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

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Part II by Sagar Airen follows this talk

Based on 2205.xxxx by Kaustubh Agashe, Sagar Airen, Roberto Franceschini, Doojin Kim, Deepak Sathyan

Outline

- Motivate and describe energy peak idea
- Measure top quark mass using *b*-jet energy peak
- Propose new method using *B*-hadron decay lengths
- Results of new method (more in Part II by Sagar Airen)

Why use energy peak to measure top quark mass?

- Top mass is an important input parameter
  - Electroweak precision tests like ρ parameter
  - Running of Higgs quartic coupling
- Most current measurement techniques assume SM production of top quark
  - Must incorporate SM production uncertainties (PDFs, top quark p_T, etc.)
  - Reconstruction of $t\bar{t}$ events requires SM knowledge due to *b*-jet / p_L^ν ambiguity
- Goal: model-independent measurement of m_t with $\mathcal{O}(1\ GeV)$ uncertainty

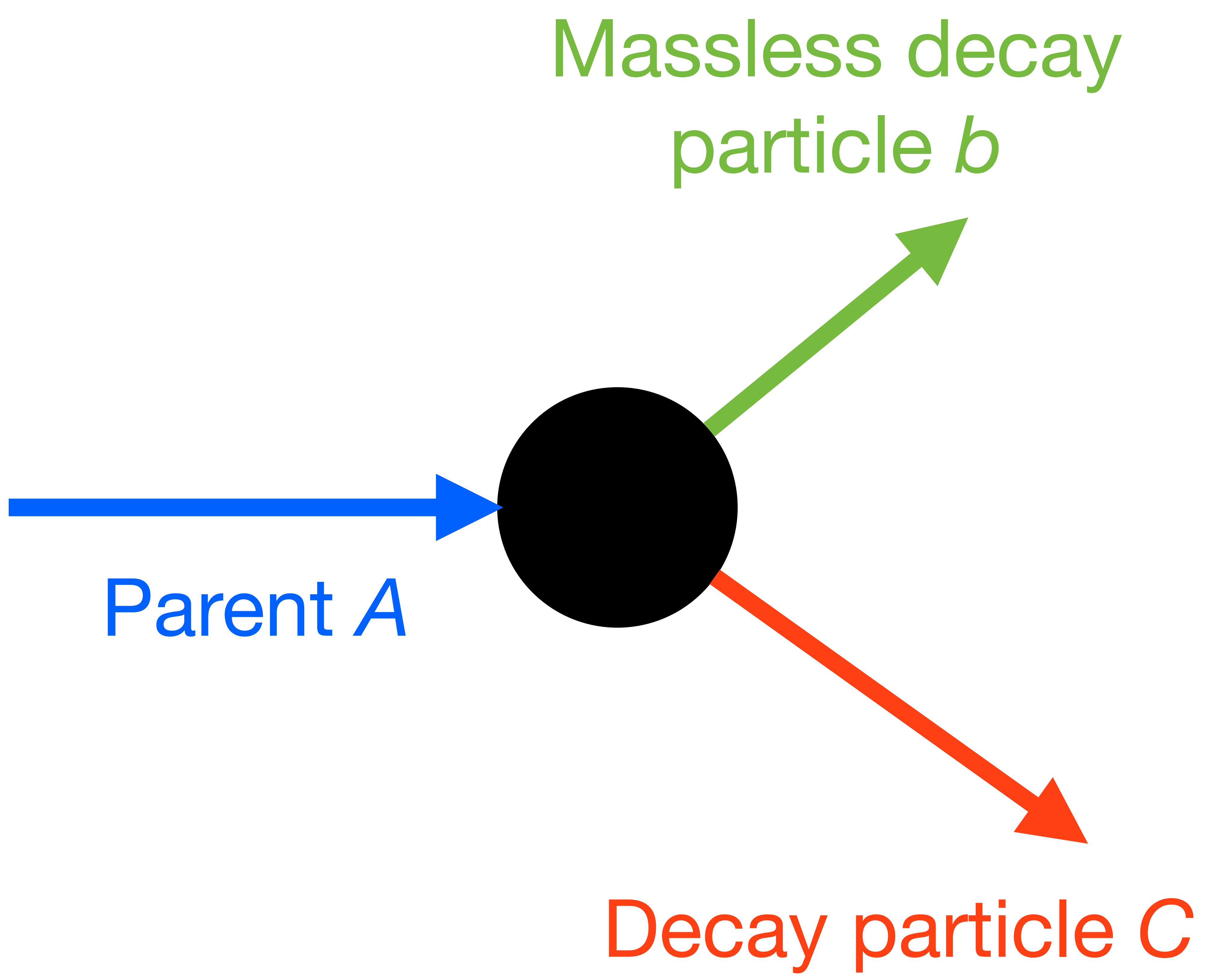
Introducing energy peak idea

- 2-body decay: $A \to bC$
  - Decay product *b* is massless
  - Particle *A* produced unpolarized

Energy of massless *b* in *A*'s rest frame:

$$E_b^* = \frac{m_A^2 - m_C^2}{2m_A}$$

- Only need mass of particle *C* to obtain m_A
  - Don't need to observe/reconstruct

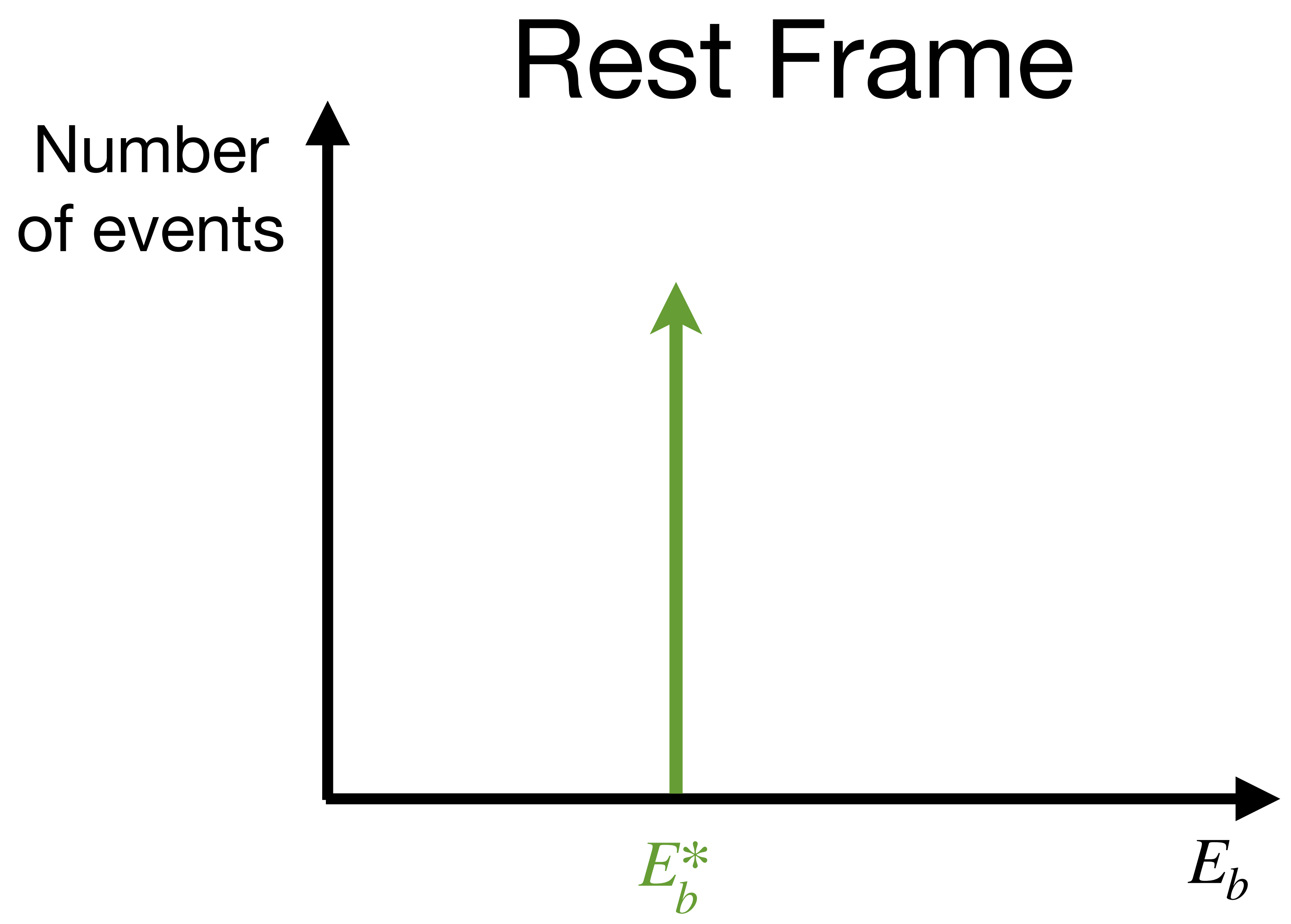


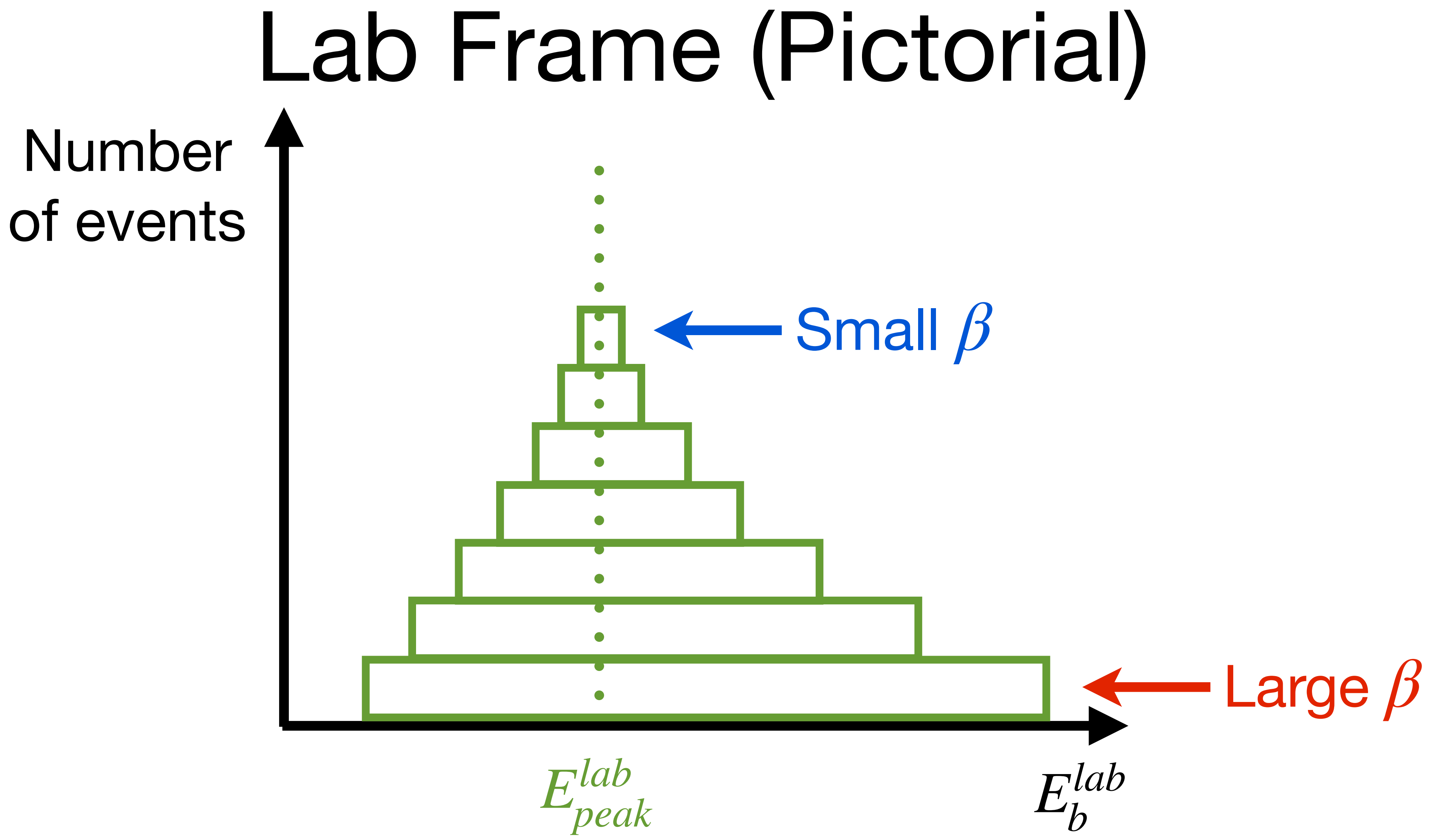
Introducing energy peak idea

- E_b^* is not Lorentz-invariant
- In lab frame, boost distribution smears energy of particle *b*:

$$E_b^{lab} = E_b^* \gamma (1 + \beta \cos \theta^*)$$

- Unpolarized parent: $\cos \theta^*$ distribution is flat for any β
  - E_b^{lab} for any β contains E_b^*





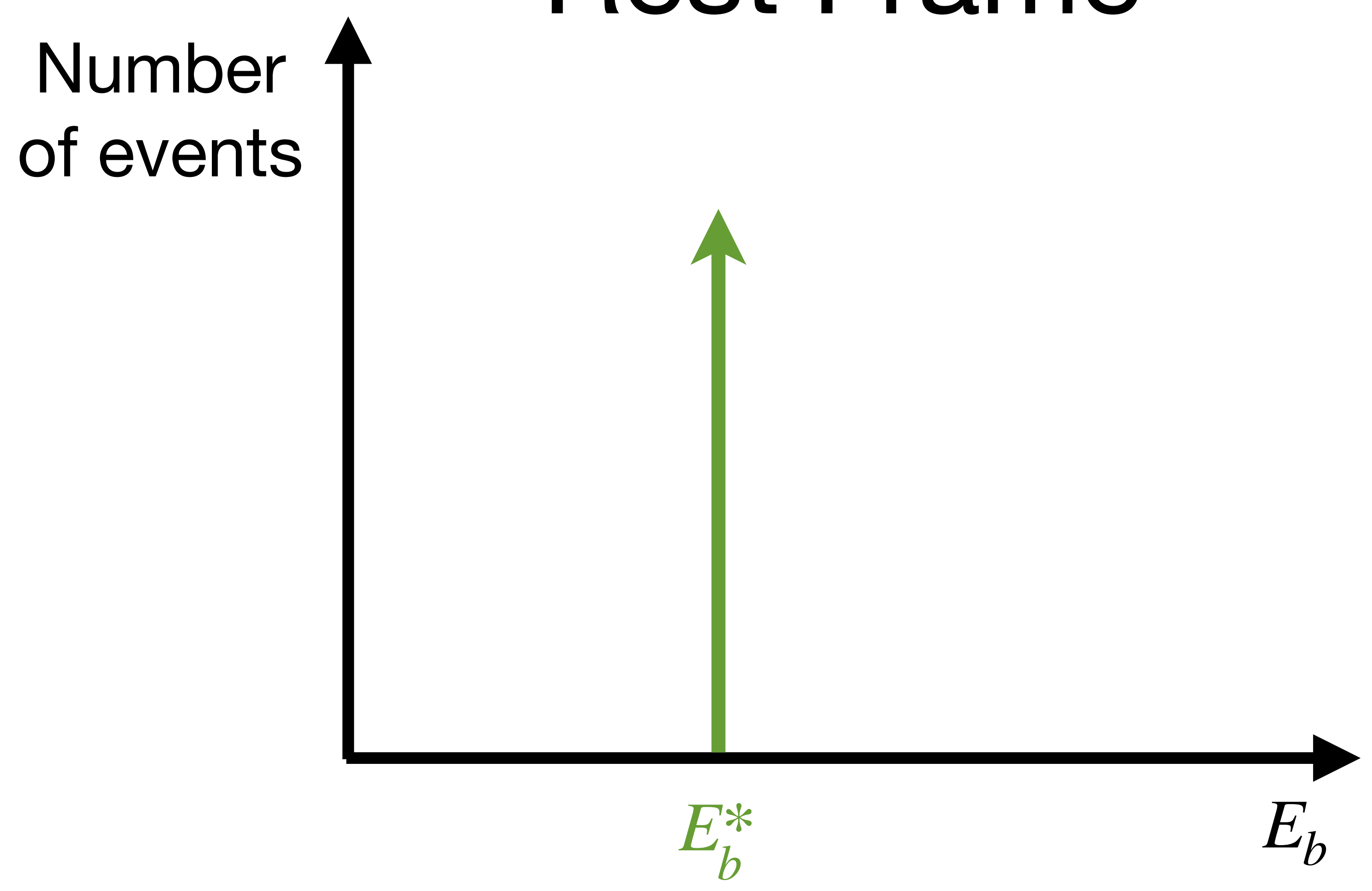
Introducing energy peak idea

- **Remarkable result:**
  - Energy in *A*'s rest frame equal to peak of energy distribution in lab frame:

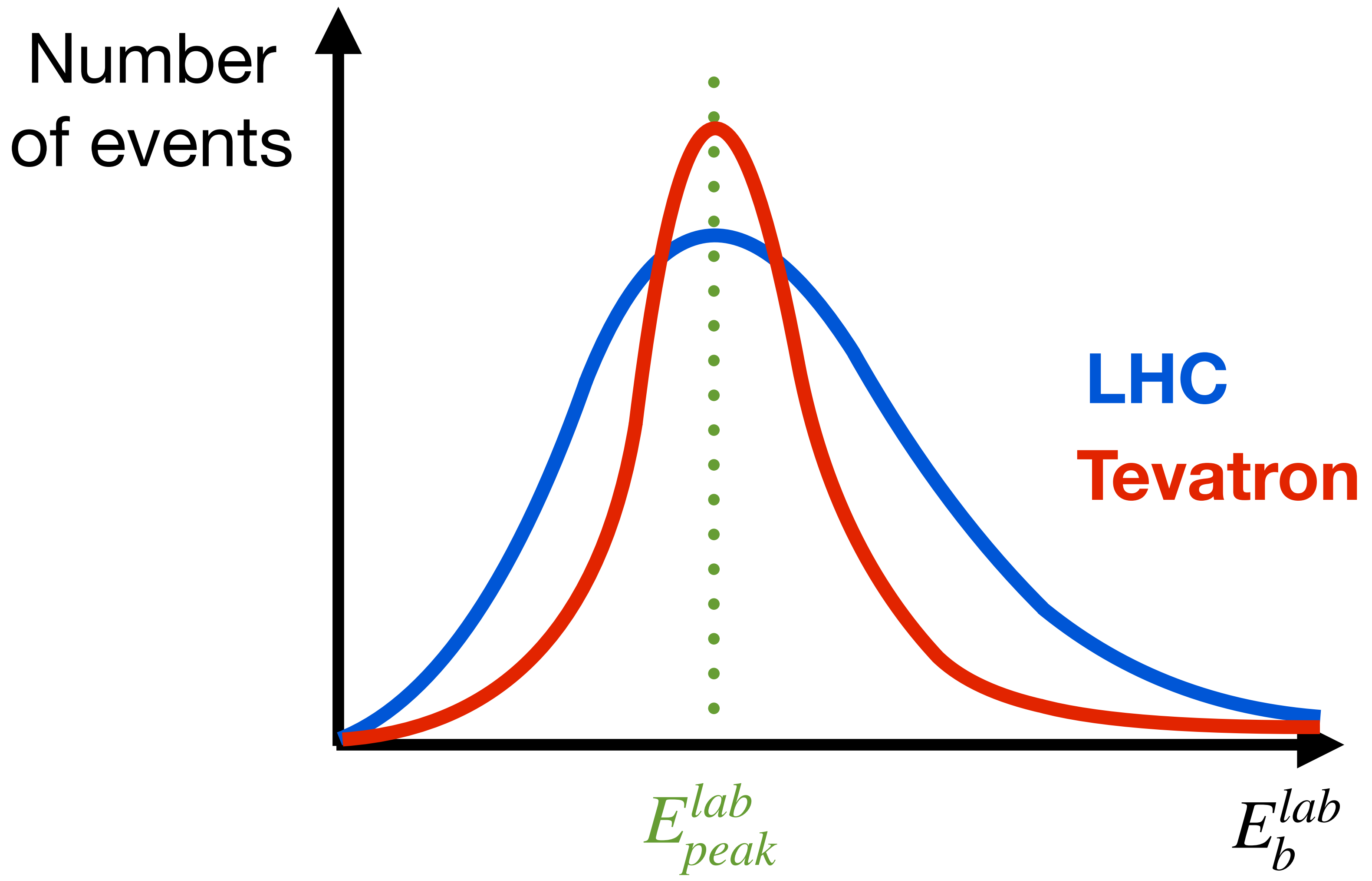
$$E_{peak}^{lab} = E_b^*$$

- Boost distribution depends on production mechanism
  - Energy peak is boost-invariant
  - **Energy peak independent of production of parent particle *A***

Rest Frame



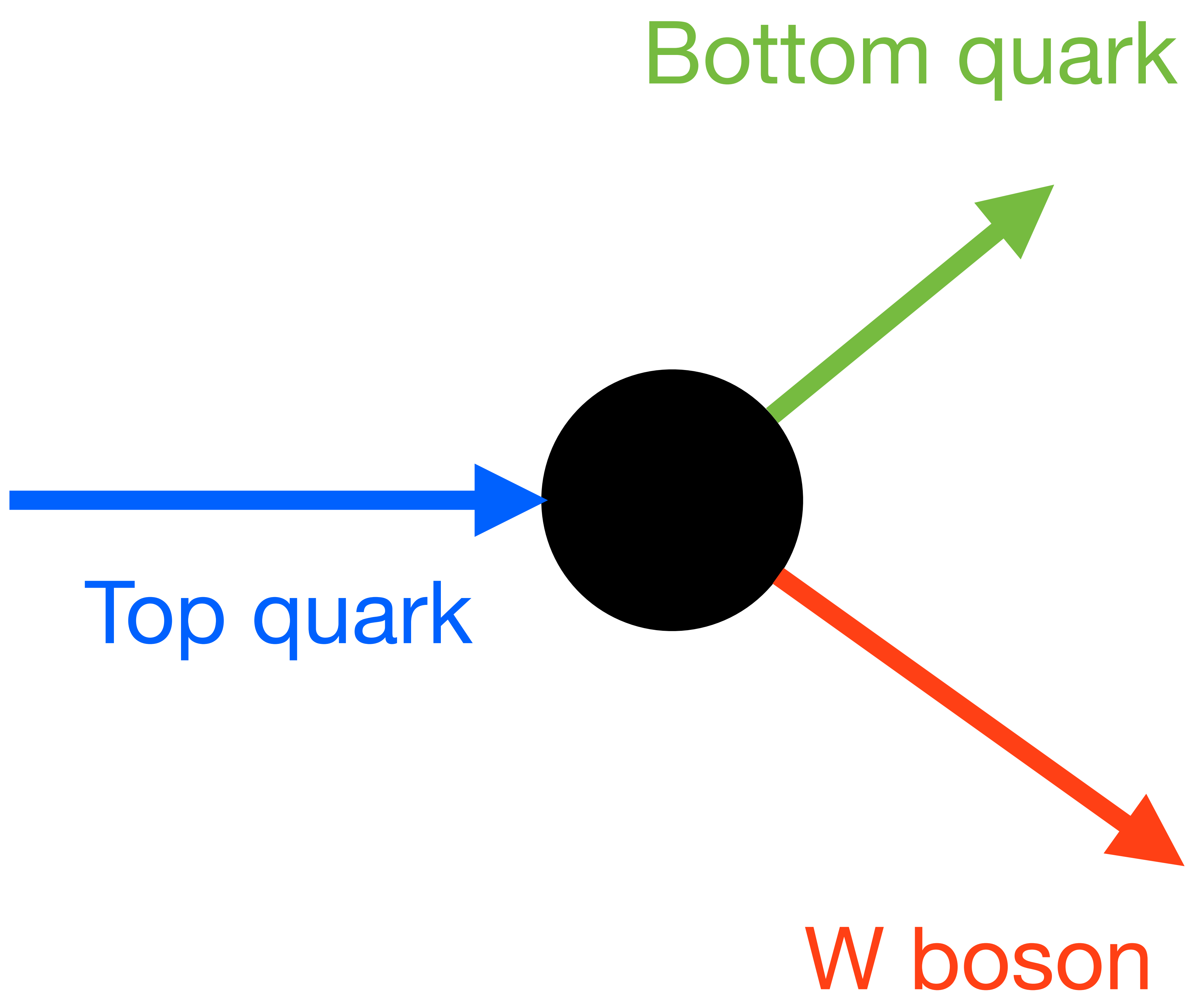
Lab Frame



Applying energy peak idea

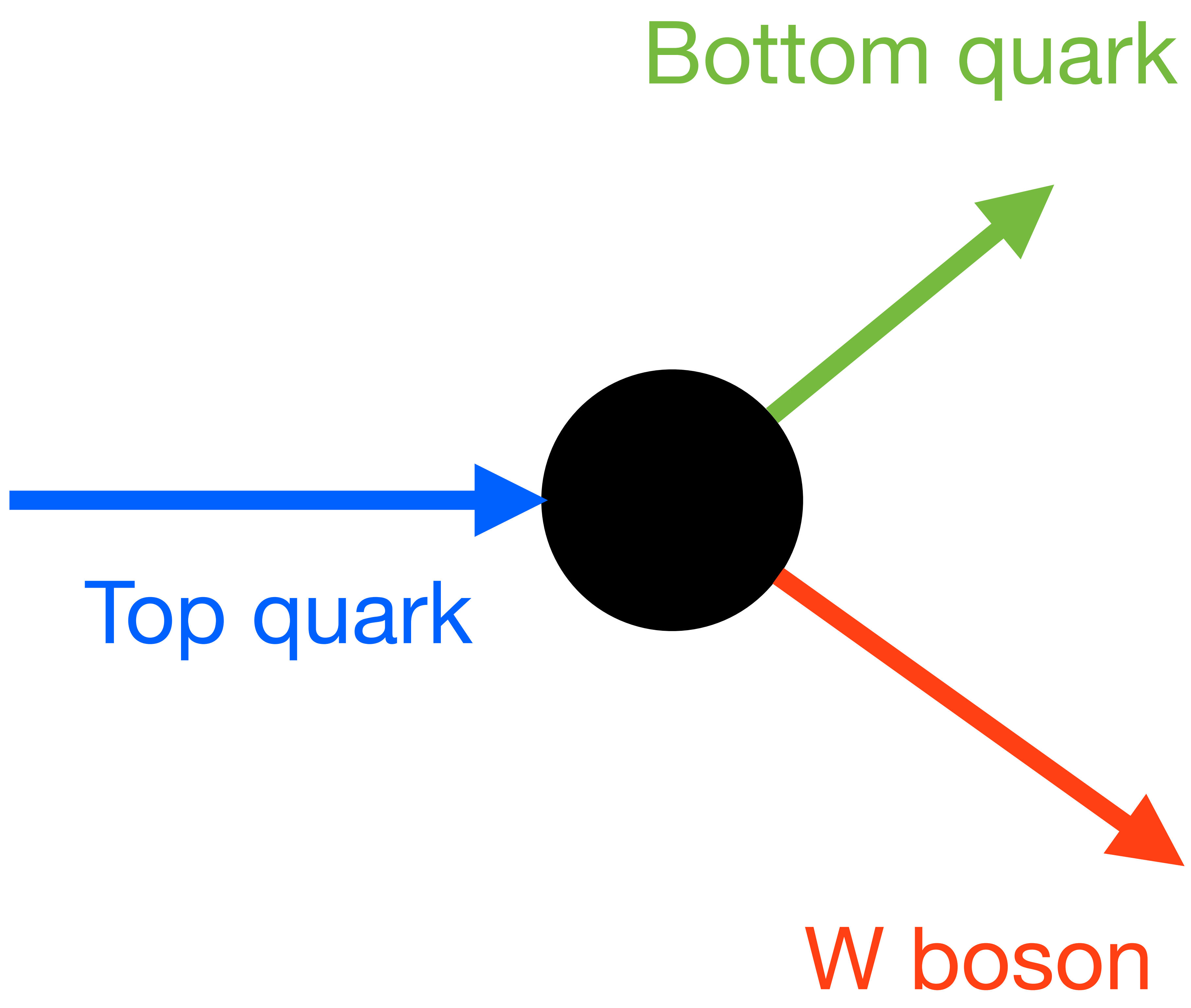
- Candidate particle: top quark
  - 2-body decay: $t \to bW^+$, $\bar{t} \to \bar{b}W^-$
  - Top quarks produced unpolarized in $t\bar{t}$ events at LHC
  - *W* mass measured independently
- Include nonzero m_b for energy of *b* in A's rest frame:

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



Obtaining *b* quark energy distribution

- Use *b*-jet energy as a proxy for *b* quark energy
- Extract peak of energy distribution from a fit
- Fit *b*-jet energy distribution to quasi-model-independent ansatz $f(x)$, $x = E/E^*$
  1. $f(x) = f(1/x)$ log-symmetric
  2. $f(x)$ maximized at $x = 1$
  3. $f(0) = f(\infty) = 0$
  4. $f(x) \to \delta(x)$ in some limit

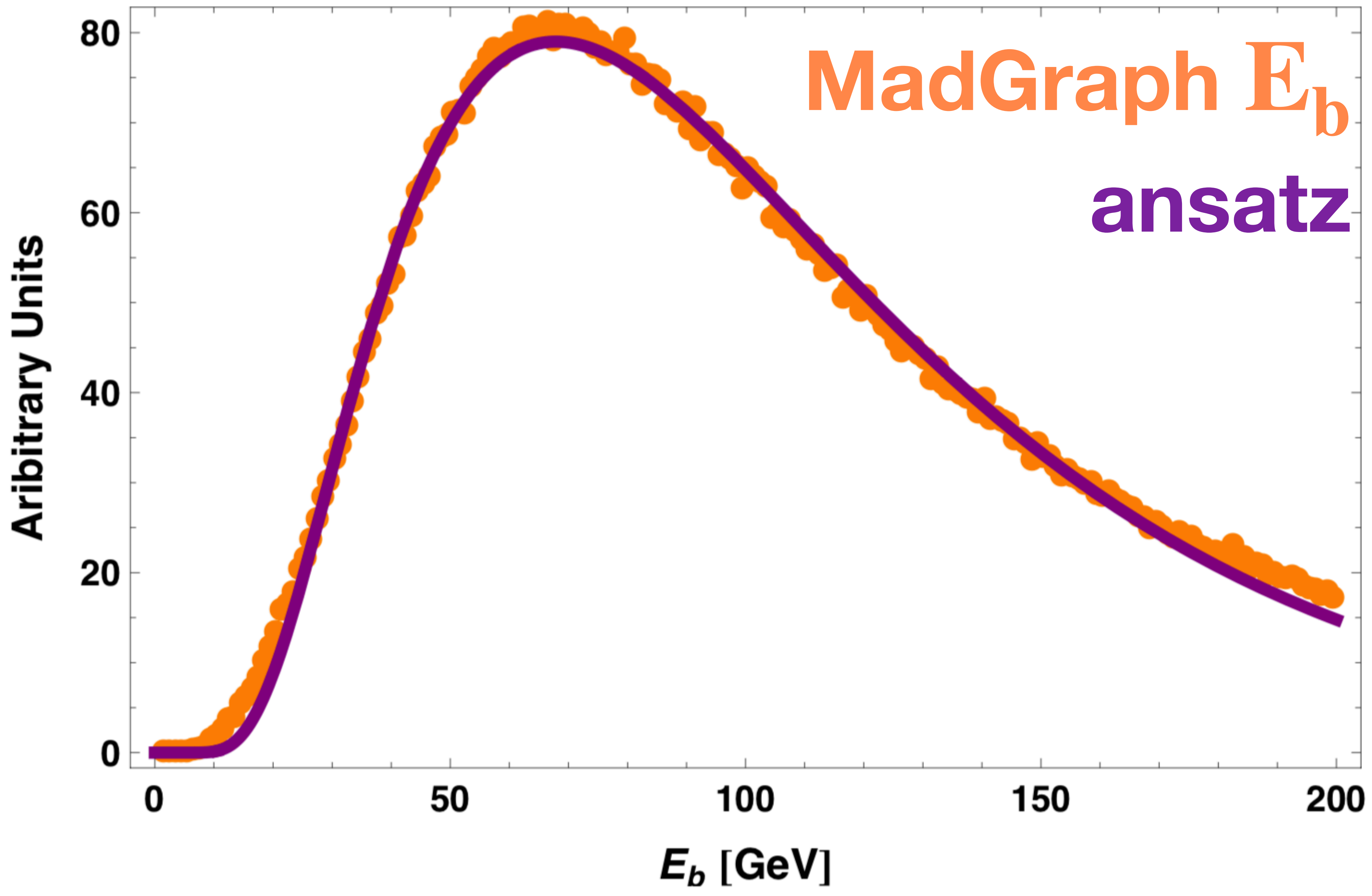


Fitting *b*-jet energies to ansatz

- Proposed ansatz:

$$f(x) = \frac{1}{N(w)} \exp\left[-\frac{w}{2}\left(x + \frac{1}{x}\right)\right]$$

- w parameter encodes width of distribution
- $x = \frac{E}{E^*}$, E^* is a fit parameter

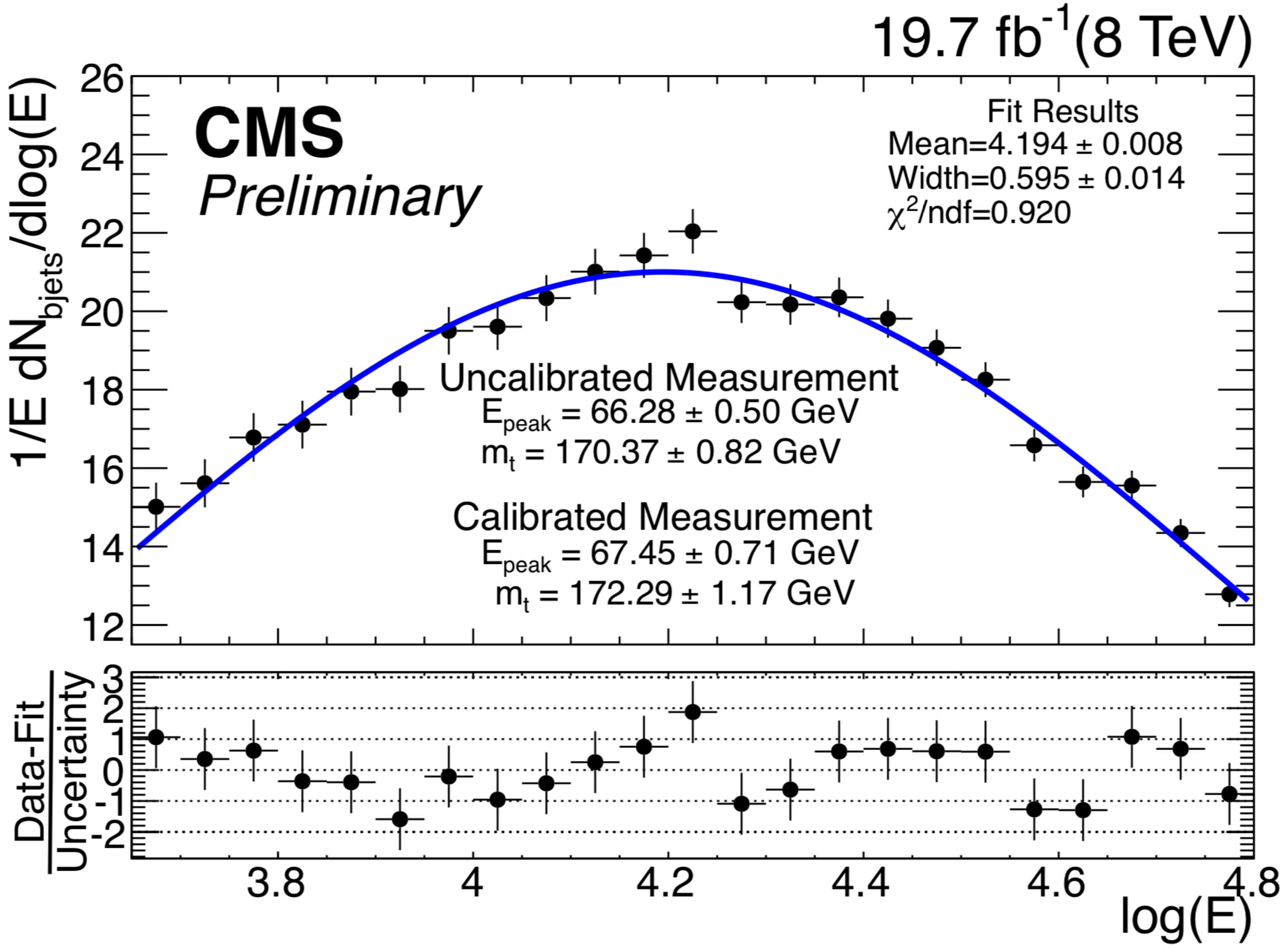


arXiv:1209.0772
Agashe, Franceschini, Kim

Snowmass White Paper: arXiv:2204.02928
Agashe et al.

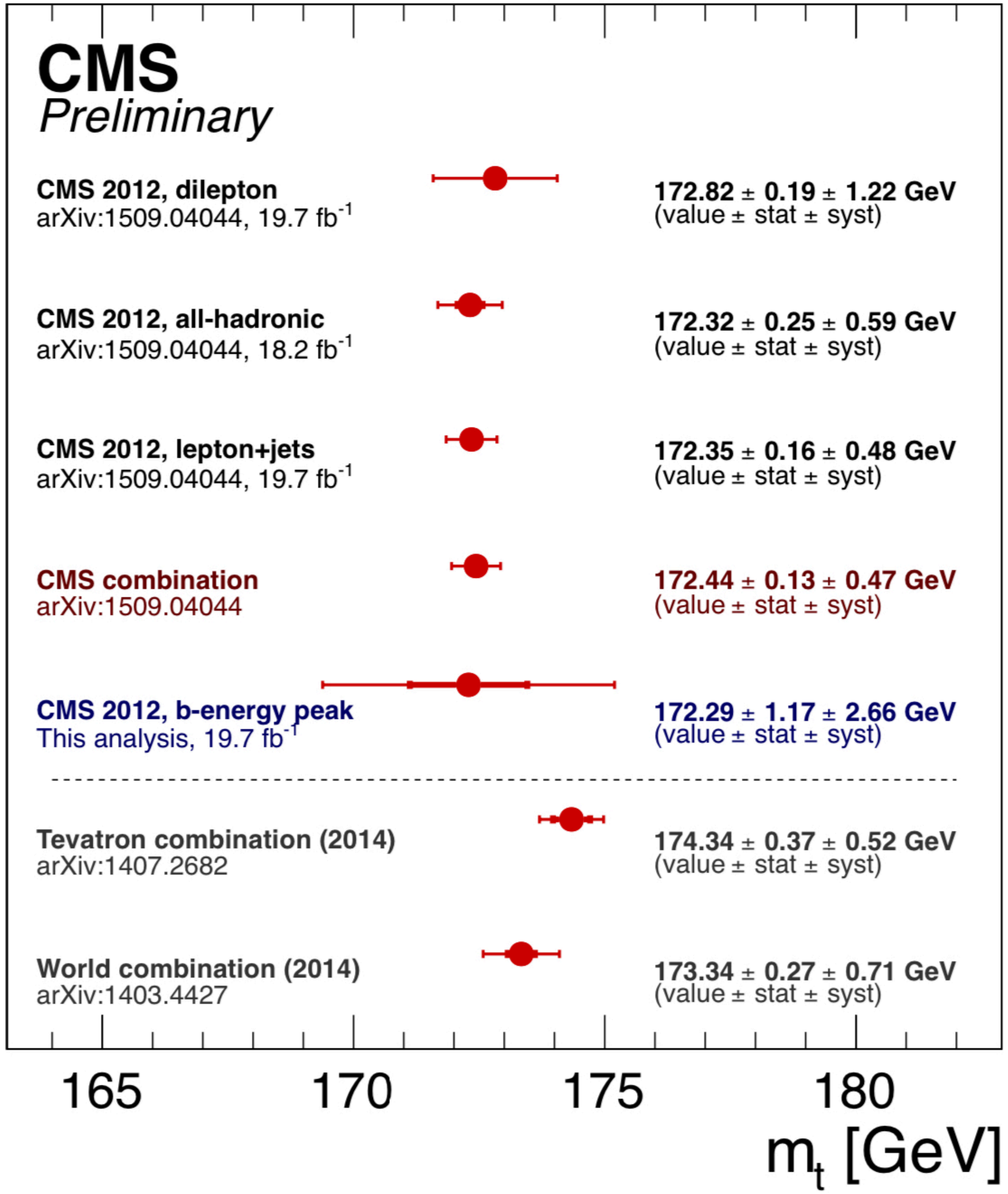
Extracting top quark mass

- CMS implemented energy peak method CMS PAS TOP-15-002
- Used a log-symmetric Gaussian ansatz consistent with conditions on $f(x)$ to fit data
- Measure E_{peak}, then use it to measure m_t



Extracting top quark mass

- CMS implemented energy peak method [CMS PAS TOP-15-002]
- Measured m_t consistent with other methods
- Large source of uncertainty is Jet Energy Scale (JES)



Proposing our method

- Bypass JES uncertainty
  - Extract m_t via *B*-hadron decay lengths
  - CMS implemented this but assumed SM production (CMS PAS TOP-12-030)
- Model-independent measurement
  - Use *B*-hadron decay lengths → combine with energy peak idea

How to extract energy from *B*-hadron decay lengths

- Extract m_t from *B*-hadron decay length
  - $L_B \rightarrow \tau_B^{lab}$ mean decay lifetime via decay exponential
  - $\tau_B^{lab} \rightarrow \tau_B^{rest}$ via $\gamma_B = E_B/m_B$ gives E_B
  - $E_B \rightarrow E_b$ via hadronization model
  - $E_b \rightarrow m_t$ via two methods
    1. SM-dependent calculation (CMS)
    2. Model-independent method: energy peak $E_b^* = \dfrac{m_t^2 - m_W^2 + m_b^2}{2m_t}$

How to extract energy from *B*-hadron decay lengths

$$G(L_B) = \int dE_B \int dE_b \; f(E_b) \; D\left(\frac{E_B}{E_b}; E_b\right) \frac{m_B}{c\tau_B^{rest} E_B} \exp\left(-\frac{L_B m_B}{c\tau_B^{rest} E_B}\right)$$

- $G(L_B)$ is PDF of *B*-hadron decay length
- $f(E_b)$ is PDF of *b* quark energy
- $D\left(\frac{E_B}{E_b}; E_b\right)$ is *b* quark fragmentation function
- τ_B^{rest} is mean decay lifetime of *B*-hadron in its rest frame

How our method works

- Energy peak idea:

$$G^{fit}(L_B) = \int dE_B \int dE_b \, \frac{1}{N(w)} \, \exp\left[-w\left(\frac{E_b}{E_b^*} + \frac{E_b^*}{E_b} \right) \right] D\left(\frac{E_B}{E_b}; E_b \right) \frac{m_B}{c\tau_B^{rest} E_B} \exp\left(-\frac{L_B m_B}{c\tau_B^{rest} E_B} \right)$$

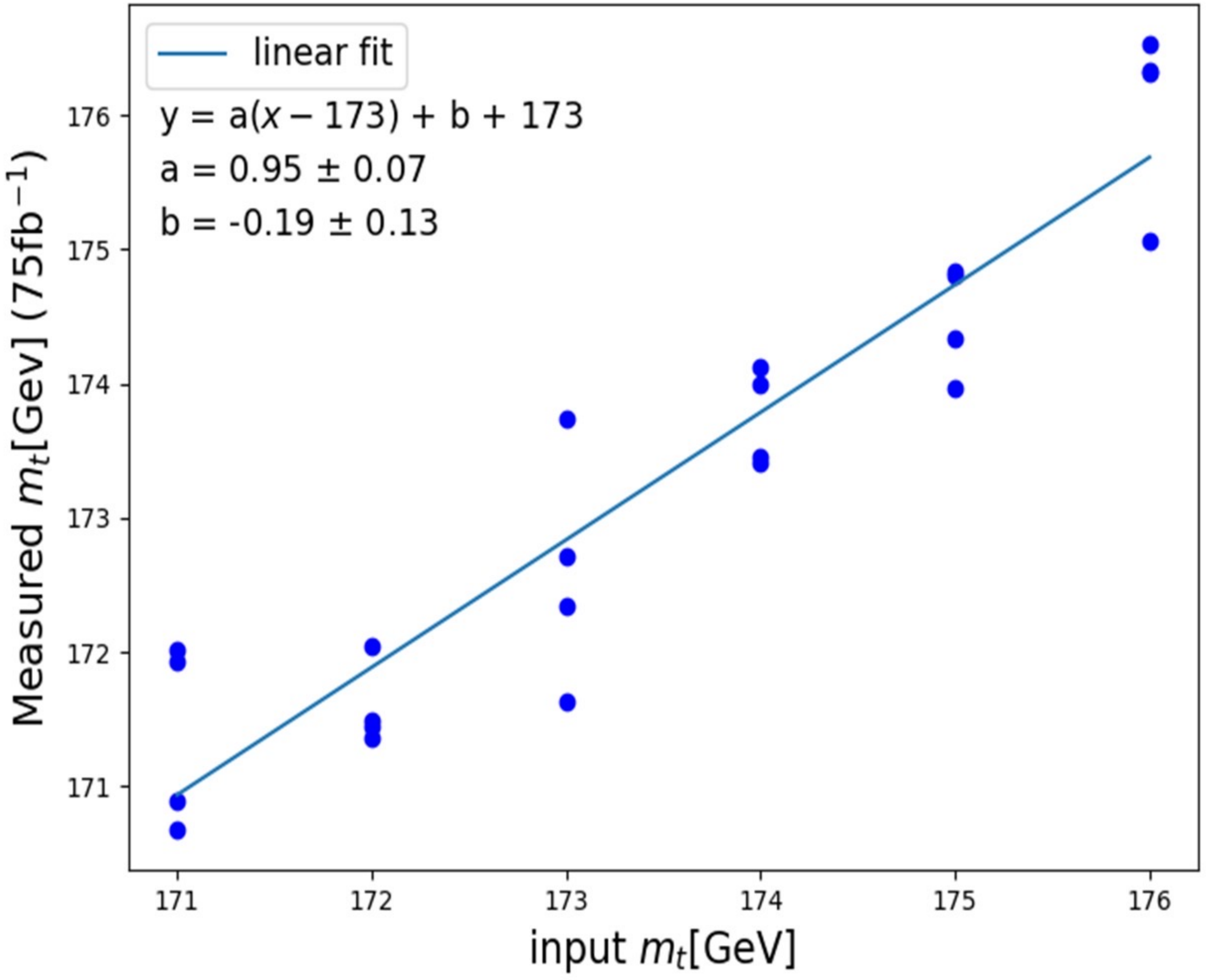
  - Doesn't assume SM production unlike previous implementation
  - Extract m_t via E_b^*, obtained by fitting decay length data to $G^{fit}(L_B)$

Testing our method

- Generate $pp \rightarrow t\bar{t}$ events in MadGraph5
  - Select events with dileptonic or semi-leptonic decay of W bosons
  - Impose cuts on jets, leptons to identify $t\bar{t}$ events
- Simulate parton hadronization and showering via Pythia8
  - Extract B-hadron decay lengths
  - Fit decay lengths to $G^{fit}(L_B)$

Results

- Use different input top quark masses from 171 GeV to 176 GeV
- Measure m_t for each input
  - Average bias in measurement: 200 MeV ± 130 MeV
  - Statistical uncertainty ~ 650 MeV for $75\ fb^{-1}$
- Comparison to SM-dependent measurement using $\langle L_{xy} \rangle$ by CMS shown in Part II by Sagar Airen



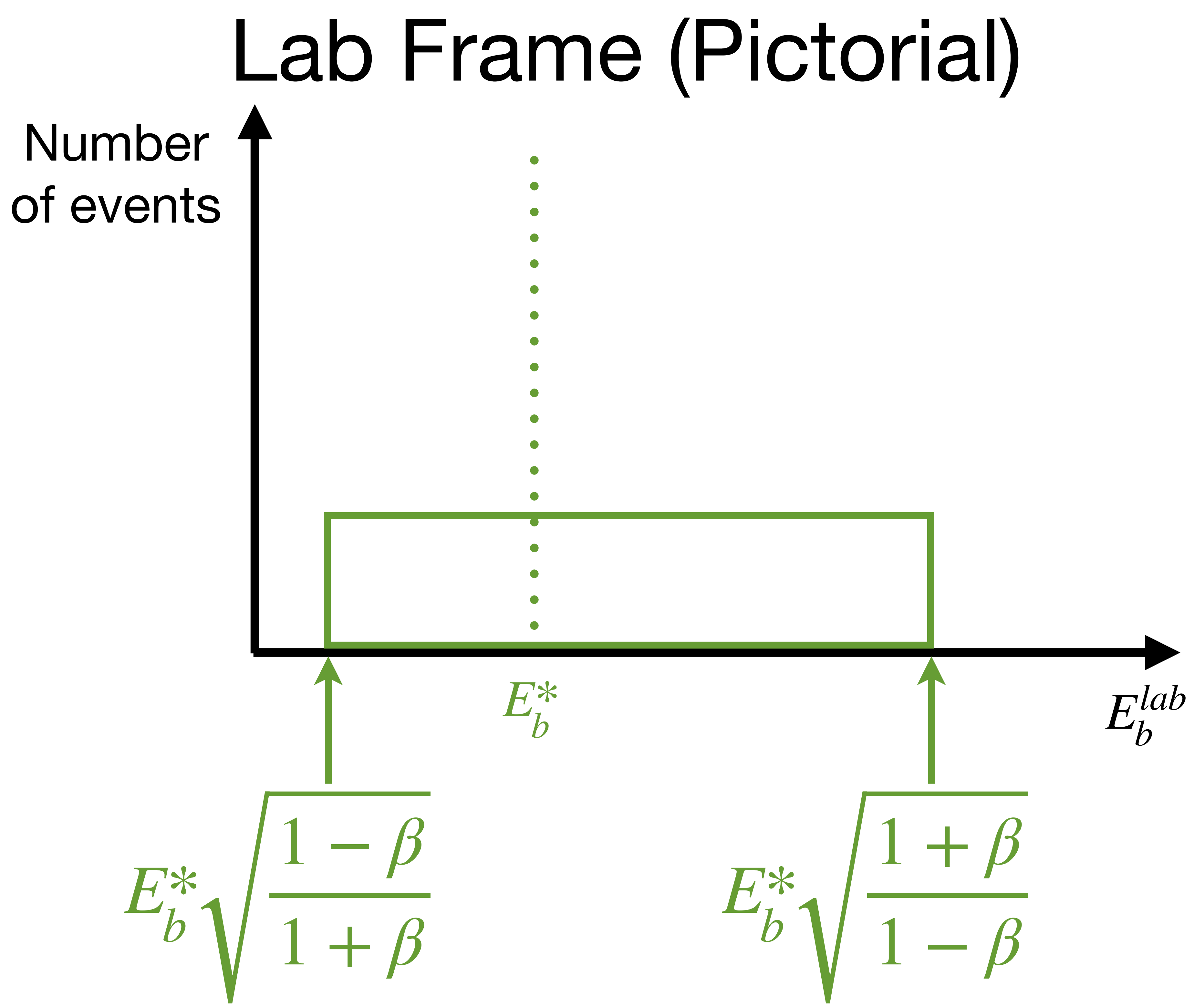
Summary and Outlook

- Can measure mass of parent particle in 2-body decay $A \to bC$ via peak of energy distribution of *b* and mass of *C*
  - Parent *A* must be produced unpolarized
- Top quark at LHC is perfect candidate to implement this method
- Initial implementation used *b*-jet energy as proxy for *b* quark energy
  - Suffers from JES uncertainty
- Extract energy peak from *B*-hadron decay lengths
  - Measured mass consistent with input mass using MC data from MadGraph5 and Pythia8
- Implementation of double convolution fit and comparison to SM-dependent measurement shown by my collaborator, Sagar Airen

Backup Slides

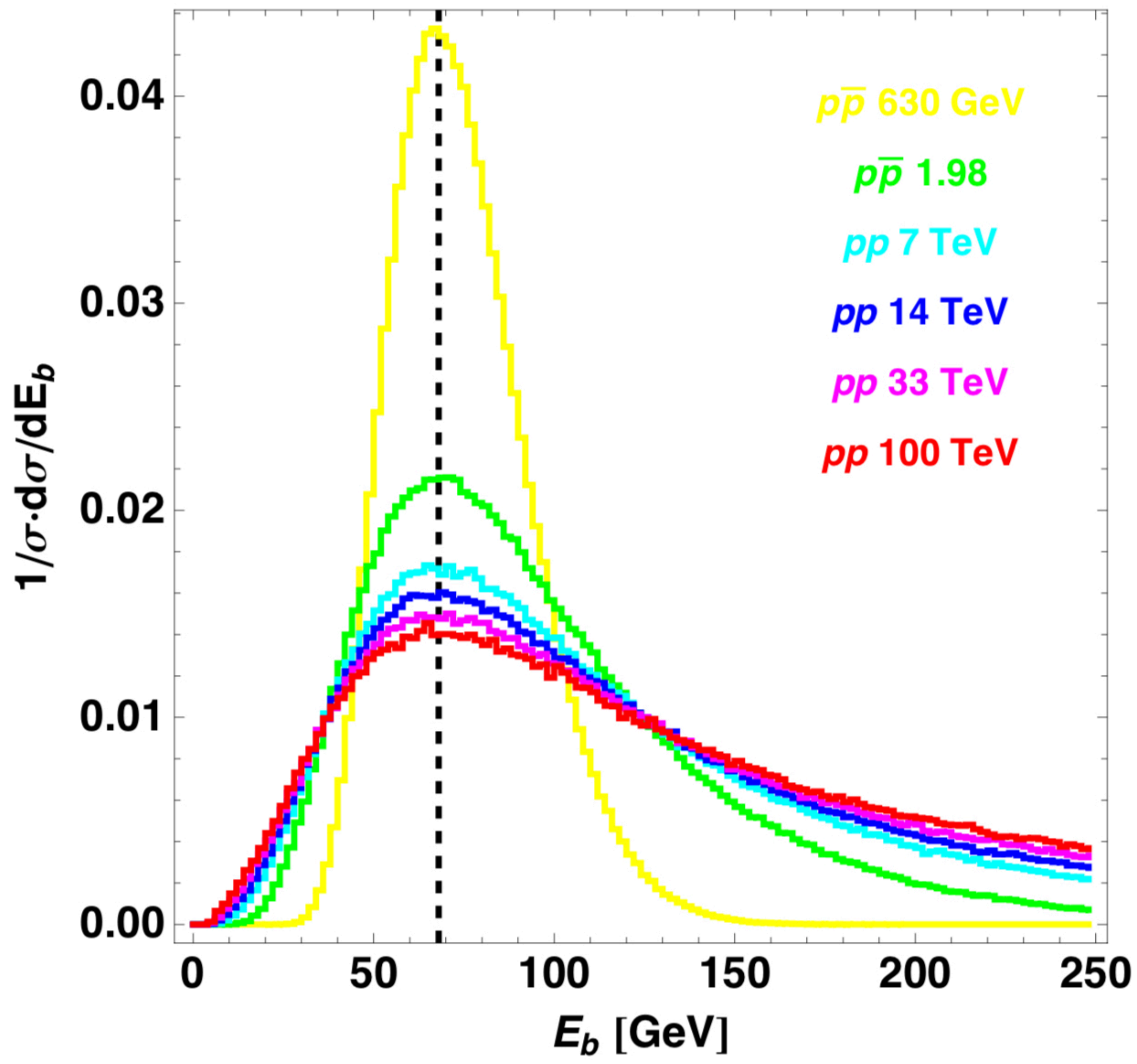
Why is energy peak equal to rest energy?

- One can show that for $E_b^{lab} = E_b^{*}\gamma(1 + \beta\cos\theta^{*})$, the energy range (rectangle) for a given β has the following properties:
  - Contains E_b^{*}
  - Log-symmetric about E_b^{*}
  - No other E_b^{lab} is contained within every rectangle ($\beta \to 0$)
  - No other E_b^{lab} gets larger contribution for given β

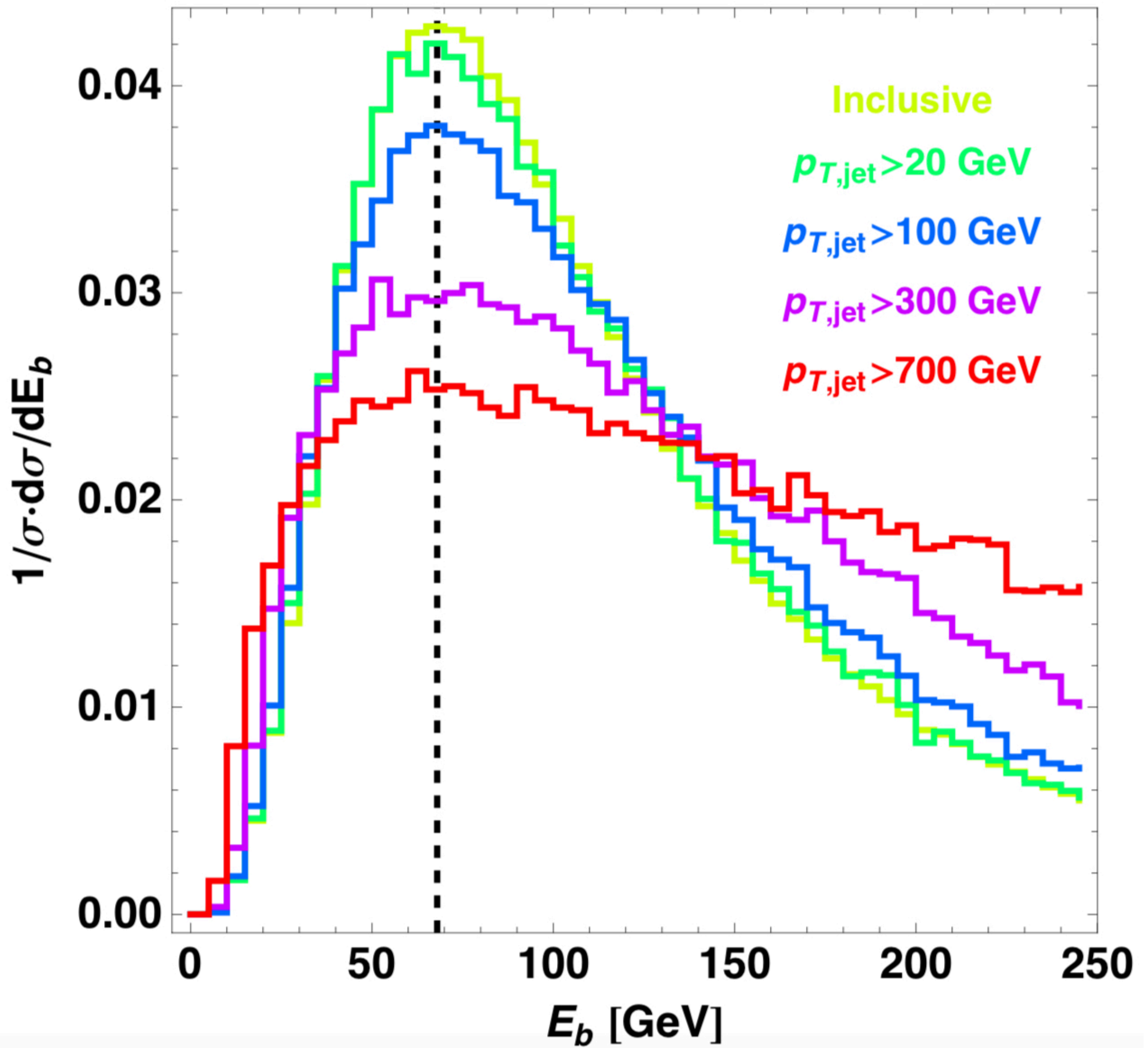


Plots showing invariance of b quark energy peak

- Varying collider energy



- Varying ISR p_T



CMS measurement uncertainties using *b*-jet energy

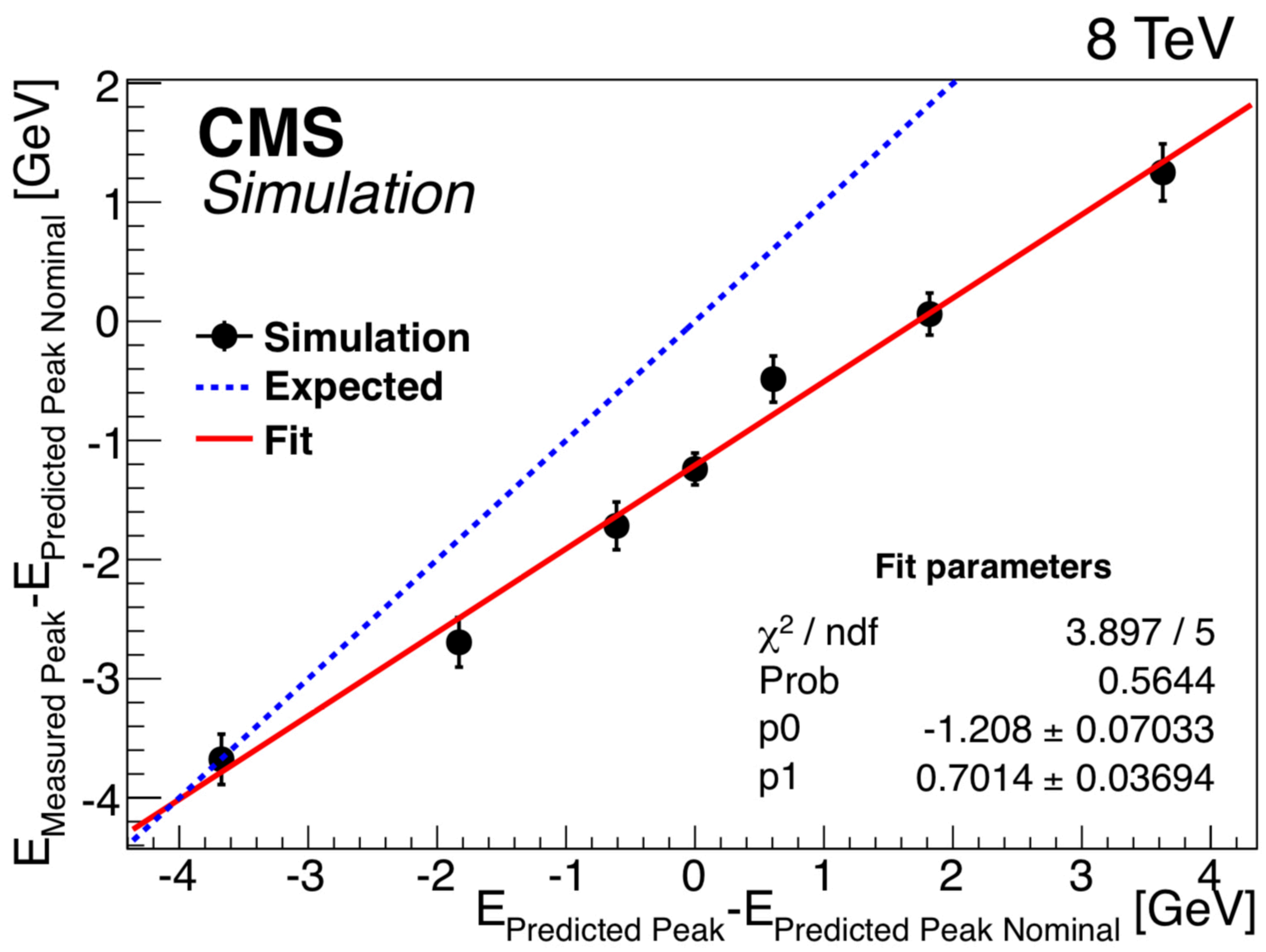
- Largest sources of uncertainty:
  - Generator modeling of scattering
  - Top p_T reweighting
  - JES

Source of uncertainty	δE_{peak} (GeV)	δm_t (GeV)
Experimental uncertainties		
Jet energy scale	0.74	1.23
b jet energy scale	0.13	0.22
Jet energy resolution	0.18	0.30
Pile-up	0.02	0.03
b-tagging efficiency	0.12	0.20
Lepton efficiency	0.02	0.03
Fit calibration	0.14	0.24
Backgrounds	0.21	0.34
Modeling of hard scattering process		
Generator modeling	0.91	1.50
Renormalization and factorization scales	0.13	0.22
ME-PS matching threshold	0.24	0.39
Top p_T reweighting	0.91	1.50
PDFs	0.13	0.22
Modeling of non-perturbative QCD		
Underlying event	0.22	0.35
Color reconnection	0.38	0.62
Total	1.62	2.66

- CMS PAS TOP-15-002

CMS calibration using *b*-jet energy

- Blue line is expected result (slope of 1)
- Calibrate fit of simulation to expected result
- Bias effects
  1. Selection cuts
  2. Reconstruction effects
  3. Purity (misidentified *b*-jets and background)
- CMS PAS TOP-15-002



(a) Calibration