Reducing the combinatorial uncertainties using kinematic variables

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III CPAN DAYS

2 November 2011

In collaboration with K. Choi and D. Guadagnoli, arXiv:1109.2201, *submitted to JHEP.*

Combinatorics?

* ... is a branch of mathematics concerning the study of finite or countable discrete structures. Aspects of combinatorics include **counting the structures of a given kind and size**, deciding when certain criteria can be met, and constructing and analyzing objects **meeting the criteria**, finding "largest", "smallest", or "optimal" objects, ...

* A mathematician who studies combinatorics is called a *combinatorialist*.

...Wikipedia, rev. 29 Oct. 2011

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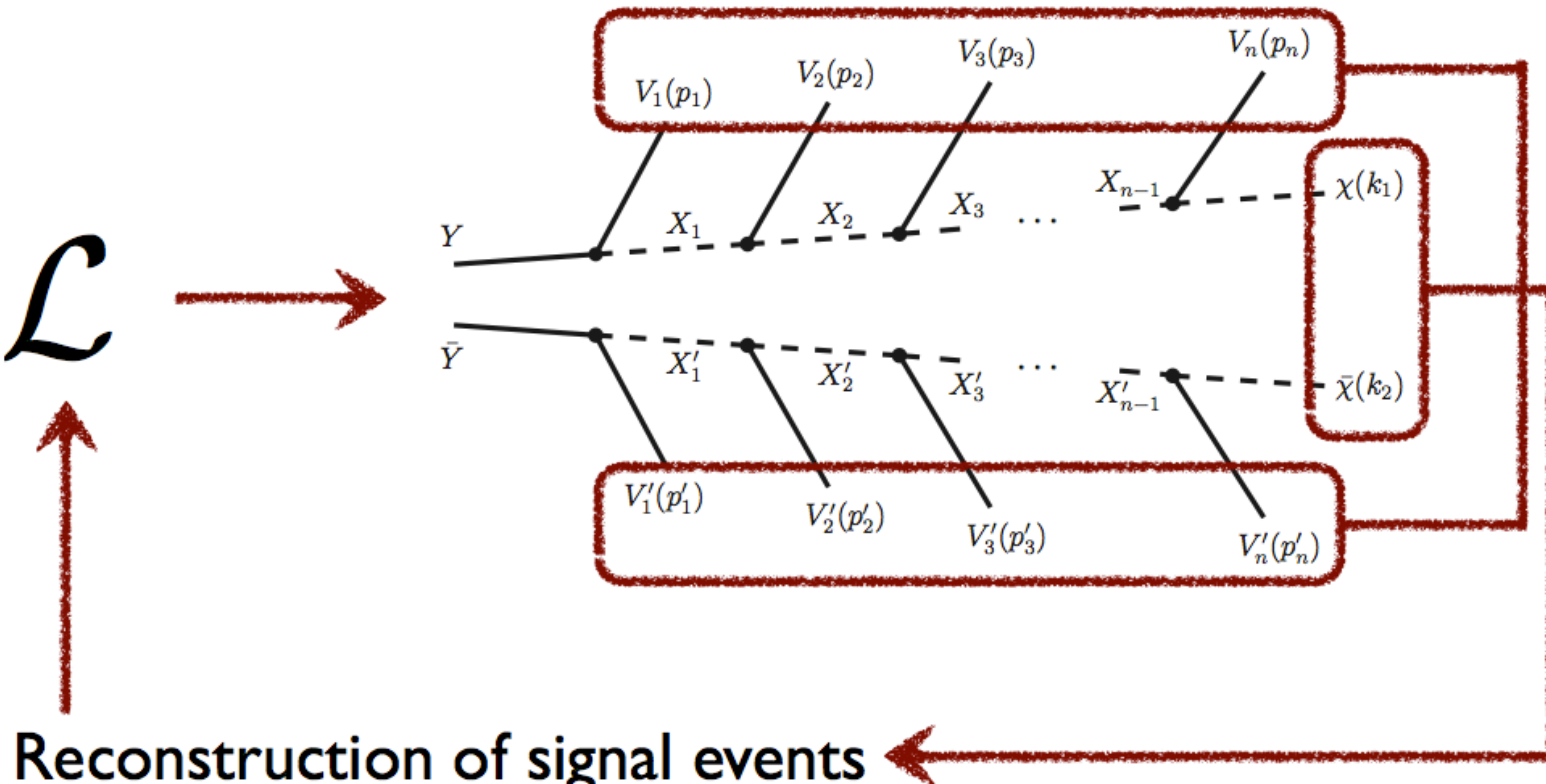
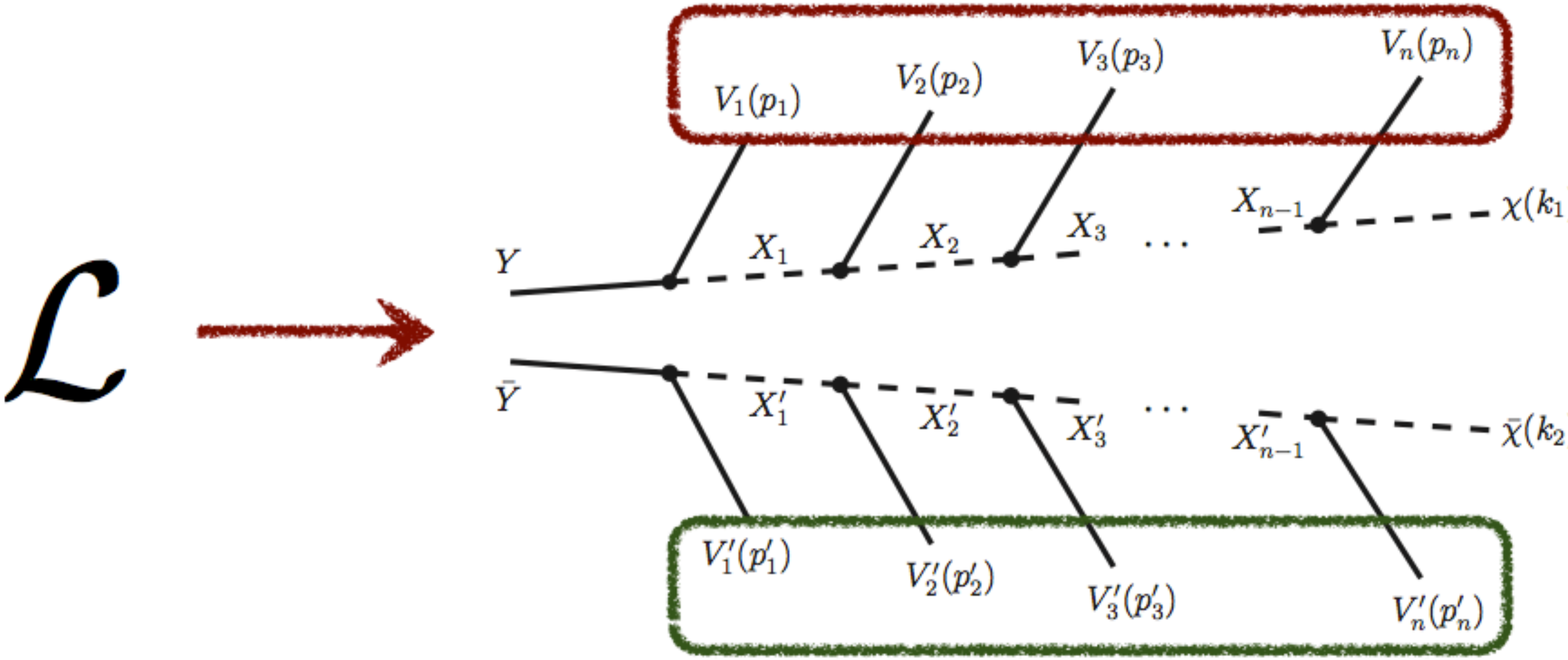
particle physicist studying LHC

Combinatorics in collider signature



Reconstruction of signal events

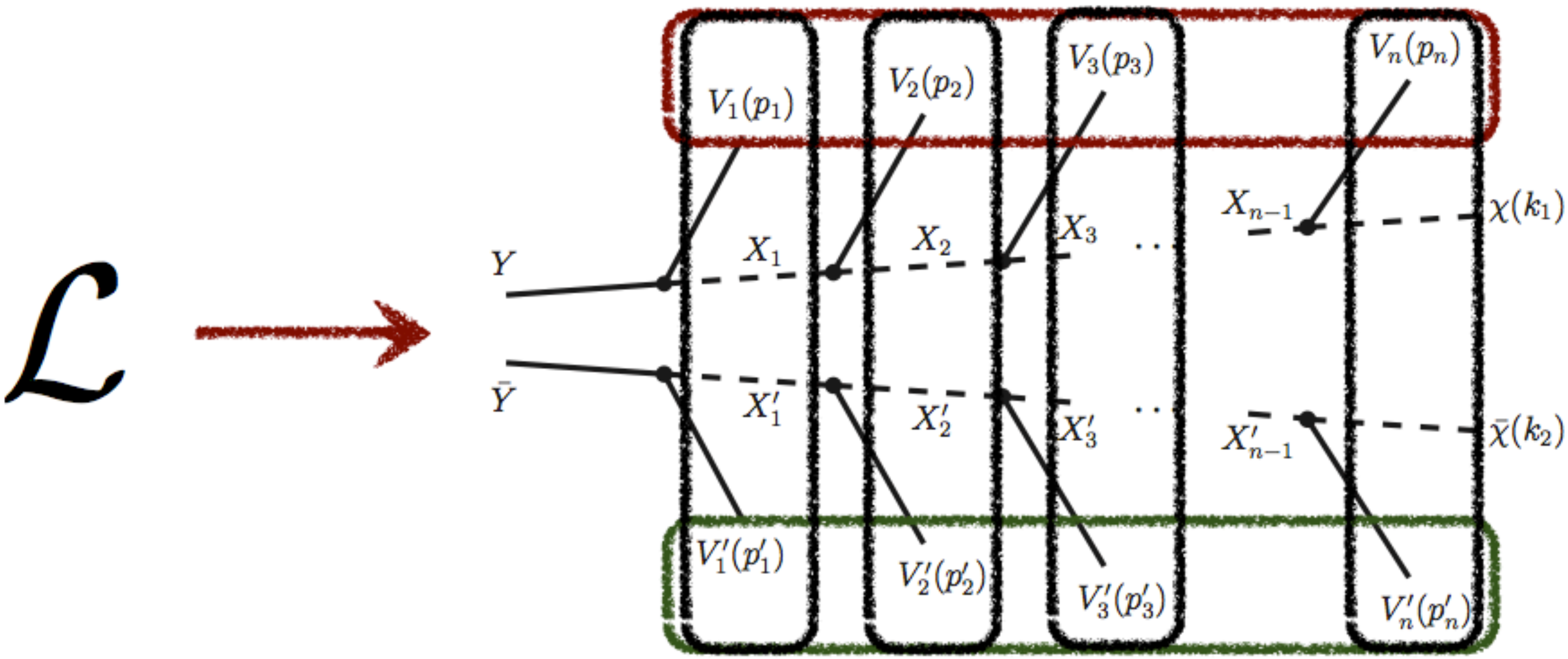
Combinatorics in collider signature



Reconstruction of signal events

* Combinatorial ambiguities of pairing

Combinatorics in collider signature



Reconstruction of signal events

* Combinatorial ambiguities of pairing and ordering

Combinatorics in collider signature: example

$$Z \to e^+ e^-$$

$$Z \to \mu^+ \mu^-$$

No combinatorial ambiguity

Combinatorics in collider signature: example

$$Z \to e^+ e^-$$

$$Z \to e^+ e^-$$

# of possible pairings = 2

can be resolved by constructing invariant masses:

$|(p^{e^+} + p^{e^-})^2 - m_Z^2| = 0$ for right pairing,

$|(p^{e^+} + p^{e^-})^2 - m_Z^2| \neq 0$ for wrong pairing,

on an event-by-event basis.

Combinatorics in collider signature: top-pair

$$t \to bW^+ \to bl^+\nu$$

$$\bar{t} \to \bar{b}W^- \to \bar{b}l^-\bar{\nu}$$

* Due to the charge ambiguity on b jets,
  # of possible pairings = 2:
  $\{l_1, b_1\}$ & $\{l_2, b_2\}$ for right pairing,
  $\{l_1, b_2\}$ & $\{l_2, b_1\}$ for wrong pairing.

$$t_1 + t_2 \to b_1(p^{b_1})l_1(p^{l_1})\nu_1(k_1) + b_2(p^{b_2})l_2(p^{l_2})\nu_2(k_2)$$

Resolving the combinatorial ambiguity: strategy

* exploit kinematic variables that have predictable features: edge, threshold, peak, ... ➛ ‘test variables’

* take a partition obeying the features as much as possible (wrong partitions will generally not obey because of no correlation).

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only depend on the decay topology
➛ 'model-independent'

Combinatorics in collider signature: top-pair

For right pairing, $m_{bl}^2 \lesssim m_t^2 - m_W^2$

For wrong pairing,

* no definite cutoff,
* distribution becomes broader for boosted events.

If $m_{bl}^2 > m_t^2 - m_W^2$, wrong pairing,

else?

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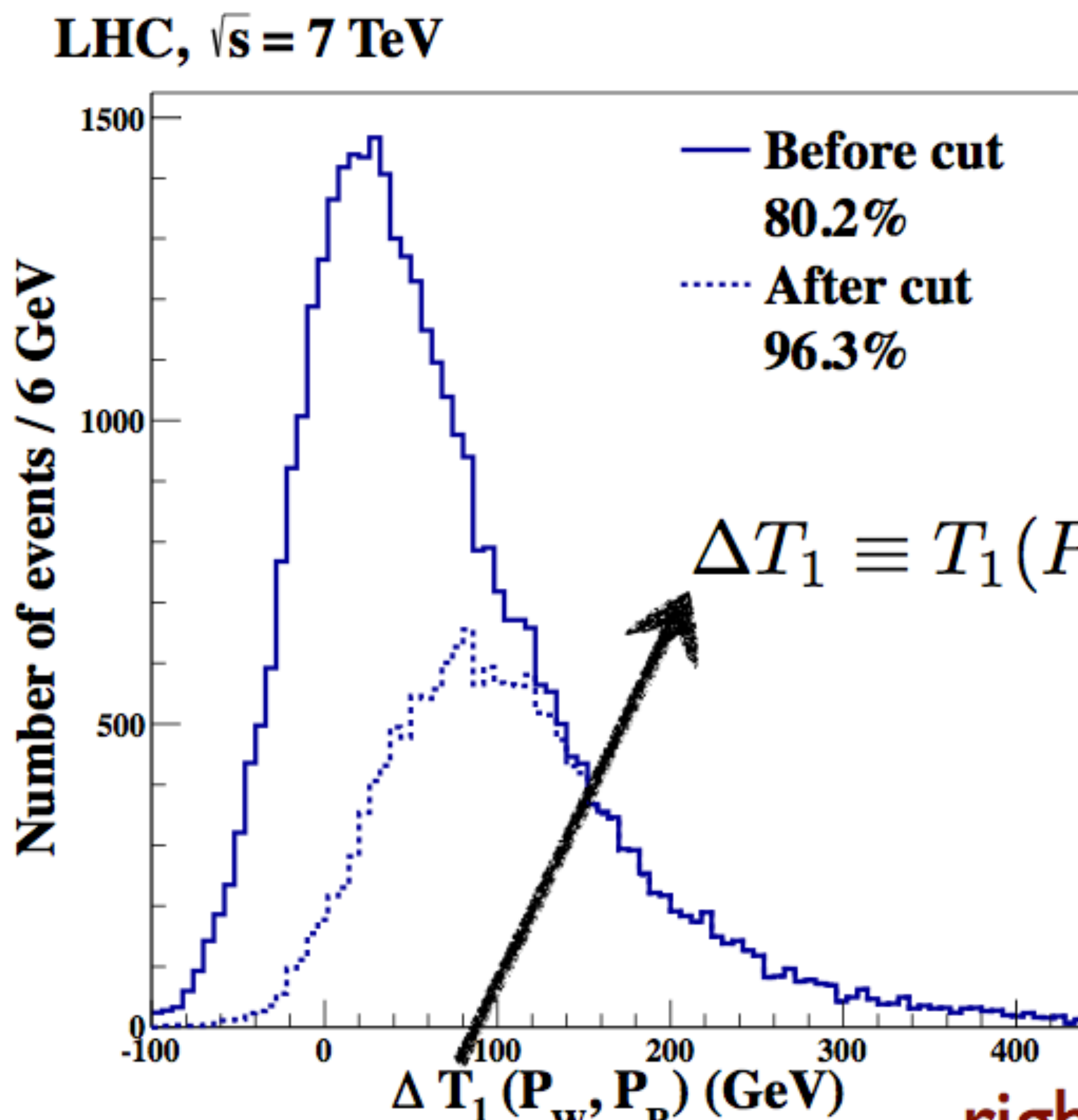
$m_{bl}(\text{wrong})$ is likely to be larger than $m_{bl}(\text{right})$

$$T_1 \equiv \max\{m_{bl}^{(1)}, m_{bl}^{(2)}\}$$

criterion: $T(P_R) < T(P_W)$.

right wrong pairing

Combinatorics in collider signature: test variable



$$\Delta T_1 \equiv T_1(P_W) - T_1(P_R)$$

right wrong pairing

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criterion: $T(P_R) < T(P_W)$.

Combinatorics in collider signature: test variable

C.Lester, D.Summers, PLB(1999)

$$M_{T2} \equiv \min_{\mathbf{k}_{1T}+\mathbf{k}_{2T}=\mathbf{p}_T^{\rm miss}} \left[\max\left\{ M_T^{(1)},\, M_T^{(2)} \right\} \right]$$

$$M_T^{(i)}(m_{bl}^{(i)},\, \mathbf{p}_T^{b_i} + \mathbf{p}_T^{l_i},\, \mathbf{k}_{iT})$$

: transverse mass in each decay chain

$M_{T2} \leq m_t$ for right paring.

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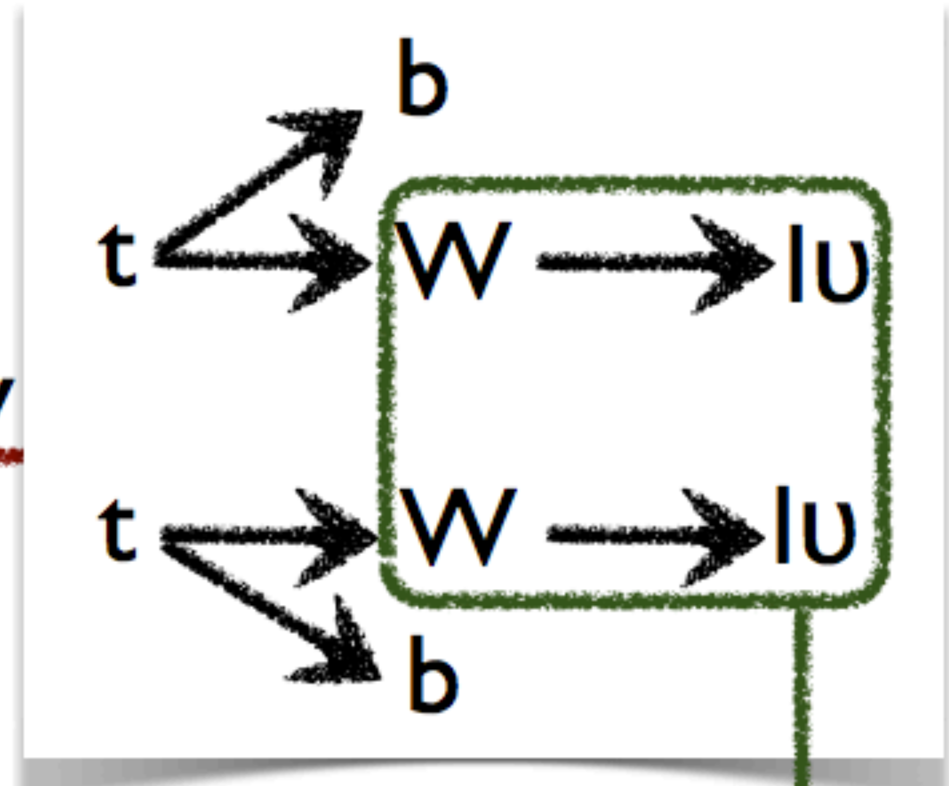
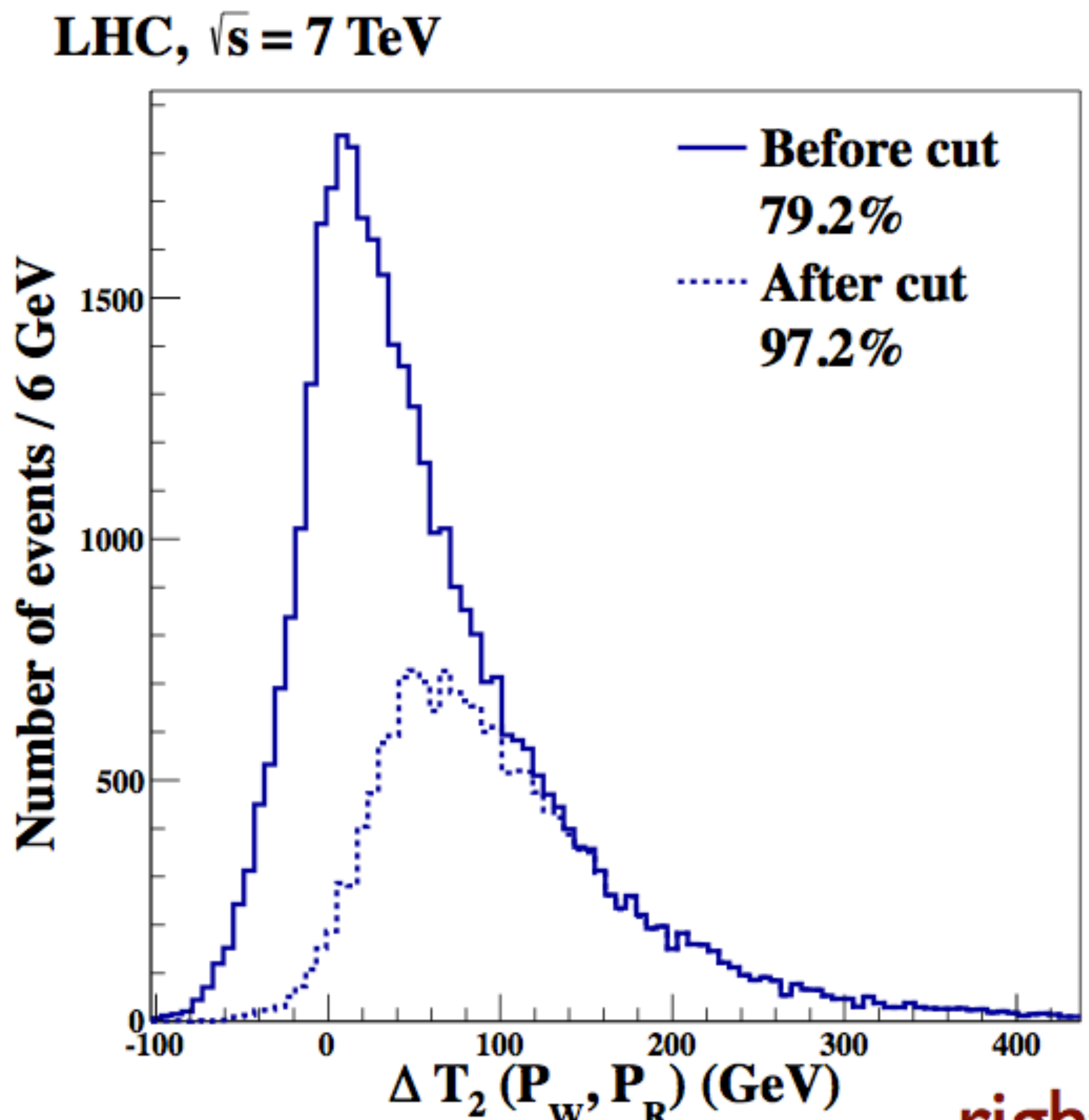


$M_{T2} \leq m_t$ for right paring.

top-pair full system (2b+2l+MET): $M_{T2}^{t\bar{t}}$

W-pair subsystem (2l+MET): M_{T2}^{WW}

Combinatorics in collider signature: test variable



right wrong pairing

$T_2 \equiv M_{T2}^{tt}$ criterion: $T(P_R) < T(P_W)$.

Combinatorics in collider signature: test variable

$$M_{T2} \equiv \min_{\mathbf{k}_{1T}+\mathbf{k}_{2T}=\mathbf{p}_T^{\rm miss}} \left[\max\left\{ M_T^{(1)},\, M_T^{(2)} \right\} \right]$$

also gives the invisible (neutrino) transverse momenta as a result of minimization.

For given k_T values, k_L can be obtained by on-shell eq. $(p^b + p^l + k)^2 = m_t^2$

W.S.Cho, K.Choi, Y.G.Kim, CBP, PRD(2009)

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$k^{\rm maos}$

M_{T2}-assisted on-shell (MAOS) reconstruction

W.S.Cho, K.Choi, Y.G.Kim, CBP, PRD(2009)

Combinatorics in collider signature: test variable

$k^{\text{maos}-WW}$ **vs** $k^{\text{maos}-t\bar{t}}$

$$(p^b + p^l + k)^2 = m_t^2,$$
$$(p^l + k)^2 = m_W^2.$$

top-pair full system (2b+2l+MET): $M_{T2}^{t\bar{t}}$

W-pair subsystem (2l+MET): M_{T2}^{WW}

Combinatorics in collider signature: test variable

$k^{\mathrm{maos}-WW}$ vs $k^{\mathrm{maos}-t\bar{t}}$

If $k^{\mathrm{maos}-WW} = k^{\mathrm{true}}$

then $(p^b + p^l + k^{\mathrm{maos}-WW})^2 = m_t^2$

If $k^{\mathrm{maos}-t\bar{t}} = k^{\mathrm{true}}$

then $(p^l + k^{\mathrm{maos}-t\bar{t}})^2 = m_W^2$

$$(p^b + p^l + k)^2 = m_t^2,$$

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Combinatorics in collider signature: test variable

$k^{\mathrm{maos}-WW}$

If $k^{\mathrm{maos}-WW} = k^{\mathrm{true}}$

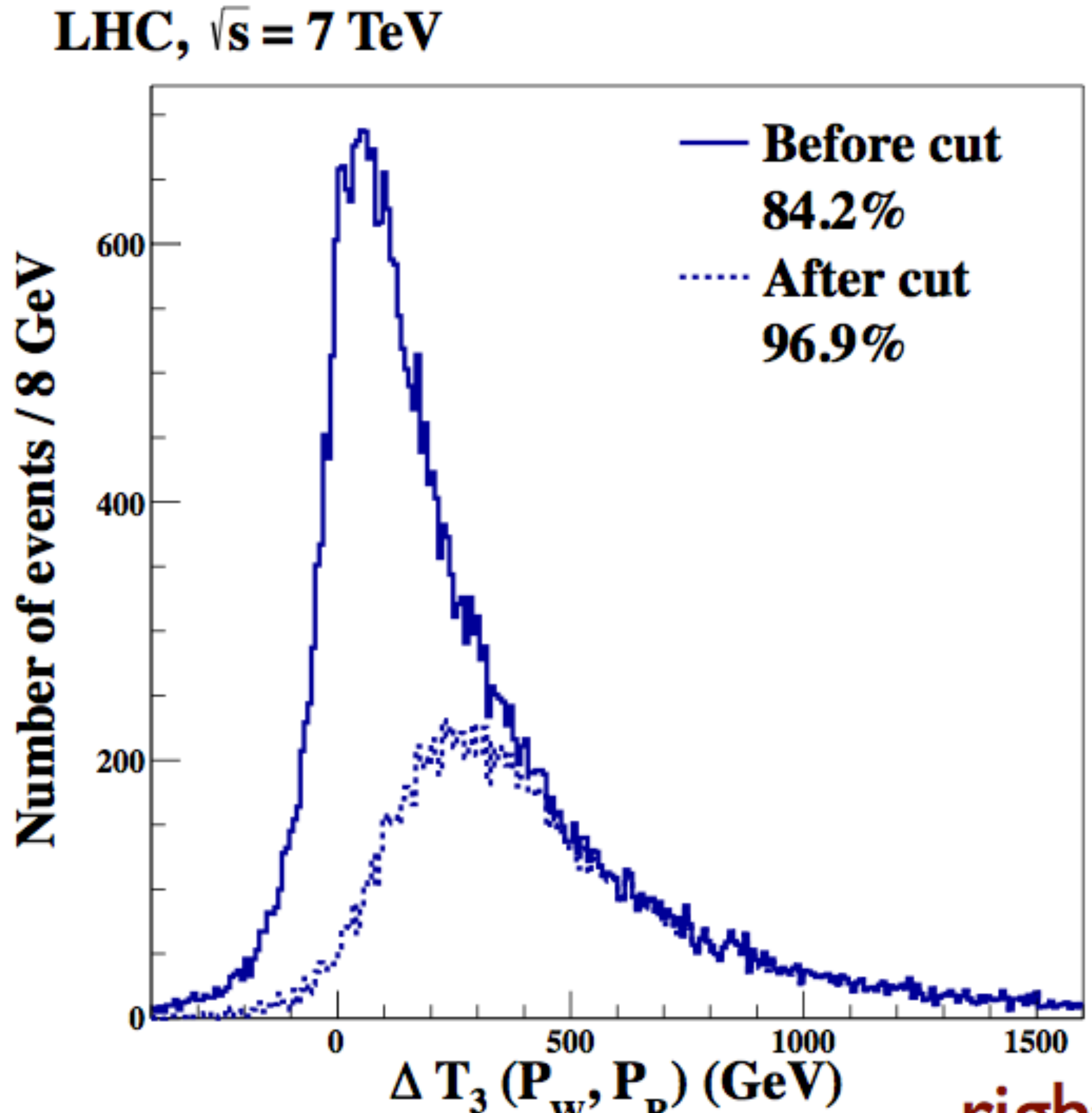
then $(p^b + p^l + k^{\mathrm{maos}-WW})^2 = m_t^2$

$\equiv (m_t^{\mathrm{maos}})^2$

$(p^l + k)^2 = m_W^2.$

W-pair subsystem (2l+MET): M_{T2}^{WW}

Combinatorics in collider signature: test variable



right wrong pairing

$$T_3 \equiv \left| m_t^{\rm maos} - m_t \right|$$

criterion: $T(P_R) < T(P_W)$.

Combinatorics in collider signature: test variable

$k^{\text{maos}-t\bar{t}}$

If $k^{\text{maos}-t\bar{t}} = k^{\text{true}}$

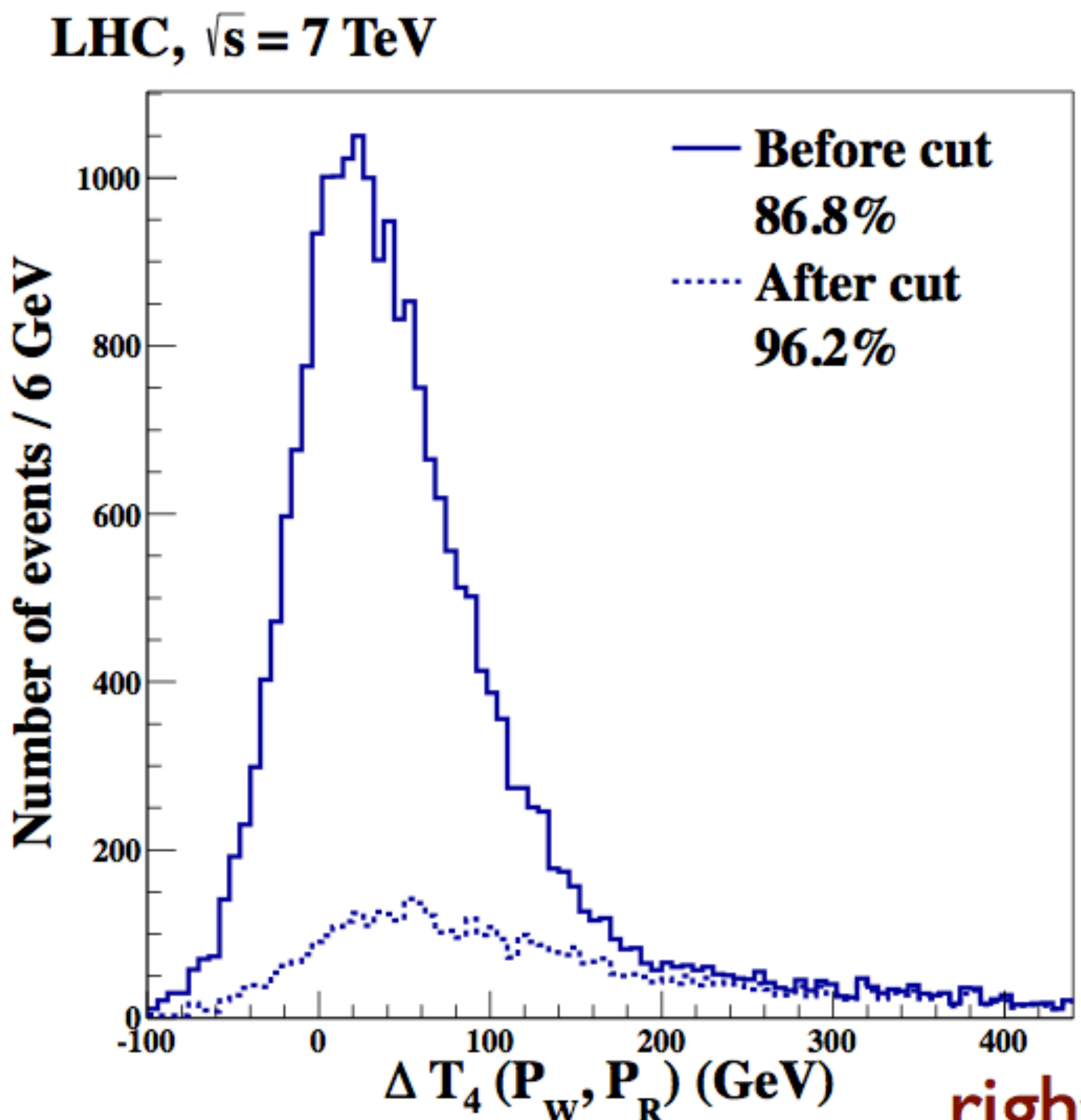
then $(p^l + k^{\text{maos}-t\bar{t}})^2 = m_W^2$

$\equiv (m_W^{\text{maos}})^2$

$$(p^b + p^l + k)^2 = m_t^2,$$

top-pair full system (2b+2l+MET): $M_{T2}^{t\bar{t}}$

Combinatorics in collider signature: test variable



right wrong pairing

$$T_4 \equiv |m_W^{\text{maos}} - m_W|$$

criterion: $T(P_R) < T(P_W)$.

Combinatorics in collider signature: test variables

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$$T_1 \equiv \max\{m_{bl}^{(1)}, m_{bl}^{(2)}\}$$

$$T_2 \equiv M_{T2}^{t\bar{t}}$$

$$T_3 \equiv |m_t^{\rm maos} - m_t|$$

$$T_4 \equiv |m_W^{\rm maos} - m_W|$$

→ combined method?

* take a partition obeying the features as much as possible.

Combinatorics in collider signature: test variables

$$t_1 + t_2 \to b_1(p^{b_1})l_1(p^{l_1})\nu_1(k_1) + b_2(p^{b_2})l_2(p^{l_2})\nu_2(k_2)$$

$$T_1 \equiv \max\{m_{bl}^{(1)}, m_{bl}^{(2)}\}$$

$$T_2 \equiv M_{T2}^{t\bar{t}}$$

$$T_3 \equiv |m_t^{\text{maos}} - m_t|$$

$$T_4 \equiv |m_W^{\text{maos}} - m_W|$$

→ combined method?

* take a partition obeying the features as much as possible.

➛ select a pairing P_i if majority of $T(P_i) < T(P_j)$ $(i \neq j)$.

*(~ **89%** efficiency without loss of statistics)*

Combinatorics in collider signature: test variables + event selection cut

wrong pairing: no definite cutoff,
distribution becomes broader for boosted events.

Combinatorics in collider signature: test variables

\+ *event selection cut*

wrong pairing: no definite cutoff,
distribution becomes broader for boosted events

Partition-insensitive kinematic variables:

$M_T^{t\bar{t}}$ (transverse mass of top-pair full system)

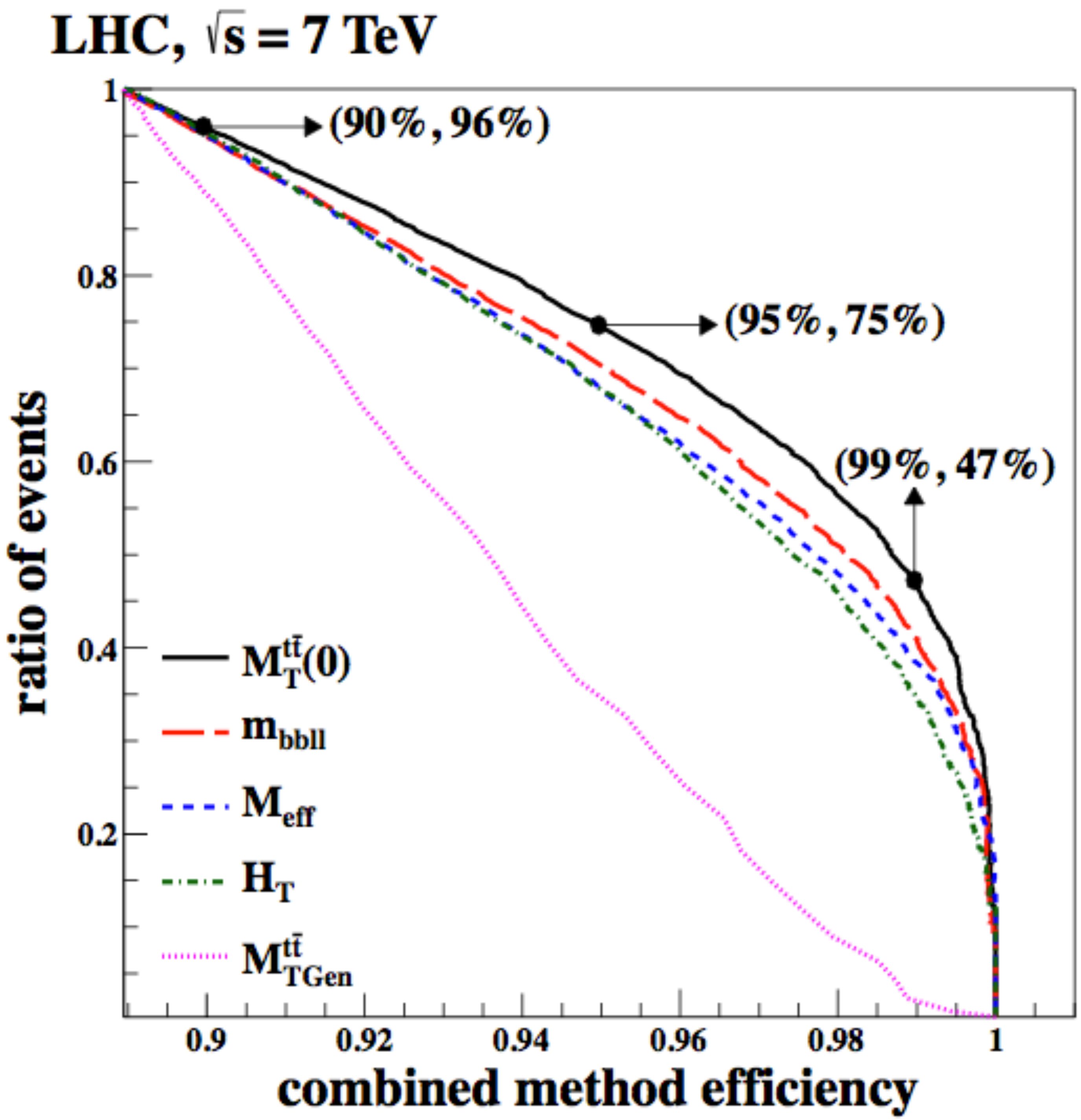
m_V (invariant mass of 2b+2l system)

$M_{\rm eff}$ (scalar sum of all P_T + missing E_T)

H_T (scalar sum of all P_T)

$M_{T\rm Gen}^{t\bar{t}}$ (smallest M_{T2} of all possible in full system)

Combinatorics in collider signature: test variables + event selection cut



Summary and Outlook

* We proposed a novel method to resolve combinatorial ambiguities in hadron collider events involving two invisible particles in the final state.

* The method is based on the kinematic variables with the assumption of decay topology.

* It can be utilized for new physics processes with pair production and WIMP - in case of pairing and/or ordering ambiguities - (e.g. R-parity conserving SUSY), as well as the dileptonic SM top-pair process.

* For practical use, we will also study the effects of momentum smearing, ISR, and poor mass information.