Measuring Invisible Particle Masses Using a Single Short Decay Chain

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Based on work in progress with Jiayin Gu

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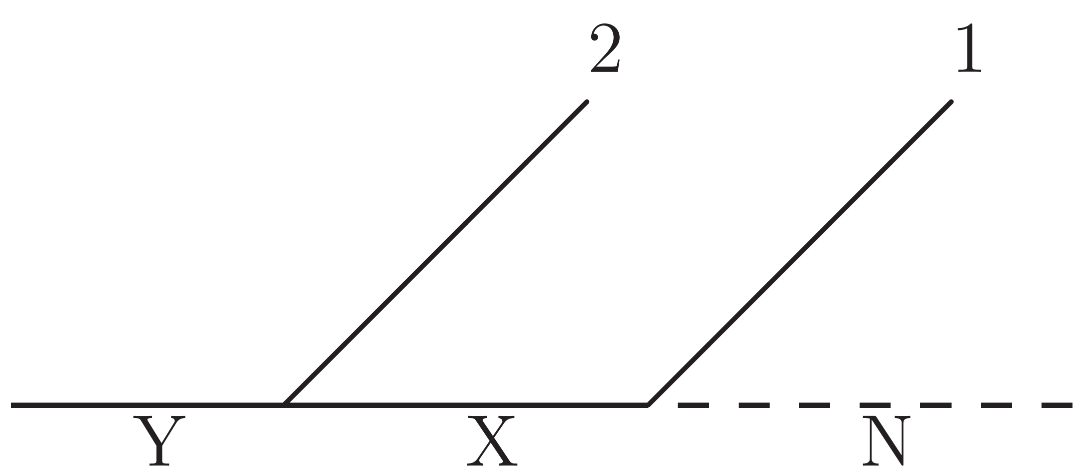
Introduction

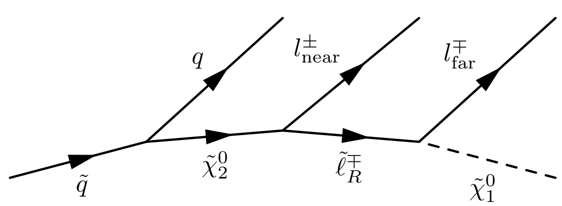
- We study the mass measurement for the following decay chain at LHC.



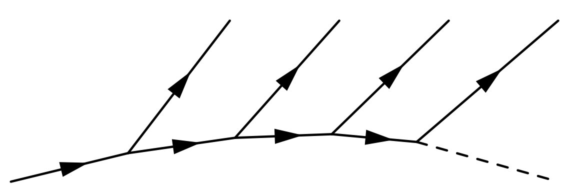
There is at least another missing particle in the event, so the transverse momentum of N is unknown.

Motivations

- Appears in many models with WIMP dark matter.
- Most recent studies focus on symmetric decay chains, but there may be many more asymmetric-chain events than symmetric ones.
- Mass measurements were only done for long decay chains for single decay chains.



Gjelsten, B. K. et al & others

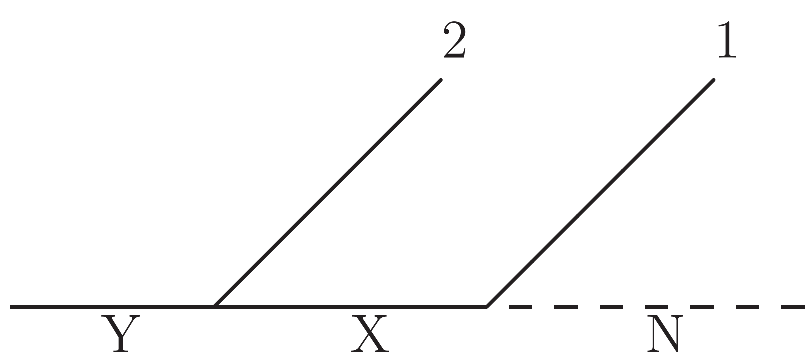


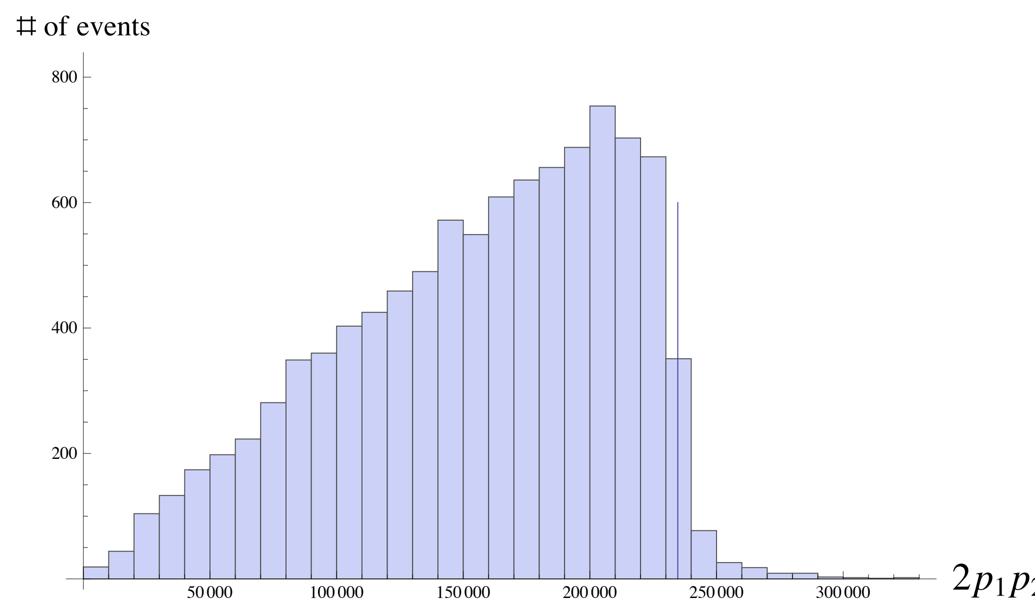
Kawagoe, K. et al & others

- It's a subprocess of many more complicated events.

Invariant mass end point

- 2 visible particles, only one invariant mass can be formed.



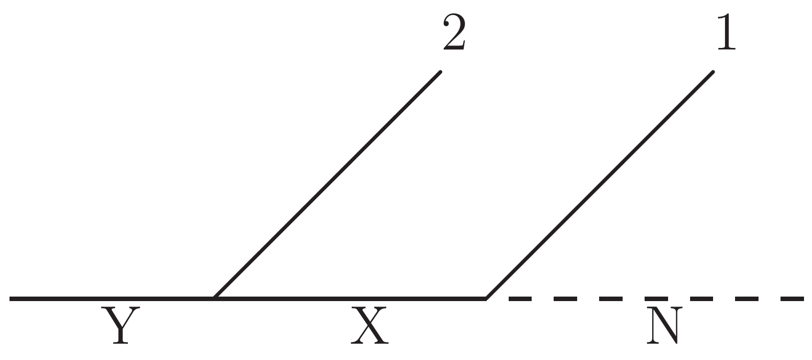


The end point provides one relation among 3 unknown masses, but cannot determine 3 masses individually.

$$(p_1+p_2)^2\big|_{\max} = \frac{(m_Y^2-m_X^2)(m_X^2-m_N^2)}{m_X^2} \equiv \frac{\Delta_1\Delta_2}{m_X^2}$$

Constraint equations

$$
\begin{aligned}
p_Y^2 &= m_Y^2, \\
(p_Y - p_2)^2 &= m_X^2, \\
(p_Y - p_2 - p_1)^2 &= m_N^2,
\end{aligned}
$$



Taking the differences, we get 2 linear equations,

$$
\begin{aligned}
2p_2\, p_Y &= m_Y^2 - m_X^2 \equiv \Delta_2, \\
2p_1\, p_Y - 2p_1\, p_2 &= m_X^2 - m_N^2 \equiv \Delta_1,
\end{aligned}
$$

assuming $p_1^2 = p_2^2 = 0.$

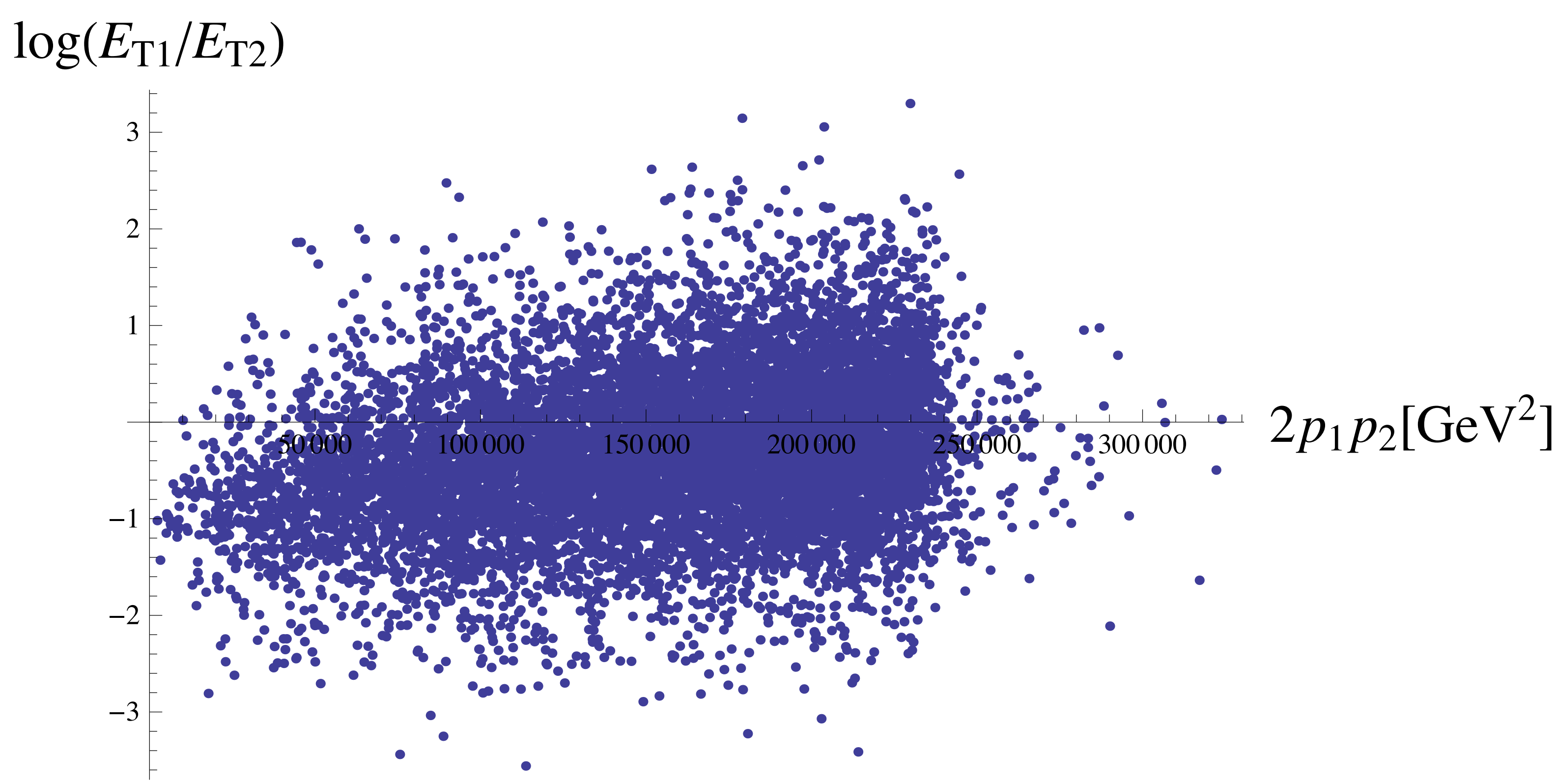
There is another type of special events: when

$$p_1 \parallel p_2 \ \ (p_1 \cdot p_2 = 0) \quad \Rightarrow \quad \frac{E_1}{E_2} = \frac{\Delta_1}{\Delta_2}.$$

We get another relation among 3 masses.

New kinematic variable

- Event distribution in $\log(E_{T1}/E_{T2})$ vs. $2p_1.p_2$ space



	Y	X	N	2	1
particle	left-handed down squark	2nd chargino	anti-sneutrino	up quark	electron
mass[GeV]	777	465	292	0	0

(LM2 point)

New kinematic variable

- Taking the ratio of 2 linear equations, we derive

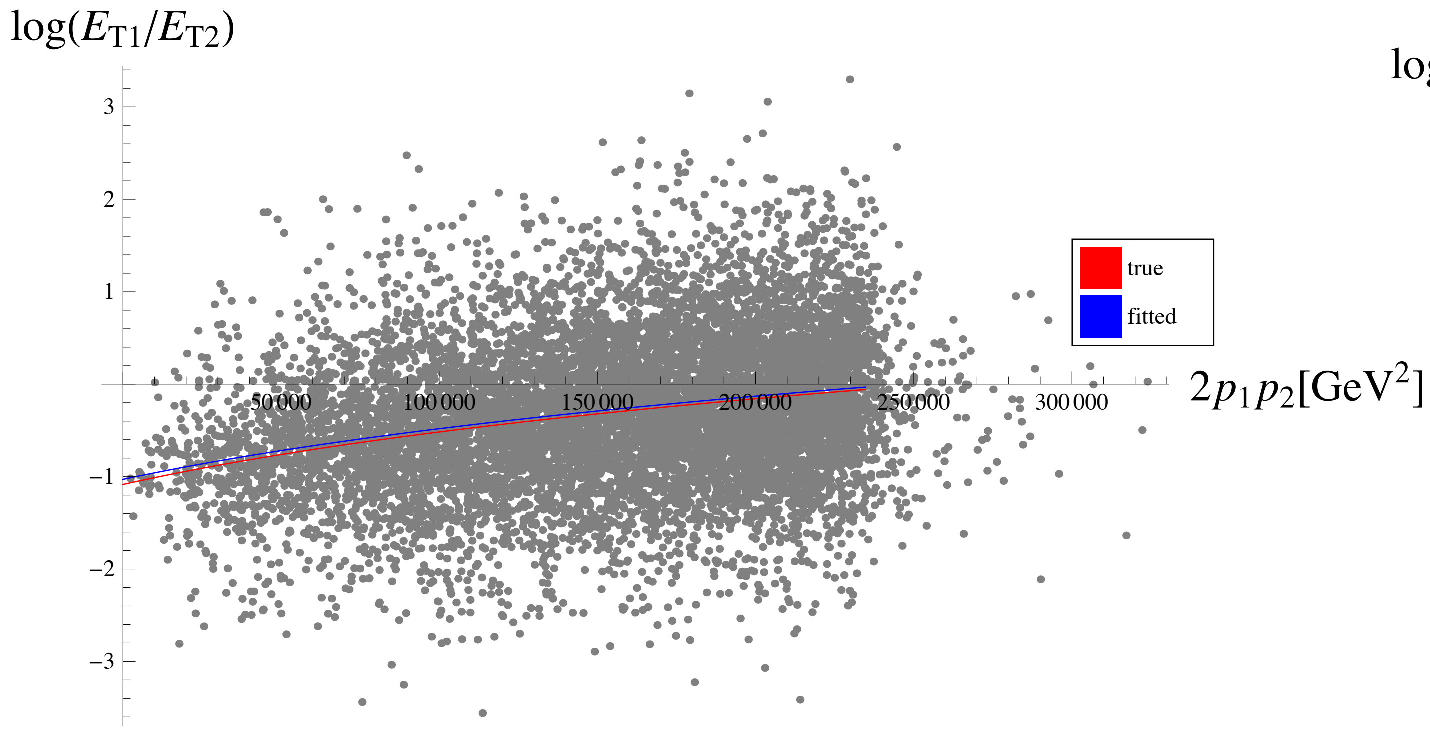
$$\log \frac{E_1}{E_2} = \log \frac{\Delta_1 + 2p_1p_2}{\Delta_2} + \log \left. \frac{1-\beta_Y \cos\theta_{2Y}}{1-\beta_Y \cos\theta_{1Y}} \right|_{\text{lab}}$$
$$= \log \frac{\Delta_1 + 2p_1p_2}{\Delta_2} + \log \left. \frac{1+\beta_Y \cos\theta_{1Y}}{1+\beta_Y \cos\theta_{2Y}} \right|_{Y},$$

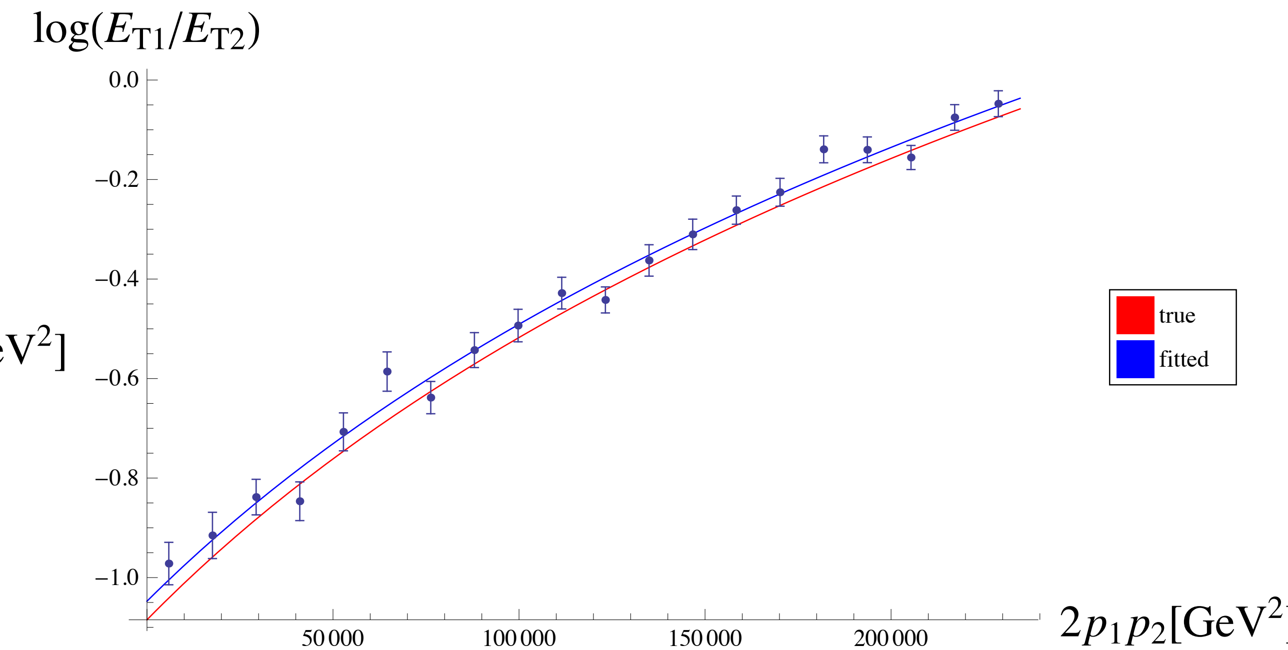
If 2nd term is randomly distributed around 0, then we can fit the distribution with a curve

$$\log \frac{\Delta_1 + 2p_1p_2}{\Delta_2}$$

to extract Δ_1 and Δ_2 individually. Plus the invariant mass end point, we can solve for 3 masses.

New kinematic variable





	$\Delta_1[\mathrm{GeV}^2]$	$\Delta_2[\mathrm{GeV}^2]$	$\log(\Delta_1/\Delta_2)$	$m_Y[\mathrm{GeV}]$	$m_X[\mathrm{GeV}]$	$m_N[\mathrm{GeV}]$
true	1.310×10^5	3.875×10^5	-1.08	777	465	292
reconstructed	1.370×10^5	3.838×10^5	-1.03	780	473	295
error	$+4.6\%$	-0.96%	$+5.5\%$	$+0.34\%$	$+1.8\%$	$+1.0\%$

for 10^4 parton-level events

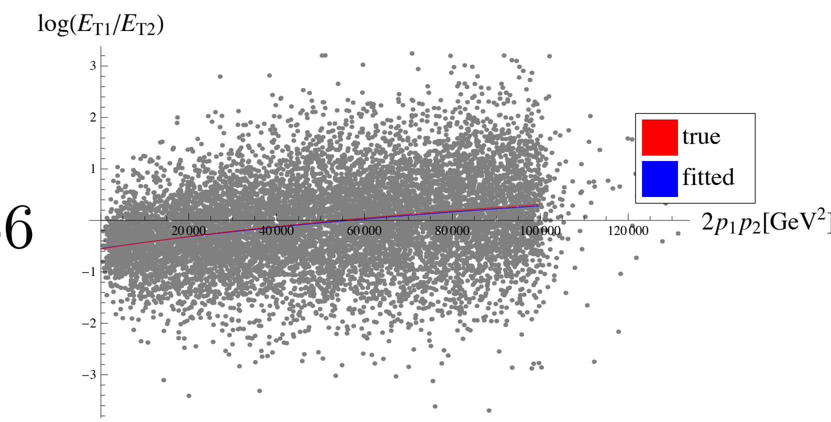
- It works well for a wide varieties of models and spectra at the parton level, except for 2 cases.

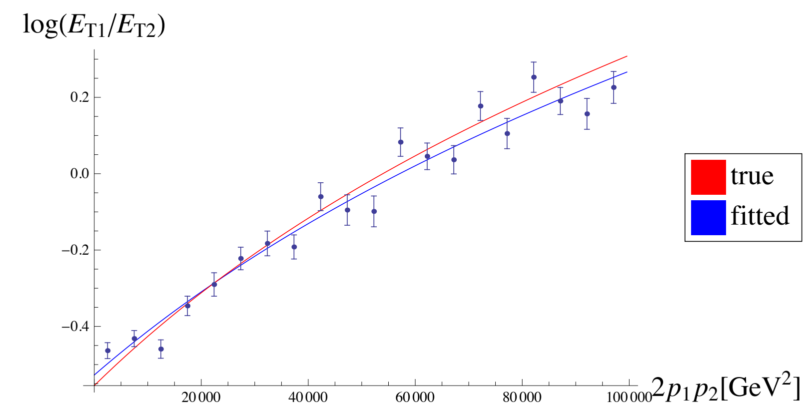
Cases where it falters

The second term has a bias if

- mother particle Y is polarized:

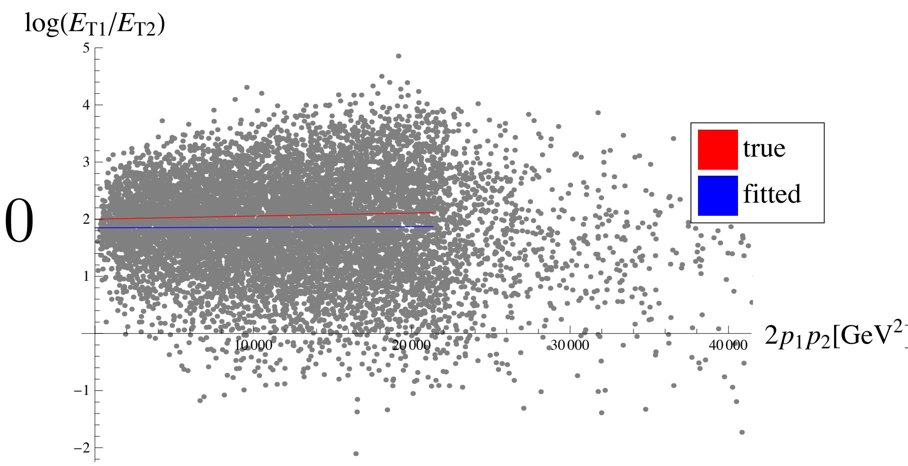
$$\left\langle \cos\theta_{2Y}\Big|_{Y}\right\rangle = 0.066$$

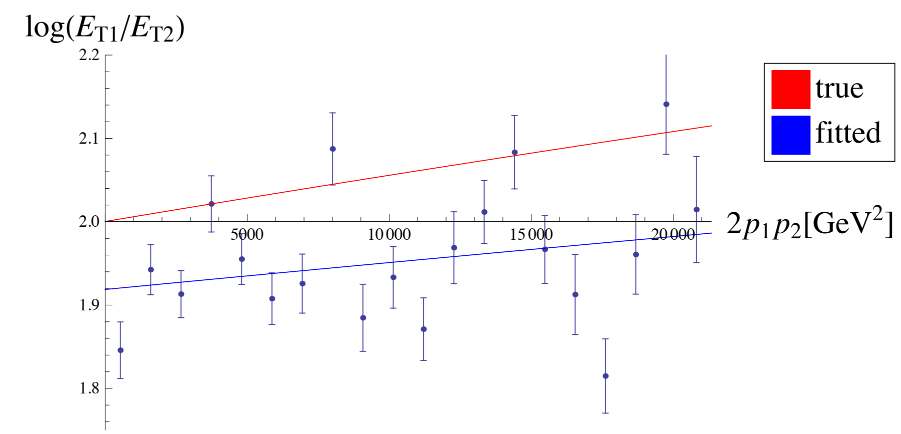




- $\Delta_1 >> \Delta_2$:

$$\log\frac{\Delta_1}{\Delta_2} = 2.0$$





However, the ratio Δ_1/Δ_2 can still be well determined.

Issues in real experiments

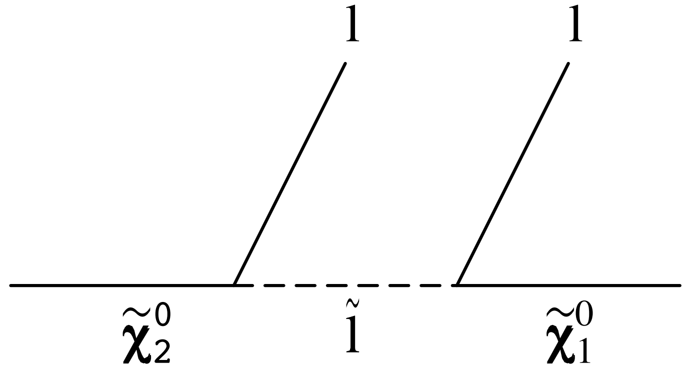
- Selecting signals from backgrounds.
- Experimental smearing: We smear events according to the Gaussian errors in the Table.

leptons:
$\lvert\eta\rvert < 2.5,\ p_T > 10$ GeV, $\frac{\delta p_T}{p_T} = 0.008 \oplus 0.00015 p_T$, $\delta\theta = 0.001,\ \delta\phi = 0.001.$
jets:
$\lvert\eta\rvert < 5.0,\ p_T > 20$ GeV, $\frac{\delta E_T}{E_T} = \begin{cases} \frac{5.6}{E_T} \oplus \frac{1.25}{\sqrt{E_T}} \oplus 0.033, & \text{for } \lvert\eta\rvert < 1.4, \\ \frac{4.8}{E_T} \oplus \frac{0.89}{\sqrt{E_T}} \oplus 0.043, & \text{for } \lvert\eta\rvert > 1.4, \end{cases}$ $\delta\eta = 0.03,\ \delta\phi = 0.02$ for $\lvert\eta\rvert < 1.4$, $\delta\eta = 0.02,\ \delta\phi = 0.01$ for $\lvert\eta\rvert > 1.4$.

- Combinatorial problems:
  - between the 2 visible particles on the decay chain,
  - between a visible particle on the decay chain and another particle somewhere else.

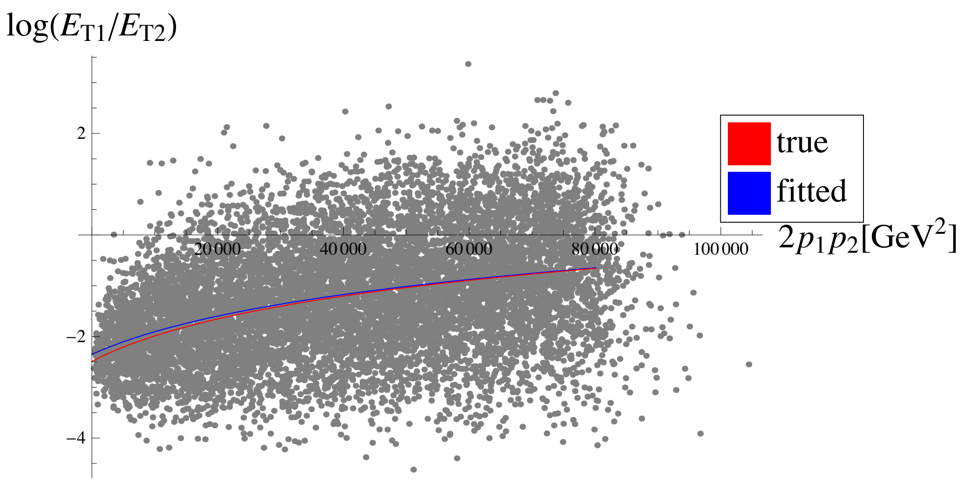
2 leptons from a neutralino decay

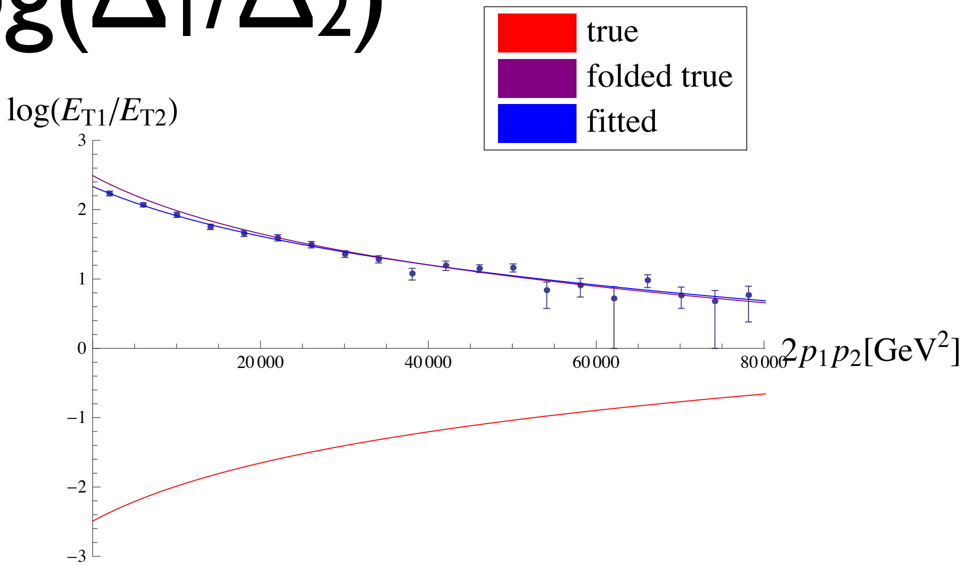
- The 2 leptons can be in either order, so we can only measure $|\log(E_{T1}/E_{T2})|$. The distribution is folded along the $\log(E_{T1}/E_{T2})=0$ axis. We can try to identify the peak points by fitting the distribution with a folded Gaussian for each invariant mass bin.



  - Still good for large negative $\log(\Delta_1/\Delta_2)$

$$\log \frac{\Delta_1}{\Delta_2} = -2.5$$

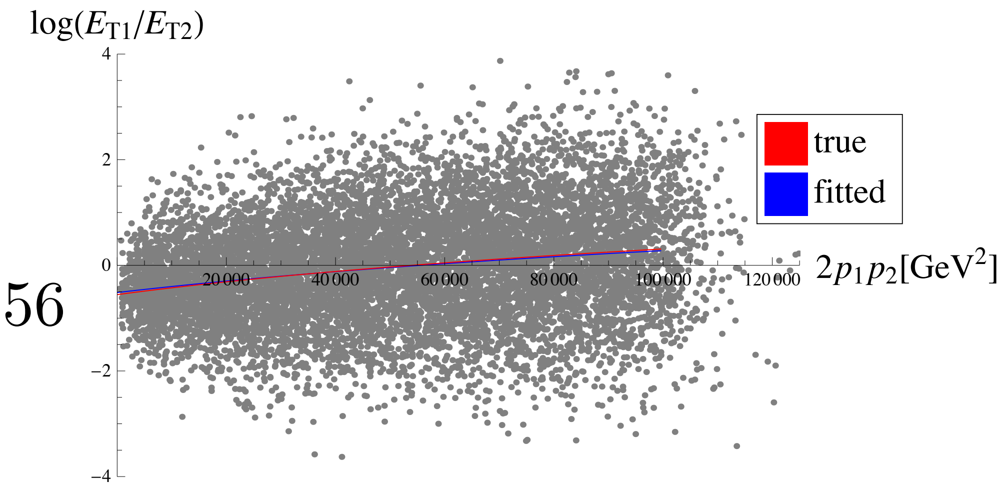


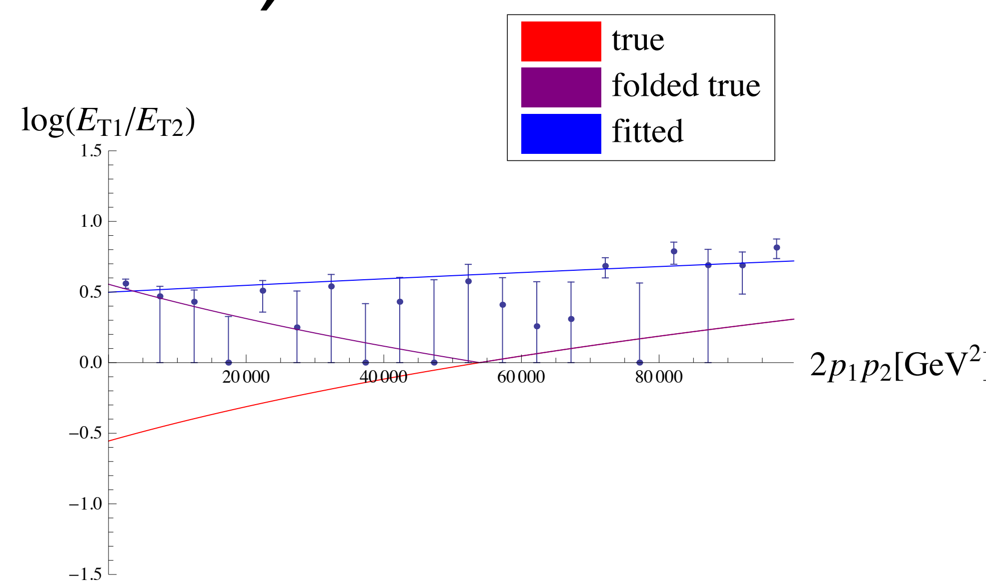


2 leptons from a neutralino decay

- Bad for small negative $\log(\Delta_1/\Delta_2)$

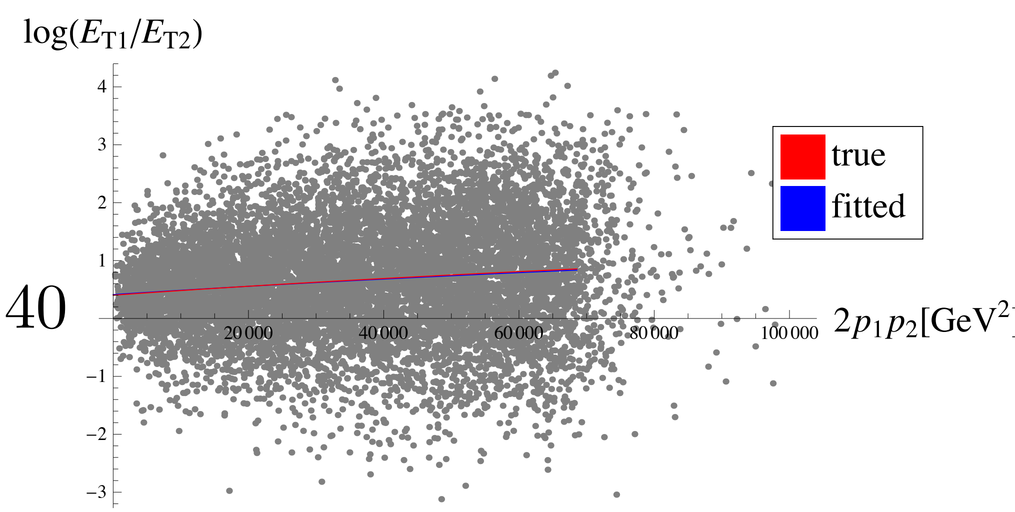
$$\log \frac{\Delta_1}{\Delta_2} = -0.56$$

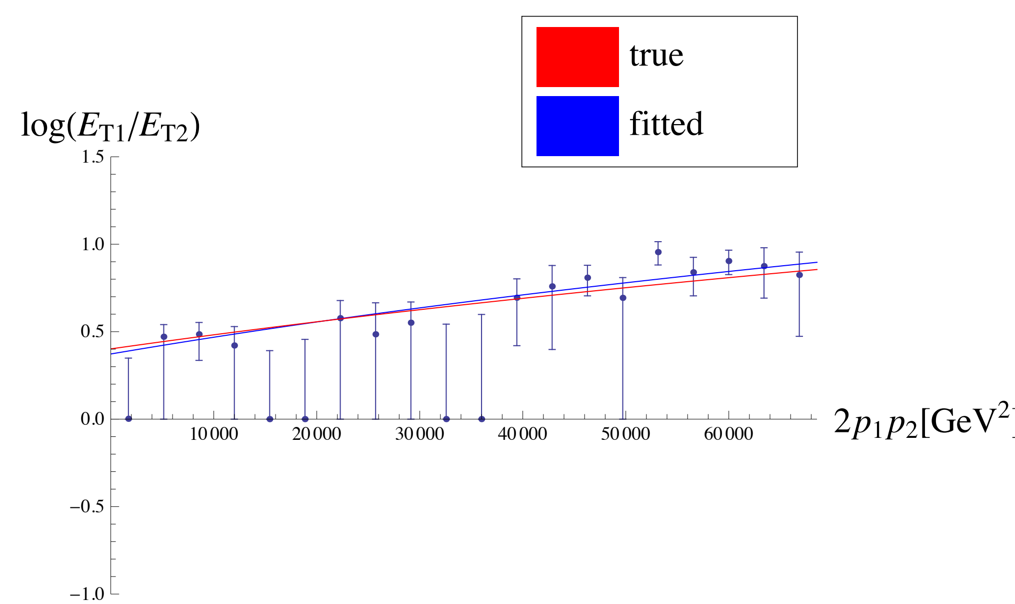




- OK for small positive $\log(\Delta_1/\Delta_2)$, but needs larger statistics

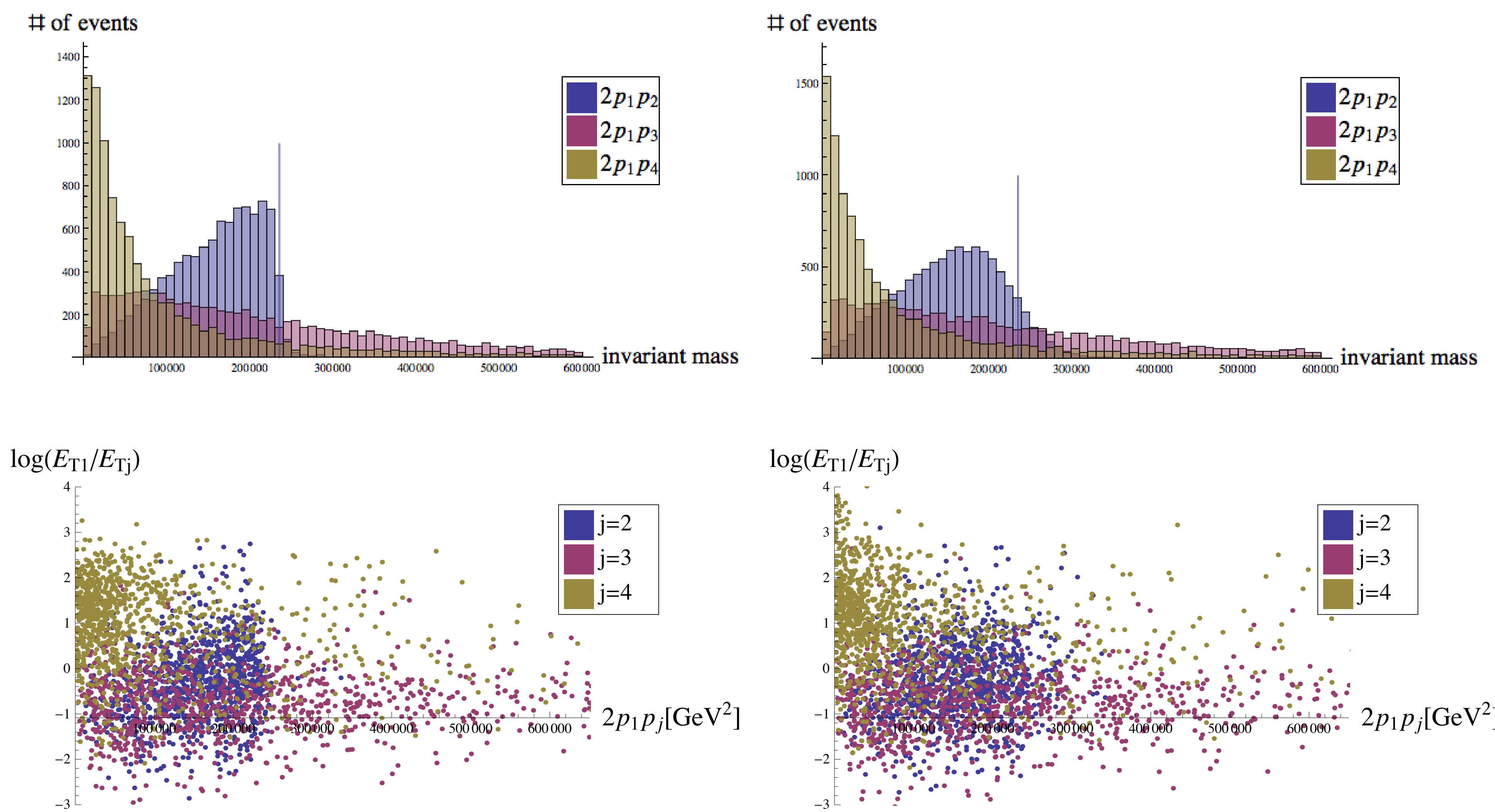
$$\log \frac{\Delta_1}{\Delta_2} = +0.40$$





1 jet + 1 lepton case

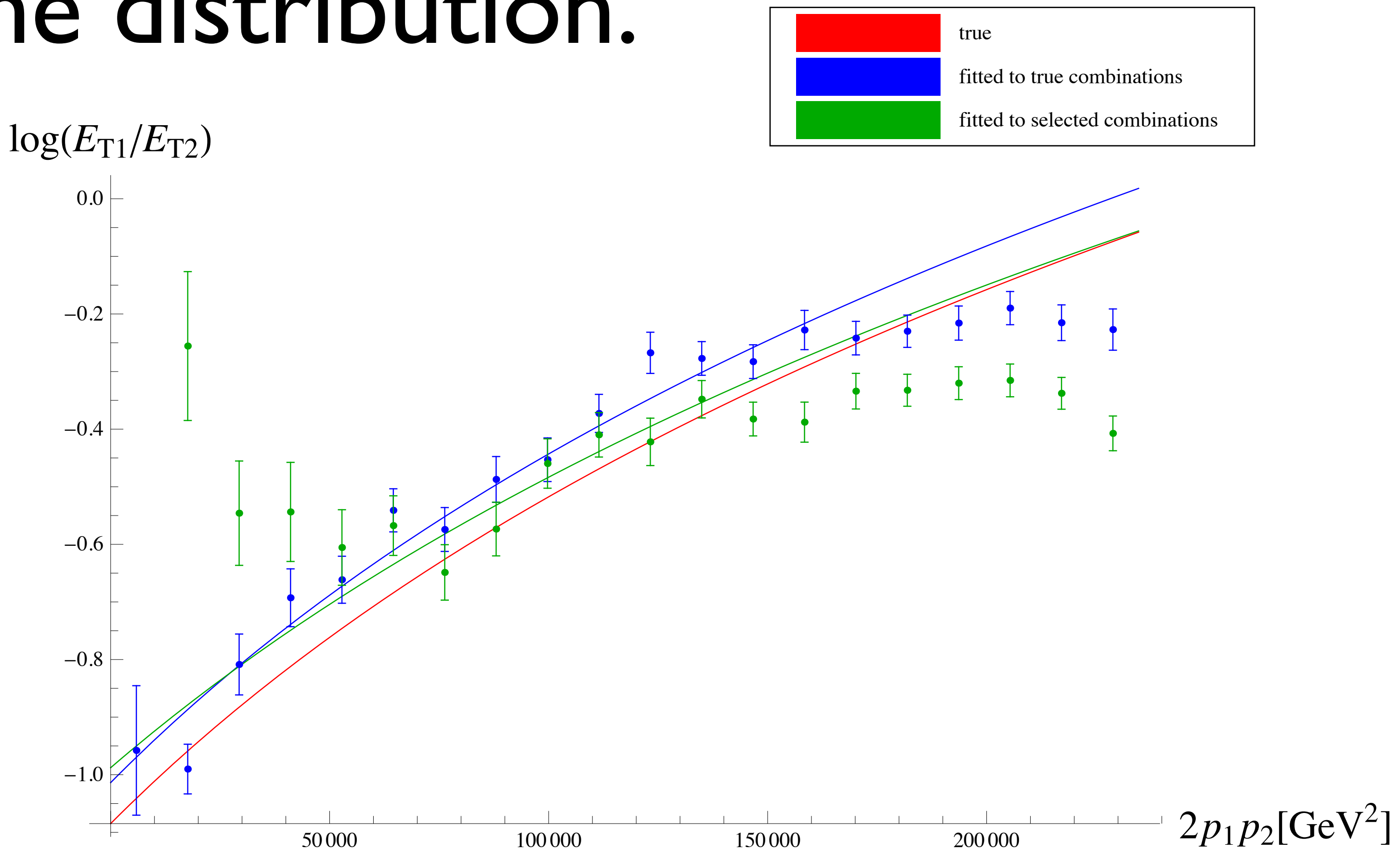
- There can be many other jets in the event. We consider 1 jet from the other decay chain (particle 3) and 1 jet from ISR (particle 4)



Before smearing After smearing

1 jet + 1 lepton case

- We select the jet-lepton pair which forms the largest invariant mass but below the "end point." The distribution is more affected at both small and large invariant mass regions. Both parts make the fit curve flatter than the true one. Reasonable results can be obtained using only the central part of the distribution.



Summaries

- We found that $\log(E_{T1}/E_{T2})$ is a useful kinematic variable in a decay chain.
- The signal events in $\log(E_{T1}/E_{T2})$ vs. invariant mass^2 space have an interesting distribution, which may be used to
  - tell the order of particles 1 & 2,
  - determine unknown masses in the decay chain,
  - separate signals from backgrounds.