Study on the azimuthal angle correlation between two jets in the top quark pair plus multi-jet process

Junya Nakamura

KEK Theory Center and SOKENDAI,

K. Hagiwara and JN (arXiv:1501.00794)

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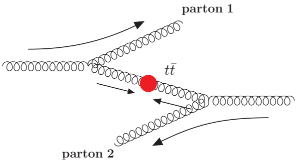
Kavli IPMU The University of Tokyo.

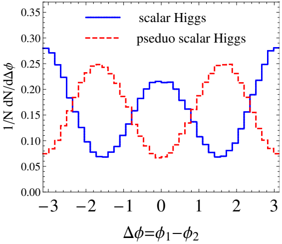
Outline

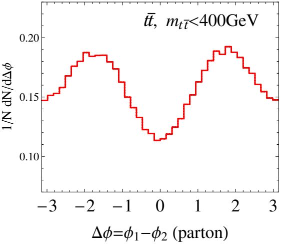
I will discuss an azimuthal angle correlation between 2 jets in the $t\bar{t}$ plus multi-jet process at the LHC.

Motivations

- The azimuthal angle difference between two partons, $\Delta\phi = \phi_1 - \phi_2$, produced in association with the Higgs boson produced by gluon fusion is very sensitive to the CP property of the Higgs boson. (Plehn et al 2001, DelDuca et al 2001, Klamke et al 2007, Hagiwara et al 2009)
- The $t\bar{t}$ plus 2partons process exhibits a strong azimuthal angle correlation between the 2partons near the threshold $m_{t\bar{t}} \sim 2m_t$ (Hagiwara and Mukhopadhyay 2013), which may be used as a preparation for the Higgs CP measurement.

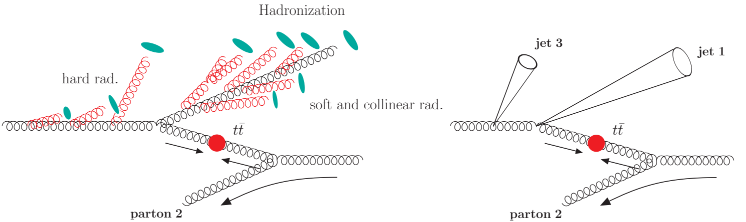






Outline

In reality,



$\Delta\phi$ between the 2partons $\longrightarrow$ $\Delta\phi$ between 2jets.

Aim

- Perform a simulation including higher order corrections, and check if a stable prediction can be obtained.

Results

- Yes, as long as the 2 highest p_T jets are selected. (^^)

The strategy in simulation.

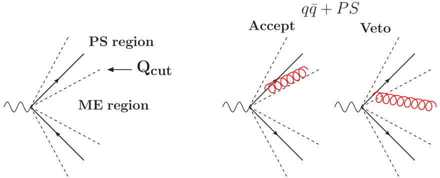
The strategy in simulation

We use the CKKW type merging algorithm, which satidfies

- 2 hard radiations are described by the matrix elements (MEs).
- Jet structure is properly modeled.
- Jet cross sections are unitarized, i.e. $\sum_{n=0}^{\infty} \sigma(t\bar{t} + n\text{-jet}) = \sigma(t\bar{t} + X)$.

The idea by Catani et al is

- Separate the ME and PS regions at some scale, $Q_{\rm cut}$ (merging scale).



- Modify the MEs by Sudakov form factors $\Delta_S(Q, q)$, and make them exclusive at $Q_{\rm cut}$ to ensure the unitarity condition.

$$\sigma(q\bar{q} + X) = \sum_{n=2}^{\infty} \sigma(n\text{-parton}, Q_{\rm cut})$$

$$= \sigma(q\bar{q})\Delta_{q\bar{q}}(Q, Q_{\rm cut}) + \sigma(q\bar{q})\Delta_{q\bar{q}}(Q, Q_1) \int d\mathcal{P}(Q_1)\Delta_{q\bar{q}g}(Q_1, Q_{\rm cut}) + \cdots,$$

$$\sigma(q\bar{q} + X) \simeq \sigma(q\bar{q})\Delta_{q\bar{q}}(Q, Q_{\rm cut}) + \sigma(q\bar{q}g)\Delta_{q\bar{q}}(Q, Q_1)\Delta_{q\bar{q}g}(Q_1, Q_{\rm cut}) + \cdots$$

The strategy in simulation

The proposed methods to calculate Sudakov form factors include

- CKKW (Catani et al) - Analytical NLL Sudakov.
- MLM (Mangano et al, Alwall et al) - PS generators are used to calculate approximated Sudakov. Any PS model can be used.
- Pseudo Shower (Mrenna et al) - Similar to MLM, but use a shower history.
- CKKW-L (Lonnblad et al) - PS generators are used to calculate exact Sudakov.

We use the CKKW-L merging scheme, because

- PYTHIA8 is ideal for this scheme.
- Exact Sudakov form factors.

Setup.

Setup

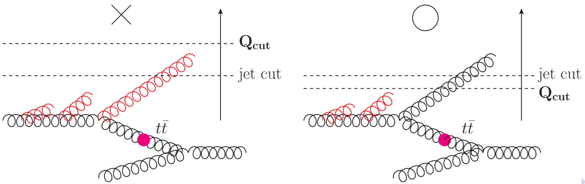
- MadGraph5aMC@NLO (Alwall et al) for the $pp \to t\bar{t} + 0, 1, 2, 3$-parton processes at $\sqrt{s} = 14$ TeV.
- PYTHIA8 (Sjostrand et al) for the parton shower generation.
- No Hadronization, No MPI. Top quarks are assumed stable.
- Anti k_T algorithm (Cacciari et al 2008) with $R = 0.4$ and $p_{T\text{cut}}^{\text{jet}} = 30$ GeV. Fastjet is used (Cacciari et al 2011).
- The two highest p_T jets are selected for $\Delta\phi = \phi_1 - \phi_2$.

Merging scale

The longitudinal-boost invariant $k_\perp$ variable (Catani et al 1993) is used as the merging scale definition, and the scale is set to 20 GeV with $R = 1$,

$$k_{\perp iB} = p_{Ti},$$

$$k_{\perp ij} = \min(p_{Ti}, p_{Tj})\sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}/R,$$

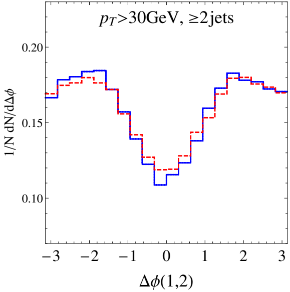


Results and analyses.

Impacts of the $t\bar{t}$ + 3-parton MEs

Blue solid: The 3-parton MEs included (N=3).

Red dotted: Not included (N=2).



Cuts

- The VBF cuts $y_1 \times y_2 < 0, \quad |y_1 - y_2| > 4$.
- $m_{t\bar{t}} < 500$ GeV.

Observations

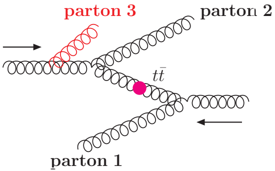
- The correlation does NOT disappear even after including the dominant higher order effects (^^).
- The correlation is increased when the 3-parton MEs are included.

Note

- The difference is NOT coming from statistical uncertainty! There is a reason.

Impacts of the $t\bar{t} + 3$-parton MEs

Suppose a parton shower radiation from the $t\bar{t} + 2$-parton events when the 3-parton MEs are NOT included.

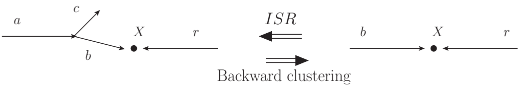


In the merging algorithm,

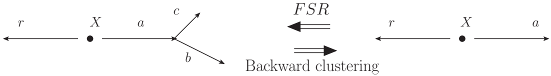
- Parton showers are constrained to be 'softer' than the partons provided by MEs.
- Construct a shower history and calculate scales of the parton1 and parton2, $p_{\perp 1} > p_{\perp 2}$. The definition of the scale is equivalent to the evolution scale, thus start a shower from $p_{\perp \mathrm{evol}} = p_{\perp 2}$.
- $p_{T\mathrm{parton1}} > p_{T\mathrm{parton2}} > p_{T\mathrm{parton3}}$ for initial state radiation (ISR). This is attractive, because the 2partons by the MEs gives rise to the highest and the second highest p_T jets, which are thus selected for $\Delta\phi = \phi_1 - \phi_2$. (^^)

However...

Constructing a shower history



Illustrating that an incoming parton a and an outgoing parton c in a process $ar \to Xc$ are clustered into an incoming parton b and hence a new process $br \to X$ is produced (from left to right), and that a process $ar \to Xc$ is induced by ISR $a \to bc$ from a process $br \to X$ in the backwards evolution (from right to left).



Illustrating that two outgoing partons b and c are clustered into an outgoing parton a (from left to right), and that a set of partons b, c and r is induced by FSR $a \to bc$ from a set of partons a and r (from right to left).

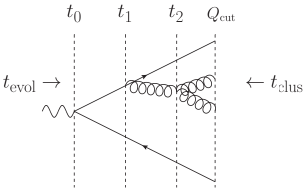
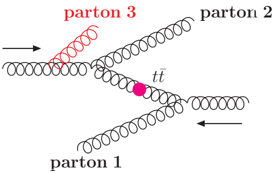
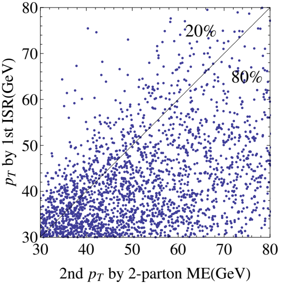


Illustration of a parton shower history for the $q\bar{q}gg$ process, which consists of the intermediate processes $q\bar{q}$ with the clustering scale t_0, $q\bar{q}g$ with t_1 and the generated process $q\bar{q}gg$ with t_2.

Impacts of the $t\bar{t}$ + 3-parton MEs

Suppose a parton shower radiation from the $t\bar{t}$ + 2-parton events when the 3-parton MEs are NOT included.





Lower right: $p_{T\text{parton2}} > p_{T\text{parton3}}$, $\sim 80\%$ (^^)

Upper left: $p_{T\text{parton3}} > p_{T\text{parton2}}$, $\sim 20\%$ (; ;)

Observations

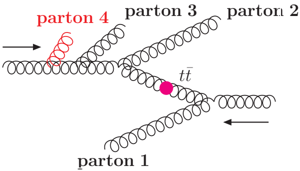
- $p_{T\text{parton3}} > p_{T\text{parton2}}$ in the considerable fraction of the samples.
- A loss of the correlation, as long as the two highest p_T jets are selected. (; ;)

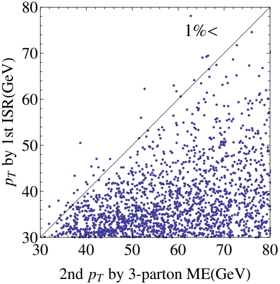
Reasons

- Radiated parton's p_T is less. But p_T is balanced, thus unordering happens at the end.
- When a shower history construction fails, we redo the clustering procedure but this time a next-higher scale is chosen. This can induce higher p_T radiation.

Impacts of the $t\bar{t} + 3$-parton MEs

Suppose a parton shower radiation from the $t\bar{t} + 3$-parton events when the 3-parton MEs are included.





Lower right: $p_{T\text{parton2}} > p_{T\text{parton4}}$.
Upper left: $p_{T\text{parton4}} > p_{T\text{parton2}}$.

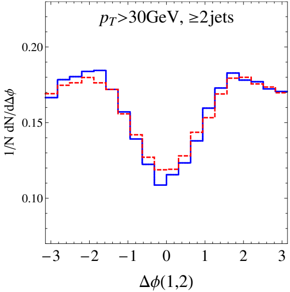
Observations

- By incorporating the $t\bar{t} + 3$-parton MEs, $p_{T\text{parton4}} > p_{T\text{parton2}}$ is avoided.
- A loss of the correlation is reduced. (^^)

Conclusions.

Conclusions

Blue solid: The 3-parton MEs included (N=3).
Red dotted: Not included (N=2).



Aim (shown in the beginning)

- Perform a simulation including higher order corrections, and check if a stable prediction can be obtained.

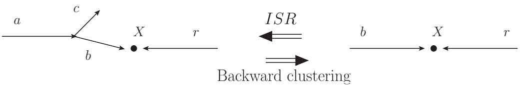
Results (in more detail)

- A simulation at LO($t\bar{t} + 0, 1, 2, 3$-parton)+LL accuracy shows the strong correlation,
- The inclusion of the $t\bar{t}$ + 3-parton MEs ensures that the prediction of the correlation $\Delta\phi = \phi_1 - \phi_2$ is stable i.e. the $t\bar{t}$ + 4-parton MEs are not needed.

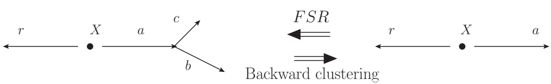
as long as the 2 highest p_T jets are chosen.

Thank you for your time!

Constructing a shower history



Illustrating that an incoming parton *a* and an outgoing parton *c* in a process $ar \to Xc$ are clustered into an incoming parton *b* and hence a new process $br \to X$ is produced (from left to right), and that a process $ar \to Xc$ is induced by ISR $a \to bc$ from a process $br \to X$ in the backwards evolution (from right to left).



Illustrating that two outgoing partons *b* and *c* are clustered into an outgoing parton *a* (from left to right), and that a set of partons *b*, *c* and *r* is induced by FSR $a \to bc$ from a set of partons *a* and *r* (from right to left).

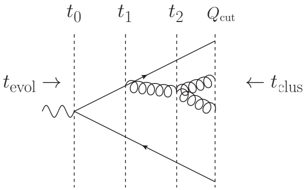
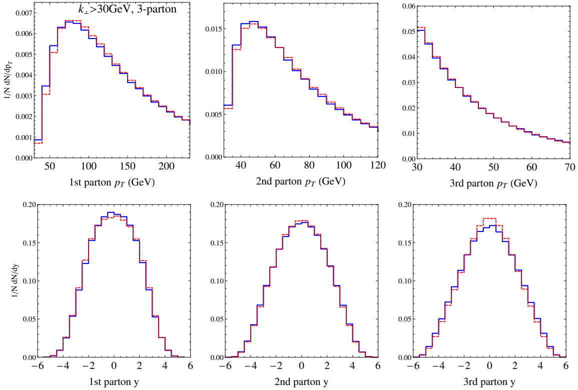


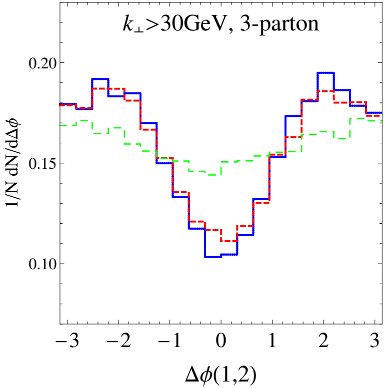
Illustration of a parton shower history for the $q\bar{q}gg$ process, which consists of the intermediate processes $q\bar{q}$ with the clustering scale t_0, $q\bar{q}g$ with t_1 and the generated process $q\bar{q}gg$ with t_2.

ME v.s. PS



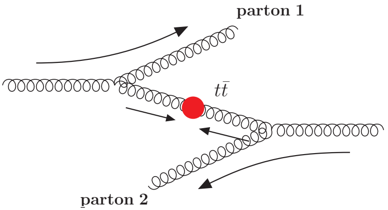
- An event sample of the $pp \to t\bar{t} + 3$-parton process is generated by the MEs and weighted by the Sudakov factor. (blue solid)
- An event sample of the $pp \to t\bar{t} + 2$-parton process is generated by the MEs and weighted by the Sudakov factor. Then 1 parton is added by the PS. (red dotted)
- PS does a great job!

Azimuthal angle correlation in 3-parton events

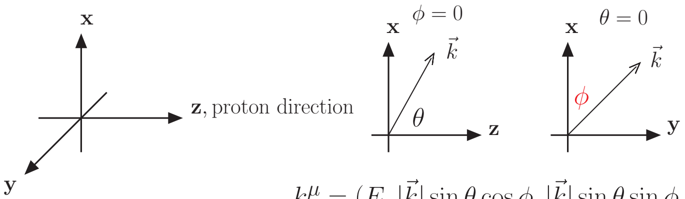


Azimuthal angle correlation

The $t\bar{t}$ plus 2partons process at hadronic collisions,



Azimuthal angle is



$$k^{\mu} = (E, |\vec{k}| \sin\theta \cos\phi, |\vec{k}| \sin\theta \sin\phi, |\vec{k}| \cos\theta)$$

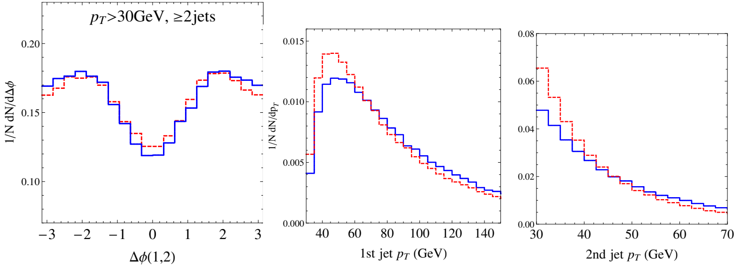
Our interest here is the difference between the two parton's azimuthal angles,

$$\Delta\phi = \phi_1 - \phi_2.$$

Comparisons with the non-merging

Non-merging approach

- Generate $t\bar{t} + 2$-parton events according to the MEs, then apply the PS.
- The 2 hardest jets can have their origin in a parton given by the MEs. (^^)
- The jets have realistic jet structures. (^^)
- Jet cross sections are not unitarized. (; ;)
- Simpler and more efficient. (^0^)



Blue solid: Merged. Red dotted: Non-merged.

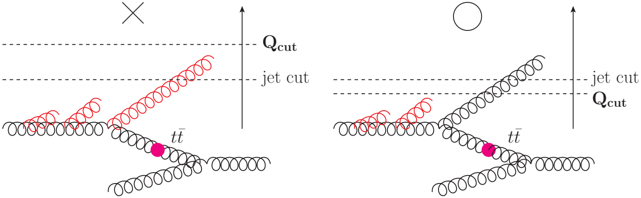
Observations

- The correlation appears. (^^)
- A clear difference between the two is induced by the strong Sudakov suppression.
- The non-merged result is not reliable. (; ;)

The merging algorithm for the angular correlation $\Delta\phi$

Strategies

- Merge the $t\bar{t}$+0, 1, 2, (3)-parton matrix elements generated by MG5aMC@NLO (Alwall et al.) with the parton shower in PYTHIA8 (Sjostrand et al.).
- Choose the merging scale $Q_{\rm cut}$ properly such that 2jets for $\Delta\phi$ have their origin in a parton provided by the matrix elements, not the PS!
  $Q_{\rm cut} < p_T^{\rm jet}$ must be satisfied.



Jet p_T cut (GeV)	20	30	40
Jet radius $R = 0.4$	11.0	4.0	2.2
Jet radius $R = 0.7$	16.4	5.3	2.7

Contamination rate (%) with different jet definitions. $N = 3$ and $Q_{\rm cut} = 20$ GeV.

Decision

- $Q_{\rm cut} = 20$ GeV
- A radius parameter $R = 0.4$ with $p_{T\rm cut}^{\rm jet} = 30$ GeV

The CKKW-L merging algorithm (Lonnblad et al)

Sudakov veto algorithm

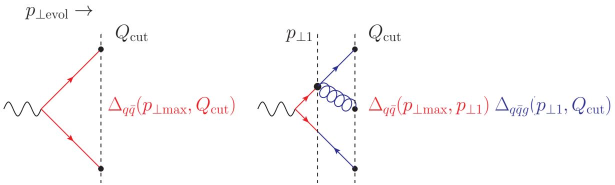
- Suppose we want to calculate $\Delta_S(p_{\perp 1}, p_{\perp 2})$.
- The PS is performed on the S, starting from $p_{\perp 1}$.
- If $p_{\perp \mathrm{evol}} > p_{\perp 2}$, veto the event.
- The prob. of accepting the event is equal to $\Delta_S(p_{\perp 1}, p_{\perp 2})$.

Advantages

- The same Sudakov form factors are used above and below the merging scale.

Procedure

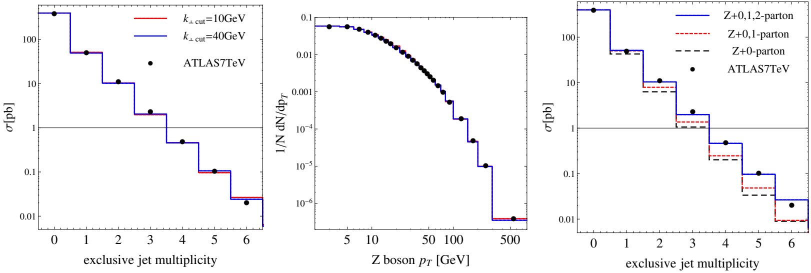
- Choose one PS generator.
- Cluster the partons in ME events and construct a shower history. The procedure should be close to the inverse of the PS generation. A set of sequential intermediates states with the scales are obtained.
- Apply the Sudakov veto algorithm to the intermediates states.



The CKKW-L merging algorithm

proton proton collisions

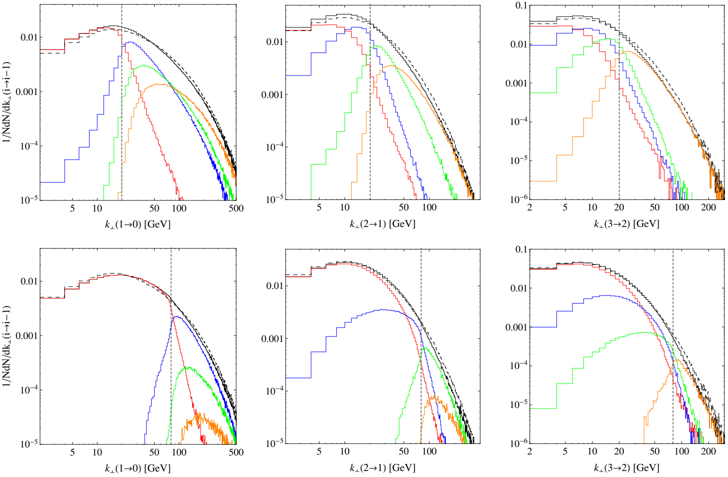
- Z boson plus jets production at the 7TeV LHC.



Observations

- Insensitive to the merging scale Q_{cut} (the left and middle figures).
- The results are improved significantly for higher values of the maximal number of partons provided by the matrix elements (the right figure).

The CKKW-L merging algorithm



Parton shower (PS) evolution - overview

Purpose

- Evolve the partons from their large production scales down to a hadronization scale.
- The soft and collinear radiation is generated as a result, thus event structure is exclusively resolved.

Feature

- The most singular and universal term $\alpha_s \log\left(t_{\mathrm{hard}}/t_{\mathrm{QCD}}\right)$ is resummed to all orders by imposing the unitarity constraint, thus physical answers are expected even at $t_{\mathrm{QCD}} \ll t_{\mathrm{hard}}$.

Advantages

- Does a good job of describing structure of jets.
- Allows to use a hadronization model tuned at a PS cutoff scale ($\sim \Lambda_{\mathrm{QCD}}$), which is independent of the hard process.

Picture representing a PS evolution from $q\bar{q}$