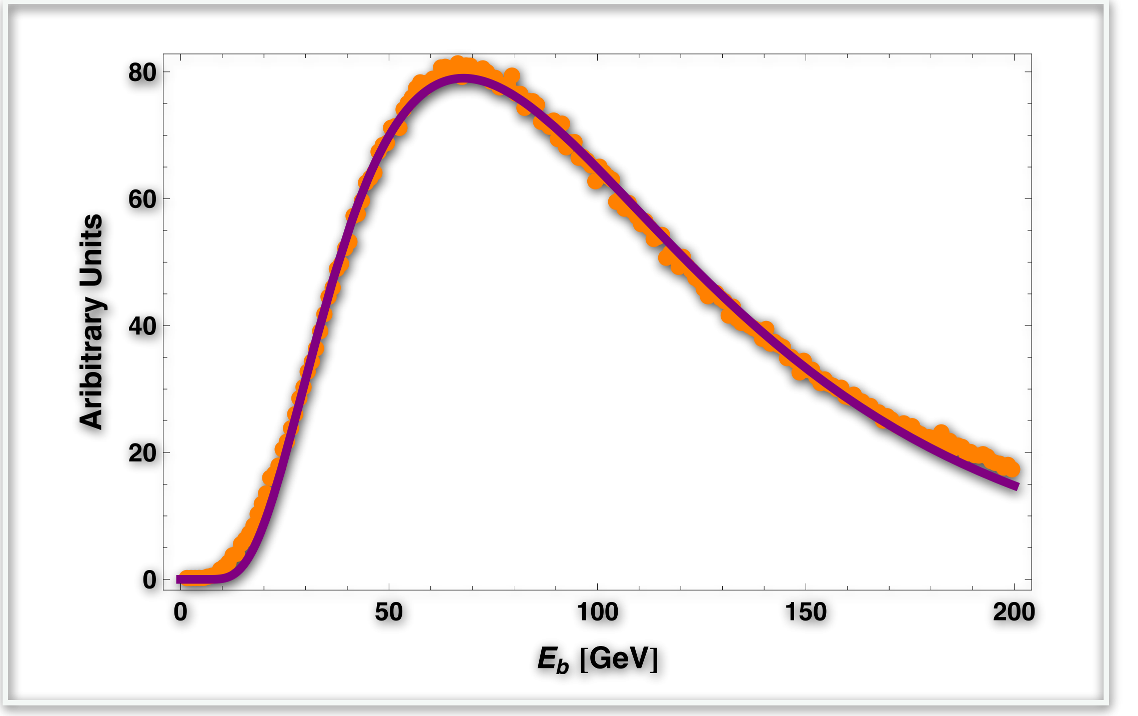
Expected distribution in the lab frame: $$E = E^* \gamma \left(1 + \beta \cos\theta^*\right) \,,$$

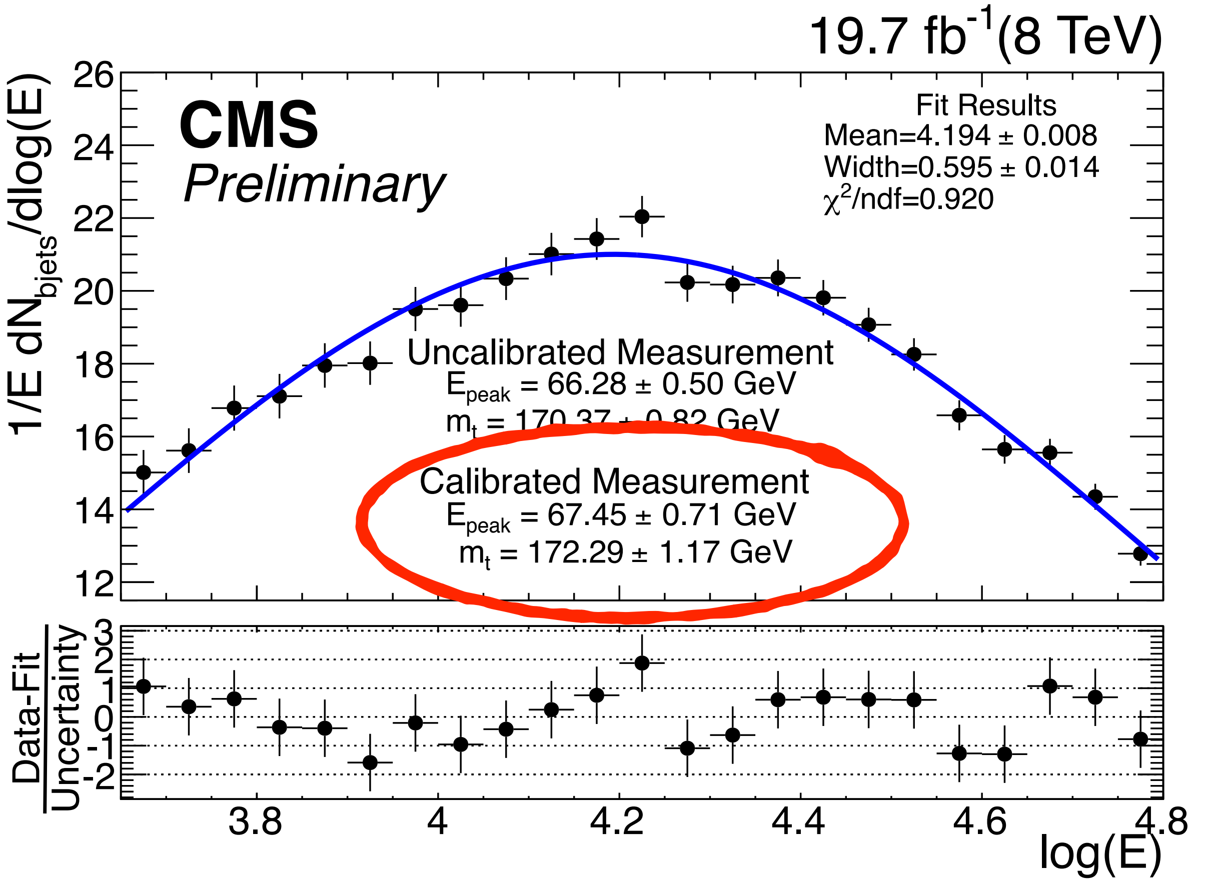
boost of B in the lab frame

emission angle of a in the B frame w/ respect to boost (flat for unpolarized B's

SHAPES IN THE SM TOP DECAYS

Basic observation: even if at the end of the day the b-energy is a distribution, the center of the distribution at the tree level does not move. This observation lead to a suggestion that one can measure this way the top mass.





The measurement has been performed by CMS (CMS-PAS-TOP-15-002). The top mass precision is better than 1%

We will try to use the b-shape for a different purposes and use the entire shape information rather than the central point.

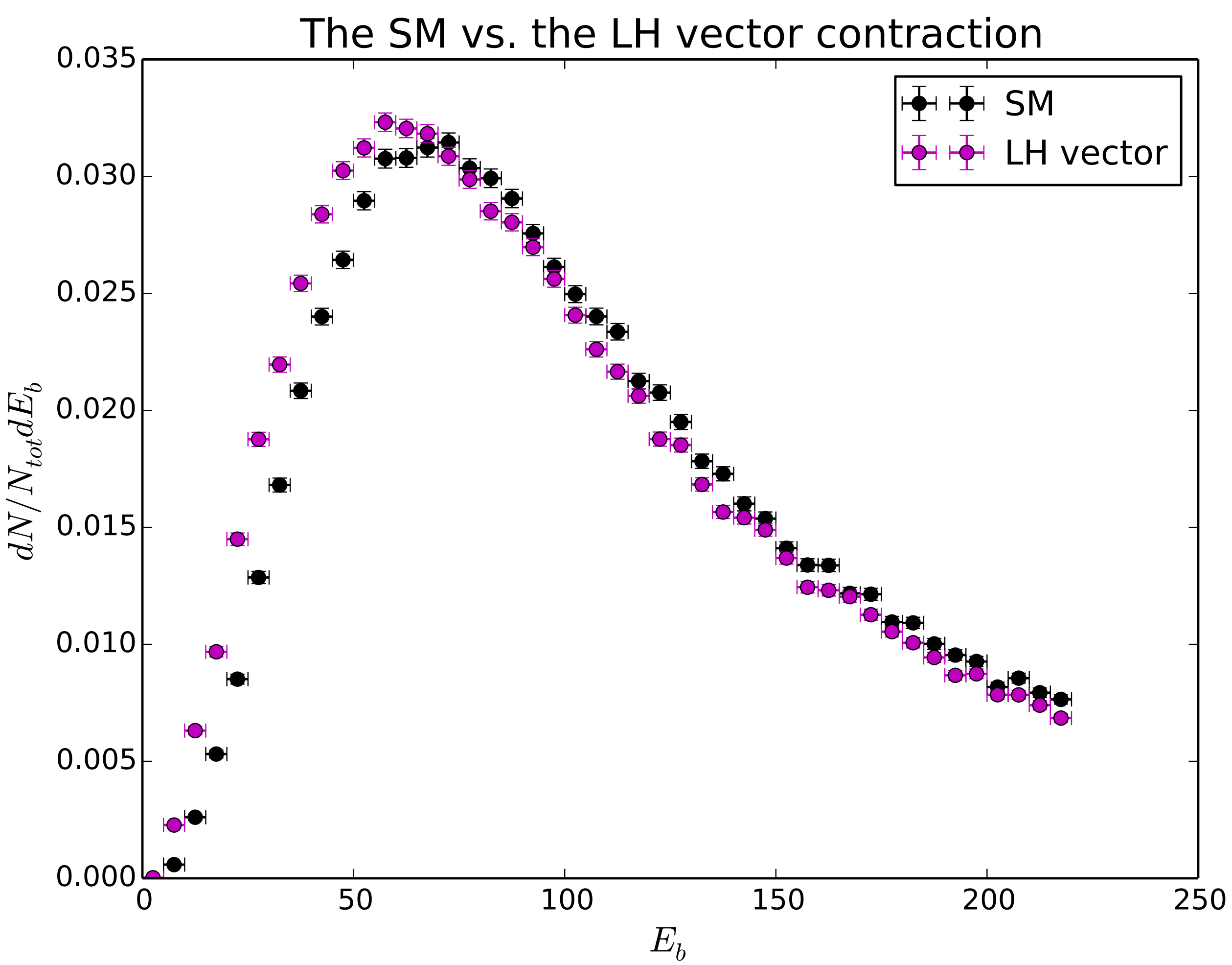
SHAPES IN 3-BODY DECAYS

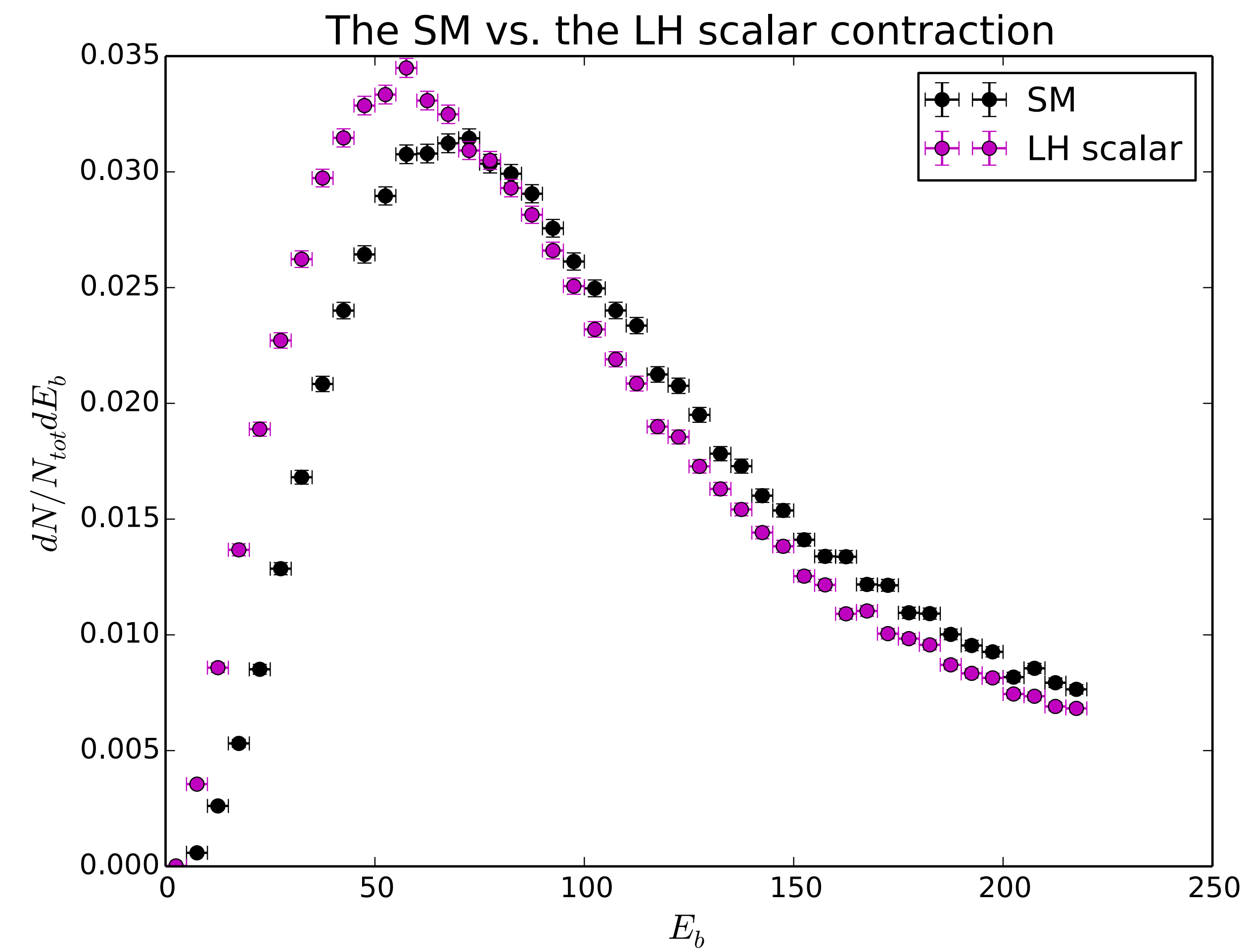
- ☑ B-jets are coming now from 3-body decays. Both the distribution and its peak should be different from the 2-body decays
- ☑ Leptons (taus) are not coming from the 2-body decays of W's

However:

- About 1% of all the observed SM top decays are via significantly off shell W's
- Effects of the interference between the SM and the NP are not negligible
- Tau energy is not even observable on event-by-event basis

SHAPES OF NEW PHYSICS



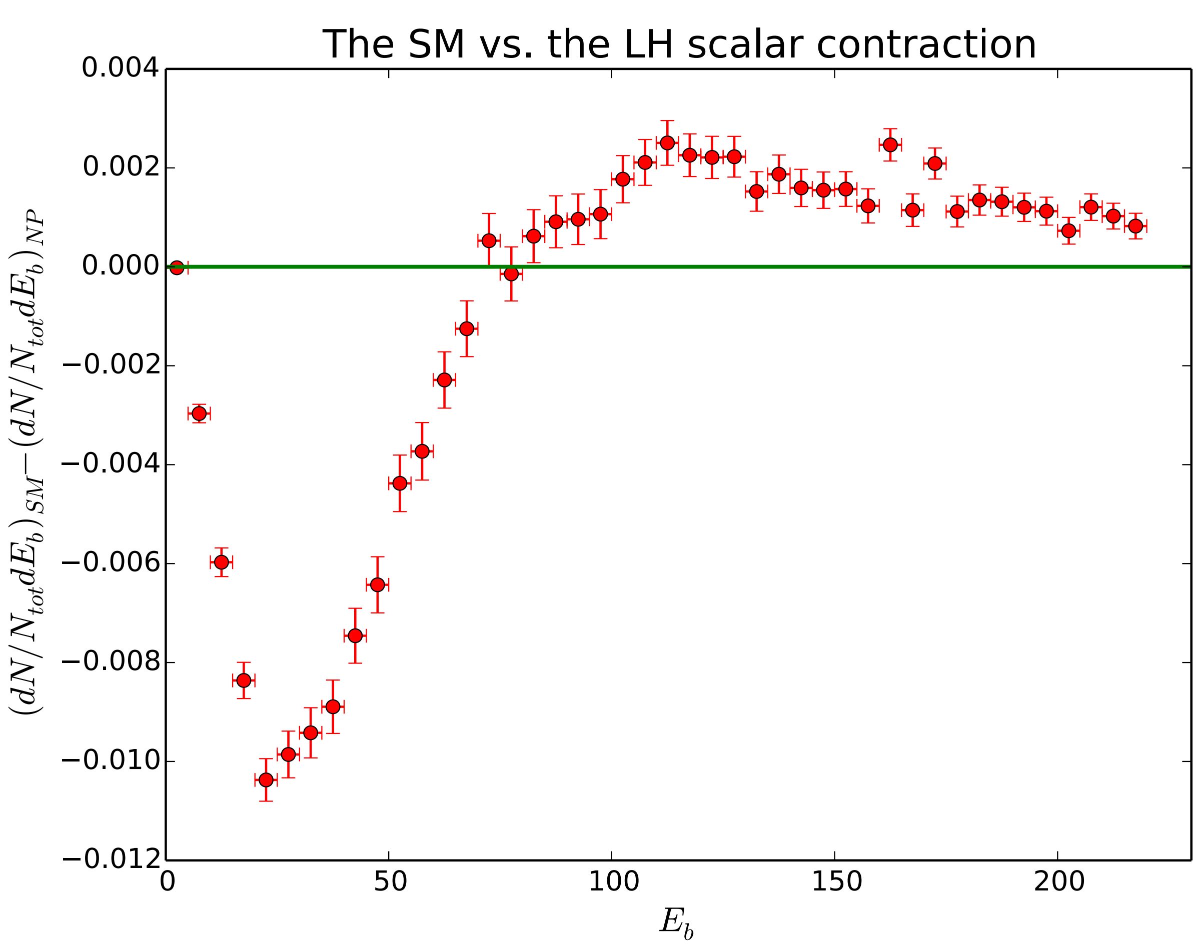


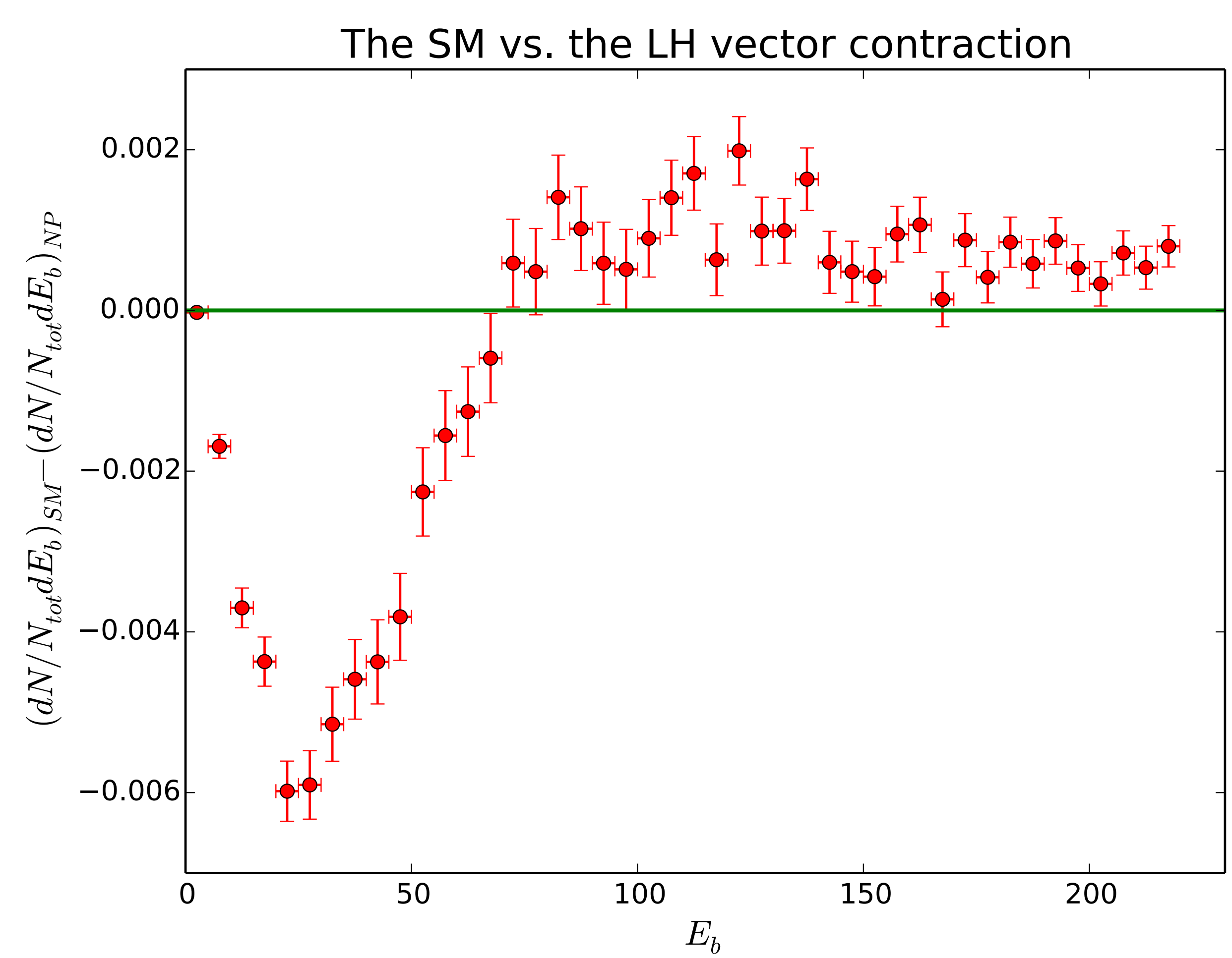
These are normalized distributions of signal and background separately. In practice of course we never get “signal”, in the best case it is background + 1% of signal.

SUBTRACTING NEW PHYSICS FROM THE OLD PHYSICS

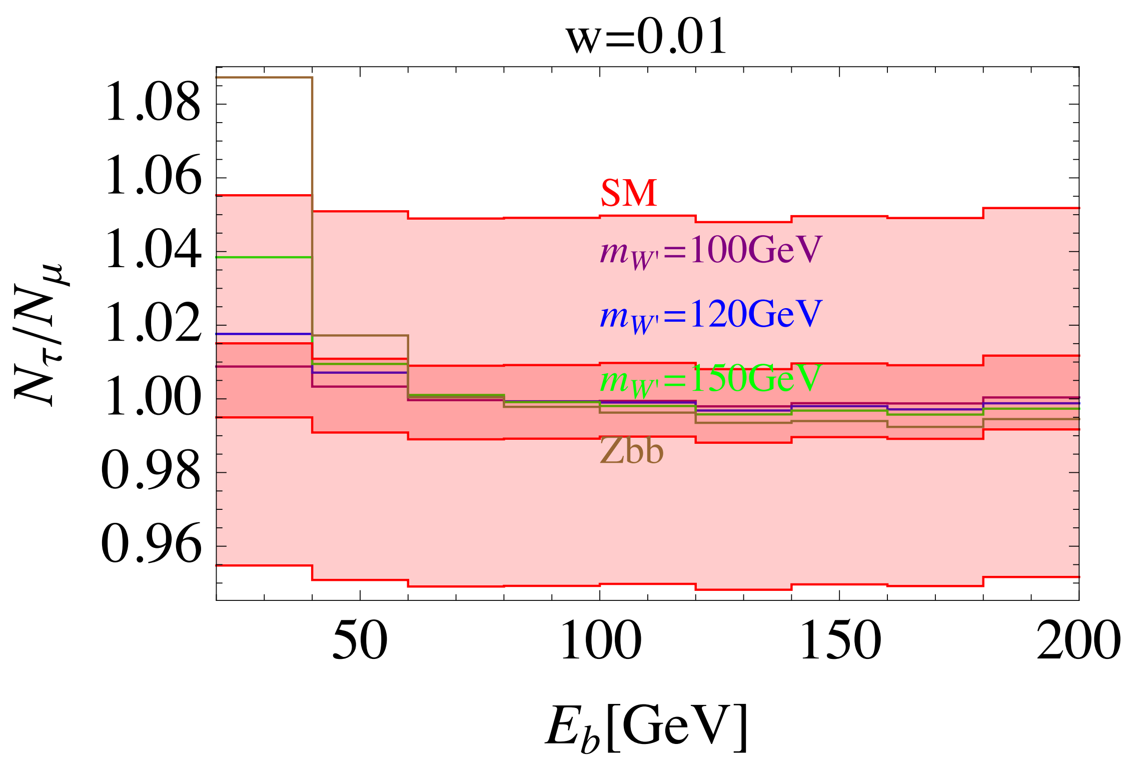
There are multiple uncertainties which have to do with understanding the b-tagging and theory corrections. However, we measure LFUV ⇒ only relative measurement between the different flavors matters. B-tagging uncertainty will cancel out, if we subtract the tau events (which may be affected by NP) from muon events!

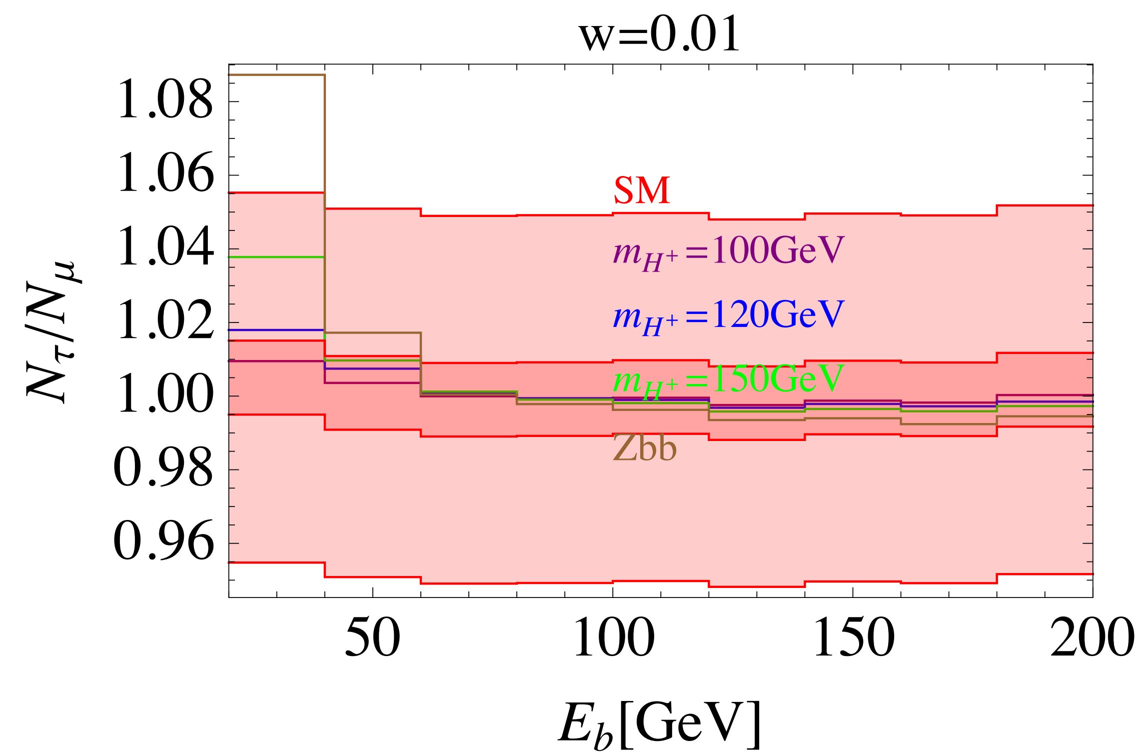
Subtraction of signal from background for 10^5 events ⇒ corresponds to 300/fb (the acceptance is around 1% and tau+mu channel is around 3.3%):





WHAT ABOUT SYSTEMATIC UNCERTAINTIES?





On these plots we assume that NP is just 1% of all the events in the tau channel. In the red band are systematic uncertainties estimated from tau tagging and (weak) correlation between the b-jet energy and the tau transverse momentum.

The relevant parameters are not absolute error bars, but bin-to-bin correlations.

If this estimation is true, the real roadblock is statistics, rather than systematics. Going below 0.5% might be possible, but we need more than 10^9 top pairs

MORE CAVEATS TO ADDRESS

- There is no real di-leptonic sample, it is always polluted by the leptonic taus. The effect is not expected to be large, but should be taken into account
- The dominant background to ttbar is ttbar. In the $\mu\tau$ LHC measurements the dominant background is coming from $\mu\mu$ with one of the muons misidentified as a hadronic tau. The ideal way to address these issues will probably be simultaneous fit (in progress)
- The dominant non-ttbar background is coming from Z + jets. What is the shape of b's there?
- Effects of the interference between the SM and the NP?

CONCLUSIONS AND OUTLOOK

- Standard techniques already constraint LFUV in top decays, and the constraints are often comparable to those that we have from B-physics
- This measurements are already systematics limited, and any significant progress in LHC13 and / or FCC-pp is unlikely
- One might have a competitive handle on LFUV in comparing the distributions of the b-jet energies in various channels, reducing possible systematics issues
- In this case statistics might become an important issue, given that the $\mu\tau$ channel is ~3.39% with acceptance around 1%.
- Backgrounds are expected to be subdominant and largely also of top-origin
- The results are very preliminary, and should be all verified in more realistic simulations — stay tuned.