Weighing Wimps with Kinks at Colliders

IPMU, Japan, 2008

Christopher Lester
Cambridge

We have just heard about …

arXiv:0709.0288

Gluino Stransverse Mass

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We introduce a new observable, 'gluino stransverse mass', which is an application of the Cambridge m_{T2} variable to the process where gluinos are pair produced in proton-proton collision and each gluino subsequently decays into two quarks and one LSP, *i.e.* $\tilde{g}\tilde{g} \to qq\tilde{\chi}_1^0\ qq\tilde{\chi}_1^0$. We show that the gluino stransverse mass can be utilized to measure the gluino mass and the lightest neutralino mass separately, and also the 1st and 2nd generation squark masses if squarks are lighter than gluino, thereby providing a good first look at the pattern of sparticle masses experimentally.

$$pp \to \tilde{g}\tilde{g} \to qq\tilde{\chi}_1^0\ qq\tilde{\chi}_1^0,$$

About to hear about:

1. Why I thought the result was wrong.
    - (it wasn't … I was!)

2. What someone else thought caused these "kinks" (arXiv:0709.2740)
    - (but which turned out to be different kinks)

3. The multiple possible causes of "kinks"
    - (arXiv: 0711.4008)

arXiv:0709.2740

Transverse Observables and Mass Determination at Hadron Colliders

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(Dated: September 18, 2007)

I consider the two-body decay of a particle at a hadron collider into a visible and an invisible particle, generalizing $W \to e\nu$, where the masses of the decaying particle and the invisible decay particle are, *a priori*, unknown. I prove that the transverse mass, when maximized over possible kinematic configurations, can be used to determine both of the unknown masses. I argue that the proof can be generalized to cover cases such as decays of pair-produced superpartners to the lightest, stable superpartner at the Large Hadron Collider.

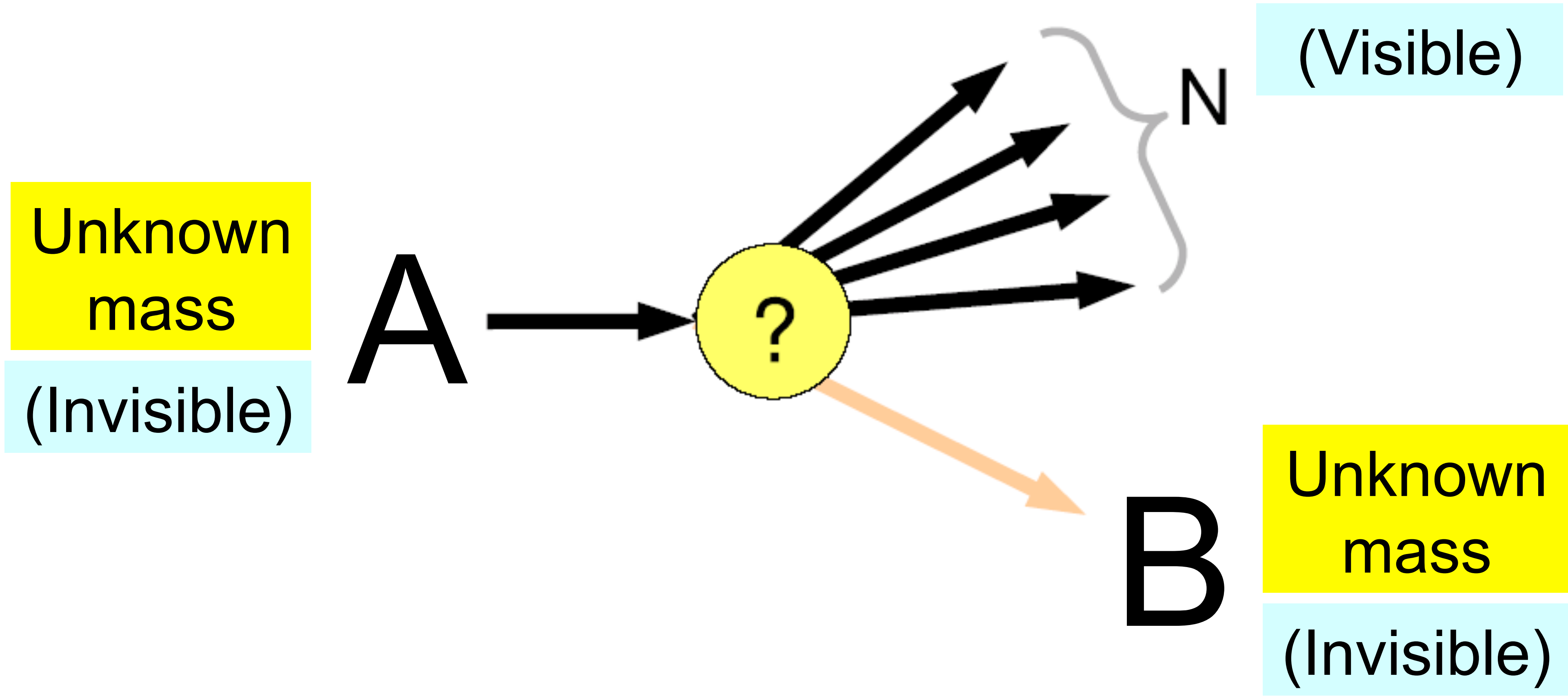
arXiv: 0711.4008

Weighing Wimps with Kinks at Colliders: Invisible Particle Mass Measurements from Endpoints

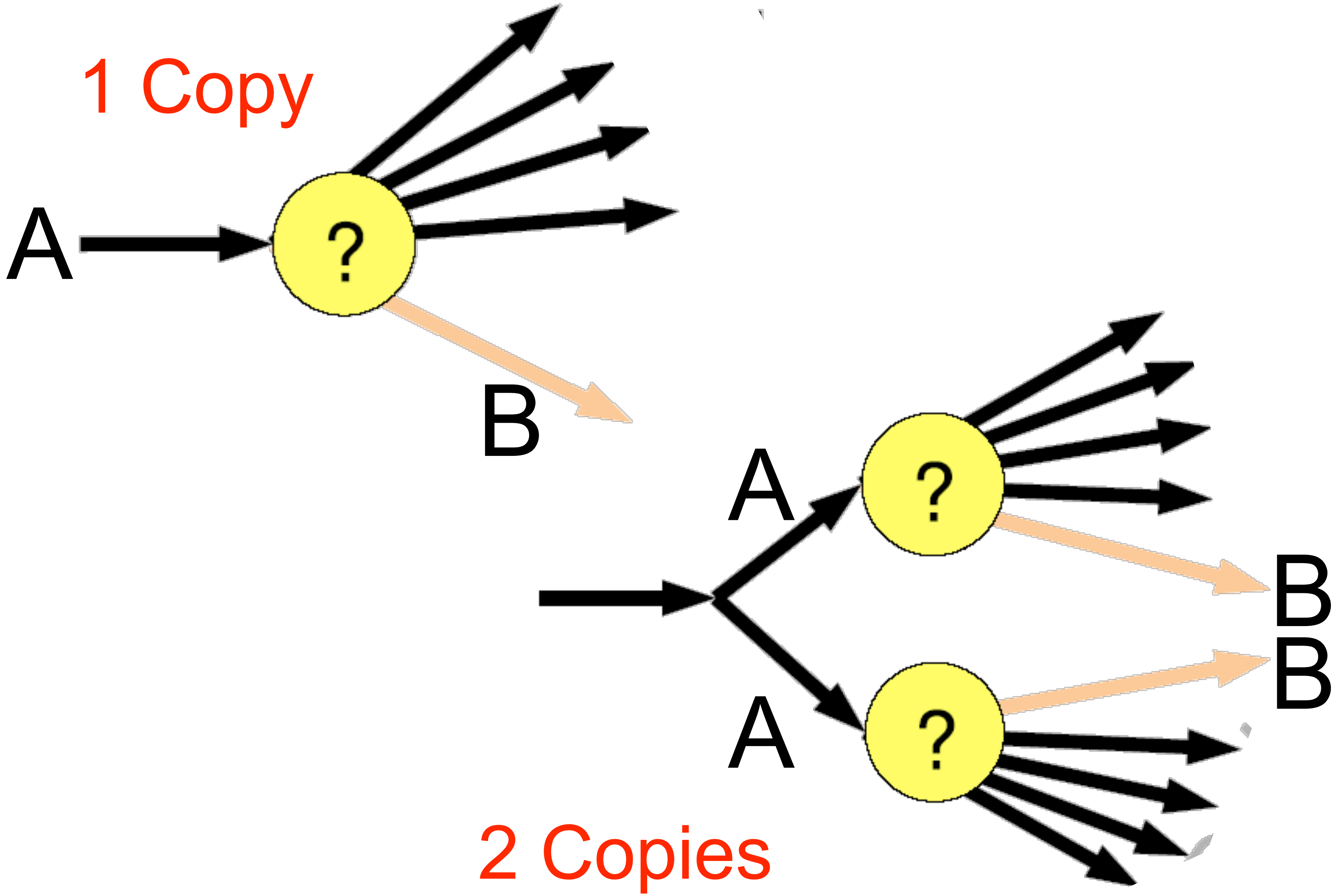
Barr, Griapos, Lester

We consider the application of endpoint techniques to the problem of mass determination for new particles produced at a hadron collider, where these particles decay to an invisible particle of unknown mass and one or more visible particles of known mass. We also consider decays of these types for pair-produced particles and in each case consider situations both with and without initial state radiation. We prove that, in most (but not all) cases, the endpoint of an appropriate transverse mass observable, considered as a function of the unknown mass of the invisible particle, has a kink at the true value of the invisible particle mass. The co-ordinates of the kink yield the masses of the decaying particle and the invisible particle. We discuss the prospects for implementing this method at the LHC.

Trying to learn about masses from:



Number of copies of decay may vary:

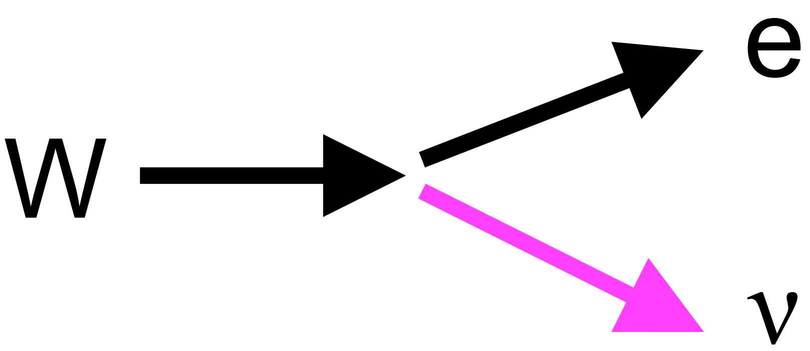


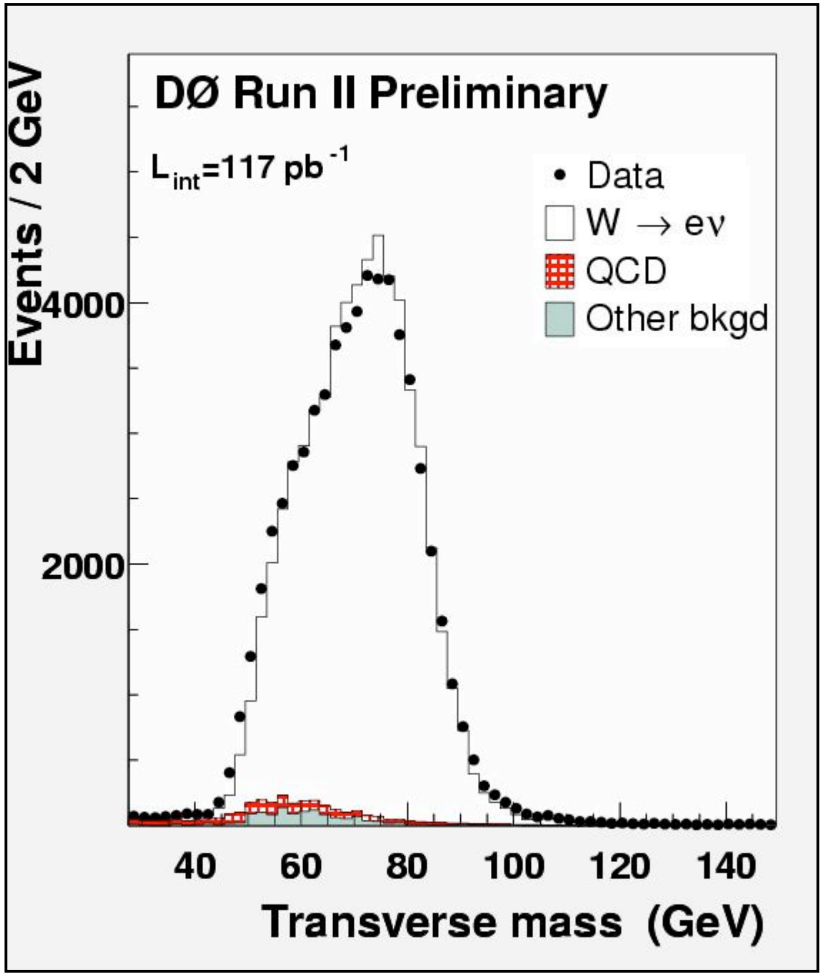
arXiv: 0711.4008

Example: W transverse mass

$$m_T^2 = m_e^2 + m_\nu^2 + 2(e_e e_\nu - \mathbf{p}_e . \mathbf{p}_\nu)$$

- Transverse mass in $W \to e\nu$
- Observable $m_T^2 = m_e^2 + m_\nu^2 + 2(e_e e_\nu - \mathbf{p}_e . \mathbf{p}_\nu)$
- Extremize, subject to constraints
- Minimum at $m_T = m_e + m_\nu$
- Maximum at $m_T = m_W$





W transverse mass : comments

All events have $m_T < m_W$
(If W on-mass shell)

m_T is an event-by-event lower limit on m_W

Use to measure m_W

Neutrino mass known to be small.
No issue as to what to use for it's mass …
Just set neutrino mass to zero!

$$m_T^2 = m_e^2 + m_\nu^2 + 2(e_e e_\nu - \mathbf{p}_e . \mathbf{p}_\nu)$$

But outside standard model …

- Don't usually know mass of invisible final state particle B.
    - (neutralino?)

- Can try to parameterize ignorance:
    - m_B represents actual mass of B

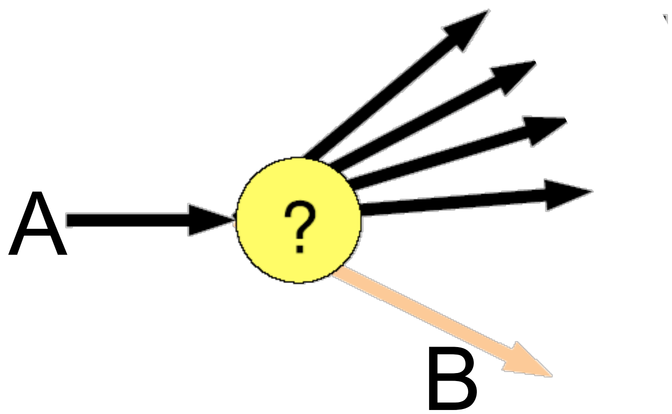
  – but
    - Chi parameter "χ" represents hypothesized mass of B

Redefine transverse mass in terms of “χ”

$$m_T^2(A) = m_{vis}^2 + A^2 + 2(E_{T\,vis}E_{T\,miss} - p_{T\,vis} \cdot p_{T\,miss})$$

where $E_{T\,vis}^2 = m_{vis}^2 + p_{T\,vis}^2$

and $E_{T\,miss}^2 = A^2 + p_{T\,miss}^2$



Chi parameter "χ"

(mass of "invisible" final state particle)

is EVERYWHERE!

(most commonly on x-axis of al
2D plots which occur later)

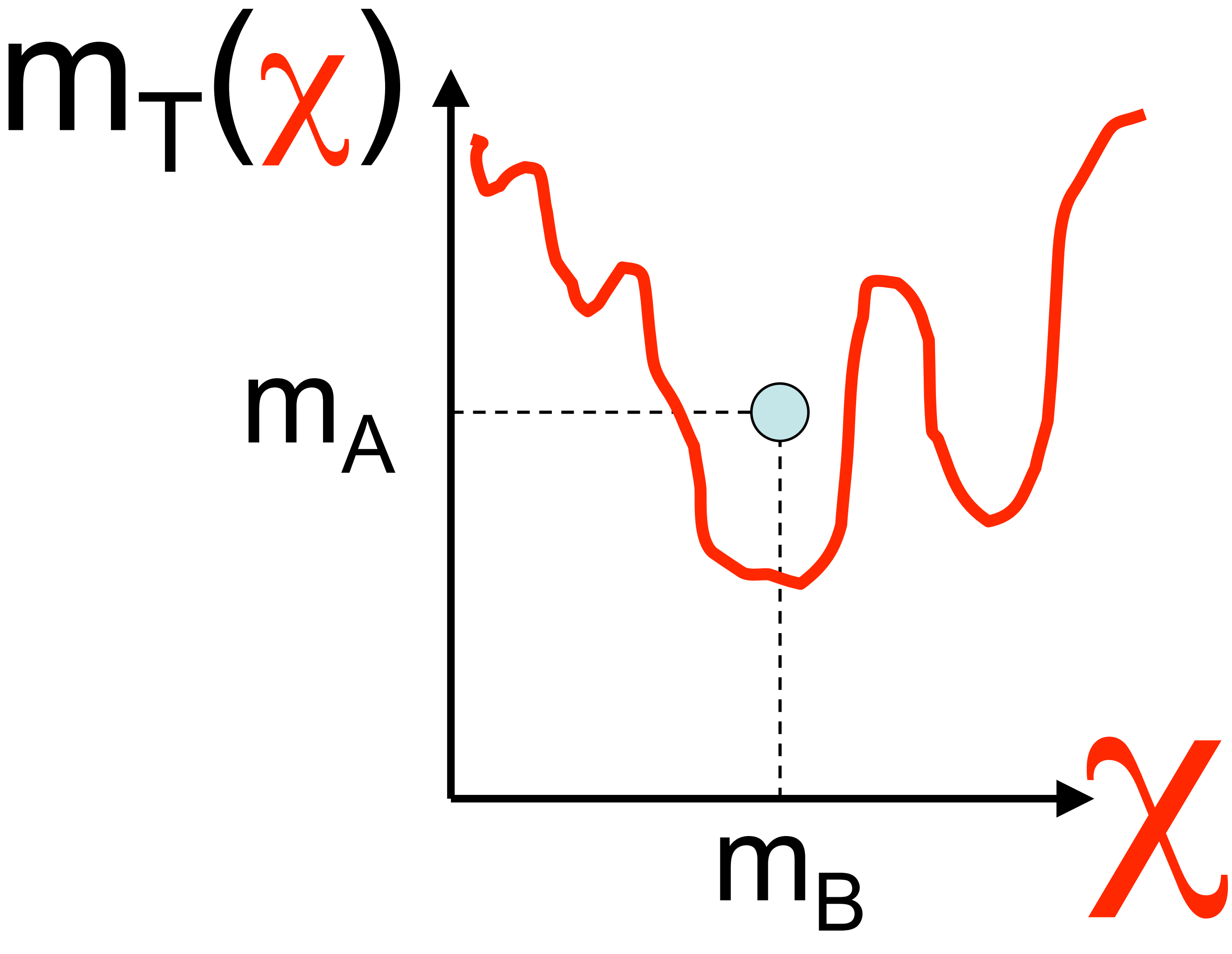
Consequences of using "χ"

- Since "χ" can now be "wrong", some of the properties of the transverse mass can "break":

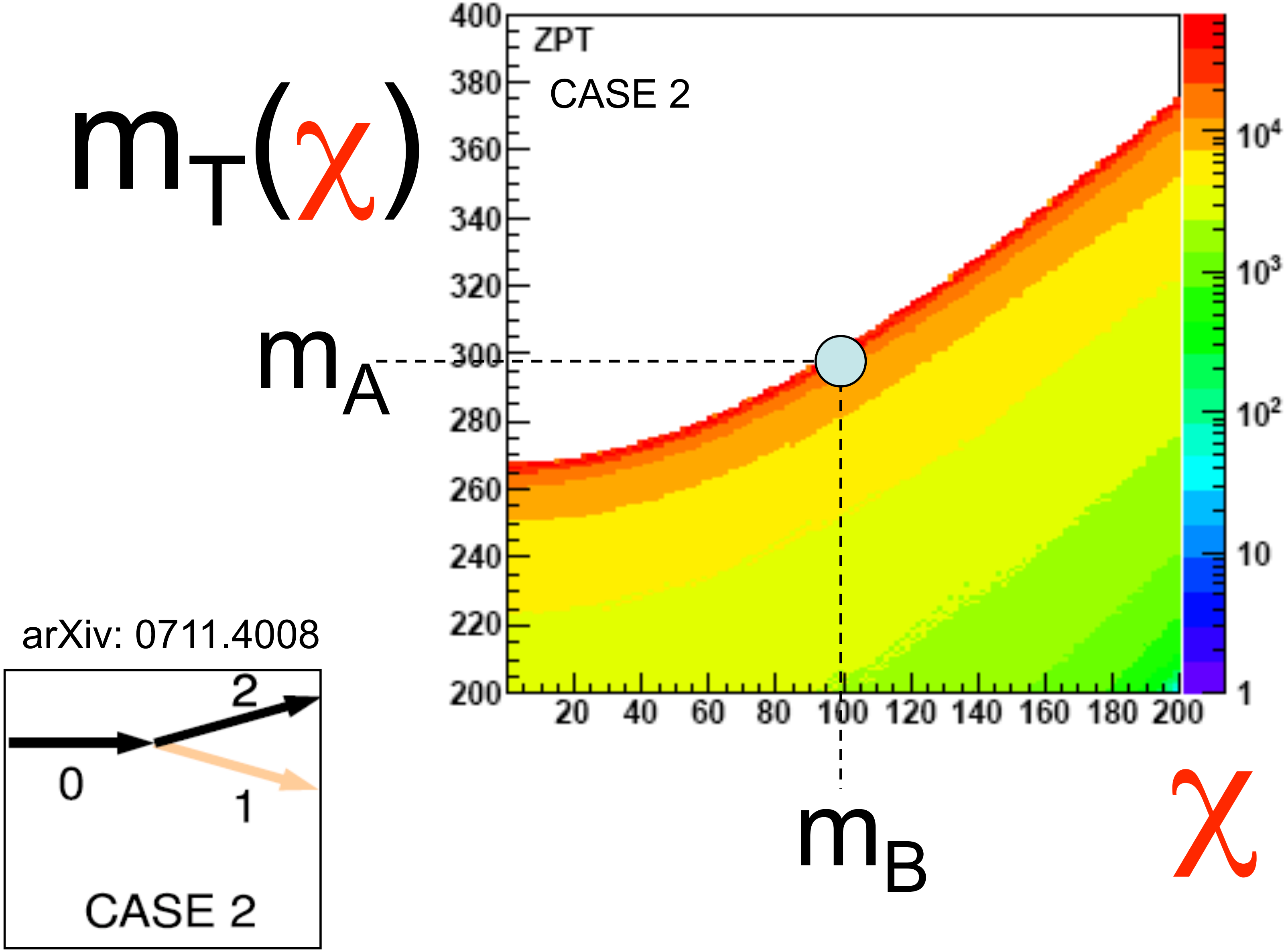
- $m_T(\chi)$ is no longer invariant under transverse boosts!
  - (except when $\chi = m_B$)

- $m_T(\chi) < m_A$ may no longer hold!
  - (however we always retain: $m_T(m_B) < m_A$)

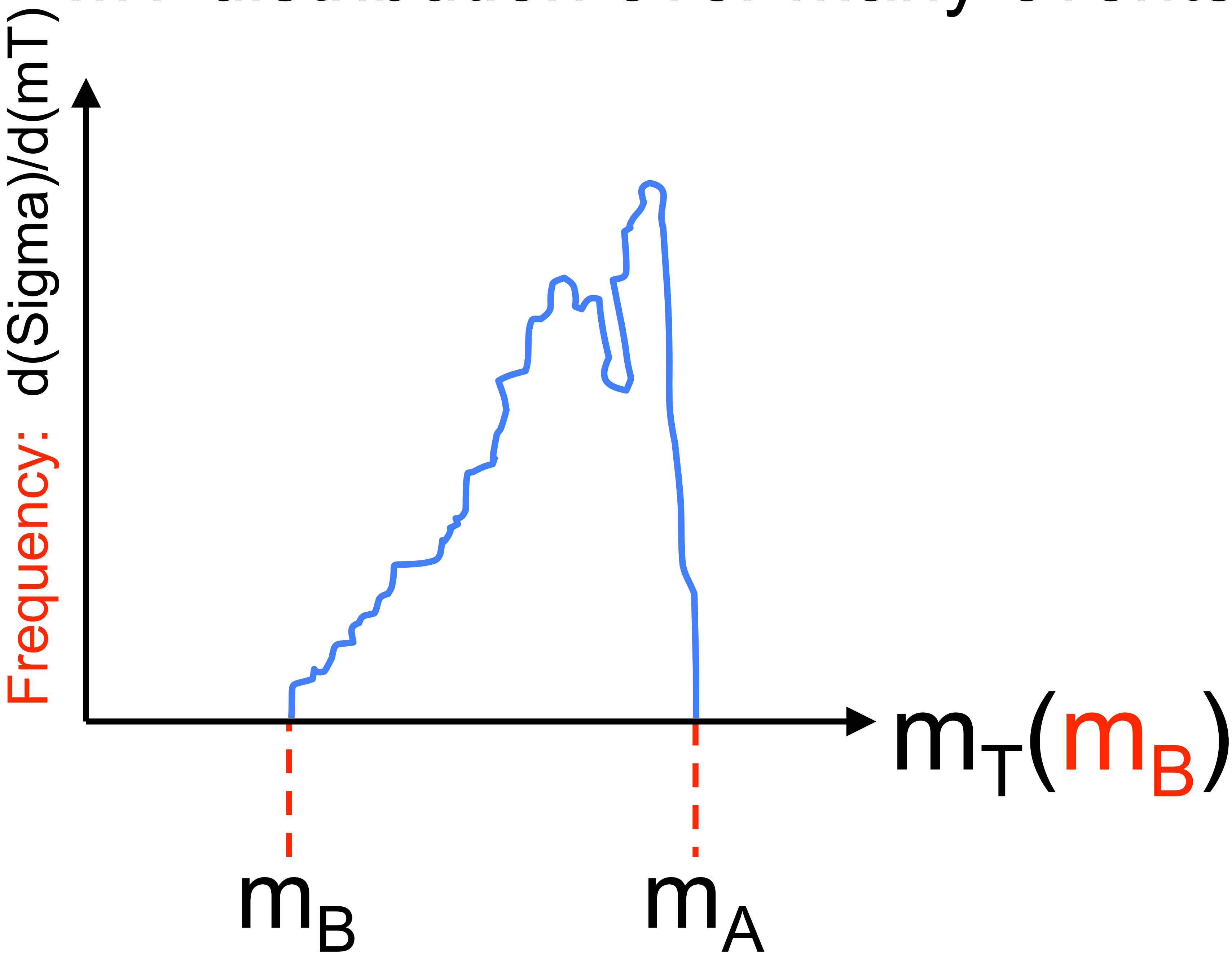
Schematically:



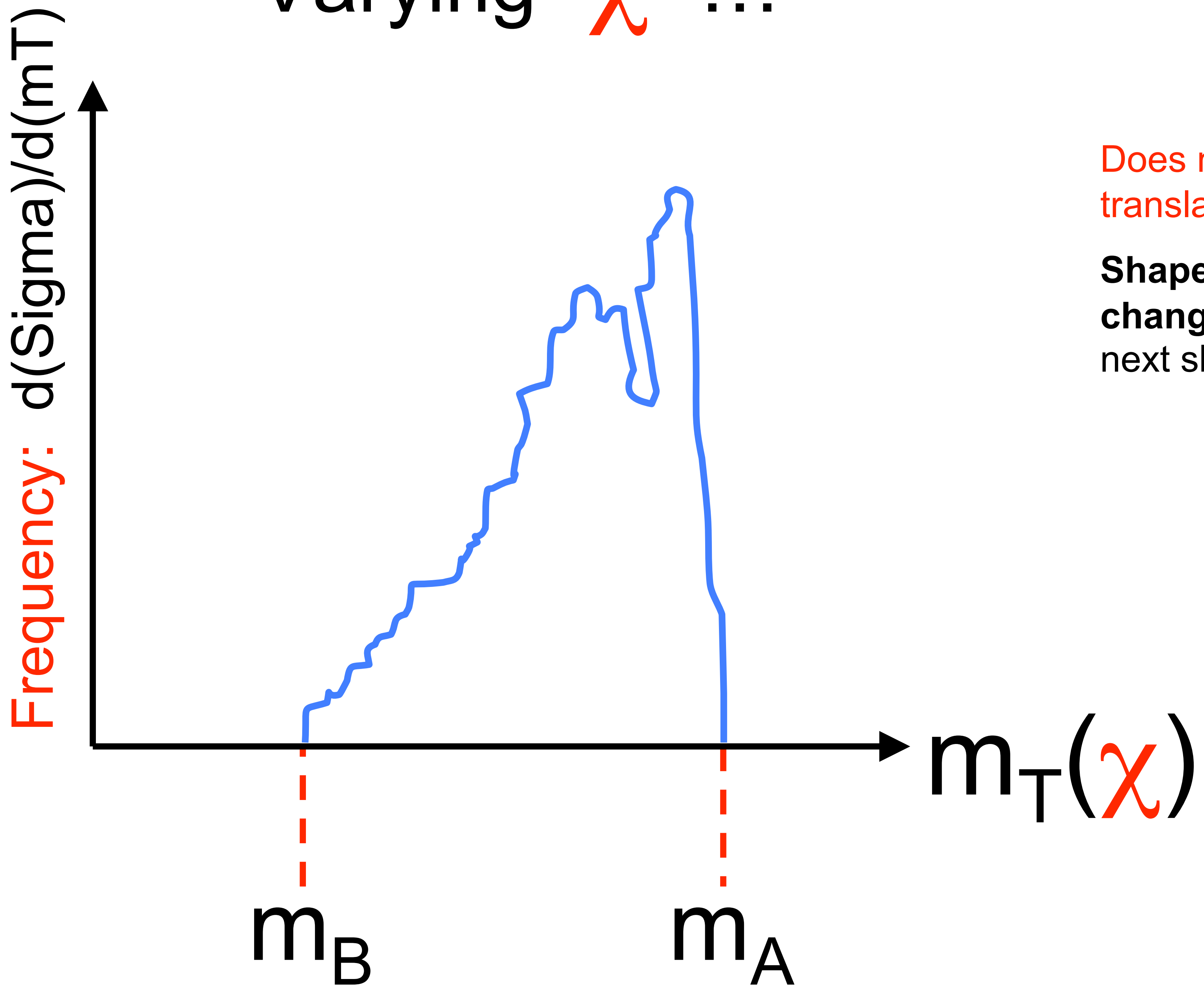
Cut to whiteboard for comment on:



MT distribution over many events:



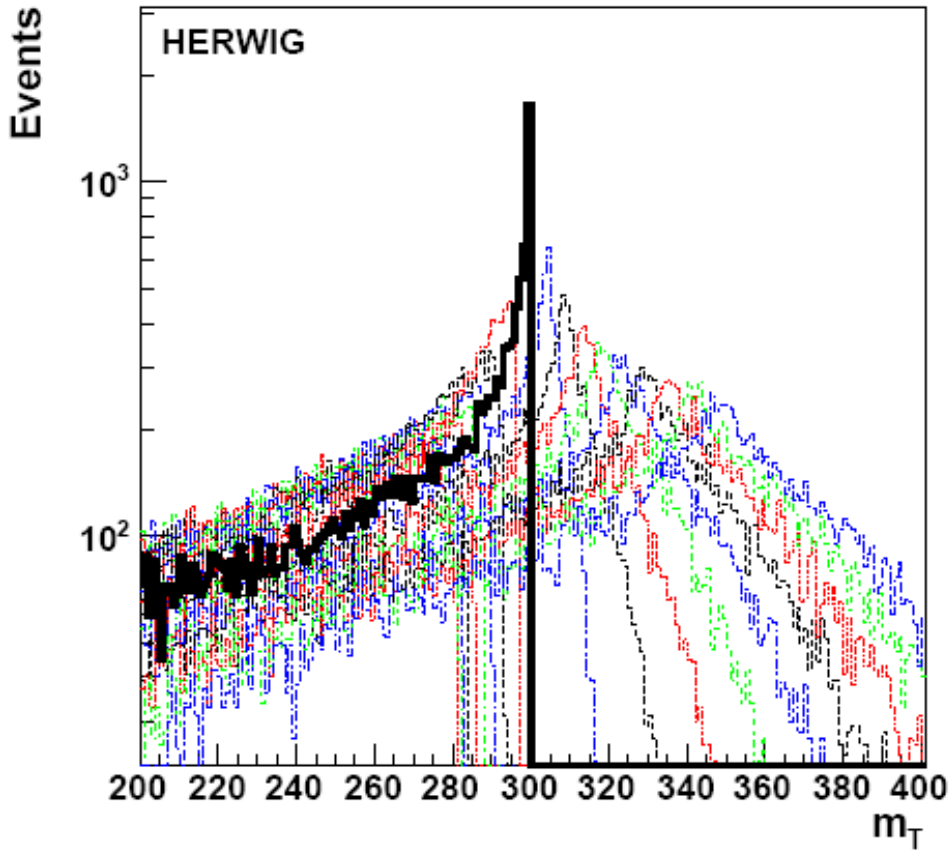
Varying “χ” …



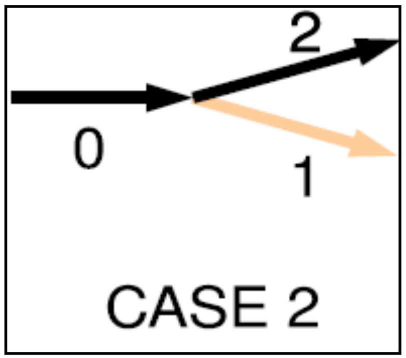
Does not just translate …

Shape may also change … see next slide.

Actual change in evidence on a log plot

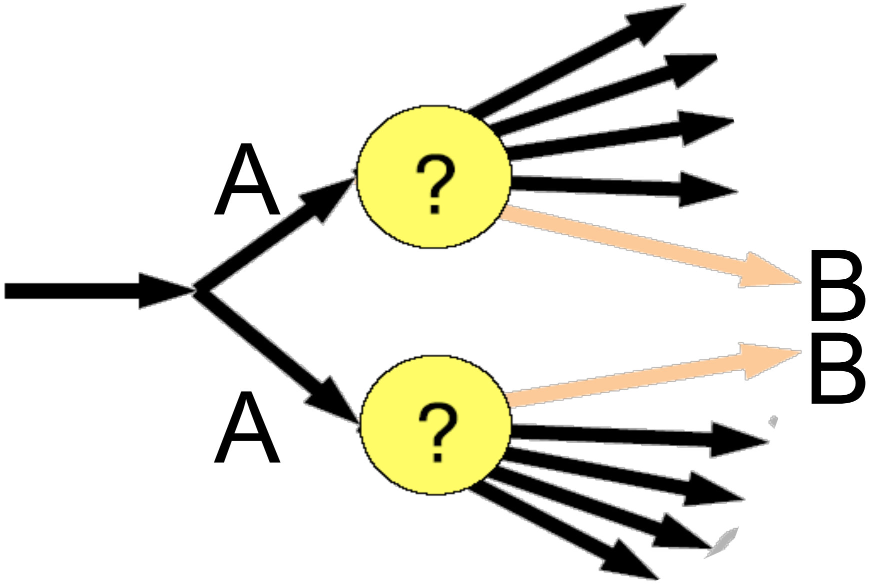


arXiv: 0711.4008



$m_T(\chi)$

For cases where there are 2 copies



arXiv: 0711.4008

…. generalize m_T to m_{T2}.

("Transverse" mass to "Stransverse" mass)

$$m_{T2}(A) = \min_{\text{splittings}} \left(\max\left[m_T(A;\text{side}1); m_T(A;\text{side}2)\right]\right)$$

arXiv: hep-ph/9906349

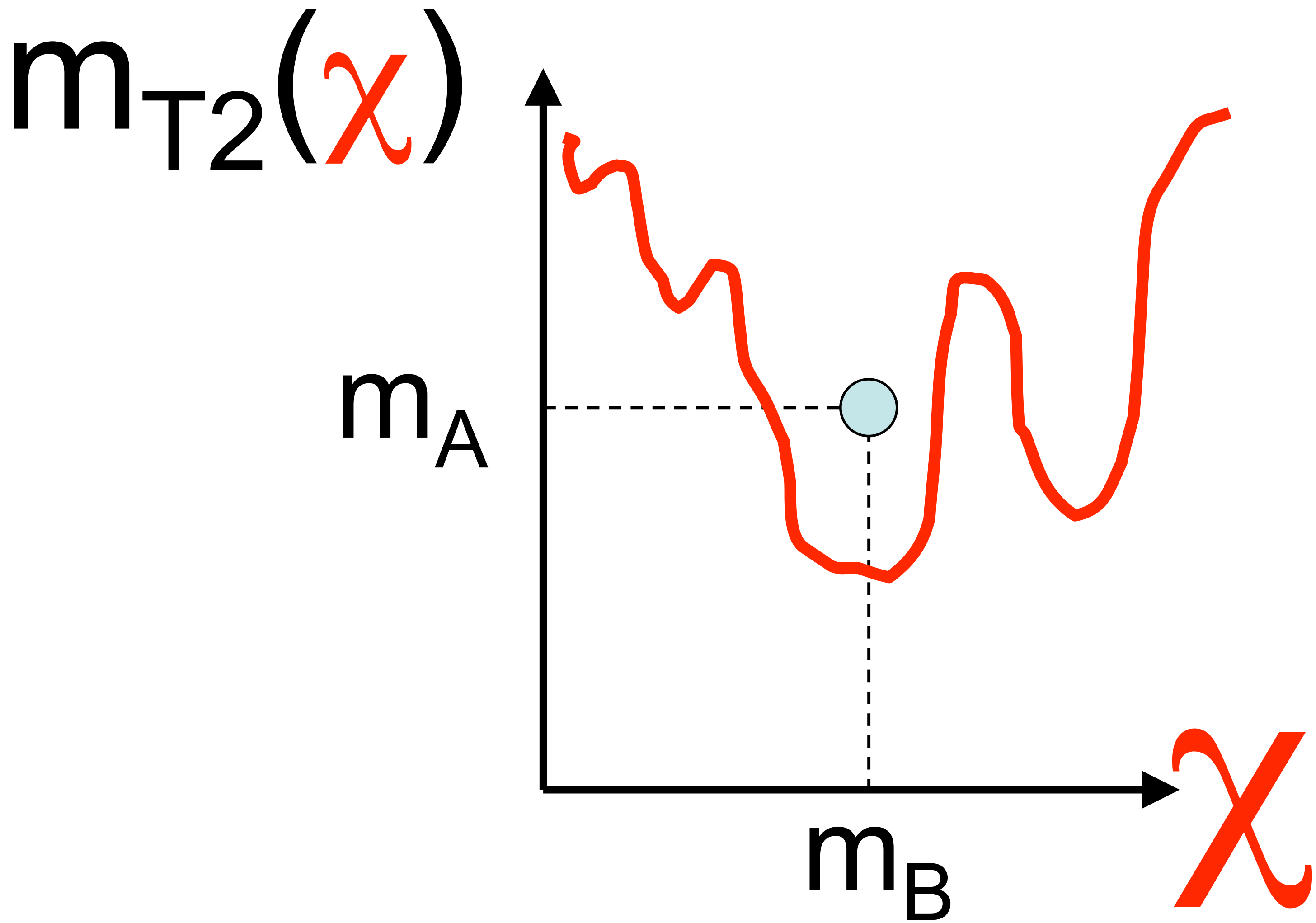
Only things worth remembering:

- m_{T2} behaves just like m_T … i.e.

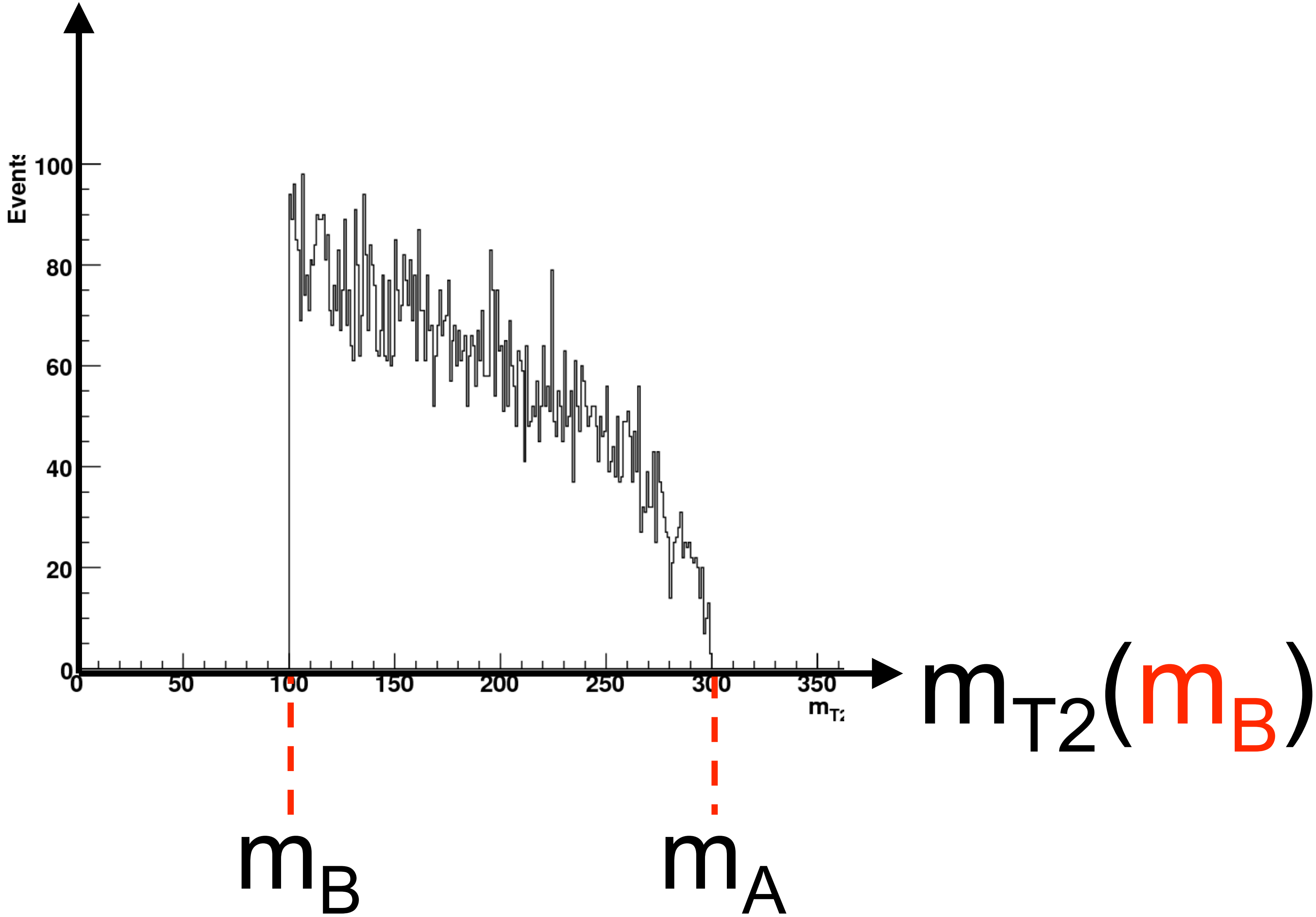
- $m_{T2}(\chi)$ is not invariant under transverse boosts!
  - (except when $\chi = m_B$)

- $m_T(\chi) < m_A$ will not always hold!
  - (however we always retain: $m_{T2}(m_B) < m_A$)

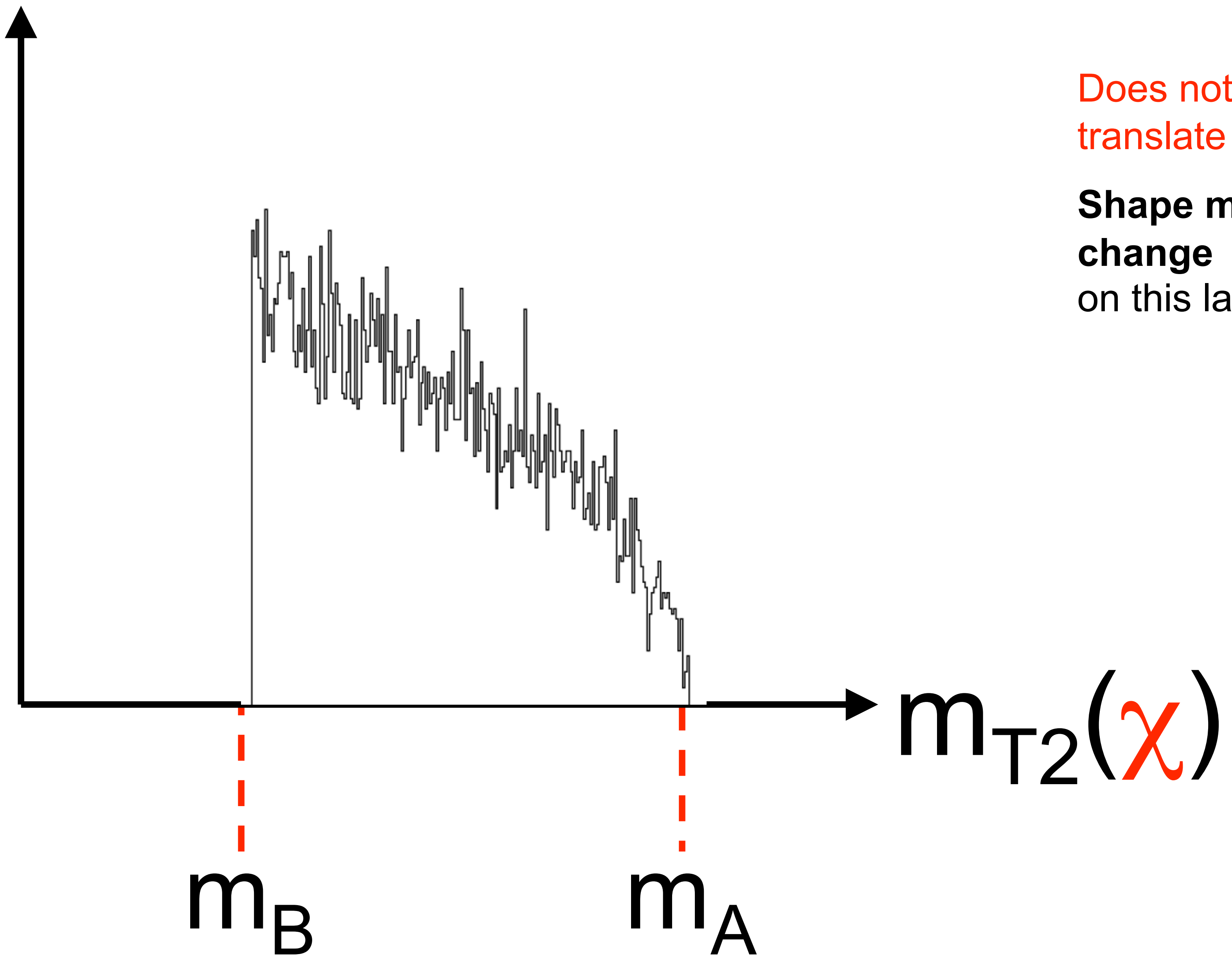
Schematically as before:



MT2 distribution over many events:



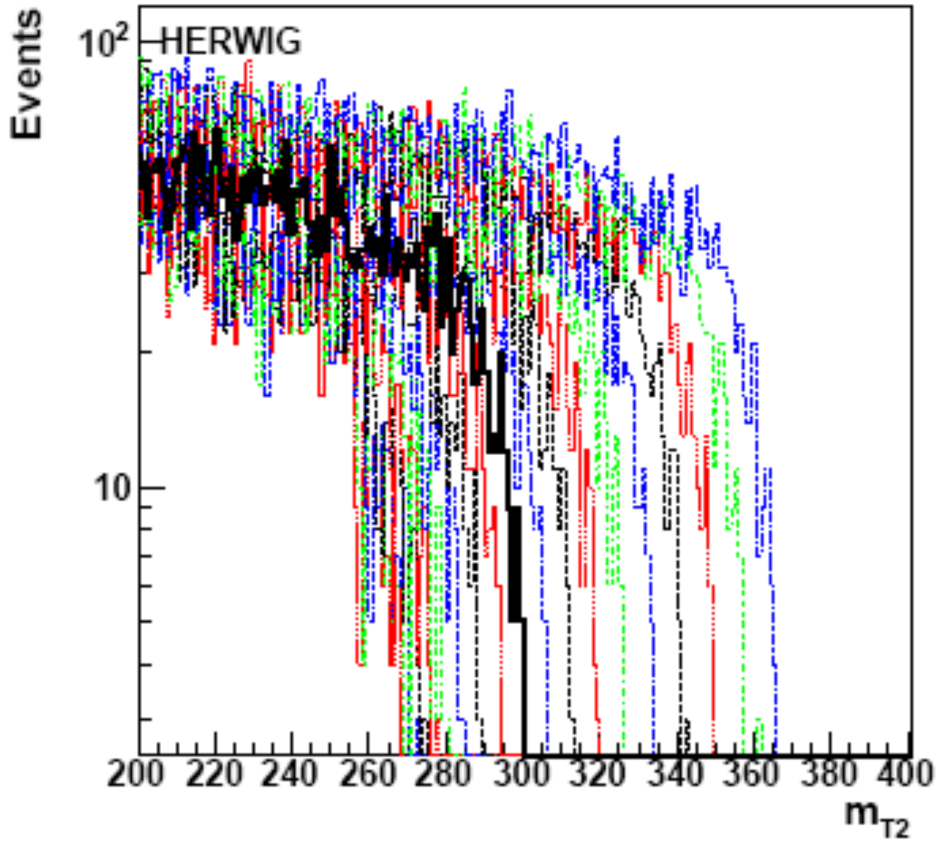
Varying "χ" …



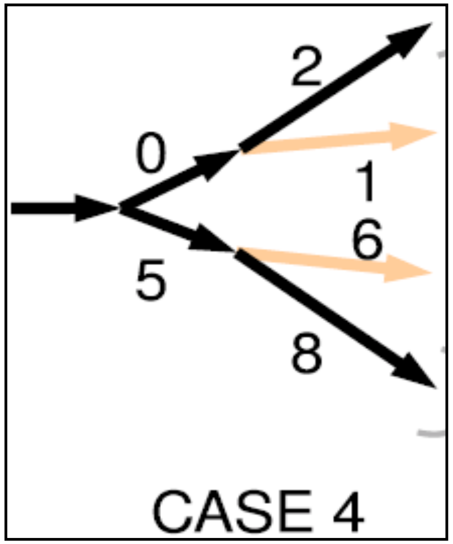
Does not just translate …

Shape may also change … more on this later.

Actual change in evidence on a log plot



arXiv: 0711.4008



$m_T(\chi)$

Since MT and MT2 behave similarly …

- Concentrate on MT for the moment

  (one copy of decay)

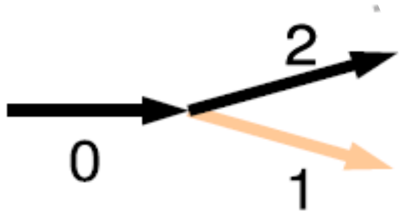
- Come back to MT2 later

  (two copies of decay)

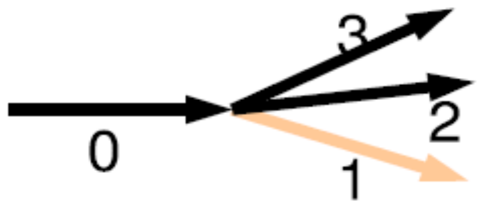
But first introduce some terminology:

The “Interesting systems”

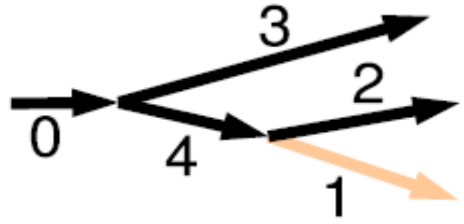
1 copy … m_T



CASE 2



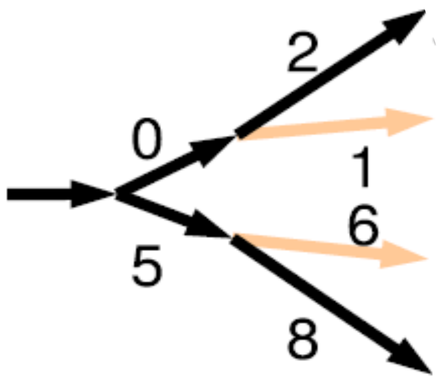
CASE 3v



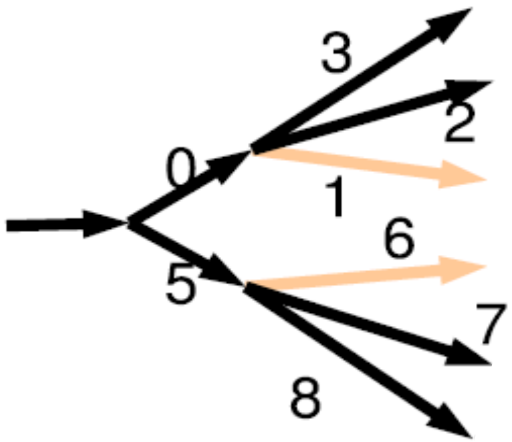
CASE 3s

arXiv: 0711.4008

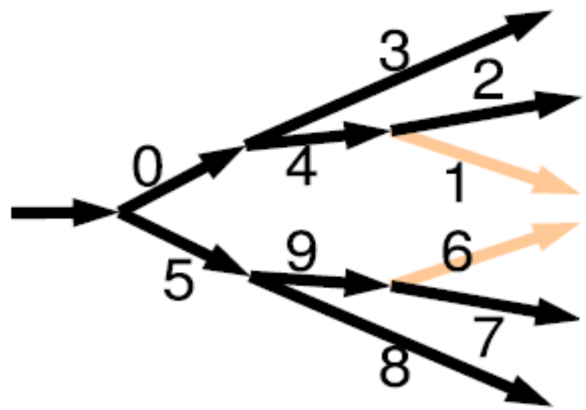
2 copies … m_{T2}



CASE 4



CASE 6v

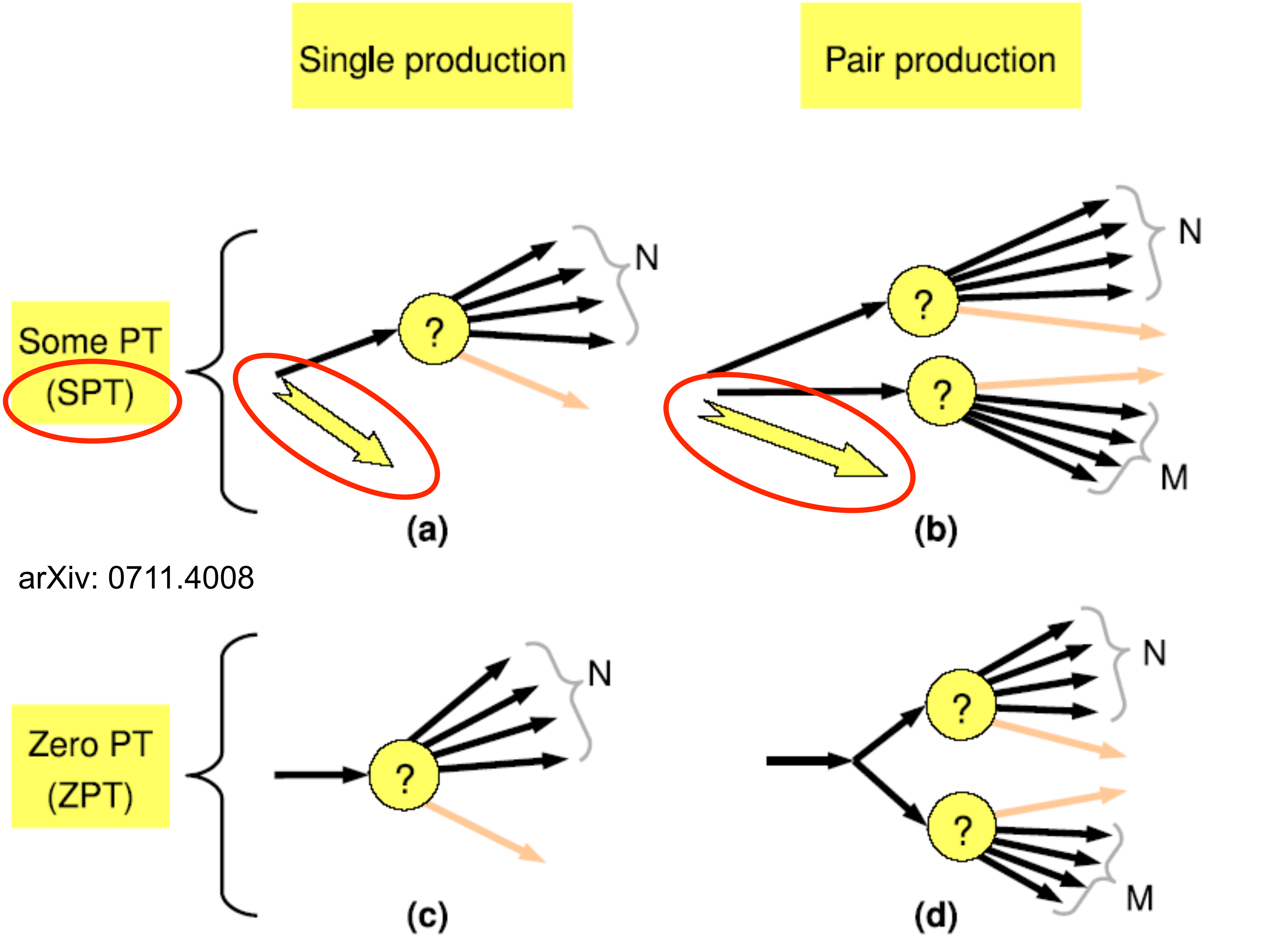


CASE 6s

Terminology: SPT versus ZPT

- SPT (Some PT)
  - “interesting system” is recoiling against something with Some PT
- ZPT (Zero PT)
  - “interesting system is recoiling against something with Zero PT

arXiv: 0711.4008



arXiv: 0711.4008

ISR = bad name
USM = better

- Up-stream momentum
  - (whiteboard)

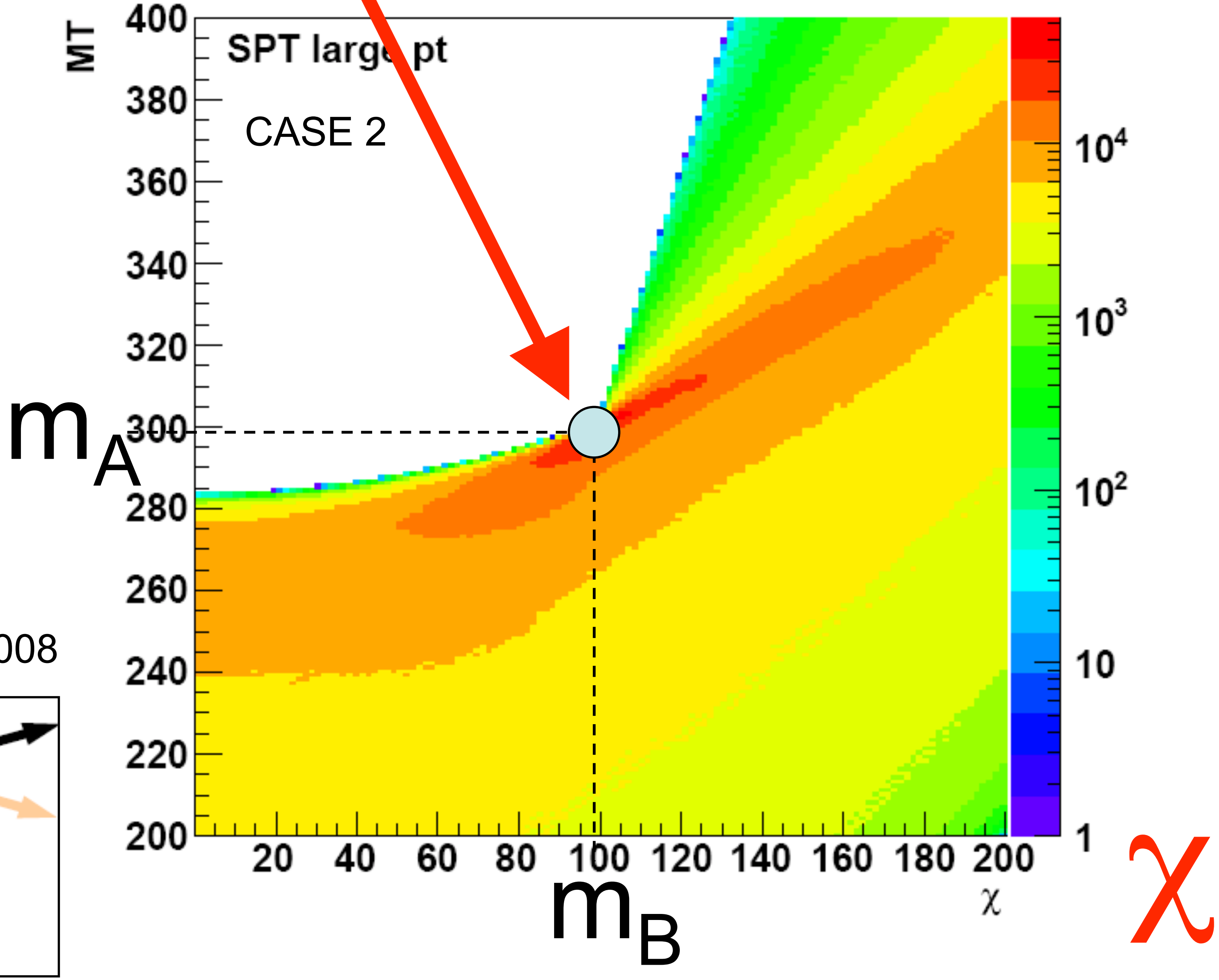
Consider increasing recoil
(increasing PT of interesting system)

- Interesting system is boosted.
- MT not invariant under transverse boosts (except when $\chi = m_B$) so *MT curves change*

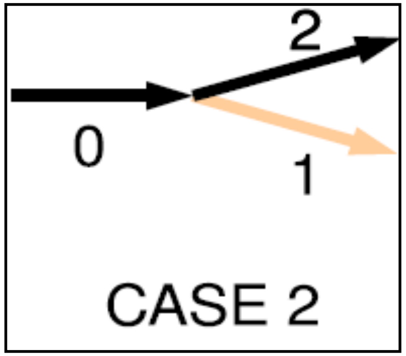
- (Cut to Whiteboard for overlay PT dependence)

Here is a KINK !

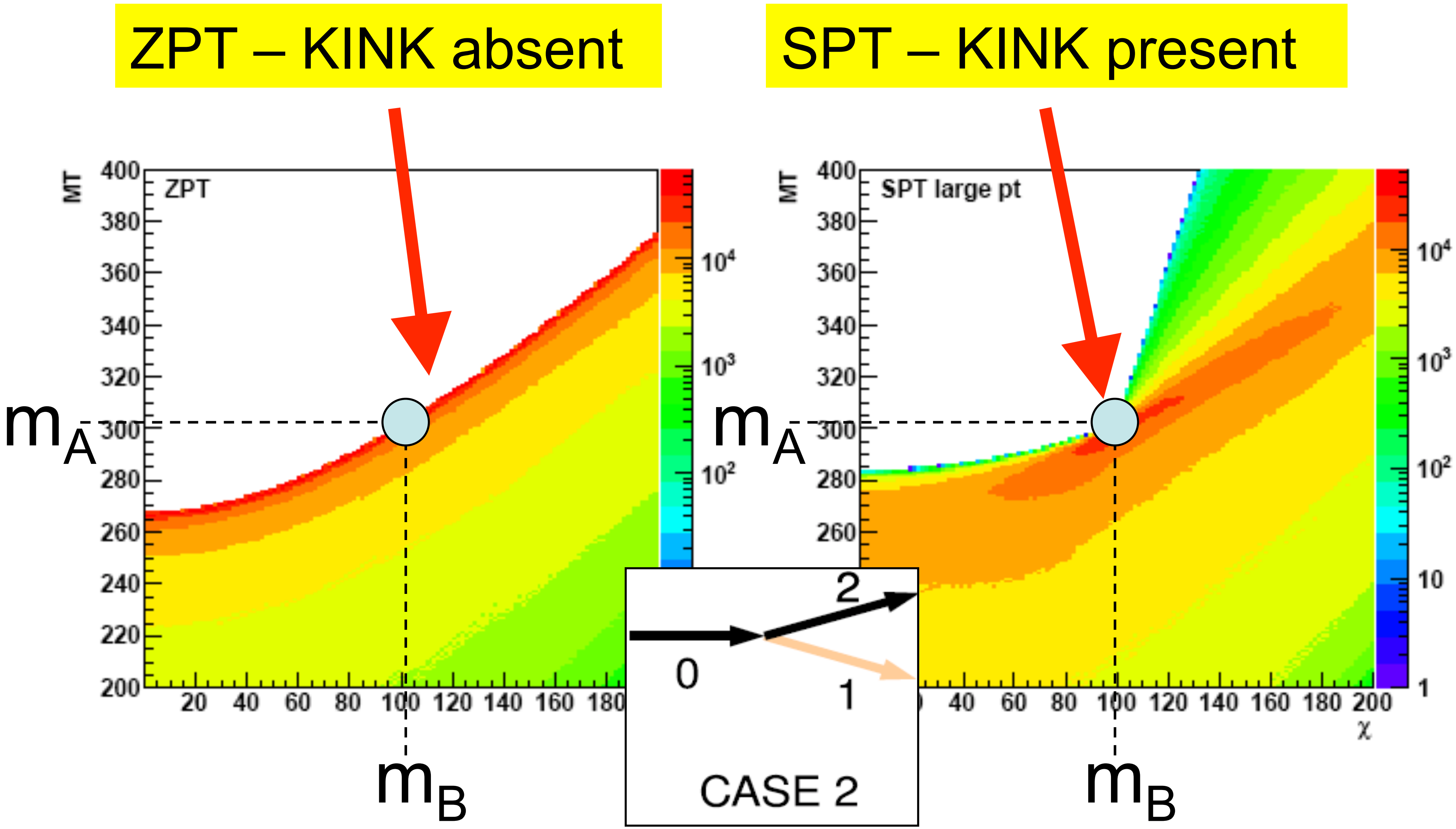
$m_T(\chi)$



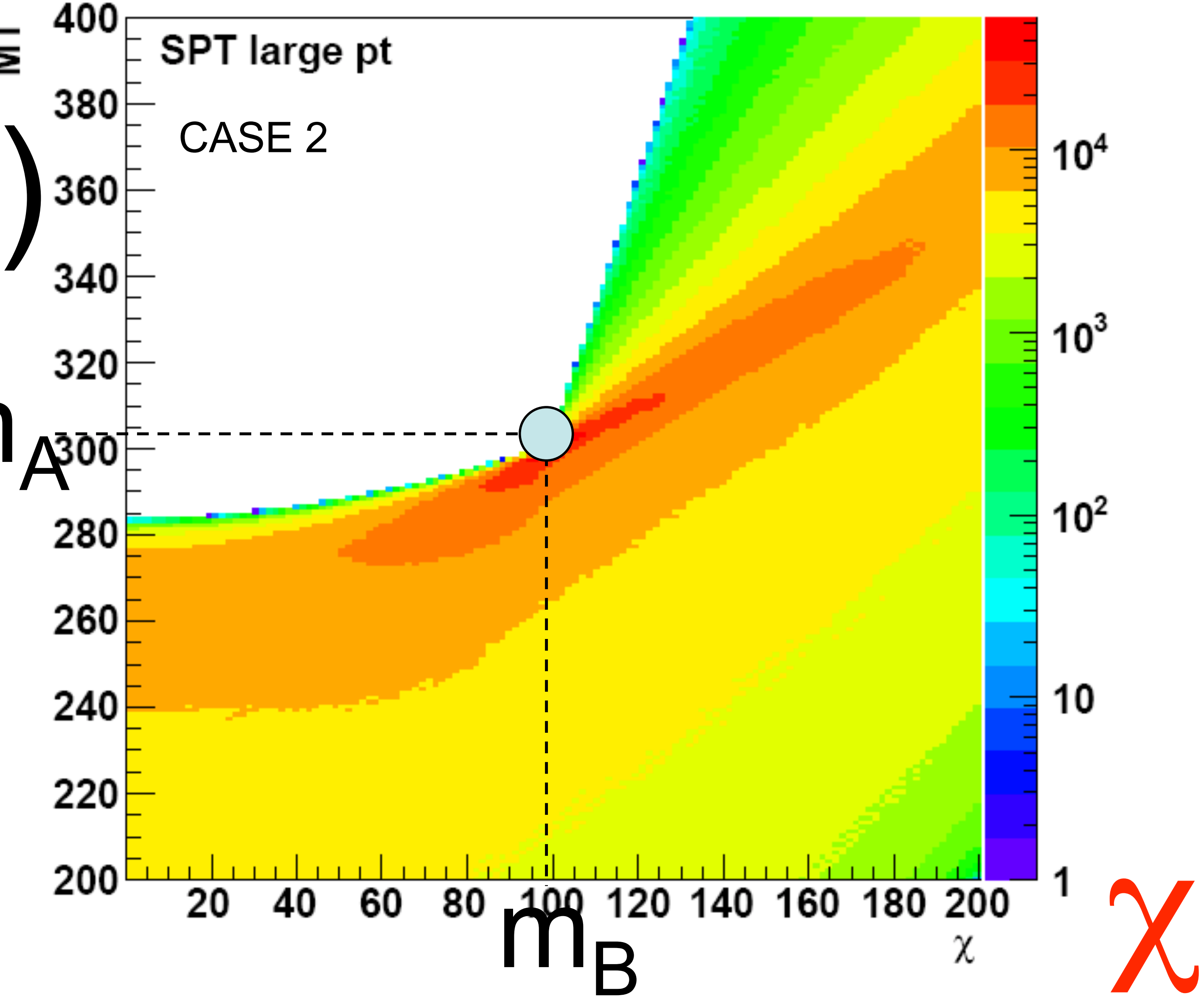
arXiv: 0711.4008



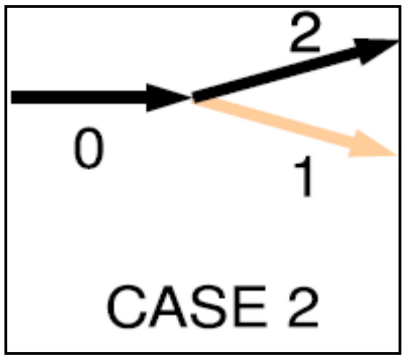
This KINK was due to non-invariance of MT under recoil induced boosts, so:



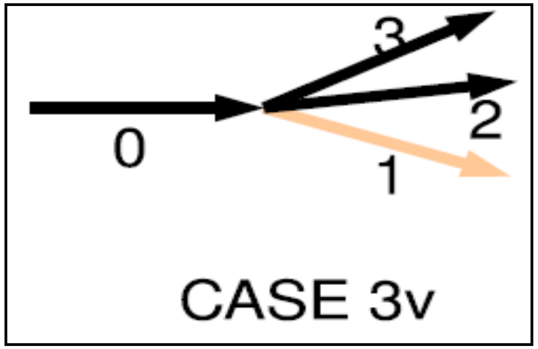
Explain feet … (whiteboard)

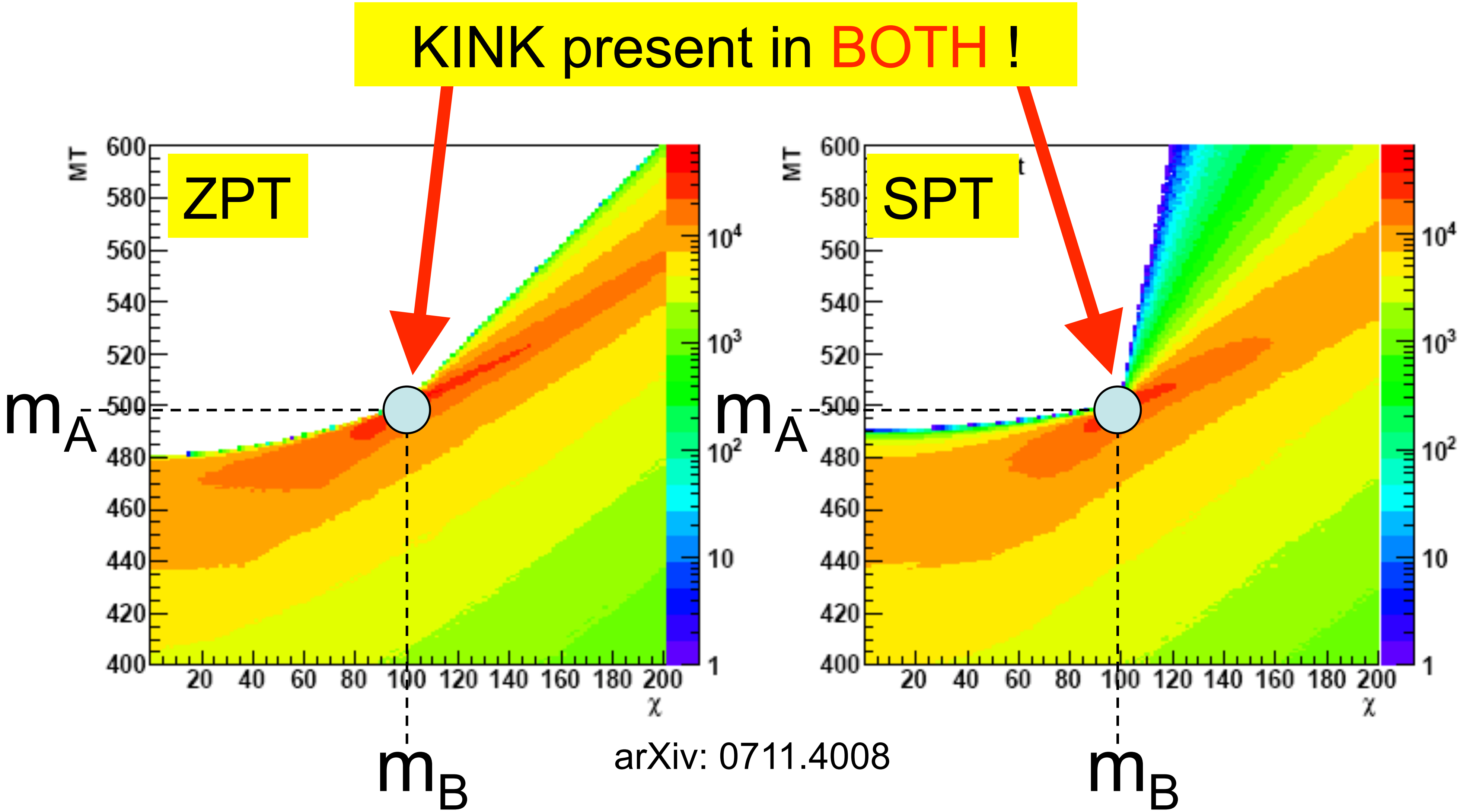


arXiv: 0711.4008



What about CASE3 ?
(Three particles in final state)





arXiv: 0711.4008

Confused?

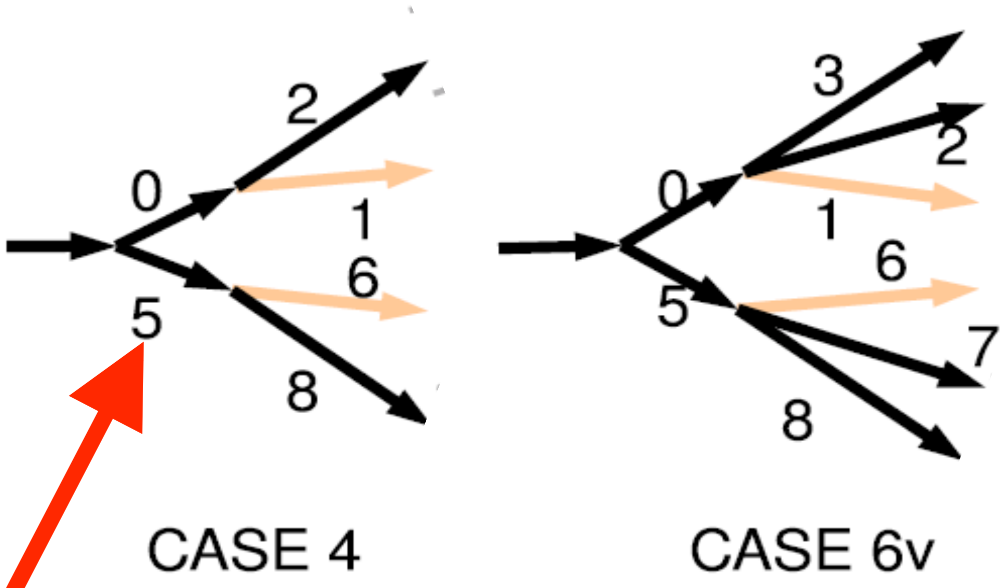
- 2 particles in final state:
  - Kink ***only*** appears when interesting system has Some PT (SPT)
- 3 particles in final state
  - Kink appears in ***both*** cases (SPT and ZPT), although:
  - Kink is stronger in SPT (recoiling) than in ZPT (zero recoil) events.
- Why?

Why 3 body final state differs from 2 body:

- With three bodies in final state, have extra degree of freedom:
  - m_{VIS} can change from event to event
- Gradient of $m_{T2}(\chi)$ curve depends on m_{vis}
- Curves with low m_{vis} tend to be "flatter"
- Curves with high m_{vis} tend to be "steeper"
- Can prove this is always true of "maximal" events
  - cut to whiteboard – show this and ZPT kink

As promised: Return to SUSY and MT2

Fortunately, **as MT and MT2 behave identically, the results are the same** as would be expected from considering either SIDE of an MT2 event in isolation.



Expect KINK only in SPT

Expect KINK in both SPT and ZPT.

Expect KINK in SPT to be “stronger”.

arXiv: 0711.4008

So everyone is happy:

- CCKP (arXiv:0709.0288) found a kink in MT2 with 6 particles in the final state in ZPT
- Griapos (arXiv:0709.2740) found a kink in MT with 2 particles in the final state in SPT
- BGL (arXiv: 0711.4008) demonstrate that
  1. Each kink type is independent of the other.
  2. Recoil (SPT) always enhances a kink.
  3. “SPT-only” kinks are sometimes found in “feet” that may be a challenge to find.

Kink trivia

- Gradients on either side of kink can be used to determine masses, just like the co-ordinates of the kink itself.
  - Cross check?
  - Must make sure that recoil distro is well understood as gradients depend on the amount of recoil PT.

Is it OK to ignore recoil PT?

- Sometimes safe to ignore recoil
- Sometimes very important to retain recoil

- Depends on
  - likely PT spectrum of “upstream momentum”
  - whether the gradients either side of the kink are to be used quantitatively
  - Whether PT is the “only” source of a kin

- Some new MT2 variables require large recoil PT
  - (see M2C shortly)

Other MT2 related variables (1/3)

- MCT ("Con-Transverse Mass") Tovey (arXiv: 0802.2879)
  - Though discovered independently of MT2, MCT was found by Serna (arXiv:0803:3344) to be MT2(χ=0) under the ZPT assignment:

$$p_{\mathbf{T}miss} = -p_{\mathbf{T}A1} - p_{\mathbf{T}A2}.$$

  - Nonetheless, arXiv:0802.2879 contains many valuable insights into the transformational properties of MCT/MT2 under transverse boosts in the χ=0 and ZPT limit, and
  - Proposes an interesting multi-stage method for measuring additional masses.

Other MT2 related variables (2/3)

- MTGEN ("MT for GENeral number of final state particles") (arXiv:0708.1028)
  - Used when
    - each "side" of the event decays to MANY visible particles (and one invisible particle) and
    - it is not possible to determine which decay product is from which side … all possibilities are tried
- Inclusive or Hemispheric MT2 (Nojirir + Shimizu) (arXiv:0802.2412)
  - Similar to MTGEN but based on an assignment of decay product to sides via hemisphere algorithm.
  - Guaranteed to be >= MTGEN

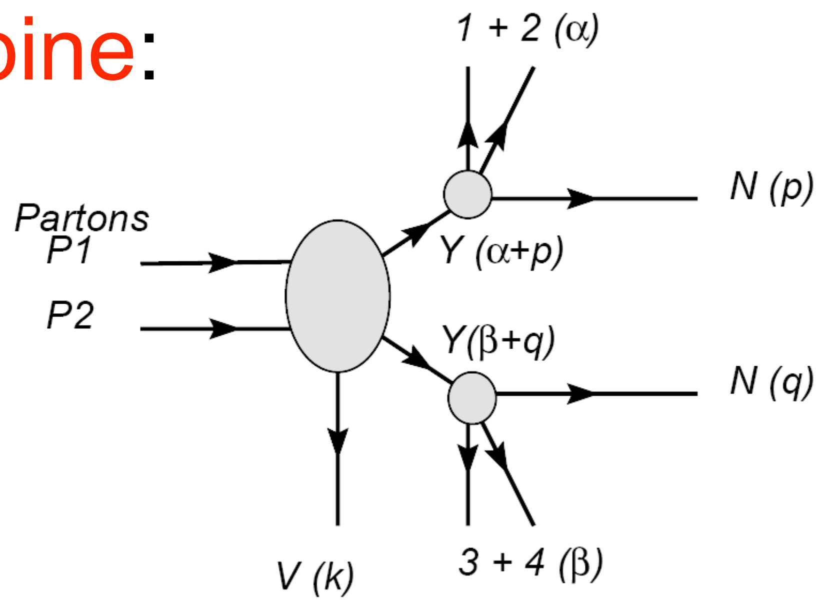
Other MT2 related variables (3/3)

- M2C ("MT2 Constrained") arXiv:0712.0943 (wait for v3 ... there are some problems with the v1 and v2 drafts)
- M2CUB ("MT2 Constrained Upper Bound") arXiv: 0806.3224

- There is a sense in which these two variables are really two sides of the same coin.
  - if we could re-write history we might name them more symmetrically
  - I will call them m_{Small} and m_{Big} in this talk.

m_{Small} and m_{Big}

- Basic idea is to combine:
  - MT2



- with
  - a di-lepton invariant mass endpoint measurement (or similar) providing:

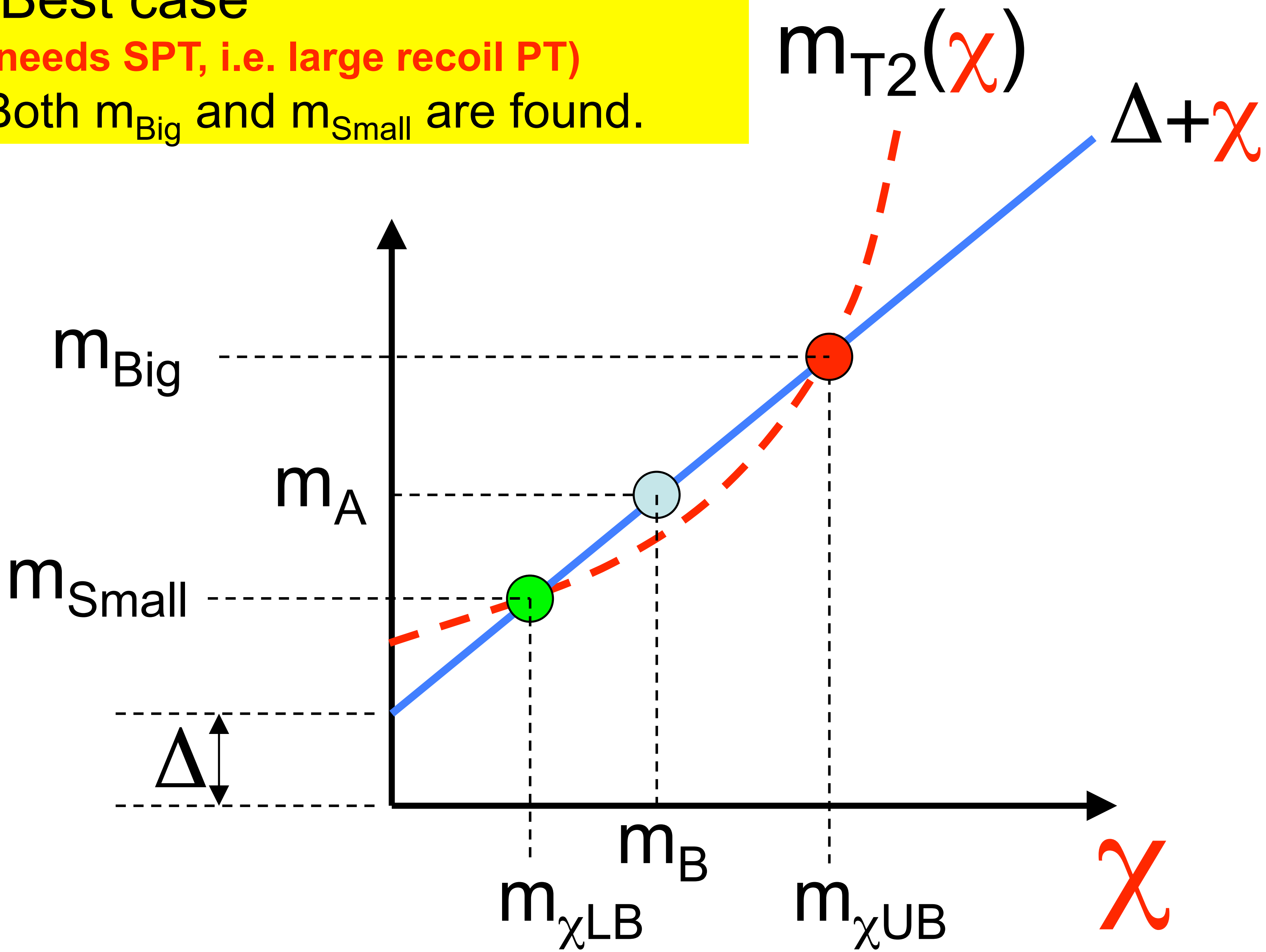
$$\Delta = M_A - M_B$$

(or M_Y-M_N in the notation of their figure above)

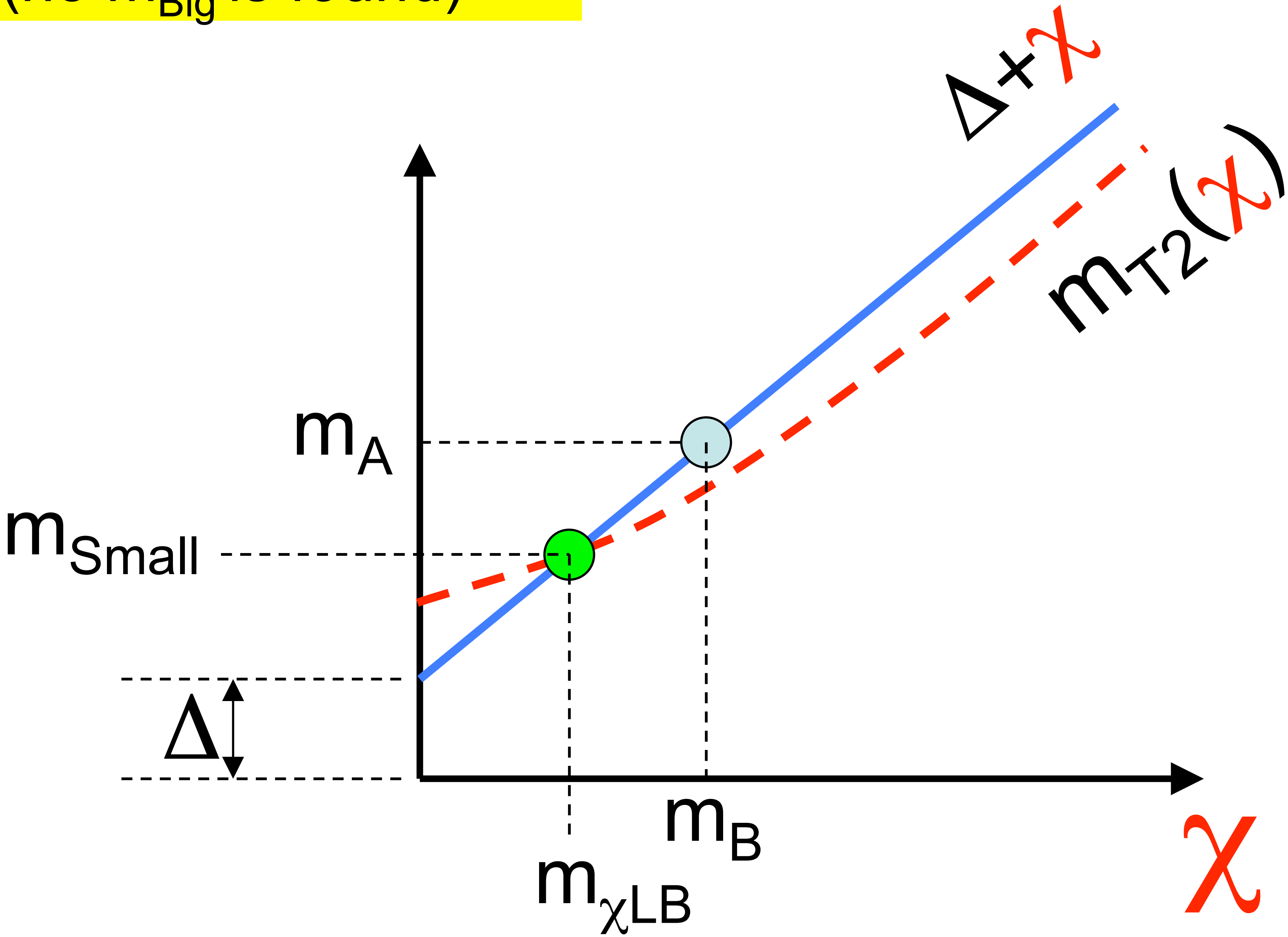
"Best case"

(needs SPT, i.e. large recoil PT)

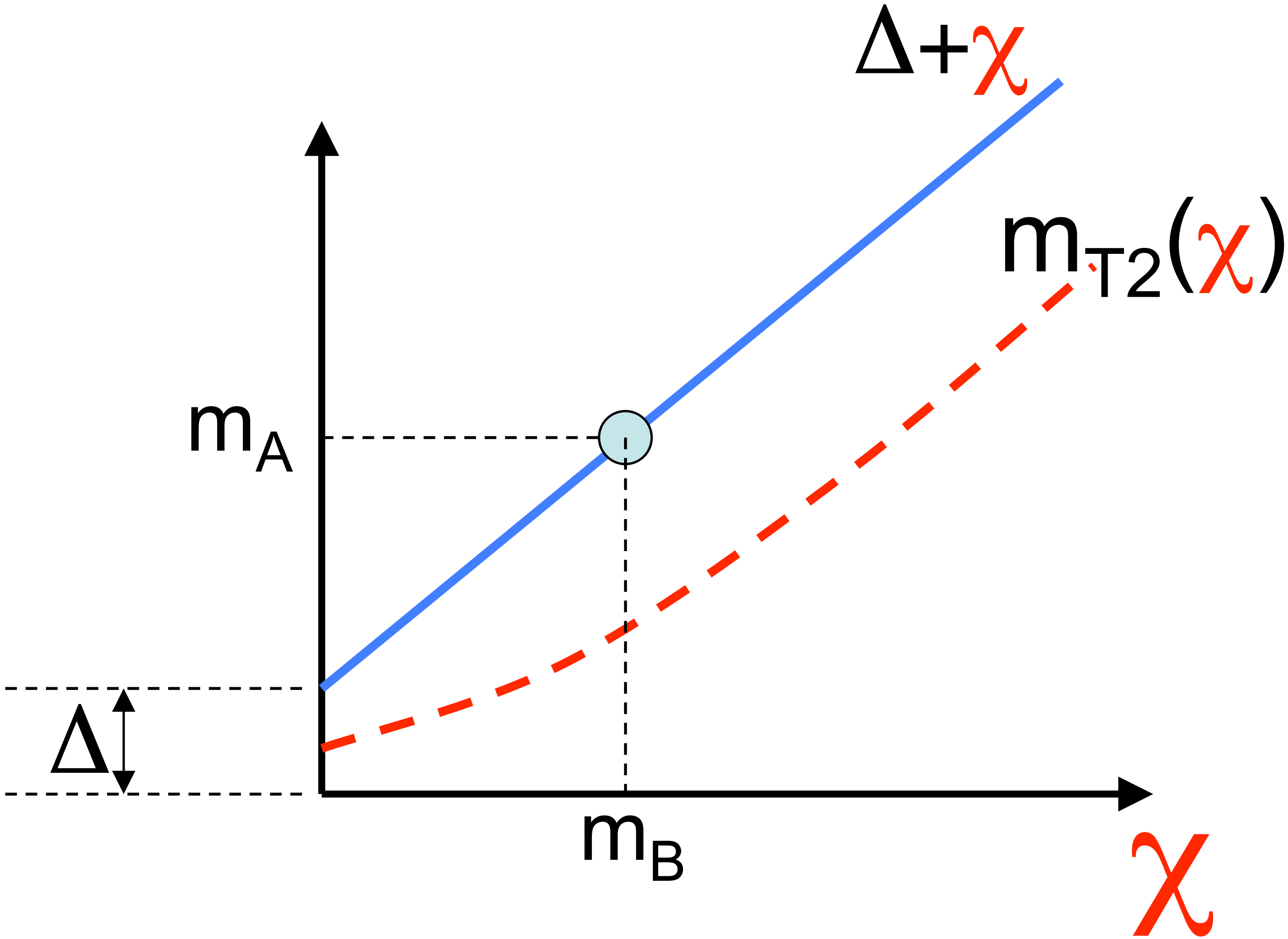
Both m_{Big} and m_{Small} are found.



“Typical ZPT case”
(no m_{Big} is found)



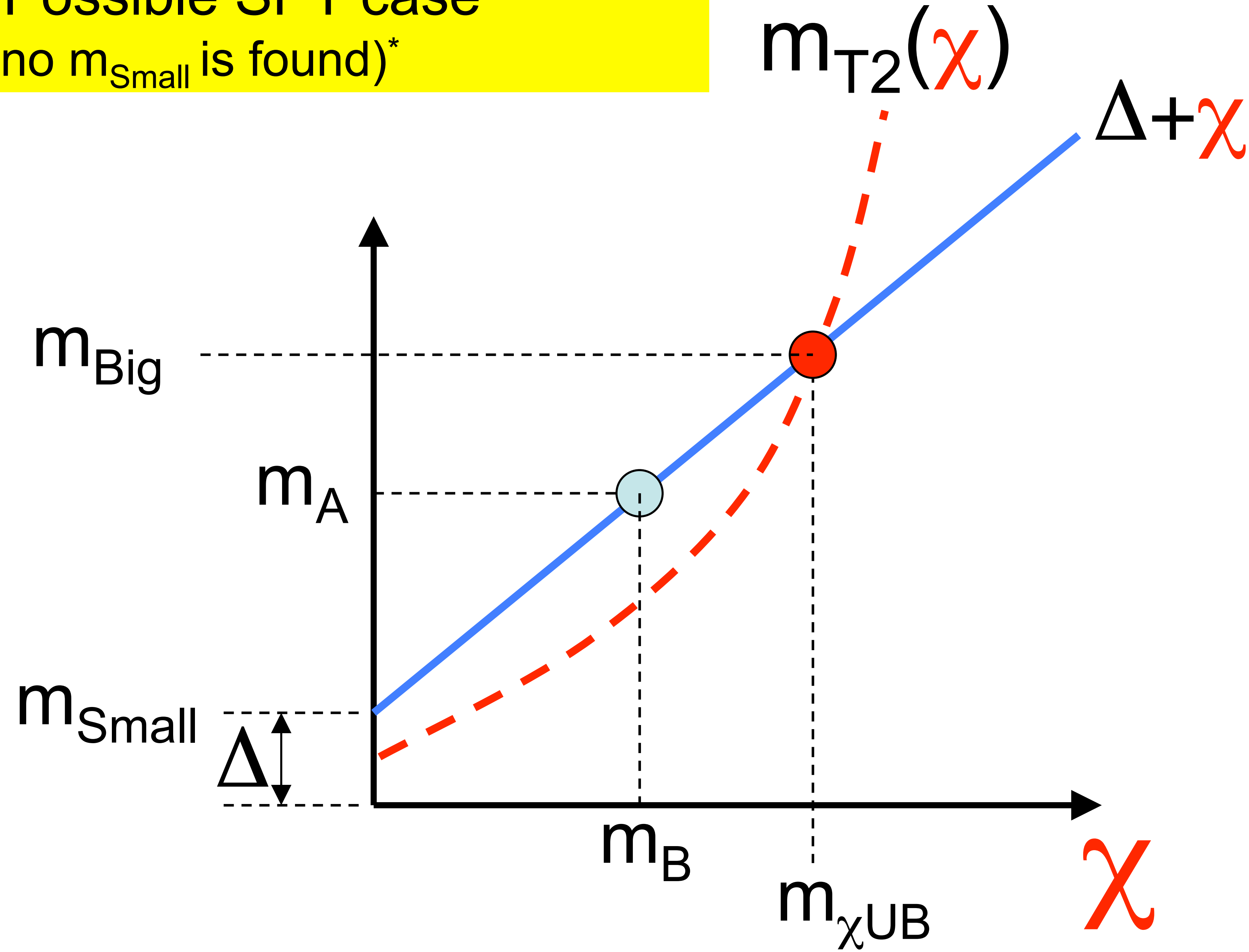
"Possible ZPT case"
(neither m_{Big} nor m_{Small} is found)*



* Except for conventional definition of m_{Small} to be Δ in this case.

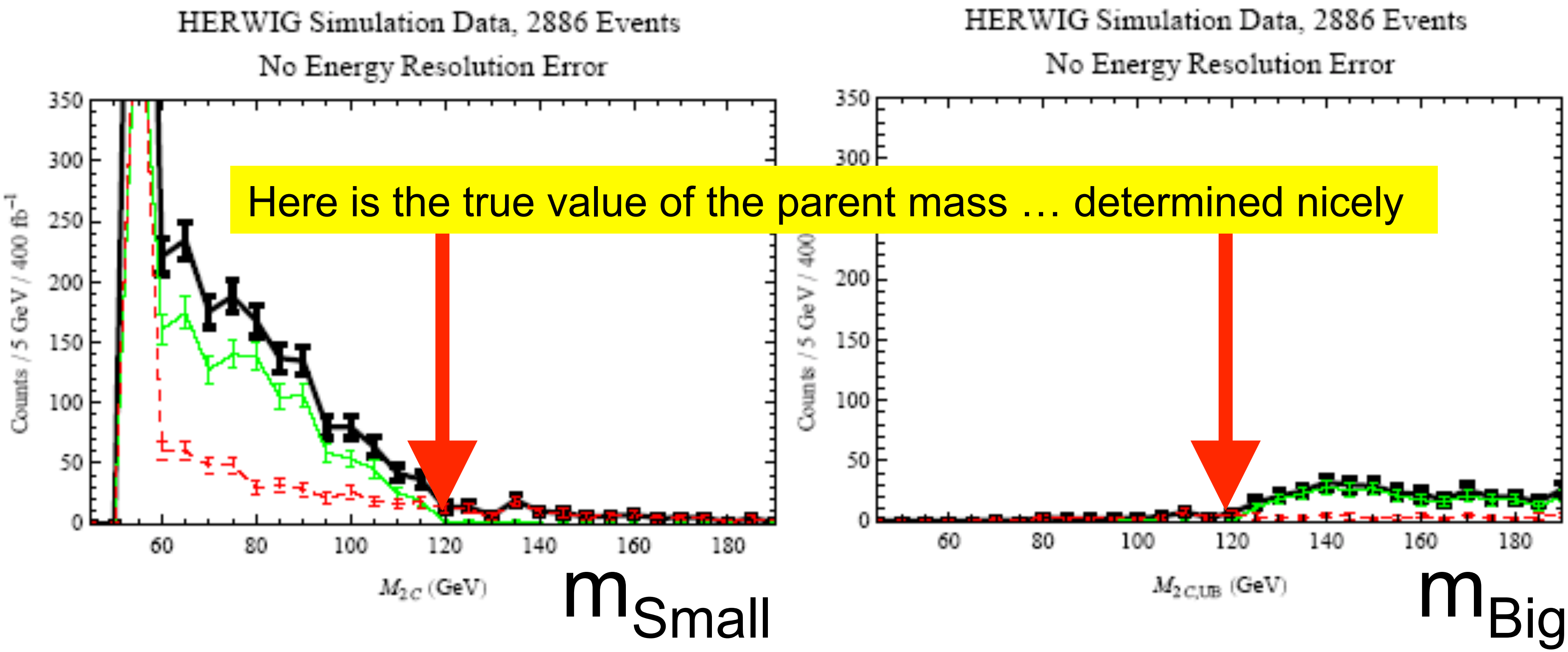
“Possible SPT case”

(no m_{Small} is found)*



* Except for conventional definition of m_{Small} to be Δ in this case.

What m_{Small} and m_{Big} look like,
and how they determine the parent mass



arXiv:0806.3224

Outcome:

- m_{Big} provides the first potentially-useful event-by-event upper bound for m_A
  - (and a corresponding event-by-event upper bound for m_B called $m_{\chi UB}$)
- m_{Small} provides a new kind of event-by-event lower bound for m_A which incorporates consistency information with the dilepton edge
- m_{Big} is always reliant on SPT (large recoil of interesting system against "up-stream momentum") – cannot ignore recoil here!

Conclusion

- There seem to be a number of different ways in which people are attempting to use the decay structure (right) to measure the mass of B
- Some of these ways use Kink structures
  - non-linear dependencies of endpoint structures on parameters like χ
- Some kink structures show up without need for recoil (ZPT)
  - gluino stransverse mass
- Others require recoil (SPT)
  - MT, M2CUB, MT2 4-body final state
- Still some work to be done to see whether kink structures coming from feet will be visible.