PROBING LEPTON FLAVOUR UNIVERSALITY VIOLATION IN TOP DECAYS

DANIEL STOLARSKI

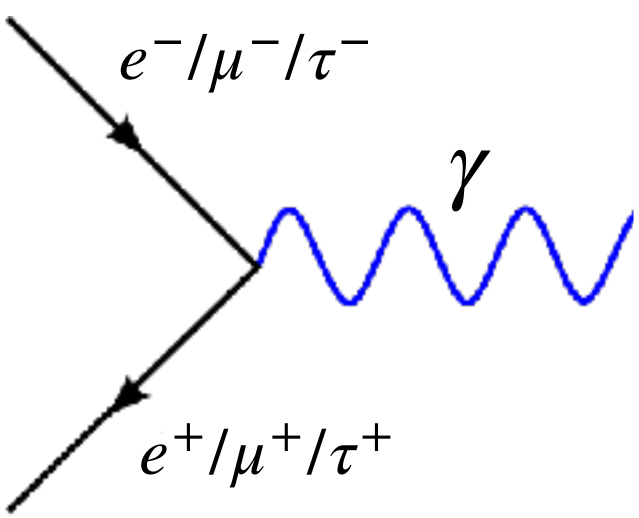
Andrey Katz, Jernej Kamenik, DS, [arXiv:1808.00964].
And work in progress with Alberto Tonero.

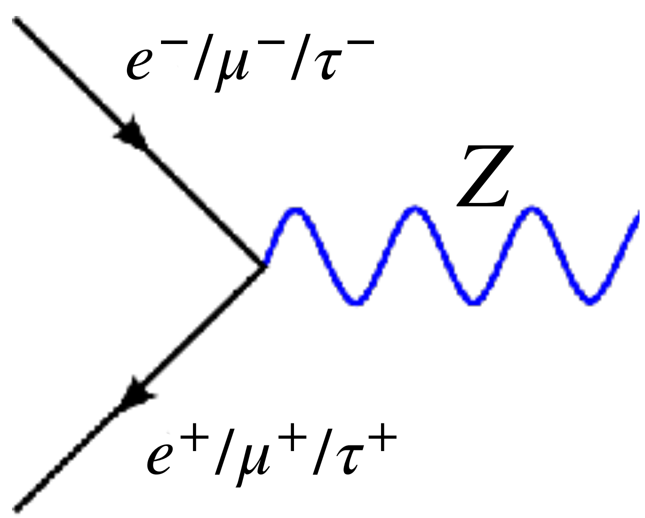
LEPTON UNIVERSALITY

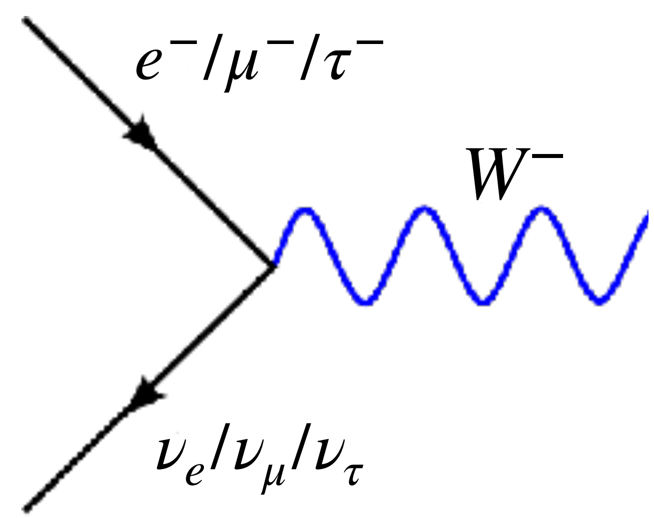
A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

SM gauge interactions are flavour universal for leptons.







LEPTON UNIVERSALITY

What breaks LFU in SM?

LEPTON UNIVERSALITY

What breaks LFU in SM?

- Masses (often easy to account for).

LEPTON UNIVERSALITY

What breaks LFU in SM?

- Masses (often easy to account for).

- Higgs interactions (often small).

LEPTON UNIVERSALITY

What breaks LFU in SM?

- Masses (often easy to account for).

- Higgs interactions (often small).

Most interactions are lepton flavour universal to very good approximation.

TESTS OF LFU

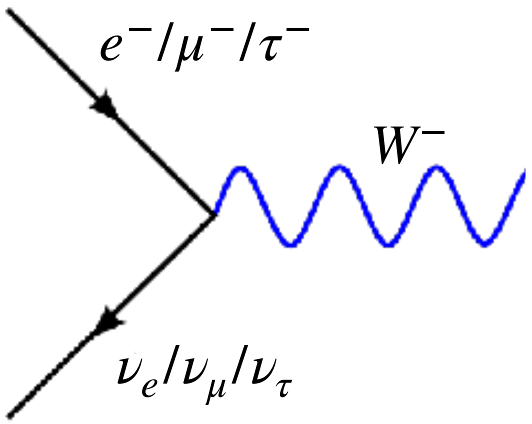
What are some tests of LFU?

TESTS OF LFU

What are some tests of LFU?

- W decays

Γ_2	$e^+\nu$	$(10.71 \pm 0.16)\%$
Γ_3	$\mu^+\nu$	$(10.63 \pm 0.15)\%$
Γ_4	$\tau^+\nu$	$(11.38 \pm 0.21)\%$

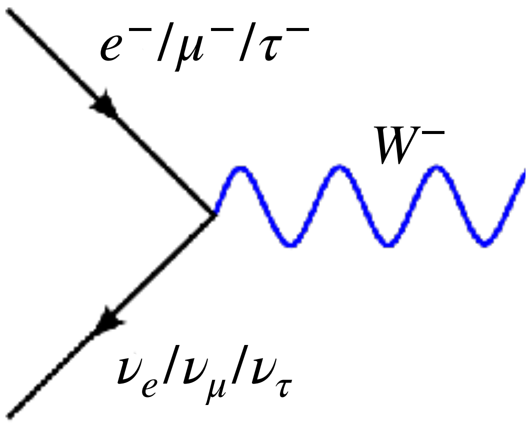


TESTS OF LFU

What are some tests of LFU?

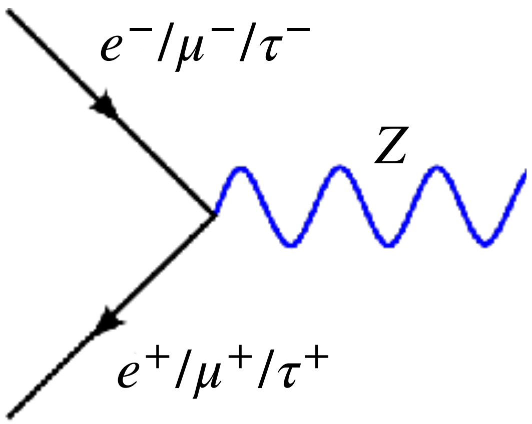
- W decays

Γ_2	$e^+\nu$	$(10.71 \pm 0.16)\%$
Γ_3	$\mu^+\nu$	$(10.63 \pm 0.15)\%$
Γ_4	$\tau^+\nu$	$(11.38 \pm 0.21)\%$



- Z decays

Γ_1	e^+e^-	$(3.3632 \pm 0.0042)\%$
Γ_2	$\mu^+\mu^-$	$(3.3662 \pm 0.0066)\%$
Γ_3	$\tau^+\tau^-$	$(3.3696 \pm 0.0083)\%$

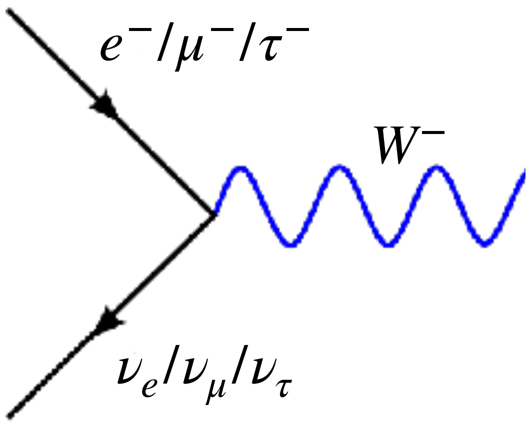


TESTS OF LFU

What are some tests of LFU?

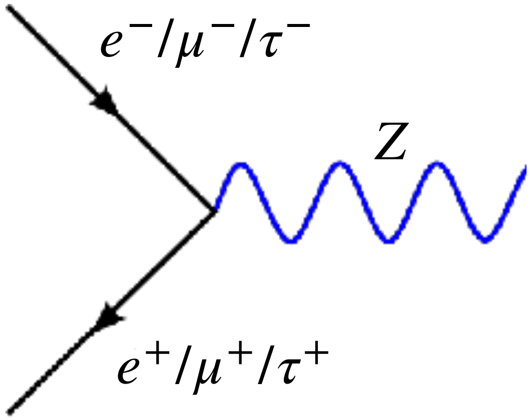
- W decays

Γ_2	$e^+\nu$	$(10.71 \pm 0.16)\%$
Γ_3	$\mu^+\nu$	$(10.63 \pm 0.15)\%$
Γ_4	$\tau^+\nu$	$(11.38 \pm 0.21)\%$



- Z decays

Γ_1	e^+e^-	$(3.3632 \pm 0.0042)\%$
Γ_2	$\mu^+\mu^-$	$(3.3662 \pm 0.0066)\%$
Γ_3	$\tau^+\tau^-$	$(3.3696 \pm 0.0083)\%$



- Less precise tests in pions, kaons, charm, and tau's.

LFU VIOLATION?

Hints of LFU violation in B decays:

- Charged current B decay to tau:

$$R(D^{(*)}) = \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)}$$

- Neutral current B decay to e and mu:

$$R(K^{(*)}) = \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)}$$

More in the discussion on Friday.

LFU VIOLATION?

Hints of LFU violation in B decays:

- Charged current B decay to tau:

$$R(D^{(*)}) = \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)}$$

- Neutral current B decay to e and mu:

$$R(K^{(*)}) = \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)}$$

More in the discussion on Friday.

WHAT ABOUT TOP?

Does top decay to leptons?

WHAT ABOUT TOP?

Does top decay to leptons?

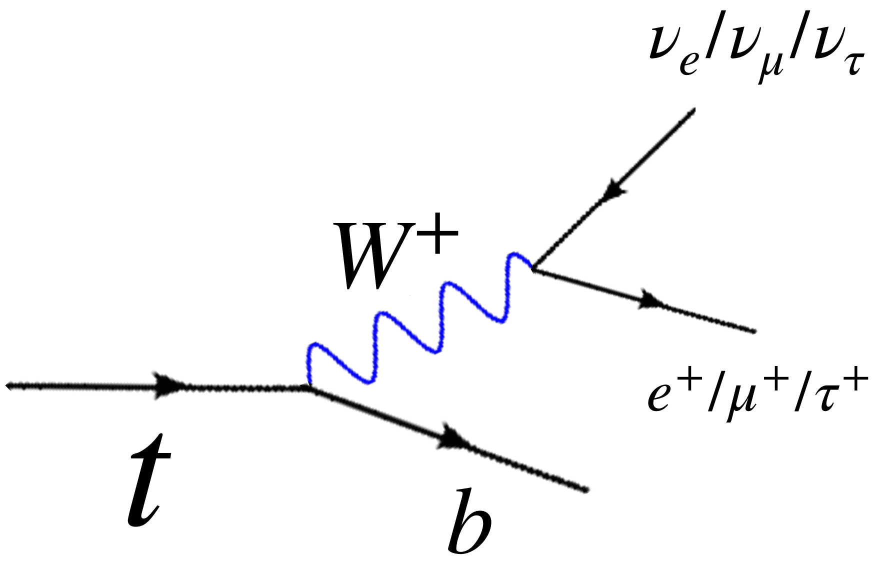
Of course it does, and its been measured at LHC:

ATLAS 1506.05074.

$$\mathrm{BR}(t \to b\, e\, \nu) = 13.3\% \pm 0.4\% \pm 0.4\,\%$$

$$\mathrm{BR}(t \to b\, \mu\, \nu) = 13.4\% \pm 0.3\% \pm 0.5\,\%$$

$$\mathrm{BR}(t \to b\, \tau_h\, \nu) = 7.0\% \pm 0.3\% \pm 0.5\,\%$$



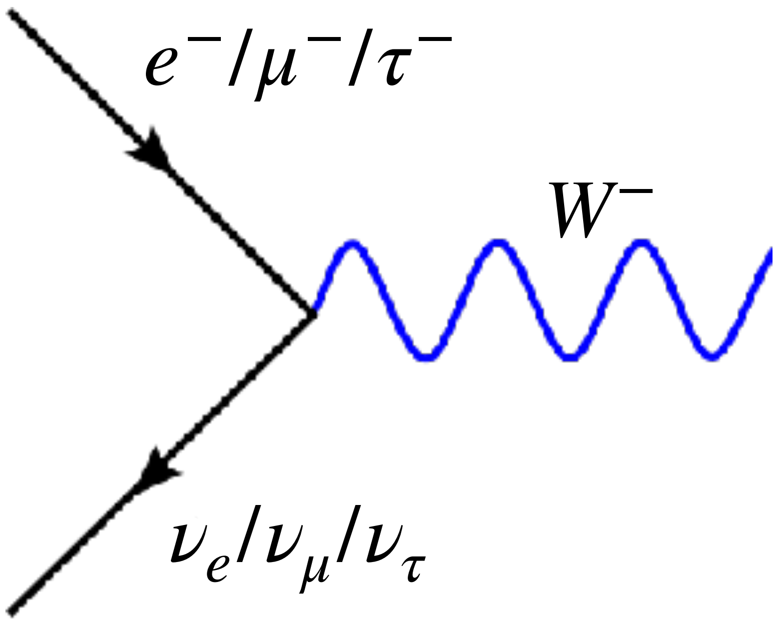
Solving coupled equations gives ~20% precision on tau/lepton universality in top decays.

WHAT ABOUT TOP

Not competitive with W decays from LEP.

- W decays

Γ_2	$e^+\nu$	$(10.71 \pm 0.16)\%$
Γ_3	$\mu^+\nu$	$(10.63 \pm 0.15)\%$
Γ_4	$\tau^+\nu$	$(11.38 \pm 0.21)\%$



Should we give up?

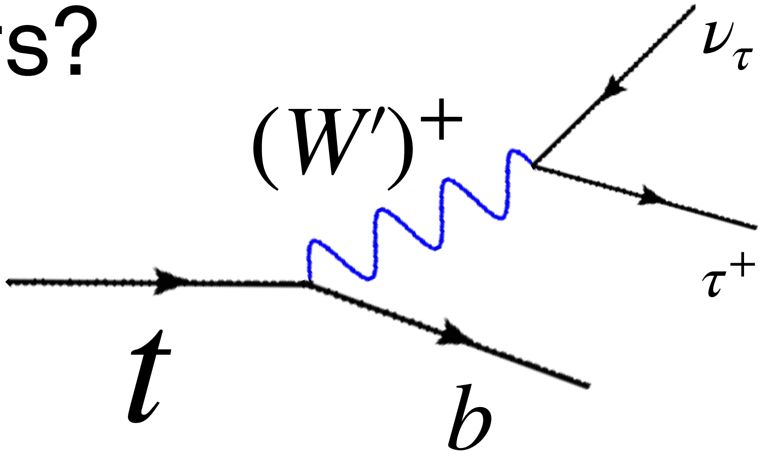
OTHER TOP DECAYS

What about other possible charged currents?

OTHER TOP DECAYS

What about other possible charged currents?

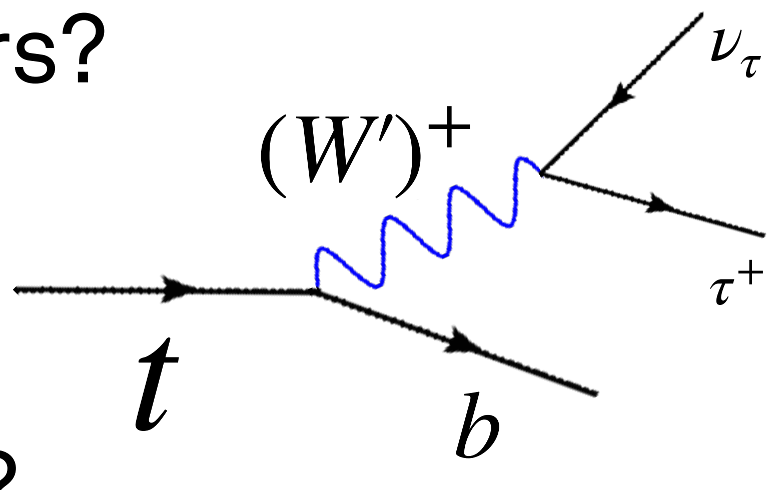
- Additional vectors?



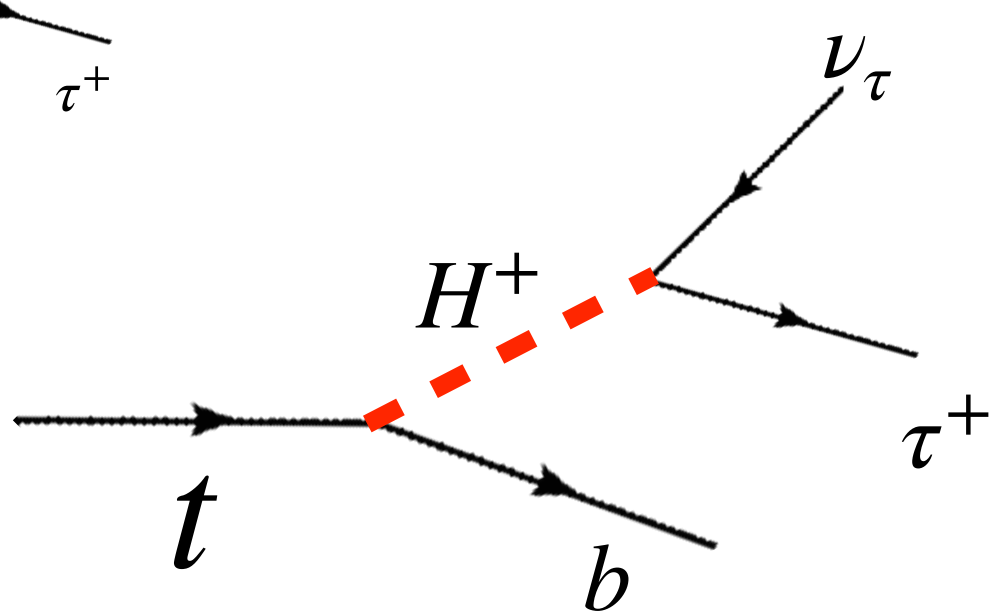
OTHER TOP DECAYS

What about other possible charged currents?

- Additional vectors?



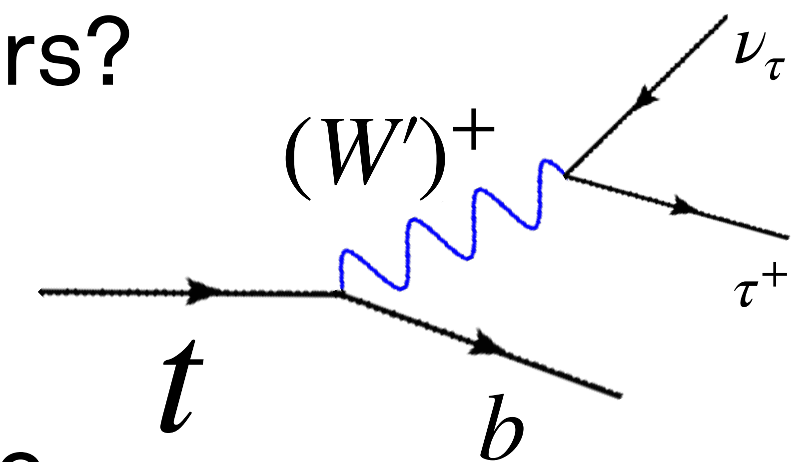
- Charged scalars?



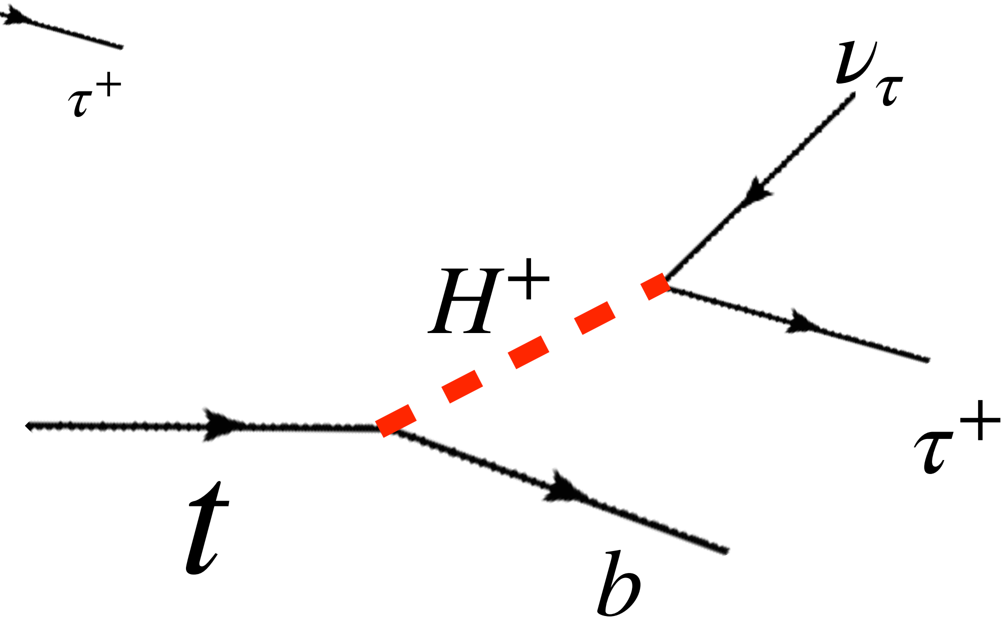
OTHER TOP DECAYS

What about other possible charged currents?

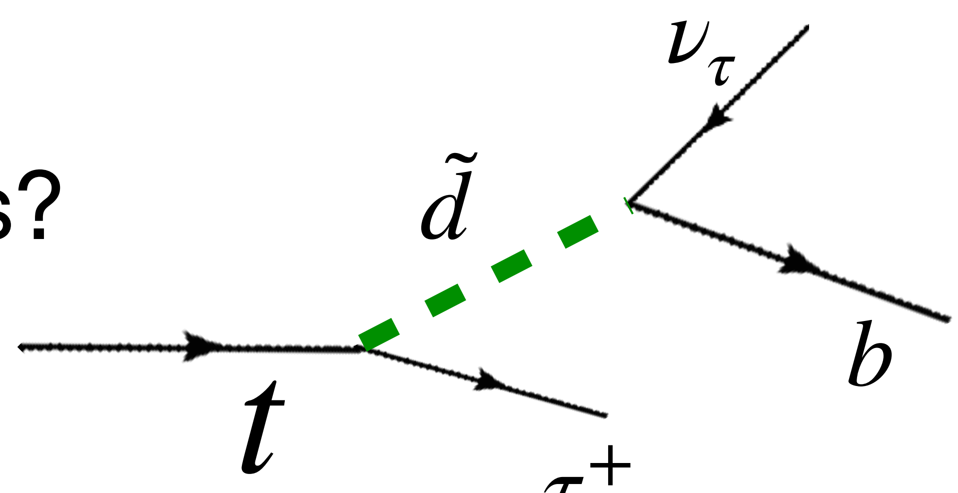
- Additional vectors?



- Charged scalars?



- Leptoquarks?



TOP CROSS SECTION

There are many tops at LHC, and there will be many more.

$$\sigma(\bar{t}t) = 820 \text{ pb} \qquad \sqrt{s} = 13\,\text{TeV}$$

$$\sigma(\bar{t}t) = 970 \text{ pb} \qquad \sqrt{s} = 14\,\text{TeV}$$

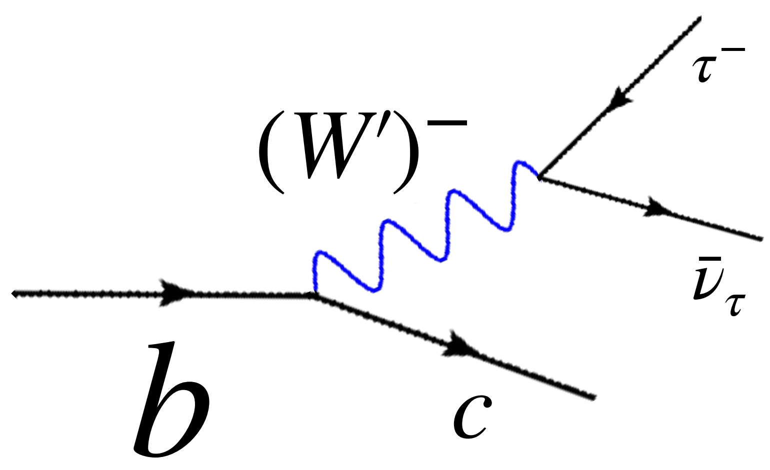
$$\sigma(\bar{t}t) = 32 \text{ nb} \qquad \sqrt{s} = 100\,\text{TeV}$$

Already have $\sim 10^8$ tops analyzed, can expect $\sim 10^{10}$ with HL LHC.

What can we do with such a huge data set?

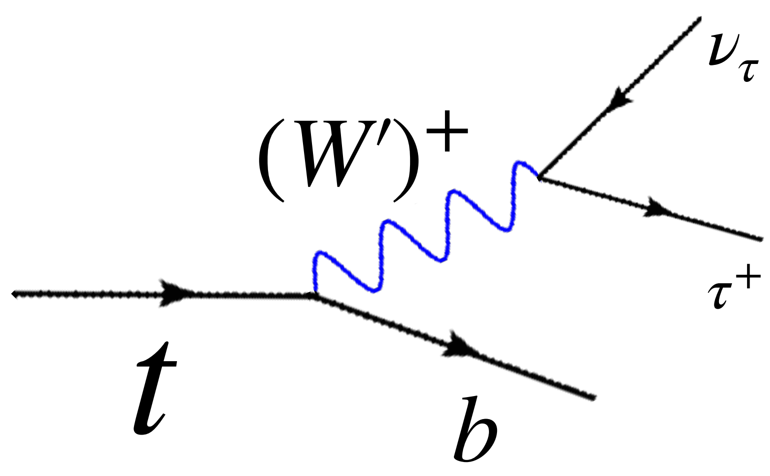
ON-SHELL TOP DECAY

Use anomaly central value to fix $g_{bc}g_{\tau}$.



Freytsis, Ligeti, Ruderman, 1506.08896.

Top decay only depends on g_{tb}, assume MFV structure.

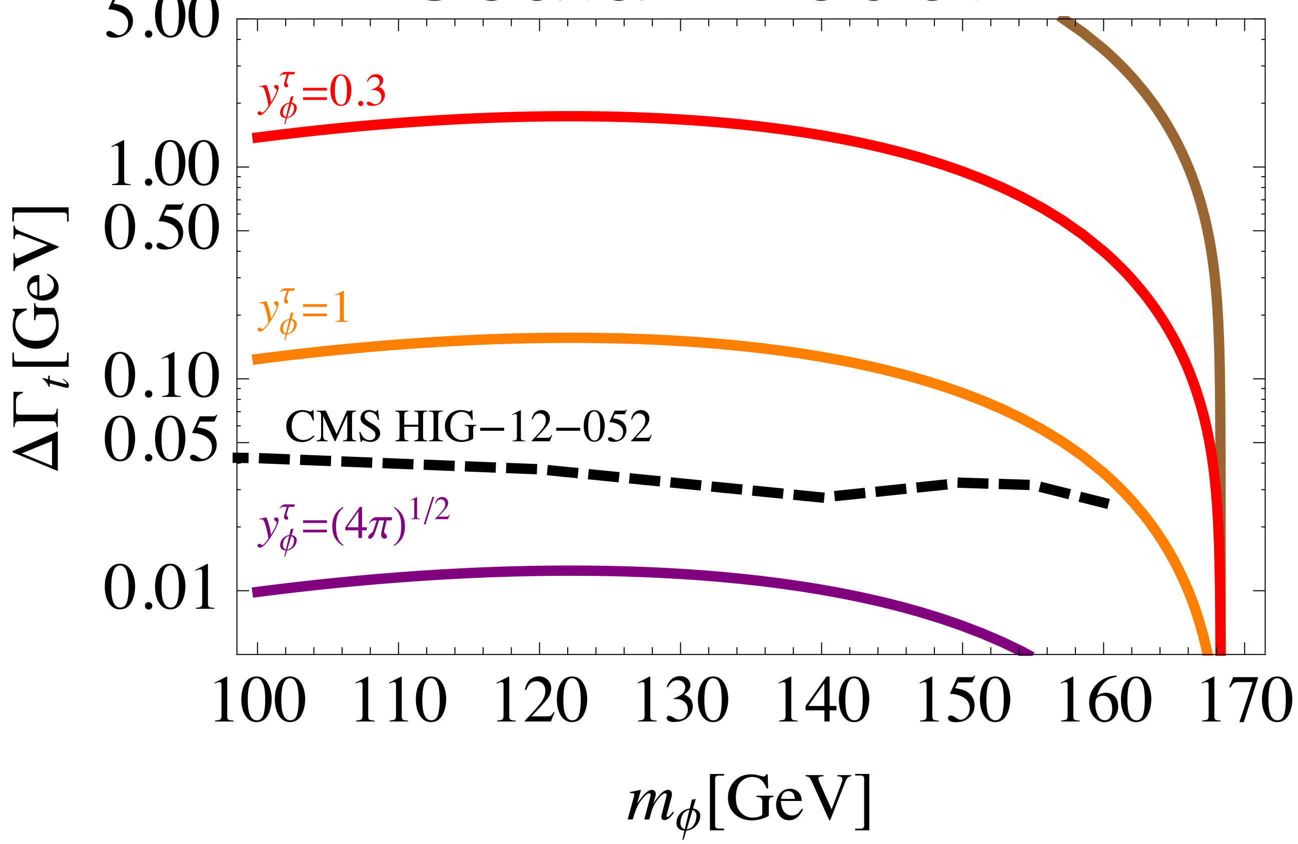


$$\frac{g_{tb}}{g_{bc}} = \frac{V_{tb}}{V_{cb}} \approx 24$$

ON-SHELL TOP DECAY

Vector model

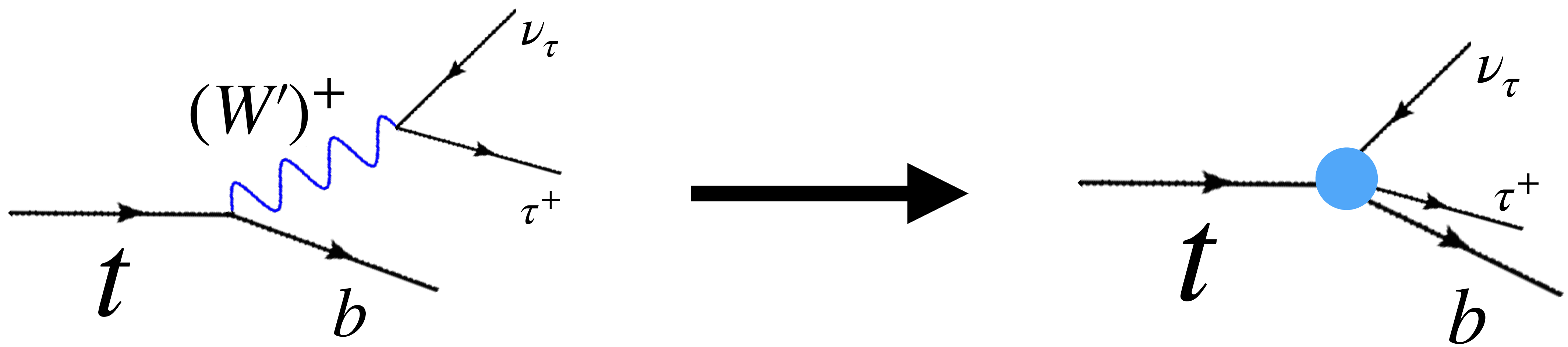
Scalar model



On-shell explanations to R_D anomaly strongly constrained.

OFF-SHELL TOP DECAY

For off shell, can use EFT picture:

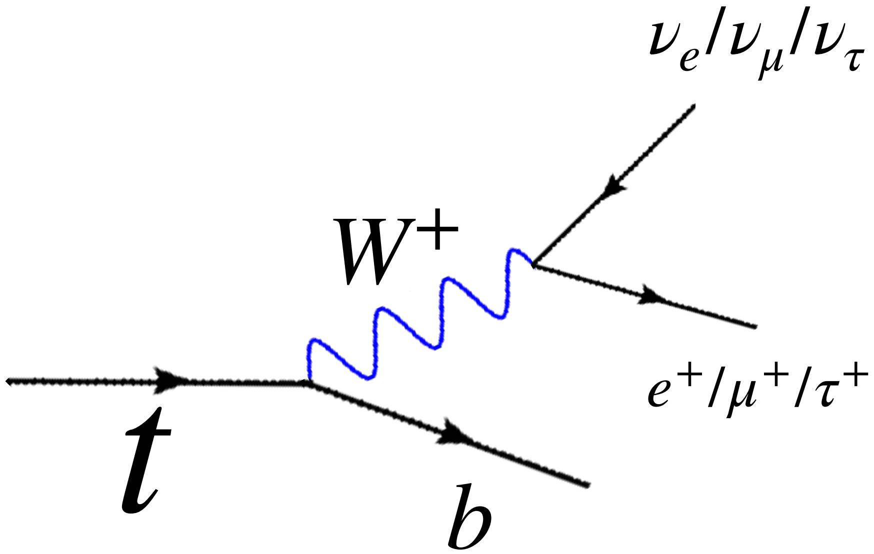


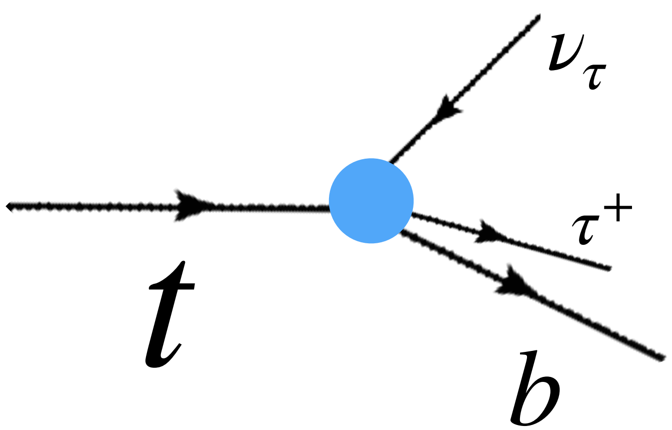
Changes in branching ratio are tiny.

$$\frac{(\bar{C}^t_{VL})}{\mathrm{TeV}^2}(\bar{t}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau) \;\;:\;\; \delta B_\tau = 1.8\times 10^{-5}\bar{C}^t_{VL} + 2.0\times 10^{-5}(\bar{C}^t_{VL})^2$$

$$\frac{(\bar{C}^t_{S(L/R)})}{\mathrm{TeV}^2}(\bar{t}P_{L/R} b)(\bar{\tau}P_L \nu_\tau) \;\;:\;\; \delta B_\tau = 5.1\times 10^{-6}\left[(\bar{C}^t_{SL})^2 + (\bar{C}^t_{SR})^2\right]$$

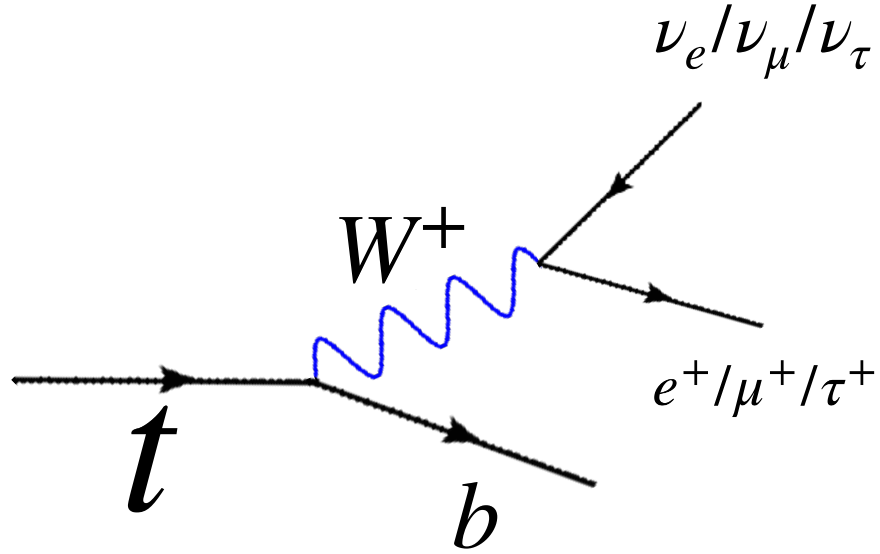
USE KINEMATICS

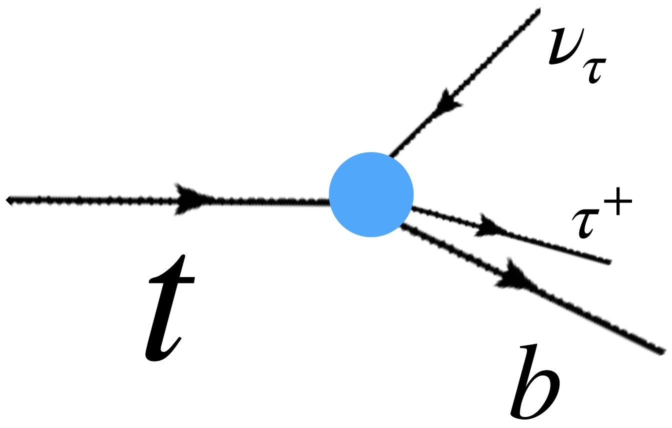




USE KINEMATICS

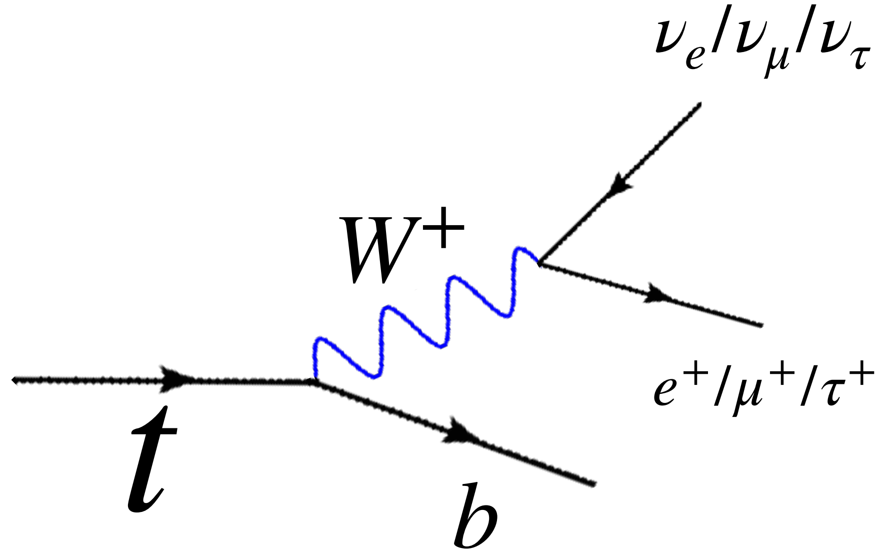
What is the difference between SM and BSM top decay?

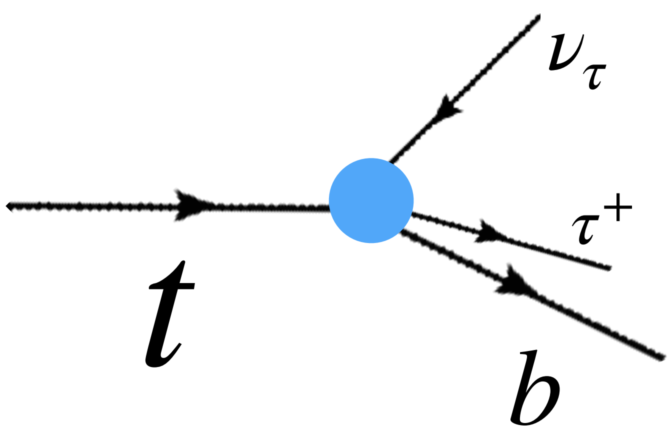




USE KINEMATICS

What is the difference between SM and BSM top decay?





SM is effectively two body, b-quark is mono-chromatic in top rest frame.

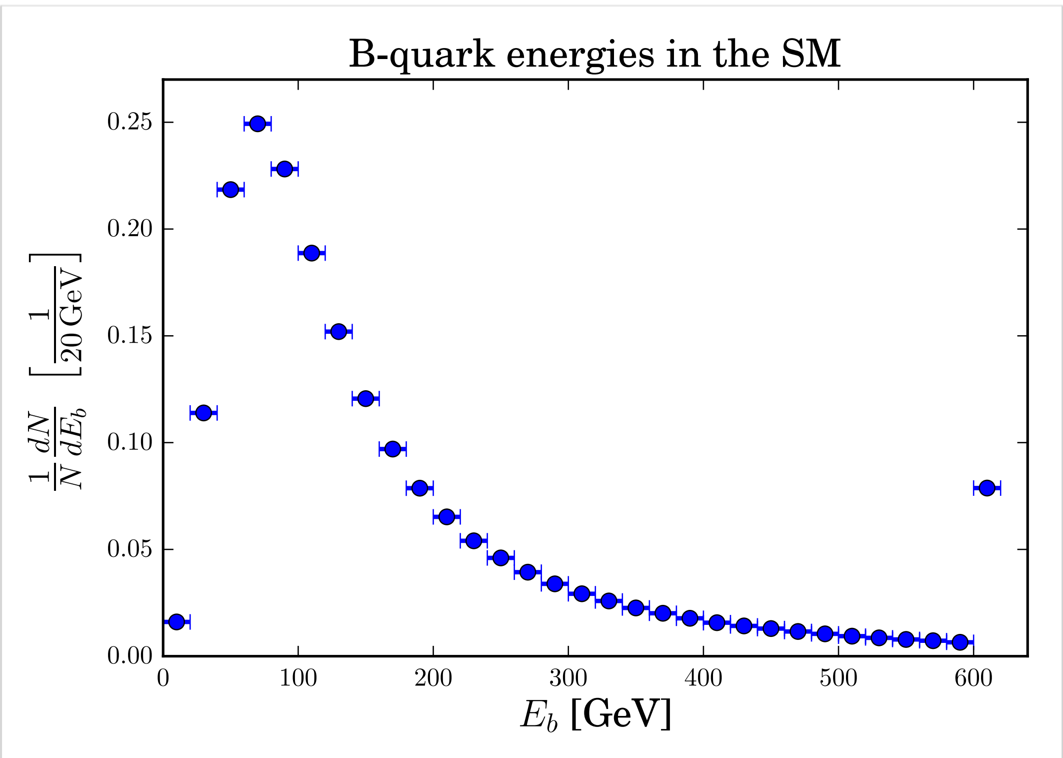
$$E_b^* = \frac{m_t^2 - m_W^2}{2m_t}$$

USE KINEMATICS

What happens in lab frame?

USE KINEMATICS

What happens in lab frame? **Agashe, Franceschini, Kim, 1209.0772.**

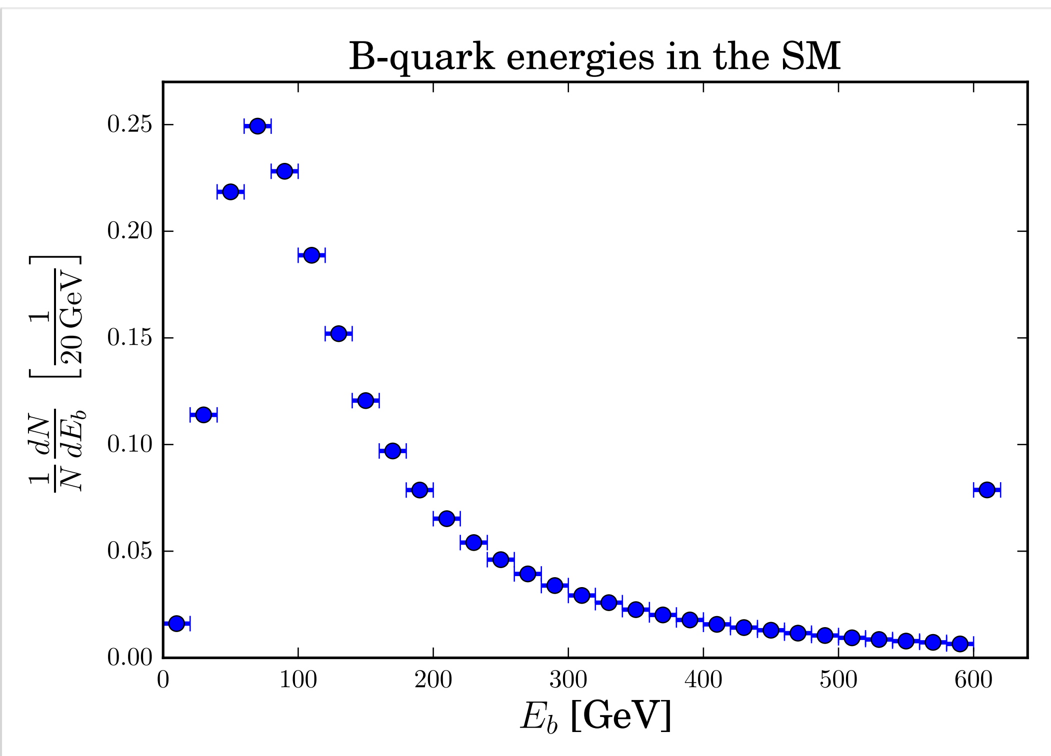


Peak is still at

$$E_b^* = \frac{m_t^2 - m_W^2}{2m_t}$$

USE KINEMATICS

What happens in lab frame? Agashe, Franceschini, Kim, 1209.0772.



Peak is still at

$$E_b^* = \frac{m_t^2 - m_W^2}{2m_t}$$

Can use this to measure m_t.

Measurement of the top-quark mass from the b jet energy spectrum

The CMS Collaboration

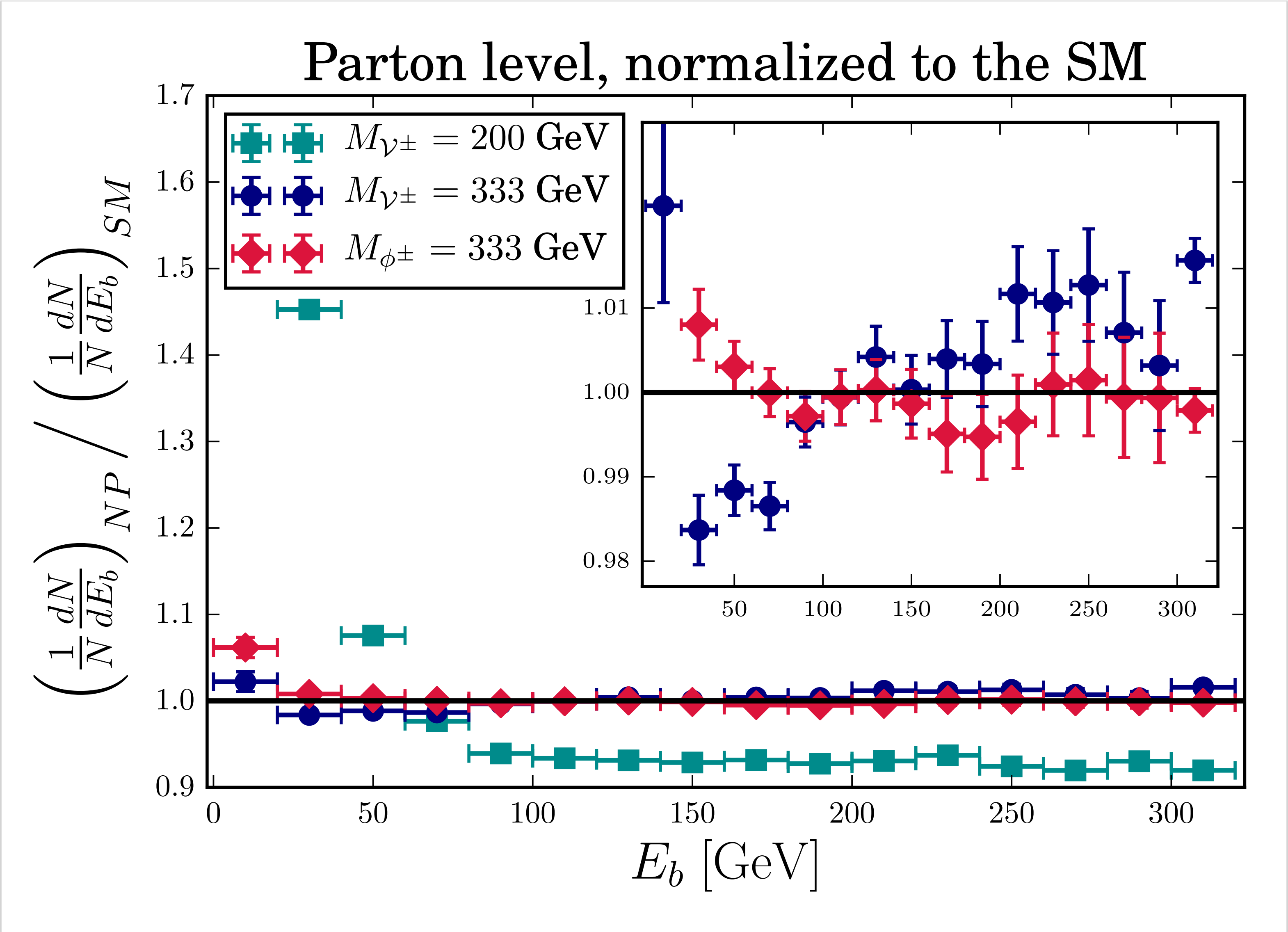
Abstract

The top-quark mass is measured using the peak position of the energy distribution of b jets produced from top-quark decays. The analysis is based on a recent theoretical proposal. The measurement is carried out selecting $t\bar{t}$ events with one electron and one muon in the final state in proton-proton collision data at $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 19.7 fb^{-1}. The fitted peak position of the observed energy distribution is calibrated using simulated events and translated to a top-quark mass measurement using relativistic kinematics, with the result $m_t = 172.29 \pm 1.17\,(\text{stat.}) \pm 2.66\,(\text{syst.})$ GeV.

CMS PAS TOP-15-002.

PARTON LEVEL STUDY

Take ratios of distributions.



$$M_V = 200\,\text{GeV}$$
$$g_\tau g_{tb} = 5$$
$$\delta B_\tau = 4\,\%$$

$$M_V = 333\,\text{GeV}$$
$$g_\tau g_{tb} = 4$$
$$\delta B_\tau = 0.3\,\%$$

$$M_H = 333\,\text{GeV}$$
$$y_\tau y_{tb}^L = -2.6$$
$$y_\tau y_{tb}^R = 3.1$$
$$\delta B_\tau = 0.1\,\%$$

MORE REALISTIC STUDY

Where do we get a “denominator” sample?

MORE REALISTIC STUDY

Where do we get a “denominator” sample?

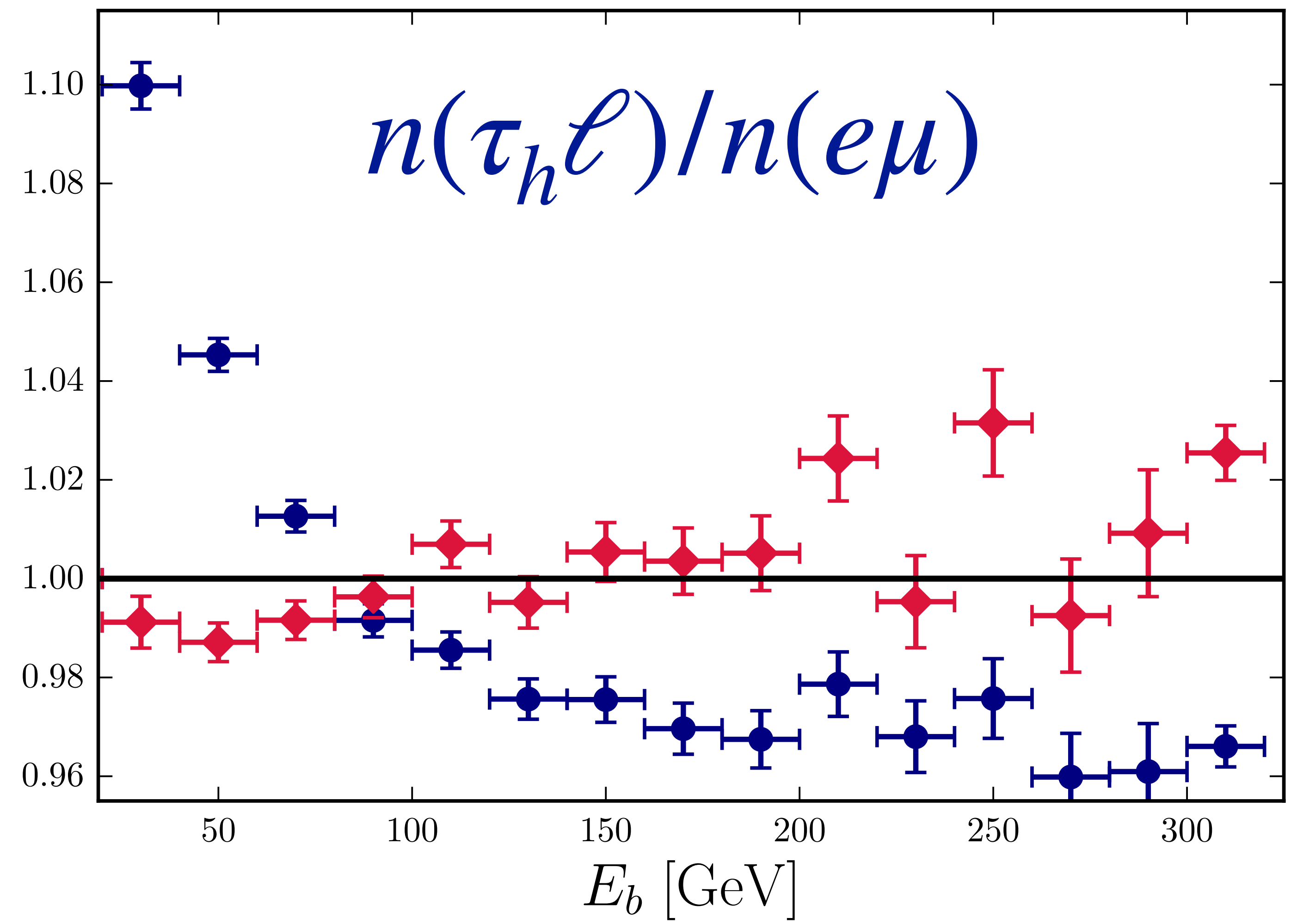
Assume new physics only couples to third generation (events with τ).

Use μ/e as control sample (avoid same flavour to reduce Z background).

MORE REALISTIC STUDY

Put minimal cuts for realistic sample:

- 2 b-jets $p_T > 20$ GeV
- Lepton $p_T > 20$ GeV
- τ_h with $p_T > 30$ GeV



Get blue points, SM control sample appears very different from signal sample! Why?

TAU DECAYS

$$\tau^- \to \nu_\tau + h^- + \ldots$$

TAU DECAYS

$$\tau^- \to \nu_\tau + h^- + \ldots$$

Measured $\boldsymbol{\tau}_h$ p_T is not the same as actual $\boldsymbol{\tau}$ p_T.

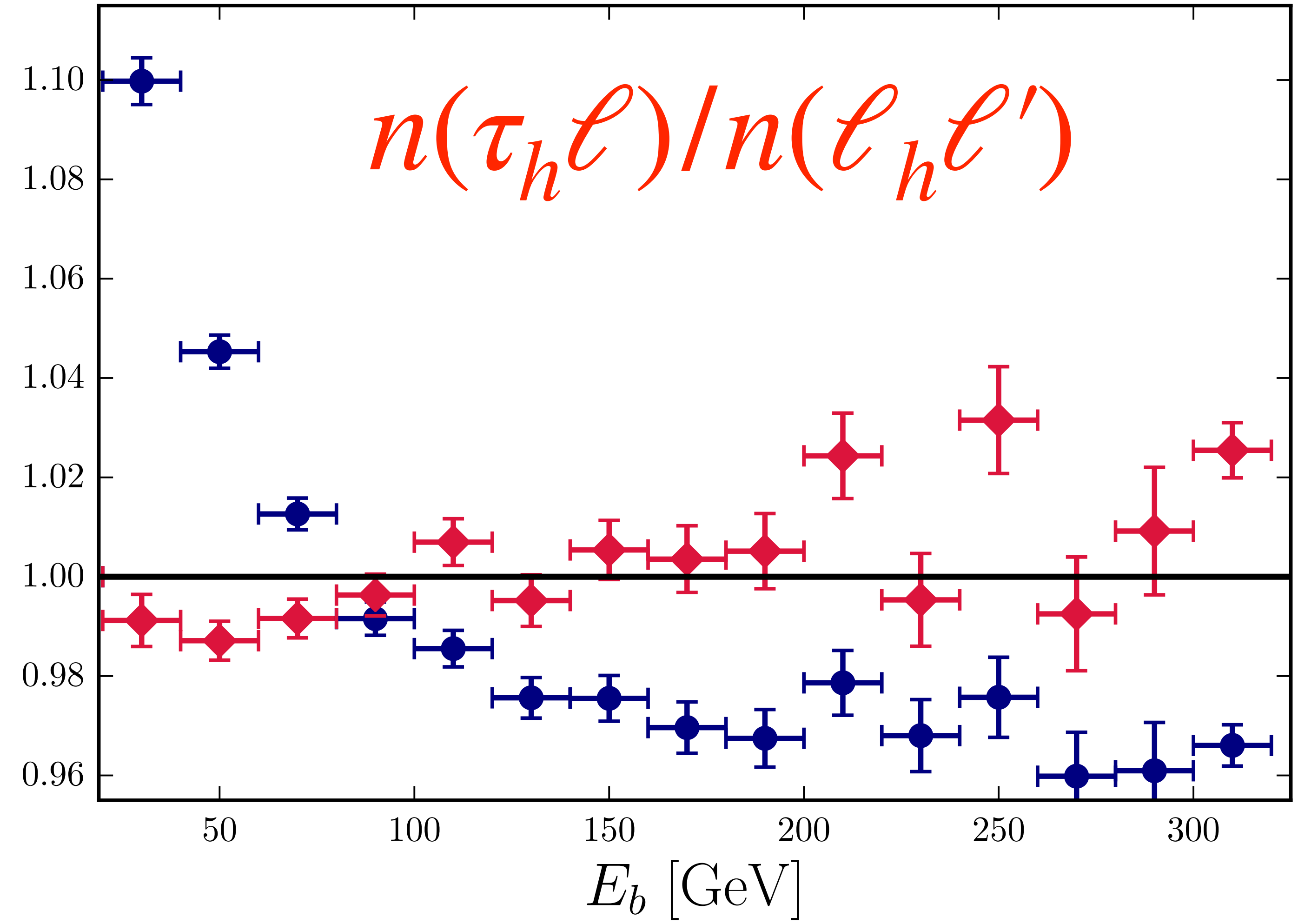
$\boldsymbol{\tau}_h$ p_T is weakly correlated with b-jet energy.

Putting p_T cut on $\boldsymbol{\tau}_h$ sculpts b-jet energy distribution changing it relative to control sample.

BETTER CONTROL SAMPLE

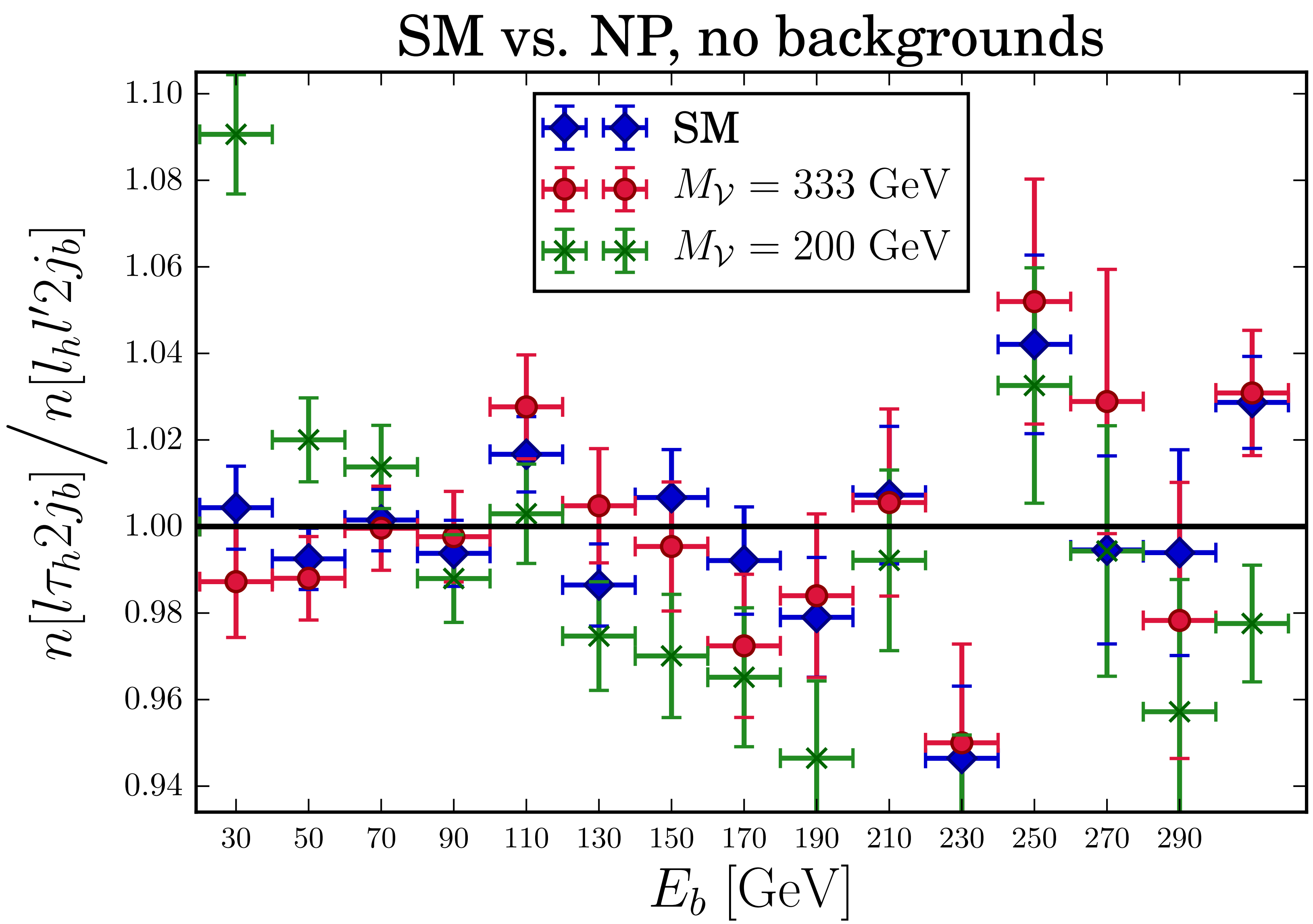
Take $\boldsymbol{\mu}$/e event and replace one lepton with a $\boldsymbol{\tau}$ in simulation, ℓ_h.

Decay $\boldsymbol{\tau}$ and apply same cuts as signal sample.



Now get red points, have a sensible control sample.

BSM SENSITIVITY



$M_V = 200\,\mathrm{GeV}$

$g_\tau g_{tb} = 5$

$\delta B_\tau = 4\,\%$

$M_V = 333\,\mathrm{GeV}$

$g_\tau g_{tb} = 4$

$\delta B_\tau = 0.1\,\%$

Errors due to MC statistics corresponding to ~300 fb^{-1}.

BACKGROUNDS

Signal region is 2b, 1 lepton,

1 (hadronic) $\boldsymbol{\tau}$.

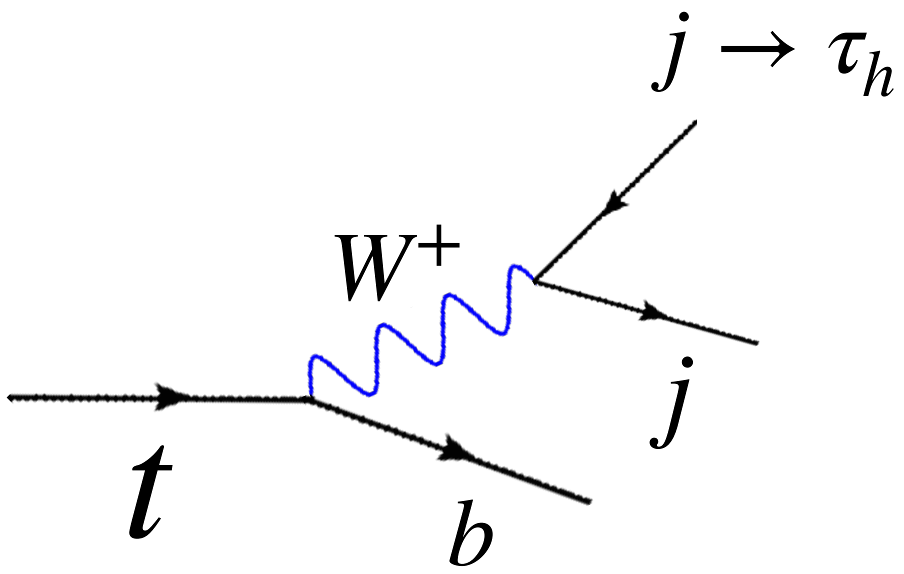
What are the backgrounds?

BACKGROUNDS

Signal region is 2b, 1 lepton, 1 (hadronic) $\boldsymbol{\tau}$.

What are the backgrounds?

- Semi-leptonic top with jet faking tau (large).

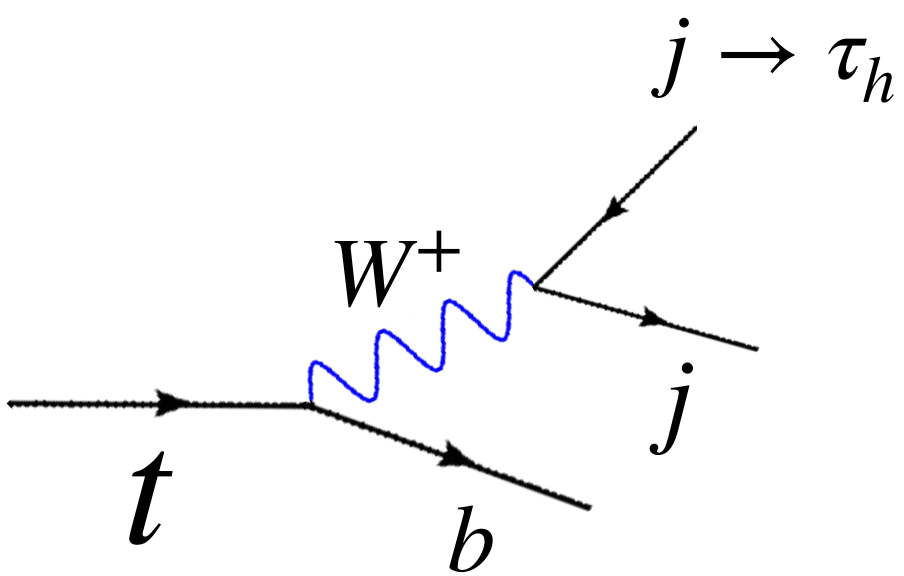


BACKGROUNDS

Signal region is 2b, 1 lepton, 1 (hadronic) $\boldsymbol{\tau}$.

What are the backgrounds?

- Semi-leptonic top with jet faking tau (large).
- $Zb\bar{b}$, $Z \to \tau_h \tau_\ell$ (non-trivial shape).



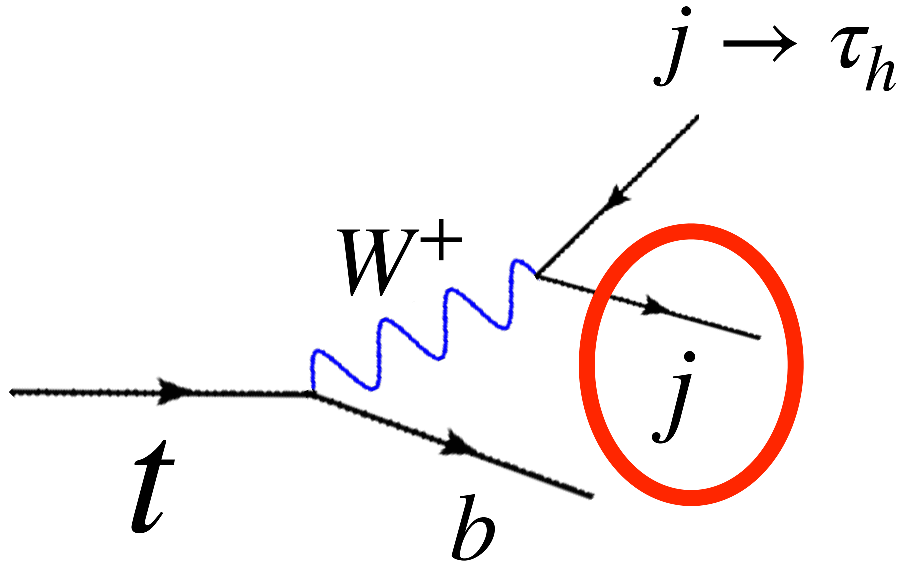
STRATEGIES

Need fairly pure signal sample.

Combine three strategies to mitigate background.

1. Veto extra jets $p_T > 20$ GeV.

Can be applied equally to signal and control.

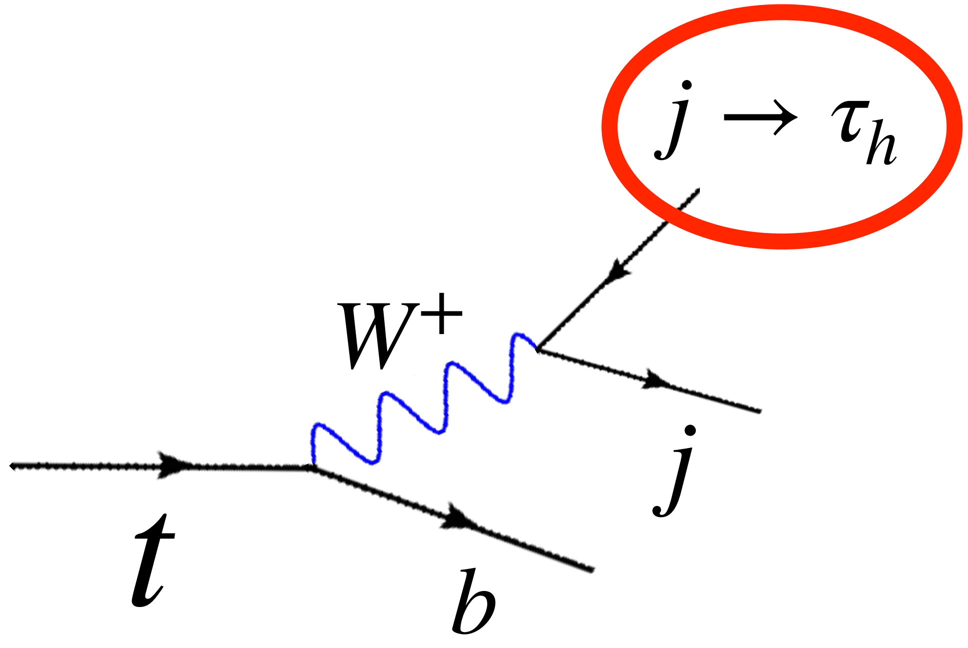


STRATEGIES

Need fairly pure signal sample.

Combine three strategies to mitigate background.

2. Use 1-prong **τ**.



Tagging rate **70%** and fake rate of **5%**.

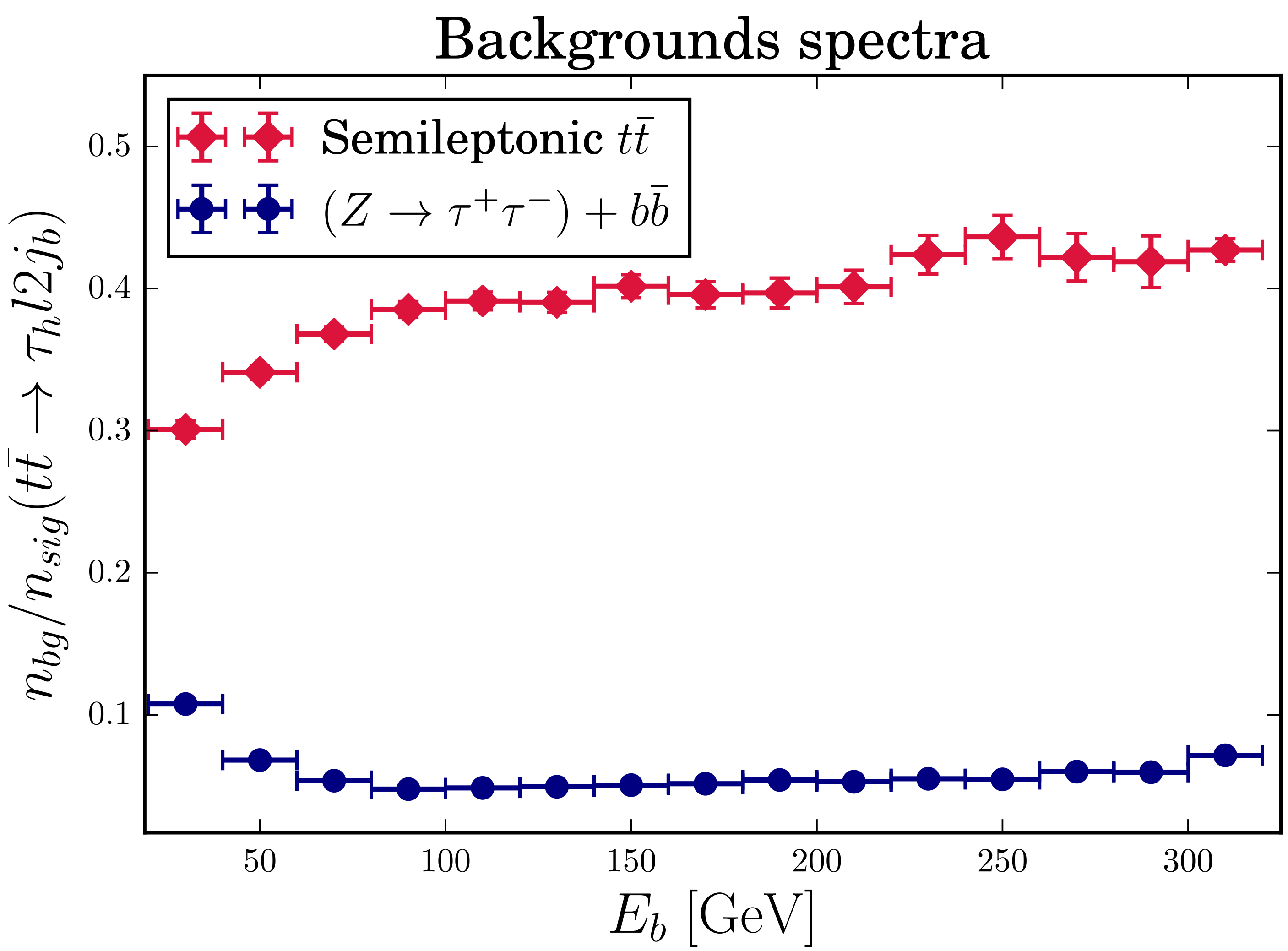
Modern taggers can probably do much better.

CMS 1510.07488. ATLAS-PHYS-PUB-2015-045.

BACKGROUND COMPOSITION

Majority of events in signal region are now signal.

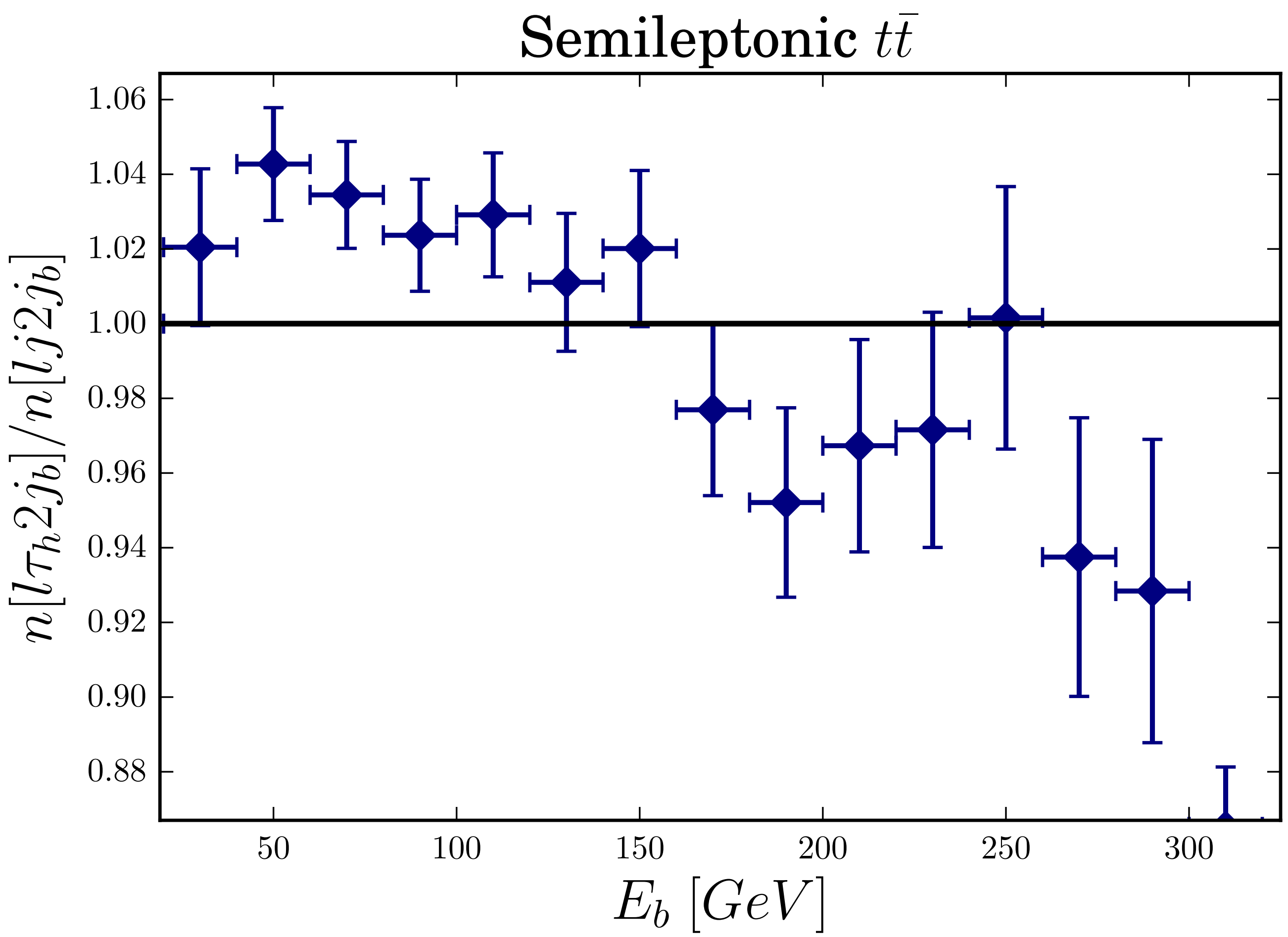
Backgrounds are still important, have non-trivial shape.



MORE CONTROL SAMPLES

Second control region which has same spectrum as semi-leptonic background.

- 2 b-jets $p_T > 20$ GeV
- Lepton $p_T > 20$ GeV
- 1 jet $p_T > 30$ GeV
- Veto τ_h and extra jets

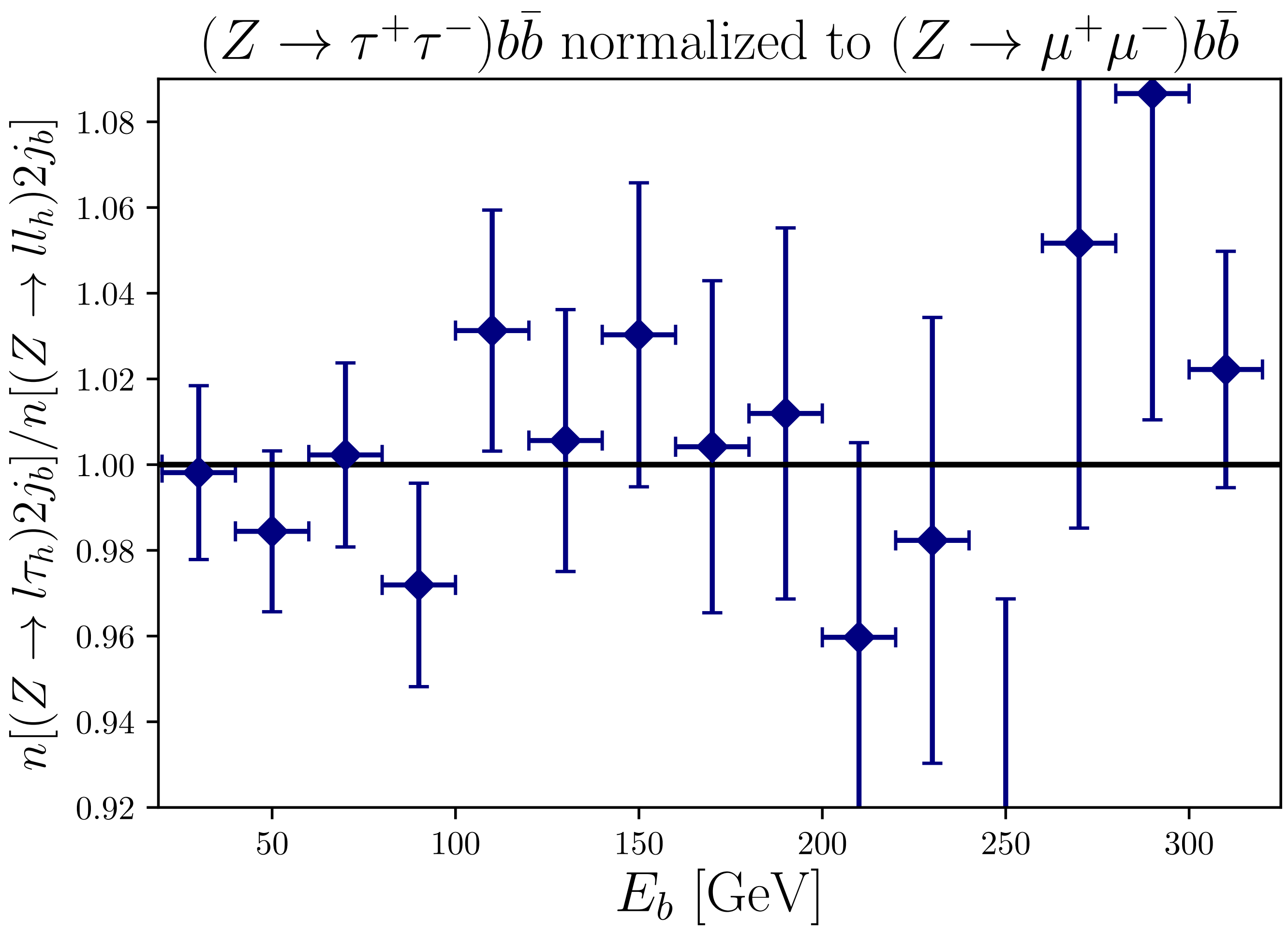


Works well at low energy. High energy?

MORE CONTROL SAMPLES

Third control region which has same spectrum as Zbb.

- Z -> $\mu\mu$ and replace both with τ.
- Apply same cuts as before.



Works well.

FINAL LFU RATIO

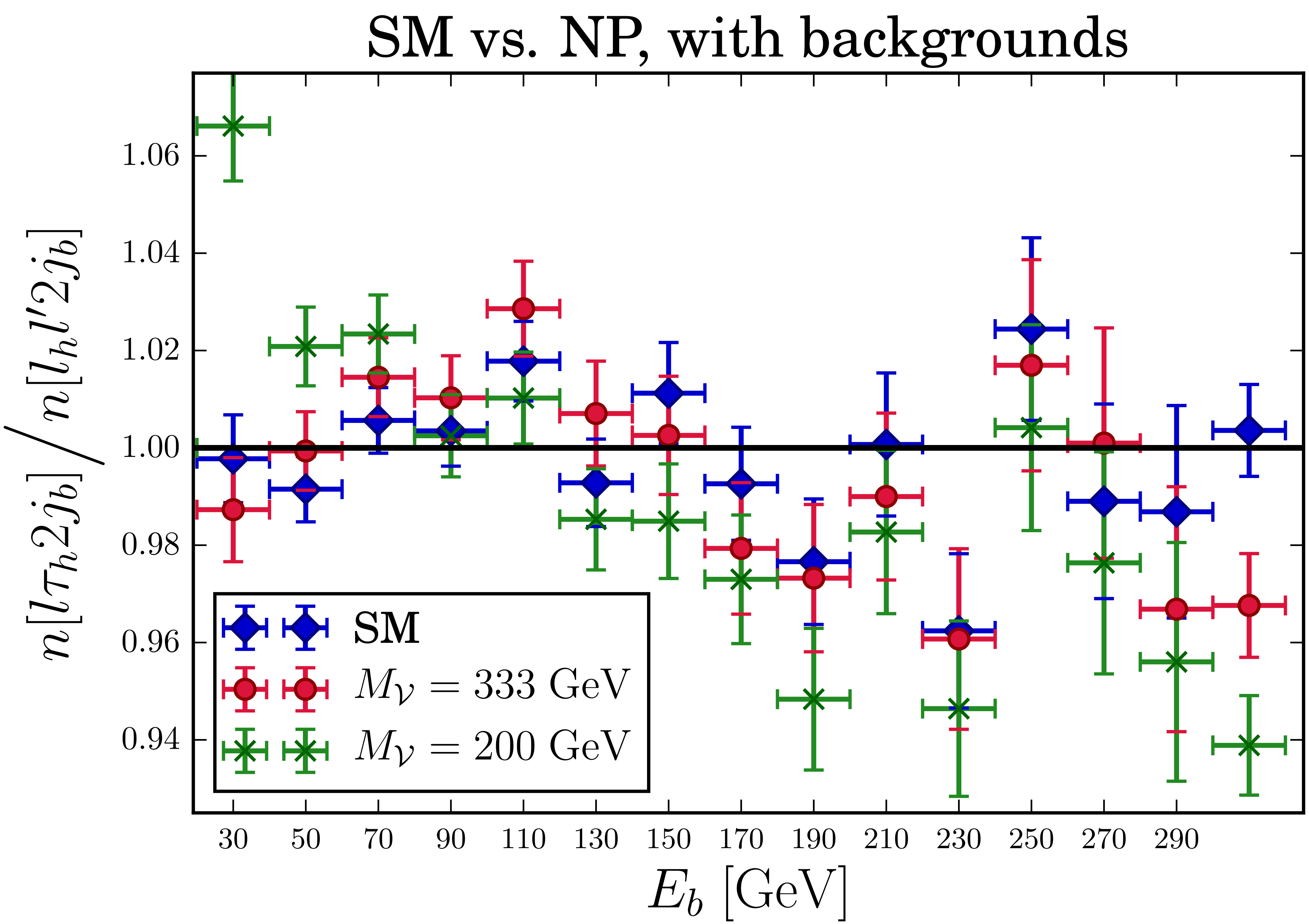
Mix together three control samples in same proportion as signal region.

$$\frac{n[\ell\tau_h 2j_b](E_b)}{n[\ell'_h\ell 2j_b](E_b) + w_{j\to\tau_h} n[\ell j 2j_b](E_b) + w_{Z\to\ell\tau_h} n[(Z \to \ell_h\ell_h)2j_b](E_b)}$$

$$w_{j\to\tau_h} \approx 0.42 \qquad w_{Z\to\ell\tau_h} \approx 0.03$$

Determine w from Monte Carlo.

RESULTS PLOT

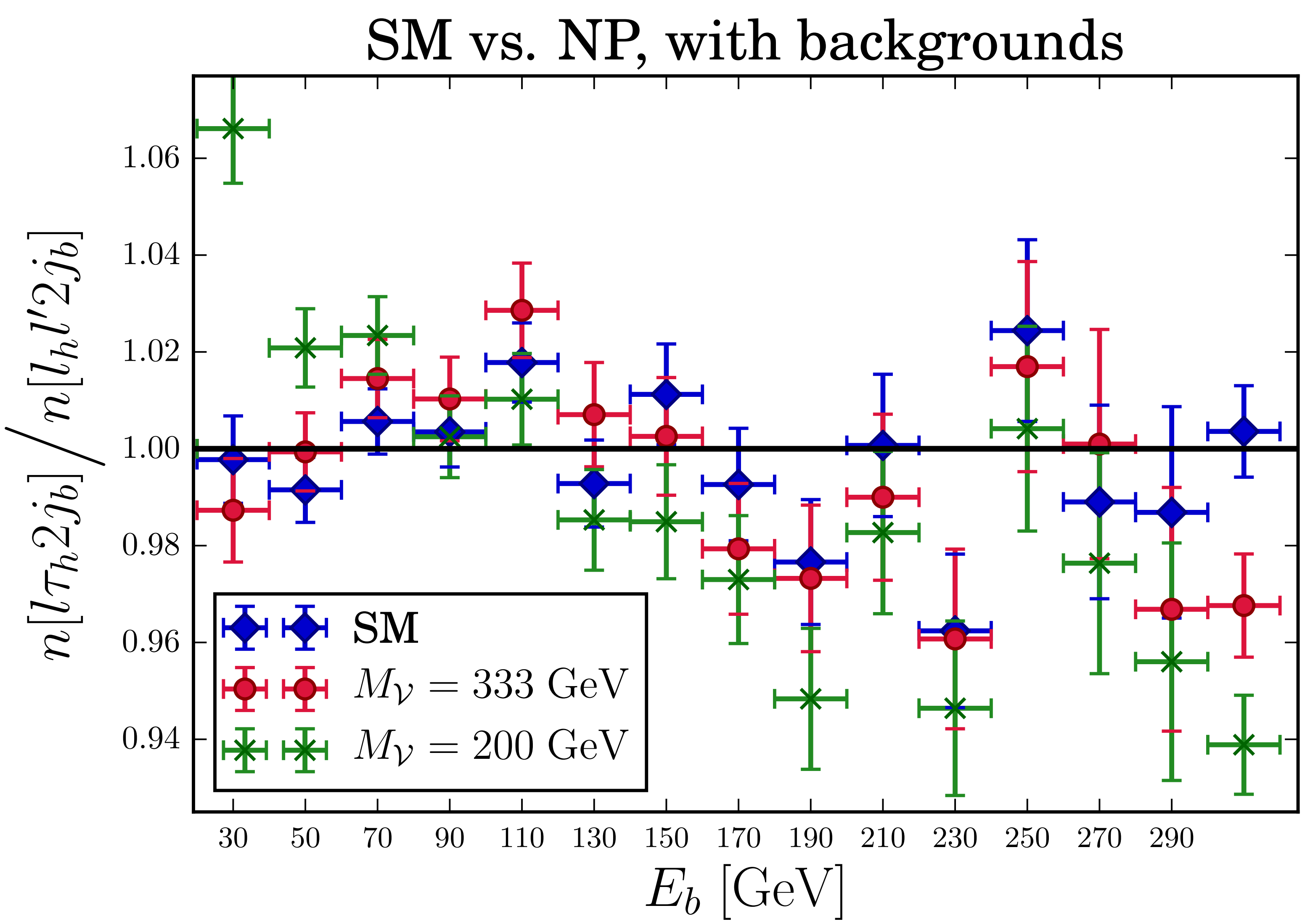


RESULTS PLOT

Looks very similar to plot without backgrounds.

Can exclude green NP at ~7σ.

No sensitivity to red NP.



ROOM FOR IMPROVEMENT

This is a first pass study showing feasibility.

Only generated MC for 300 fb^{-1}. LHC will eventually have much more.

Used simplistic τ tagging procedure, probably can be improved with smart experimentalists/machines.

WORK IN
PROGRESS

OTHER EFT OPERATORS

$$(\bar{t}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu P_L \nu_\ell) \qquad (\bar{t}P_L\nu_\ell)(\bar{\ell}P_L b)$$

$\ell = e, \mu$ there are essentially no direct limits.

Two-heavy-two-lepton ($8+3$ CPV d.o.f. $\times 3$ lepton flavours)	
$c_{Ql}^{3(\ell)}$	$\equiv C_{lq}^{3(\ell\ell 33)}$
$c_{Ql}^{-(\ell)}$	$\equiv C_{lq}^{1(\ell\ell 33)} - C_{lq}^{3(\ell\ell 33)}$
$c_{Qe}^{(\ell)}$	$\equiv C_{eq}^{(\ell\ell 33)}$
$c_{tl}^{(\ell)}$	$\equiv C_{lu}^{(\ell\ell 33)}$
$c_{te}^{(\ell)}$	$\equiv C_{eu}^{(\ell\ell 33)}$
$c_t^{S[I](\ell)}$	$\equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{C_{lequ}^{1(\ell\ell 33)}\}$
$c_t^{T[I](\ell)}$	$\equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{C_{lequ}^{3(\ell\ell 33)}\}$
$c_b^{S[I](\ell)}$	$\equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{C_{ledq}^{(\ell\ell 33)}\}$

Aguilar Saavedra et. al, 1802.07237. See also Buckley et. al. 1506.08845, Jung and Straub 1801.01112, Greljo and Marzocca, 1704.09015.

OTHER EFT OPERATORS

$$(\bar{t}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu P_L \nu_\ell) \qquad\qquad (\bar{t} P_L \nu_\ell)(\bar{\ell} P_L b)$$

$\ell = e, \mu$, how can we probe them?

OTHER EFT OPERATORS

$$(\bar{t}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu P_L \nu_\ell) \qquad\qquad (\bar{t}P_L \nu_\ell)(\bar{\ell}P_L b)$$

$\ell = e, \mu$, how can we probe them?

- Flavour physics (assuming MFV)

OTHER EFT OPERATORS

$$(\bar{t}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu P_L \nu_\ell) \qquad (\bar{t}P_L \nu_\ell)(\bar{\ell}P_L b)$$

$\ell = e, \mu$, how can we probe them?

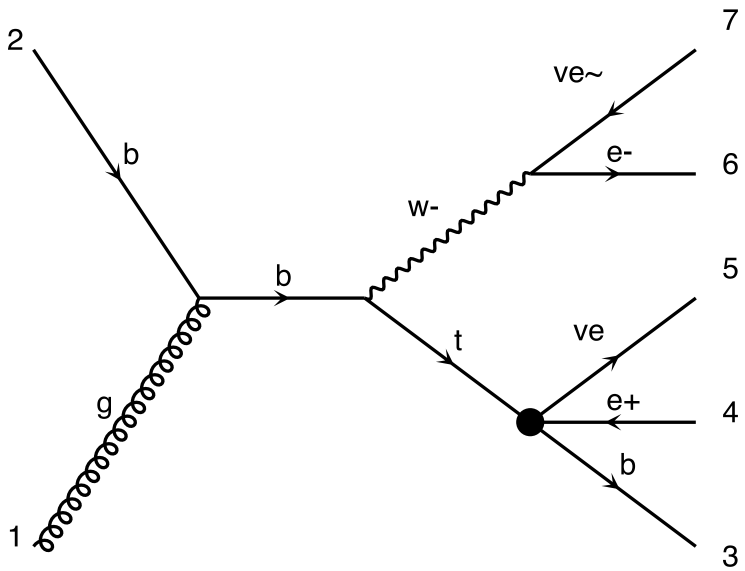
- Flavour physics (assuming MFV)
- Ratios of distributions

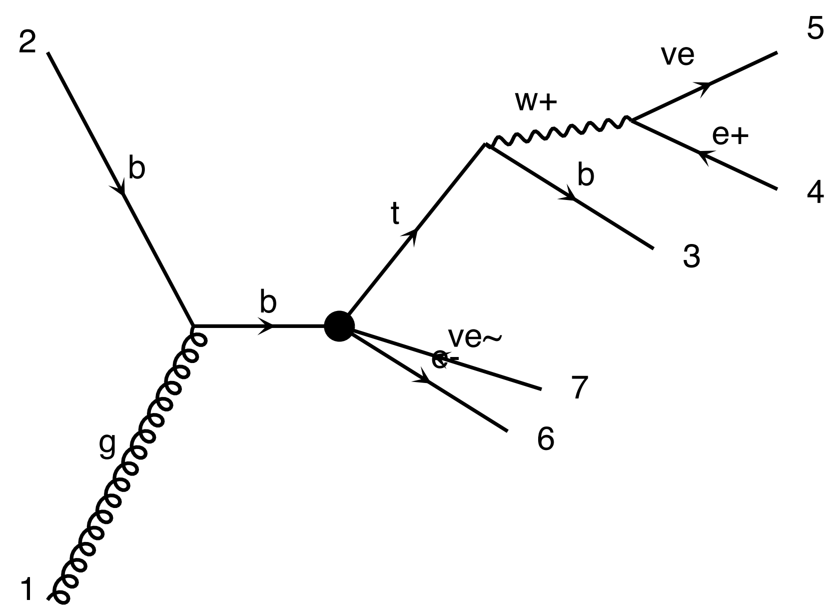
OTHER EFT OPERATORS

$$(\bar{t}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu P_L \nu_\ell) \qquad (\bar{t}P_L\nu_\ell)(\bar{\ell}P_L b)$$

$\ell = e, \mu$, how can we probe them?

- Flavour physics (assuming MFV)
- Ratios of distributions
- Top + W production



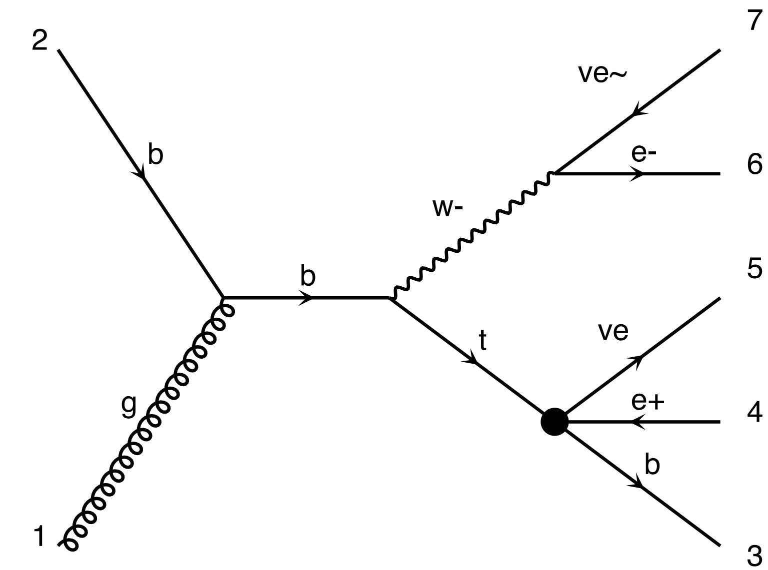


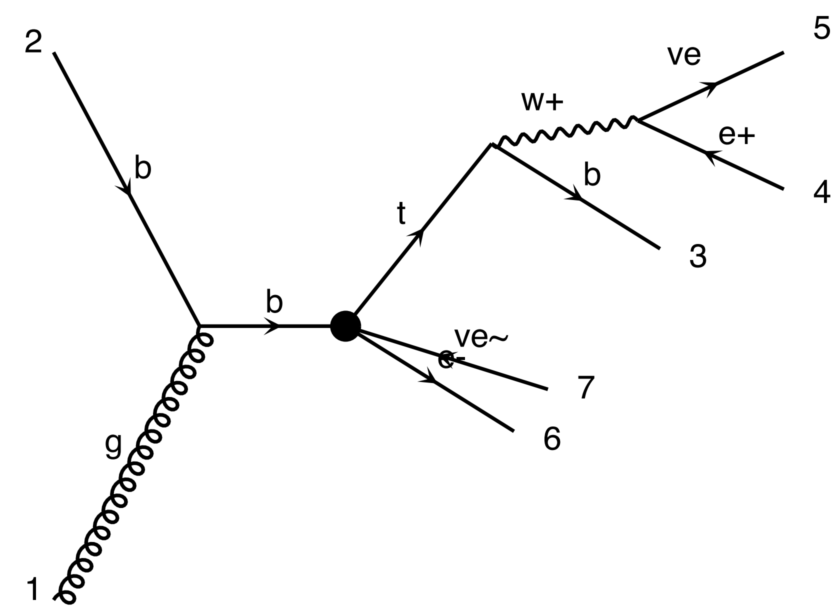
OTHER EFT OPERATORS

$$(\bar{t}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu P_L \nu_\ell) \qquad\qquad (\bar{t}P_L \nu_\ell)(\bar{\ell}P_L b)$$

$\ell = e, \mu$, how can we probe them?

- Flavour physics (assuming MFV)
- Ratios of distributions
- Top + W production
- ???



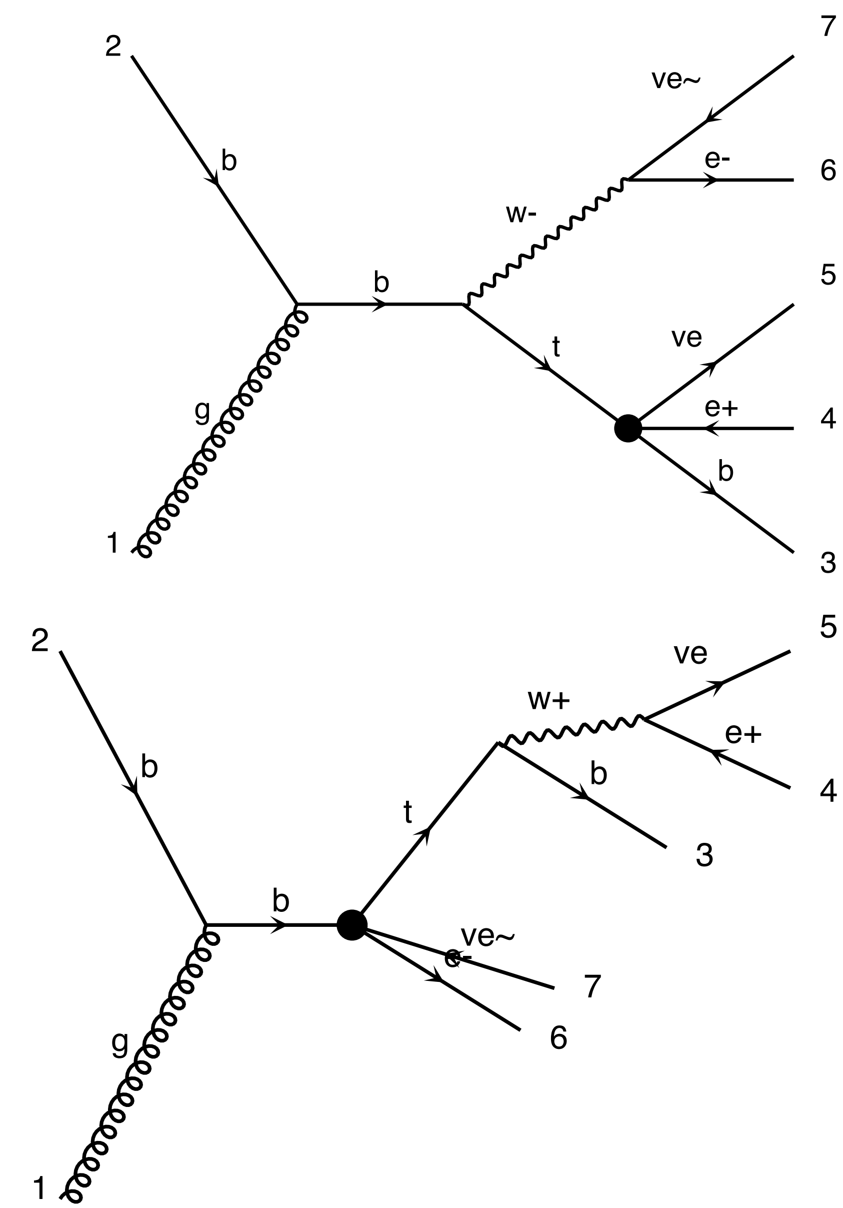


OTHER EFT OPERATORS

$$(\bar{t}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu P_L \nu_\ell) \qquad\qquad (\bar{t}P_L\nu_\ell)(\bar{\ell}P_L b)$$

$\ell = e, \mu$, how can we probe them?

- Flavour physics (assuming MFV)
- Ratios of distributions
- $\boxed{\text{Top + W production}}$
- ???



SHOULD WE CARE

$(\bar{t}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu P_L \nu_\ell)$ $(\bar{t}P_L \nu_\ell)(\bar{\ell}P_L b)$

$\ell = e, \mu$, why should we care?

SHOULD WE CARE

$$(\bar{t}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu P_L \nu_\ell) \qquad\qquad (\bar{t} P_L \nu_\ell)(\bar{\ell} P_L b)$$

$\ell = e, \mu$, why should we care?

- General probes of SMEFT

SHOULD WE CARE

$(\bar{t}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu P_L \nu_\ell)$ $(\bar{t} P_L \nu_\ell)(\bar{\ell} P_L b)$

$\ell = e, \mu$, why should we care?

- General probes of SMEFT
- Does this somehow relate to anomalies?

SHOULD WE CARE

$$(\bar{t}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu P_L \nu_\ell) \qquad (\bar{t}P_L \nu_\ell)(\bar{\ell}P_L b)$$

$\ell = e, \mu$, why should we care?

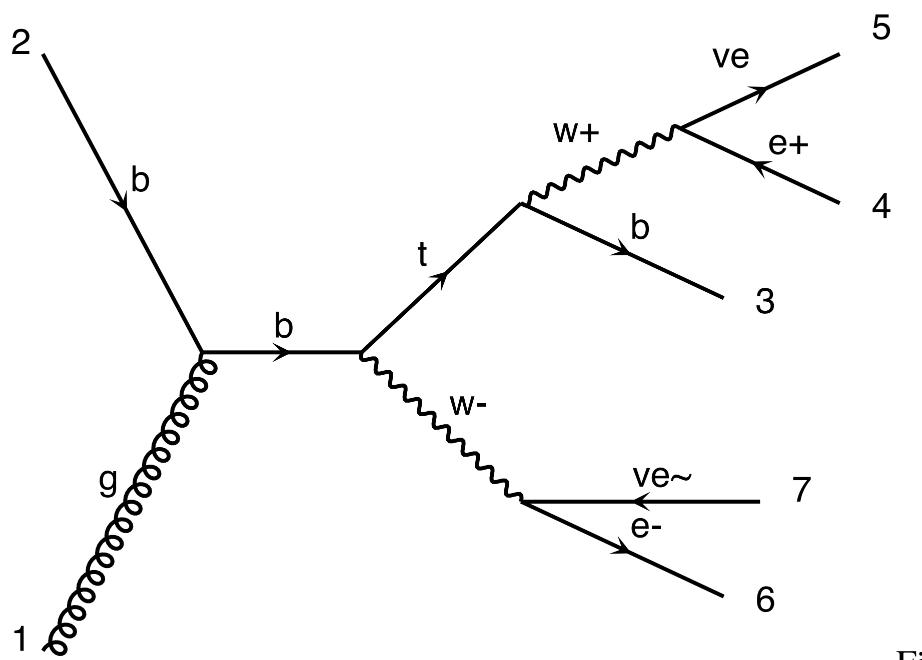
- General probes of SMEFT
- Does this somehow relate to anomalies?
- ???

SINGLE TOP MEASUREMENT

Measurement of differential cross-sections of a single top quark produced in association with a *W* boson at $\sqrt{s}$ = 13 TeV with ATLAS

The ATLAS Collaboration

1712.01602



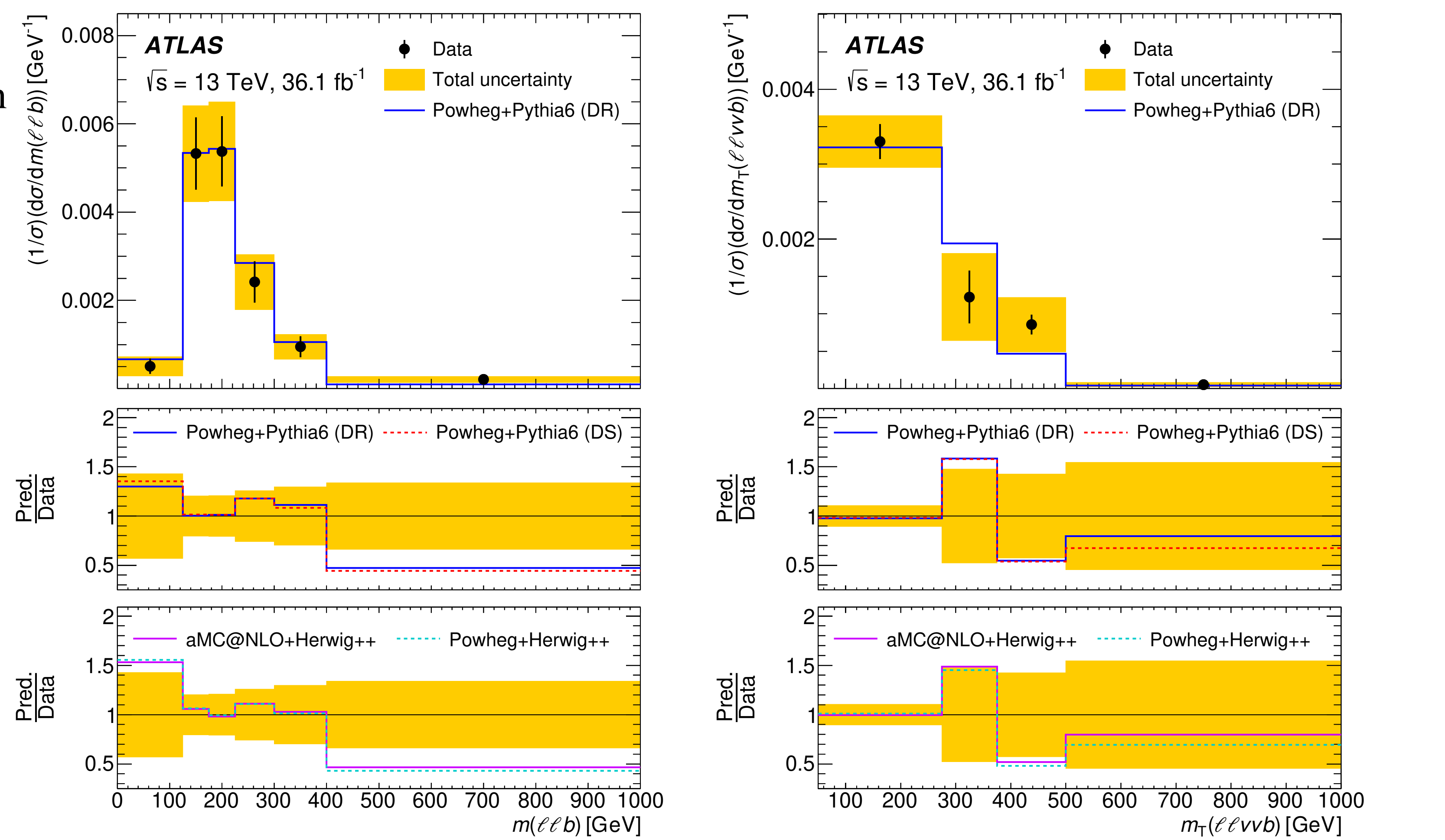


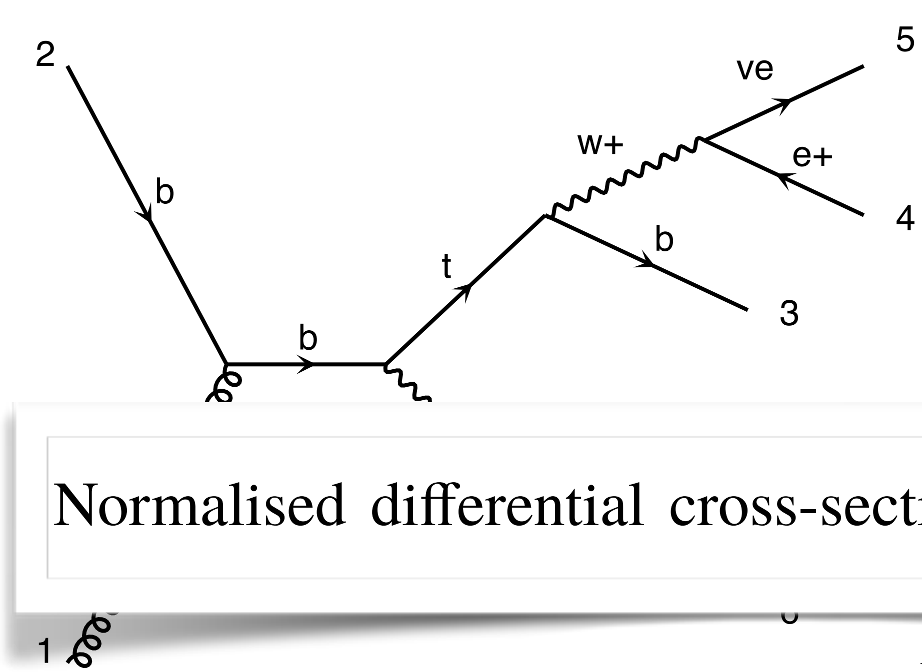
Figure 6: Normalised differential cross-sections unfolded from data, compared with selected MC models, with respect to $m_{\mathrm{T}}(\ell\ell\nu\nu b)$ and $m(\ell\ell b)$. Data points are placed at the horizontal centre of each bin. See Section 1 for a description of the observables plotted.

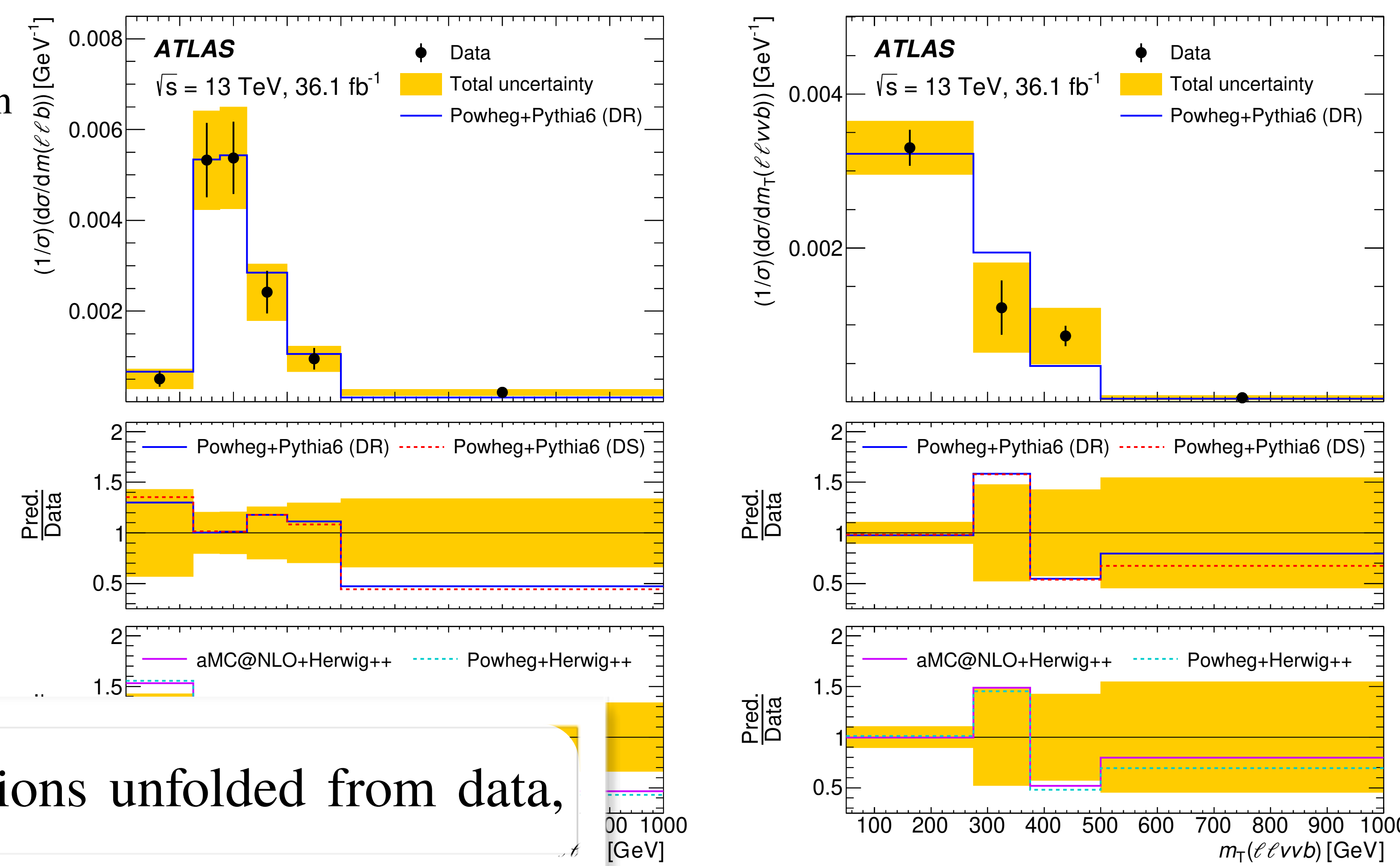
SINGLE TOP MEASUREMENT

Measurement of differential cross-sections of a single top quark produced in association with a *W* boson at $\sqrt{s}$ = 13 TeV with ATLAS

The ATLAS Collaboration

1712.01602

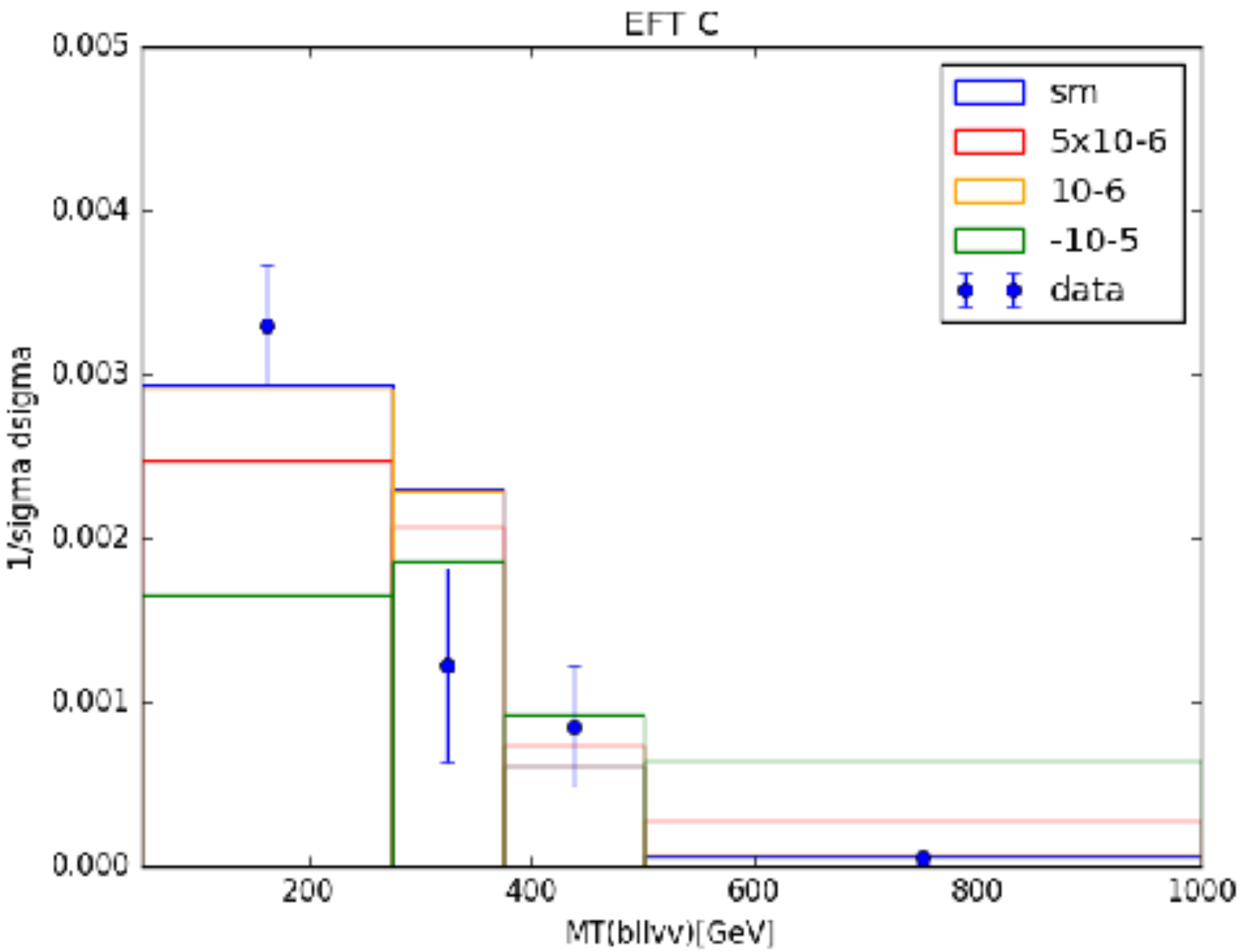




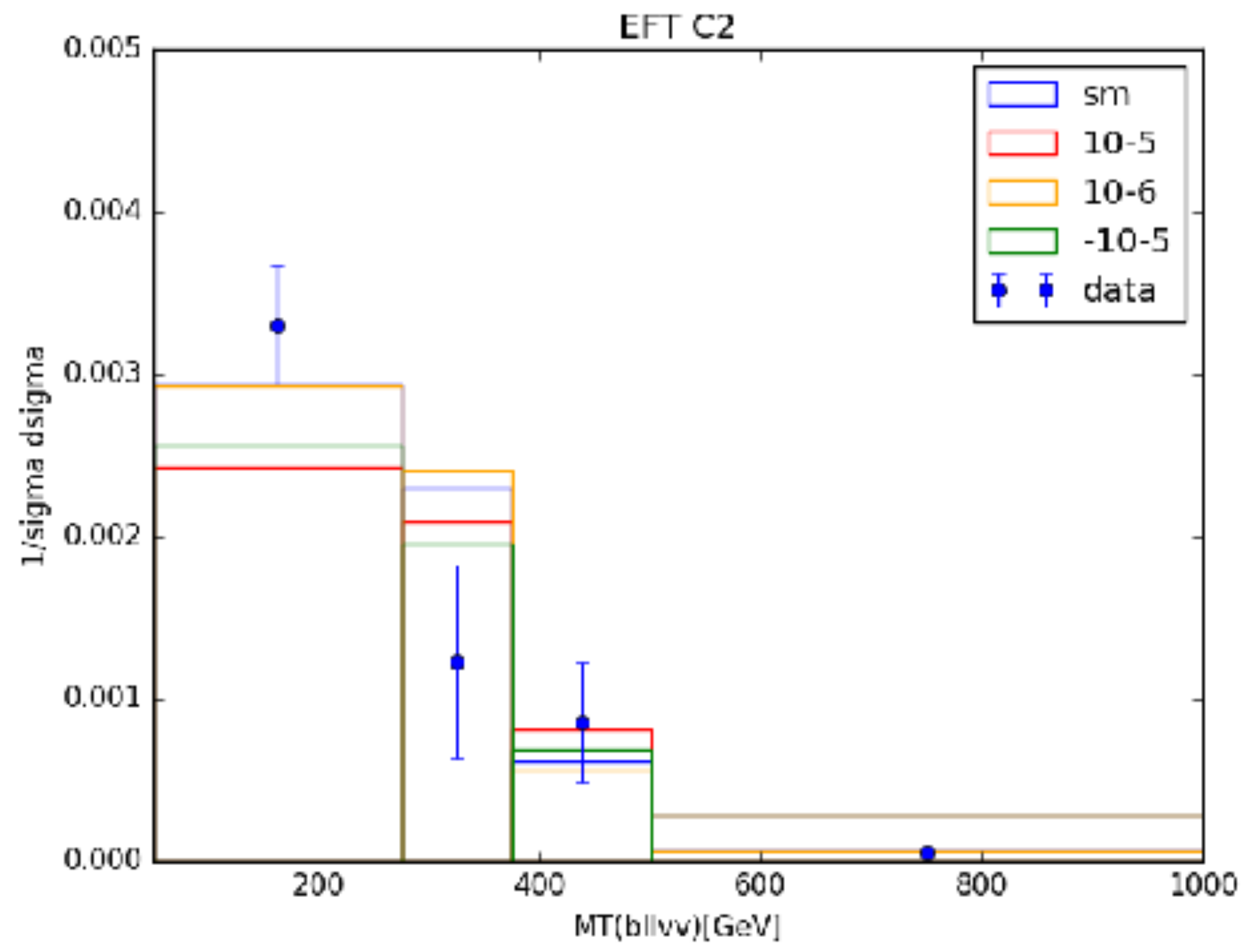
Normalised differential cross-sections unfolded from data,

Figure 6: Normalised differential cross-sections unfolded from data, compared with selected MC models, with respect to $m_T(\ell\ell\nu\nu b)$ and $m(\ell\ell b)$. Data points are placed at the horizontal centre of each bin. See Section 1 for a description of the observables plotted.

SINGLE TOP MEASUREMENT



Scalar operator,
GeV^{-2} units.



Vector operator,
GeV^{-2} units.

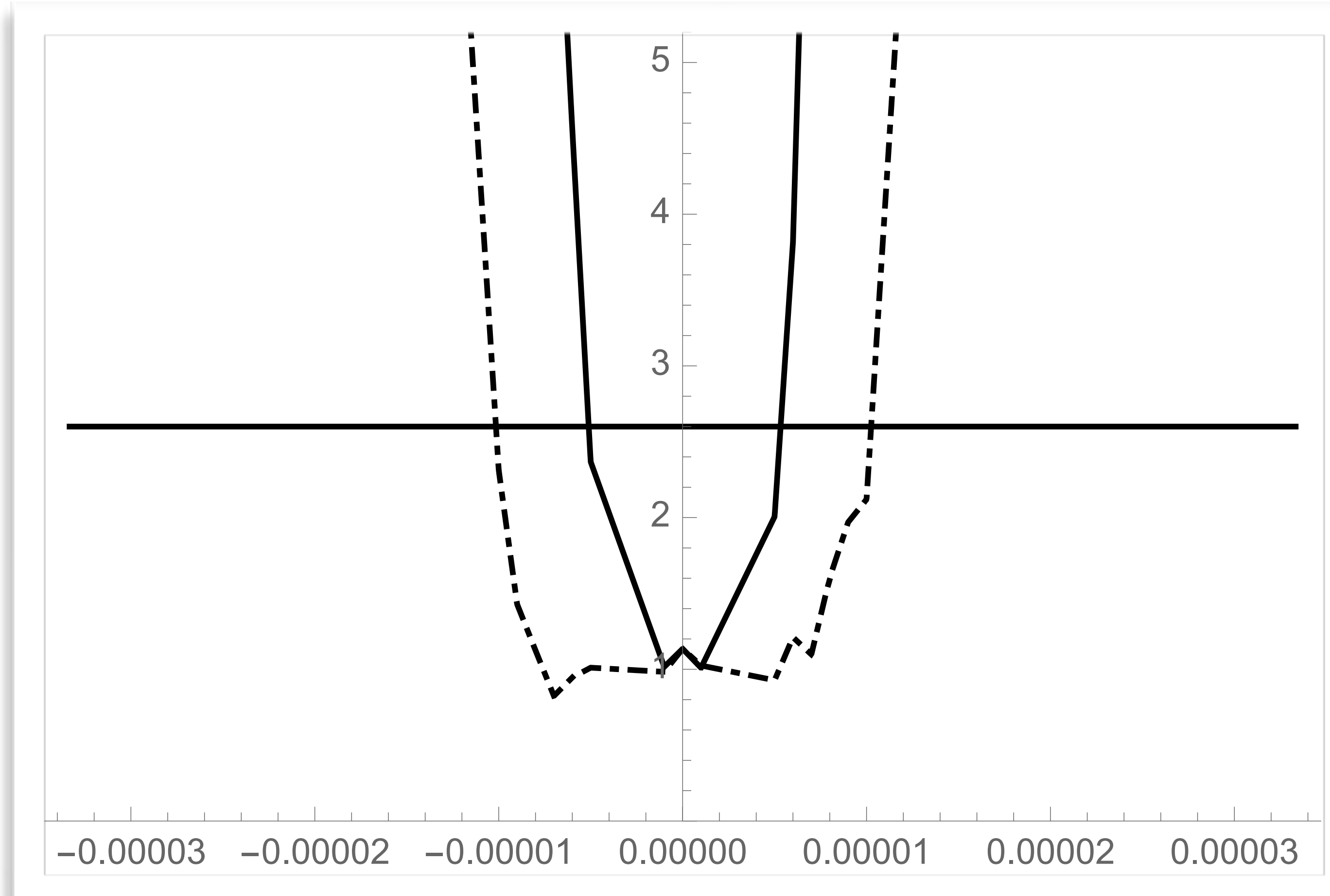
Get constraints from last bin.

BOUNDS

Can bound scale at 430 (310) GeV for scalar (vector) operator.

Does better than total x-section measurement.

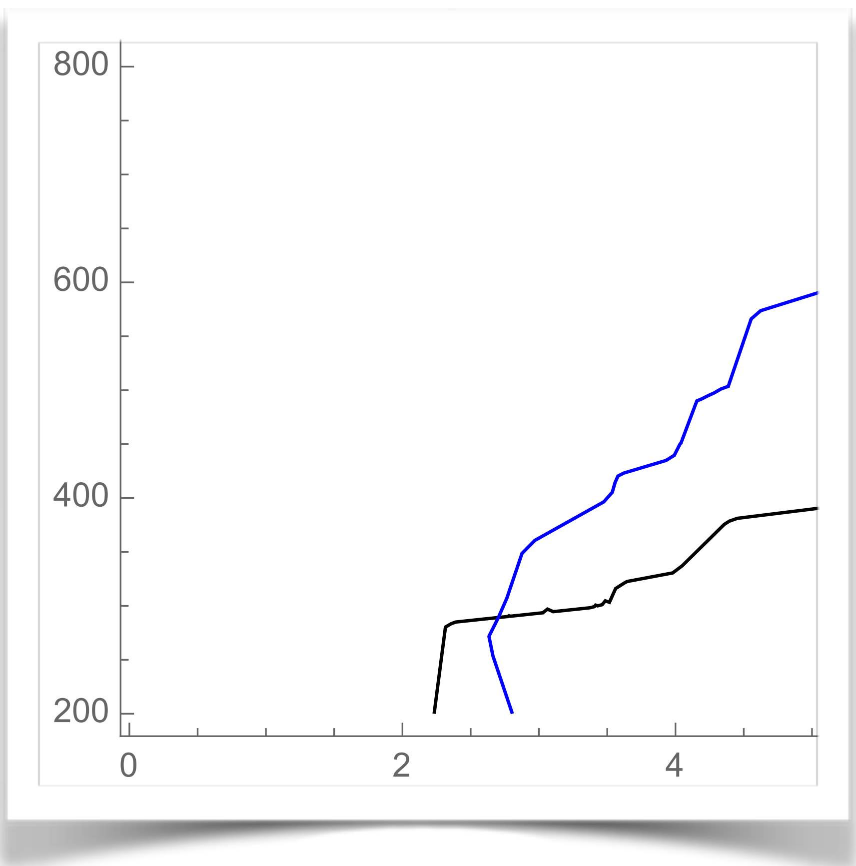
Probably not in regime of validity of EFT.



UV COMPLETIONS

Leptoquark

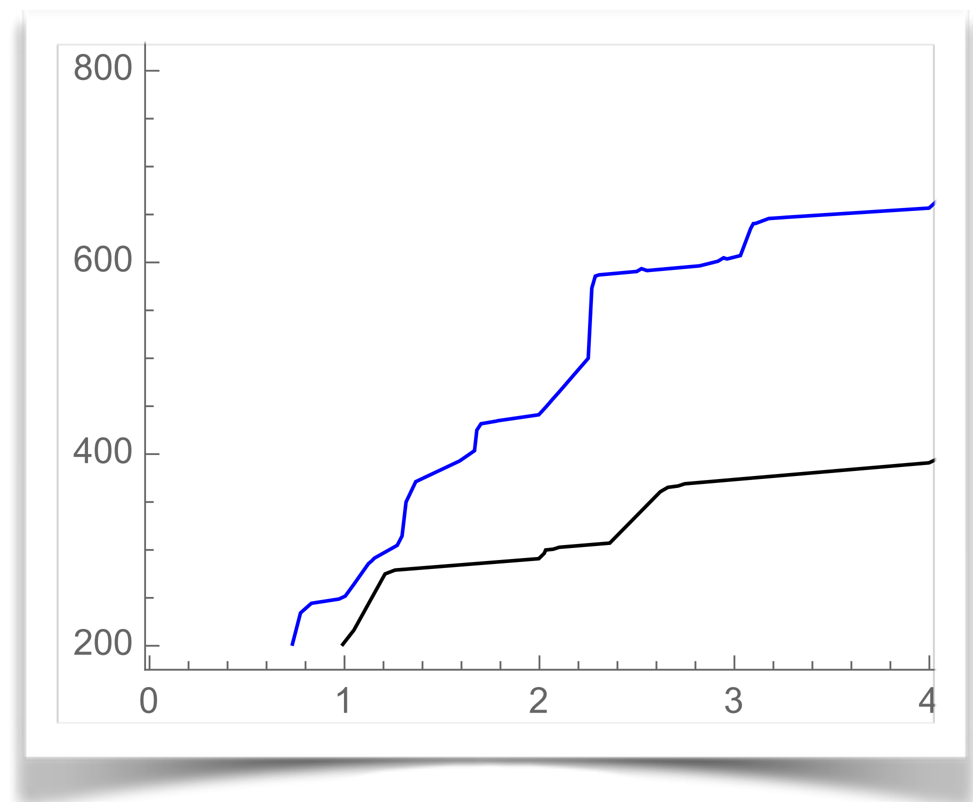
Mass (GeV)



Coupling

W'

Mass (GeV)



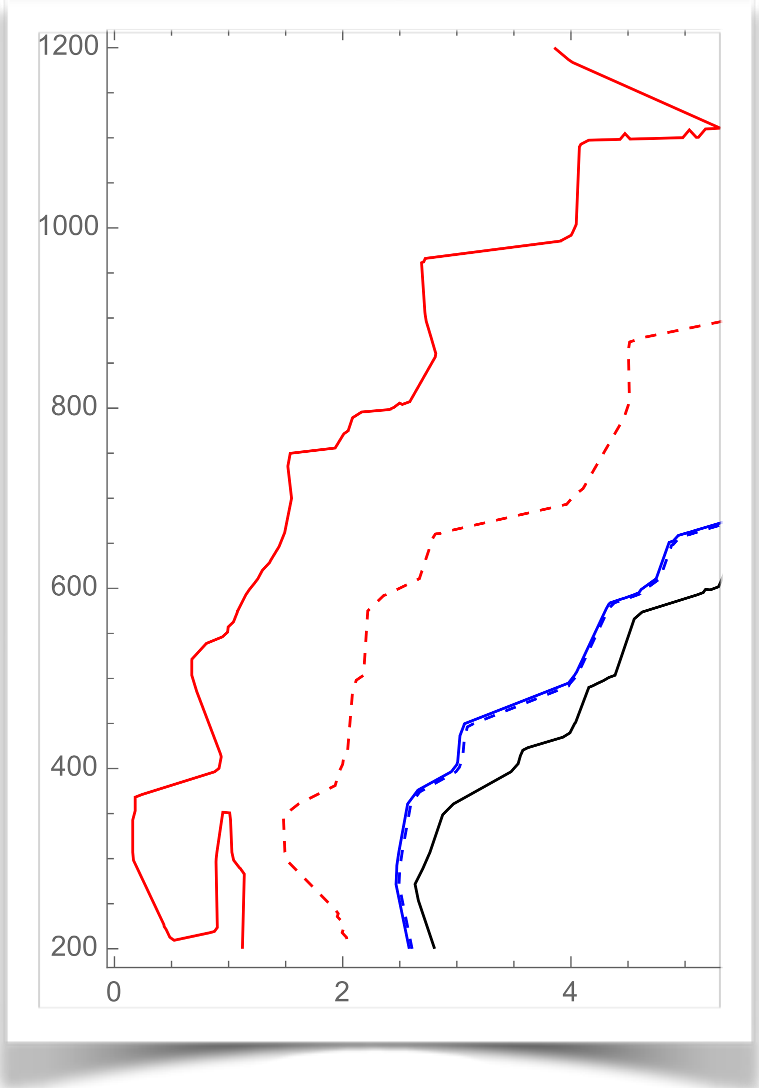
Coupling

Cross section

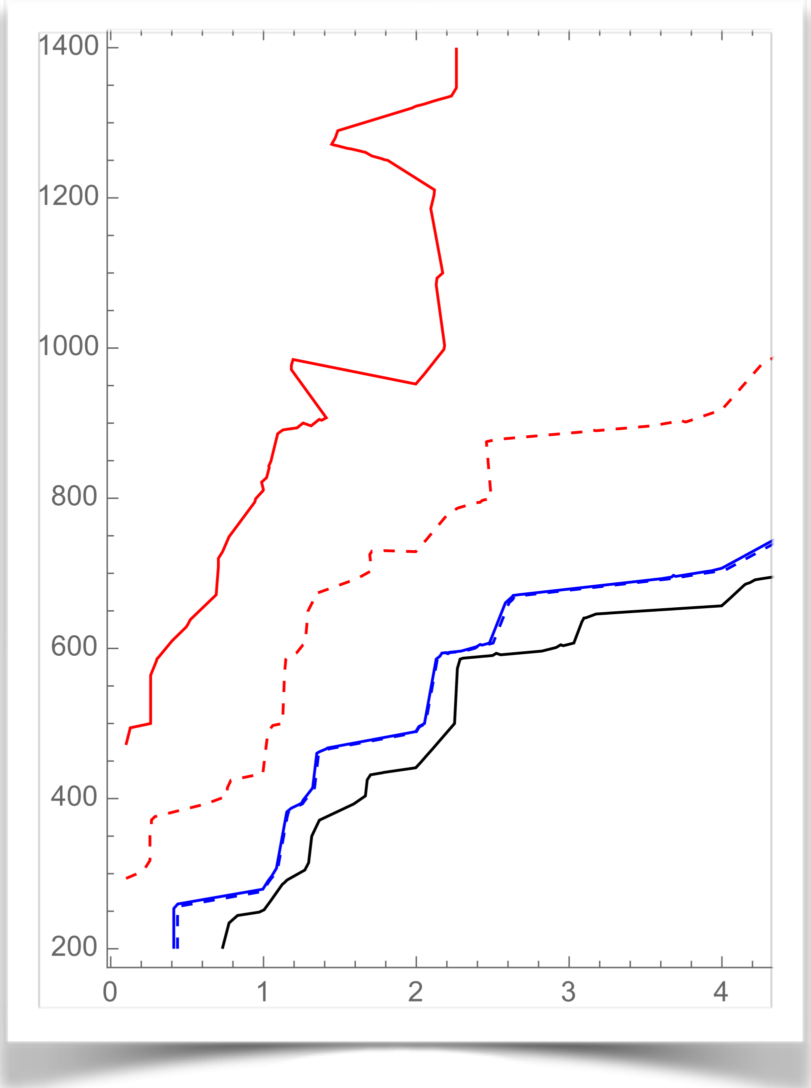
m_T distribution

PROJECTIONS

Leptoquark



W’



Current bounds

Pessimistic

Optimistic

BACK TO EFT

Can get EFT bounds at 980 (710) GeV for scalar (vector) operator.

Depends on how uncertainties are scaled to higher luminosities. Suggestions?

Could be other interesting variables to look at…

CONCLUSIONS

Lepton flavour universality is much less well established in top than in gauge sector.

Enormous top sample at LHC (and future hadron collider?) is an opportunity to do better, current measurements nearly systematics limited.

Ratios of distributions could provide very stringent tests of new physics models with sensitivity of ~few%.

THANK YOU

NUMBERS

Signal $[\ell\tau_h 2j_b]$

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

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

NP vs. SM

Model	$\epsilon_{\rm inc}(\%)$	$\epsilon_{\rm ex}(\%)$	χ^2	χ^2_3
SM (unmatched)	6.82	1.71	41.3	4.1
$m_{\mathcal{V}}=333$ GeV	6.75	1.69	41.0	4.1
$m_{\mathcal{V}}=200$ GeV	7.69	1.93	147	61.6