NEW TECHNIQUE(S) FOR MASS MEASUREMENT AT HADRON COLLIDERS

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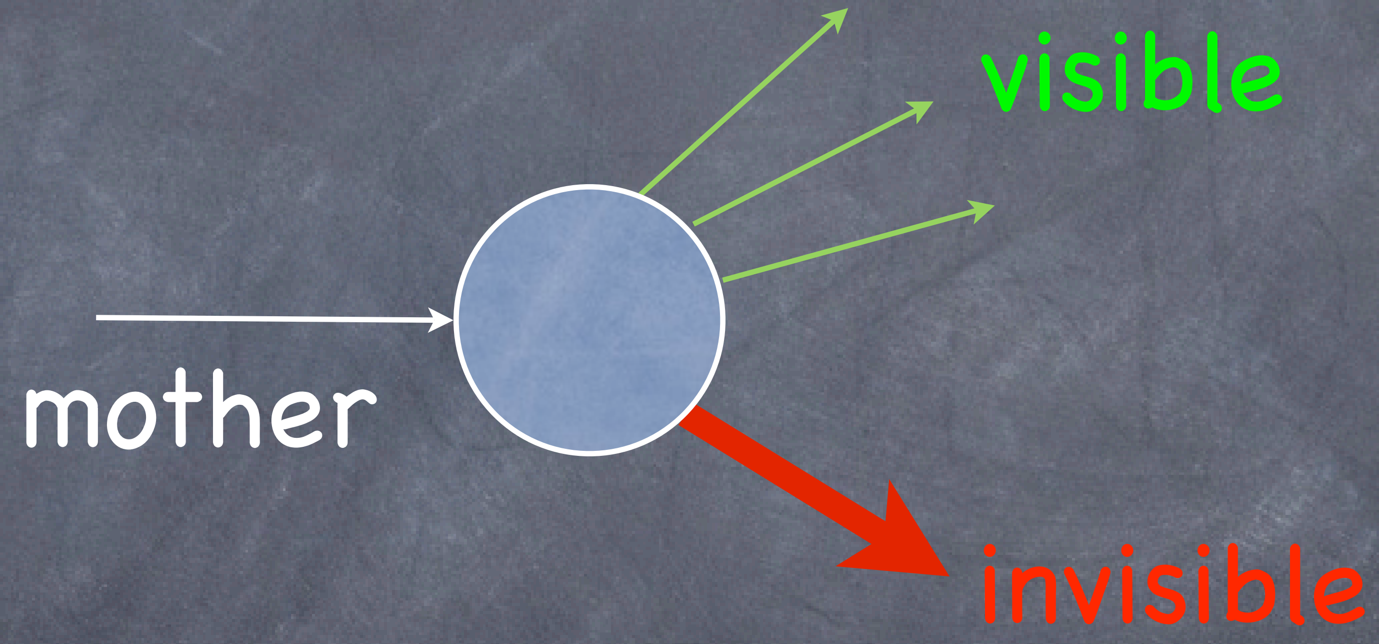
(with Doojin Kim, Roberto Franceschini, Kyle Wardlow: 1209.0772, 1212.5230 and to appear)

Basic goal

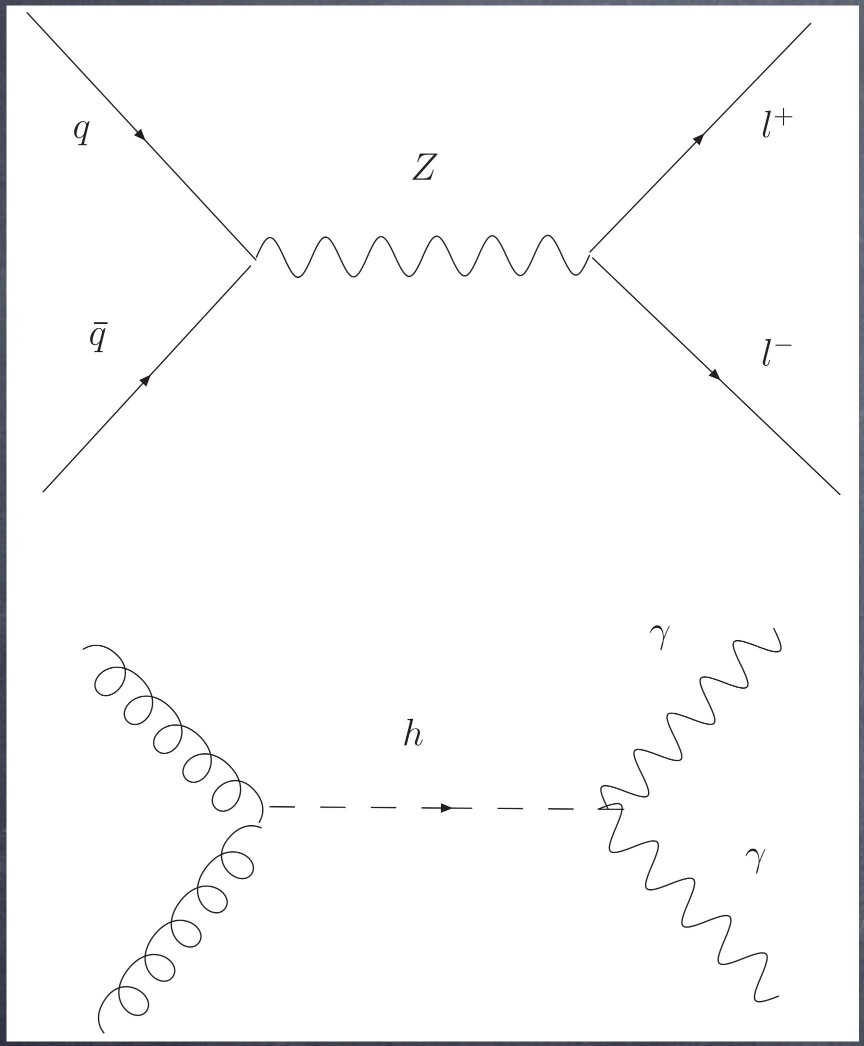
- determine mass of mother by measuring energy/momentum of (visible) decay products

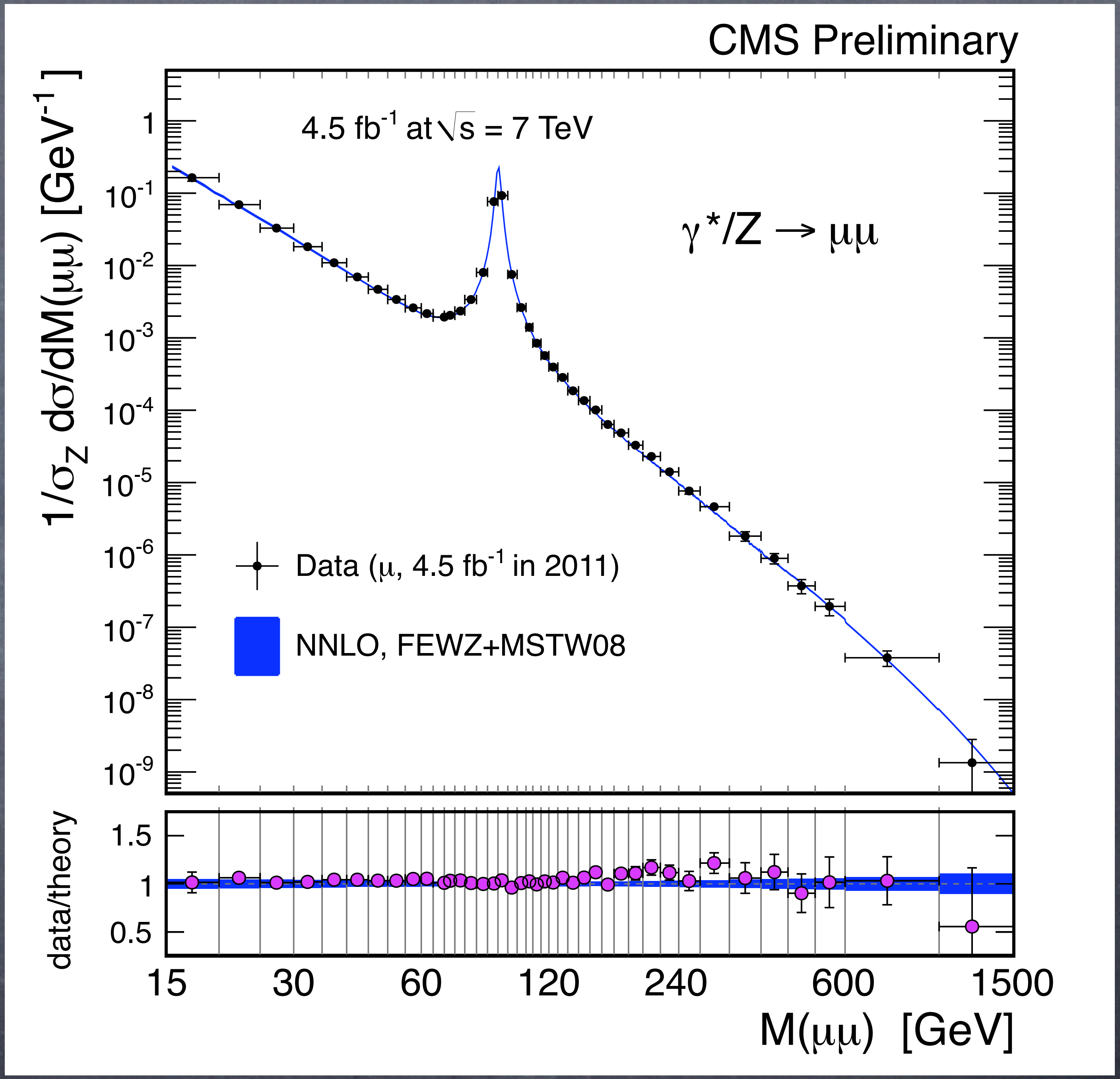


Techniques so far (many cases)

Fully visible I (``clean”)

- invariant mass of decay products has Breit-Wigner peak

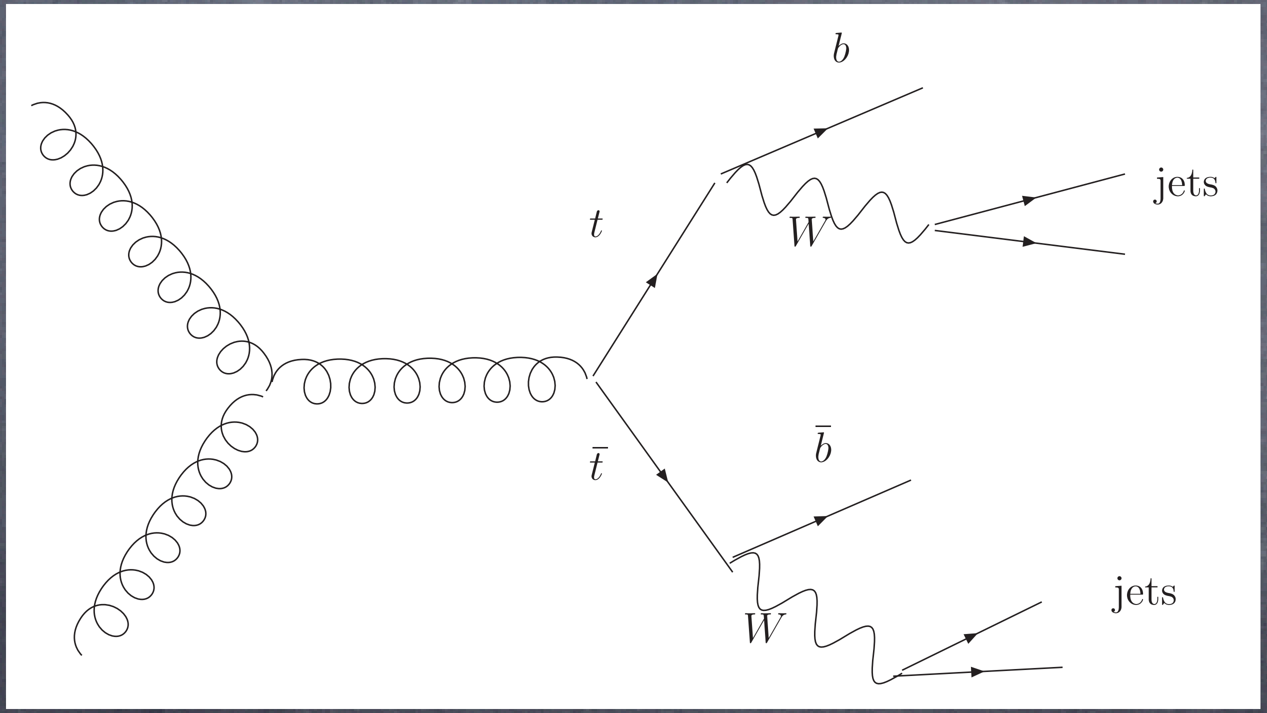




- have to be ``lucky”!

Fully visible II (not so clean)

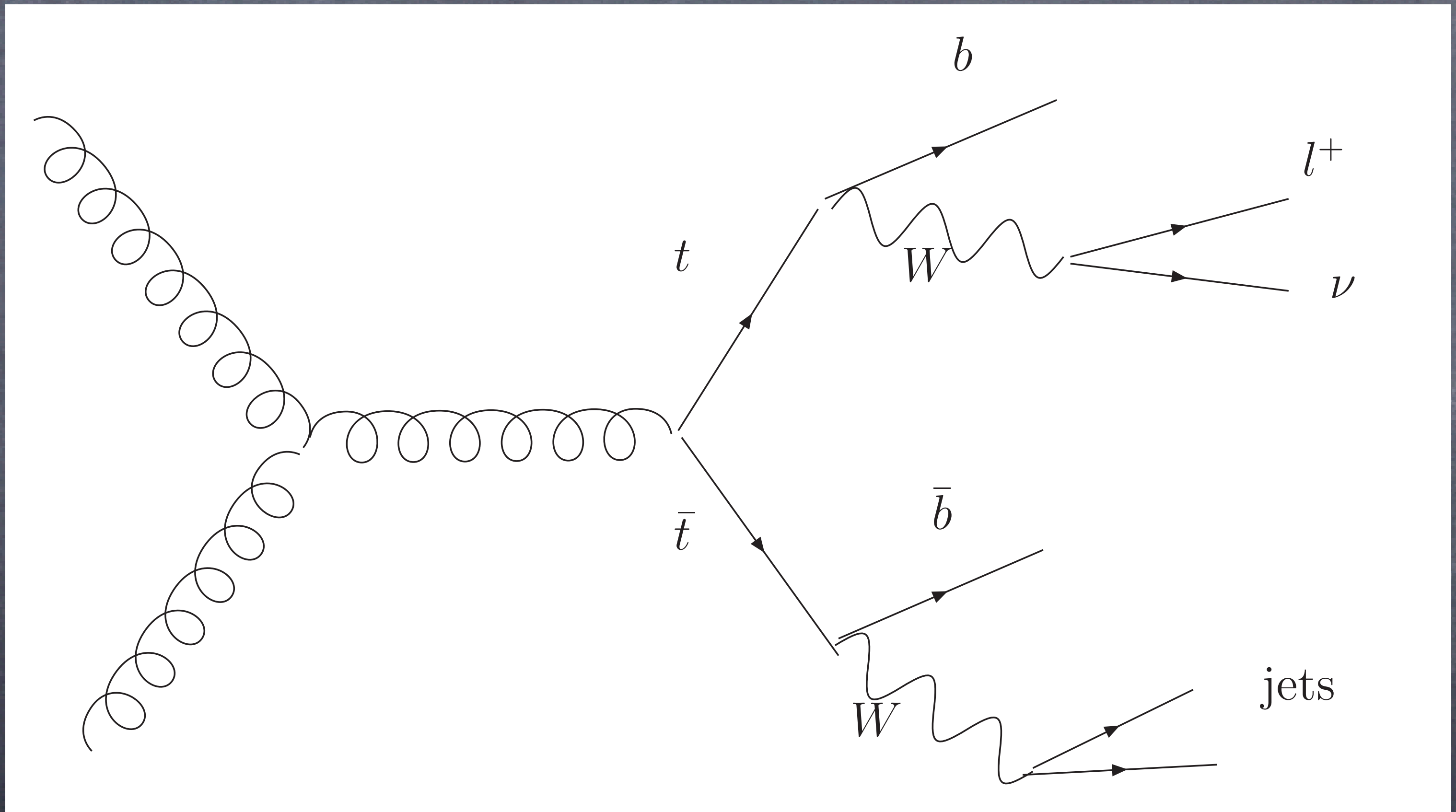
- fully hadronic top decay



- problem: combinatorics (especially with jets from initial state radiation)

``Partially" visible I (can be reconstructed)

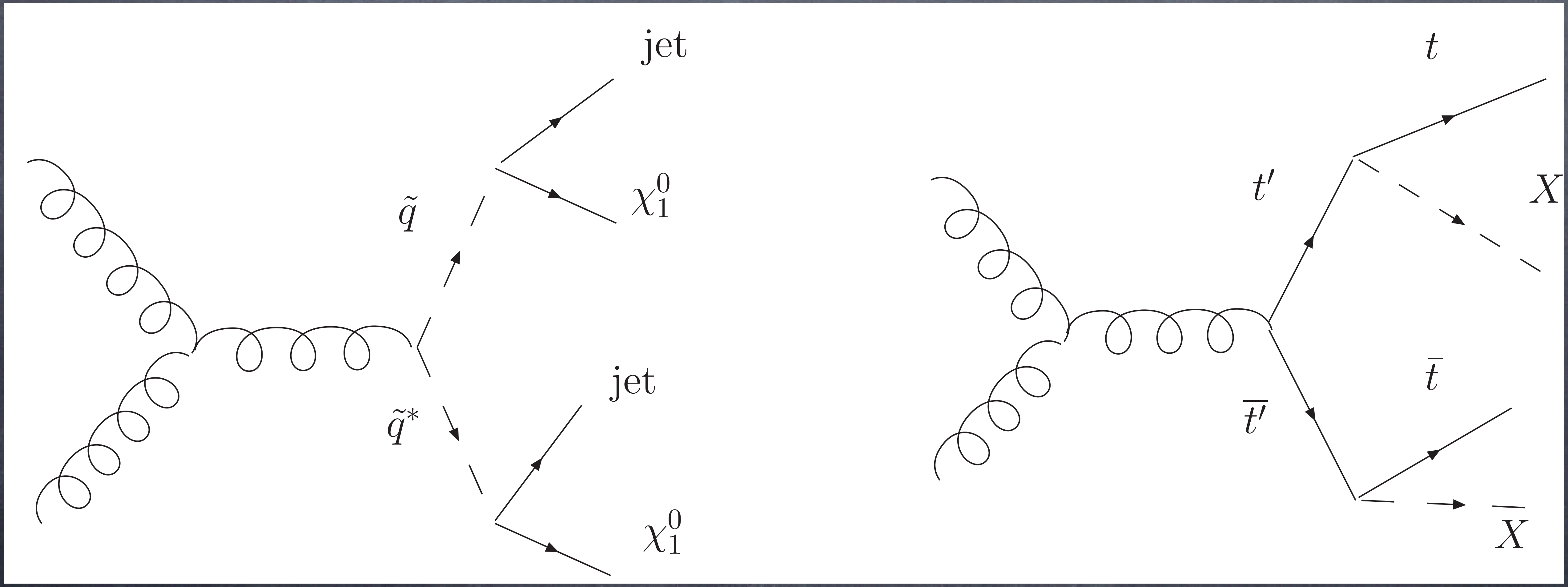
- 1 daughter fully visible, other partially
- semileptonic top decay (cleaner)



- problem: discrete ambiguity in reconstructing W; must use 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...



- Use transverse mass (M_{T2}): ``involved"; need MET...

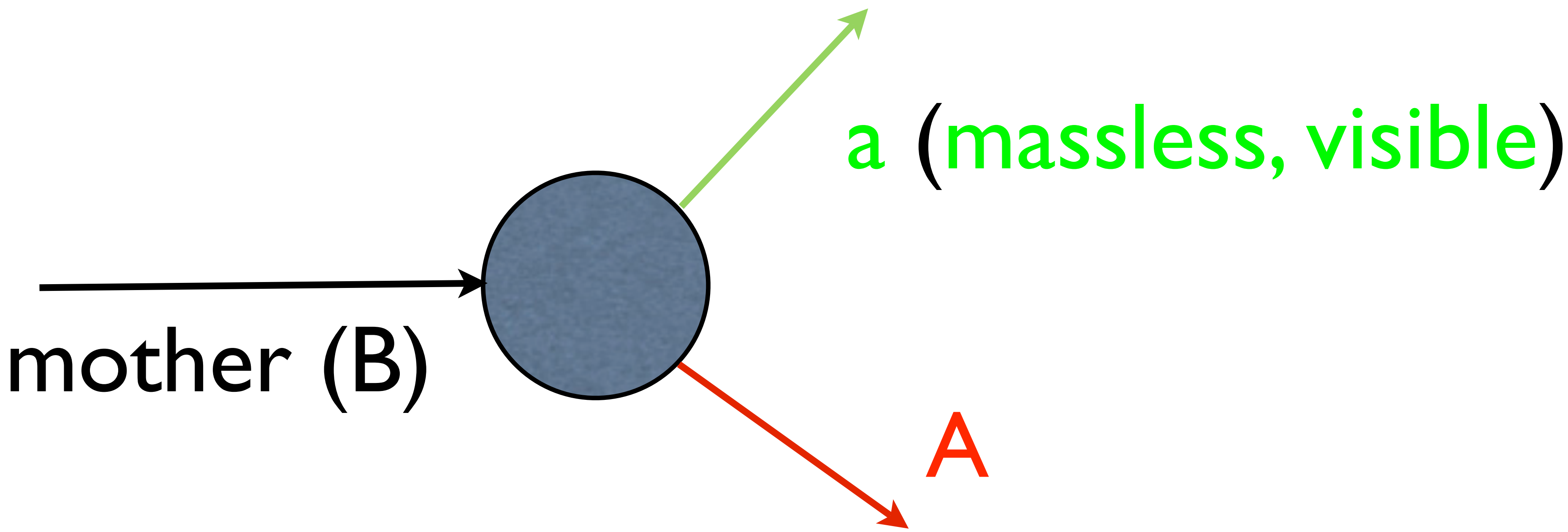
Bottomline: no slam dunk!

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

NEW OBSERVATION TECHNIQUE →

Basic assumptions

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



- ...other (A) don't care (almost)!
- more assumptions later
- extensions/generalizations later

Energy (not invariant) of daughter

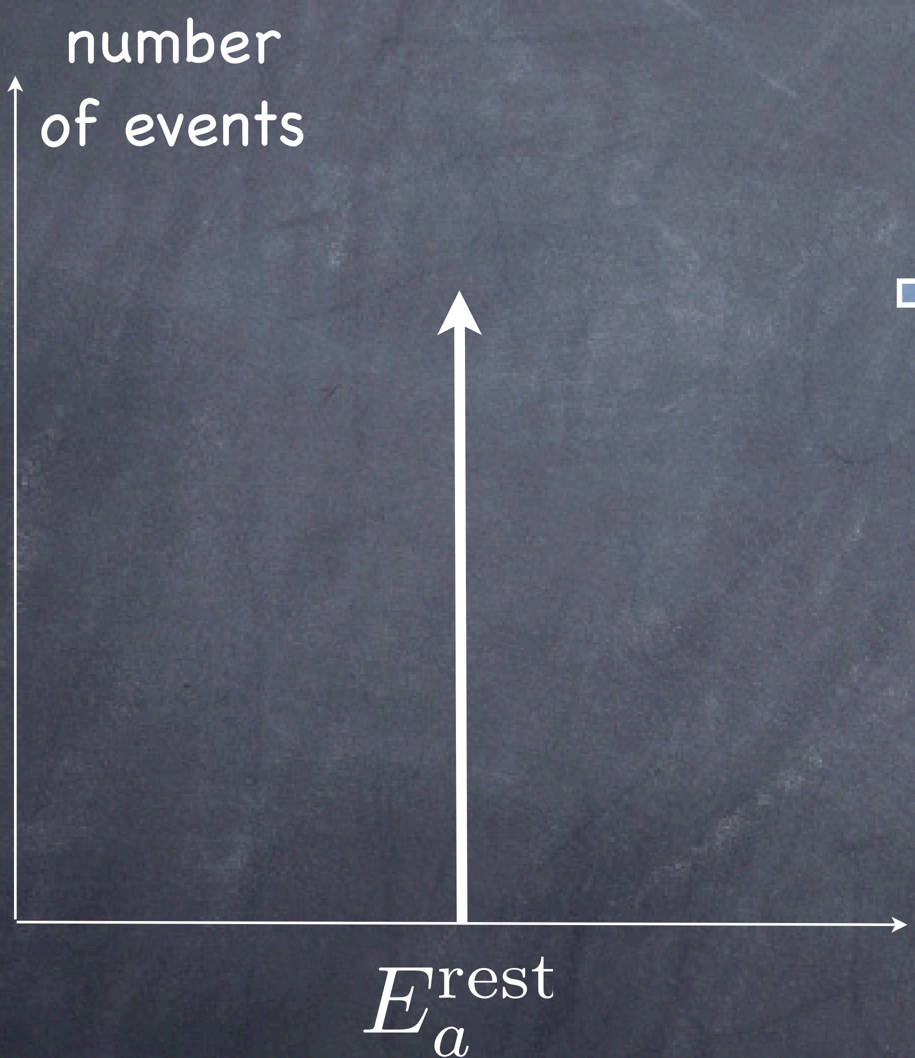
- simple function of masses in rest frame of mother:

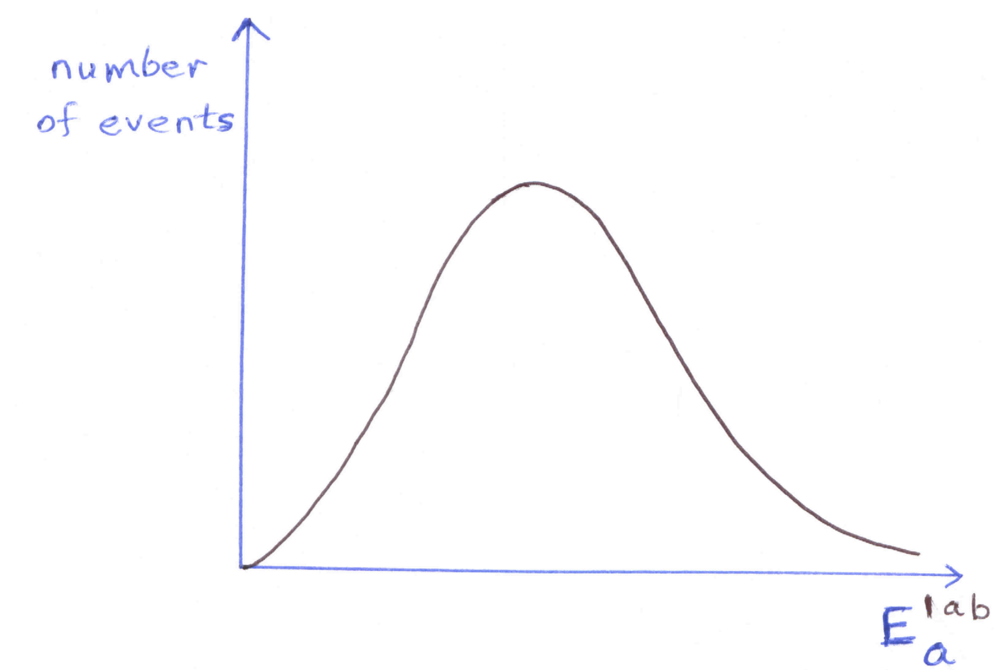
$$E_a^{\text{rest}} = \frac{M_B^2 - M_A^2}{2M_B}$$

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

…too simple to be practical/useful?!

- hadron collider: mother has unknown boost; varies event to event ⇒ distribution in E_a^{lab}

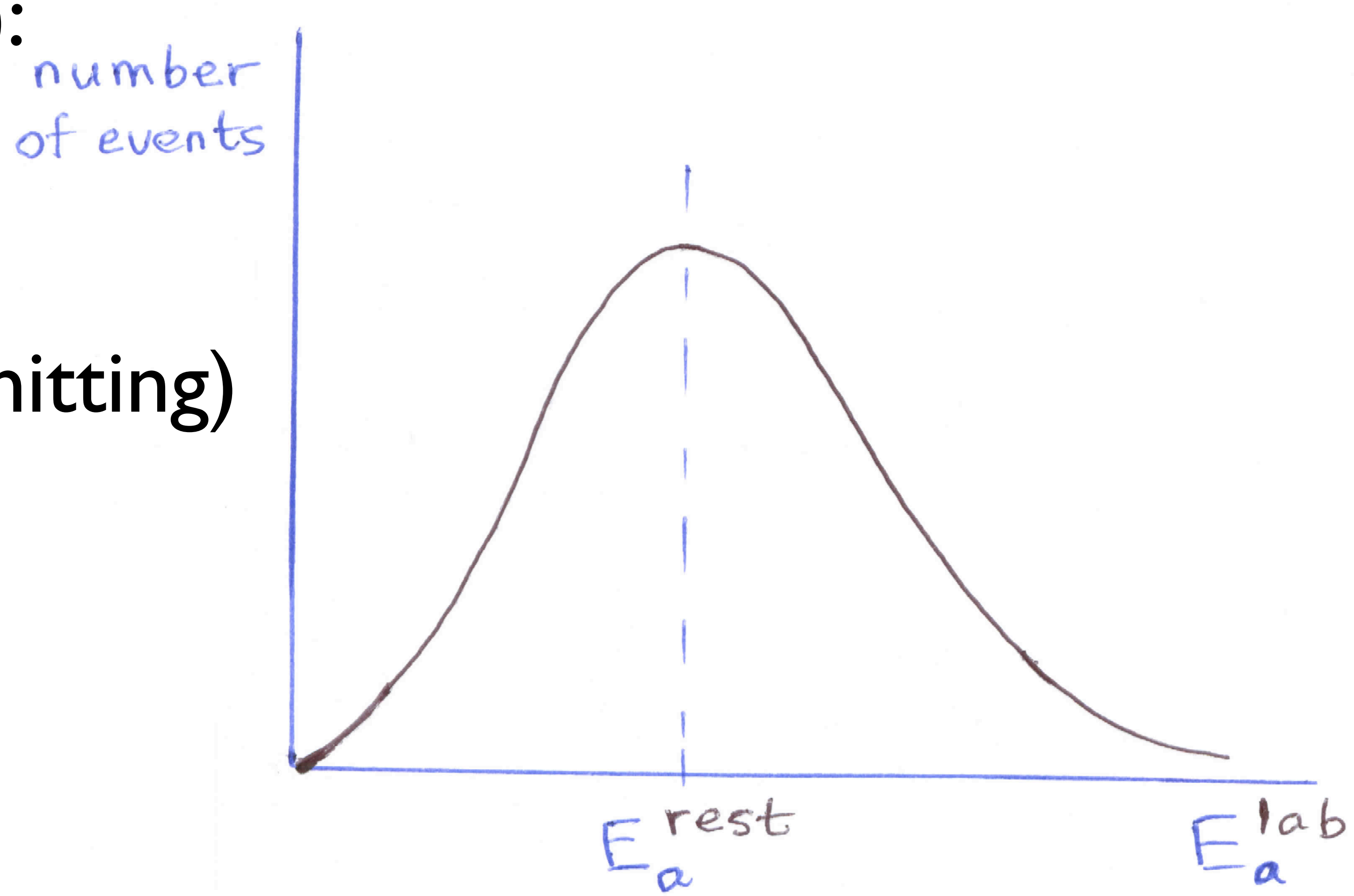




- lose rest-frame information?!

Outline

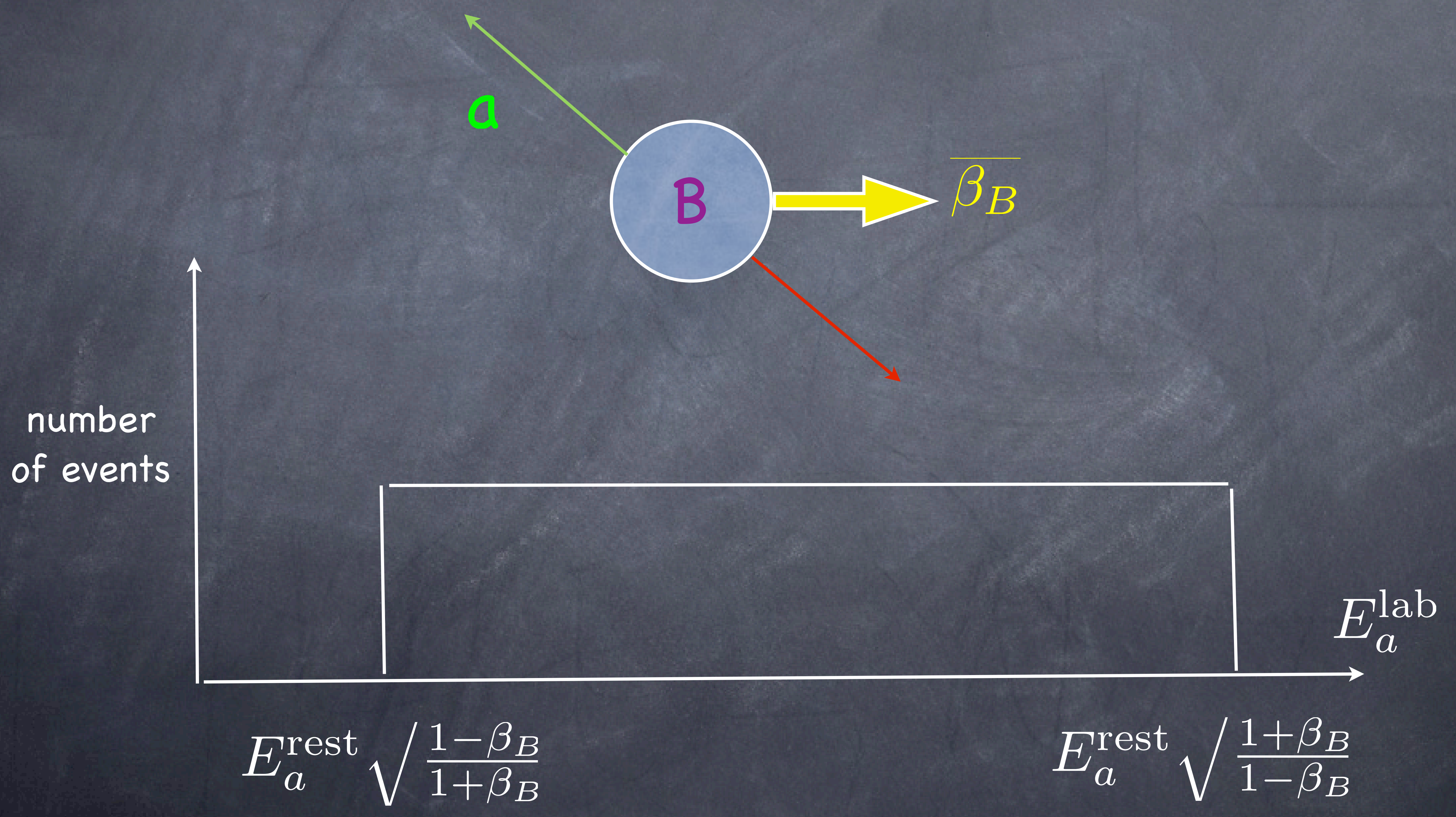
- Peak (of lab. distribution) still retains this information...as simply and precisely!
- ``Test'' application (top mass): obtain approximation to theory curve Fit it to (simulated) data for extracting peak
- New physics (Cascade decay): general SUSY example (preliminary)
- Three-body decay (time permitting)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



``Invariance'' of two-body decay kinematics

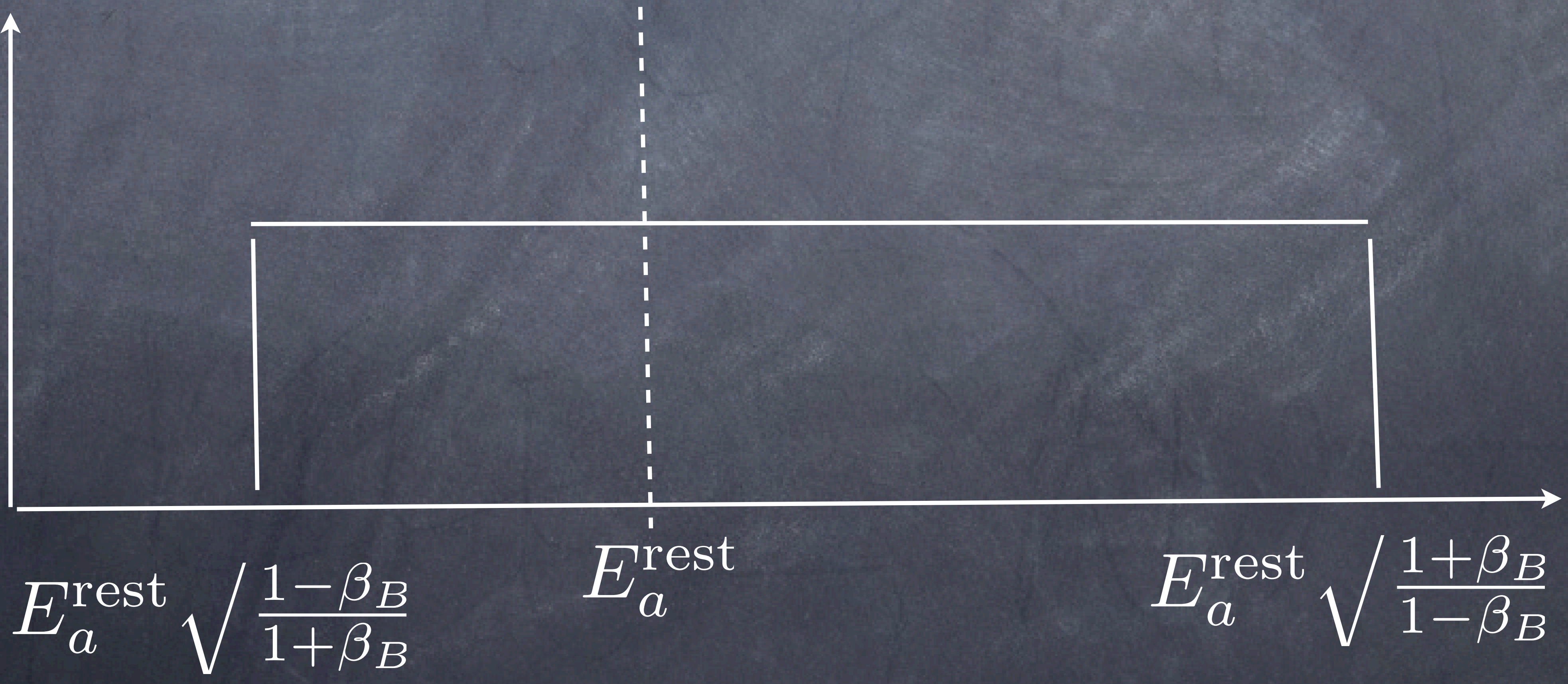
Rectangle for fixed, but arbitrary boost

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



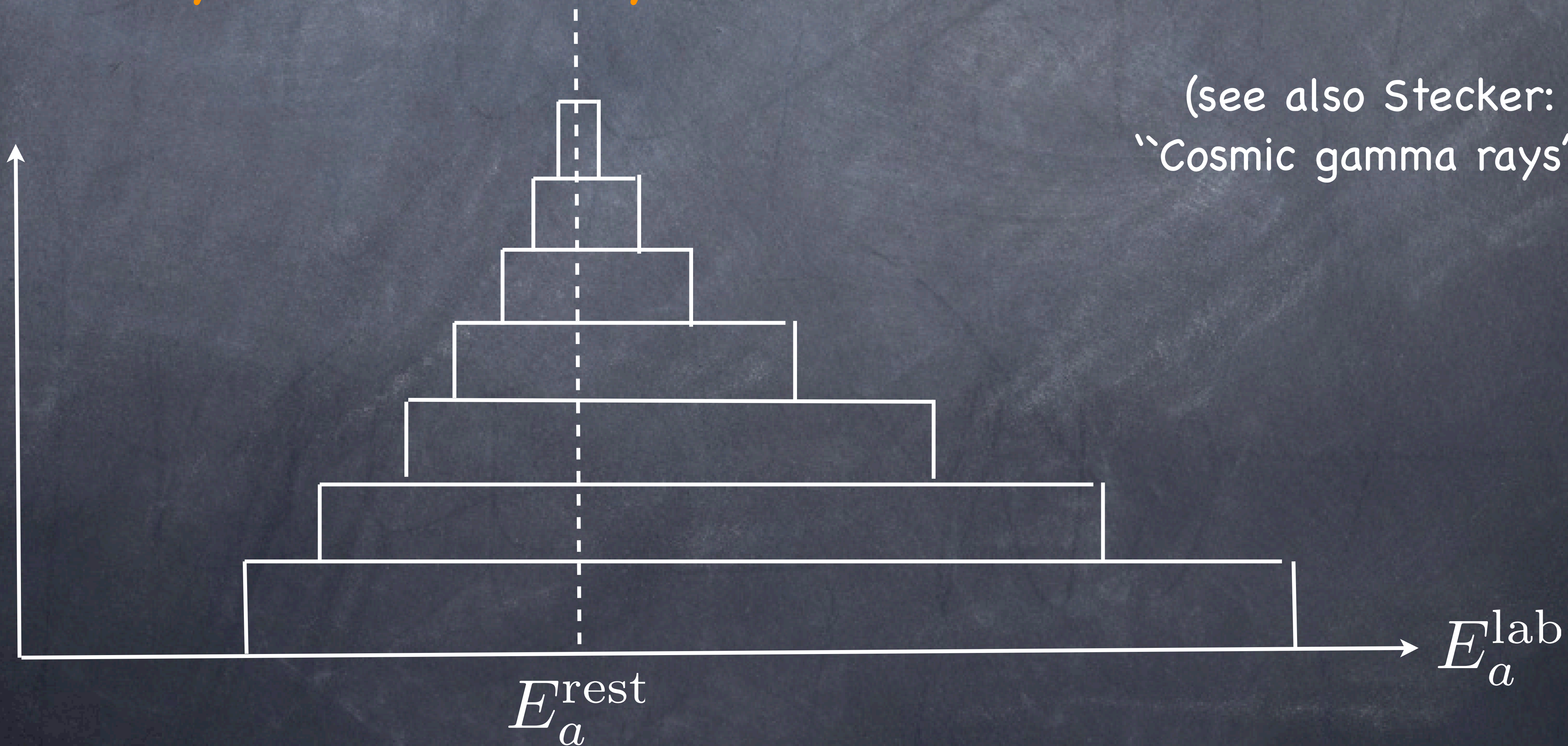
Rectangle vs. rest energy

- 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
- asymmetric on linear (symmetric on log...)



(Generic) Boost distribution: ``stacking'' up rectangles

- 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, mother mass, PDF's...



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

How to "avoid" plateau

- Boost distribution does not vanish close to $\gamma_B = 1$

``Massive'' daughter

- argument goes thru' (rectangle contains E_a^{rest}...) even for massive daughter if boost distribution restricted to $\gamma_B < \left[2 \left(\gamma_a^{\mathrm{rest}} \right)^2 - 1 \right]$
- This critical boost is typically large value for massive, but ``light'' daughter

Formal proof

- Single Rectangle ($x = \frac{E_a^{\rm lab}}{E_a^{\rm rest}}$) :

$$\frac{1}{\Gamma}\frac{d\Gamma}{dx}\Big|_{\text{fixed }\gamma_B} = \frac{\Theta\left(x-\gamma_B+\sqrt{\gamma_B^2-1}\right)\Theta\left(-x+\gamma_B+\sqrt{\gamma_B^2-1}\right)}{2\sqrt{\gamma_B^2-1}}$$

- Stacking up rectangles:

$$f(x) \equiv \frac{1}{\Gamma}\frac{d\Gamma}{dx} = \int_{\frac{1}{2}\left(x+\frac{1}{x}\right)}^{\infty} d\gamma_B \frac{g(\gamma_B)}{2\sqrt{\gamma_B^2-1}}$$

- Slope:

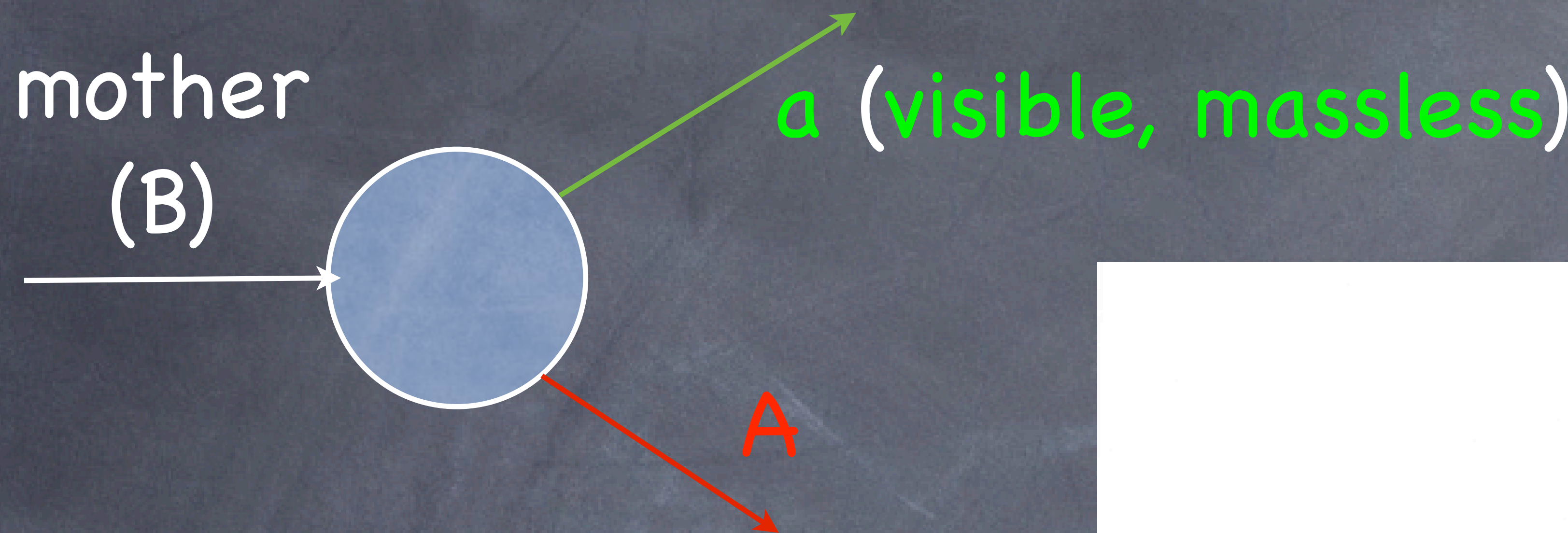
$$f'(x) = \frac{\text{sgn}(1-x)}{2x} g\left(\frac{1}{2}\left(x+\frac{1}{x}\right)\right)$$

- Behavior at x = 1:

$f'(x=1) \propto g(1) = 0 \Rightarrow$ extremum or
$f'(x)$ flips its sign at $x = 1 \Rightarrow$ a cusp
$f(x)$ is positive and vanishes for both $x \to 0$ and $x \to \infty$
$\Rightarrow$ peak at $E_a^{\rm rest}$

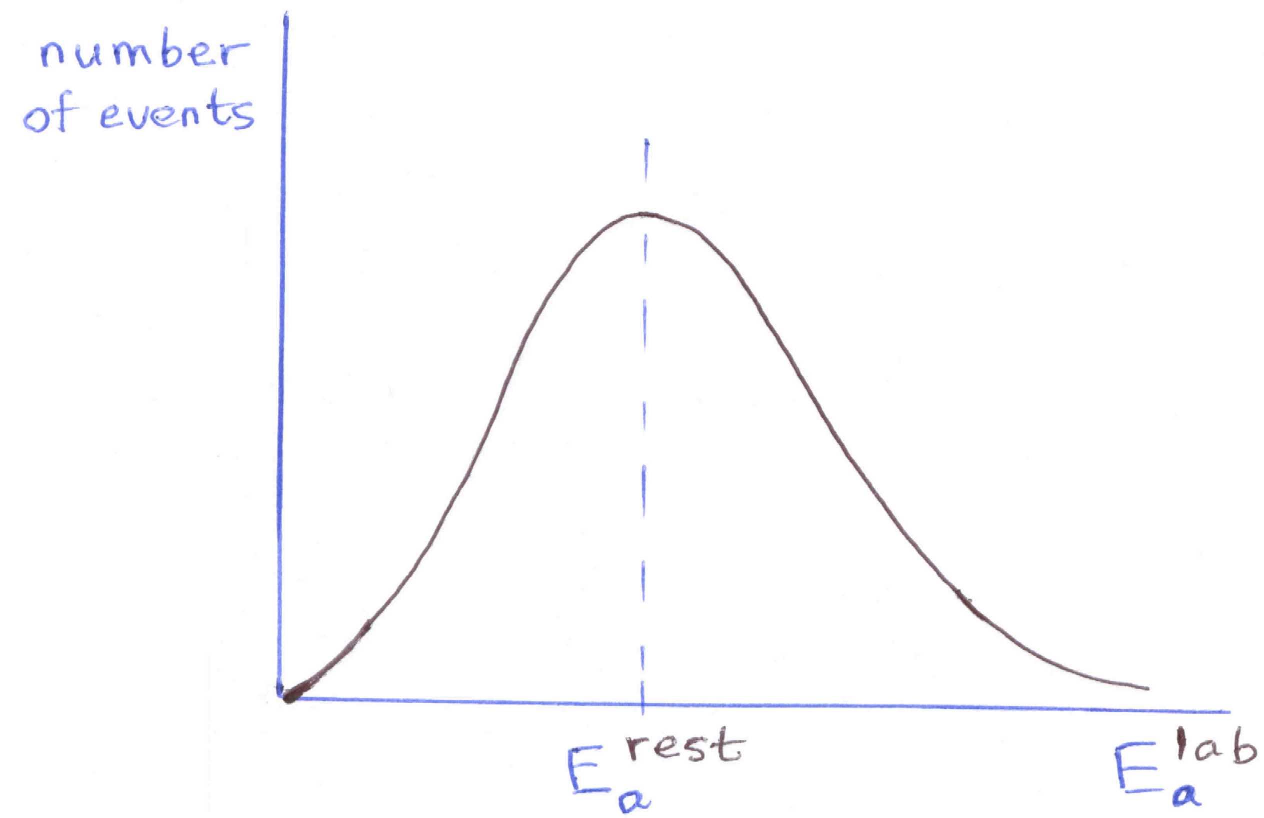
(POSSIBLE) APPLICATIONS

General Idea



- determine M_B (if M_A known) using $E_a^{\rm rest}$ (measured from peak in $E_a^{\rm lab}$)

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



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, analytic function)
- ...but exact, analytic formula difficult to obtain here
  (depends on boost distribution, thus PDF's...)

Approximation to theory curve

Do know (analytically) properties of distribution

- value of $f(x)$ remains the same under $x \leftrightarrow \frac{1}{x}$
- f is maximized at $x = 1$
- f vanishes as x approaches 0 or ∞
- f becomes a δ-function in some limit of its parameters

Ansatz (based on properties)

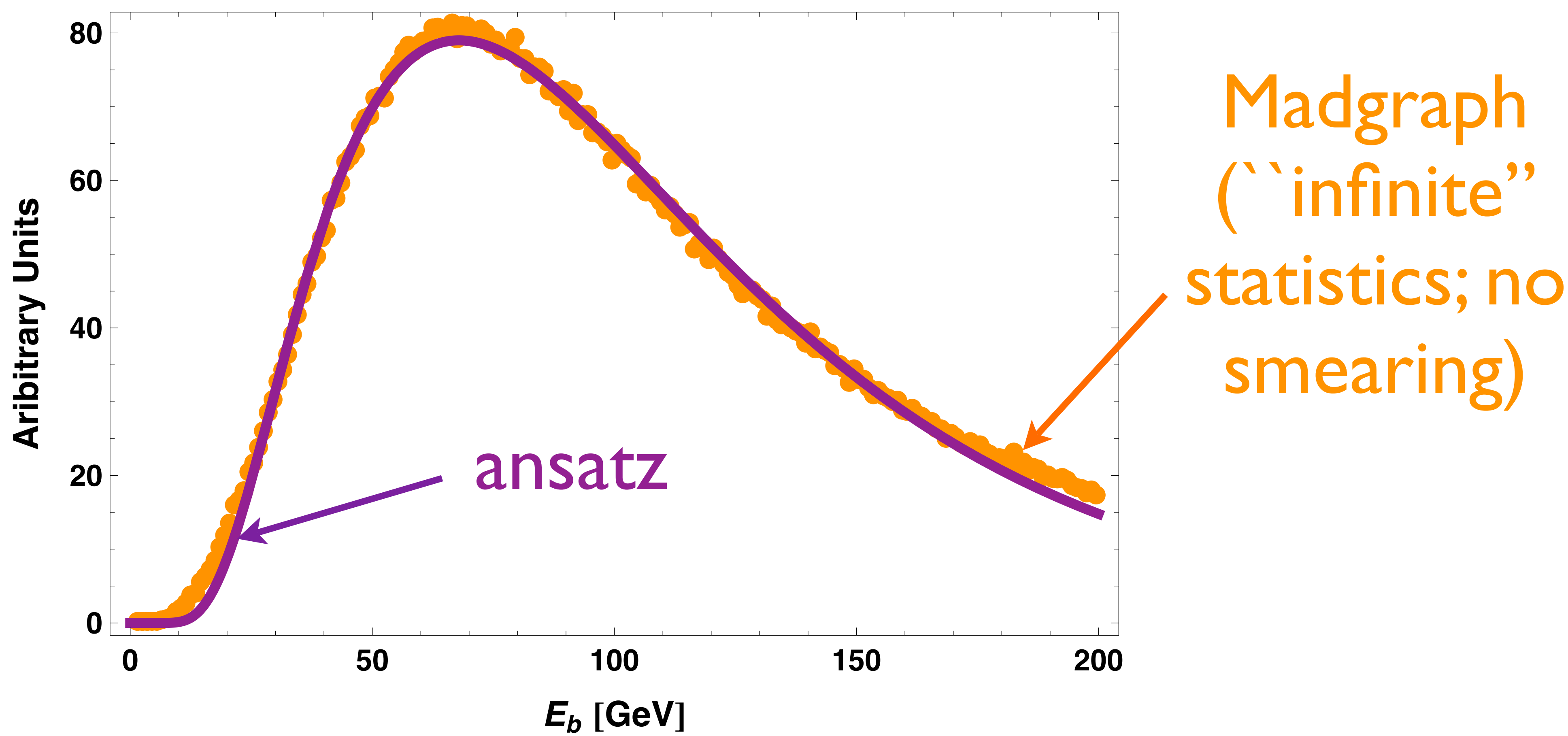
width parameter

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

Bessel function

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

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



- bottom ``massless": $\gamma_b^{\text{rest}} \approx 15 \Rightarrow \gamma_{\text{top}} \lesssim 500$ suffices
- good fit for heavier ``top" quark as well: different PDF's, boost distribution (width parameter encompasses this variation)

"New" Breit-Wigner

- Based on theory fits, assume

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

Further test: fit to (simulated) data

(Again) Top quark decay: basic idea

neglect m_b in E_b^{rest}

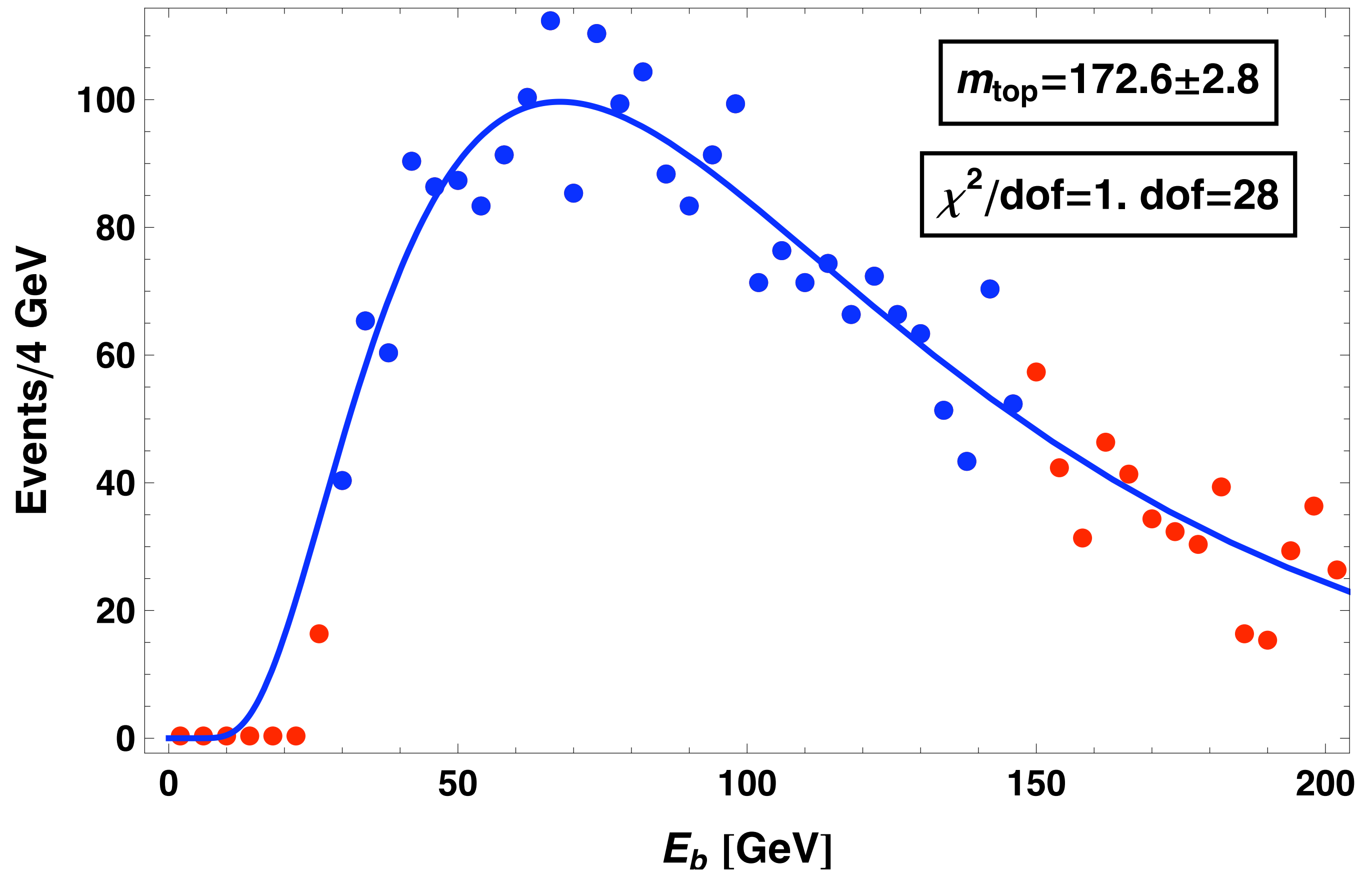
- Peak in measured b-jet energy distribution $\approx \frac{M_t^2 - M_W^2}{2M_t}$
- Assuming M_W (but no need to detect it at all!), get M_t

Top mass measurement: details

- Fully leptonic with 5/fb at LHC7
- Madgraph $\longrightarrow$ Pythia $\longrightarrow$ Delphes/Fastjet
- 100 pseudo-experiments
- ATLAS choice of cuts
- no background

Result

(1 pseudo-experiment shown)

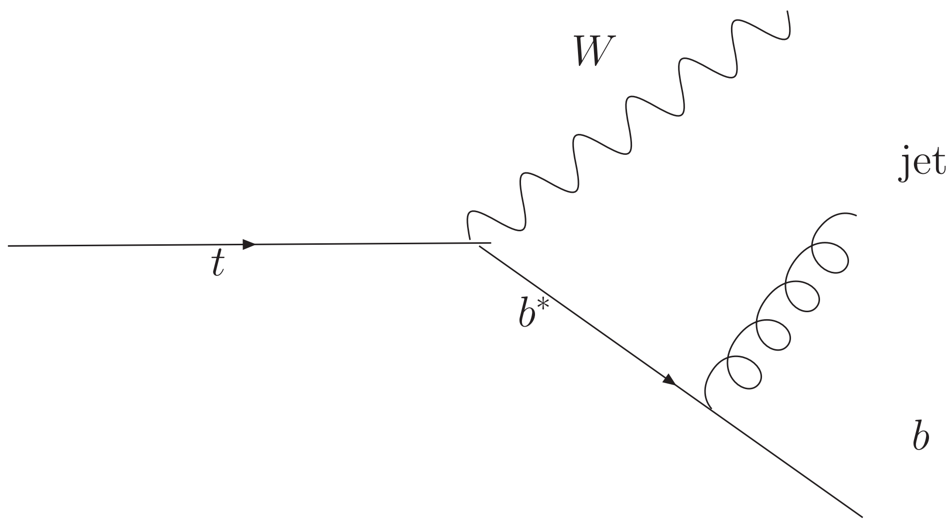


(use only blue dots)

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

Discussion

- neglect hard radiation from bottom (3-body): suppressed by α_s/π + jet-veto

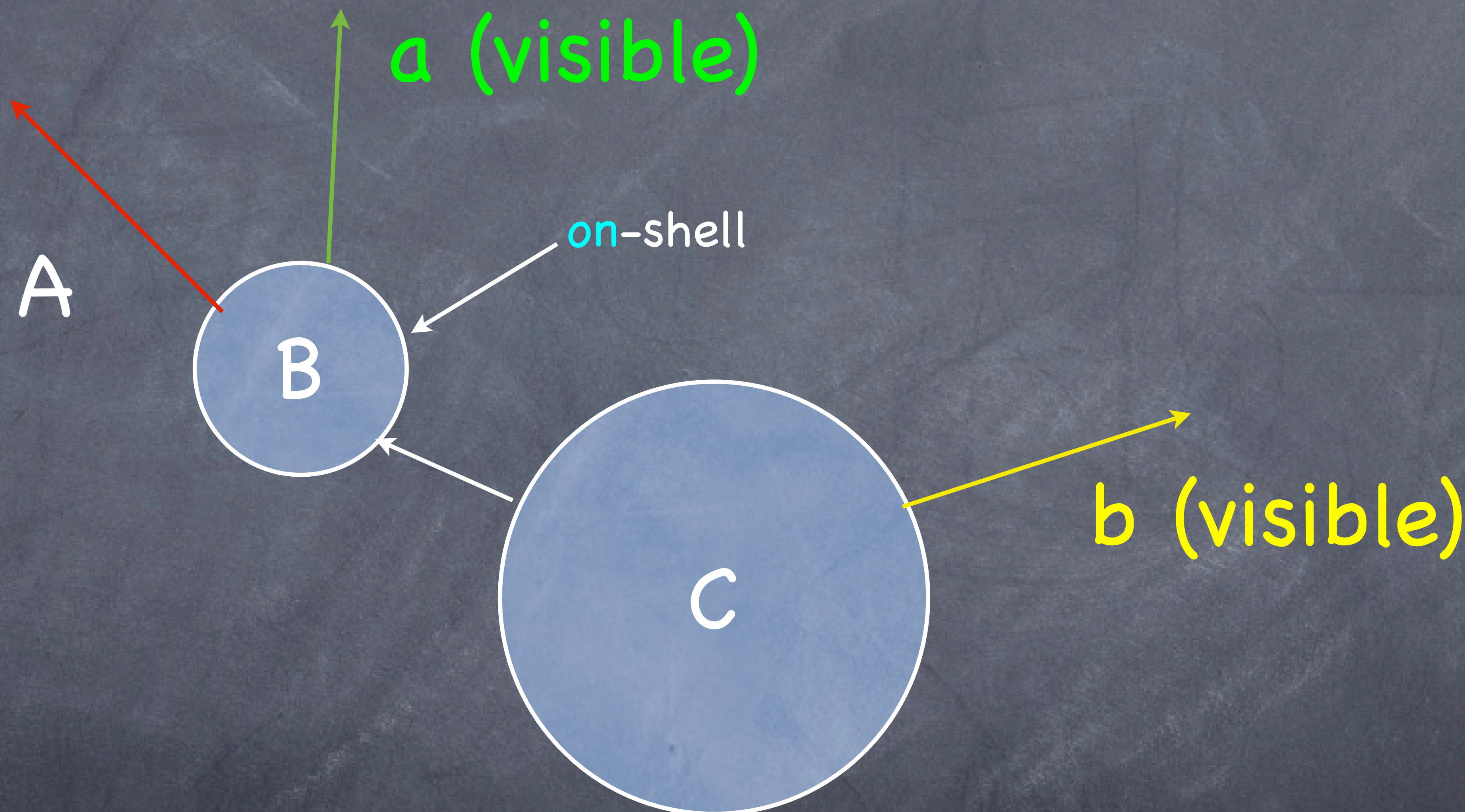


- safe from soft radiation off of bottom
- safe from ISR (include both b's)
- no combinatorics
- independent of production mechanism (single or pair) as long as unpolarized (cf. matrix element method)

A NEW PHYSICS APPLICATION: CASCADE DECAY

In General: Topology

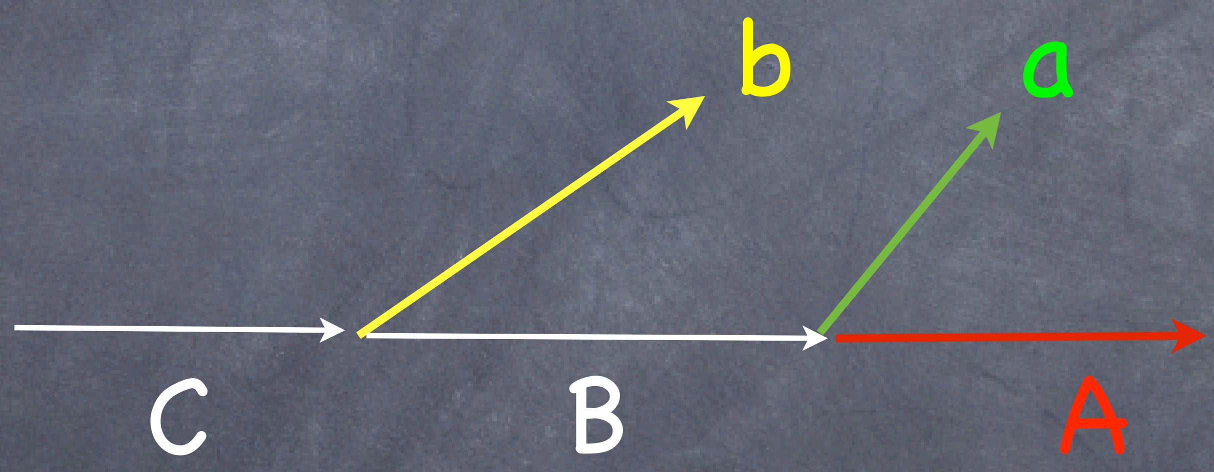
- Two 2-body decays: primary (C) and secondary (B) mothers)



Two energy peaks

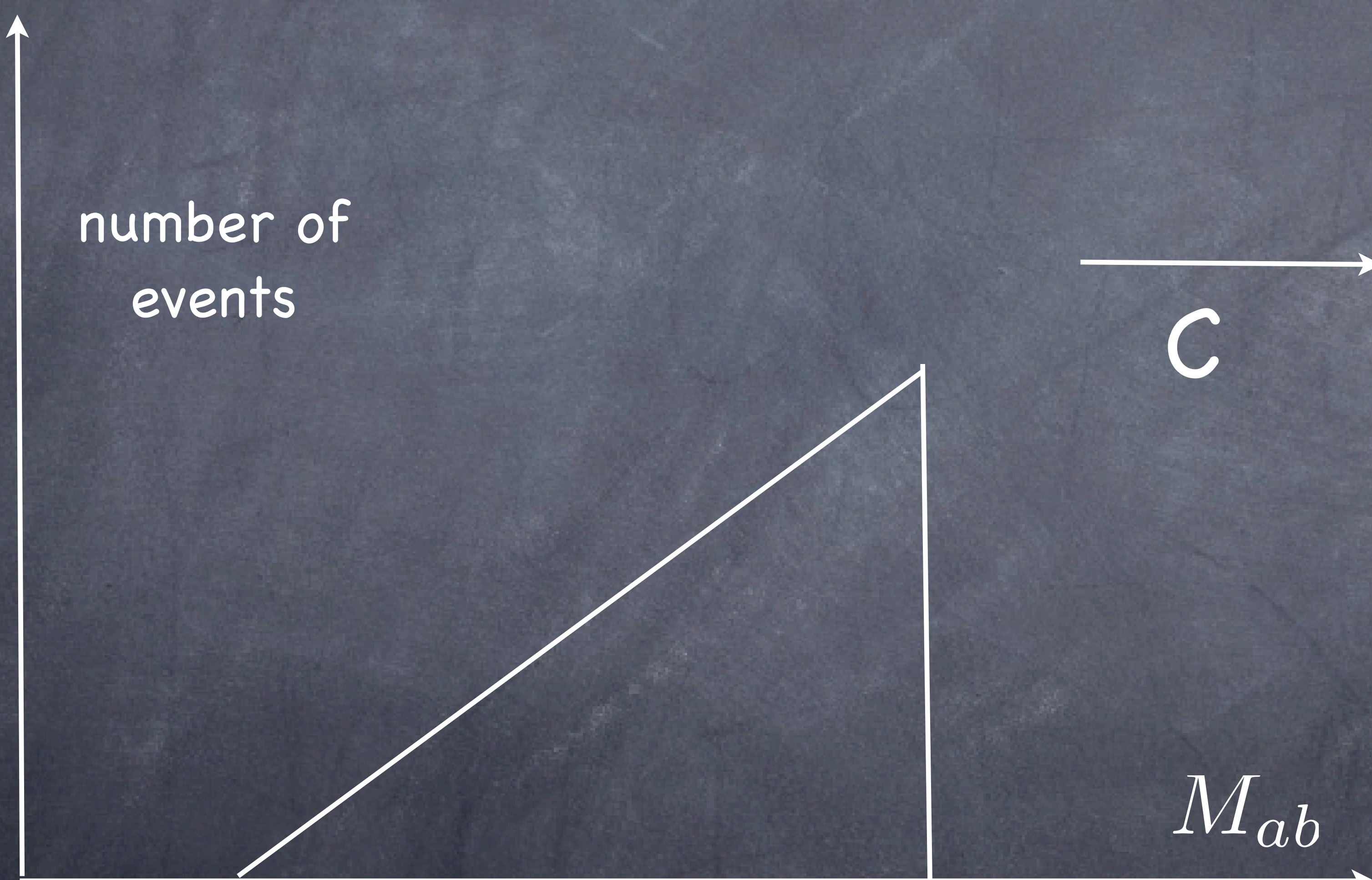
- Based on new observation:

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

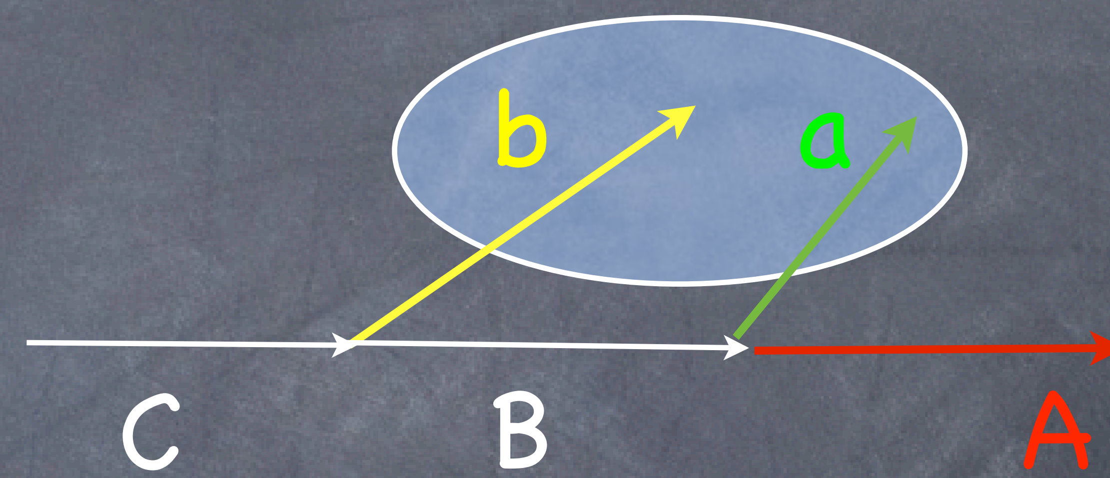


Edge in invariant mass (old)

- On-shell intermediate particle ⇒ (sharp) edge



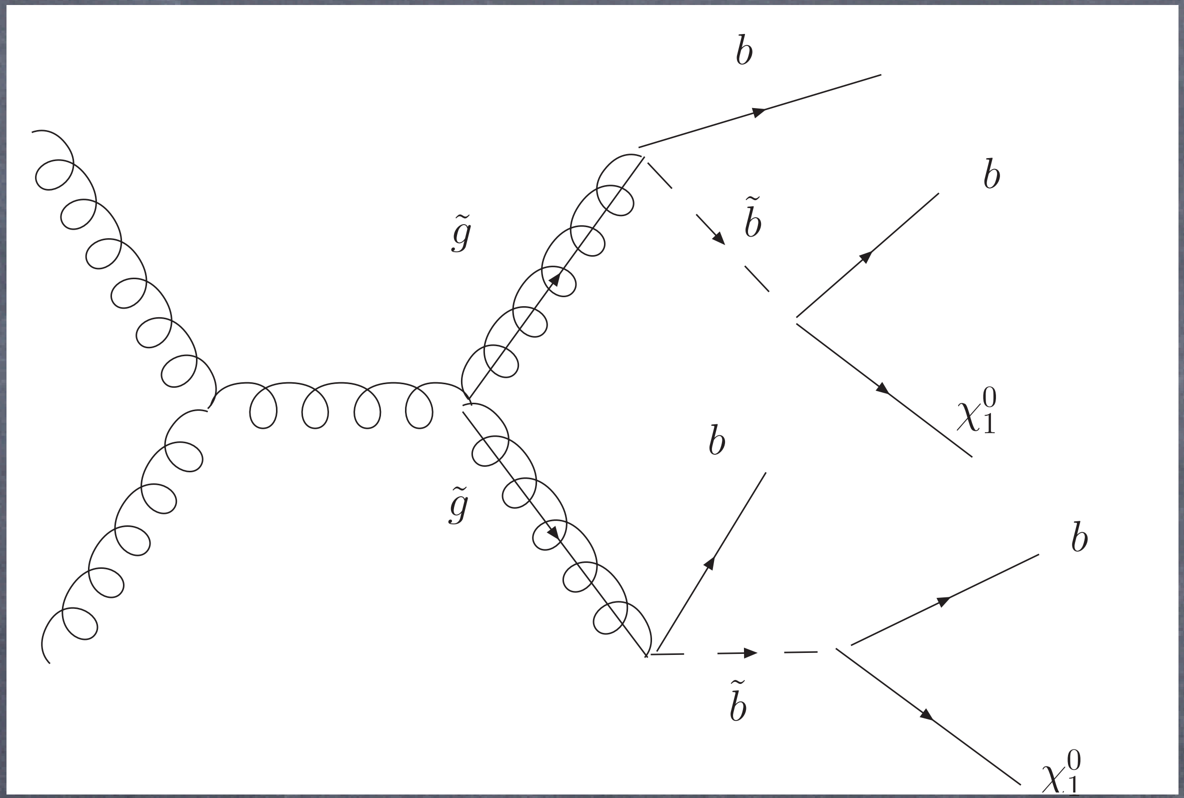
$$\sqrt{\frac{\left(M_C^2 - M_B^2\right)\left(M_B^2 - M_A^2\right)}{M_B}}$$



= 3 (independent) observables for determining 3 masses!

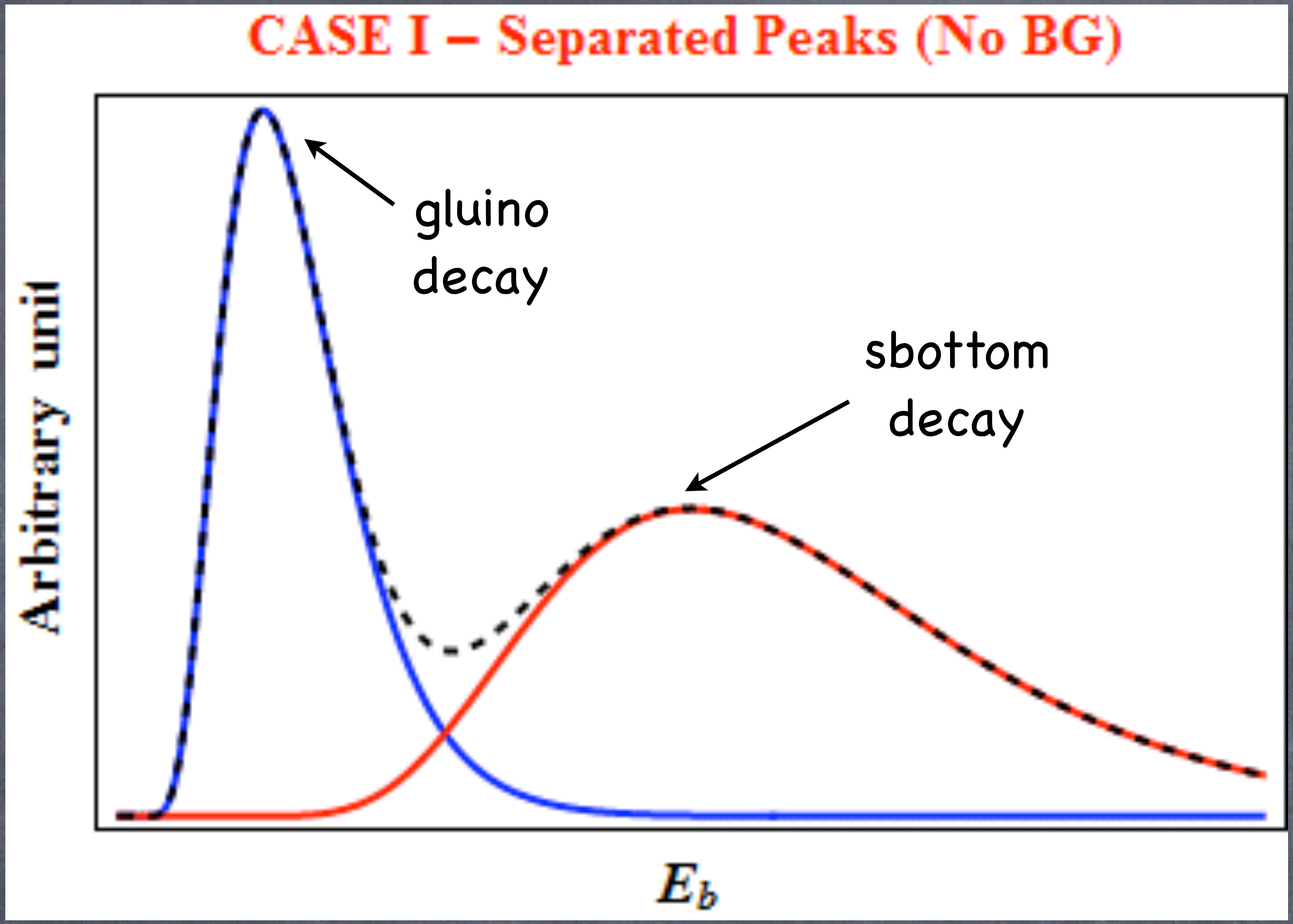
Cascade decay in SUSY
(preliminary)

Gluino, sbottom, neutralino



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

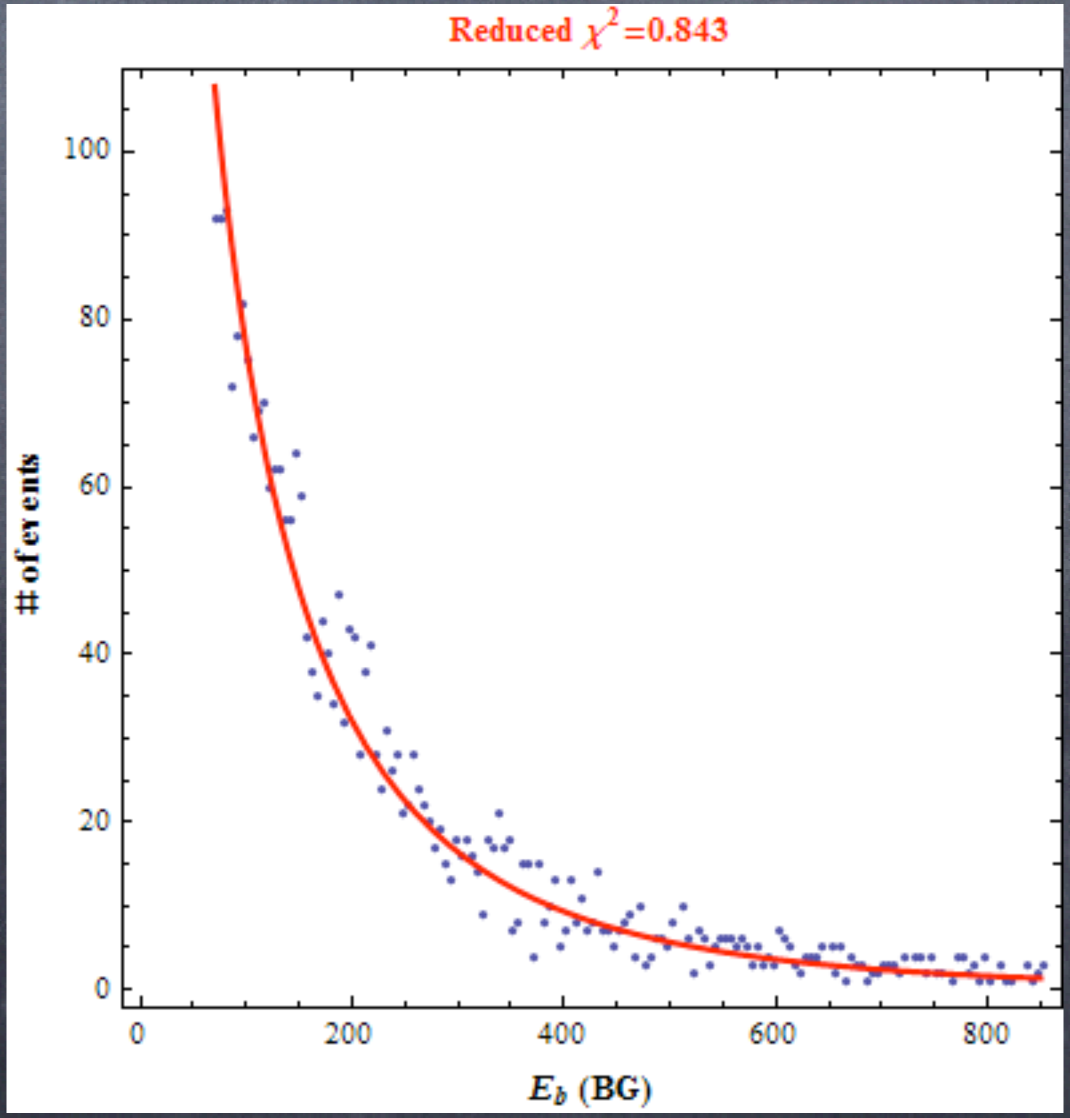
Double (b-jet energy) peak



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

Background

- $\bar{t}t\bar{b}b$ reducible and $Z+4b$ irreducible
- template for background: $N_{p'} \exp\left(-p'\sqrt{E}\ \right)$

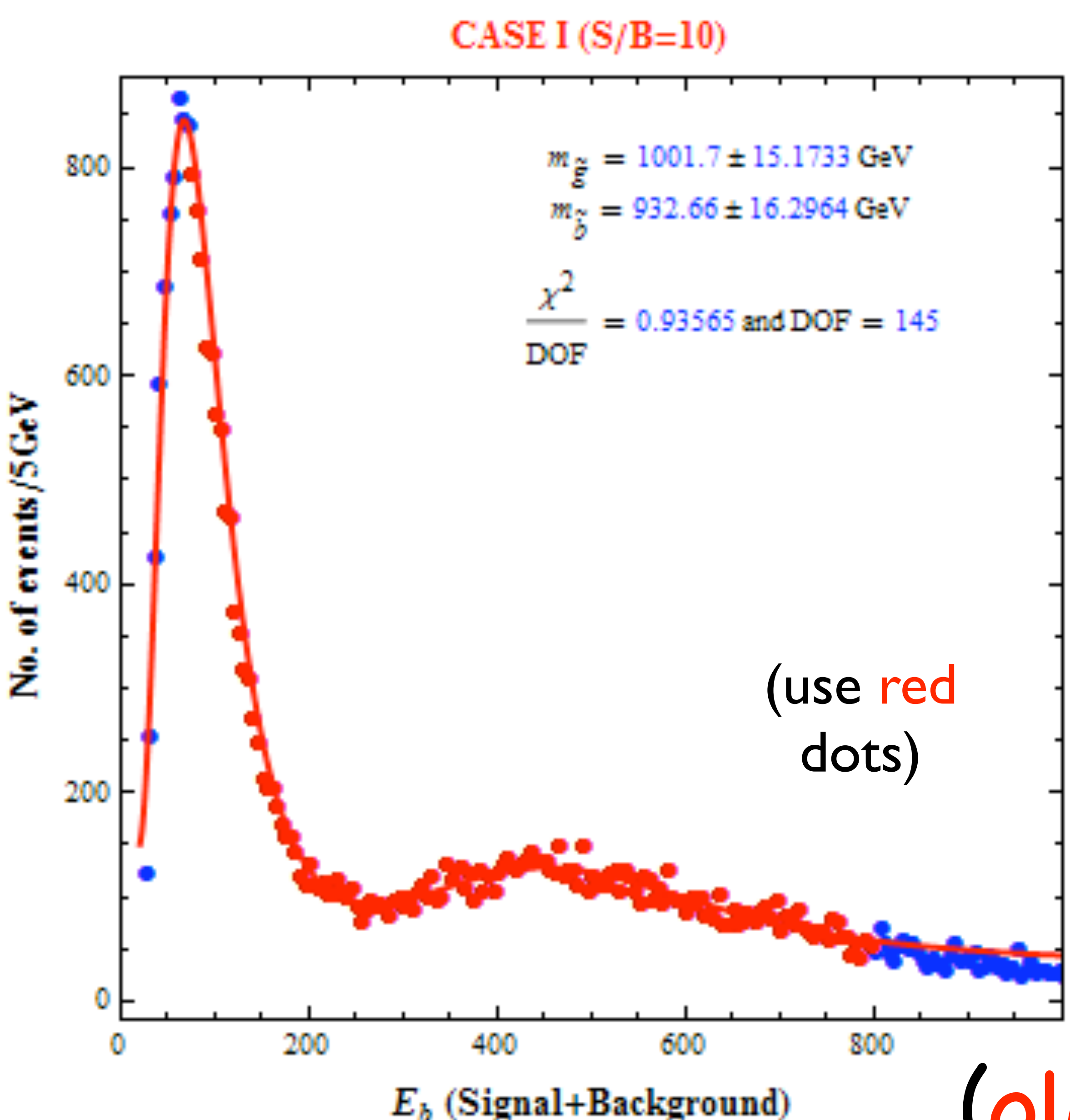


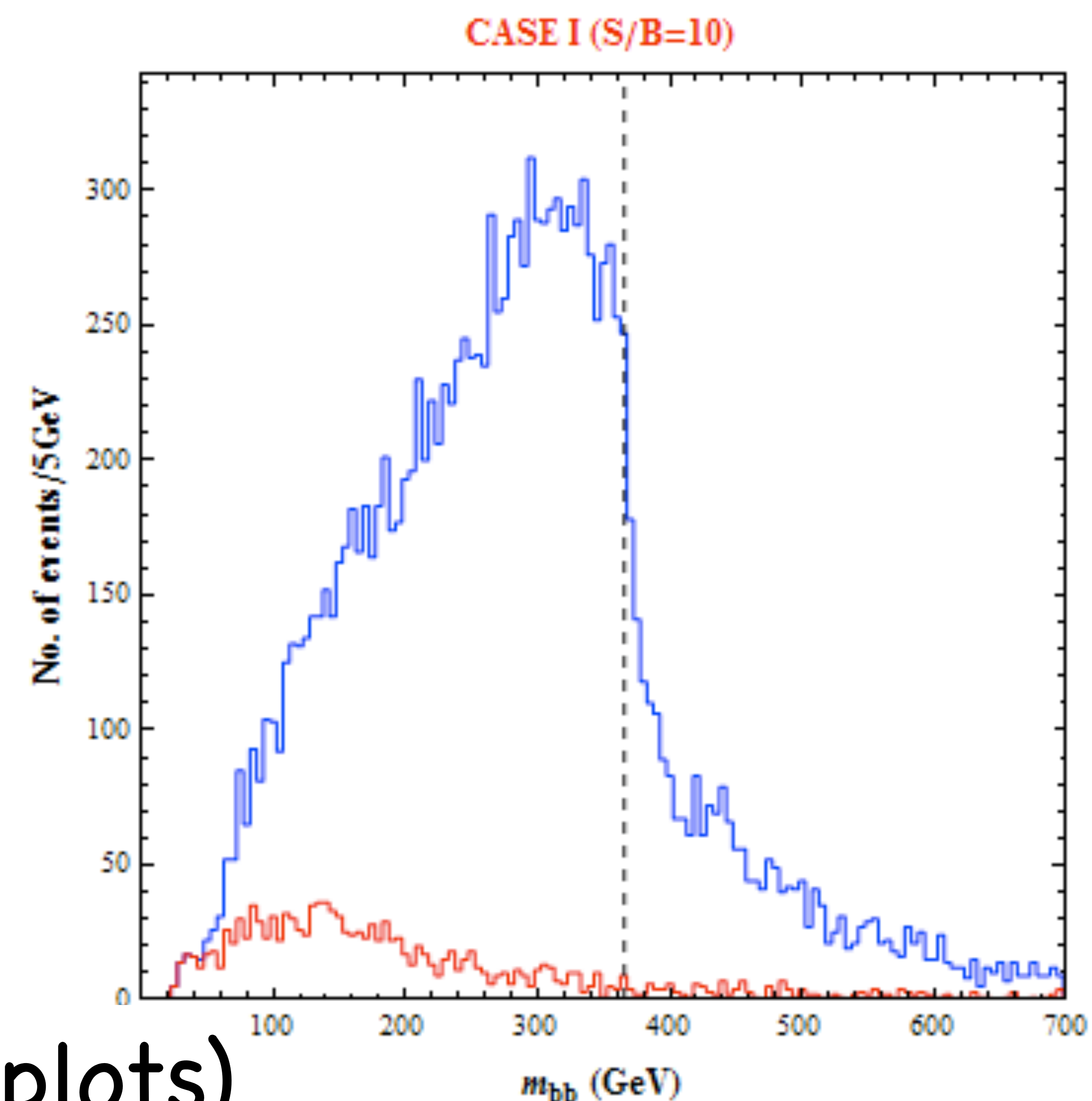
$Z+4b$

(old plot)

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)
- no sensitivity to $M_{\chi_1^0}$: $2\sqrt{E_b^{\text{peak 1}} E_b^{\text{peak 2}}} \approx M_{bb}^{\text{max}}$





(old plots)

➡ ansatz/fitting function works for (boost distribution of) a ``secondary" mother as well!

Conclusions

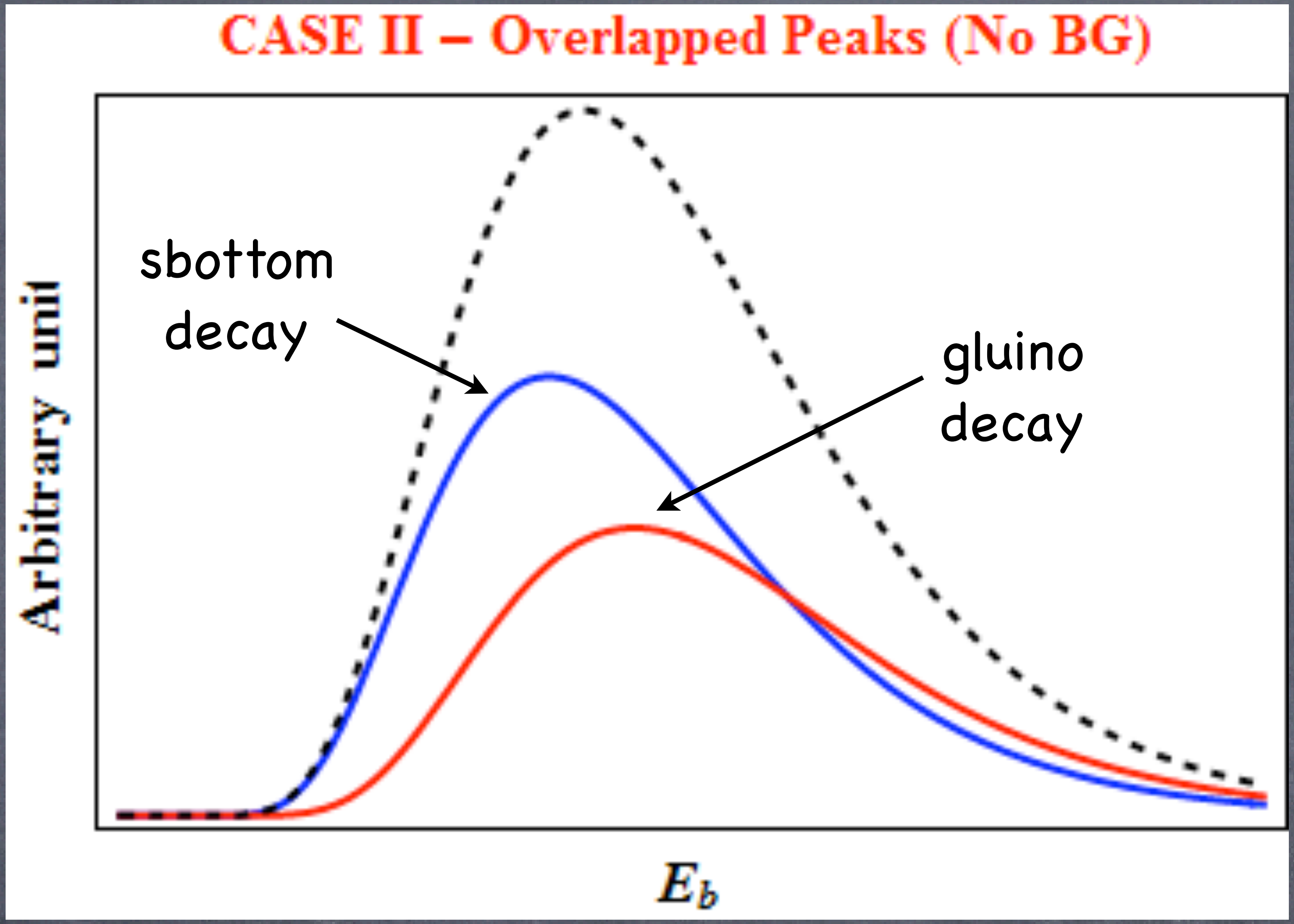
- Two body decay of unpolarized mother at hadron colliders:
  peak in energy distribution of massless daughter same as rest frame energy (simple function of masses)
- Obtain approximation to theory curve (for fitting to data to extract peak)
- Application(s):
  top quark mass (test)
  new particles decaying semi-invisibly: extract all masses from cascade decay (e.g., gluino to sbottom...)

BACK-UP

Another spectrum: sensitivity to neutralino mass

- mass hierarchy: $M_{\tilde{g}} \gg M_{\tilde{b}} \gtrsim M_{\chi_1^0}$ ⇒ both b-jets hard

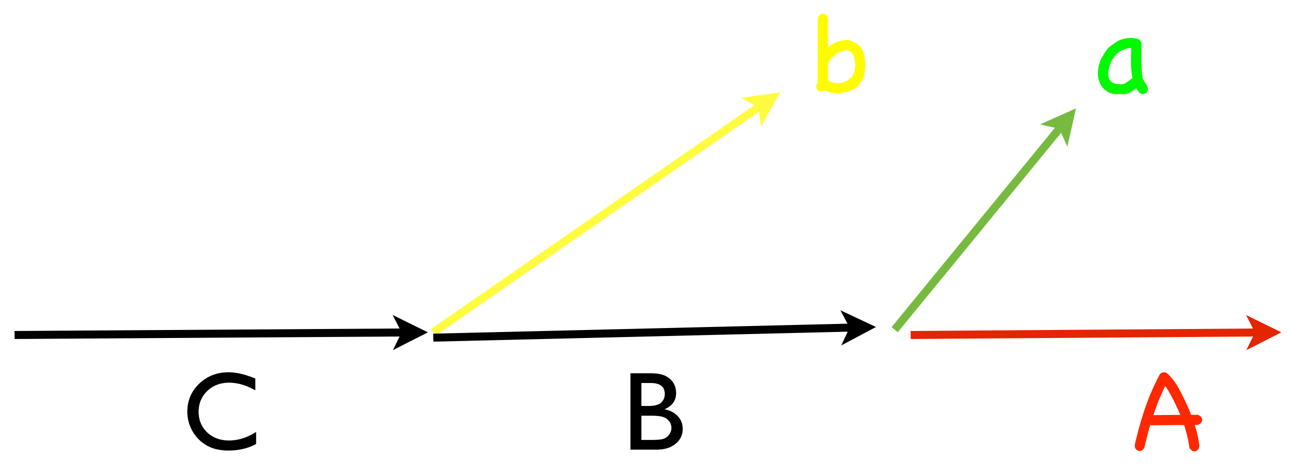
Overlapping peaks



- Ansatz can extract 2 peaks separately (assume this model)

Other/cleaner possibilities

- $a \neq b$: peaks in different distributions (no ``pollution" between peaks)

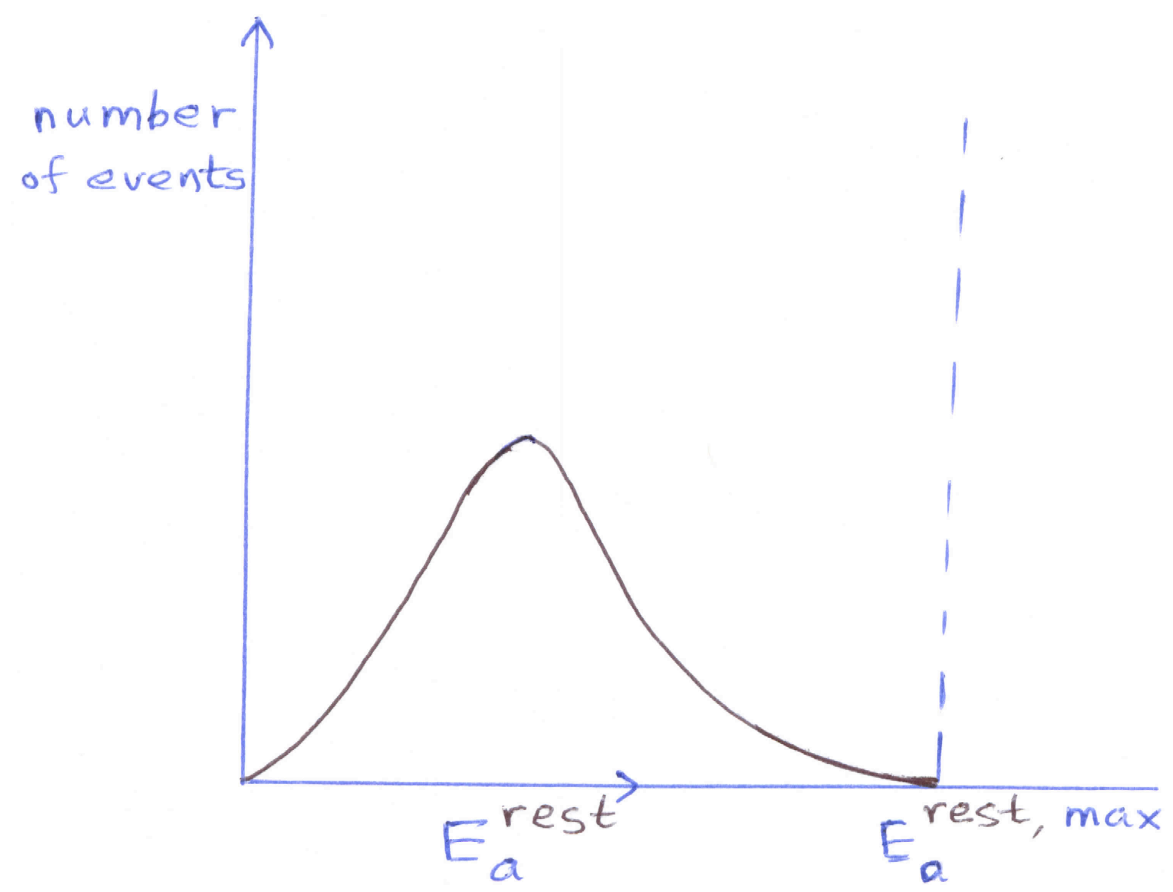


- lepton instead of jet

THREE-BODY DECAY

Endpoint of distribution in rest frame

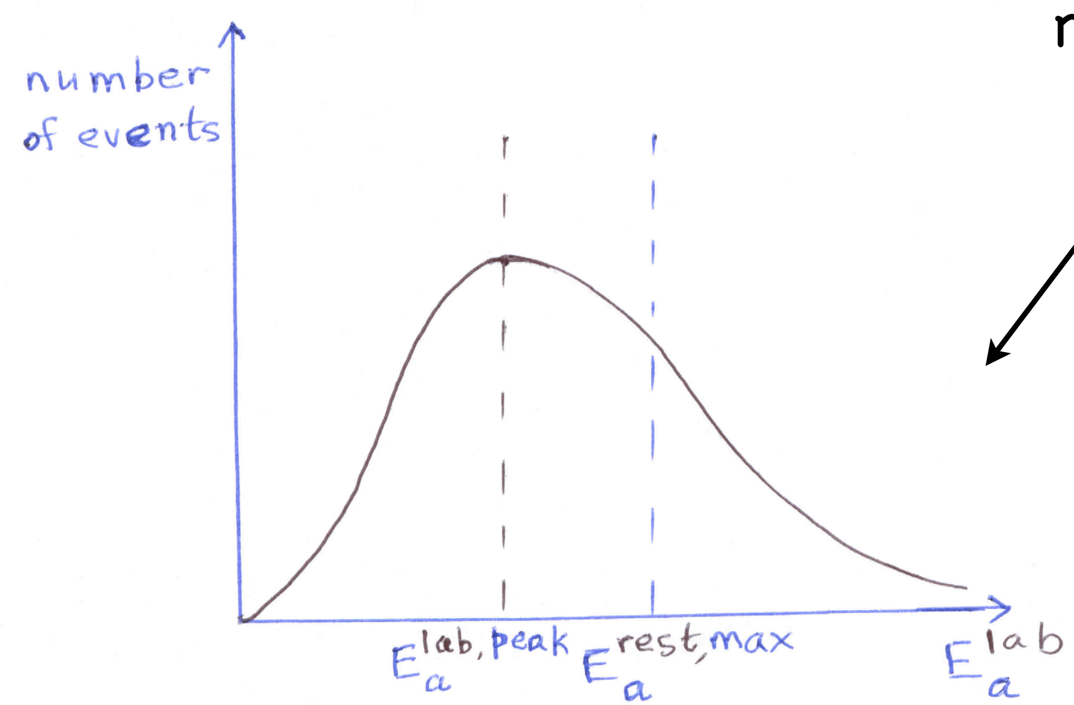
- Endpoint related simply to masses



Peak of distribution in lab frame

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

- Obtain inequality for masses
- used in distinguishing Z_3 vs. Z_2-stabilized dark matter

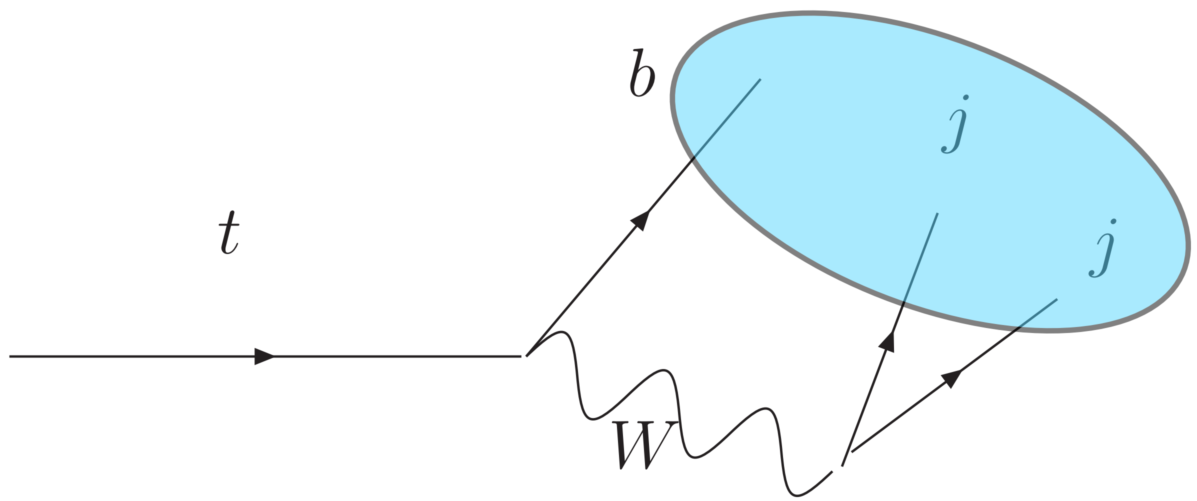


goes beyond rest frame endpoint

(Motivation: fundamental parameter of SM;enters calculation of other observables)

Conventional methods

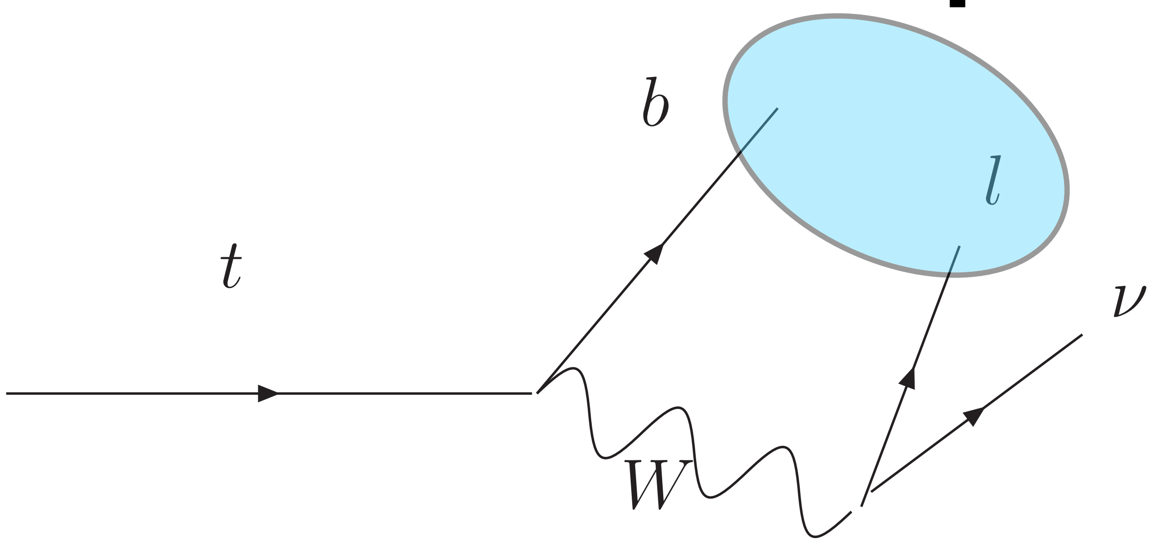
- Basic idea: reconstruct (full) decay of top

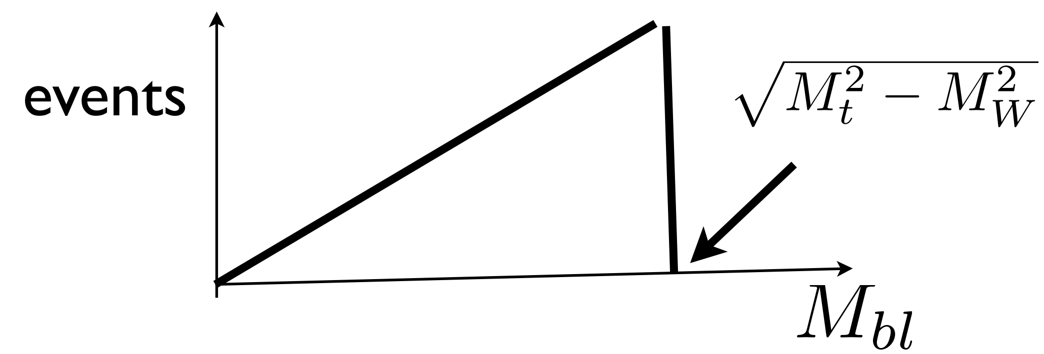


- can achieve O(0.6 GeV) uncertainty at LHC14, with 300/fb
- further gain may be possible with 3000/fb by using a more extended approach to constraining uncertainties using data

- Simulation (using SM matrix element in production) is used to handle combinatorics

Latest: endpoint of M_{bl}





- more cleanly interpreted as measurements of the pole quark mass

- combinatorics resolved with*out* assuming SM matrix element in production
  resulting top quark mass immune to possible contaminations from New Physics in production of top quarks

- can provide precision competitive with more conventional methods, especially using 3000/fb at LHC14

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 $\tilde{t} \to t\tilde{\chi}_1^0$)