Title: Using energy-peaks to measure (new and old) particle masses

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Abstract: <p> I will first analytically show a simple, yet subtle "invariance" of two-body decay kinematics for the case of a massless daughter and a mother particle which is unpolarized and has a *generic* boost distribution in the laboratory frame. Namely, the laboratory frame energy distribution of the massless decay product has a peak, whose location is identical to the (fixed) energy of that particle in the rest frame of the corresponding mother particle. In turn, this value of the energy is a simple function of the other masses involved in the decay.<br>
As a proof of principle of the usefulness of this observation, I will then apply it for measuring the mass of the top quark at the LHC, using simulated data (including experimental effects). In fact, CMS collaboration (in CMS-PAS-TOP-15-002) has recently implemented our method for measuring the top quark mass! Finally, I will show how it can be used to measure all the superpartner masses in a cascade decay chain of the gluino.</p>

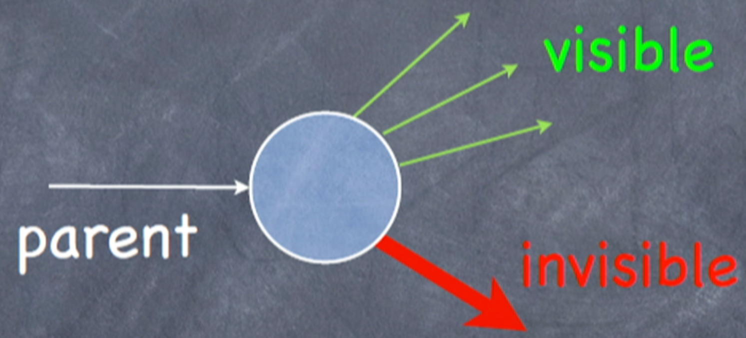
# USING ENERGY-PEAKS FOR MEASURING (OLD AND NEW) PARTICLE MASSES

★ ★ ★ ★ Kaustubh Agashe (University of Maryland) ★ ★ ★ ★

(with Roberto Franceschini, Sungwoo Hong, Doojin Kim, Kyle Wardlow: 1209.0772; 1212.5230; 1309.4776; 1503.03836 and to appear)

# Basic goal (simple!)

- determine mass of parent by measuring energy/momentum of (visible) decay products




- kinematics-based (independent of production mechanism)

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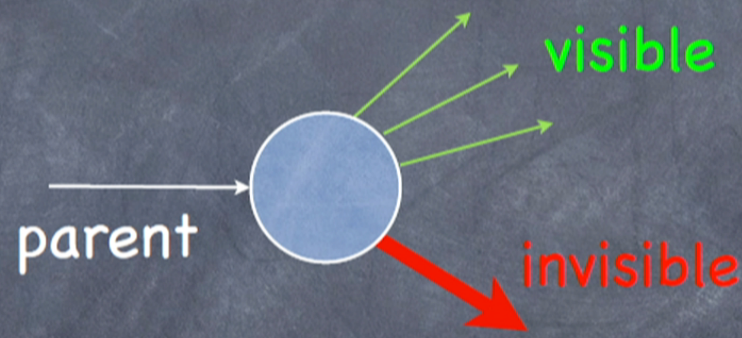
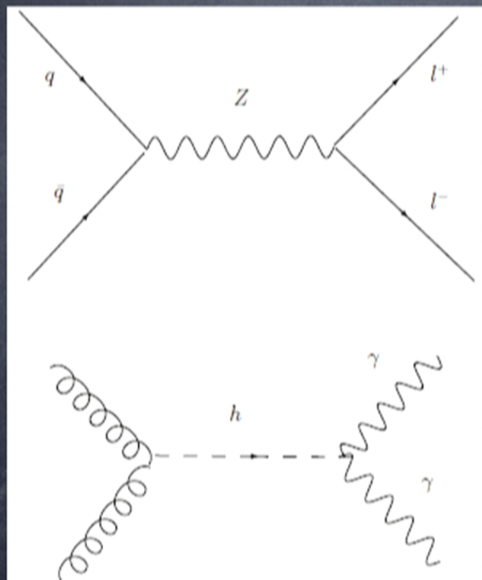
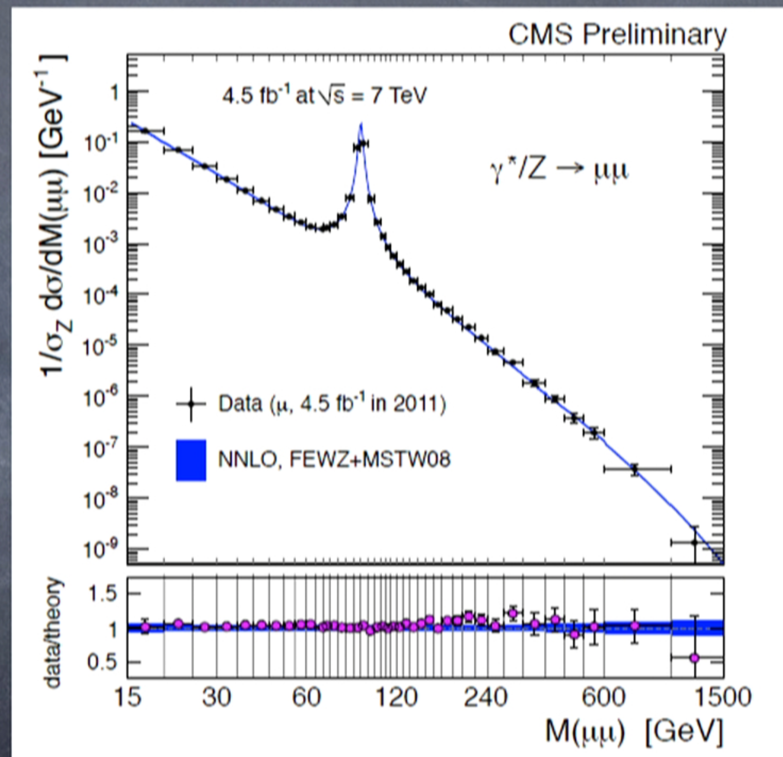



- kinematics-based (independent of production mechanism)

# Fully visible I (``golden'')

- invariant mass of decay products has Breit-Wigner peak

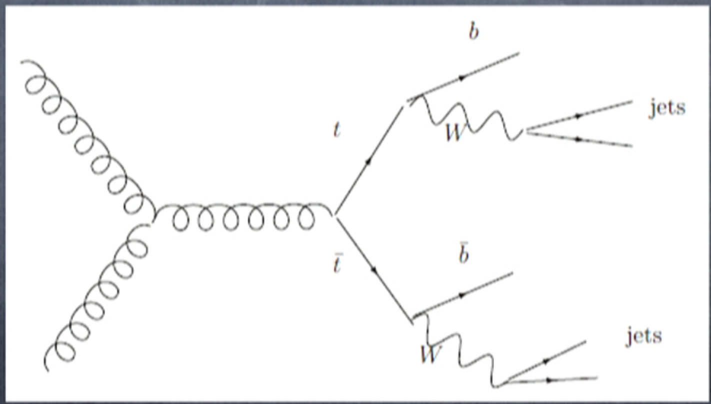



- have to be ``lucky''!

# Fully visible II (not so easy)

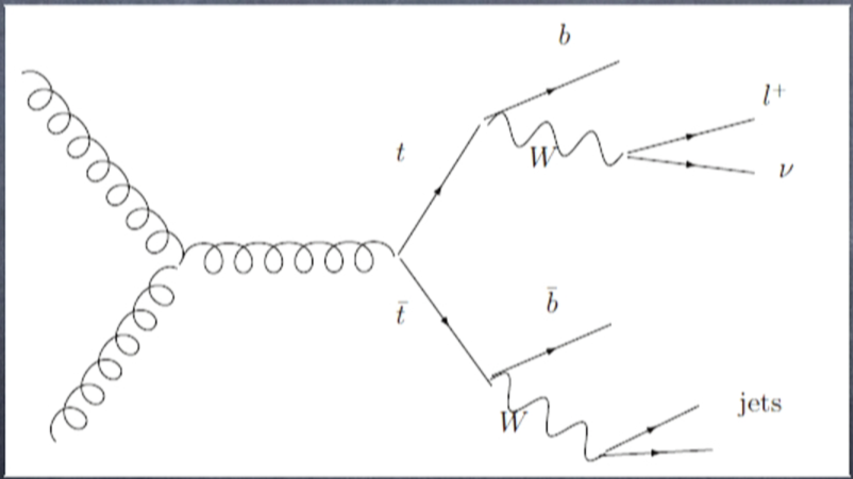
- fully hadronic top decay




- problem: all jetty + combinatorics (compounded by jets from initial/final state radiation)

# "Partially" visible I (can be reconstructed)

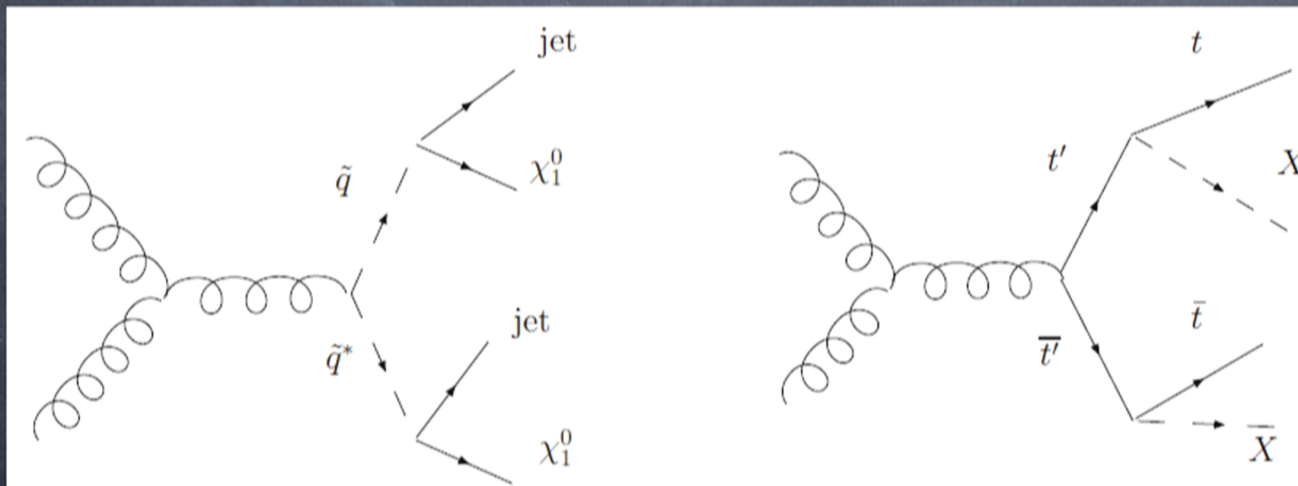
- 1 daughter fully visible, other partially
- semileptonic top decay ("less" jetty)




- still "issues": discrete ambiguity in reconstructing W; uses MET; still combinatorics (which W with which b)...

# "Partially" visible II (cannot be reconstructed)

- 1 daughter fully visible, other fully invisible (maybe DM)
- R-parity conserving SUSY, top-partner in T-parity little Higgs models...




- (generalized) transverse mass ($M_{T2}$): uses MET
- razor: $M_R$ based on (plausible) assumptions about boosts

# Bottomline: (in my opinion)

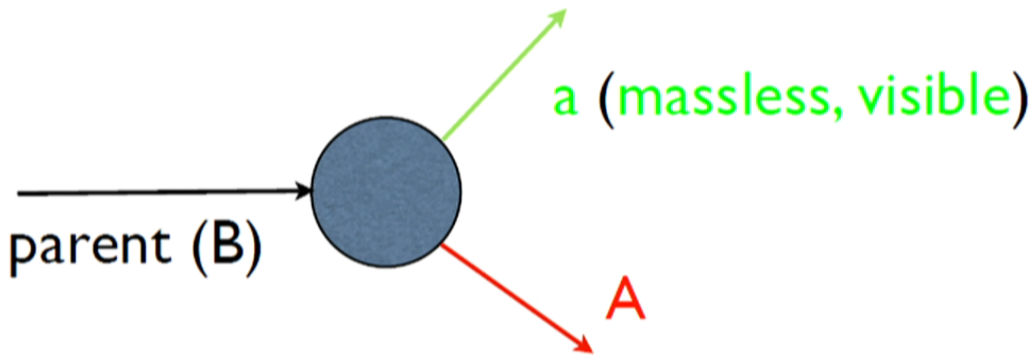
## no slam dunk!

- useful to have more techniques, especially simpler; complementary (different systematics, e.g., avoid MET or combinatorics or assumptions about boosts)

# NEW OBSERVATION TECHNIQUE →

# Basic assumptions

- 2-body decay: one child particle (fully) visible, massless:




- ...other (A) don't care (except for its mass)!
- unpolarized mother (all spin orientations equal)
- extensions/generalizations later

# Energy of child particle

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

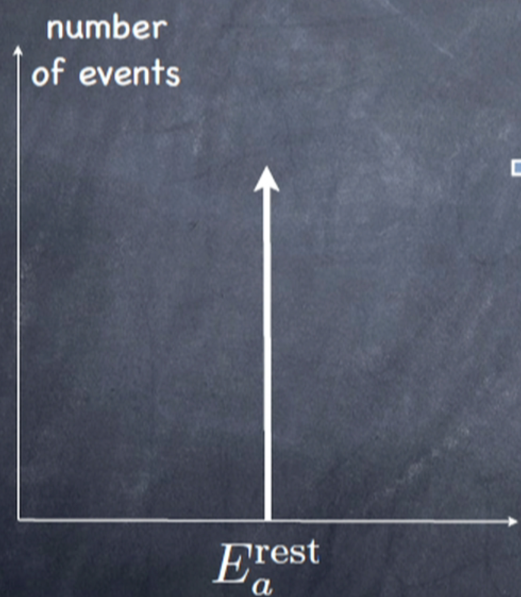
$$E_a^{\text{rest}} = \frac{M_B^2 - M_A^2}{2M_B}$$

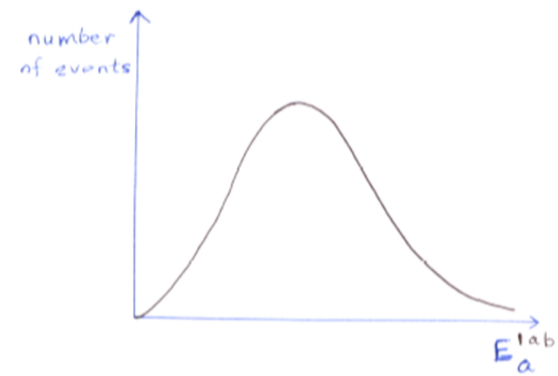
- determine $M_B$ if $M_A$ known and $E_a^{\text{rest}}$ measured

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

# ...too simple to be practical/useful?!

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

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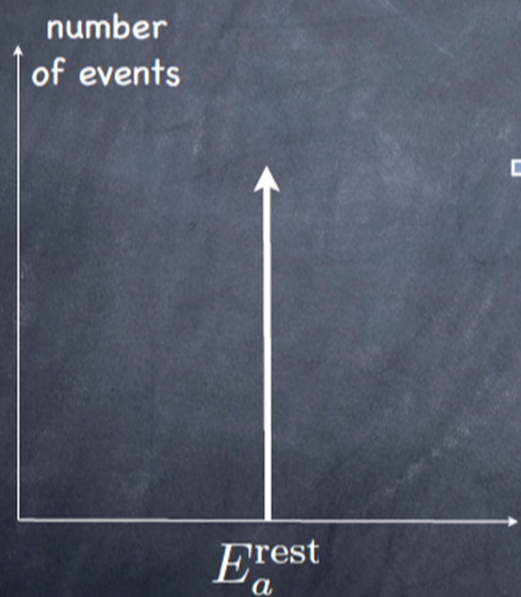
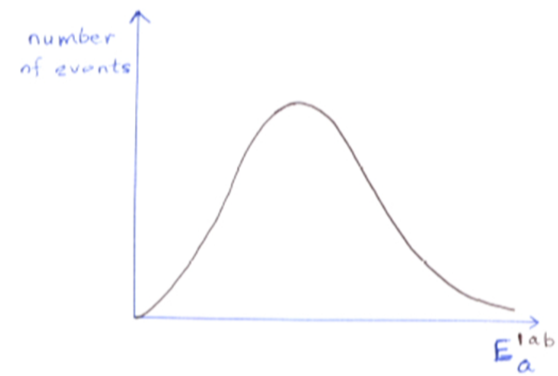


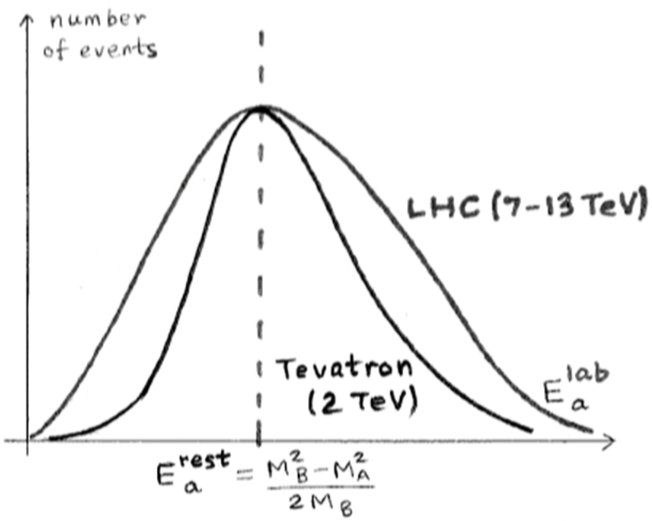




- lose rest-frame information?!

# Outline

independent of boosts of mother

- Peak (of lab. distribution) still retains this information...as simply, precisely, robustly!
- ``Test'' application (top mass):
  obtain approximation to theory curve
  Fit it to (simulated) data for extracting peak
- New physics:
  (Cascade decay)
  general idea
  SUSY example
- Three-body decay
- Conclusions



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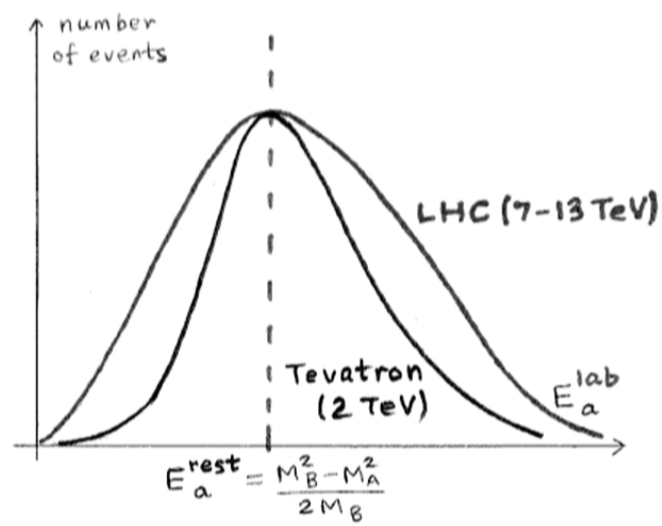
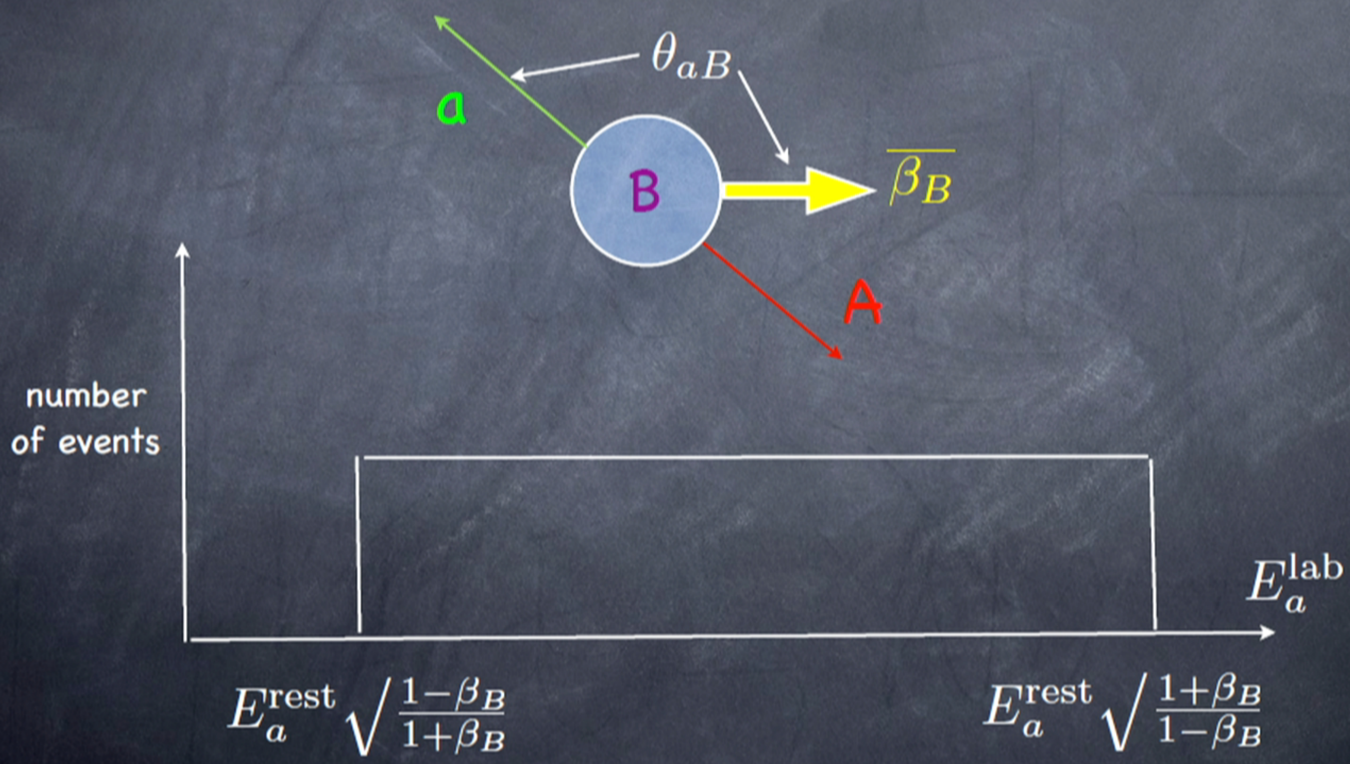


# Rectangle for fixed, but arbitrary boost

- In general: $E_a^{\rm lab} = E_a^{\rm rest}\gamma_B\left(1+\beta_B\cos\theta_{aB}\right)$
- Assume unpolarized parent: $\cos\theta_{aB}$ is flat



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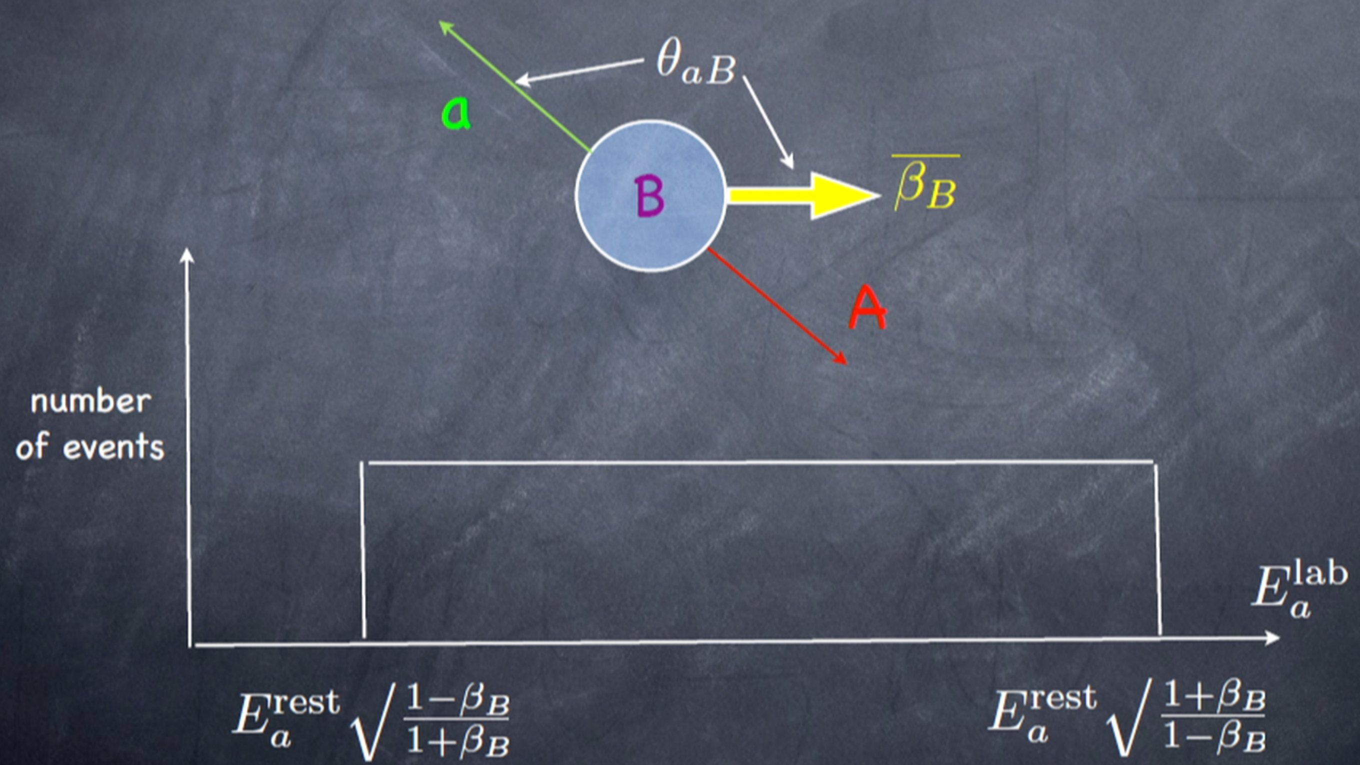
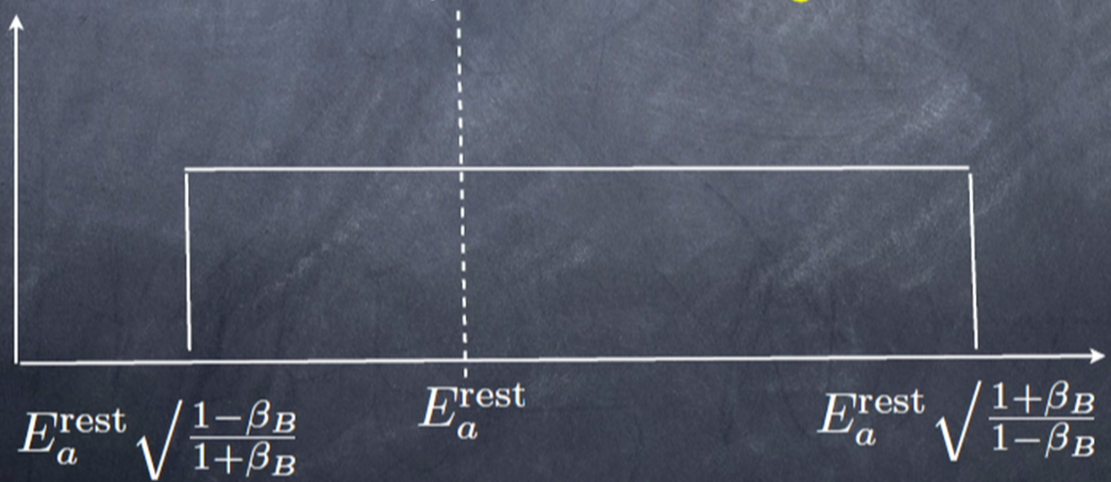


# Rectangle vs. rest energy

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



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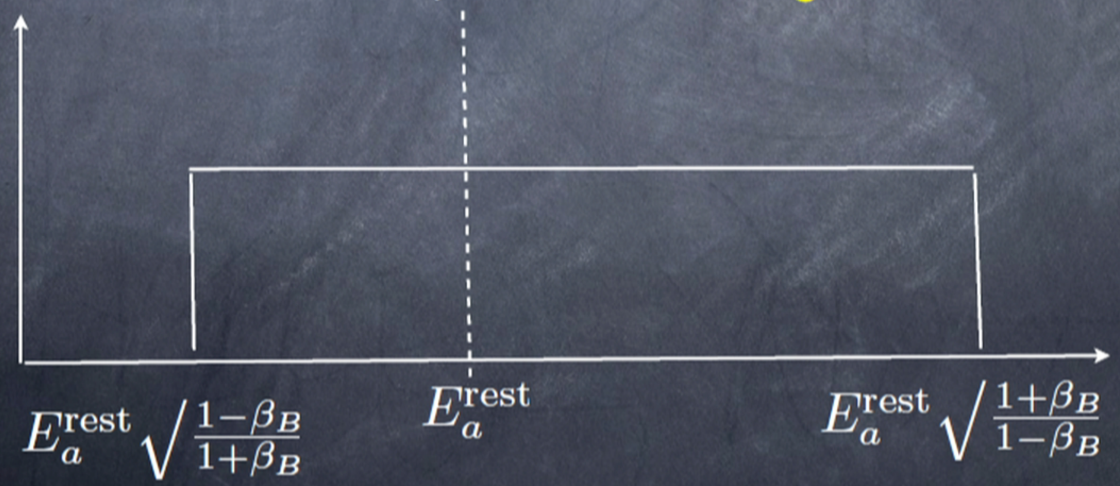
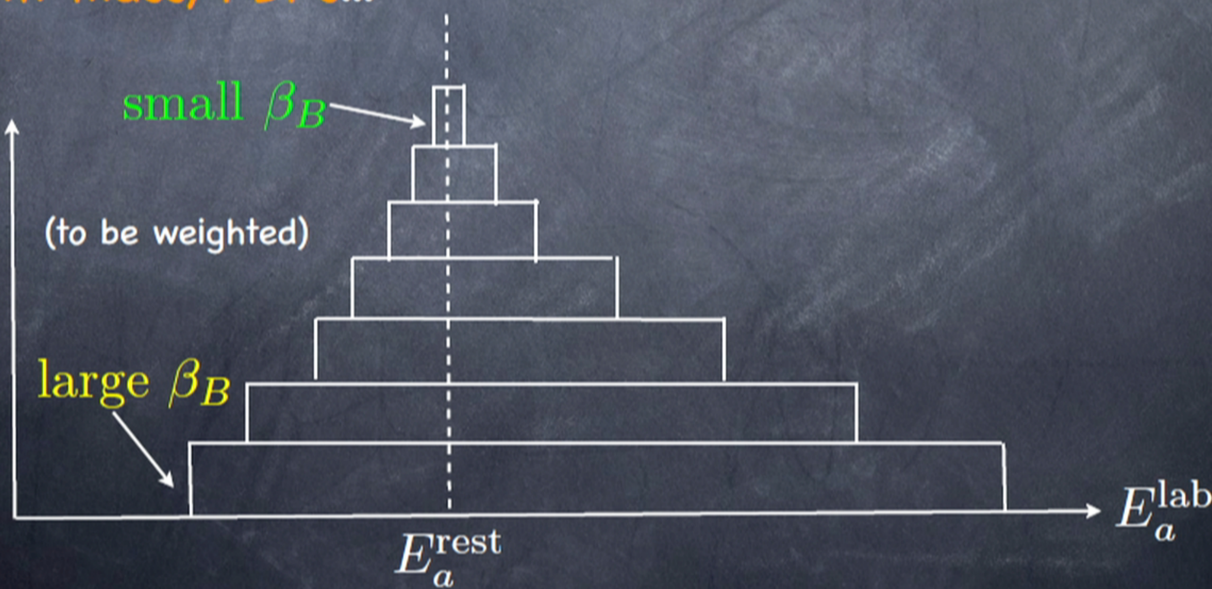


# (Generic) Boost distribution: ``stacking" up rectangles

(KA, Franceschini, Kim: 1209.0772)

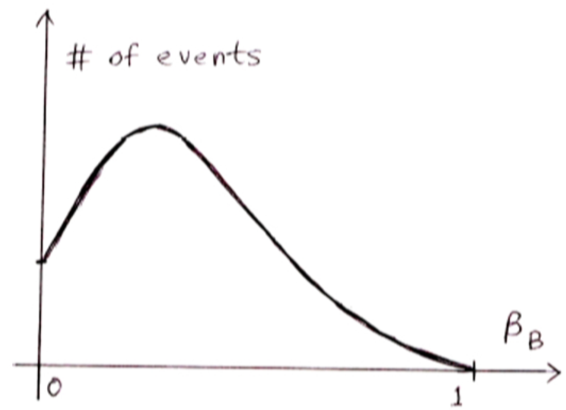
(see also Stecker: ``Cosmic gamma rays" )

- 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...



# Boost distributions: I & II


boost distribution for 2→2 (previous)




boost distribution for 2→1 (next)

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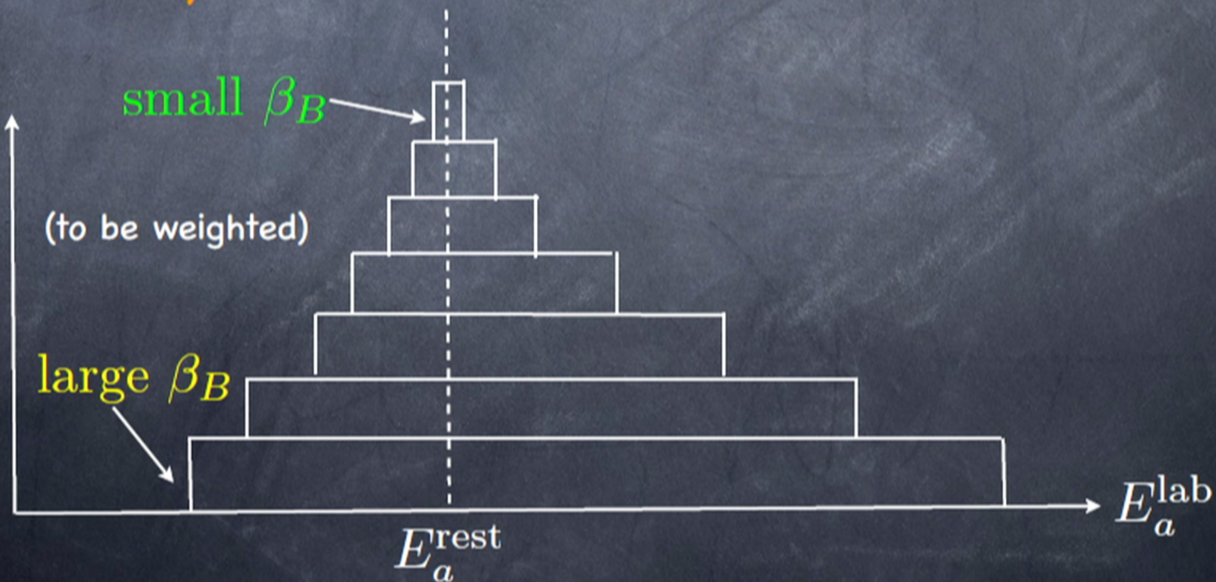
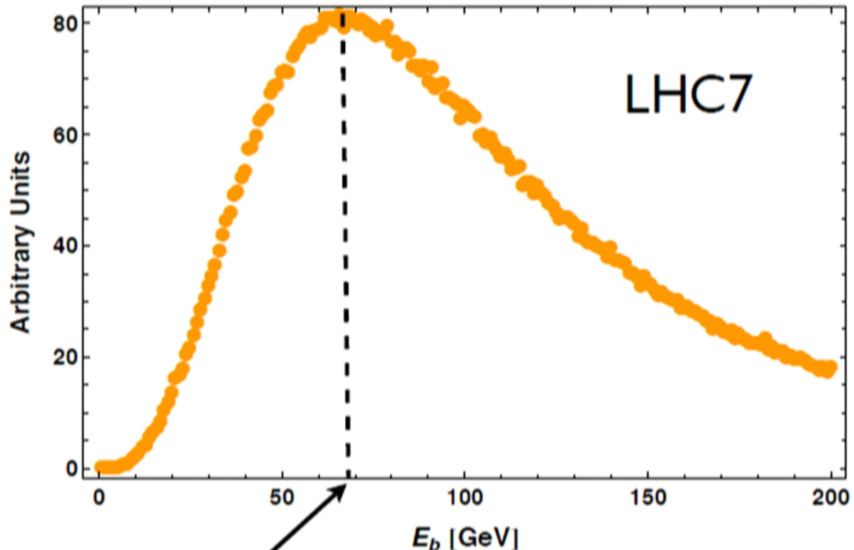


# ...plateau is not "generic"

# No need really, but anyway, actual calculation...

- bottom from top quark decay as example:

bottom mass negligible ➡ peak is not expected to shift from $E_b^{\mathrm{rest}} = \frac{M_t^2 - M_W^2 + m_b^2}{2M_t}$ ← modified




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

- ...maybe an "accident"?!

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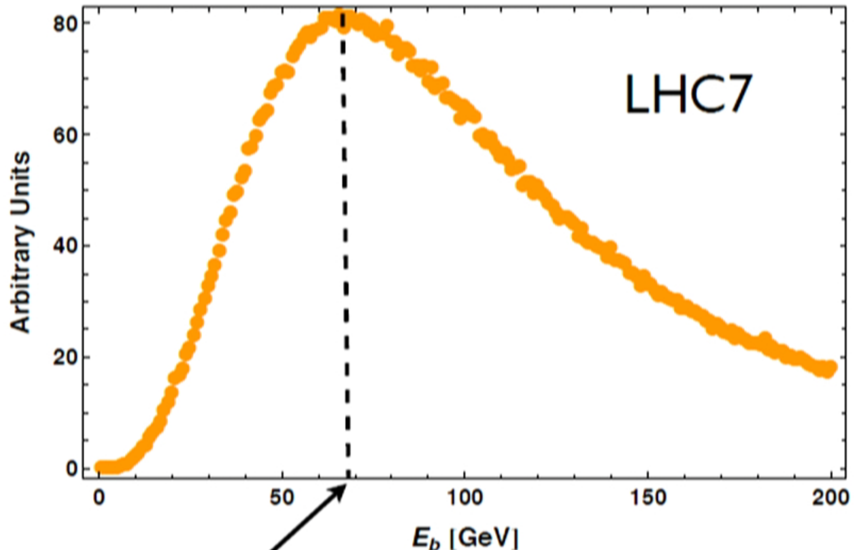


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# Measuring the peak

- peak can be wide (difficult to read-off value ``by eye")
- extract peak by fitting to ``theory curve": a la Breit-Wigner [simple (2-parameter), analytic, model-independent function]
- ...but exact, analytic formula difficult to obtain here (depends on boost distribution, thus PDF's...)

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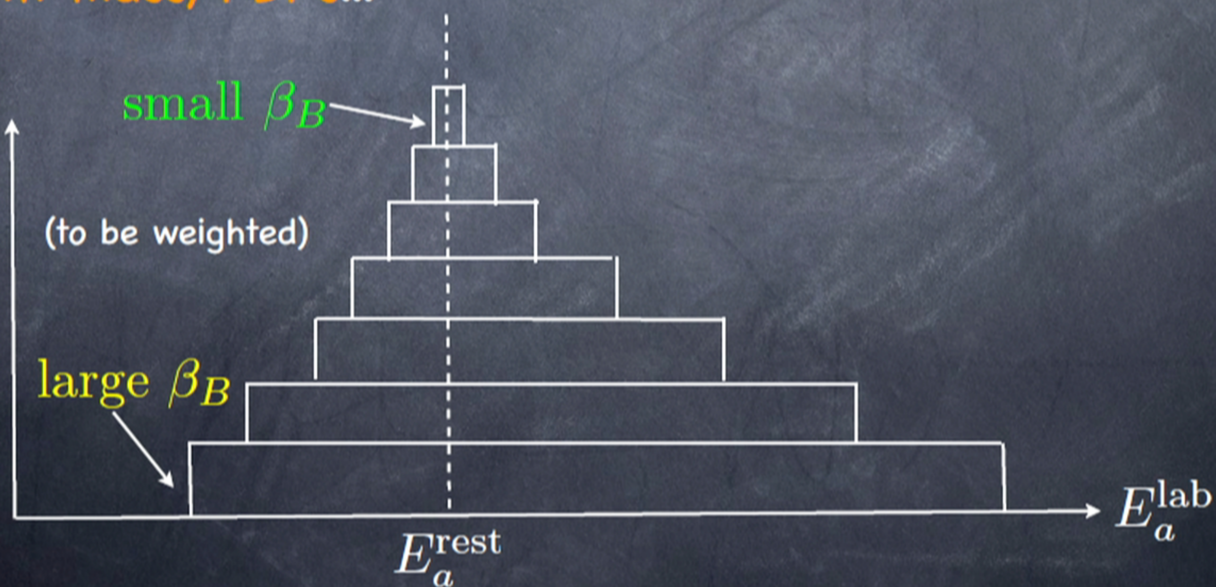


# ...plateau is not "generic"

# Ansatz (based on properties)

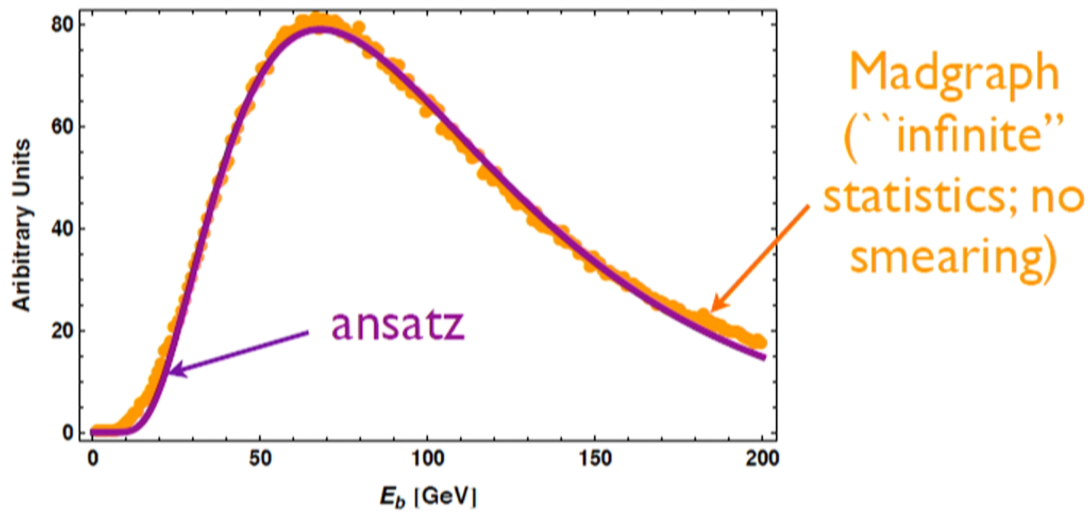
width parameter

$$f(x) = K_1^{-1}(p)\exp\left[-\frac{p}{2}\left(x + \frac{1}{x}\right)\right]$$

Bessel function (normalization)

- simple, but not unique "peak finder"...

# ``Test" on b-jet energy from top quark decay (production unpolarized...)




- 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)

# "New" Breit-Wigner

## (use it to extract peak by fitting data)

- Based on theory fits, assume

$$f(x) = K_1^{-1}(p) \exp\left[-\frac{p}{2}\left(x + \frac{1}{x}\right)\right]$$

# (Again) Top quark decay: basic idea

neglect $m_b$ in $E_b^{\mathrm{rest}}$

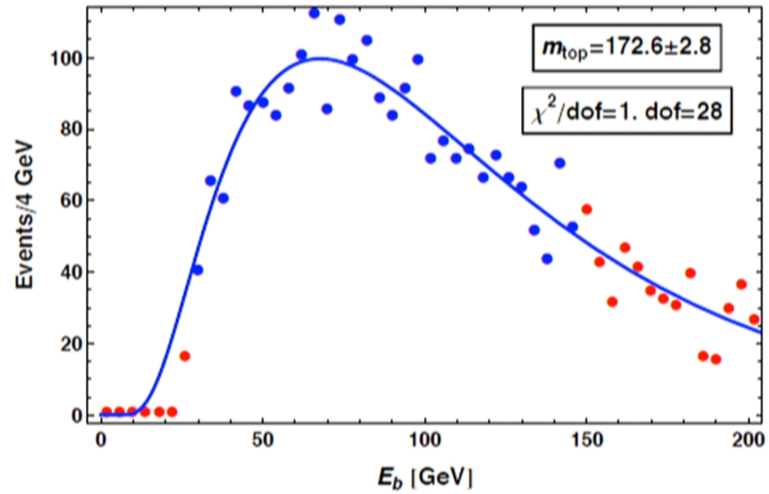
- Peak in measured b-jet energy distribution $\approx \frac{M_t^2 - M_W^2}{2M_t}$
- Assuming $M_W$ (but no need to detect it at all!), get $M_t$

# Top mass measurement: details

- Fully leptonic (opposite flavor) and 2 b-tags, with 5/fb at LHC7: expect 4000 S vs. 200 B
- Madgraph $\longrightarrow$ Pythia $\longrightarrow$ Delphes/Fastjet
- 100 pseudo-experiments
- ATLAS/CMS choice of (mild) cuts: 1209.2393; ATLAS-CONF-2012-097
- neglected background

# Result

(1 pseudo-experiment shown)

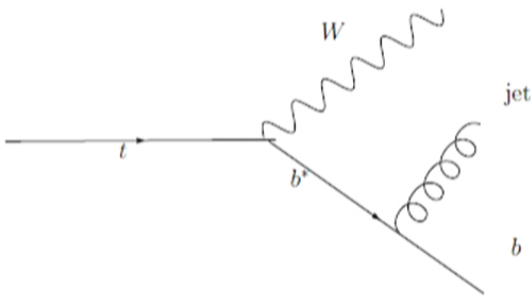



(use only blue dots)

- consistent with input value
- fitting not spoiled by cuts or detector effects

# Discussion

- neglected hard radiation from bottom (3-body): suppressed by $\alpha_s/\pi$ + jet-veto (calculable in QCD)




(KA, Franceschini, Kim, Schulze: 15xx.yyyyy)

- safe from soft radiation off of bottom
- safe from initial state radiation
- no combinatorics (include both b's)
- independent of production mechanism (single or pair; uncertainty in PDF's; new physics or SM) as long as unpolarized

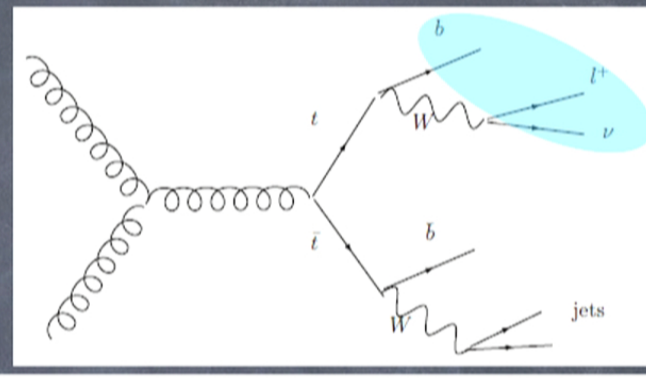
# On "full" reconstruction of top decay (II)

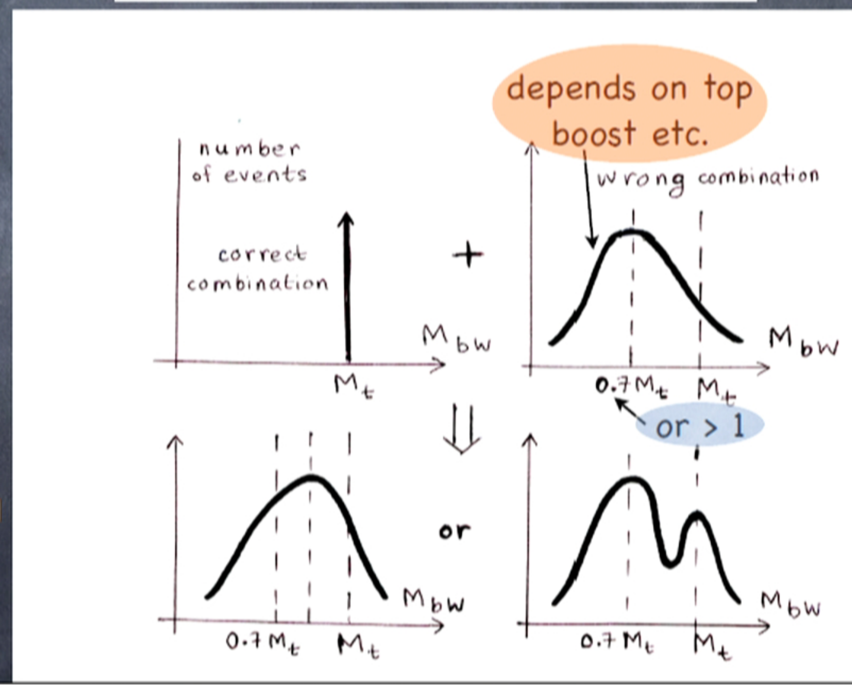
- ...either way, cannot (robustly) measure $M_t$!

- existing analyses: assume SM matrix element, compute entire distribution ⇒ $M_t$ valid only in SM!

# On "full" reconstruction of top decay (I)

- semi-leptonic channel...
- 4 solutions (a priori) to top mass in each event: 2 from $p^{\nu}_{\text{long.}}$ (W mass constraint quadratic) x 2 from which b combined with reconstructed W
- only 1 correct: peaks at $M_t$
- wrong combinations: do not peak exactly at $M_t$...but "support" is in region of $M_t$, $M_W$ ⇨ peak "somewhere" there



# Theory (II): even if assume SM, "which" top mass?

- pole/physical vs. $\overline{\mathrm{MS}}$ mass (~ Lagrangian parameter):

$$M_t^{\mathrm{pole}} = M_t^{\overline{\mathrm{MS}}} \left(1 + \frac{4}{3}\frac{\alpha_s}{\pi} + ...\right)$$

- b-jet energy-peak measures (``closer to") pole mass
- some other methods: rely heavily on parton-shower, Monte-Carlo (MC) simulation → measure ``MC/Pythia" mass instead
- exception: "clean" kinematic distributions (e.g., lepton energy/momentum) or pole mass from endpoint in $M_{bl}$

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# Experimental

- different systematics, e.g., use of MET in some earlier methods (e.g., full reconstruction) vs. not for b-jet energy peak
- Jet energy scale (JES) uncertainty impacts b-jet energy-peak (cf. using leptons)
- use B-decay length as "proxy" for energy: spatial (pixel size etc.) - not energy - resolution matters...

# ...cut to CMS (real data!)

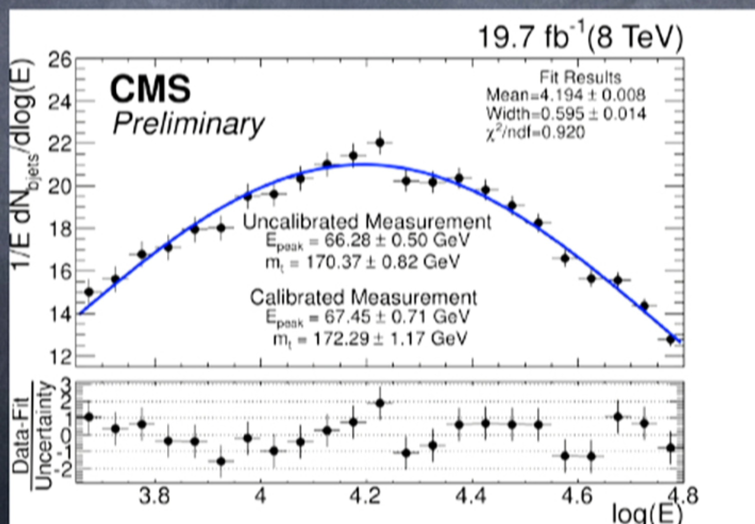
- implementation on run 1 data in CMS PAS TOP-15-002:

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

- Complementary to other methods (error ~1 GeV)
- Sources of error: jet-energy scale; modeling of top $p_T$

use B-decay length?

higher-order (theory) calculation?




note!

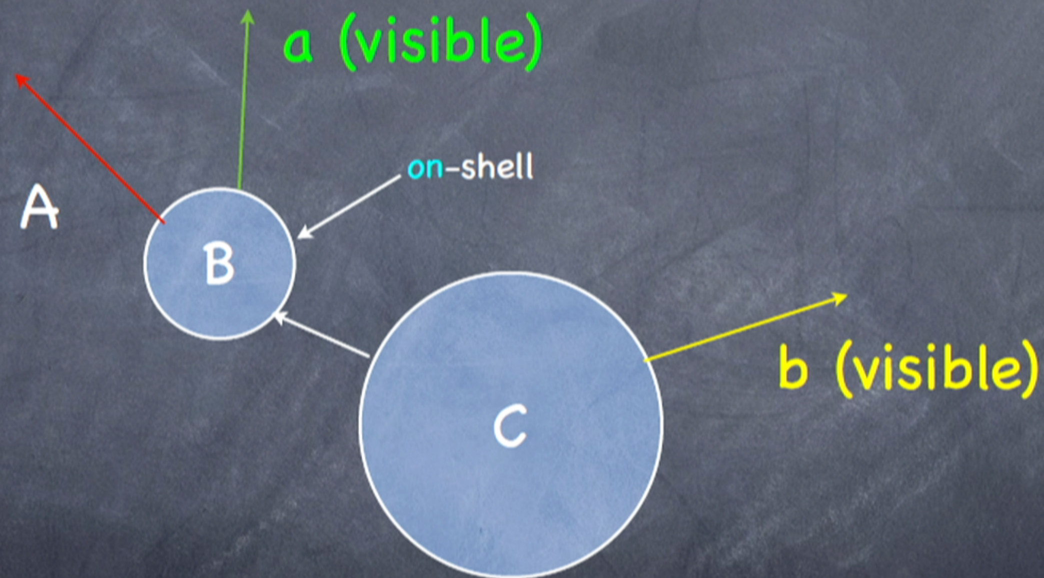
- Can ATLAS be far behind?!

# A NEW PHYSICS APPLICATION (METHOD "TESTED" ON TOP MASS ): CASCADE DECAY

(KA, Franceschini, Kim: 1309.4776)

# In General: Topology

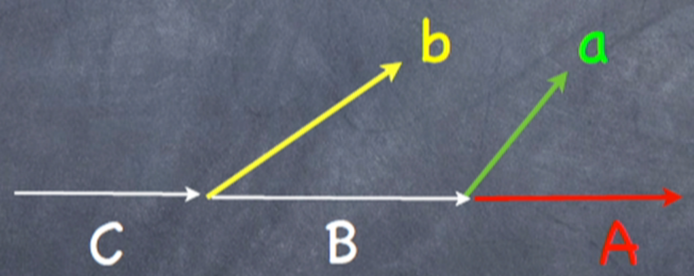
- Two 2-body decays: primary (C) and secondary (B) parents)



# Two energy peaks

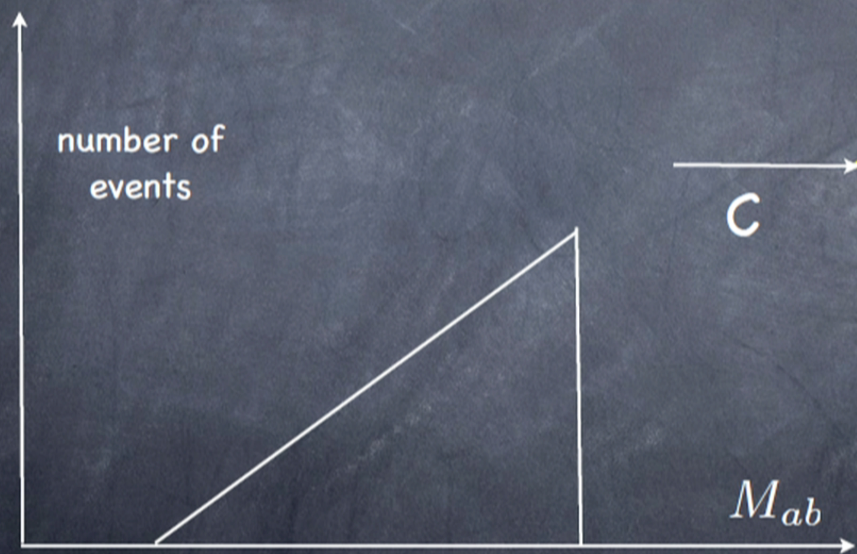
- Based on new observation:

$$E_b^{\text{peak}} = \frac{M_C^2 - M_B^2}{2M_C} \text{ and } E_a^{\text{peak}} = \frac{M_B^2 - M_A^2}{2M_B}$$

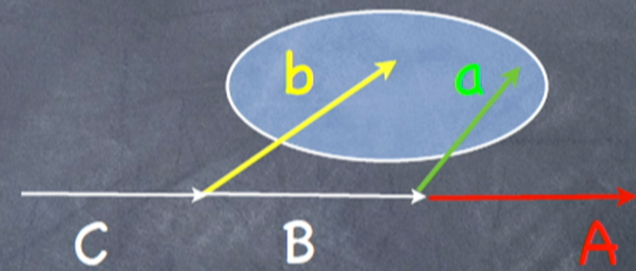


# Edge in invariant mass (old)

- On-shell intermediate particle ⟹ (sharp) edge




$$\sqrt{\frac{\left(M_C^2-M_B^2\right)\left(M_B^2-M_A^2\right)}{M_B}}$$



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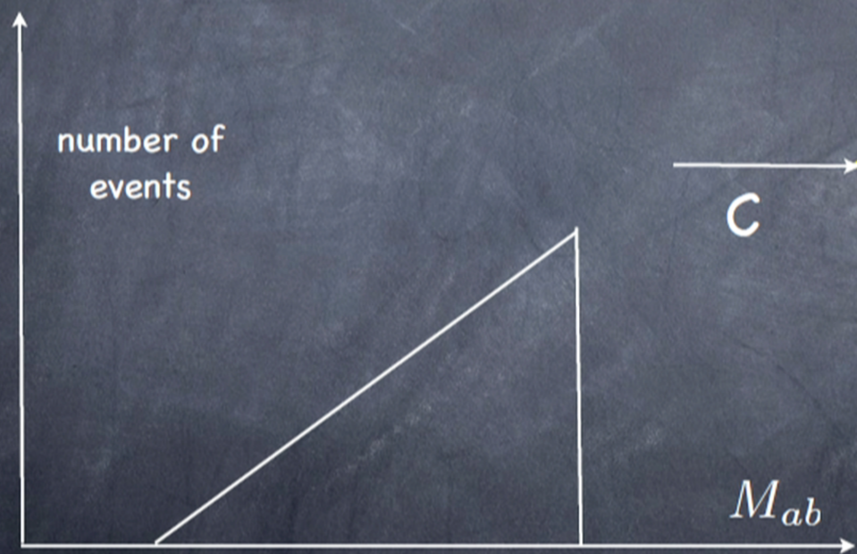
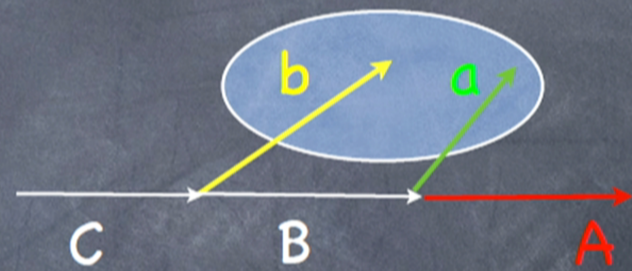


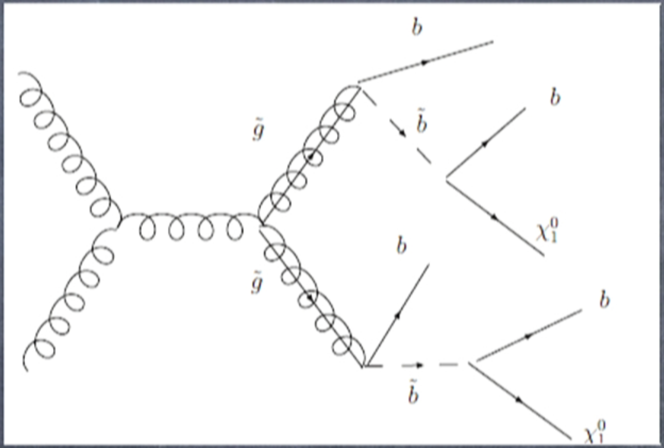

$$\sqrt{\frac{\left(M_C^2 - M_B^2\right)\left(M_B^2 - M_A^2\right)}{M_B}}$$



= 3 (independent) observables for determining 3 masses!

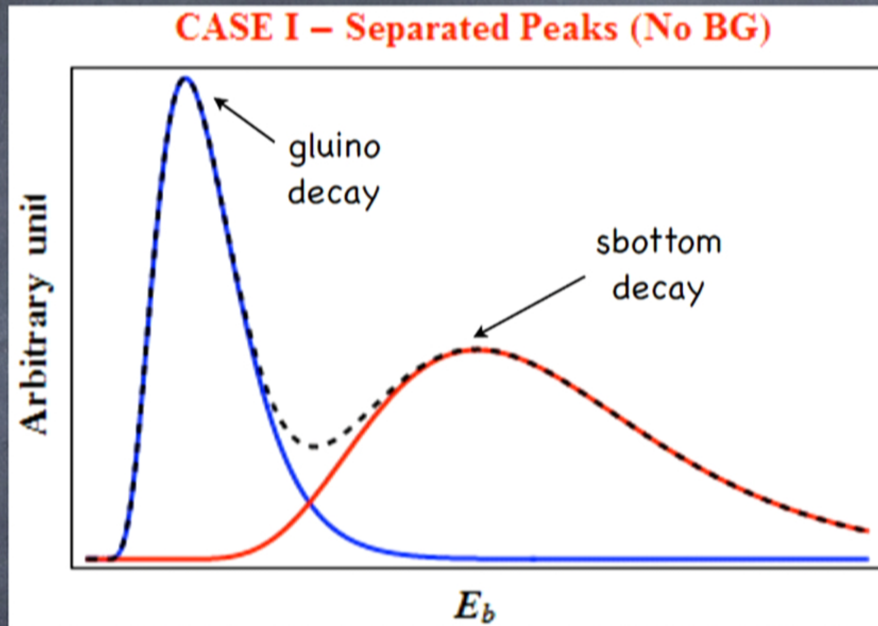
...(in principle) determine invisible particle mass without measuring MET!

# Gluino, sbottom, neutralino




- natural SUSY: 1st/2nd generation squarks heavy, stop/sbottom and gluino, Higgsino light

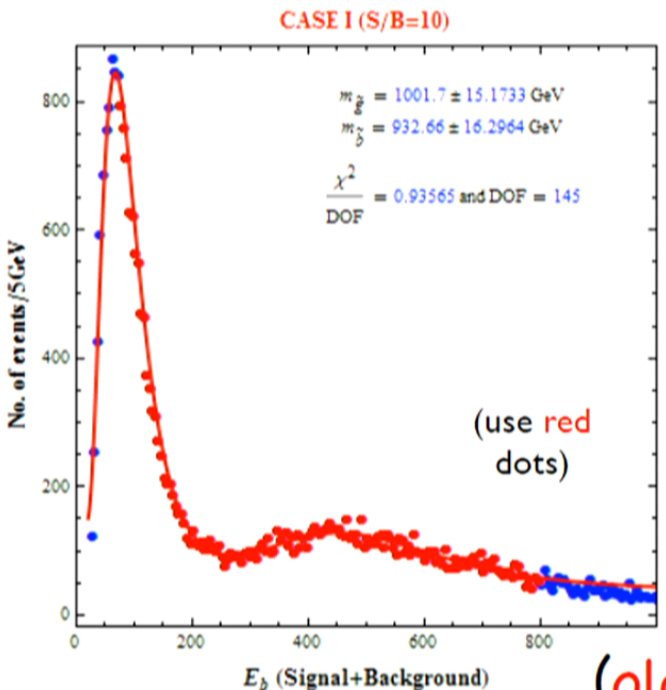
# Double (b-jet energy) peak

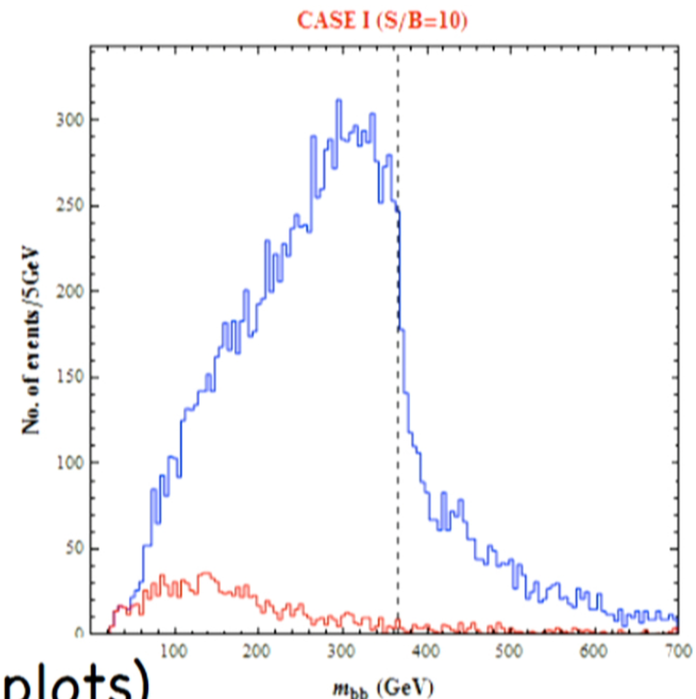



- mass hierarchy: $M_{\tilde{g}} \approx M_{\tilde{b}} \gg M_{\chi_1^0}$ ⇒ "soft" & hard b-jets

# Results

- $M_{\tilde{g}} = 1000$ GeV; $M_{\tilde{b}} = 930$ GeV and $M_{\chi_1^0} = 100$ GeV with 300 / fb at LHC14
- 3 (2 signal + 1 background) template fit (assume this model)
- little sensitivity to $M_{\chi_1^0}$: $2\sqrt{E_b^{\text{peak 1}} E_b^{\text{peak 2}}} \approx M_{bb}^{\max}$




(old plots)

- ansatz/fitting function works for (boost distribution of) a "secondary" parent as well!

# Generalizations

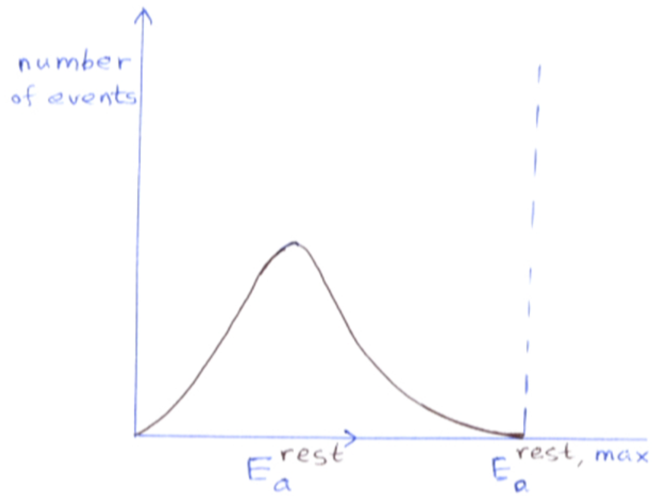
- Massive child particle from 2-body decay:
  peak shifts from rest-frame value (in general), but
  modified ansatz/fitting function still good
  (KA, Franceschini, Hong, Kim: 15xx.yyyyy)

- 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)

THREE-BODY DECAY:
ONE VISIBLE
(CANNOT "REDUCE" TO 2-BODY)

# Endpoint of distribution in rest frame

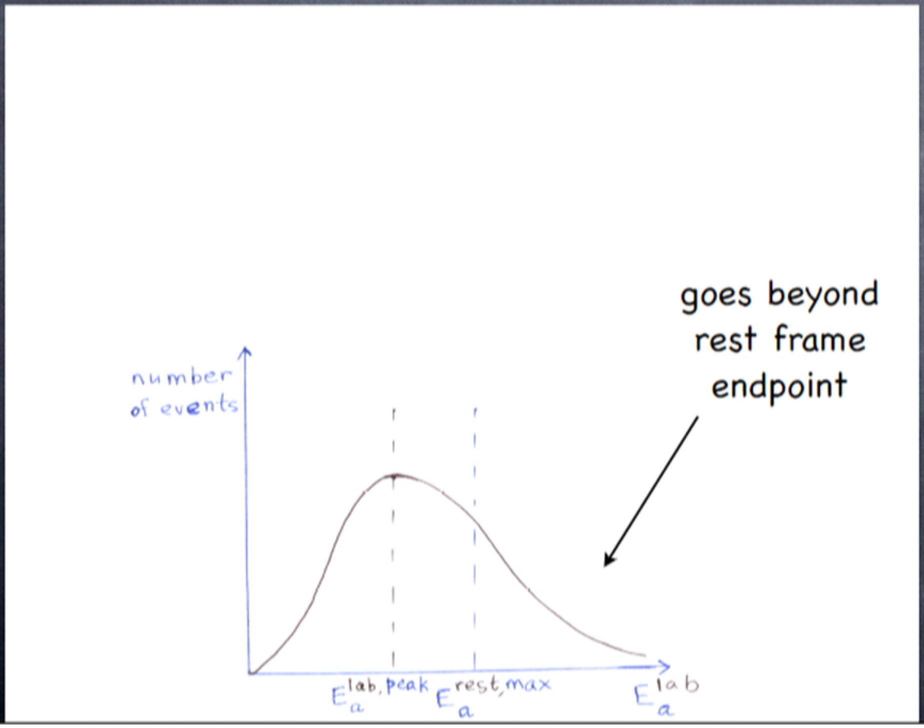
- Endpoint related simply to masses



# Peak of distribution in lab frame

$$E_a^{\text{lab,peak}} < E_a^{\text{rest,max}}$$

- Obtain inequality for masses
- distinguishing $Z_3$ vs. $Z_2$-stabilized dark matter (DM): decay into 1 visible + 2 vs. 1 DM ("same" final state!)



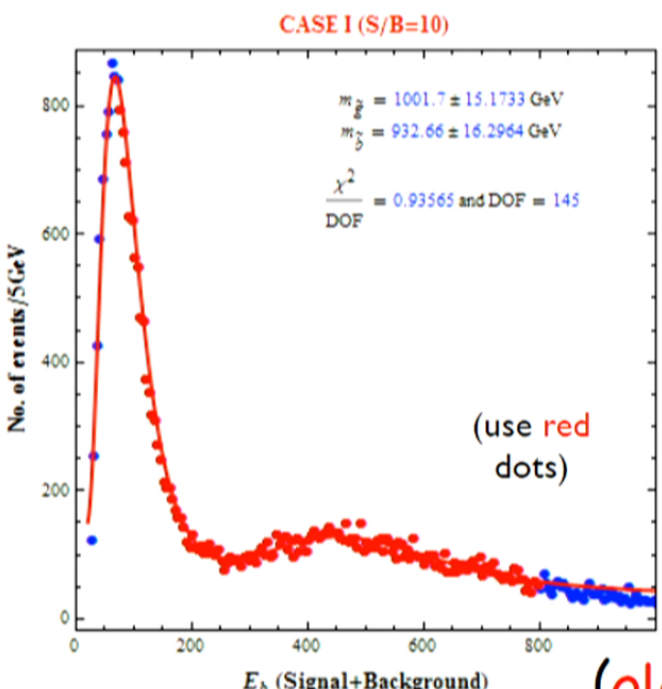

(KA, Franceschini, Kim, Wardlow: 1212.5230)

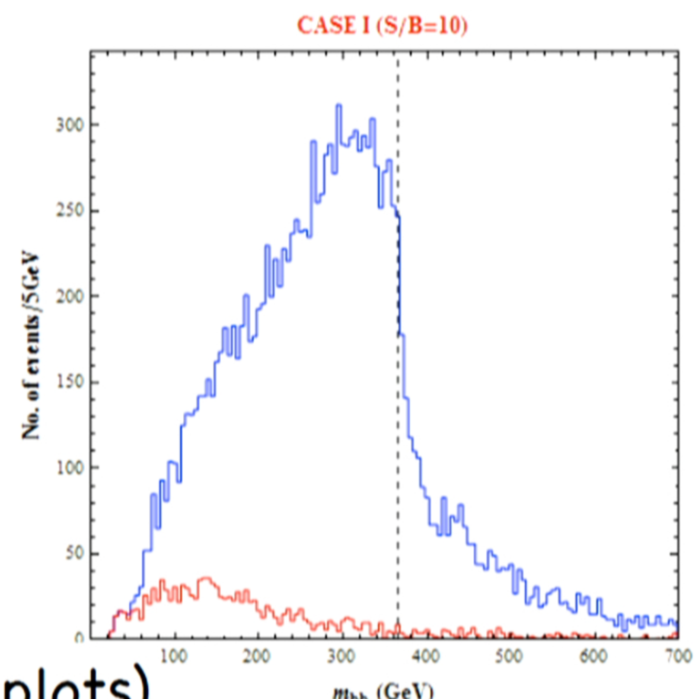
# Conclusions

- Two body decay of unpolarized parent at hadron colliders:
  peak in energy distribution of (massless) child particle same as rest frame energy (simple function of masses)
- Obtain approximation to theory curve (for fitting to data to extract peak)
- Application(s):
  top quark mass (as test + for "real"): use b-jet energy/$L$
  new particles decaying semi-invisibly: extract all masses from cascade decay (e.g., gluino to sbottom...)

# Results

- $M_{\tilde{g}} = 1000$ GeV; $M_{\tilde{b}} = 930$ GeV and $M_{\chi_1^0} = 100$ GeV with 300 / fb at LHC14
- 3 (2 signal + 1 background) template fit (assume this model)
- little sensitivity to $M_{\chi_1^0}$: $2\sqrt{E_b^{\text{peak 1}} E_b^{\text{peak 2}}} \approx M_{bb}^{\max}$




(old plots)