What has been achieved since Les Houches 2005 ?

What has been done in session 1 ?

NLO multi-leg group

Gudrun Heinrich

Les Houches 05: NLO wishlist for LHC

process ($V \in \{Z, W, \gamma\}$)	background to
1. $pp \to V\,V$ jet	$t\bar{t}H$, new physics
2. $pp \to H + 2$ jets	H production by VBF
3. $pp \to t\bar{t}\,b\bar{b}$	$t\bar{t}H$
4. $pp \to t\bar{t} + 2$ jets	$t\bar{t}H$
5. $pp \to V\,V\,b\bar{b}$	VBF$\to H \to VV$, $t\bar{t}H$, new physics
6. $pp \to V\,V + 2$ jets	VBF$\to H \to VV$
7. $pp \to V + 3$ jets	various new physics signatures
8. $pp \to V\,V\,V$	SUSY trilepton

achieved (from wishlist):

- $pp \to H + 2$ jets   Campbell, Ellis, Giele, Zanderighi '05/06
- $pp \to Z\,Z\,Z$ Lazopoulos, Melnikov, Petriello '07
- $\mathcal{O}(\alpha^6 \alpha_s)$:

  $pp \to Z\ \ Z + 2$ jets via VBF,
  $pp \to W\,W + 2$ jets via VBF,   Jäger, Oleari, Zeppenfeld '06
  $pp \to W\ \ Z + 2$ jets via VBF   Bozzi, Jäger, Oleari, Zeppenfeld '07

Les Houches 07 wishlist

process ($V \in \{Z, W, \gamma\}$)	# groups working on
1. $pp \to V\,V$ jet	2
2. $pp \to t\bar{t}\,b\bar{b}$	1
3. $pp \to t\bar{t} + 2$ jets	
4. $pp \to W\,W\,W$	1 (?)
5. $pp \to V\,V\,b\bar{b}$, $V\,V\,t\bar{t}$	
6. $pp \to V\,V + 2$ jets	
7. $pp \to V + 3$ jets	
8. $b\bar{b}b\bar{b}$	1
9. $gg \to W^*W^*$ (NLO, 2 loops)	?
10. EW corrections to VBF	1
11. NNLO to VBF, $t\bar{t}$, Z/γ+jet, W+jet	?

That's all ???

NO !

- processes which were not on the wishlist

  examples: (SM, LHC kinematics only, $N > 4$ only)

  - $pp \to t\bar{t}+$ jet Dittmaier, Uwer, Weinzierl ’07
  - $pp \to Z+$ 2 jets, $W+$ 2 jets with one b-quark tag
    Campbell, Ellis, Maltoni, Willenbrock ’06, ’07
  - $pp \to H\, b\bar{b}$ Febres Cordero, Reina, Wackeroth ’06
  - $pp \to H\,H\,H$ Plehn, Rauch ’05; Binoth, Karg, Kauer, Rückl ’06
  - . . .

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  - analytic methods (twistor/string inspired)
    $\longrightarrow$ Zoltan's talk this afternoon,
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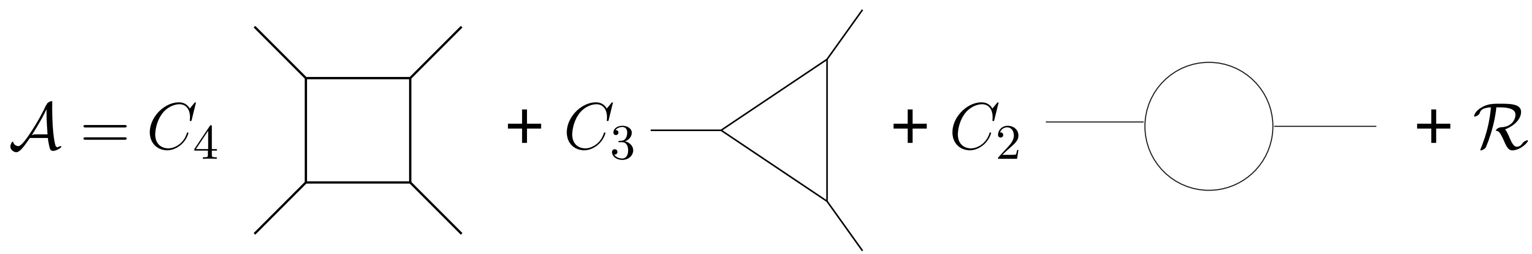
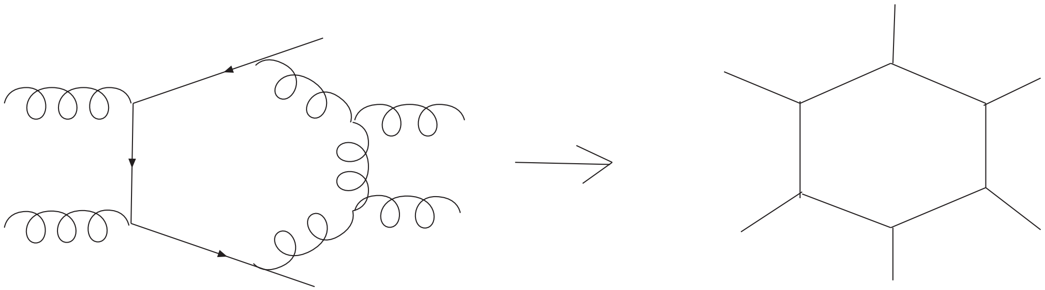
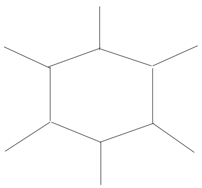


tensor reduction

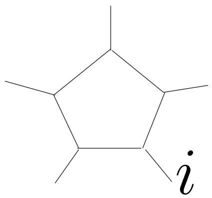


+ integrals with less legs from reduction of tensor rank and number of legs at the same time

non-trivial tensor structure — scalar 6-point function



$$= \sum_{i=1}^{6} b_i$$



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factorial growth in complexity !

(semi-)numerical methods cont'd.

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- solve system of equations which determines coefficients of basis integrals numerically
  Papadopoulos, Pittau, Ossola; Ellis, Giele, Kunszt

technical developments cont'd.

- fully numerical methods:
  do integration over loop momenta and/or Feynman parameters numerically
  problem: isolation of singularites
  Anastasiou, Beerli, Daleo, Kunszt; Ferroglia, Passera, Passarino, Uccirati;
  Lazopoulos, Melnikov, Petriello; Krämer, Nagy, Soper; Kurihara, Kaneko, . . .

- improved methods for real radiation at NLO
  (partly inspired by NNLO efforts)
  Daleo, Gehrmann, Maître; Nagy, Somogyi, Trocsanyi;
  Weinzierl, Schwinn, Gleisberg, . . .

superficial comparison of methods

- analytic methods
  - + compact expressions
  - + evaluation of analytic expressions fast
  - - processes with massive particles in the loop and/or many different mass scales difficult
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- numerical methods
  - + do not generate large analytic expressions
  - - numerical integration in multi-dimensional parameter space with intricate pole structure non-trivial

towards NLO 2 $\rightarrow$ 4 scattering

6-point results achieved:

- complete one-loop amplitudes for
  - 6 gluons
    Britto, Feng, Mastrolia; Ellis, Giele, Zanderighi;
    Berger, Bern, Dixon, Dunbar, Forde, Kosower; Xiao, Yang, Zhou;
    Bedford, Brandhuber, Spence, Travaglini;
    Britto, Buchbinder, Cachazo, Feng, . . . '94-'06
  - 6 photons
    Nagy, Soper; Binoth, Gehrmann, GH, Mastrolia;
    Papadopoulos, Ossola, Pittau; Forde '06/07
- full electroweak corrections to $e^+e^- \rightarrow 4\,f$
  Denner, Dittmaier, Roth, Wieders Feb. 05, but should be mentioned
- $e^+e^- \rightarrow HH\nu\bar{\nu}$
  GRACE group (Boudjema et al.) 10/05

- important developments towards matching NLO with parton showers

  Frixione, Nason, Webber, . . . , Nagy, Soper, . . . , Giele, Kosower, Skands, Krämer, Mrenna, . . . , Gieseke, Latunde-Dada, Ridolfi, . . . , Gleisberg, Höche, Krauss, Schälicke, Schumann, Winter, . . .

  enormous activity in session 1

- resummation:
  - H production, doubly differential in q_T and y

    Bozzi, Catani, DeFlorian, Grazzini ’07
  - single-inclusive jet production near threshold

    DeFlorian, Vogelsang ’07

- . . .

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achieved in session 1 . . .

Les Houches Accord on Master Integrals

needed by most of the approaches:

one-loop master integrals

Les Houches accord on Master Integrals:

- agreement on format to uniquely characterise the integral (LoopTools conventions)
- WIKI page where everybody can post previously unknown MI's
- hosted at http://durpdg.dur.ac.uk/hepdata/

  (put up by Jeppe Andersen)

automatisation/modularity

- one-loop tensor integrals:

  Keith Ellis suggested to provide (public) code for one-loop tensor integrals with massless internal lines up to rank 5 pentagons

- real radiation:

  T. Gleisberg is working on a code (to be made public) for automated generation of dipole subtraction terms

to be addressed during this workshop

- How can "string inspired/standard approaches" maximally profit from each other?
  - make use of complementarity of different approaches
  - assess limitations and future prospects of "traditional/new" approaches
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agreement in session 1:

dedicated section on rational parts in the proceedings

topics to be addressed

- NNLO:
  - asses where it is needed
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- numerical stability in NLO multi-leg calculations:

  classify types of singularities which can occur in an amplitude

Numerical Stability

"Numerical instabilities are like bad spots on an apple"
(Dave Soper)

Singularities in scattering amplitudes

questions:

- where do the bad spots come from? (which type of singularity?)

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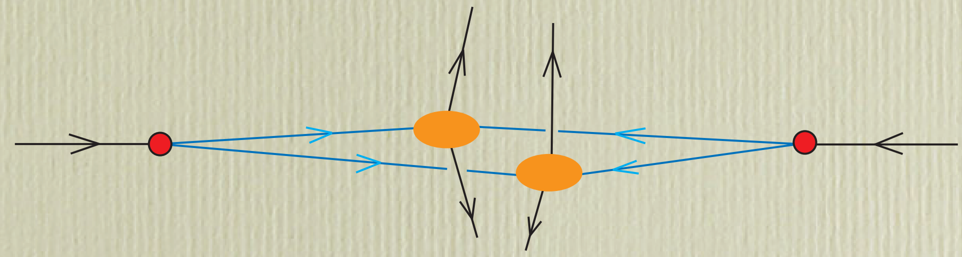
- where do the bad spots come from? (which type of singularity?)
- are they only on the surface of the apple?
  (are they always at the phase space boundaries?)
- if I make an apple cake:
  (integrate the amplitude over the phase space)
  - are the spots harmless? (integrable?)
  - can I cut out the bad spots and still have enough apple left for the cake? (to drop or interpolate problematic phase space points: do they represent a negligible fraction of phase space?)
  - if I cut the cake, do hidden bad spots suddenly show up? (how do kinematic cuts affect the numerical stability?)

disadvantages ...

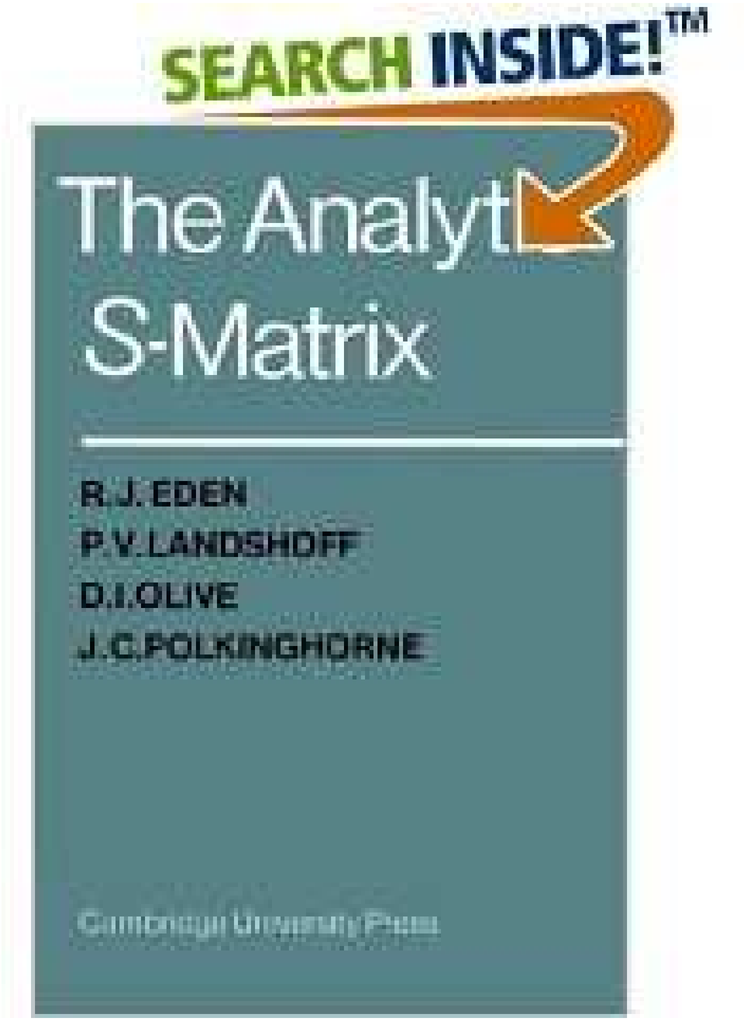
Z.Nagy

- There can be problems from double parton scattering singularities.



- This starts at $N = 6$.

Revenge of the Analytic S-matrix



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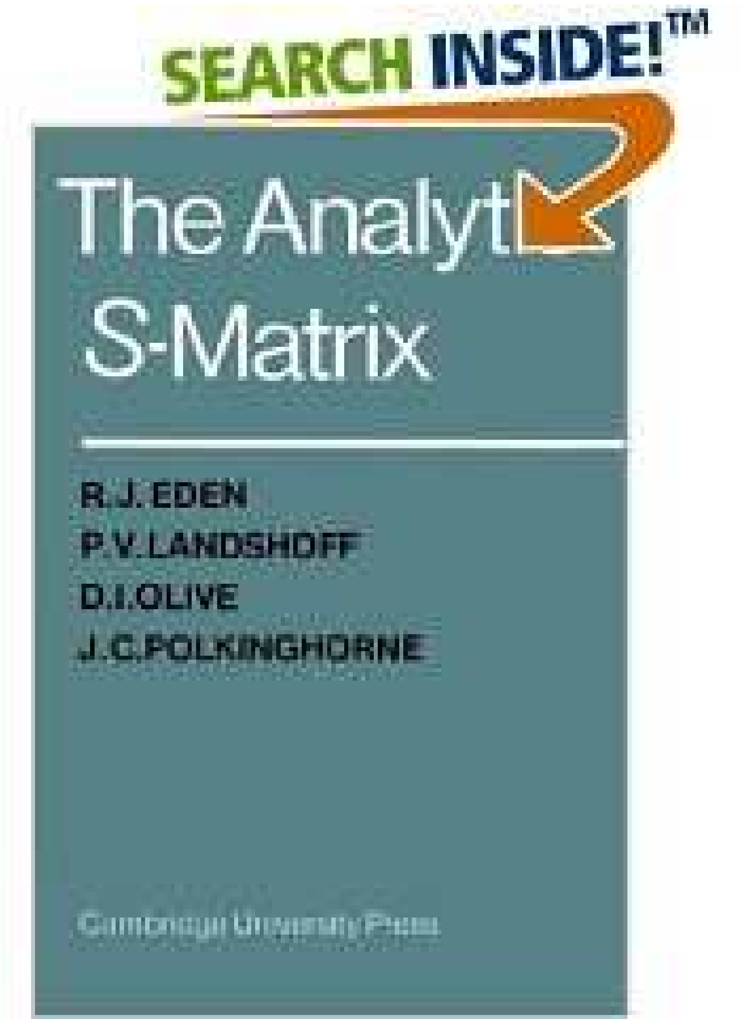


translate the Bible
into modern language !

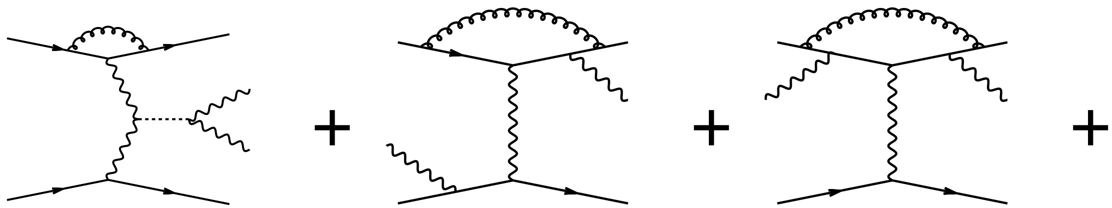
extra slides

Numerical Stability

- plan: dedicated section in the proceedings on different types of singularities (Giele, Duplancic, et al)
- agreement on information that would be useful in a publication:
  - amplitudes in analytical form: give numerical value at certain phase space point(s) such that others can compare
  - integrated amplitudes/cross sections: statements about numerical behaviour
    - what fraction of phase space shows instabilities ?
    - how have they been dealt with ?

Virtual Corrections

...interference of LO diagrams with

$$\mathcal{M}_V = $$  $$+ \ldots$$

$$= \mathcal{M}_B\, F(Q) \left[-\frac{2}{\varepsilon^2} - \frac{3}{\varepsilon} \right] + \tilde{\mathcal{M}}_V^{finite}$$

$\tilde{\mathcal{M}}_V^{finite}$ computed with Passarino-Veltman reduction

cumbersome: (numerically small) pentagon contributions

combination of real emission and virtual contributions with subtraction terms according to dipole approach of *Catani & Seymour*

poles canceled analytically $\longrightarrow$ finite results