Model Independent Measurement of Top Quark Mass using B-Hadron Decay Lengths (Part II)

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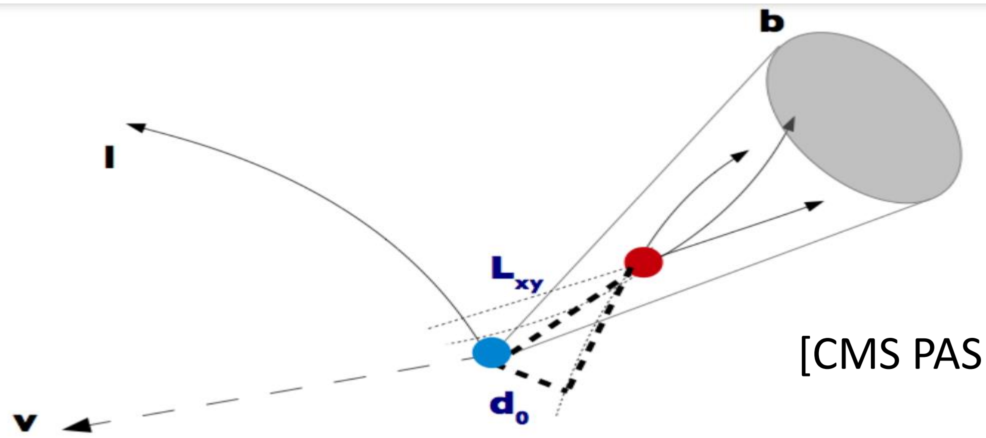
Part I
(D. Sathyan)

- Energy spectrum of bottom quark, produced from unpolarized top quarks has an invariant energy peak $E^* = \frac{m_t^2 - m_W^2 + m_b^2}{2m_t}$
- This result can be used to measure m_t independent of details of top production mechanism
- Using b-jet energies directly suffers from JES uncertainty

Part I
(D. Sathyan)

- B hadron decay lengths L_{xyz} (Energy Peak) can be used instead as a proxy, no JES uncertainty
- Transverse component of B hadron decay lengths , L_{xy} (SM), have been used by CMS to measure m_t
- L_{xy} (SM) sensitive to top production mechanism, L_{xyz} (Energy Peak) is insensitive



[CMS PAS TOP-12-030]

Outline

- B hadron decay length spectrum ansatz
- Event generation and selection
- Theory inputs and calibration
- Uncertainties
    - Statistical
    - Systematic
- Comparison to L_{xy} method
- Summary

L_B spectrum ansatz (revisit)

$$G^{fit}(L_B; E_b^{\text{rest}}, w) = \int d\,E_B \int d\,E_b \, \frac{1}{N(w)} \exp\left[-w\left(\frac{E_b}{E_b^{\text{rest}}} + \frac{E_b^{rest}}{E_b}\right)^{\nu}\right] \times$$

$\boldsymbol{f(E_b)}$

b Energy Spectrum

L_B spectrum ansatz (revisit)

$$G^{fit}(L_B; E_b^{\text{rest}}, w) = \int d\,E_B \int d\,E_b \;\; \frac{1}{N(w)} \exp\left[-w\left(\frac{E_b}{E_b^{\text{rest}}} + \frac{E_b^{rest}}{E_b}\right)^{\nu}\right] \times \sum_i D_i\left(\frac{E_B}{E_b}; E_b\right) f_i$$

Fragmentation

$\boldsymbol{i} \rightarrow$ **Multiple species**

L_B spectrum ansatz (revisit)

$$G^{fit}(L_B; E_b^{\mathrm{rest}}, w) = \int d\,E_B \int d\,E_b \;\; \frac{1}{N(w)} \exp\left[-w\left(\frac{E_b}{E_b^{\mathrm{rest}}} + \frac{E_b^{rest}}{E_b}\right)^{\nu}\right] \times$$

$$\sum_i D_i\left(\frac{E_B}{E_b}; E_b\right) f_i \frac{m_{B_i}}{c\tau_{B_i}^{rest}\sqrt{E_B^2 - m_{B_i}^2}} \exp\left[-\left(\frac{L_B m_{B_i}}{c\tau_{B_i}^{rest}\sqrt{E_B^2 - m_{B_i}^2}}\right)\right]$$

Exponential Decay

L_B spectrum ansatz (revisit)

$$G^{fit}(L_B; E_b^{\text{rest}}, w) = \int d\,E_B \int d\,E_b \;\; \frac{1}{N(w)} \exp\left[-w\left(\frac{E_b}{E_b^{\text{rest}}} + \frac{E_b^{rest}}{E_b}\right)^{\nu}\right] \times$$

$$\sum_i D_i\left(\frac{E_B}{E_b}; E_b\right) f_i \frac{m_{B_i}}{c\tau_{B_i}^{rest}\sqrt{E_B^2 - m_{B_i}^2}} \exp\left[-\left(\frac{\mathrm{L_B m_{B_i}}}{c\tau_{\mathrm{B_i}}^{\text{rest}}\sqrt{\mathrm{E_B^2 - m_{B_i}^2}}}\right)\right]$$

$E_b^{\text{rest}} = (m_t^2 \; - \; M_W^2 \; + \; m_b^2)/(2m_t) \rightarrow$ peak energy

$w \rightarrow$ width of the fitting function

$i \rightarrow$ B hadron species

$\tau_{B_i}^{rest} \rightarrow$ mean rest frame lifetime for "i" B hadron

$D_i\left(\frac{E_B}{E_b}; E_b\right) \rightarrow$ bottom quark fragmentation for species i

$f_i \rightarrow$ relative fraction of species i

$N(w) \rightarrow$ normalization factor

Event generation and Selection

- Generate signal events at parton level using MadGraph5
  $p\,p \;\rightarrow\; t\,\bar{t}\,;\; (t \rightarrow\; W^{+}\,b);\; \left(\bar{t} \rightarrow\; W^{-}\,\bar{b}\,\right)$; only semi-leptonic and leptonic events

- Impose selection cuts [arXiv:1603.0653]
  $\longrightarrow$ Semi-leptonic events
  - $e^{\pm}$ with $p_T > 25\,GeV$ and $|\eta| < 2.5$ or $\mu^{\pm}$ with $p_T > 25\,GeV$ and $|\eta| < 2.1$
  - 4 jets with $p_T > 25\,GeV$ and $|\eta| < 2.5$

  $\longrightarrow$ Leptonic events
  - 2 leptons with $p_T > 25\,GeV$ and $|\eta| < 2.5$
  - 4 jets with $p_T > 25\,GeV$ and $|\eta| < 2.5$
  - MET $> 40\,GeV$
  - $M_{ll} > 20\,GeV$ and $|M_{ll} - M_z| > 15\,GeV$

  [Note: All p_T cuts set to the same value]

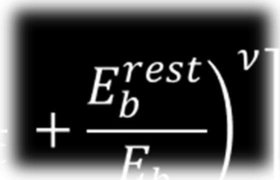
- Parton shower and hadronization using Pythia8

Theory inputs

- B hadron properties – mass and lifetimes
- Fragmentation function
- Relative fraction of different species

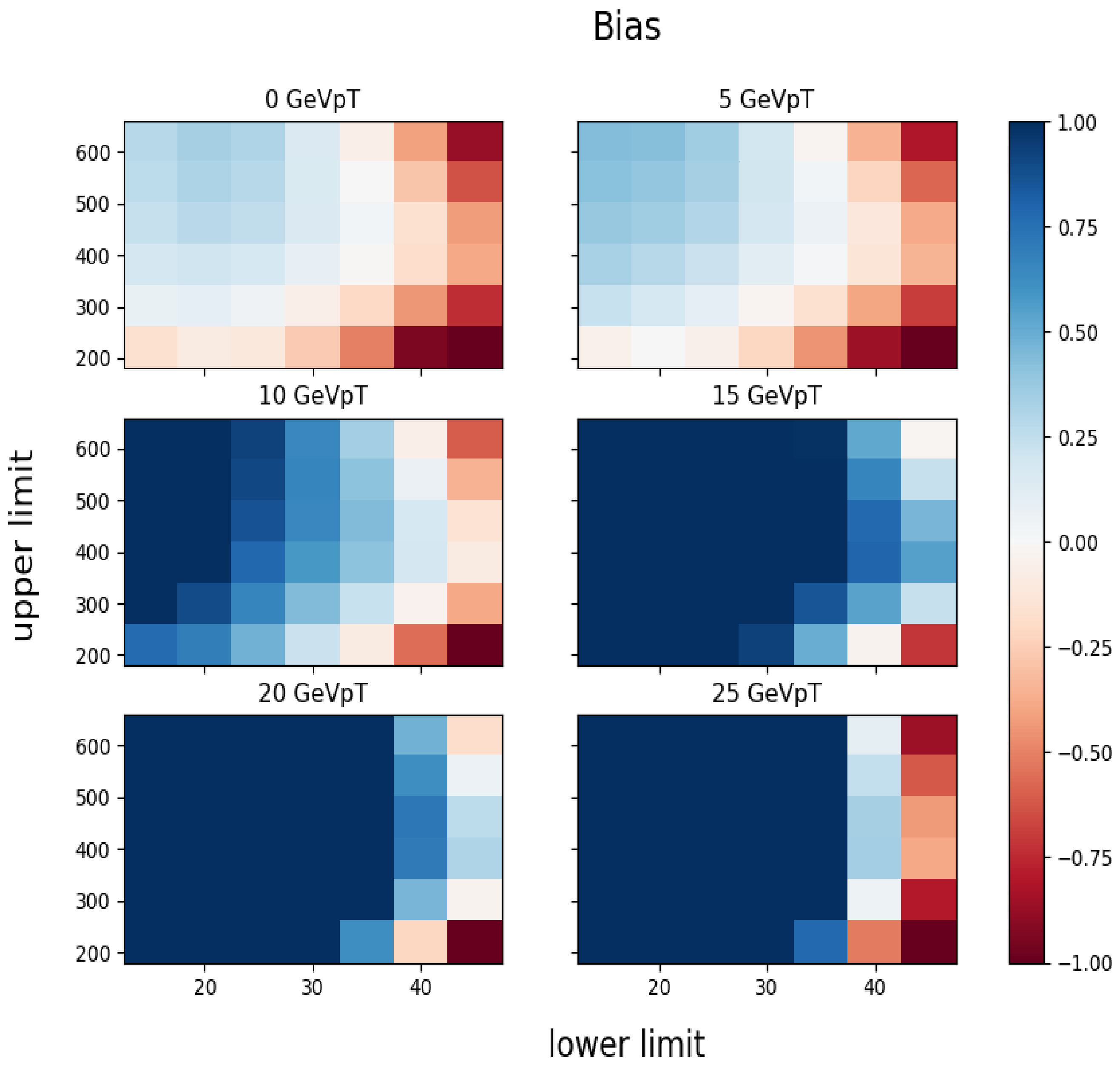
All can be measured or calculated in principle. We use the values used in simulation.

Hyper-parameters



- ν parameter (0.3)
- Bounds on E_b integral ([40, 450] GeV)
- Fitting range ([0, 20] mm)

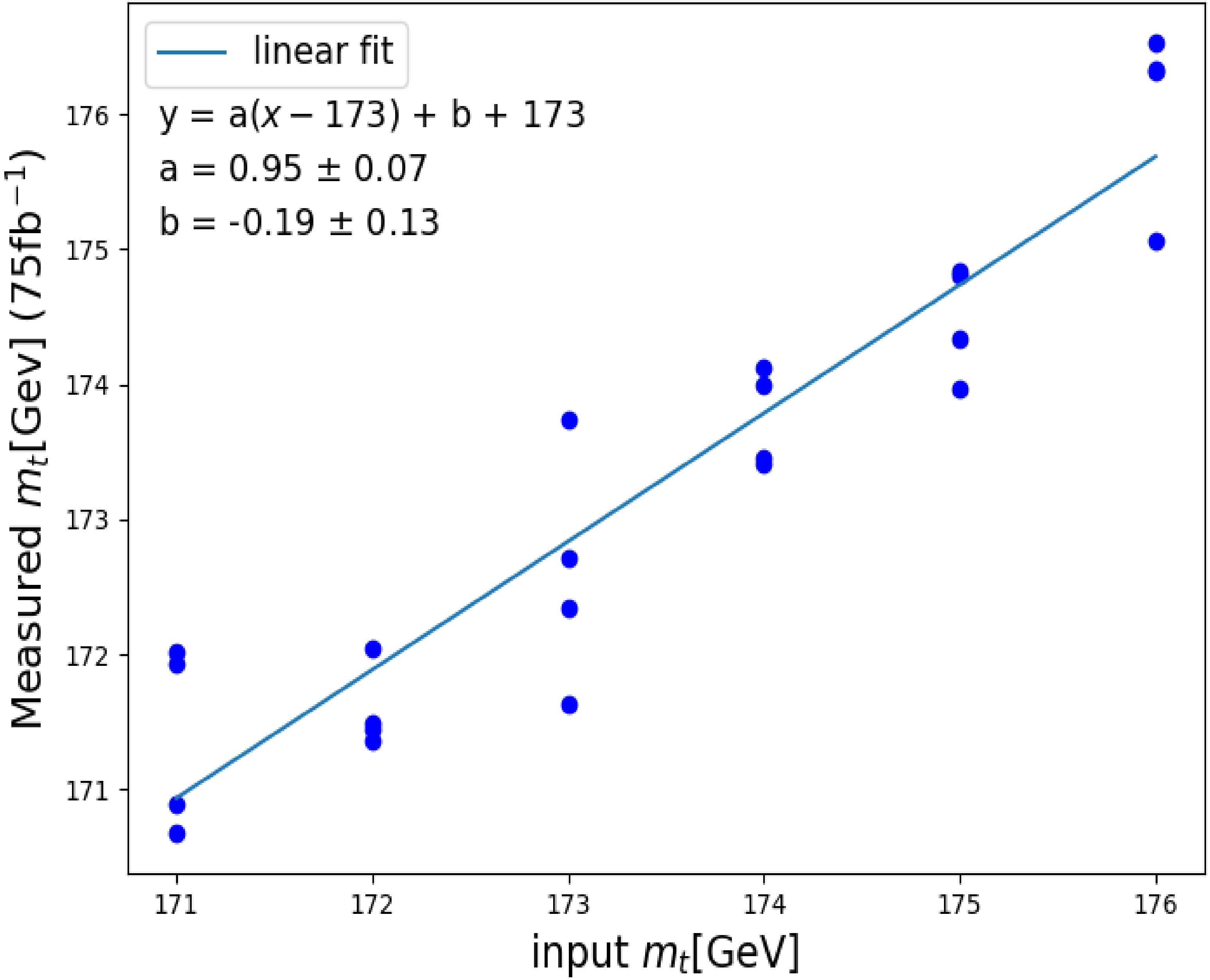
Hyper-parameters and selection cuts can lead to a bias in the measured mass. We optimize for minimal bias in the measurement.



Results at $\sim 75\ fb^{-1}$ and parameters set to optimal values

Bias = -0.19 ± 0.13 GeV

Stat. Error = 0.65 GeV



Uncertainties

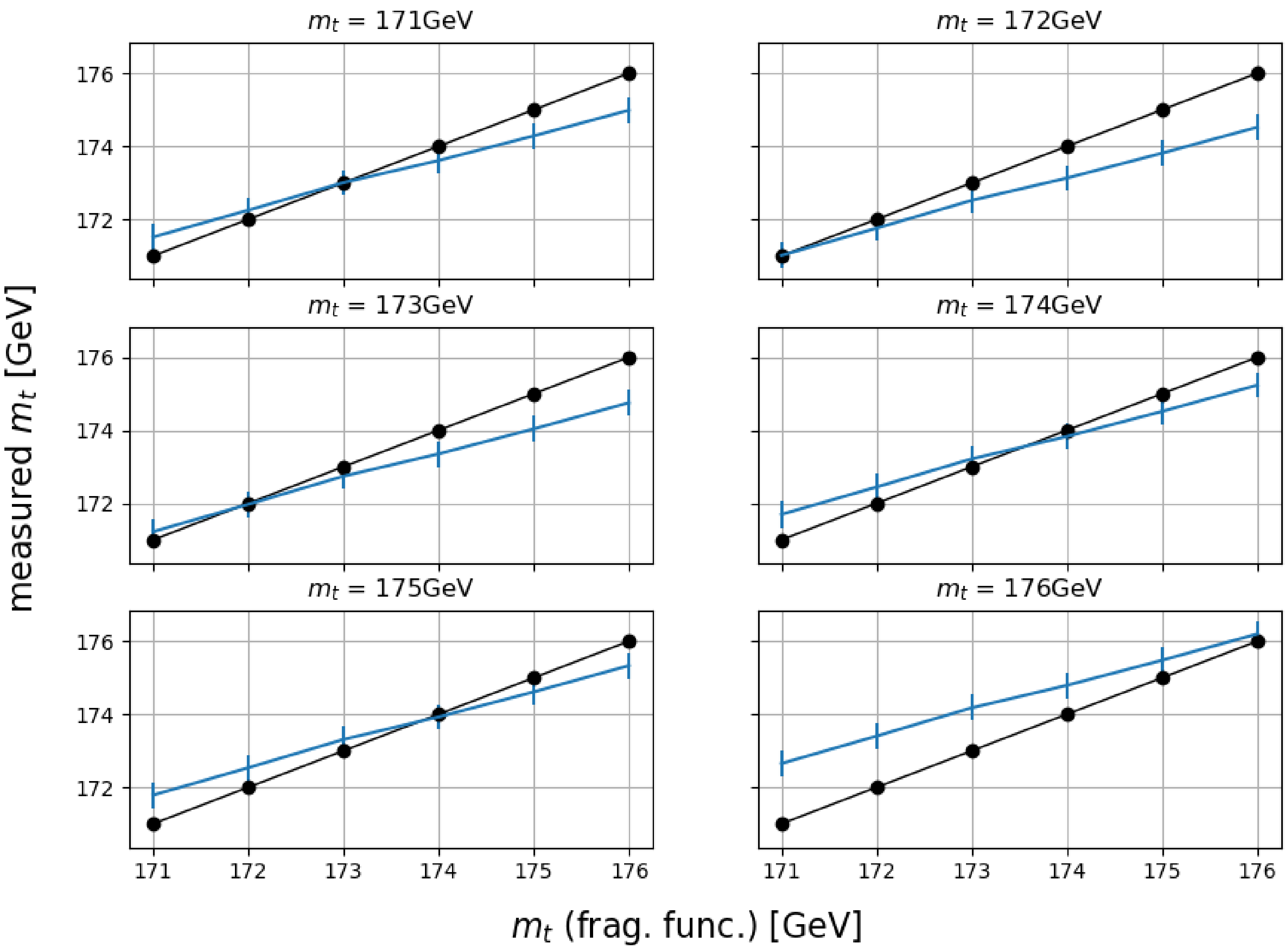
Theory inputs

- B hadron properties – mass and lifetimes
- Fragmentation function
- Relative fraction of different species

Uncertainties

- Statistical error at 300 $fb^{-1} \approx 0.35\ GeV$ and at 3 $ab^{-1} \approx 0.1\ GeV$
- Systematics - Masses and lifetimes are varied by the known uncertainty [*PTEP* 2020 (2020) 8, 083C01]
- 10% variation in fractions correspond to roughly the difference between fractions measured at LEP and Tevatron [CMS PAS TOP-12-030]

Input	Variation	Maximum shift in m_t
m_{B_i}	0.005 %	0.004% (7 MeV)
$\tau_{B_i}^{rest}$	0.25 %	0.18 % (350 MeV)
f_i	10 %	0.4 % (700 MeV)



Variation with fragmentation function

- A large uncertainty comes from fragmentation
- Moments of the fragmentation function shift with input m_t
- 5 GeV shift in $m_t \leftrightarrow \lesssim 1\,\%$ shift in the moments move the prediction by about 3.5 GeV ($\sim$ 2%)

Comparison to L_{xy} (SM) method

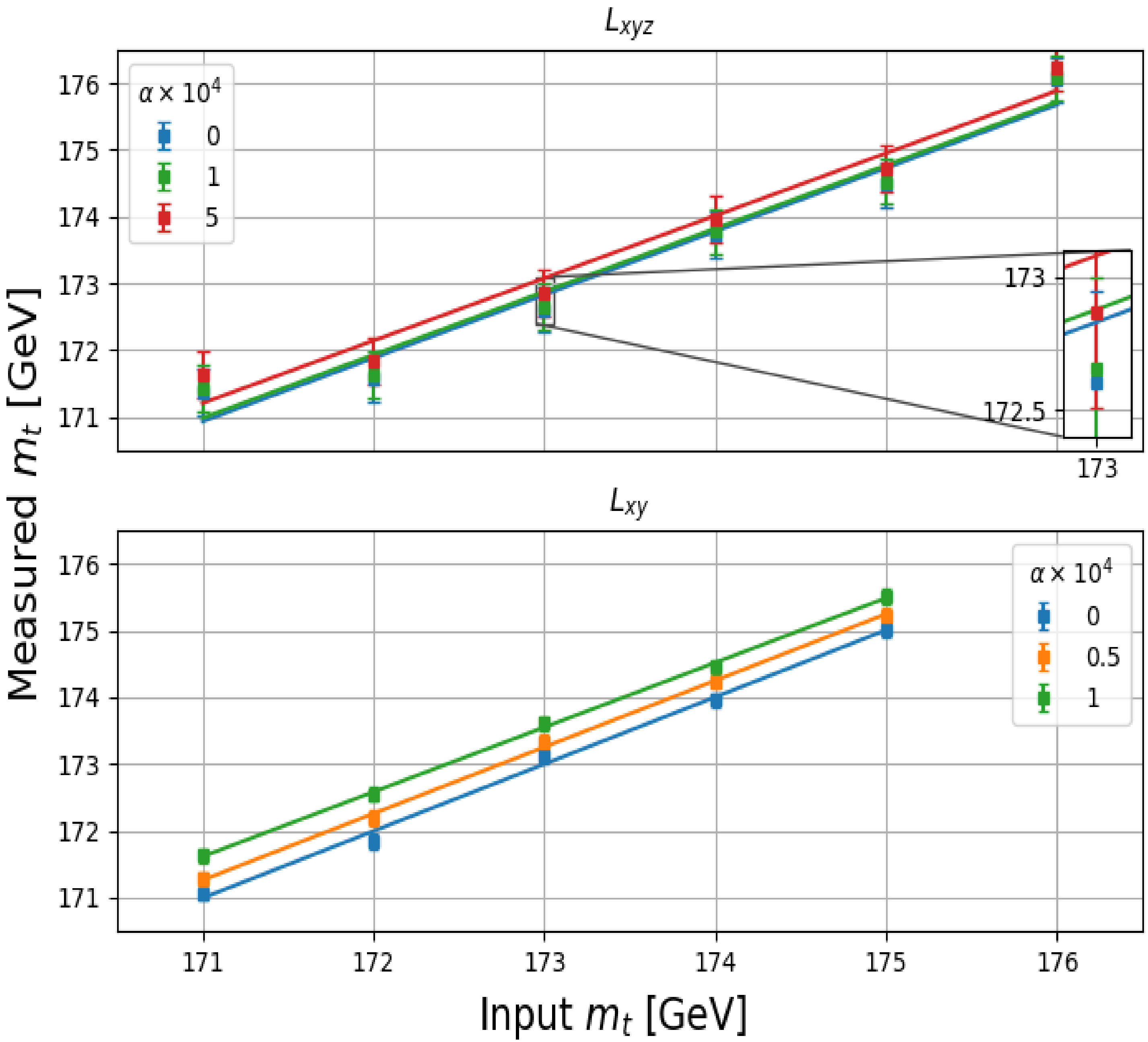
Comparison to L_{xy} method

- CMS already has used B hadron decay lengths to measure m_t
- Transverse decay length $\langle L_{xy} \rangle$, calculated using SM and then fit to data
- Modelling of p_T distribution of the top quark is the major source of systematic uncertainty (2.6 GeV) [CMS PAS TOP-12-030]
- L_{xyz} based on the energy peak idea is production mechanism independent
- Residual sensitivity to the top quark p_T spectrum due to the selection cuts and the hyper-parameters, but substantially less

[Note: Hadronization uncertainties same for both the methods]

p_T reweighting to test the sensitivity –
$\widetilde{w} = w[\, 1 + \alpha\theta(p_T < 400)(p_T - 200)]$

For $\alpha = 10^{-4}$, $\langle p_T \rangle$ shifts by ≈0.5 %
(roughly the discrepancy/uncertainty)
[Phys. Rev. D, 104(9):092013, 2021]



Summary

- Invariant energy peak idea to calculate B hadron decay length spectrum
- Unlike b-jet energy peak no JES uncertainty
- Compared to CMS L_{xy} (SM), insensitive to top quark transverse momentum distribution re-weighting
- A more thorough detector level analysis needed to confirm