# Jet angular correlation in the top quark pair production

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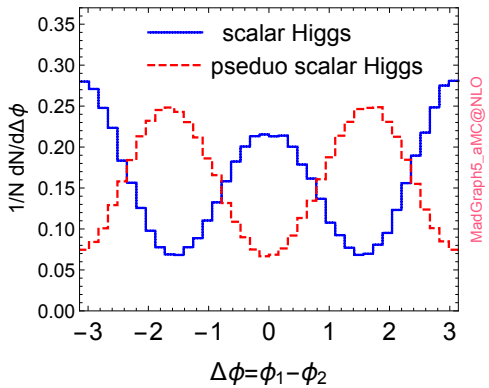
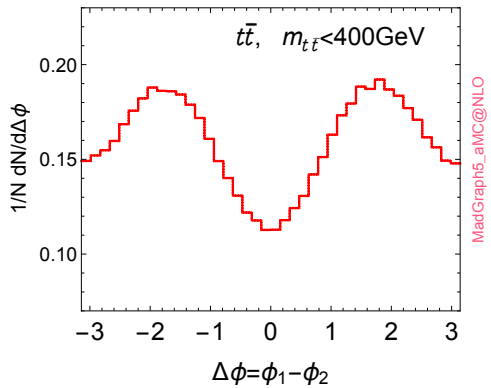
# Angular correlations between jets

can provide important information about heavy particles produced together with the jets.

**For instance**, the azimuthal angle difference between two jets ($\Delta\phi = \phi_1 - \phi_2$) in $gg \to H + 2$-jet is very sensitive to a CP property of the Higgs boson. (Plehn et al 2001, $\cdots$)




- The accurate prediction of $\Delta\phi$ will be necessary.
- The $t\bar{t}$ production shows a distribution similar to the CP odd Higgs boson production near the threshold $m_{t\bar{t}} \sim 2m_t$. (Hagiwara et al 2013)

**In this work, I present a merging method designed particularly to predict $\Delta\phi$. The $t\bar{t}$ production is chosen as a process to be examined numerically.**

## Approaches to jet simulations for angular correlation studies

**The traditional approach** is to identify each parton produced according to a fixed order calculation with a jet.

- Angular correlations between jets are robust. (^^)
- Events cannot be used for realistic detector simulations. (- -)
- The prediction cannot be reliable in kinematic regions where higher order corrections are enhanced. (- -)

**A modern approach** is to merge leading order (LO) cross sections for multi-parton final states and the leading logarithmic (LL) parton shower. (Catani et al 2001,$\cdots$)

- Events can be used for realistic detector simulations by incorporating a hadronization model. (^^)
- The Sudakov suppression as an effect of the re-summation can be taken into account. (^^)
- Ambiguity in angular correlations between jets. (more detail in the next slide)

## Merging approaches to jet angular correlation studies

- A LO multi-parton production cross section
  - predicts angular correlations between the produced partons at the LO accuracy.
- The LL parton shower
  - cannot predict angular correlations between any partons.

**Considering this fact,**

- Observables which measure angular correlations between jets are quite different from other observables, such as a jet $p_T$.
- If the kinematics of a jet is determined or largely influenced by the LL parton shower during a merging procedure, then it hardly has the LO accuracy and leads to a wrong prediction of angular correlations.

**Merging approaches potentially have the ambiguity in the accuracy of jets,**

- It is not necessarily clear whether a jet constructed after a merging procedure has the LO accuracy or not.
- This is because their virtue is smooth combination of LO cross sections and the LL parton shower.
- We will confirm this numerically later.

## A new merging approach to jet angular correlation studies (ideas)

**satisfies**

- the LO accuracy of angular correlations between jets is guaranteed, as is the case in the traditional approach.
- events can be used for realistic detector simulations and the Sudakov suppression can be taken into account, as is the case in other merging methods.

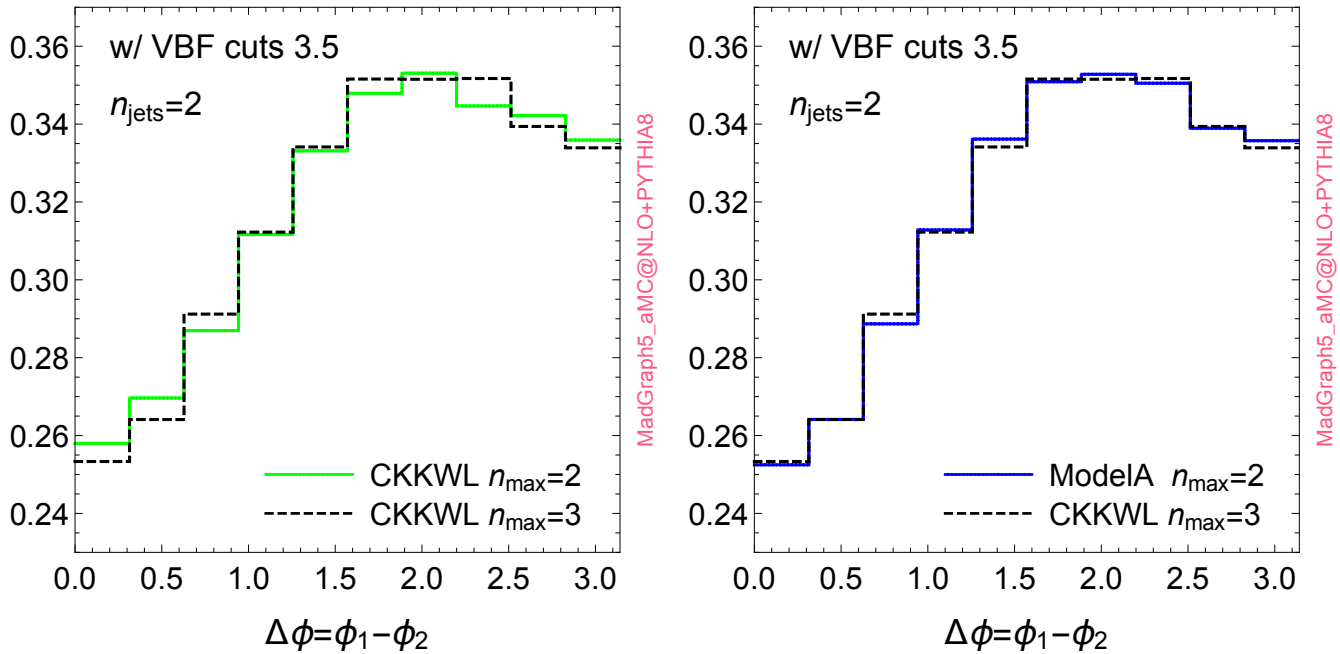
The new method proceeds in the similar way as the MLM approach (Mangano et al 2006, $\cdots$). The differences from the MLM approach are

- The definition of jets used during a merging procedure is set identical to the one used during physics analyses of jets.
  - As a result, $n$-jet events are generated exclusively according to the LO $n$-parton production cross section, and angular correlations between the $n$ jets follow those between the $n$ partons and thus the LO accuracy of them should be robust.
- A LO $n_{\max}$-parton production cross section is not allowed to produce the events which contain more than $n_{\max}$-jet.
  - The events which contain more than $n_{\max}$-jet are not reliable (i.e. less than the LO accuracy) in angular correlation studies, because the production of the additional jet(s) relies on the LL shower and they can affect angular correlations kinematically.

# A new merging approach to jet angular correlation studies (numerical analyses)

**Setup**

- Study the 2-jet events in the $t\bar{t}$ production at the 14 TeV LHC.
- Impose the VBF cuts, $y_1 \times y_2 < 0$ and $|y_1 - y_2| > 3.5$.




**Observation**

- The new method at $n_{\max} = 2$ (solid in the right) produces a consistent result with the CKKW-L at $n_{\max} = 3$ (dashed).
- The consistency implies that the LO accuracy of $\Delta\phi$ is achieved in the CKKW-L at $n_{\max} = 3$ but not in the CKKW-L at $n_{\max} = 2$.

**Comment**

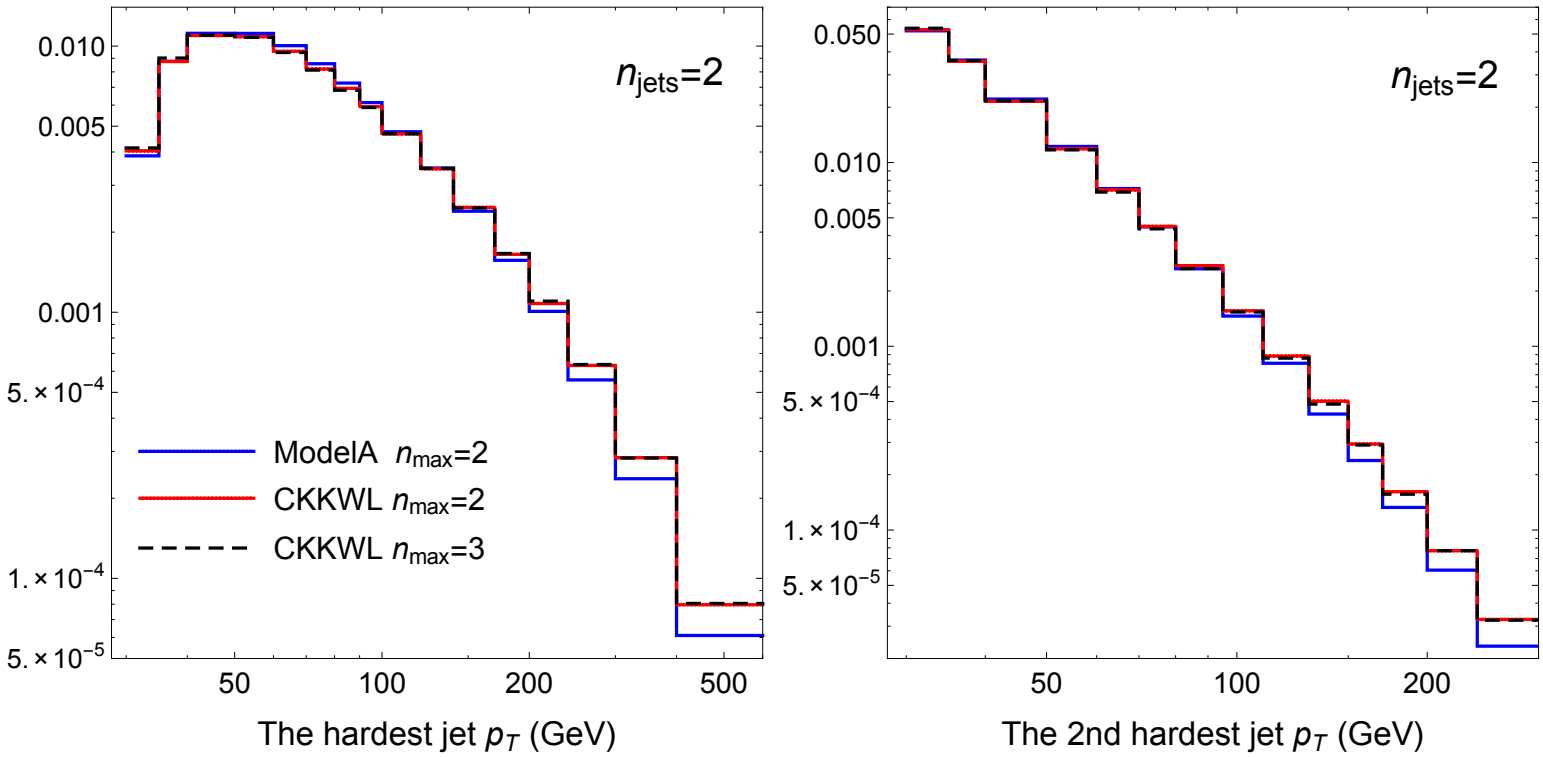
- In the new method, the LO $t\bar{t} + 3$-parton cross section does not contribute to the observable in the Figure, since it contributes exclusively to the 3-jet events.

## Summary

- Angular correlations between jets can provide important information about heavy particles produced together with the jets, for instance $\Delta\phi = \phi_1 - \phi_2$ can be used to measure CP violation in the Higgs sector.
- Producing the accurate prediction of observables which measure the angular correlations will be necessary.
- I have presented a new merging method which satisfies
  - the LO accuracy of angular correlations between jets is guaranteed, as is the case in the traditional approach.
  - events can be used for realistic detector simulations and the Sudakov suppression can be taken into account, as is the case in other merging methods.
- The new method is demonstrated by comparing its prediction and the prediction of a well-established method, the CKKW-L algorithm.
- In my view, this method is the most appropriate approach to jet angular correlation studies at the moment in the sense that the accuracy of angular correlations between jets is clearly known, i.e. the LO.

Thank you so much!

# Backup 1

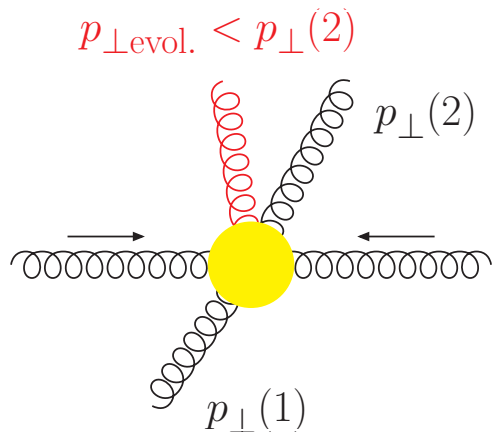

0.010
0.005
0.001
5. × 10^-4
1. × 10^-4
5. × 10^-5
n_jets=2
ModelA n_max=2
CKKWL n_max=2
CKKWL n_max=3
50
100
200
500
The hardest jet p_T (GeV)
0.050
0.010
0.005
0.001
5. × 10^-4
1. × 10^-4
5. × 10^-5
n_jets=2
50
100
200
The 2nd hardest jet p_T (GeV)

# Backup 2

Suppose a parton shower radiation from the $t\bar{t}+2$-parton events, when the $t\bar{t}+3$-parton LO cross section is NOT additionally merged. In the merging algorithm (CKKW-L algorithm),

- Parton showers are constrained to be softer than the partons provided by LO cross sections in terms of the shower evolution variable.
- Construct a shower history and calculate the scales of the parton1 and parton2, $p_\perp(1) > p_\perp(2)$. The definition of the scale is equivalent to that of the shower evolution variable.
- A shower starts from $p_{\perp\mathrm{evol}} = p_\perp(2)$.
- It is not guaranteed that the two hardest jets reflect the kinematics of the two partons at the end!

**For instance**




$p_T(1) > p_T(2) > p_T(3)$ is NOT guaranteed.