

# Probing Lepton Flavor Universality Violation in Top Decays

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# Outline

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- ❖ Why flavor universality in top decays?
- ❖ Current bounds and assumptions
- ❖ New observables: use the shapes
- ❖ The backgrounds and the potential reach
- ❖ Conclusions

# Why in Tops? The First Look

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Tops production cross sections in proton colliders:

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

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

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

By the end of the HL LHC run we expect to produce  $2.5 \times 10^9$  top pairs.

If FCC-pp will indeed materialize we will have as many as  $10^{12}$  top pairs!

What are the new precision measurements that we can perform with this huge amount of data?

# What Do We Already Know about Exotic Top Decays?

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Currently measured constraints on the exotic top decays are extremely weak, weaker than almost all BSM predictions (and of course the SM):

- ❖  $\text{BR}(t \rightarrow ch) < 0.16\%$  (Atlas, 2018)
- ❖  $\text{BR}(t \rightarrow uh) < 0.19\%$  (Atlas, 2018)
- ❖  $\text{BR}(t \rightarrow uZ) < 0.022\%$  (CMS, 2017)
- ❖  $\text{BR}(t \rightarrow cZ) < 0.049\%$  (CMS, 2017)
- ❖  $\text{BR}(t \rightarrow u\gamma) < 0.013\%$  (CMS, 2015; indirectly from production)
- ❖  $\text{BR}(t \rightarrow c\gamma) < 0.17\%$  (CMS, 2015; indirectly from production)
- ❖ CMS: bounds on  $tbW$  anomalous vertex, and consequently indirect limits on  $t \rightarrow g \sim O(0.001\%)$

All these modes probe exotic neutral currents. What about exotic charged current decays?

# Are Top Decays Lepton Flavor Universal?

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Until now the question was addressed only via direct BR measurement of the tops:

$$BR(t \rightarrow e b \cancel{E}_T) = 13.3\% \pm 0.4\% \pm 0.4\%$$

$$BR(t \rightarrow \mu b \cancel{E}_T) = 13.4\% \pm 0.3\% \pm 0.5\%$$

$$BR(t \rightarrow \tau_h b \cancel{E}_T) = 7.0\% \pm 0.3\% \pm 0.5\%$$

By solving the system of coupled equations we see that the LFU between the light leptons has been probed to the level of slightly more than 5%, and between the taus and the light leptons  $\sim 10\%$ .

Can we do better than that?

# Hints from Another Sector

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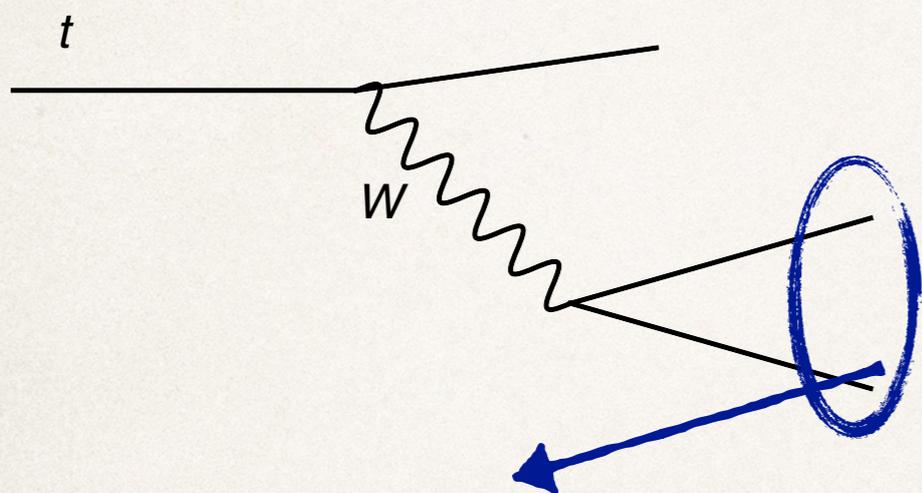
Have we ever seen LFUV in different sectors? Not really, however:

- ❖  $R_D / R_{D^*}$  anomaly: enhanced tau channel compared to the light flavors (**charged current**).
- ❖  $R_K / R_{K^*}$  anomaly: statistically non-vanishing discrepancy between the light flavors (**neutral current**).

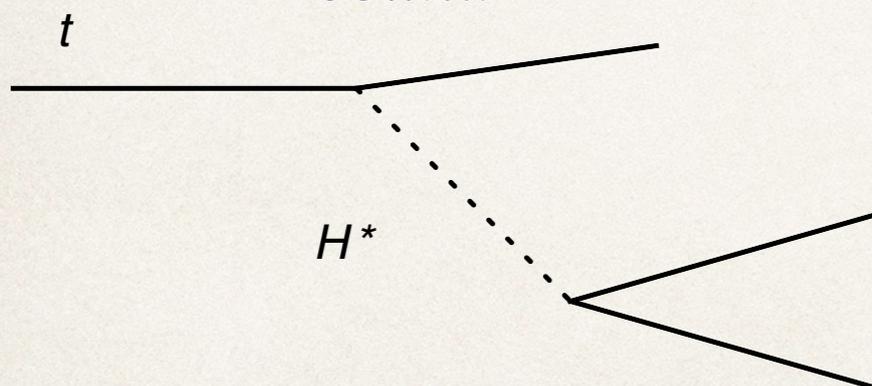
None of these observations is sufficiently robust to claim discovery or to exclude the possibility of systematics. However, if the charged current “anomaly” is real, it is expected to also affect the tops (SU(2) symmetry).

The exact size is model dependent. Can we make progress in this direction?

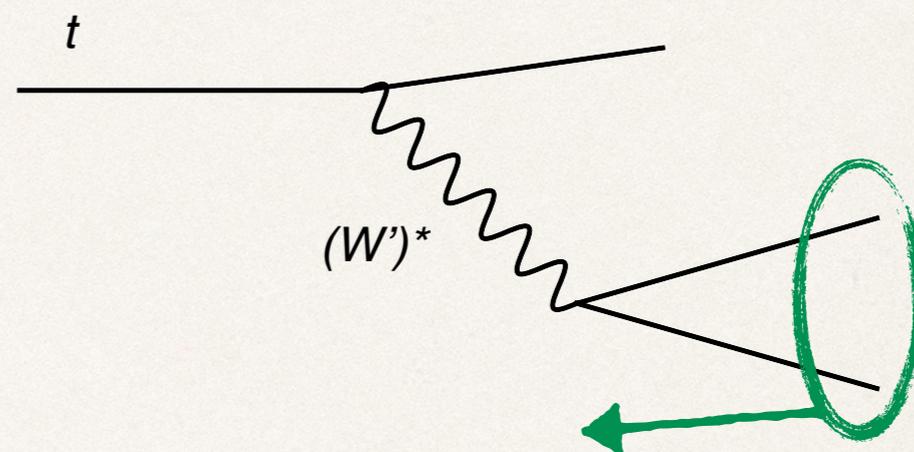
# Off-Shell Top Decays



*As flavor universal as  $W$  decays are, LEP still provides the best bound*



*Charged Higgs decays always violate (L)FU.*



*We have no good prediction about the flavor structure of these decays. If  $W'$  comes from a composite theory, it is likely to be LFUV*

The off shell decays can never be dominant and will be  $\sim$ few % at best (and the interference with the SM should always be taken into account). Probably hopeless if we only measure BRs. Distributions?

# LFUV Simplified Models in Tops

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Heavy  $W'$  — might mediate LFUV:

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

*EFT vector contraction*

Heavy Higgs — expected to violate LFUV:

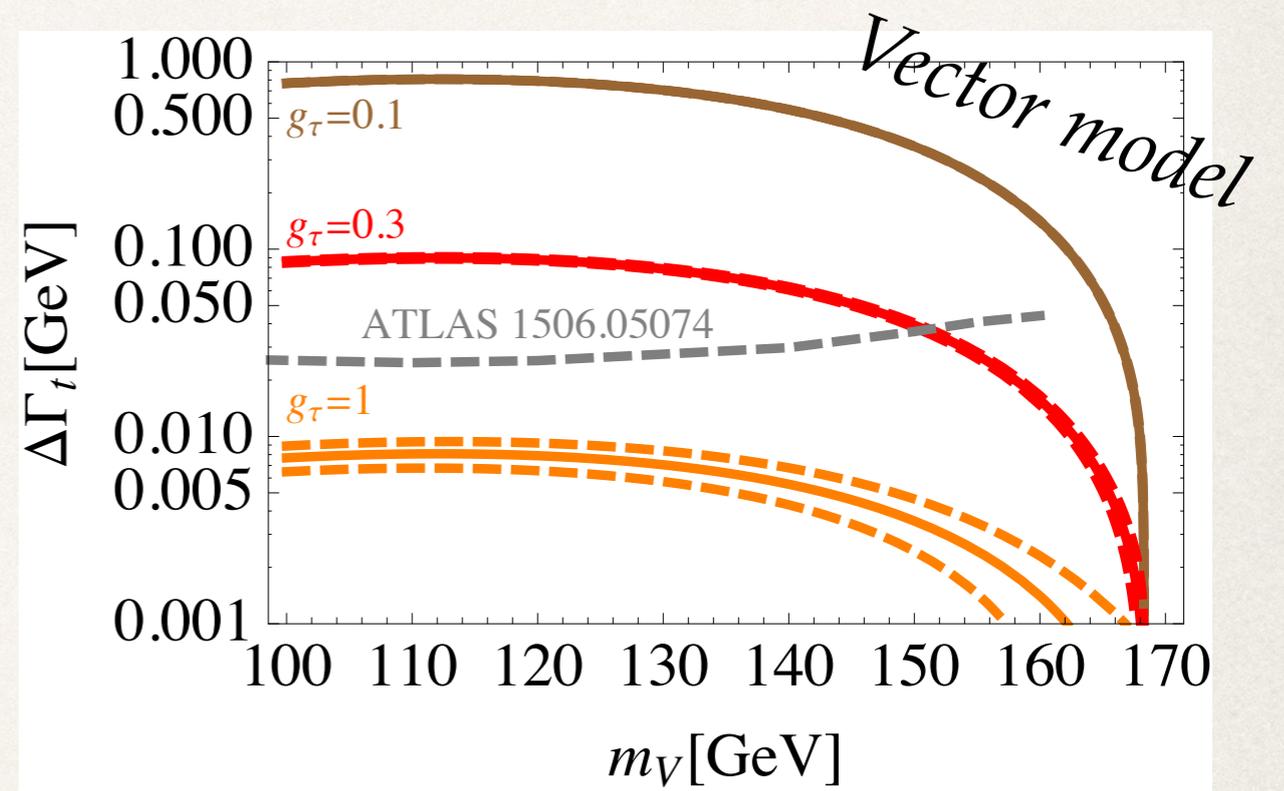
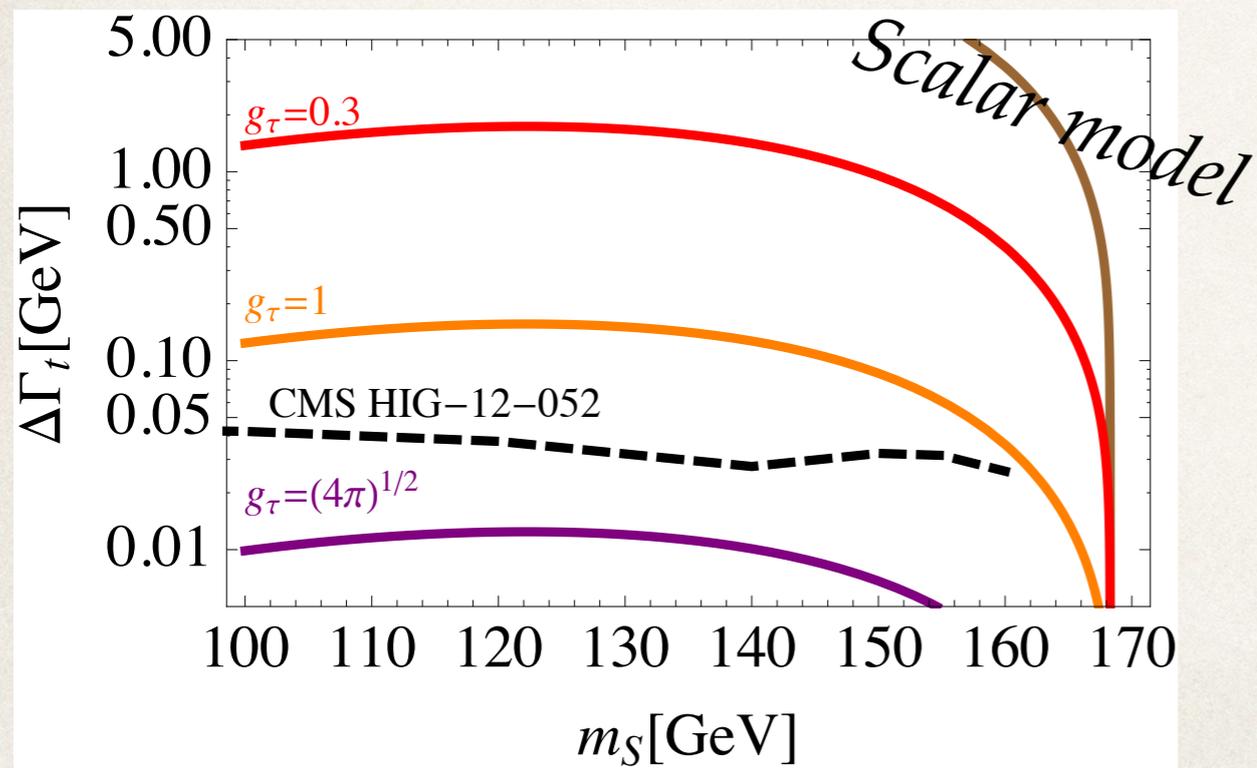
$$\mathcal{L}^{(b)} = \mathcal{L}_{\text{SM}} + \partial_\mu \phi^+ \partial^\mu \phi^- - m_\phi^2 \phi^+ \phi^- + [\sum_q V_{qb} \phi^+ (y_\phi^L \bar{q} P_L b + y_\phi^R \bar{q} P_R b) + y_\phi^\tau \phi^- \bar{\tau} P_L \nu_\tau + \text{h.c.}],$$

*EFT scalar contraction*

Leptoquarks: might violate LFU. Map onto EFT tensor + scalar contraction (if scalars) or simply to vectors (if spin-1)

# Existing Constraints

Fix the product of the couplings to the b and to the tau to match the central value of the charged current “anomaly”



Bounds are coming from the BRs of the top + kinematics (at least in the CMS case)

# Top Shapes in the SM

*Agashe, Franceschini, Kim; 2012*

A priori we have no idea if a particle, that mediates LFUV in top decays (if it does) has a mass above or below 170 GeV. However, very little room is left below 170 GeV.

What is special about the kinematics of 2-body decays?

Two body decay  $B \rightarrow Aa$  with massless  $a$ :  $E^* = \frac{m_B^2 - m_A^2}{2m_B}$ .

In the B rest frame

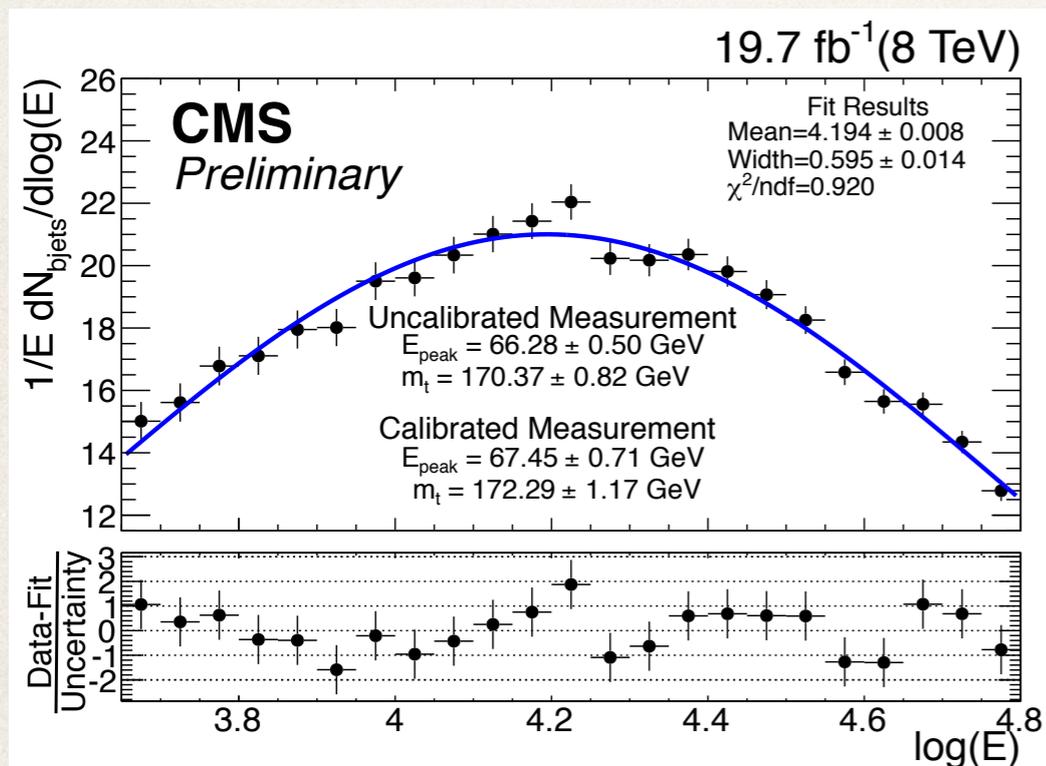
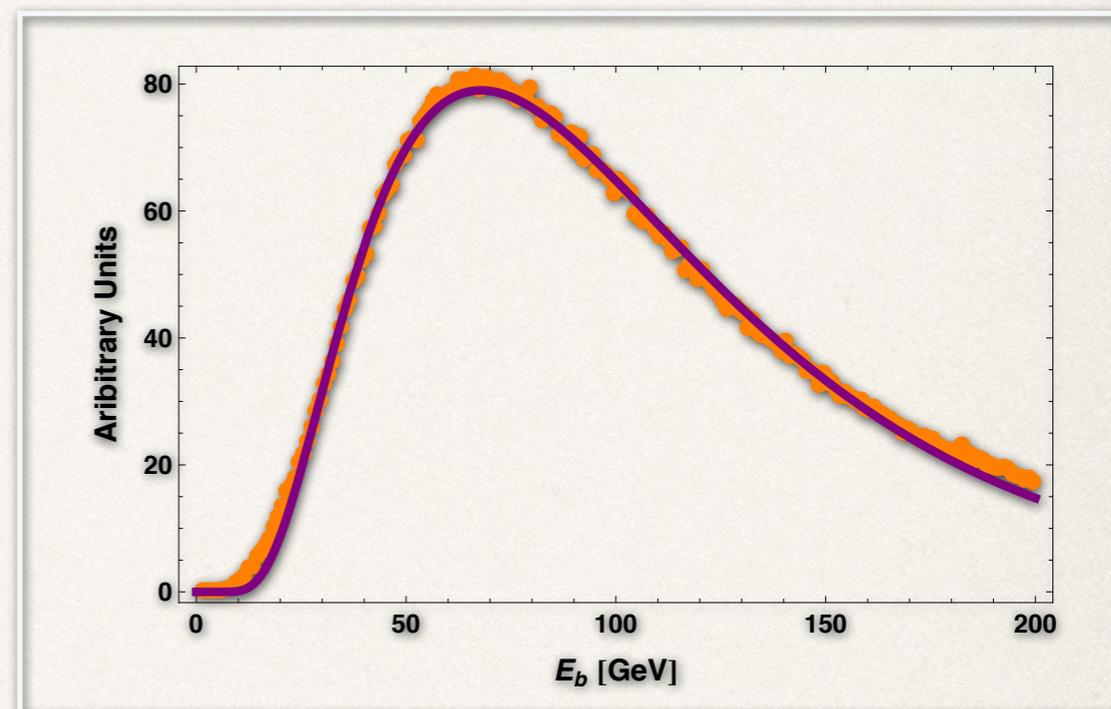
Expected distribution in the lab frame:  $E = E^* \gamma (1 + \beta \cos \theta^*)$ ,

Boost of B in the lab frame

Emission angle of  $a$  in the B frame  
w/ respect of the boost

# Top Shapes in the SM — II

Basic observation: in the lab frame the b-energy is a distribution, it's center is completely boost independent. The shape of course depends on the boost distribution of the tops events



This method has been used in CMS-PAS-TOP-15-002 to measure the top mass to the precision better than 1%

# What Happens in 3-body Decays?

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There is still a compact expression for the energy of the pseudo-particle (ab):

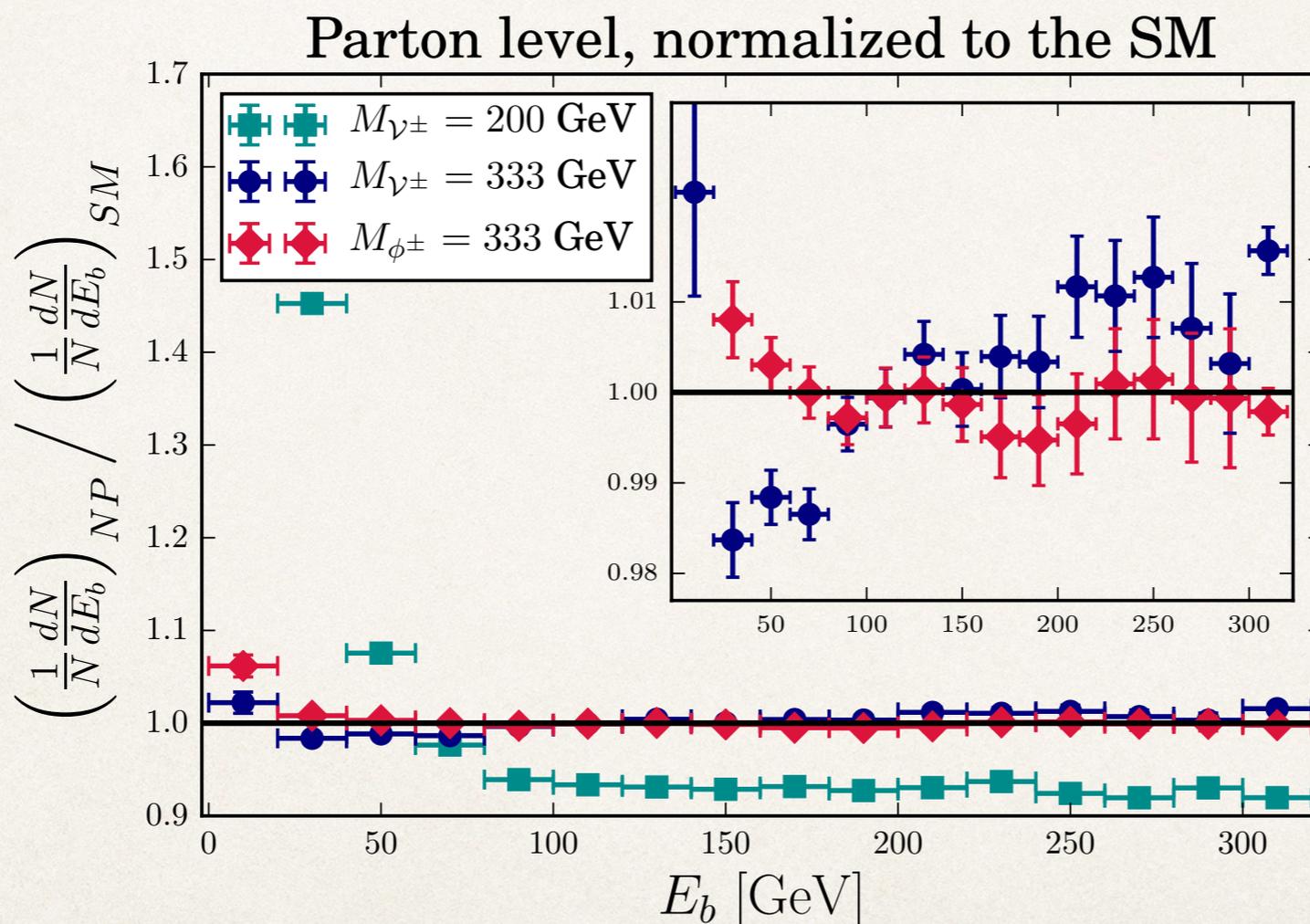
$$E_{(ab)}^* = \frac{m_B^2 - m_A^2 + m_{ab}^2}{2m_B}$$

However, the distribution of the b-jet energies should in principle be different from one predicted by the 2-body dynamics

- ❖ The portion of the events is small (at or below 1%)
- ❖ We cannot rely on the distribution of tau energies since we do not measure it — can use only b-jets
- ❖ In most of the cases, the interference effects will be important

# Shapes of the New Physics (+SM)

At the parton level: (SM+NP) / SM



$$g_\tau g_b = 5$$

$$y_\phi^L y_\phi^\tau = -2.6, y_\phi^R y_\phi^\tau = 3.1$$

$$g_\tau g_b = 4.5$$

The plots are normalized to the same amount of passing events

# Takeaways from the Parton Level Distributions

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- ❖ The shape of the b-jet energies is affected, but the peak is (almost) unaffected — hard measurement, we will have to control the boosts distribution
- ❖ The shapes of the distribution where the  $|NP|^2$  dominates and the one which is interference dominated are completely different, and depends on the interference sign
- ❖ The effect is quite pronounced at the low energies, but can be easily affected by the efficiency near the lower threshold
- ❖ The effect can be as big as 20% in certain bins, but mostly it is in the  $\sim 1\%$  range, we are unlikely to get any reliable theoretical prediction — use data

# Shapes of the New Physics: More Realistic Approach:

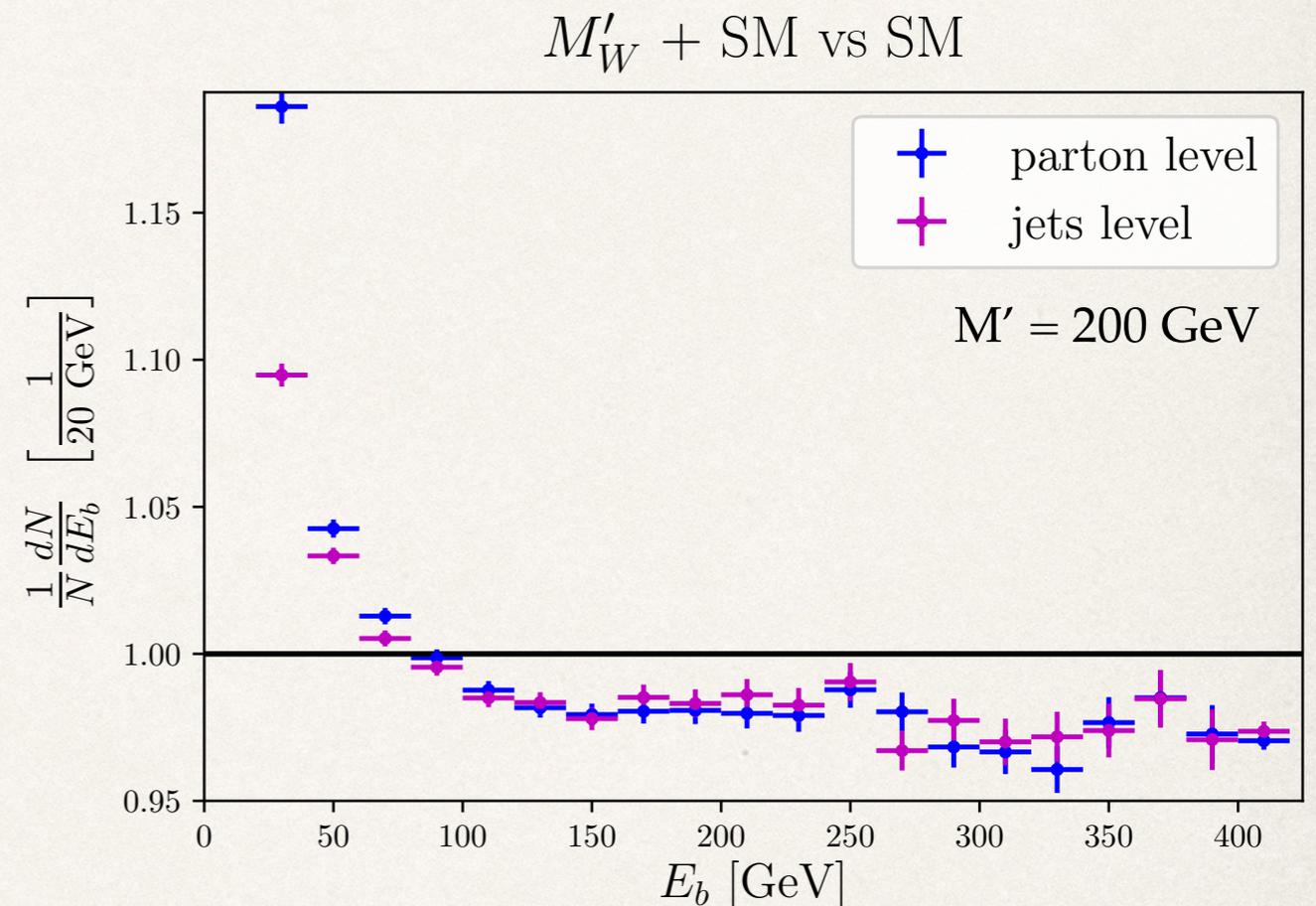
As expected, the lower bins can be easily affected by the showering and hadronization, however the basic effect is intact.

Variable to consider:

$$n[\text{signature}](E_b) \equiv \frac{N[\text{signature}](E_b)}{\sum_{(E_b)} N[\text{signature}](E_b)}$$

❖ Where do we take the SM from?

❖ How do we control the shape of the distribution (boost of the events) in non-inclusive samples — how do cuts affect the distribution?



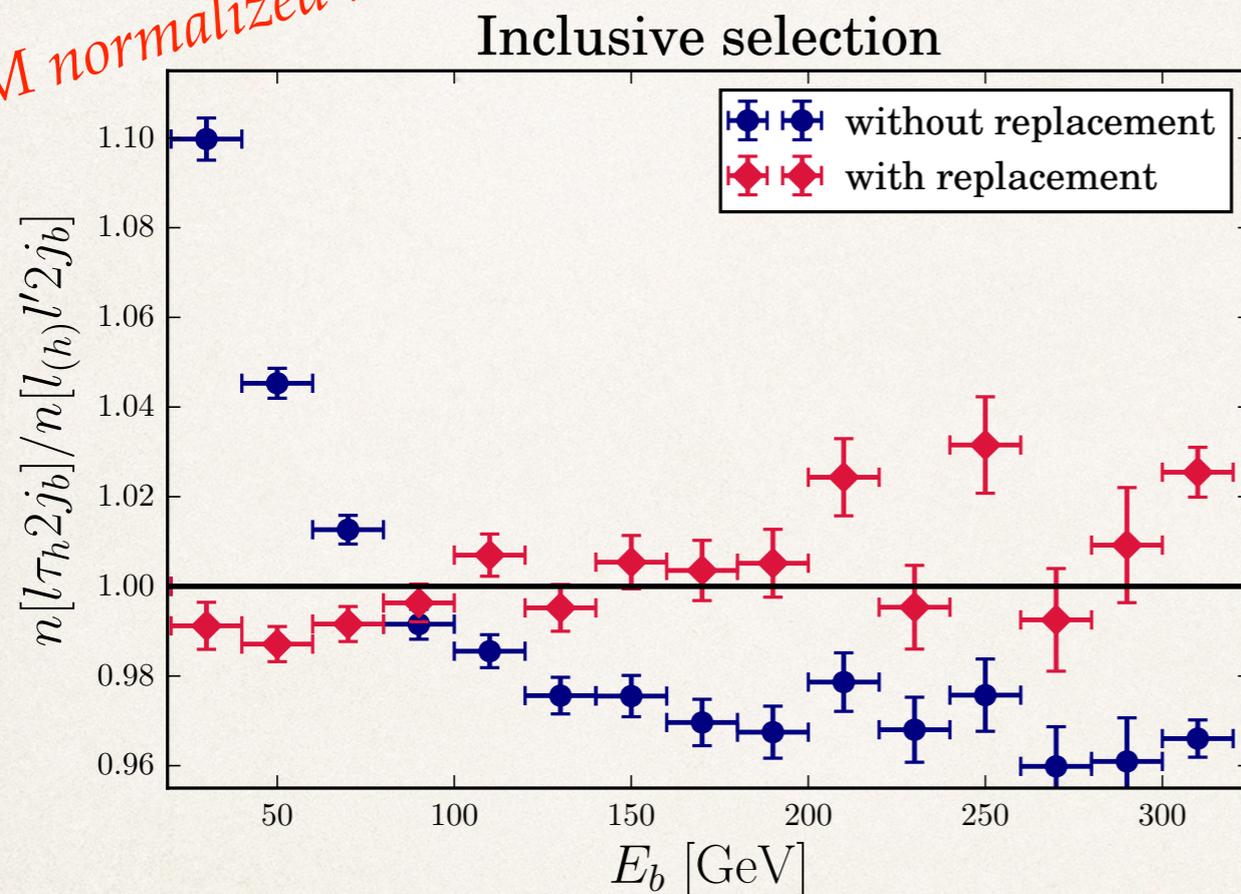
# How Do We Get the “Right” SM Shape?

Basic idea: use the shapes from the data with the controlled sample being top decays into electron + muon (to avoid cutting out the Z-window that potentially introduces a bias)

- ❖ We assume that the first two generations are not affected by the NP
- ❖ Take for the control sample only the “good” top pair events: with 2 b-tags, each lepton should have a  $p_t$  above 20 GeV and well isolated
- ❖ To compare properly the distributions we pick up a random lepton and substitute it with the tau and further decay the tau in Tauola. Since the top decays are measured to the level better than 1 % this does not introduce any unmanageable systematic uncertainty
- ❖ After the substitution include only those events that pass exactly the same cuts as we impose on the tau+lepton “signal” sample

# How Well Does this Routine Work?

*The SM normalized to the control sample*



Lumi  $\sim$  250 / fb

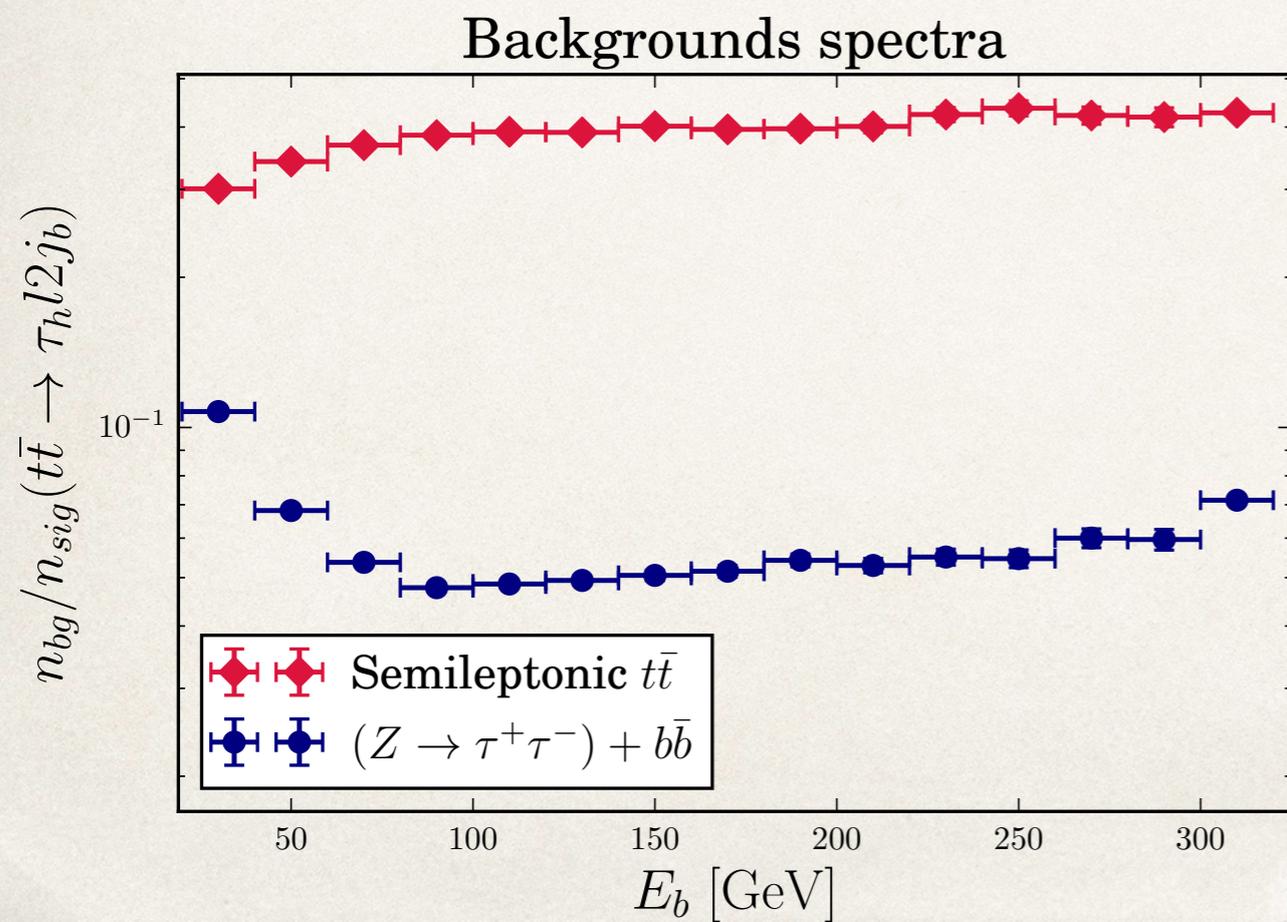
If we do not follow the replacement procedure, we get a shape that exceeds by far any possible NP effects. The replacement essentially solves the problem.

What about the backgrounds?

# More Backgrounds and More Cuts

The control sample is largely background free, but the signal sample has a huge background: semileptonic  $t\bar{t}$ . In fact, with the tau fake rate being several percent, it is comparable to the true signal sample.

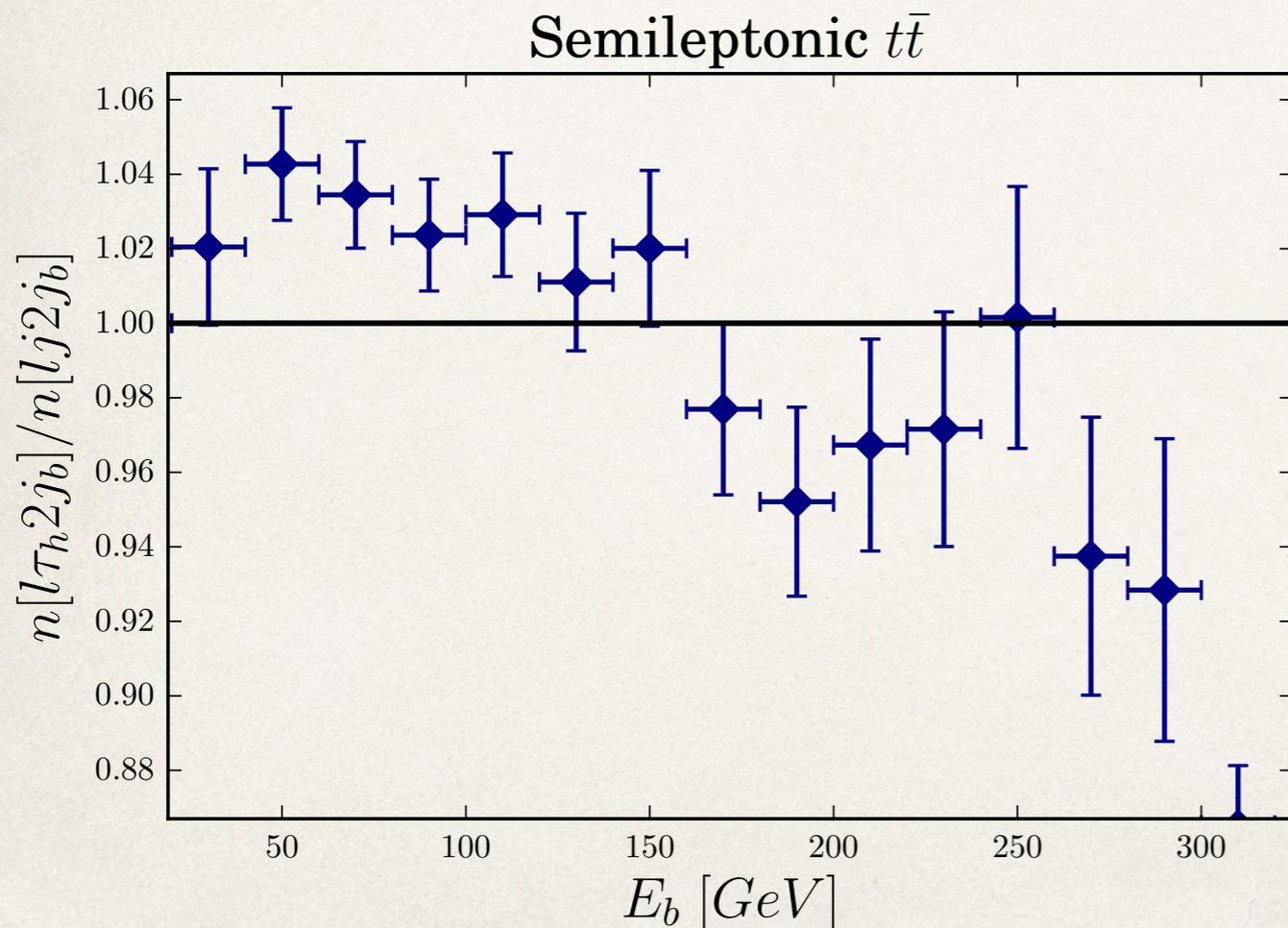
How bad is that?



The shape is very clear both in tops and Z + jets and these shapes mimick the shape of certain NP in scenarios, where the dominant derivation is due to the negative interference. Z +jets has much more prominent shape, but the the overall is rate is small. Semileptonic tops are  $O(1)$ .

# Semileptonic tops

Step 1: veto all the events with non b-tagged jets with  $p_T > 20$  GeV. Allow only 1-prong taus (this might not be needed in reality but makes our samples much cleaner). This removes big portion of the background, but does not solve the problem with the shape

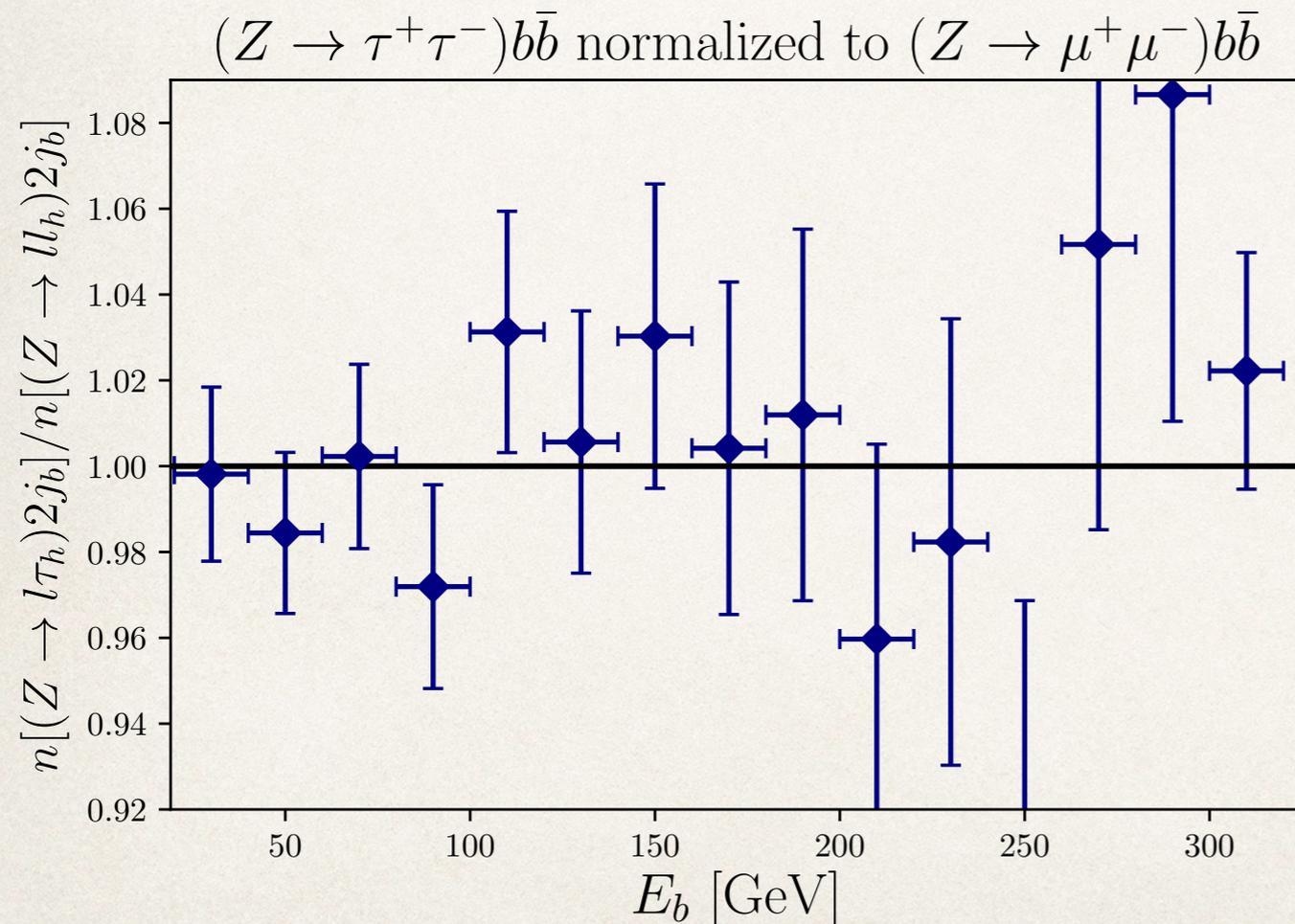


Step 2: for the remaining semileptonic tops background, subtract it from data. Add to the control sample events with 1, 2 b-jets and one non-tagged jet with  $p_T > 30$  GeV.

This does not give a perfect shape, but it is acceptable for our purposes.

# Z + b's with Jets

Much smaller background (but still pretty nasty).



Trick here: add to the controlled sample events  $Z \rightarrow \mu\mu$  with 2 b-jets. Replace one of the muons with tau and apply appropriate cuts.

In fact this procedure works pretty well.

# Cross Sections and Subtraction Coefficients

The control sample is bit tricky here. We must include together with the (replaced) leptonic sample, the semileptonic sample with 1 non b-jet and even some  $Z \rightarrow \mu\mu$  events. We make some assumptions about this coefficients based on our (highly imperfect) tau-tagging routine.

One should still be cautious with the uncertainties.

Signal [ $\ell\tau_h 2j_b$ ]

Process	$N_{MC}$	$\sigma$ (pb)	$\epsilon_{inc}(\%)$	$\epsilon_{ex}(\%)$
$t\bar{t} \rightarrow b\bar{b}\tau\ell 2\nu$	6.3M	84.2	6.7	1.9
$t\bar{t} \rightarrow b\bar{b}\ell\nu 2j$	40M	416	1.6	0.046
$Z(\rightarrow \tau\tau)b\bar{b}$	5.4M	4.79	1.2	0.32

Process	$N_{MC}$	$\epsilon_{inc}(\%)$	$\epsilon_{ex}(\%)$	$w$
CR [ $\ell_h\ell' 2j_b$ ]				
$t\bar{t} \rightarrow b\bar{b}\ell\ell' 2\nu$	6.6M	7.4	2.1	0.908
$t\bar{t} \rightarrow b\bar{b}\ell\tau 2\nu$	7.6M	0.33	0.087	0.092
CR [ $\ell j 2j_b$ ]				
$t\bar{t} \rightarrow b\bar{b}\ell\nu 2j$	40M	28	4.2	0.42
CR [ $Z(\rightarrow \ell_h\ell_h) 2j_b$ ]				
$Z(\rightarrow \ell\ell)b\bar{b}$	5M	1.2	0.32	0.033

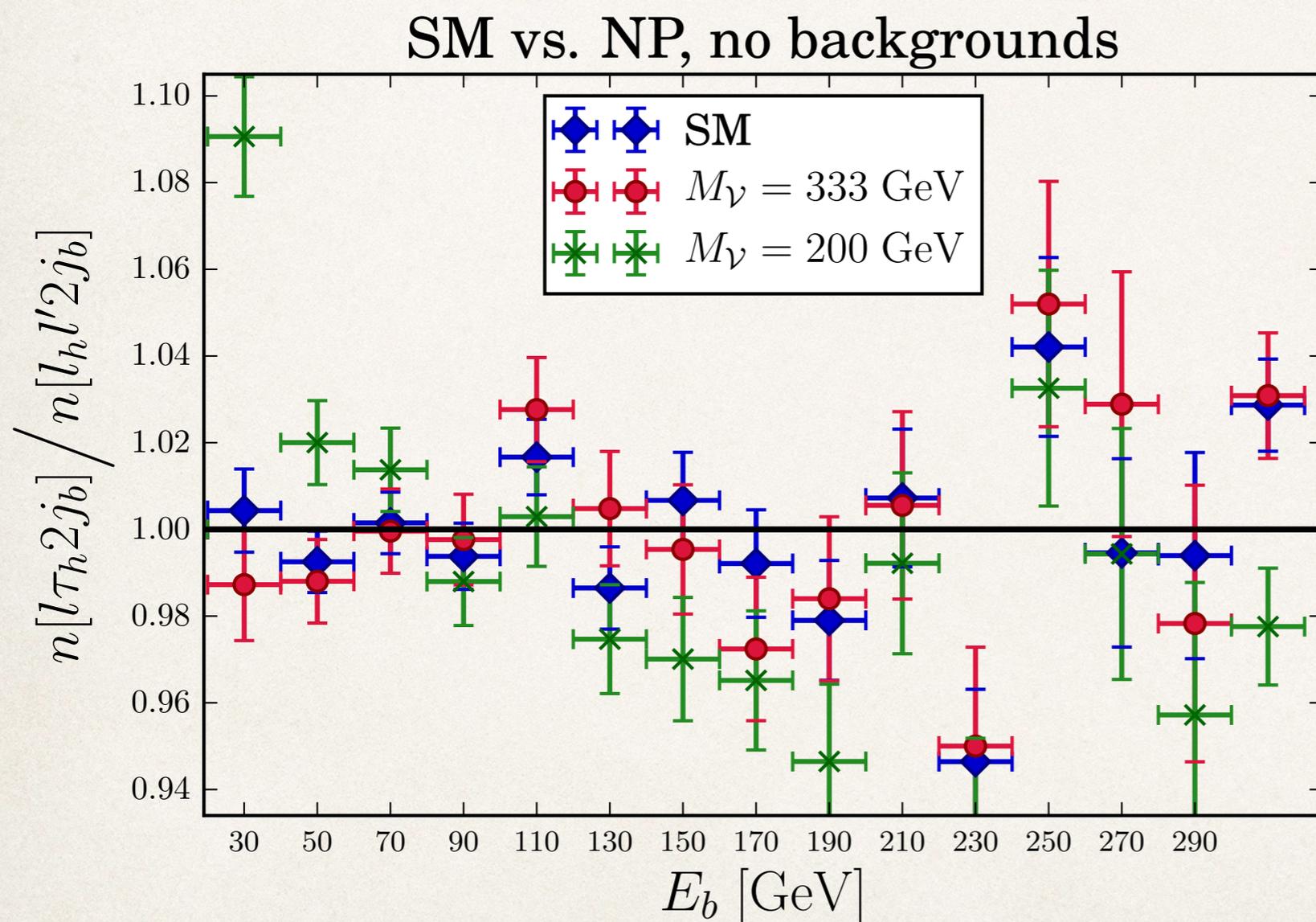
*Irreducible*

The K-factors almost cancel out:

$$K_{NNLO}(t\bar{t}) = 1.8$$

$$K_{NLO}(Zb\bar{b}) = 1.7$$

# The Results — No Backgrounds



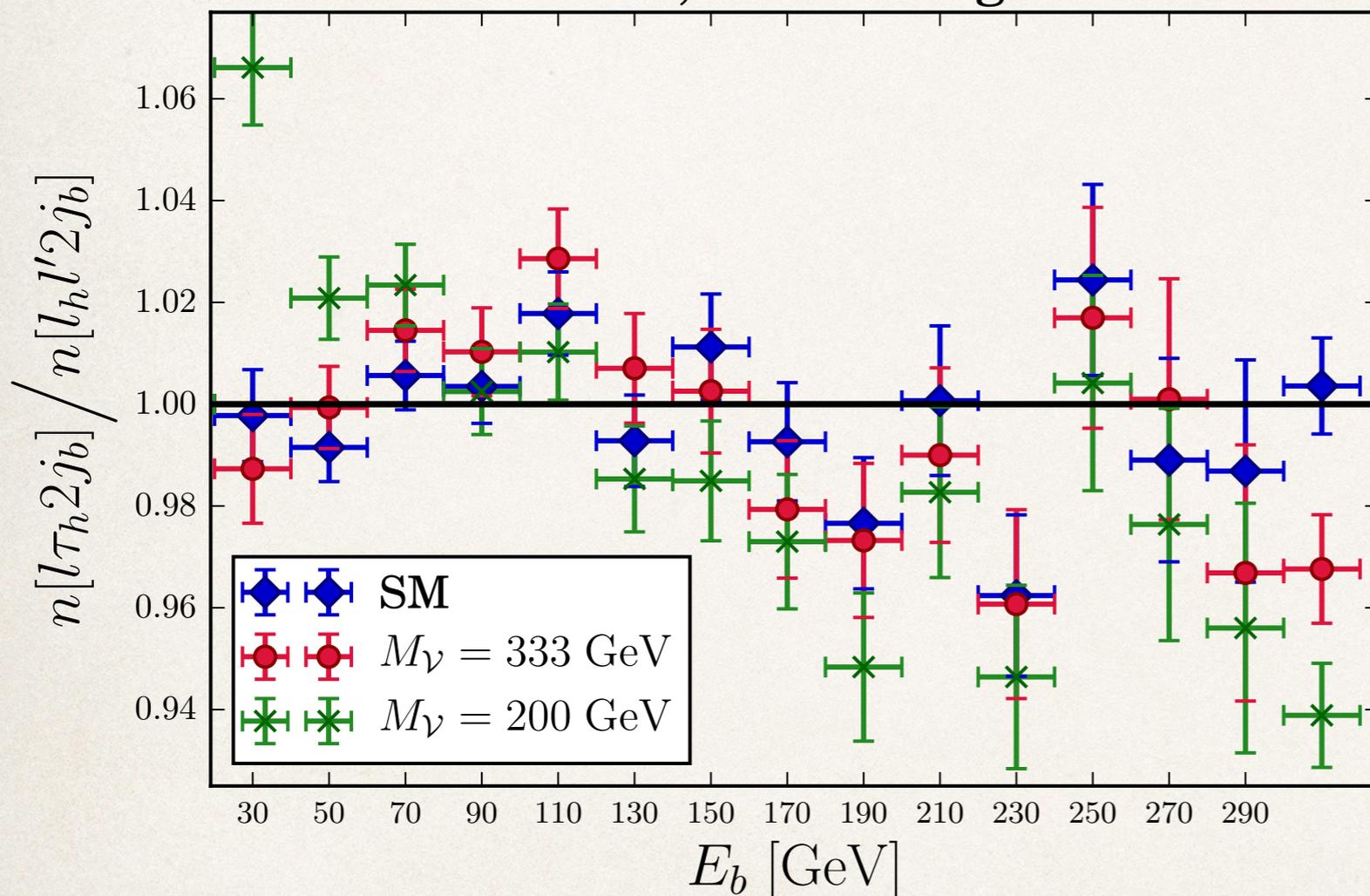
$$g_\tau g_b = 4.5$$

$$g_\tau g_b = 5$$

The “green” point can practically be done now. The rest — maybe at HL LHC?

# The Results — Backgrounds

SM vs. NP, with backgrounds



$$g_\tau g_b = 4.5$$

$$g_\tau g_b = 5$$

Background somewhat deteriorate the effect, but do not was it out. Still order 3...8% deviations due to the NP must be visible

# Conclusions

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- ❖ The standard techniques already constrain the LFUV in top decays roughly at the level of the LFUV in B decays (but of course **do not** have comparable reach to the same NP)
- ❖ The current measurements are systematics limited and any further progress is unlikely
- ❖ One might have a competitive handle on the LFUV in top decays via the b-jet distributions
- ❖ These techniques can be used only in comparing the distributions to the data, as getting a theoretical prediction at the desired level is challenging
- ❖ The backgrounds are an important issue, and are mostly of the top origin, can be also managed by subtracting from data
- ❖ The reach of the new techniques is expected to be vastly superior to the current ones