BlackHat

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MC4LHC Readiness Workshop March 2010

In collaboration with C. Berger, Z. Bern, L. Dixon, F. Febres Cordero, H. Ita, D. Kosower, D. Maître, T. Gleisberg

Overview

- Automating NLO computation.
- BlackHat.
- What it can do.
- Release timetable.

NLO?

- Increased precision beyond Leading Order (LO).
- Gives better control of shapes and normalization's of distributions.
- Reduced scale dependance, e.g. for W+jets, jet E_T

No. of Jets	LO	NLO
1	16%	7%
2	30%	10%
3	42%	12%

NLO Calculations

- Leading order requires only a single piece - Tree amplitudes. Many tools exist for this.
- Three pieces are needed for a complete NLO computation,
  - Real piece - Tree amplitudes with one extra leg. Re-use leading order tools.
  - Virtual piece - One-loop amplitudes with the same number of legs.

Virtual Term

- The virtual term has been considered the bottleneck in such computations up until now.

$$\sigma_n^{\mathrm{NLO}} = \int_n \sigma_n^{\mathrm{tree}} + \int_n \sigma_n^{\mathrm{virtual}} + \int_{n+1} \sigma_{n+1}^{\mathrm{real}}$$

- Only recently has significant progress been made on automating the computation of one-loop amplitudes.

NLO Calculations

- Automated One-loop amplitude codes using new techniques-
  - BlackHat [Berger, Bern, Dixon, DF, Febres Cordero, Gleisberg, Ita, Kosower, Maître],
  - CutTools [van Harmeren, Bevilacqua, Czakon, Papadopoulos, Pittau, Worek],
  - Rocket [Ellis, Giele, Kunszt, Melnikov, Zanderighi],
  - Others [Lazopoulos], [Giele, Kunszt, Winter].
- Feynman diagram approach : Golem [Binoth, Guillett, Heinrich, Pilon, Reiter]+[Guffanti, Karg, Kauer]

Automated IR Subtractions

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- Real and virtual terms are separately IR divergent. Numerically subtract IR singularities from real and add back to the virtual. Procedure now automated.
- Catani-Seymour Dipoles
  - Automation within Sherpa [Gleisberg, Krauss]
  - MadDipole (in MadGraph) [Frederix, Gehrmann, Greiner]
  - Others [Seymour, Tevlin], [Hasegawa, Moch, Uwer].
- Frixione, Kunzst and Signer subtraction, MadFKS [Frederix, Frixione, Maltoni, Stelzer]

Automated IR Subtractions

$$\sigma_n^{\text{NLO}} = \int_n \sigma_n^{\text{tree}} + \int_n \left(\sigma_{n+1}^{\text{real}} - \sigma_{n+1}^{\text{sub}}\right) + \int_n \left(\sigma_n^{\text{virtual}} + \int_1 \sigma_{n+1}^{\text{sub}}\right)$$

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Current Situation

- In the past the analytic formula for a specific process was implemented in a specific code or combined into a program such as MCFM.
- Each new process requires knowledge and skill to produce. Takes time.
- Many processes (and their many sub-processes) wanted at the LHC.
- Doing everything is a difficult task.

The Goal

- Automation & Mass Production
- Use computers to do the tedious work!
- **BlackHat** - an automated package for computing one-loop amplitudes.

Automation

- NLO computation Goal: pick an automatic tree-level code, a one-loop level code and a subtraction code, combine to get full NLO result.
- Great flexibility. Combine one-loop code with your other favorite tools.
  - Choose the best tool for each part.
  - Reduces the sources of potential error.

BlackHat+Sherpa

- How does this work in practice?
- Example : BlackHat + Sherpa.

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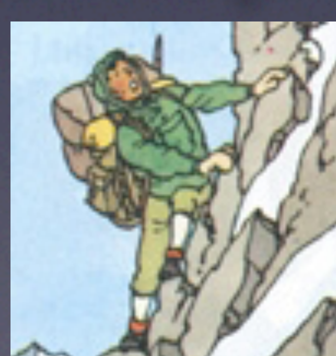
Sherpa

BlackHat



The Role of Sherpa

[Gleisberg, Hoeche, Krauss, Schoenherr, Schumann, Siegert, Winter]

- We use this at the parton level only (AMEGIC++).
- Event generation.
- Efficient phase space integration of the real and virtual terms.
- Automated Dipole subtraction. [Catani, Seymour], [Gleisberg, Krauss]

The Role of BlackHat

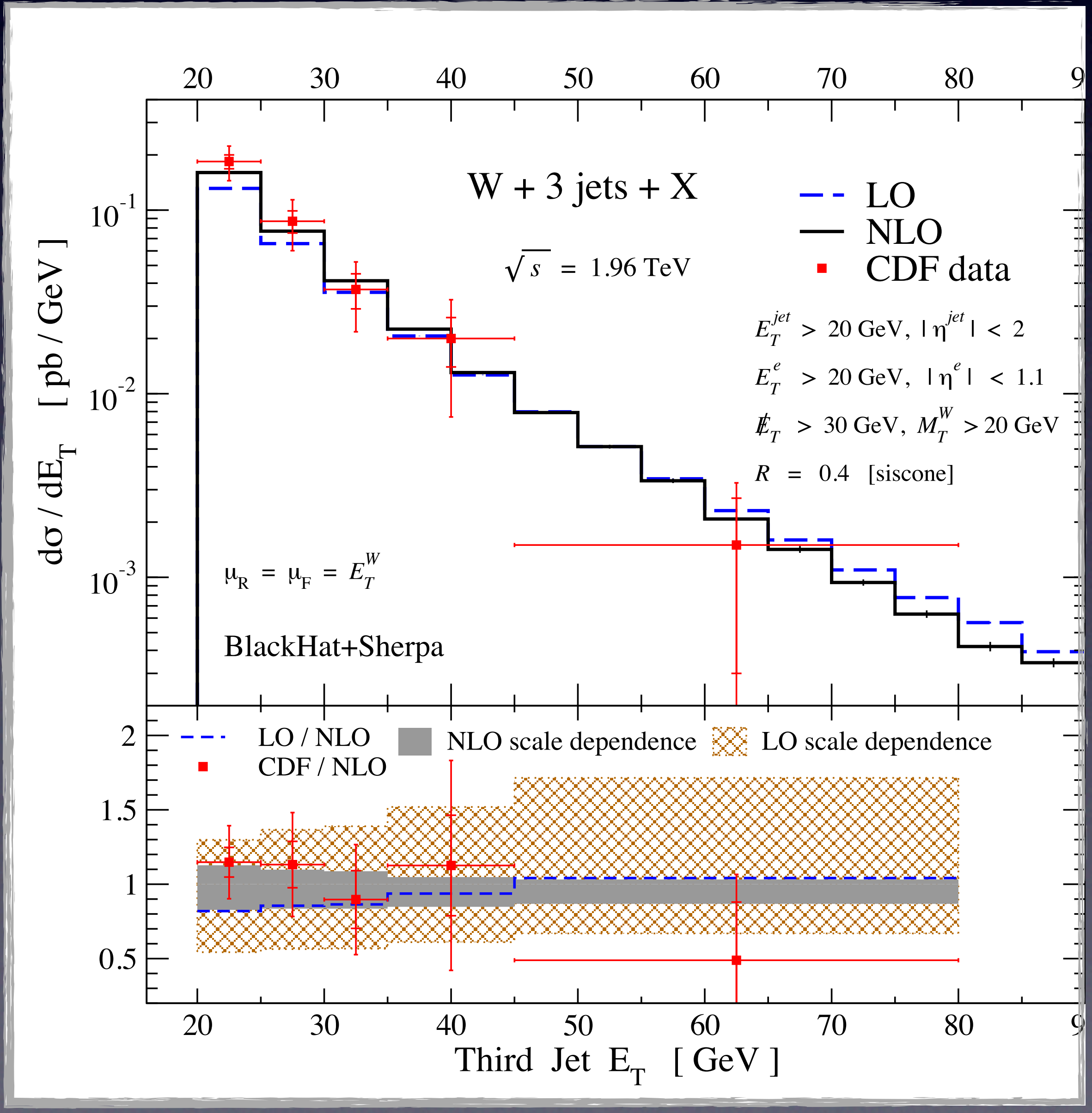
[Berger, Bern, Dixon, DF, Febres Cordero, Ita, Kosower, Maître, Gleisberg]

- Automated one-loop amplitude computation.
- Uses recent developments in unitarity & on-shell methods.
- Efficient computation of processes which would be much harder using Feynman diagram approaches.
- c++ framework.

Example: W+3 jets

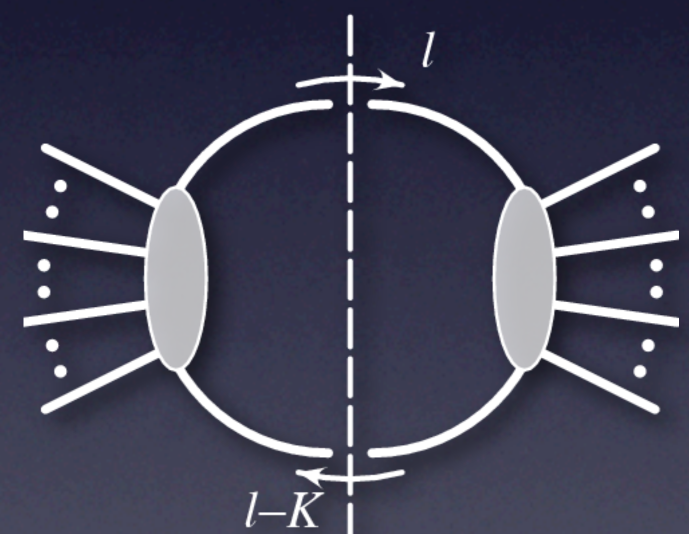
[Berger, Bern, Dixon, DF, Febres Cordero, Ita, Kosower, Maître, Gleisberg]

- Combining SHERPA+BlackHat get new results. e.g. (see David Kosower's talk on Thursday)



Unitarity & On-shell methods

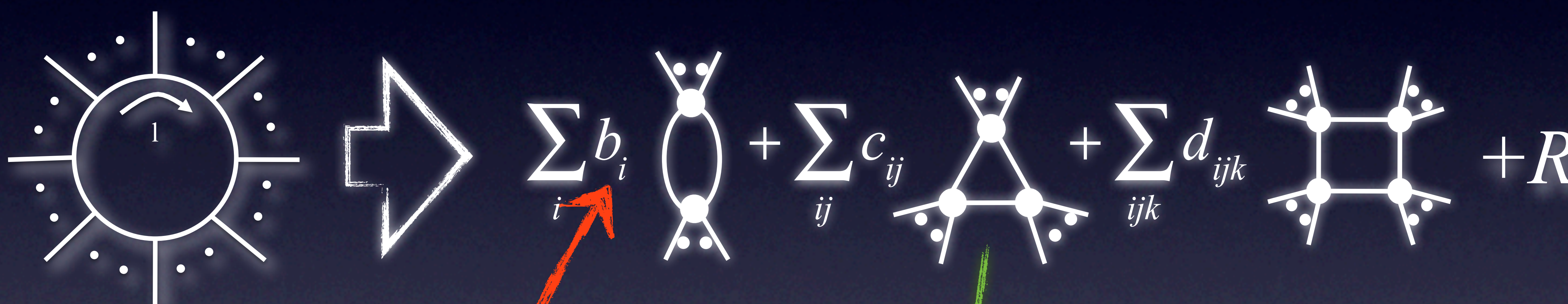
- Want to avoid using gauge dependent quantities, use only on-shell amplitudes.
- Unitarity: "Glue" together trees to produce loops.



- Efficient methods for computing trees lead to efficient computation of loops.

One-loop Basis

- Any one-loop amplitude can be decomposed into a standard basis of scalar integral functions,

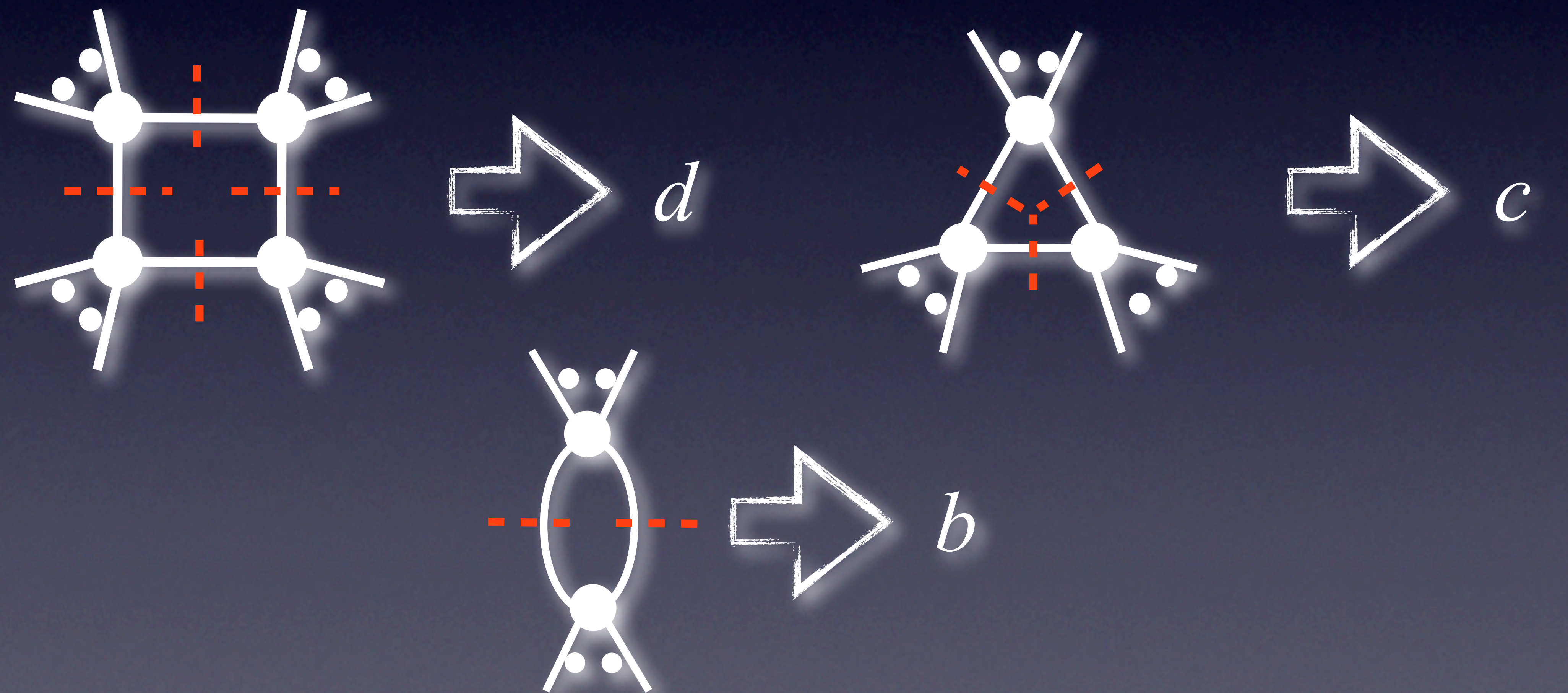


Scalar coefficients we want

All One-loop basis integrals known.

Computing Coefficients

- Generalized unitarity, cut the loop more than two times, use to compute these coefficients.



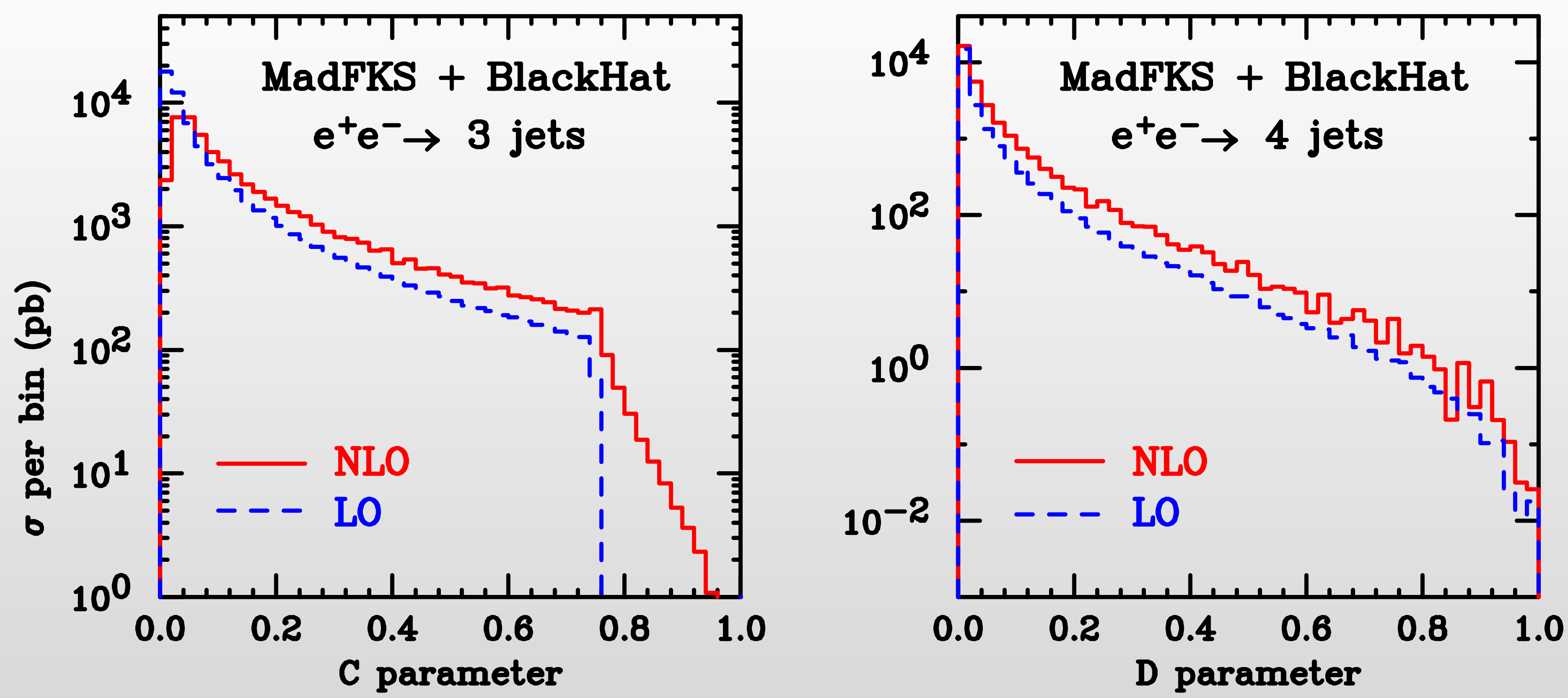
- Similar approach for rational terms or On-shell recursion.

BlackHat

- BlackHat is a numerical implementation of this.
- For massless particles and massive particles that do not enter the loop.
- Unitary approach completely general, will implement all massive particles in the future.
- Implements Binoth-Les Houches accord interface. Enables easy connection to external code.

2nd Example: BlackHat+MadFKS

- The C and D parameters for 3 and 4 partons respectively. [Frederix]



BlackHat In Use

- For a fixed order NLO computation BlackHat needs to be combined with programs/code to do
  - real part, IR subtraction, phase space integration.
- Combine with SHERPA.
- Can also be used wherever one-loop amplitudes are required e.g. NLO parton showers.
- Setup provides great flexibility.

Computing using BlackHat

- High multiplicity processes (e.g. W/Z+3 jets) are more computationally demanding than in the past.
  - Requires control of multiple separate jobs for real and virtual terms (e.g. SHERPA and BlackHat pieces).
  - Combine results of multiple jobs for each piece for high statistics results.
  - Important, for example, to fill tails of distributions at the high energies seen at the LHC.
- Can then maximize use of computational resources; use multiple different clusters or GRID computing.

Public Release

- Multiple steps.
- Now: Initially release ROOT n-tuples of events for specific NLO processes.
- 6-12 months: Code release of BlackHat for one-loop amplitudes.
- 12+ months: Full SHERPA+BlackHat control setup for complete NLO calculations.

Root n-tuples

- Give out n-tuples for specific NLO processes. e.g. W/Z+3 jets for the LHC at 7 TeV.
- Straightforward and quick to use in an NLO analysis.
- For example: Amanda Deisher from CMS has been successfully testing n-tuples produced by BlackHat +SHERPA.

BlackHat Code Release

- Release in 6-12 months.
- Will produce one-loop amplitudes for validated processes.
- No other restrictions; can be used however you want with any other code.
- Validated processes will include: $pp \to W/Z$+jets, $e^+e^- \to$ jets and $pp \to$ jets.

Conclusion

- BlackHat - An automated one-loop computation package.
- Can be used in combination with any program that needs one-loop amplitudes (via Binoth-Les Houches accord interface).
- Public code release 6-12 months, NLO n-tuples available now.