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学位（専攻分野）	博士（理学）
学 位 記 番 号	総研大甲第 1498 号
学位授与の日付	平成２４年３月２３日
学位授与の要件	高エネルギー加速器科学研究科　素粒子原子核専攻 学位規則第６条第１項該当
学 位 論 文 題 目	Generating multi-jet events with MadGraph
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論文内容の要旨

Generating multi-jet events with MadGraph

In this thesis, we discuss a new method of event generation with more than 4 jets on MadGraph platform. Many new physics models predict high-multiplicity-jet events at the LHC. There we need to estimate QCD multi-jet backgrounds in searching for new physics. To estimate those backgrounds, it is essential to simulate multi-jet production at the LHC. MadGraph is one of the powerful platforms that can simulate the Standard Model backgrounds and new physics signals on the same footing. However, it cannot generate QCD events with more than 4 jets. Therefore, we propose an efficient method to generate QCD multi-jet events. The new and important point of our method is to sample "color flows "in order to deal with time-consuming color summations.

The obstacles for multi-jet event generation are threefold: rapid growth of the number of Feynman diagrams, the number of phase space channels and the number of color configurations to be summed. First, we introduce off-shell recursive relations in the color-flow basis to generate multi-jet scattering amplitudes in MadGraph, taming the factorial growth of the number of Feynman diagrams. We then discuss efficient phase space integration of recursively generated scattering amplitudes, modifying Single-Diagram-Enhanced multi-channel integration employed in MadGraph. Finally, we deal with the color summation by sampling color flows. Obtained leading color results are then corrected with higher order contributions, generating unweighted events with arbitrary accuracy in 1/Nc expansion, where Nc is the dimension of the fundamental representation of SU(Nc). We demonstrate the comparison of cross sections, distributions and event generation efficiency with other event generators and discuss the efficiency and validity of our method.

Firstly, we implement the off-shell recursive relations in color-flow basis in MadGraph and generate each color-ordered helicity amplitudes directly for a multi-jet process. The introduction of off-shell recursive relations can significantly reduce the number of function calls to evaluate amplitudes by avoiding calculation redundancy appeared in the Feynman diagram method. The direct calculation of color-ordered amplitudes is also crucial for our purpose because of two reasons. One reason is that our new method requires evaluating each color-ordered amplitude separately since we samples each color-flows, that is, each color-ordered amplitudes. The other reason is more practical; MadGraph cannot generate executable helicity-amplitude function for multi-jet QCD processes. To evaluate color-summed amplitude squared of a process, the current MadGraph generates all the diagrams and helicity amplitudes, and performs the color decomposition of the process. This method breaks down when a given process involves more than five external particles. Therefore, we need to separate the whole scattering amplitude into color-ordered amplitudes.

To implement the off-shell recursive relations, we introduce new HELAS subroutines in MadGraph, which make n-point gluonic off-shell currents, and n-gluon amplitudes in the color-flow basis. We also define a new Model, CFQCD, with which MadGraph generates HELAS amplitudes in the color-flow basis since default MadGraph computes them in the different color basis. We explain new particles and their interactions we introduce in the CFQCD Model.

We then calculate total cross sections by combining those color-ordered amplitudes and summing colors by sampling color assignments of external particles. More specifically, we compute each terms of color-fixed amplitude squared by multiplying color-ordered amplitudes and computing the color coefficient from their color-flow information. The color-summed amplitude is then obtained by summing up many color assignments in Monte Carlo fashion.

As an example, we present total cross sections for up to 5 final parton processes; that is, pure gluonic processes, quark anti-quark annihilation processes and t-channel quark scattering processes. The maximum number of quark lines we consider is 2. These cross sections agree well with previous studies, showing the validity of our implementation and computation of color-ordered amplitudes in color-flow bases with recursive relations. The presented result for gg > 5g process is the first calculation in MadGraph.

Next, we discuss the method for efficient phase space integrations of color-ordered recursive amplitudes. MadGraph employs Single-Diagram-Enhanced multi-channel integration method for phase space integration. However, this method uses information of each Feynman diagram amplitude. Therefore, we need to modify it for our recursively-generated amplitudes.

This task consists of two steps: specification of singularities in color-ordered amplitudes and efficient mapping of them. For the first step, we propose the Peripheral-Propagator-Enhanced method. Peripheral propagators are propagators, which are formed by two external particles and represent major peaking behavior of color-ordered amplitudes. Possible peaking patterns of a color-ordered amplitude can be identified systematically by considering all the possible combinations of peripheral propagators. We use these combinations as channels for Single-Diagram-Enhanced method. Since these channels do not care about the internal structure of amplitudes, the number of channels is significantly reduced, comparing with the number of channels current MadGraph uses.

For the second step, we employ recursive phase space generation. In general, an n-body phase space is decomposed into 2-body phase spaces and can be generated in the recursive way. We generate phase space for each channel recursively and optimized Phase space mappings according to the peripheral propagator structures.

Phase space integrations are then performed by the multi-channel integration method. We show that this technique works well, comparing with other phase space integrators.

Finally, we discuss the event generation of multi-jet processes. Here the main problem arises from the huge number of color configurations to be summed; exact color summation becomes unrealistic when the number of external colored particles grows.

1/Nc expansion of color-summed scattering amplitude squared is a useful way to organize and approximate the color summation. Since the next-to-leading terms are of order of (1/Nc)^2 ~ 10% with respect to the leading order terms, leading 1/Nc, or leading color, approximation is already a feasible approximation in LHC physics. Moreover, phase space mapping becomes much simpler in leading color summation. Therefore, we would like to generate events in leading 1/Nc accuracy and improve them with higher order corrections.

Color summation in leading color order is performed by sampling color flows and multiplying the appropriate color factor. Algorithm of generating leading 1/Nc unweighted events is discussed. Unweighted events with arbitrary accuracy are then obtained by re-weighting and re-unweighting method by identifying interference terms contributing to a given 1/Nc order.

We present selected results and discuss the reliability and efficiency of our method. Sampling color flows and re-weighting method gives consistent cross sections and distributions with other generators with reasonable errors. This method generates unweighted events efficiently. Re-weighting method correctly account for the higher order corrections. It can therefore be concluded that our method efficiently generate unweighted events beyond leading 1/Nc accuracy.

We have proposed a method to generate multi-jet QCD events efficiently in the MadGraph platform. Generating multi-jet QCD events is important in new physics search at the LHC, but none of the simulation tools can simulate both of new physics signals and multi-jet backgrounds sufficiently. MadGraph is one of the simulation platforms, which is suit to this task. The proposed method will open the way for multi-jet event generations in MadGraph platform.

博士論文の審査結果の要旨

高江洲氏の学位論文の内容は、LHCの物理解析で多くの実験家と理論家に使用されている素粒子のイベント生成パッケージMadGraph における QCD 振幅の新しい生成手法の開発である。MadGraph は標準模型によるバックグランド事象と共に、多くの新しい物理、新粒子シグナルのシミュレーションが可能な拡張性の高いツールであるが、基本的にファインマン振幅を計算するプログラムであるため、ファインマン図の数が5000を超える過程、特に４つ以上のジェット生成を伴う過程の振幅を計算することができなかった。高江洲氏は萩原氏と共同で、カラーフローベースのオフシェルの再帰的振幅計算の方法を使ってMadGraph 上で振幅計算を行う方法を開発した。この方法はファインマン図計算手法との共存が可能で、MadGraph の汎用性を損なうことなく多重ジェット生成過程の高速シミュレーションを可能にする。さらに、QCDの高次補正計算を効率化するために、カラー自由度の足し上げを 1/N 展開で行うアルゴリズムを開発した。

本研究の内容は、MadGraph をより高次の QCD 摂動に拡張するために重要な内容であり、本研究の内容は十分に博士論文に値すると認められる。また、研究内容はすでに European Physical Journal C (2011) 71:1668 に発表されている。

高江洲氏は上記の研究内容以外にもいくつかの学術論文を発表している。すべて共同研究であるが、本研究の主要部分は独力で完成させたものであり研究者としての高い能力が証明されている。提出された博士論文には、カラーフローベースのオフシェルの再帰的計算方法、MadGraph の開発状況、他の同様の計算ツールとの結果の比較などが詳しく記述されている。

以上のことから、本研究は博士論文の研究として十分な内容を持っていると認められ、博士論文審査に合格と判断する。