(Towards a) Production Model-Independent Top Mass Measurement Using B-hadron Decay Length

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[(very) preliminary work with R. Franceschini, J. Incandela, D. Kim, M. Schulze: parts of talk is my personal opinion only!]

Outline

- Why another method for top quark mass measurement?!

- Review of bottom quark/b-jet energy-peak for top quark mass: (quasi-)production model-independent (done by CMS: improvement using 13 TeV, NLO…)

- B-hadron decay length: "proxy" for bottom quark energy trade-off: avoid jet energy scale (JES) uncertainty of above, but bring-in hadronization model/fragmentation function (done by CDF/CMS, but assuming SM production)

- Combining above two: new (quasi-)model-independent and JES uncertainty-free ("best of both worlds"!) proposal for measuring top quark mass using B-hadron decay length… …but still subject to hadronization model/fragmentation (theory improvement possible?)

Motivation for new methods for top quark mass measurement

(skip review of why top quark mass is crucial parameter of SM and Beyond)

Systematics (statistics not an issue at LHC?!)

Theoretical

- uncertainties about top quark (pair) production: Beyond SM (BSM) contribution (e.g. light stop decaying into top: see 1407.1043; 1909.09670); PDF's, higher-order effects (even in SM); hadronization of bottom quark

Experimental

- JES uncertainty for b-jet vs. using ("cleaner"?) leptonic measurements

- each method insensitive to some systematics, but affected by others

Bottomline

- In my opinion, no "slam dunk" top quark measurement method!

→ motivates new ideas, especially

- independent of details/modeling of production [based on kinematics of (only) decay, thus avoid theory systematics] and/or

- insensitive to some experimental systematics (complementarity)

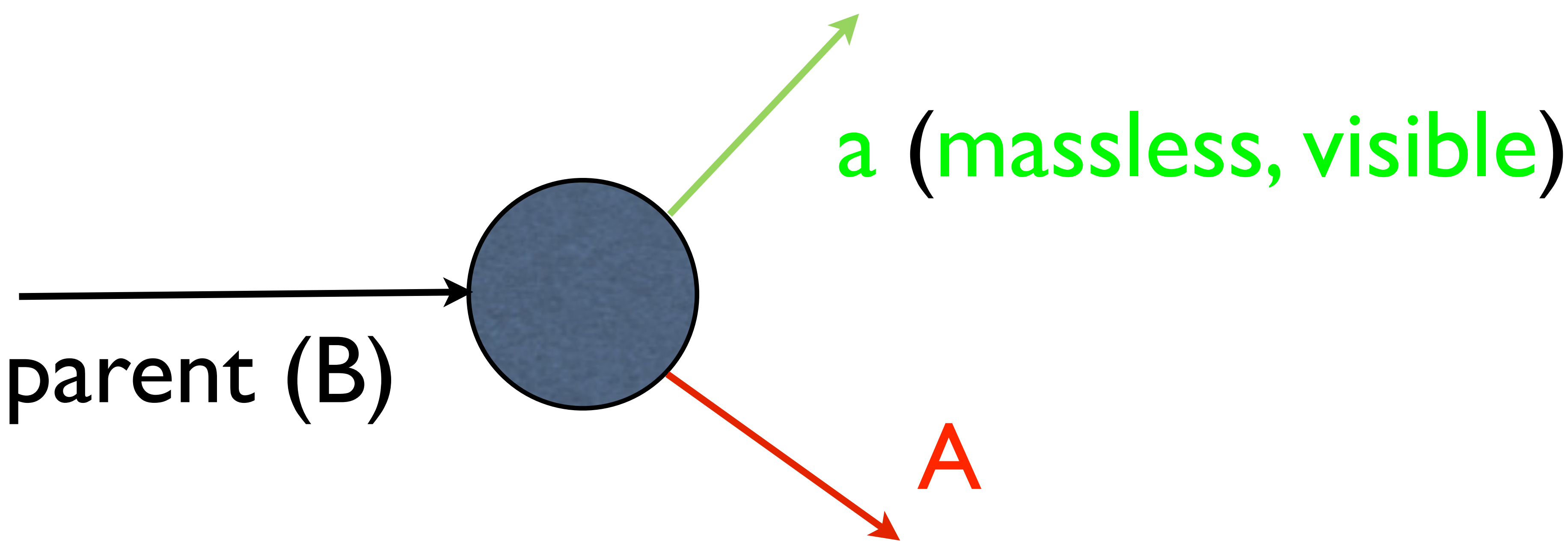
Review of energy-peak:
general

[(quasi-)decay kinematics-based]

NEW OBSERVATION/``INVARIANCE"

Basic set-up/assumptions

- 2-body decay: one child particle visible, massless:



- ...other (A) don't "care" (except for its mass): no need to reconstruct it!
- unpolarized parent (all spin orientations equal) ➡ "quasi" (production) model-independent

Energy of child particle

- mono-chromatic and simple function of masses in rest frame of parent:

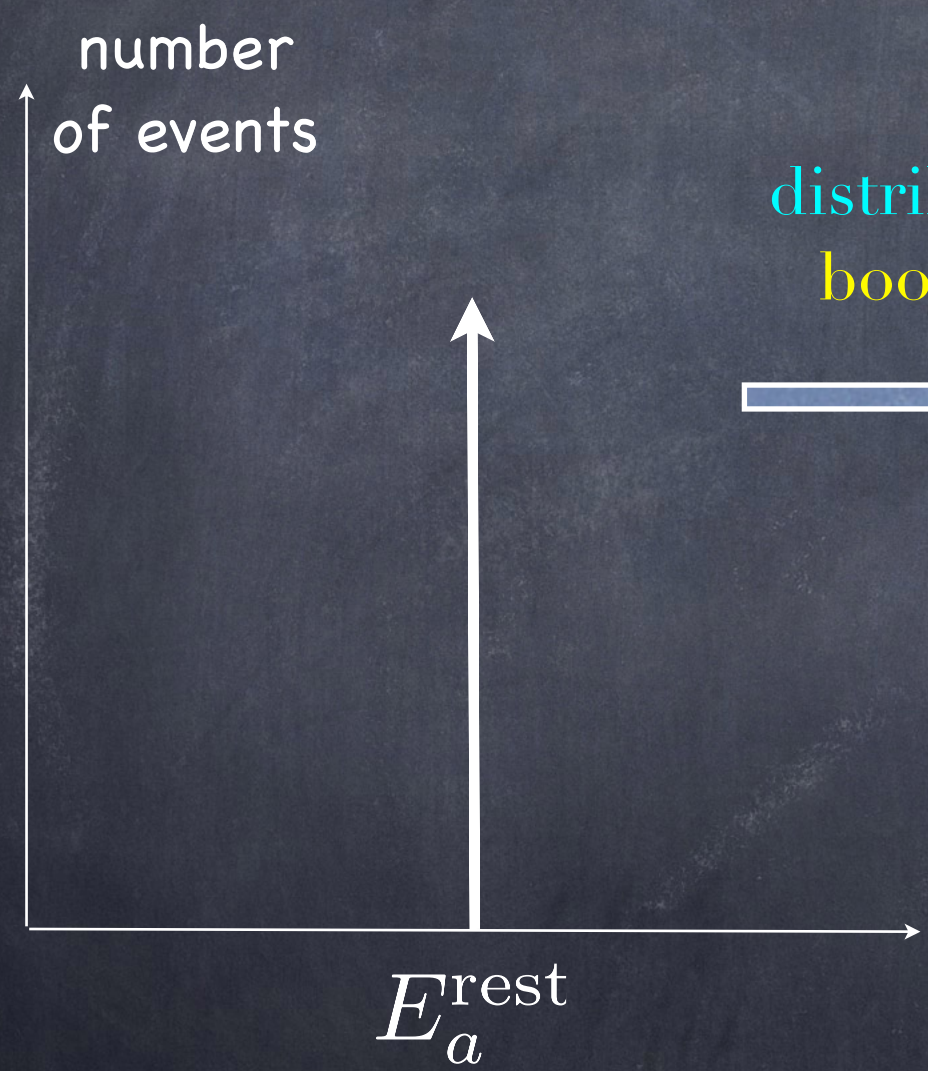
$$E_a^{\text{rest}} = \frac{M_B^2 - M_A^2}{2M_B}$$

- determine M_B if M_A known and E_a^{rest} measured

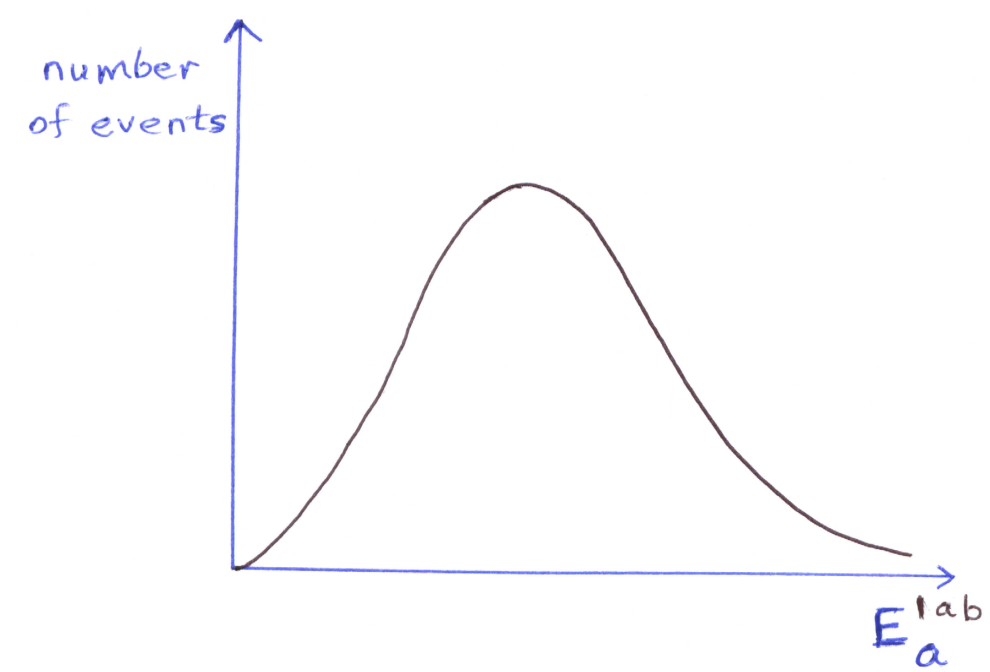
...but not Lorentz (parent boost)-invariant

…too simple to be practical/useful?!

- hadron collider: parent has unknown boost; varies event to event $\Longrightarrow$ distribution in E_a^{lab}



distribution of boosts of B $\Longrightarrow$



- "lose" rest-frame information??!!

"Conservation" of invariance!

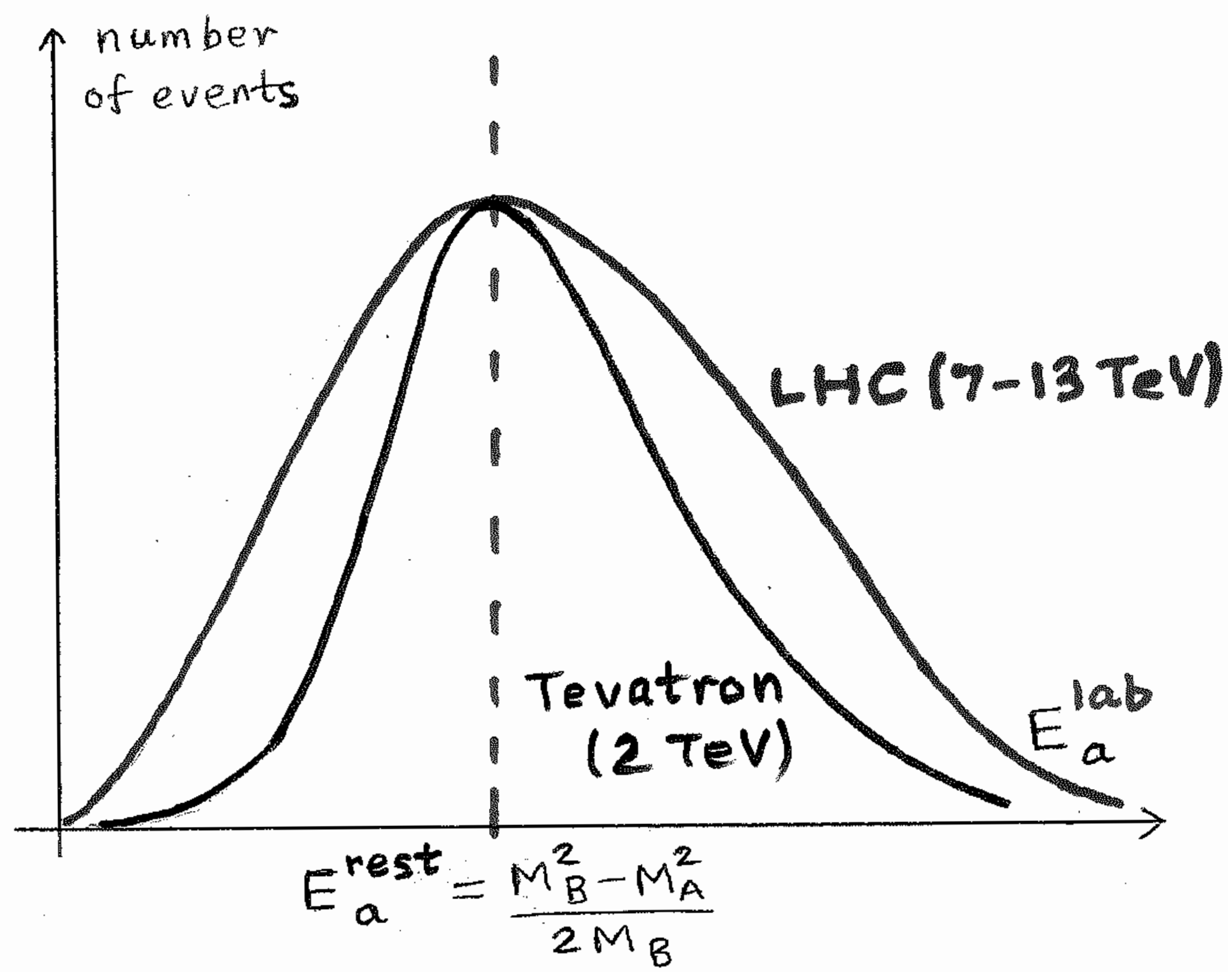
- Show analytically (in 3 back-up slides!): peak (of lab. distribution) still retains this information... simply, precisely, robustly!

independent of boosts of parent, hence production details

- Distribution of log of energy is symmetric about peak

(KA, Franceschini, Kim: 1209.0772)

(see also Stecker: "Cosmic gamma rays")



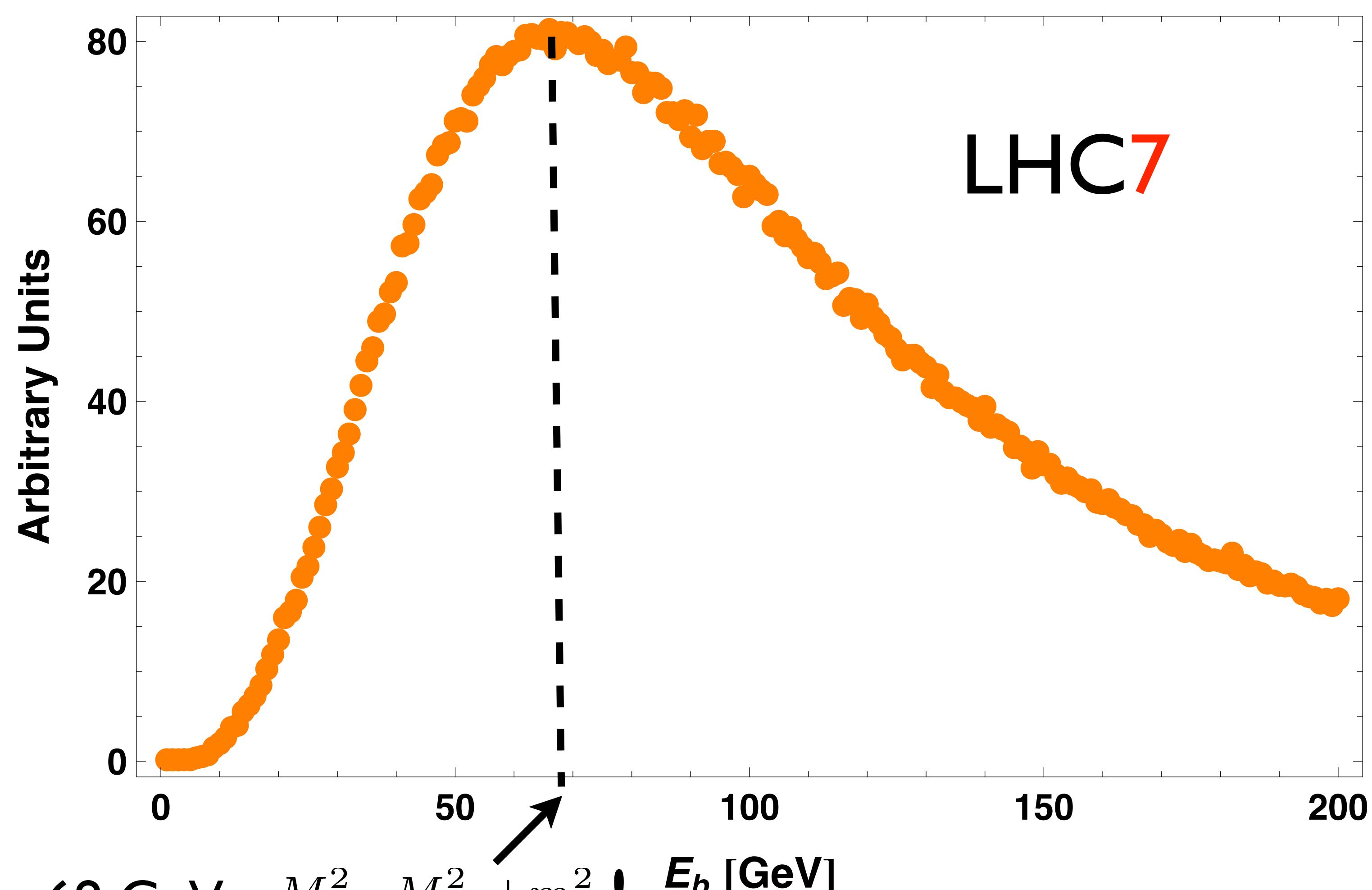
Analytical result (in 3 back-up slides!) ➡ no need really to check via full calculation/simulation, but anyway…

- (“massless”) bottom (parton-level) from 2-body top quark decay (production unpolarized) as example of general result:

bottom mass non-zero, but negligible ➡ peak of energy distribution in lab frame is not expected to shift from single value in top quark rest frame:

$$E_b^{\text{rest}} = \frac{M_t^2 - M_W^2 + m_b^2}{2M_t}$$

modified vs. massless

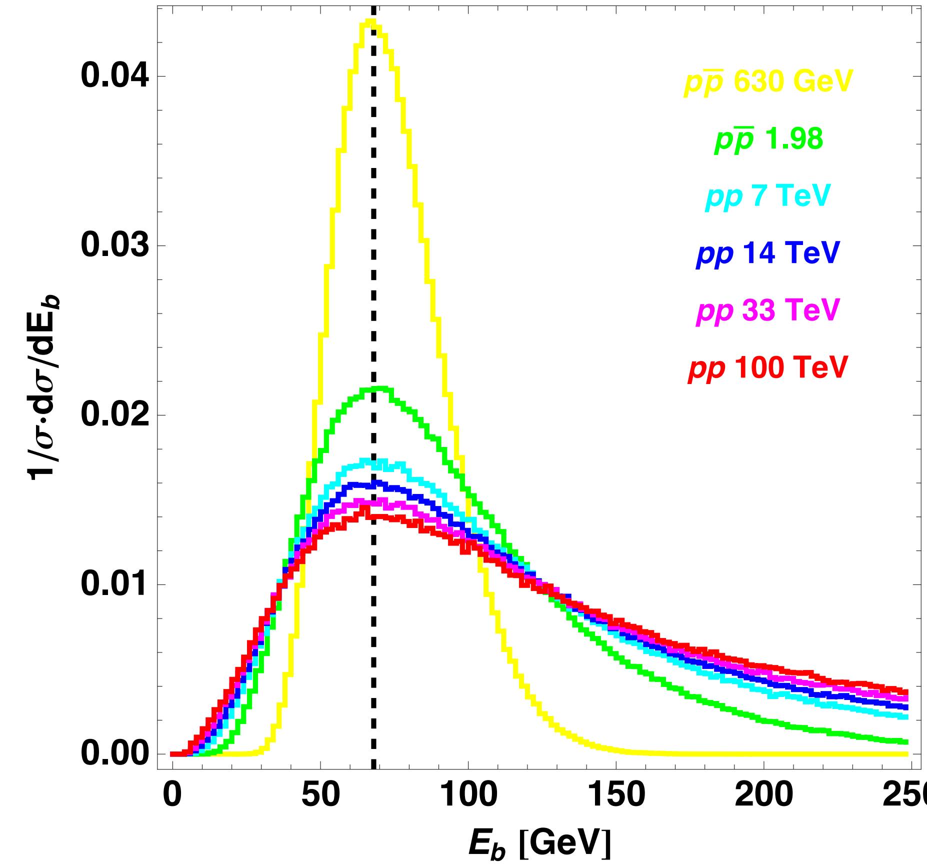


68 GeV $= \frac{M_t^2 - M_W^2 + m_b^2}{2M_t}$!

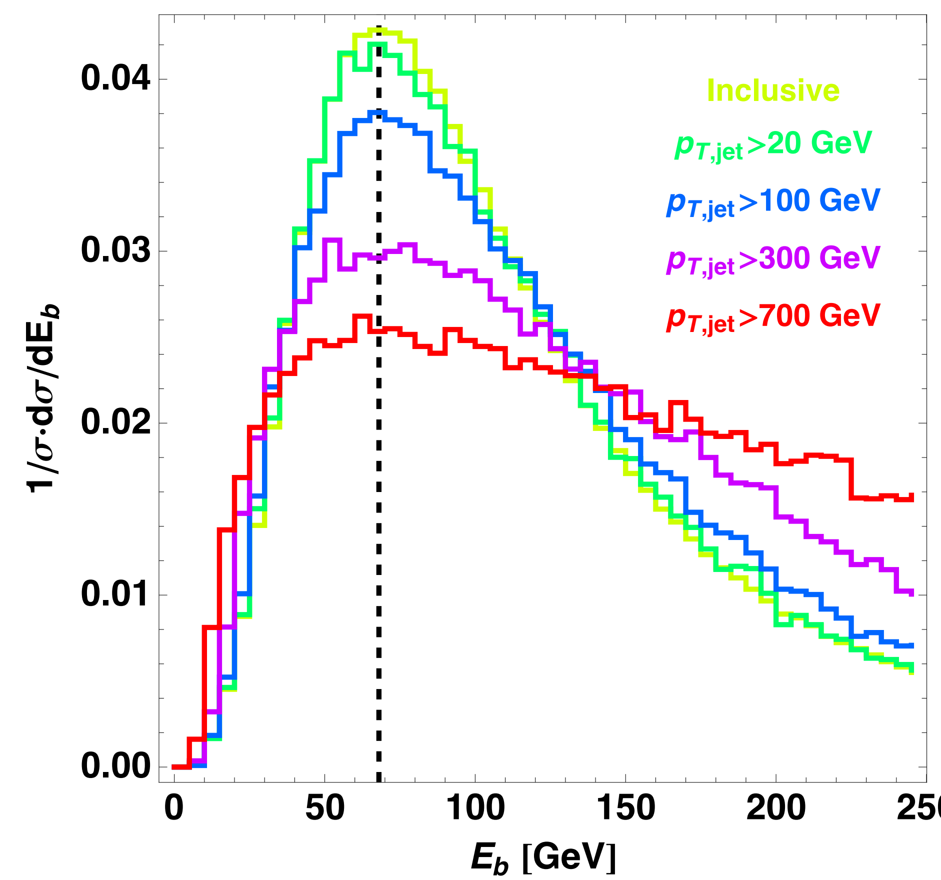
- …maybe an “accident” of specific boost distribution (production model) of top quark?!

``Invariant'' (under boost distributions) feature in non-invariant (energy) distribution: subtle!

- vary collider energy

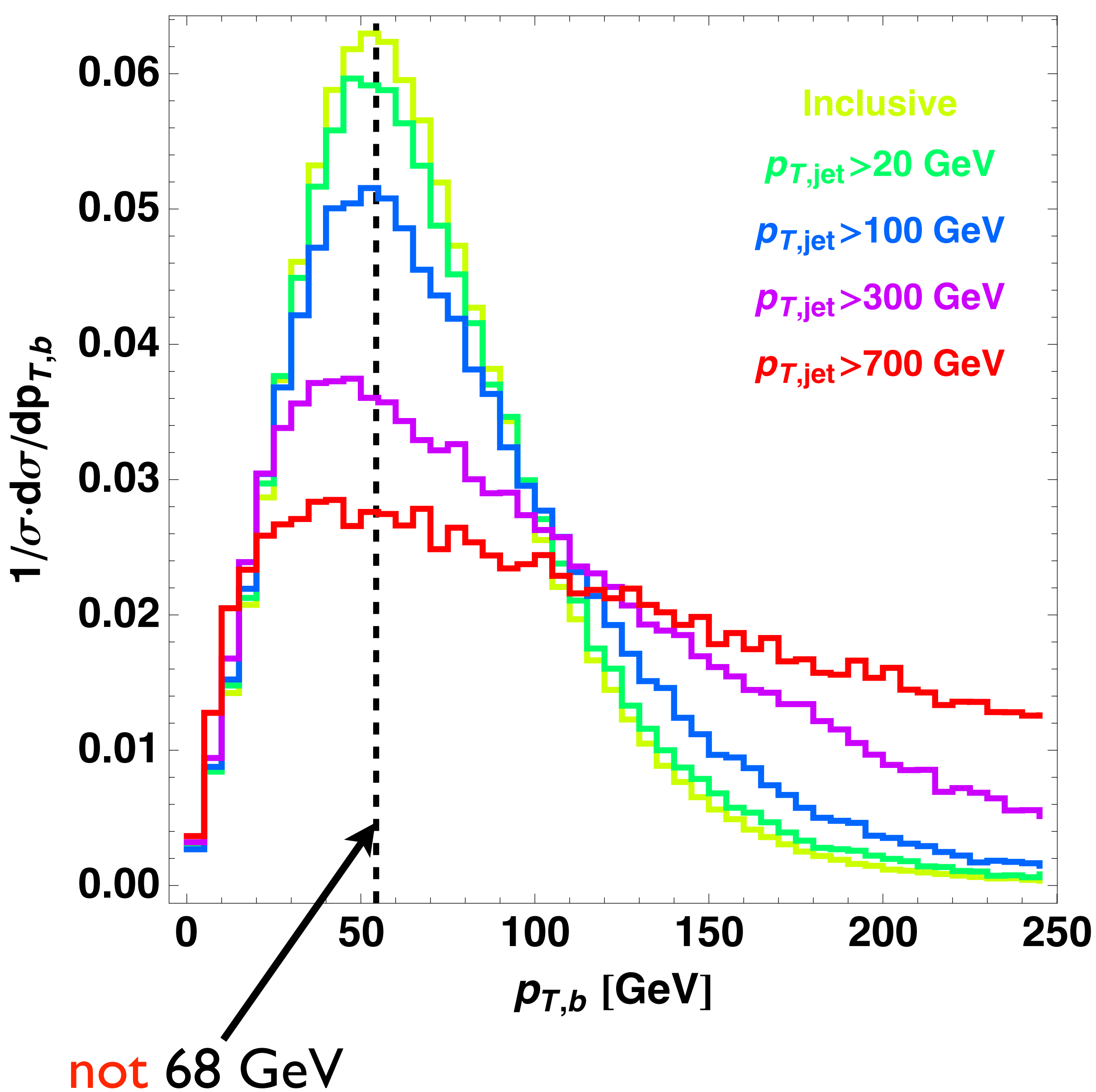


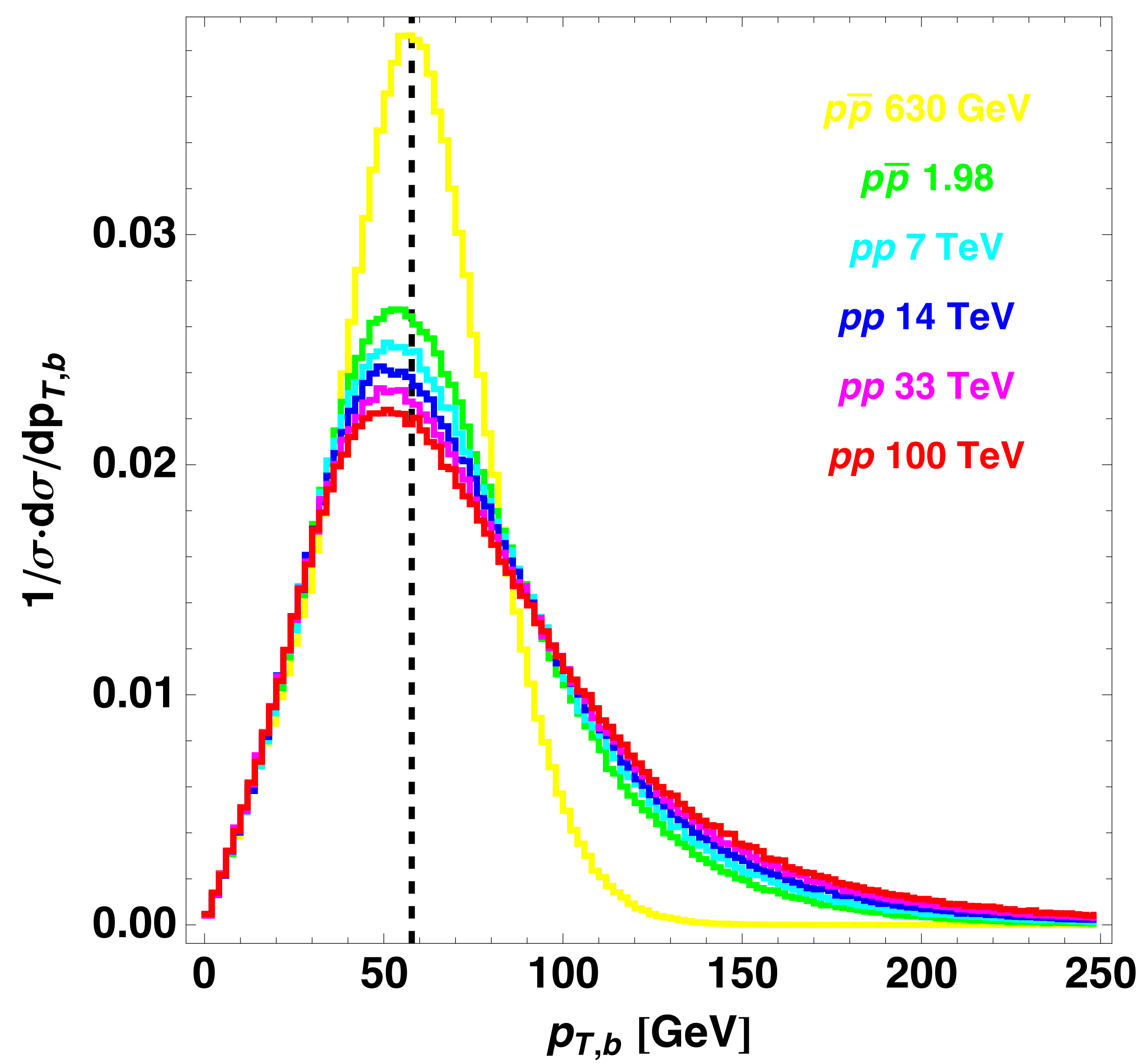
- vary ISR



- ...but, peak stays put, even though shape changes (broadens for more boosted top)

...accidents don’t happen: no such invariance for p_T!





- peak (and shape) change...

....

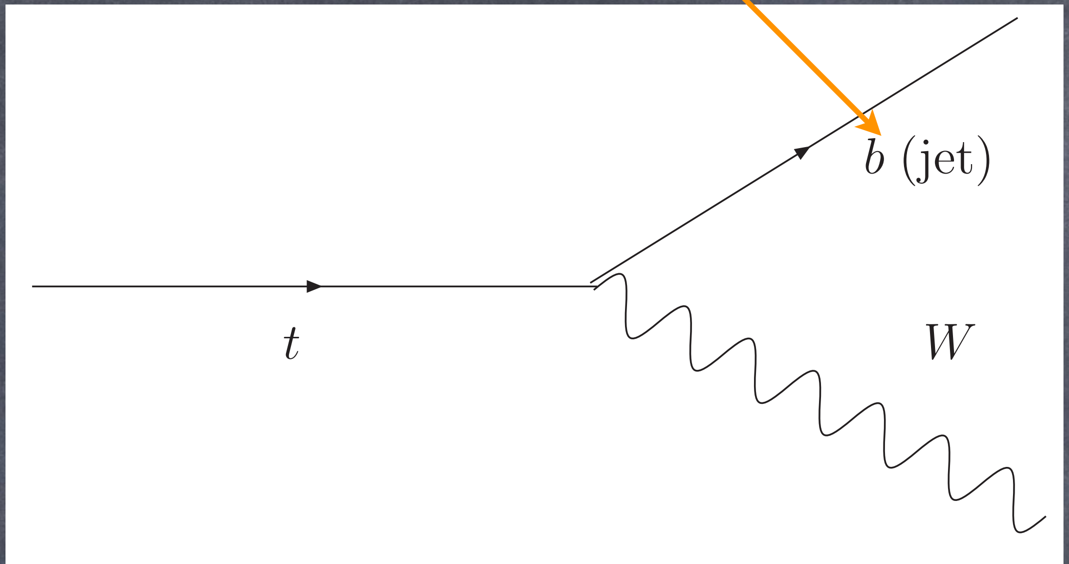
TECHNIQUE/APPLICATION

Review of energy-peak:for top quark decay

[mass measurement using (entire) b-jet;
main motivation: (quasi-)independent of production details]

Top quark mass

(almost) massless



- bottom quark energy (E_b) $\approx$ energy of b-*jet* (inclusive)

- Equate location of peak in measured b-jet energy distribution to $E_b^{\text{rest}} \left(= \frac{M_t^2 - M_W^2 + m_b^2}{2\ M_t} \right)$:

$$E_{b\text{-jet}}^{\text{lab,mode}} \quad = \quad \frac{m_t^2 - M_W^2 + m_b^2}{2\ m_t}$$

- Assuming M_W (but no need to reconstruct it!), get M_t

....we studied using simulated data, including effects of cuts, detector etc. but...

...cut to CMS (real data!)

- implementation on run 1 data in CMS PAS TOP-15-002:

$$m_t = 172.29 \pm 1.17\,(\text{stat.}) \pm 2.66\,(\text{syst.})\ \text{GeV}$$

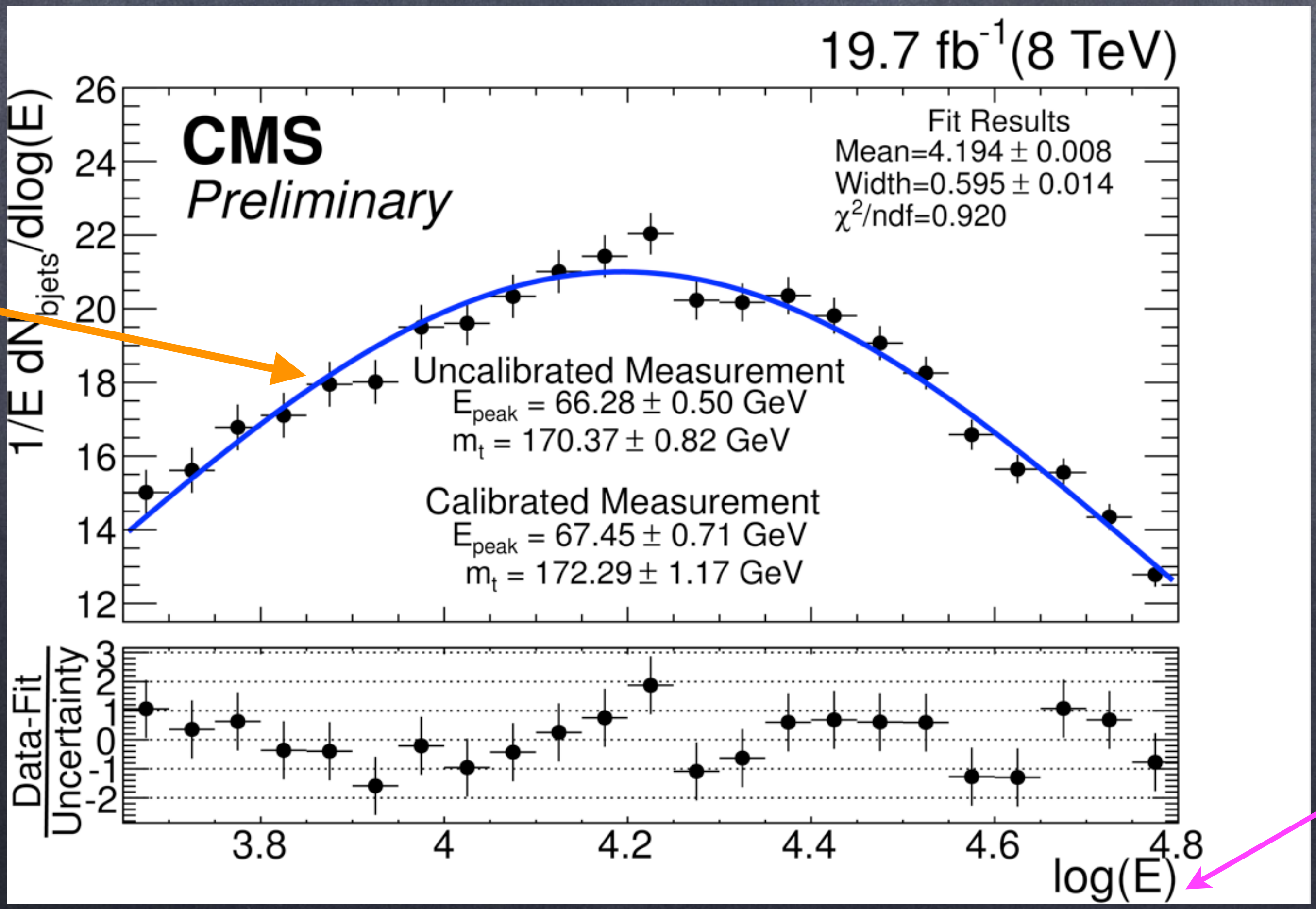
- Complementary to other methods (whose error $\sim$ 1 GeV)

- Sources of error: JES uncertainty; modeling of top p_T

use B-hadron decay length

higher-order (theory) calculation (KA, Franceschini, Kim, Schulze: 1603.03445; see also Ravasio, Jezo, Nason, Oleari: 1801.03944 and 1906.09166)

fitting function (see later)



note!

- Can 13 TeV (with NLO)...and/or ATLAS be far behind?!

Summary of b-jet energy-peak method for top quark mass measurement

advantage

- (quasi-)independent of top quark boost distribution/production details (only assumption: top quark unpolarized), cf. most other methods assume SM matrix element , e.g., compute distribution of decay product as function of m_t, find best fit to data:

$$\text{prediction } (m_t; \text{theory}) = \text{data, with theory} = \text{SM}$$

(others) valid only if BSM in top production is negligible

- even with SM (only) production, our method might have reduced sensitivity to PDF's, higher-order (QCD) effects (in production)

disadvantage

- (b-)JES uncertainty

Generalizations of energy-peak (a program!)

- Massive child particle from 2-body decay: peak shifts from rest-frame value (in general), but modified ansatz/fitting function still good (KA, Franceschini, Hong, Kim: 1512.02265)
- Direct three-body decay with 2 visible (e.g., off-shell sbottom in gluino decay): for fixed invariant mass of 2 visible, apply 2-body result for massive child particle (KA, Franceschini, Kim, Wardlow: 1503.03836)
- Cascade of 2-body decays: determine masses of 3 new particles [A (invisible), B and C] via (only) visible (a and b) measurements in decay chain $C \to B\, b \to A\, a\, b$ (e.g., gluino decay to on-shell bottom, then neutralino) (KA, Franceschini, Kim: 1309.4776)

Using energy-peak for searches

- if background is flat or peaks elsewhere from signal
- Stops (Low: 1304.0491):

for $\tilde{t} \to b\tilde{\chi}_1^+$, peak in E_b^{lab} at $\left(M_{\tilde{t}}^2 - M_{\tilde{\chi}_1^+}^2\right) / (2M_{\tilde{t}})$...
can be $\gg \left(M_t^2 - M_W^2\right) / (2M_t)$ from $t\bar{t}$ background (from SM or from $\tilde{t} \to t\tilde{\chi}_1^0$)

B-hadron decay length as "proxy" for bottom quark energy (instead of b-jet)

(motivation: avoid JES uncertainty)

(Very) Basic Idea (I)

(more details in 2 slides)

- going from (measured) B-hadron decay length (L_B) to bottom quark energy

$$L_B \xrightarrow{\text{decay exponential}} \tau_B^{\text{lab}}$$

$$\tau_B^{\text{lab}} \text{ vs. } \tau_B^{\text{rest}} \longrightarrow \gamma_B^{\text{lab}} \text{ or } E_B (\text{energy of } B\text{-hadron})$$

$$E_B \xrightarrow{\text{hadronization model}} E_b$$

(Very) Basic Idea (II)

Going from bottom quark energy to top quark mass:

- earlier implementation (Hill, Incandela, Lamb: hep-ex/0501043; CDF: hep-ex/0612061; CMS:PAS TOP-12-030): relate E_b (distribution) to m_t by assuming SM production:

$$E_b \xrightarrow{\text{SM production}} m_t$$

- new idea (in this talk): use above energy-peak result instead [(quasi-) model-independent]:

$$E_b \xrightarrow{\text{energy}-\text{peak}} m_t$$

Working it all out (in "reverse": still schematic/ theory version!): from E_b to E_B distribution…

- Hadronization ($b \to b\text{-jet} = B\text{-hadron} + X$): fixed E_b still gives distribution of E_B

- fragmentation function [$D(x; E_b)$]: probability for $\frac{E_B}{E_b}$ to be $\approx x$

$$\int dx \ D(x; E_b) = 1 \text{ for any (fixed) } E_b$$

- probability distribution function (pdf's) of two energies related by

$$\underbrace{F(E_B)}_{\text{pdf}} = \int dE_b \ \underbrace{f(E_b)}_{\text{pdf}} \ D\left(\frac{E_B}{E_b}; E_b\right)$$

- (recall) energy-peak result [information about $f(E_b)$]:

$$\text{location of maximum of } f(E_b) = E_b^{\text{rest}} \left(= \frac{m_t^2 - m_W^2 + m_b^2}{2m_t} \right)$$

...from E_B to mean decay lifetime/length

- Even for fixed E_B, (exponential) distribution of decay times with mean (going from B-hadron's rest to lab frame):

$$\begin{aligned} \tau_B^{\text{lab}} &= \gamma_B \tau_B^{\text{rest}} \\ &= \frac{E_B}{m_B} \tau_B^{\text{rest}} \end{aligned}$$

not of top quark!

velocity

- convert to mean decay length: $$\begin{aligned} \lambda_B &= c \gamma_B \beta_B \tau_B^{\text{rest}} \\ &= c \frac{E_B}{m_B} \sqrt{1 - \left(\frac{m_B}{E_B} \right)^2} \tau_B^{\text{rest}} . \end{aligned}$$

- B-hadron relativistic:

$$\lambda_B \approx c \frac{E_B}{m_B} \tau_B^{\text{rest}} \left[1 + \mathcal{O} \left(\left(\frac{m_B}{E_B} \right)^2 \right) \right] .$$

- pdf of mean decay length:

$$\begin{aligned} g(\lambda_B) &= \frac{F(E_B)}{\frac{d\lambda_B}{dE_B}} \\ &\approx F(E_B) \frac{m_B}{c \tau_B^{\text{rest}}} \end{aligned}$$

pdf

…finally (!) distributions of (measured) decay length (L_B) and E_b related

- use decay exponential to go from λ_B to L_B, then previous relations

$$
\begin{aligned}
G\left(L_B\right) &= \int d\lambda_B \left[\frac{g\left(\lambda_B^{\text{lab}}\right)}{\lambda_B}\right] \exp\left(-\frac{L_B}{\lambda_B^{\text{lab}}}\right) \\
&\approx \int dE_B \frac{F\left(E_B\right)}{E_B} \frac{m_B}{c\tau_B^{\text{rest}}} \exp\left(-\frac{L_B m_B}{c\tau_B^{\text{rest}} E_B}\right) \\
&= \int dE_B \int dE_b \; f\left(E_b\right) D\left(\frac{E_B}{E_b}; E_b\right) \frac{m_B}{c\tau_B^{\text{rest}} E_B} \exp\left(-\frac{L_B m_B}{c\tau_B^{\text{rest}} E_B}\right)
\end{aligned}
$$

pdf

B-hadron relativistic

m_t

(double convolution)

$$
\begin{aligned}
G\left(L_B\right) &\rightarrow \text{pdf of decay length of } B\text{-hadron, } L_B \\
f\left(E_b\right) &\rightarrow \text{pdf of energy of bottom quark, } E_b \\
D\left(\frac{E_B}{E_b}; E_b\right) &\rightarrow \text{bottom quark fragmentation function} \\
\tau_B^{\text{rest}} &\rightarrow \text{mean decay lifetime of } B\text{-hadron in its rest frame}
\end{aligned}
$$

Earlier (CDF/CMS) implementation (explicitly)

- pdf of E_b (f) computed using SM matrix element, with top quark mass as a parameter
- SM "fitting" function for decay length:

fitting function

observable (transverse)

model-dependence

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

(unknown) parameter

Our Proposal for B-hadron decay length (in detail)

(same starting point, but use energy-peak result instead of assuming SM production; main motivation: (quasi-)model-independent)

[uses full/3d decay length (cf. transverse in earlier CMS)]

General (new) idea

- Recall relation between L_B and E_b distributions:

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

new proposal: relate to m_t using energy-peak (instead of SM production)

- (twice) "de-convolve" (impossible?!) decay length distribution [$G(L_B)$] to obtain that of bottom quark [$f(E_b)$]

$$\text{location of peak of } f(E_b) \quad \rightarrow \quad \frac{m_t^2 - M_W^2 + m_b^2}{2\, m_t}$$

- Or, energy-peak result [+ log symmetry of $f(E_b)$] materializes as "some" robust feature in $G(L_B)$?!

More practically/realistically:

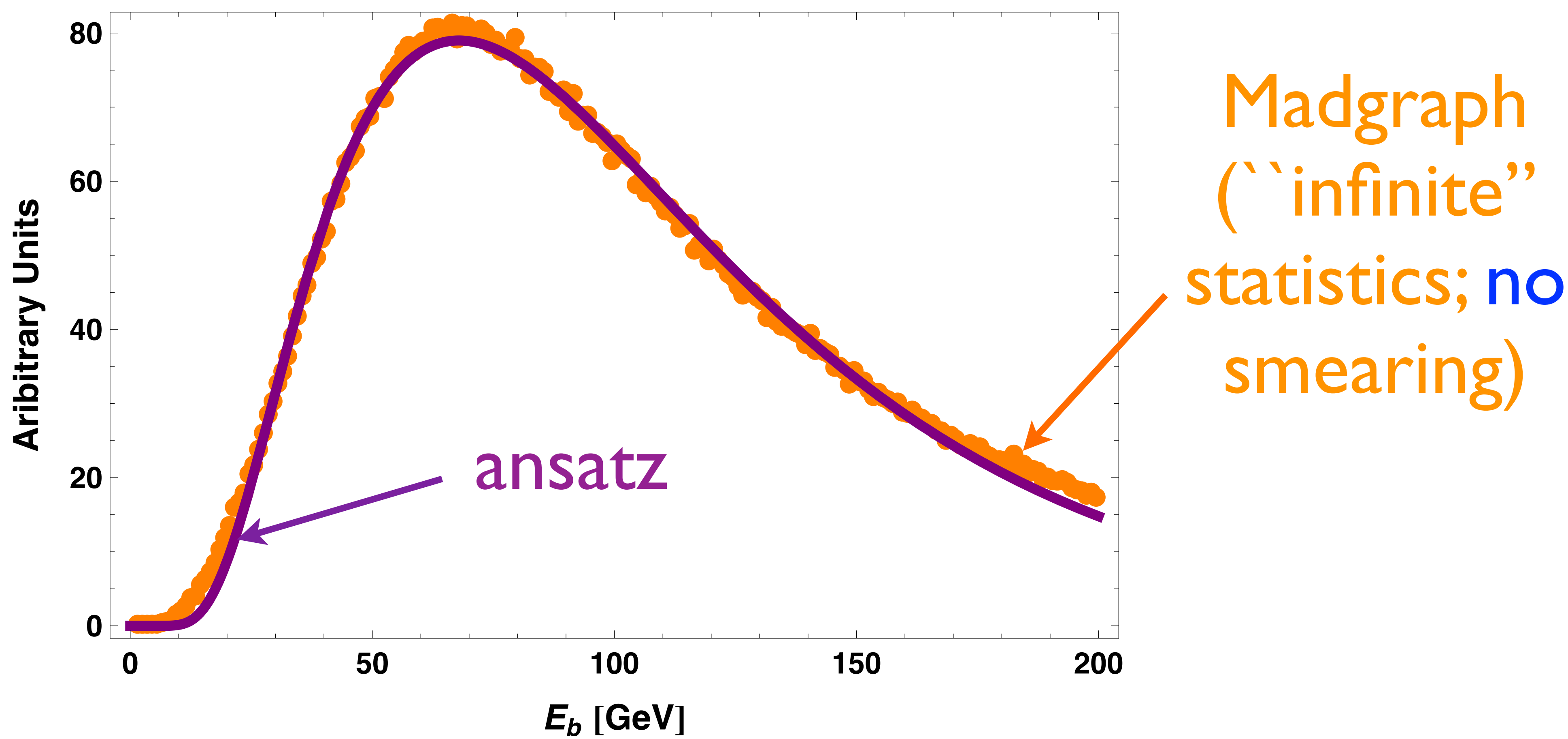
- Model-independent ansatz/fitting function for bottom (b-jet) quark energy (peak at E_b^{rest} + log-symmetric etc.)

$$f^{\text{fit,us}}\left(\underbrace{E_b}_{\text{observable}}; \underbrace{E_b^{\text{rest}}, w}_{\text{parameters}}\right) = \frac{1}{N} \exp\left[-w\left(\frac{E_b}{E_b^{\text{rest}}} + \frac{E_b^{\text{rest}}}{E_b}\right)\right]$$

$$f^{\text{fit,CMS}}\left(E_b; E_b^{\text{rest}}, w\right) = \frac{1}{N} \exp\left[-w \log^2\left(\frac{E_b}{E_b^{\text{rest}}}\right)\right]$$

- fit above function to measured b-jet energy distribution
- best fit value of E_b^{rest} matched to $\frac{M_t^2 - M_W^2 + m_b^2}{2\ M_t}$ ...
- ...as in earlier CMS plot...

…``test" of our fitting function on b-jet energy from top quark decay



- bottom (almost) "massless": peak does not shift, shape property negligibly violated
- good fit for heavier ``top" quark as well: different PDF's, boost distribution (width parameter encompasses this variation)

Bottomline of our proposal

- Plug $f^{\text{fit, us}}\left(E_b; E_b^{\text{rest}}, w\right)$ for $f\left(E_b\right)$ $\longrightarrow$ **new fitting function** (for decay length distribution now):

$$G^{\text{fit, us}}\left(L_B; \underbrace{E_b^{\text{rest}}, w}_{\text{parameters}}\right) \approx \int dE_B \int dE_b \overbrace{\frac{1}{N(w)} \exp\left[-w\left(\frac{E_b}{E_b^{\text{rest}}} + \frac{E_b^{\text{rest}}}{E_b}\right)\right]}^{\text{fitting function for } E_b} \times D\left(\frac{E_B}{E_b}; E_b\right) \frac{m_B}{c\tau_B^{\text{rest}} E_B} \exp\left(-\frac{L_B m_B}{c\tau_B^{\text{rest}} E_B}\right)$$

observable

parameters

(similar procedure to b-jet energy-peak method: different observable and (double) convolution in fitting function)

$G^{\text{fit}}\left(L_B; E_b^{\text{rest}}, w\right)$ $\rightarrow$ fitting function for observed decay length (L_B) distribution

best-fit value of parameter E_b^{rest} $\rightarrow$ $\dfrac{m_t^2 - M_W^2 + m_b^2}{2\, m_t}$

τ_B^{rest} $\rightarrow$ mean decay lifetime of B-hadron in its rest frame

$D\left(\dfrac{E_B}{E_b}; E_b\right)$ $\rightarrow$ bottom quark fragmentation function

parameter w $\rightarrow$ width of fitting function (its extracted value is *not* relevant here)

$N(w)$ $\rightarrow$ normalization factor

Hadronization model/fragmentation function (D): going from bottom quark to

$$b\text{-jet} = B\text{-hadron} + X$$

- important for B-hadron decay length (exclusive) vs. not so much for b-jet energy (inclusive)
- effects studied by CDF/CMS: error in m_t~1 GeV (?)
- more detailed (theory) work: Corcella, Franceschini, Kim: 1712.05801 (further theory improvements possible?)

Summary of new B-hadron decay length proposal

- advantage: no JES uncertainty (same as earlier CDF/CMS analysis); (quasi-)model-independence (cf. earlier SM production assumed)

- new systematics (also for earlier CDF/CMS analysis): hadronization modeling (theory); tracker resolution [experimental, but (much) better than JES?!]

Conclusions

- reviewed (relatively new, but not really for CMS!) method for top quark mass measurement using bottom quark/b-jet energy peak: (quasi-)production model-independent (cf. others assume SM), but afflicted by JES uncertainty (improvement using 13 TeV, NLO…)

- how to "extend" it to B-hadron decay length (correlated with bottom quark energy): circumvent JES uncertainty, "replaced" by hadronization model/fragmentation function (theory improvement possible?)

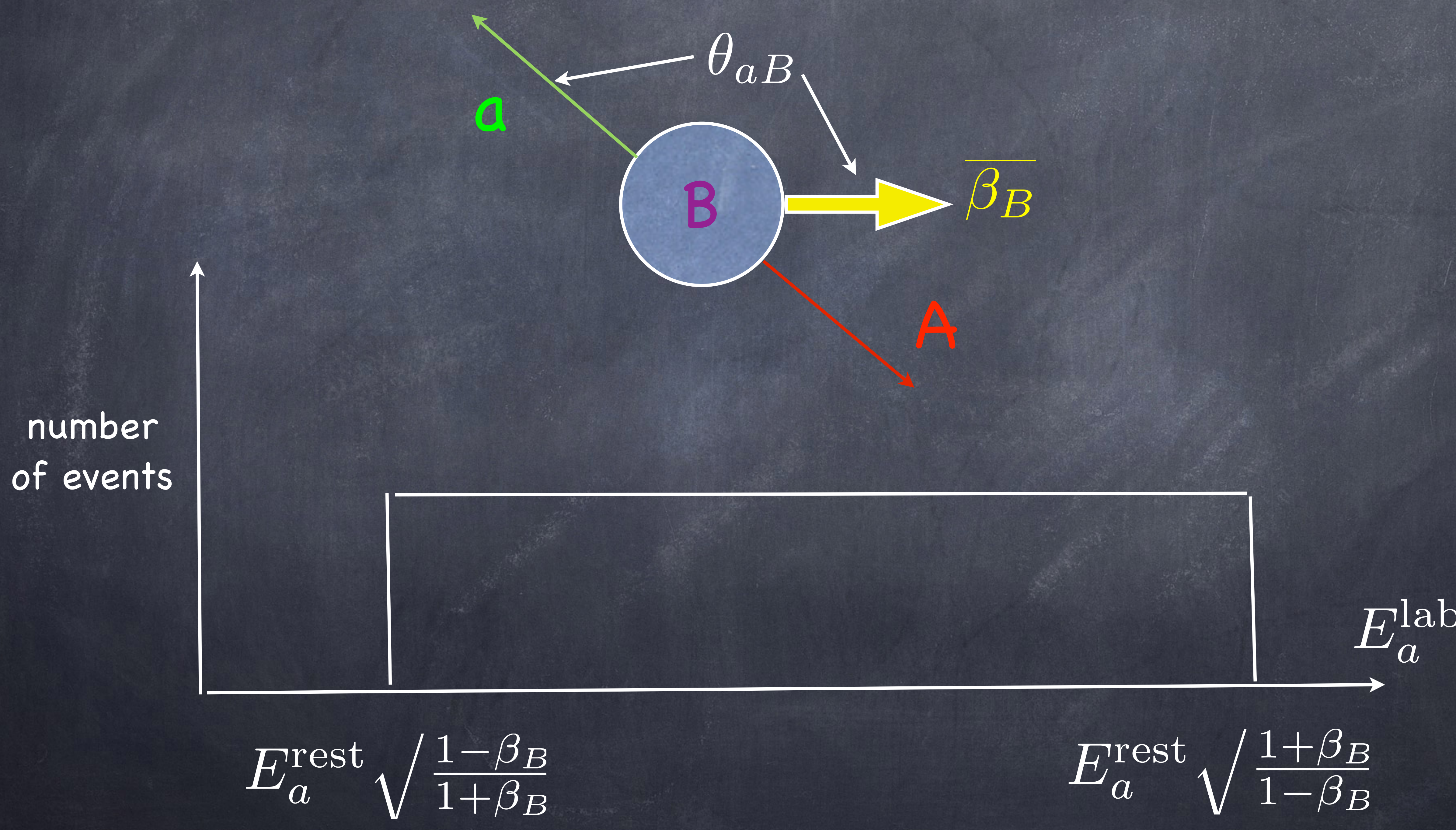
BACK-UP

``Invariance” of two-body decay kinematics

Rectangle for fixed, but arbitrary boost

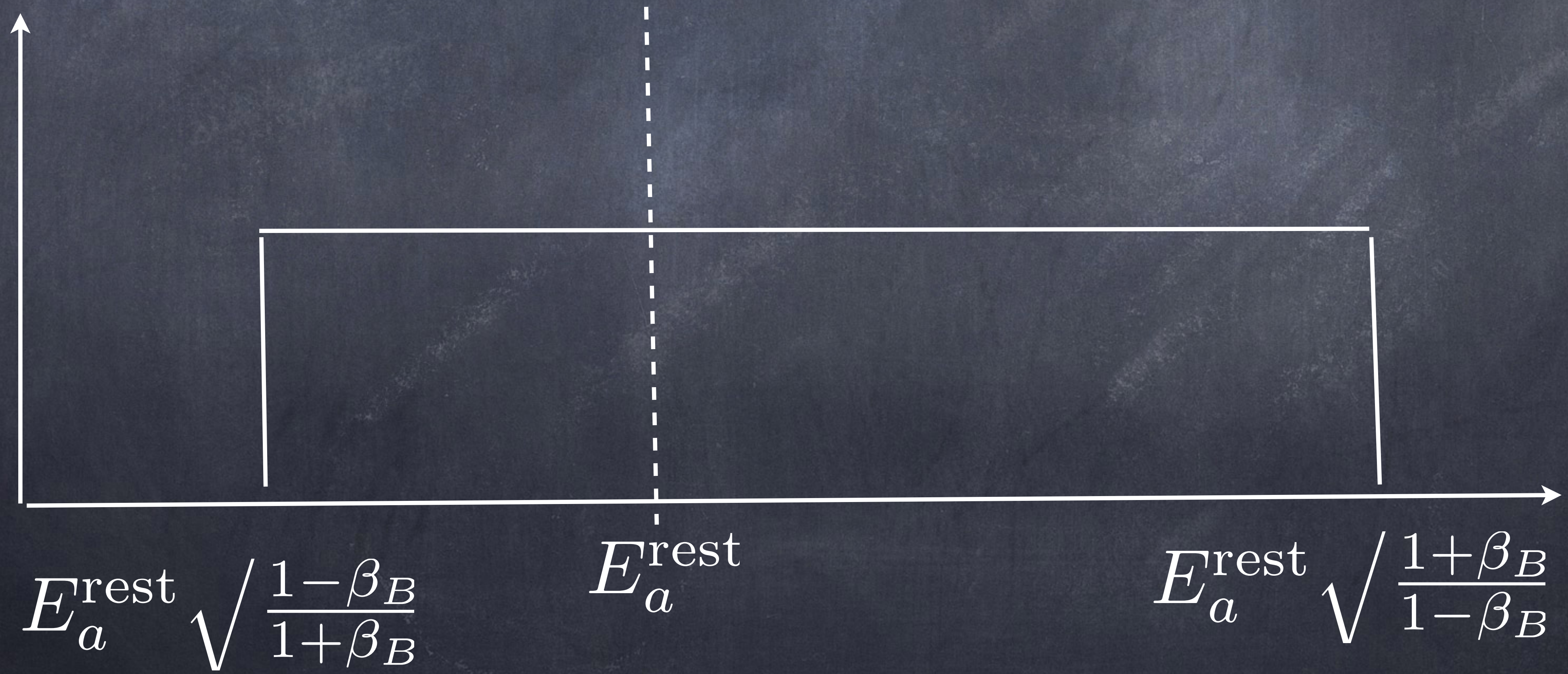
- In general: $E_a^{\mathrm{lab}} = E_a^{\mathrm{rest}} \gamma_B \left(1 + \beta_B \cos\theta_{aB}\right)$

- Assume unpolarized parent: $\cos\theta_{aB}$ is flat



Rectangle vs. rest energy

- contains E_a^{rest} (for any boost)
- no other E_a^{lab} gets larger contribution from given boost than does E_a^{rest}
- no other E_a^{lab} is contained in every rectangle (e.g., $\beta_B \to 0$)
- asymmetric on linear (symmetric on log...)



(Generic) Boost distribution: "stacking" up rectangles

(KA, Franceschini, Kim: 1209.0772)

(see also Stecker: "Cosmic gamma rays")

- distribution of $E_a^{\rm lab}$ has peak at $E_a^{\rm rest}$
- ....no matter what is the boost distribution!
- boost distribution depends on production mechanism, parent mass, PDF's...