EdgeFinder

A proof-of-concept for unbiased kinematic edge measurements in heavily polluted samples

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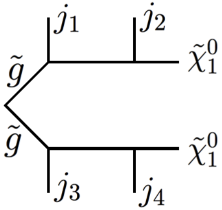
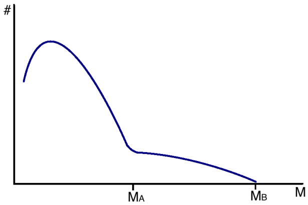
Problem:

- You have some kinematic distribution (M_{jj}, M_{T2}, . . .)



$\rightarrow$

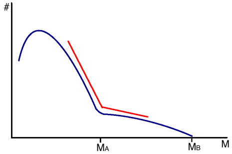


- Don't know the global shape, but you want to measure the position of the edge/endpoint because it gives you some information about the masses in the decay chain.

- How do you measure this edge?

Old Solution

Construct a fit function (commonly a linear kink, maybe with detector-motivated smearing, or something else depending on the shape of your edge) and fit to find the edge:



This has a lot of problems:

- The fit function is only an approximation to the shape of some subset of the distribution near the edge feature. Which subset? Where to fit? How good an approximation?
- This systematic error will not be included in the statistical uncertainty of the fit
- Do you introduce bias by picking a fit-domain?
- **Dreaming up more clever fit functions won't solve this problem.** Edges are difficult and ill-defined features.

Why Care?

1. Edge Measurements are difficult but important.
   - New kinematic variables like M_{T2} are extremely powerful and we would like to use them to perform mass measurements at the LHC.
   - Unfortunately they are very fragile to contamination and wash-out, making their endpoints/edges difficult to measure.
   - Need a reliable way to extract low-quality edges that accurately includes the uncertainty in their position.
2. Edge Measurements are not just difficult but deceiving!
   - Fake measurements can arise from combinatorics, cut artifacts, background, low statistics . . . . **Worst-Case Scenartio!**
   - You can deal with the false-positive problem by using two 'orthogonal' ways of cleaning up your distribution, measuring all the edges and only keeping those where both methods agree. (Examples later.)
   - This requires a way of extracting all the edges from a distribution without bias, stressing accurate uncertainties (otherwise we have no concept of two edge measurements 'agreeing' with each other).

New Solution

Objective

Find all the edges in a distribution, find their uncertainties, include systematic errors, do it automatically (no bias), and use as much or as little information about the shape of the edge as we want.

EdgeFinder

Non-Deterministic Edge Measurement

Idea: a 'Monte-Carlo' based approach.

- Come up with a fit function that includes as much or as little info as you'd like (linear kink, linear kink + smearing, . . .)
- Generate **a lot** of random fit domains over your data (no bias)
- Fit your function over each fit domain. Each fit returns a possible edge position. (Could weigh it with a goodness-of-fit test.)

→ **Build up a distribution of found edges.**

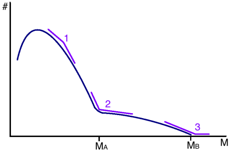
- **True edges show up as peaks.** You've just turned *edge measurement* into *bump hunting.*
- Finds all the edges without bias.
- Width of peaks give uncertainties that includes just about all possible sources. Self-measuring measurement resolution!

This **Edge-to-Bump Method** obviously needs more exploration & verification, but let's see how it works in a simple proof-of-concept.

Edge-to-Bump Method

Step-by-Step:

1. Fit a simple kink function (**no smearing**) 1000's of times to random subdomains of data (without domain length or position bias).



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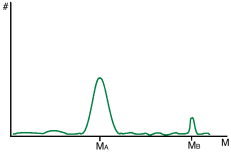
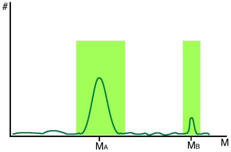


Obtain Kink Distribution

2. Detect Peaks in Kink Distribution → **Edge Detection.**



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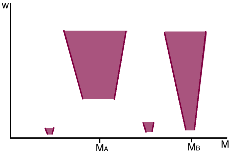
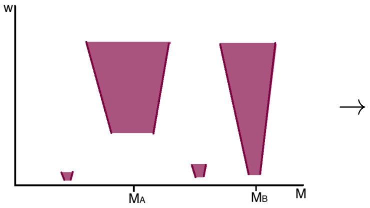


Scan over peak width w looking for 3σ excesses in central vs side bins

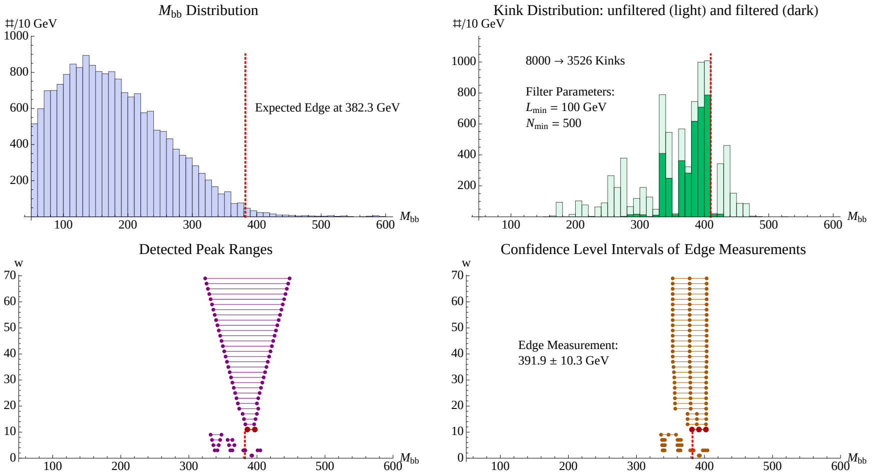
Edge-to-Bump Method

3. Turn these found peaks into edge measurements by taking the mean & standard deviation of the edge distribution around the peak:



(The absence of an edge is signaled by the absence of clear peaks in the kink-distribution. Works very reliably.)

Example

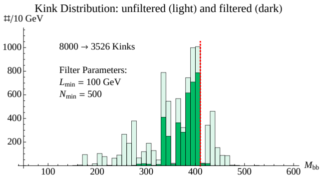


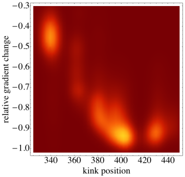
M_{bb} Distribution
♯/10 GeV
Expected Edge at 382.3 GeV
M_{bb}
Kink Distribution: unfiltered (light) and filtered (dark)
♯/10 GeV
8000 → 3526 Kinks
Filter Parameters:
L_{min} = 100 GeV
N_{min} = 500
M_{bb}
Detected Peak Ranges
w
M_{bb}
Confidence Level Intervals of Edge Measurements
w
Edge Measurement:
391.9 ± 10.3 GeV
M_{bb}

Possible Extensions

Main Idea: analyze a *distribution* of fits rather than a single fit.

- One could imagine much more sophisticated ways of analyzing the distribution of fits, can almost treat them like "events"





→ Could also include a statistical weight for each found edge.

- The method is completely general: to detect different kinds of features just use different fit functions.

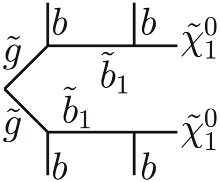
EdgeFinder

- Publicly available `Mathematica` implementation of the Edge-to-Bump method:

  `http://insti.physics.sunysb.edu/~curtin/edgefinder/`

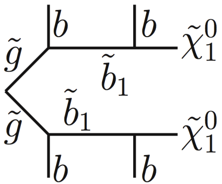
- Simple proof-of-concept: many refinements & optimizations possible.

- We demonstrate its utility in a few collider studies (including **blind verification**) by measuring **all the masses in a fully hadronic 2-step symmetric decay chain with maximal combinatorial ambiguity:**



Practical Demonstration

Use M_{T2} endpoints to measure all the masses in



Combinatorial worst-case!

But let's introduce M_{T2} first...

Some useful M_{T2} references:

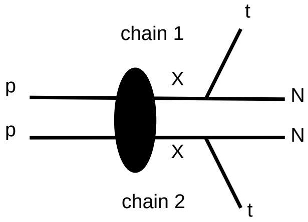
- Barr, Lester, Stephens '03 [hep-ph/0304226] (old-skool M_{T2} review)
- Cho, Choi, Kim, Park '07 [0711.4526] (analytical expressions for M_{T2} event-by-event without ISR, M_{T2}-edges)
- Burns, Kong, Matchev, Park '08 [0810.5576] (definition of M_{T2}-subsystem variables, analytical expressions for endpoints & kinks w. & w.o. ISR)
- Konar, Kong, Matchev, Park '09 [0910.3679] (Definition of $M_{T2\perp}$ to project out ISR-dependence)

(More in the paper.)

Classical M_{T2} Variable

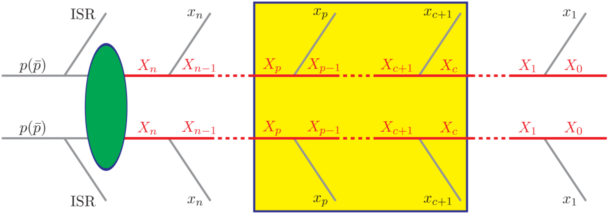
$$M_{T2}(\vec{p}_{t1}^T, \vec{p}_{t2}^T, \tilde{m}_N) = \min_{\vec{q}_1^T + \vec{q}_2^T = \vec{\not{p}}^T} \left\{ \max \left[m_T\left(\vec{p}_{t1}^T, \vec{q}_t^T, \tilde{m}_N\right), m_T\left(\vec{p}_{t1}^T, \vec{q}_t^T, \tilde{m}_N\right) \right] \right\}$$

- If p_{N1}^T, p_{N2}^T were known, this would give us a lower bound on m_X
- However, we only know total $\vec{\not{p}}^T$ $\Rightarrow$ minimize wrt all possible splittings, get 'worst' but not 'incorrect' lower bound on m_X.
- We don't even know the invisible mass m_N! Insert a testmass $\tilde{m}_N$.

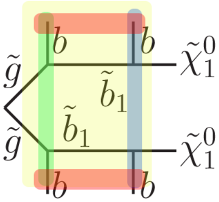


For the correct testmass, $M_{T2}^{\max} = m_X \quad \Rightarrow$ **Effectively get $\mathbf{m_X(m_N)}$.**

Multi-Step: M_{T2}-Subsystem Variables



Complete Mass Determination Possible for 2+ Step Decay Chain.

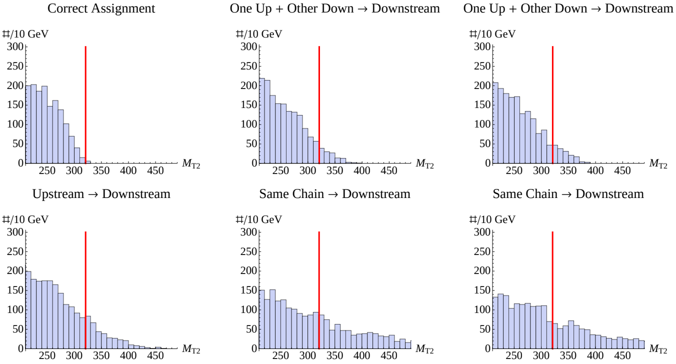


Measure 3 masses. Available variables:

M_{bb},

M_{T2}^{221}, M_{T2}^{210}, M_{T2}^{220}

M_{T2} combinatorics are awful...



M_{T2} Combinatorics Problem

M_{T2} is 'powerful but fragile', much more problematic than M_{jj}:

- There are more wrong-sign combinations.
- Edges are shallow $\rightarrow$ less well defined, more easily washed out (ISR, detector effects, background).
- The combinatorics background has nontrivial structure $\rightarrow$ **Fake Edges!**
- No one method of reducing combinatorics background works reliably all of the time.

$\Longrightarrow$ Combinatorics Background doesn't just reduce quality of edge measurement, it can invalidate measurement completely.
Have to reject fakes!

Golden Rule for M_{T2} Measurements

Always use more than one method to reduce combinatorics background.

Only accept endpoint measurement if they agree

For each M_{T2} variable we perform the following steps:

1. Apply two CB reduction methods $\rightarrow$ two M_{T2} distributions.
2. Apply Edge-to-Bump to each $\rightarrow$ two kink distributions.
3. Good quality edges in both distributions that agree?

YES: **merge & accept measurement**
(can increase error bars)

NO: **discard variable**.
(e.g. disagreeing edges, no edge in one distribution, . . .)

Combinatorics Background: DL Method

If we're going to analyze multi-step decay chains we need to get a handle on combinatorics background.

Simplest thing you could do: drop largest few M_{T2}'s per event.

- For each event, the true M_{T2} is a lower bound for M_{T2}^{max}.
- If there are several M_{T2}-possibilities per event, the largest one(s) are more likely to be wrong.

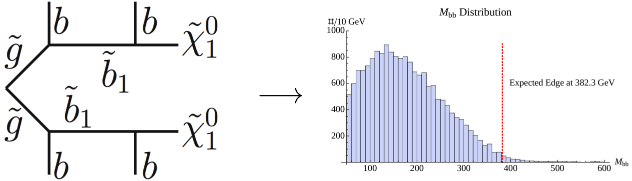
→ Discard Them!

- **Works surprisingly well, some of the time.**

Combinatorics Background: KE Method

What else could we do?

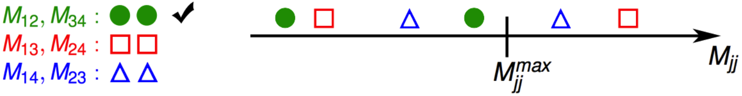
Edge in M_{bb}-distribution (invariant mass of decay chain) is relatively easy to measure using Edge-to-Bump, combinatorics are benign.



Could we make use of this M_{bb}^{max} information?

Combinatorics Background: KE Method

Known M_{bb}^{max}



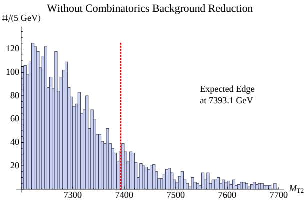
$\Rightarrow$ deduce correct decay chain assignment for 15 – 30% of events.

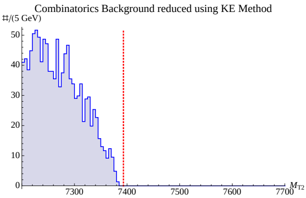
100% purity! (Before mismeasurement & detector effects)

Extremely simple & high-yield method for determining decay chain assignment.

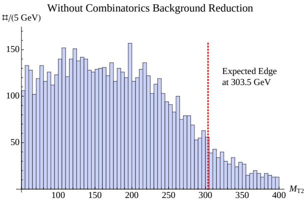
CB Reduction Example

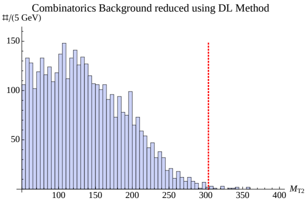
$M_{T2}^{220}(E_b)$:





$M_{T2}^{221}(0)$:

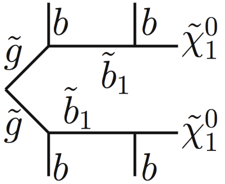




No one method works reliably all of the time. Sometimes they fail, sometimes they produce fake edges.

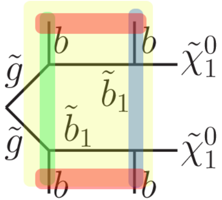
Now we're finally ready for . . .

Monte Carlo Studies



First Monte Carlo Study

Apply our methods to a **fully hadronic combinatorics-worst-case scenario** without other backgrounds.



Measure 3 masses. Available variables:

M_{bb},

M_{T2}^{221}, M_{T2}^{210}, M_{T2}^{220}

(use both ISR-binned & $\perp$ versions, for zero and large testmass).

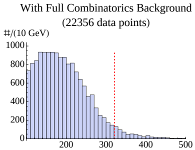
- Choose a particular MSSM Benchmark Point w/o SUSY-BG.

m_{t1}	m_{t2}	s_t	m_{b1}	m_{b2}	s_b	$m_{\tilde{g}}$	$m_{\tilde{\chi}_1^0}$
371	800	-0.095	341	1000	-0.011	525	98

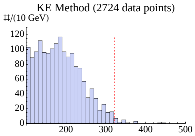
(Already excluded by LHC, but that doesn't matter for us.)

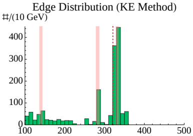
- $\sigma_{\tilde{g}\tilde{g}} \approx 11.6$ pb @ $\sqrt{s} = 14\,\mathrm{TeV}$. Use $\mathcal{L} = 100\ \mathrm{fb}^{-1}$ (pessimistic).
- Simulate with `MadGraph/MadEvent`, **`Pythia, PDG`**.
- Require 4 b-tags & MET > 200 GeV $\rightarrow$ 58k Signal Events, Eliminates SM BG.

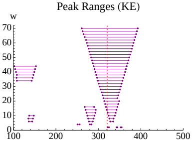
Full M_{T2} Measurement Example

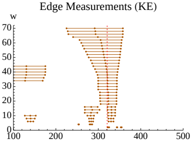


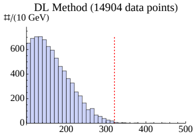
$\leftarrow M_{T2}^{210}(0)$

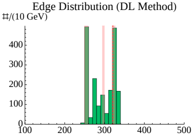


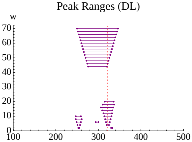


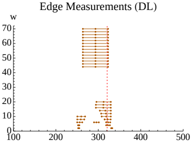




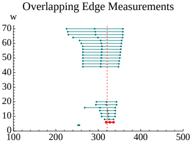








Measurement:
$327 \pm 8.7\,\mathrm{GeV}$
[320.9]

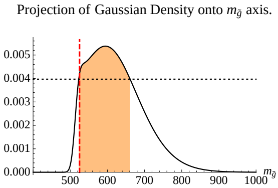


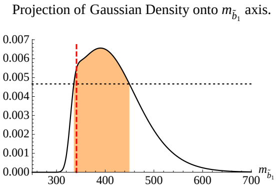
Edge Measurements

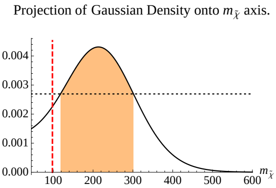
Variable	Prediction	Measurement	Deviation/σ	Quality
$\mathbf{M_{bb}}$	382.3	391.8 ± 10.3	$+0.93$	—
$M_{T2\perp}^{221}(0)$	303.5	240 ± 140	-0.45	C
$M_{T2}^{221}(0)$		301 ± 47	-0.05	A
$M_{T2\perp}^{221}(E_b)$	7153.4	7154 ± 42	$+0.01$	A
$M_{T2}^{221}(E_b)$		7171 ± 42	$+0.42$	A
$M_{T2\perp}^{210}(0)$	320.9	283 ± 44	-0.86	A
$\mathbf{M_{T2}^{210}(0)}$		327.2 ± 8.7	$+0.72$	A
$M_{T2\perp}^{210}(E_b)$	7239.8	7141 ± 54	-1.84	A
$M_{T2}^{210}(E_b)$		7176 ± 37	-1.75	A
$M_{T2\perp}^{220}(0)$	506.7	509 ± 211	$+0.01$	C
$M_{T2}^{220}(0)$		528 ± 56	$+0.38$	B
$M_{T2\perp}^{220}(E_b)$	7393.1	7484 ± 106	$+0.86$	B
$M_{T2}^{220}(E_b)$		7456 ± 70	$+0.90$	B
$M_{T2\perp \mathrm{all}}^{210}(0)$	312.8	249 ± 52	-1.23	B
$M_{T2\perp \mathrm{all}}^{210}(E_b)$	7158.2	7129 ± 40	-0.73	A

NO FALSE MEASUREMENTS!

Mass Measurements







$m_{\tilde{g}}^{meas} = 592 \pm 69 \;\; (525)$ $\quad$ $m_{\tilde{b}_1}^{meas} = 393 \pm 57 \;\; (341)$ $\quad$ $m_{\tilde{\chi}_1^0}^{meas} = 210 \pm 92 \;\; (98)$

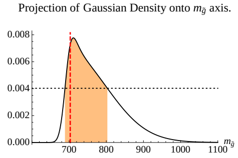
Gluino and sbottom masses measured with $\sim$ 10% precision!

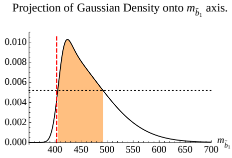
Blind Study

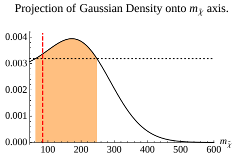
- Want to verify our methods with a different spectrum:

$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$	$\sin\theta_{\tilde{t}}$	$m_{\tilde{b}_1}$	$m_{\tilde{b}_2}$	$\sin\theta_{\tilde{b}}$	$m_{\tilde{g}}$	$m_{\tilde{\chi}_1^0}$
1016	1029	0.76	404	1012	1	703	84

- Somewhat more luminosity to get same number of events. Analysis otherwise identical to first study.
- **Did not know the spectrum prior to completing analysis!**
- **Worked equally well:**







$m_{\tilde{g}}^{meas} = 746 \pm 57 \;\; (703)$ $\quad$ $m_{\tilde{b}_1}^{meas} = 449 \pm 44 \;\; (403)$ $\quad$ $m_{\tilde{\chi}_1^0}^{meas} = 155 \pm 92 \;\; (84)$

Conclusion

Conclusion

- Edge-to-Bump Method: MC-based edge **detection** and **measurement** that addresses most of the edge-measurements problems that were prohibitive to LHC application (bias, systematic error, self-determined sensible uncertainties).
- The **`EdgeFinder`** `Mathematica` package is a publicly available proof-of-concept of the Edge-to-Bump method. Demonstrated utility, but obviously much room for extension & optimization.
- We showed for the first time that M_{T2} can be used to determine all the masses in a fully hadronic 2-step symmetric decay chain with maximal combinatorial ambiguity.
  - KE-method of deducing decay chain assignment: extremely simple & high-yield.
  - Application to M_{T2}: Simultaneous use of 2+ methods of reducing combinatorics background allows for rejection of fake edges & artifacts.

Conclusion

UPDATE:

These methods might find their way into an upcoming CMS analysis.

So stay tuned :).