Summary of activities in

NLO multi-leg/NNLO working group

June 29, 2007

Les Houches 07 wishlist

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

progress

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  more automatisation/modular tools

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- better methods:

  $\rightarrow$ learn, discuss, compare

  $\rightarrow$ "what is a good method depends on the type of the problem"

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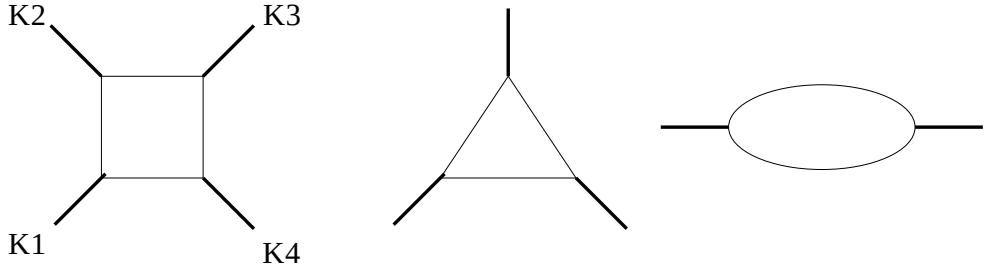
- Reconstruction of coefficients of one-loop master integrals and of the rational terms by solving a system of equations numerically (Costas Papadopoulos)
- "The magic of cut-construction" (Zvi Bern)
  complex momenta are the key to new solutions (and new pitfalls)
  "unreal" poles can cause "real" headaches

Master Integrals

Passarino-Veltman reduction brings the one-loop amplitude to the form

$$A_{n;1} = \sum_i d_i \text{ (box)} + \sum_i c_i \text{ (triangle)} + \sum_i b_i \text{ (bubble)} + \text{rational}$$

where expressions for scalar bubble, scalar triangle and scalar box integrals are known explicitly. (in dim. reg.: Bern, Dixon, Kosower)



box triangle bubble

Les Houches Accord on MI's

needed by most of the approaches:

one-loop master integrals

Les Houches accord on Master Integrals:

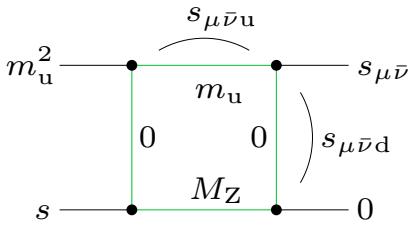
- agreement on format to uniquely characterise the integral (LoopTools conventions)
- WIKI page where everybody can post previously unknown MI's
- hosted at http://durpdg.dur.ac.uk/hepdata/

semi-numerical approaches

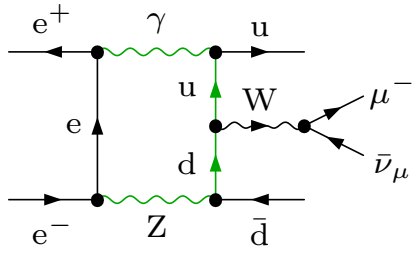
- Techniques for multi-leg one-loop tensor integrals (Ansgar Denner)
  - detailed discussion of numerical stability issues (det(Gram)$\to$ 0,det(Cayley)$\to$ 0, both dets $\to$0)
  - "phase space integration reveals weaknesses of methods"

A very delicate example with small Gram and mod. Cayley determinants:

Box integral

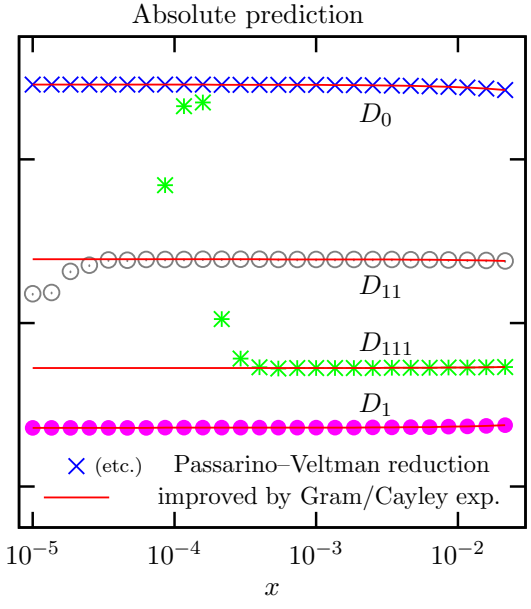


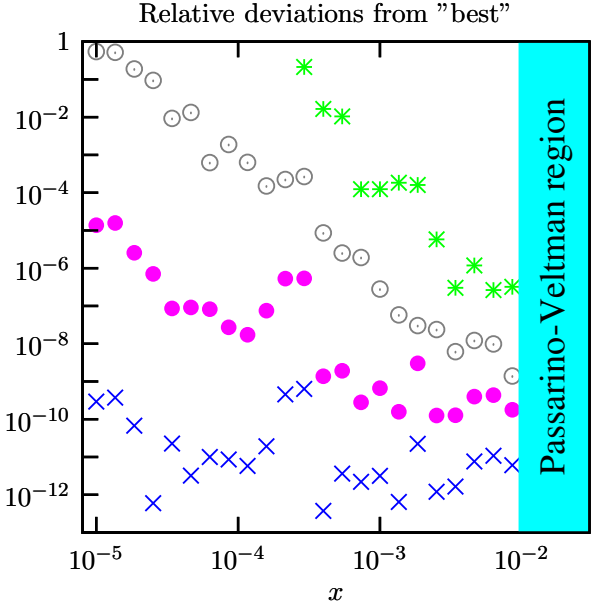
appears, e.g., in subgraph of diagram



Gram det.: $\det(Z), \det(X) \to 0$ if $s_{\mu\bar{\nu}\mathrm{d}} \to s$ and $s_{\mu\bar{\nu}\mathrm{u}} \to s_{\mu\bar{\nu}}$

Numerical comparison: maximal tensor rank $= 25$





$$x \equiv \frac{s_{\mu\bar{\nu}\mathrm{d}}}{s} - 1 \equiv \frac{s_{\mu\bar{\nu}\mathrm{u}}}{s_{\mu\bar{\nu}}} - 1$$

$s = 4\times10^4\,\mathrm{GeV}^2$
$s_{\mu\bar{\nu}} = 64\times10^2\,\mathrm{GeV}^2$

PV reduction breaks down,
but Gram/Cayley exp. stable
for $\det(Z), \det(X) \to 0$!

Phenomenological results

- $pp \to t\bar{t}$ jet production (Peter Uwer)
- $pp \to V\,V$ j j via VBF (Dieter Zeppenfeld)
- Electroweak corrections to gauge boson production at high p_T (Stefano Pozzorini)
  $pp \to VV'$, differences to massless gauge theories, discussion of real W/Z emission
- EW (and QCD) corrections to Hjj production via VBF (Ansgar Denner)

Recent studies for pp$\longrightarrow VV'$

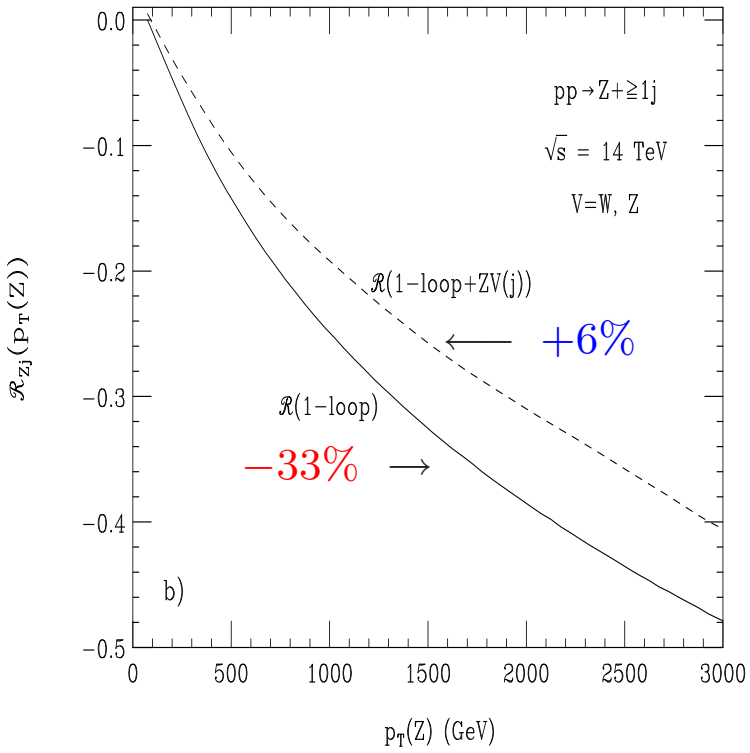
- all processes apart from pp$\longrightarrow \gamma\gamma$ computed

process	decay	hard γ	corrections	
Wγ, WZ	yes	no	NLL	**Accomando, Denner, S.P. (2002)**
Zγ	no	yes	exact	**Hollik, Meier (2004)**
WW, WZ, ZZ	yes	yes	NLL	**Accomando, Denner, Kaiser (2005)**
Wγ, Zγ	yes	yes	exact+NLL	**Accomando, Denner, Meier (2005)**

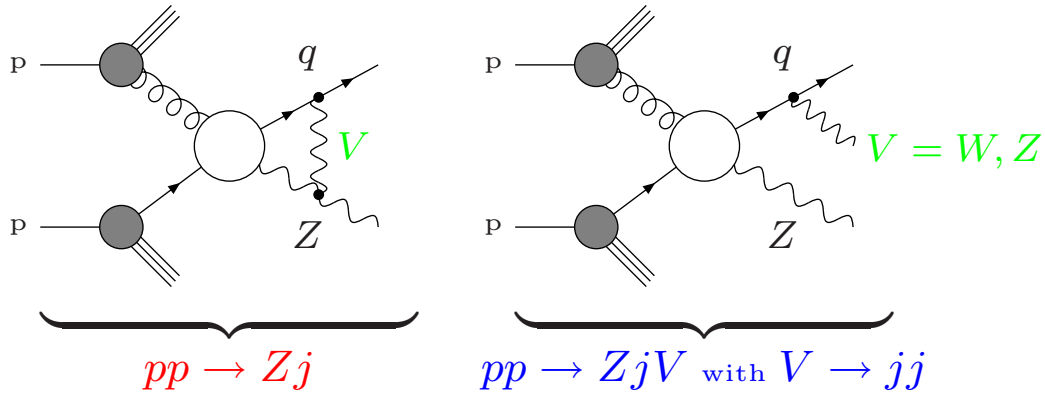
- similar conclusions as for Wγ, WZ

Real W and Z emission for $pp \to Zj$ [Baur (2006)]

" Since the number of jets is not fixed in a measurement of the Z boson p_T distribution, $\mathcal{O}(\alpha_s \alpha^2)$ ZVj production with $V \to jj$ has to be included when calculating weak radiative corrections "



Virtual and real $\mathcal{O}(\alpha)$ corr. to $pp \to Zj$



- W, Z emission can be non-negligible and partially cancel EW virtual corrections
- depends on observable definition and can be reduced by jet veto

NNLO corrections

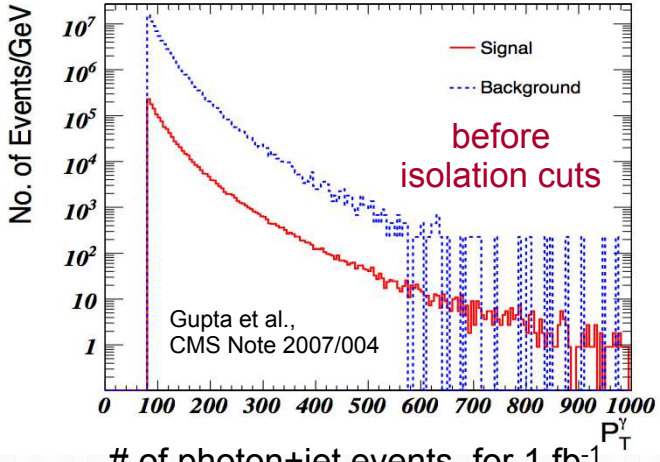
- Expected uncertainties at the LHC (Günther Dissertori)

NNLO corrections

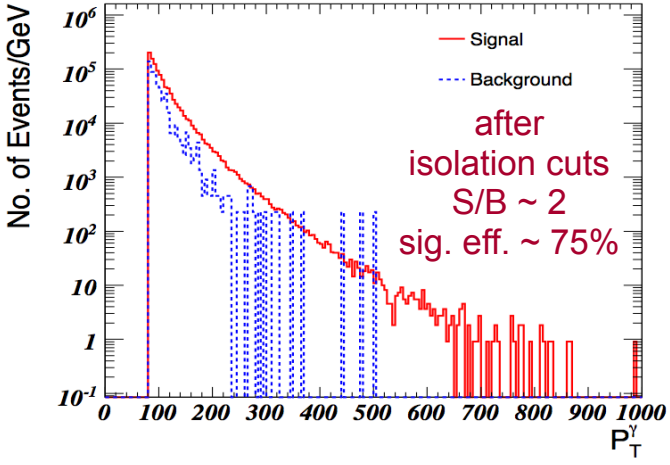
Prompt Photon Production

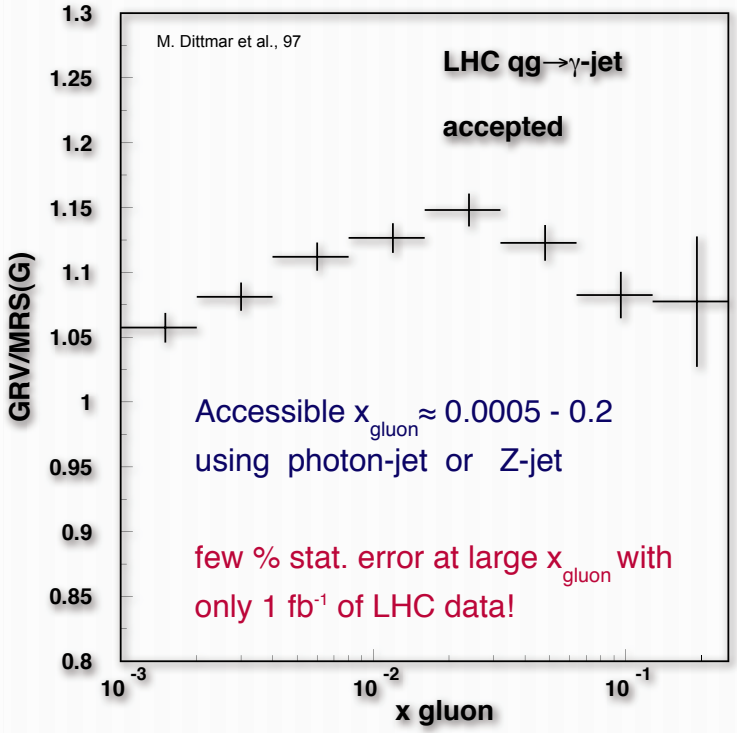
ETH Institute for Particle Physics

- it's all about isolation
- reduce background by combination of isolation requirements using Tracker, ECAL and HCAL



# of photon+jet events, for 1 fb^{-1}





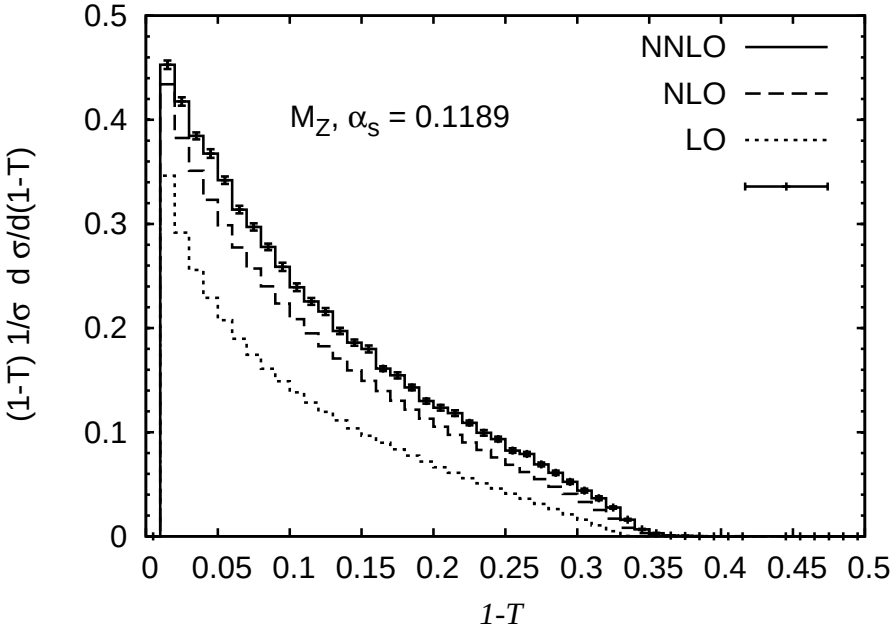
- constrain gluon pdf
- energy scale well controlled by photon
- other issues there:
  interplay real radiation - fragmentation
- Z+jet : smaller rate, best possible prediction needed

NNLO corrections

- Expected uncertainties at the LHC (Günther Dissertori)
- $e^+e^- \to$ 3 jets at NNLO (Aude Gehrmann-De Ridder)
  initiated at Les Houches '01 . . . 6 years
  of man-and woman-power !

Results

The thrust distribution



- errors are numerical
- comparaison with data ongoing
- visible enhancement due to NNLO contributions (15 %)

NNLO corrections

- Virtual corrections for $pp \to t\bar{t}$ production at NNLO (Michael Czakon)

$pp \to t\bar{t}$ at 2 loops

Direct computation

- Statistics
- annihilation channel
  - 190 diagrams expressed through 2812 integrals
  - 145 master integrals in the full result
  - 69 master integrals needed in the present calculation
- fusion channel
  - 726 diagrams expressed through 8676 integrals
  - 422 master integrals in the full result
  - 174 master integrals needed in the present calculation

Publicly available Software

- MB.m package (MC) written in MATHEMATICA
  - FORTRAN interface for numerics
  - CUBA library for integration
  - CERNlib for Gamma functions

http://theorie.physik.uni-wuerzburg.de/~mczakon

MC, Comput.Phys.Commun.175:559-571,2006.

- Basic functionality
  - MBoptimizedRules : determination of contours
  - MBcontinue : analytic continuation
  - MBexpand : expansion in a chosen parameter (e.g. Epsilon)
  - MBintegrate : numerical integration for specified kinematics

- Input
  - Mellin-Barnes representation

- Useful external software
  - AMBRE (Automatic Mellin-Barnes Representations) Gluza, Kajda and Riemann
  - XSummer (evaluation of harmonic sums) S. Moch and P. Uwer

Private software components for generic computations

- C++ library DiaGen (9.700 lines of code)
  - topology and diagram generation
  - topological isomorphism and symmetry groups
  - integral identification
  - QFT topological properties

  + 1100 lines of Utlities library

- C++ library IdSolver (9.600 lines of code)
  - solution of identity systems between integrals
  - simplification by topological analysis
  - handling of large databases

- Mathematica packages for Mellin-Barnes integrals (8.200 lines of code)
  - generation of representations from Feynman integrals
  - analytic continuation and numerical evaluation
  - expansion in small parameters
  - application of Barnes lemmas
  - conversion to nested sums and resummation by PSLQ

- HNNLO: Fully differential program for Higgs production at NNLO (Massimiliano Grazzini)

An example: $gg \to H \to \gamma\gamma$

Use cuts as in CMS TDR

$$p_T^{\min} > 35 \text{ GeV} \qquad |y| < 2.5$$
$$p_T^{\max} > 40 \text{ GeV}$$

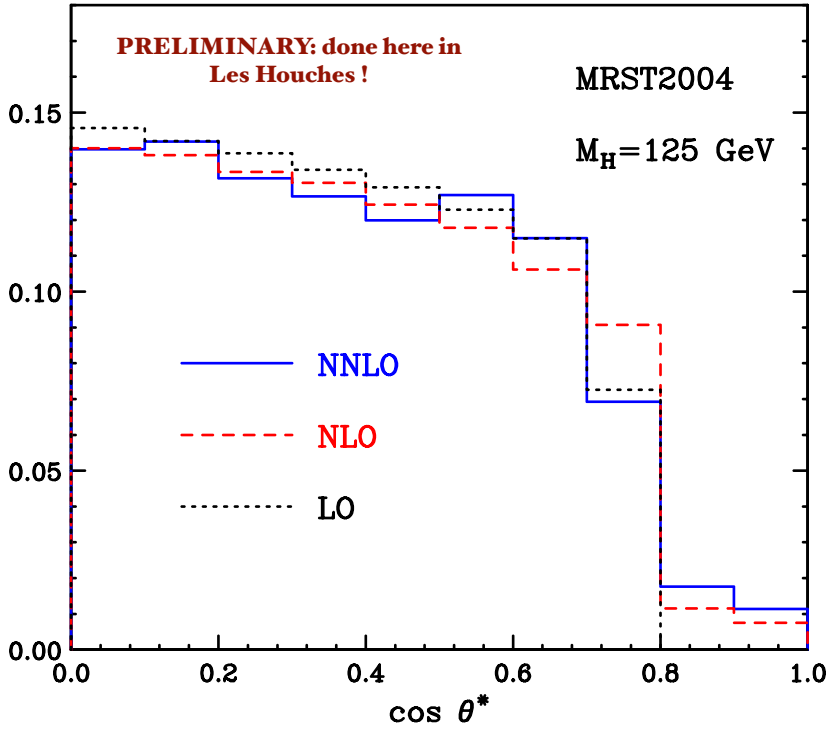
Photons should be isolated: total transverse energy in a cone of radius $R = 0.3$ should be smaller than 6 GeV

define $\cos\theta^*$ distribution

θ^* **polar angle of one of the photons in the Higgs rest frame (used by ATLAS: thanks to Suzanne Gascon and to Markus Schumacher)**

note upper bound on $\cos\theta^*$ at LO

➡ again perturbative instability beyond LO !



Outlook

After all these efforts . . .

we are eager to compare to data at

Les Houches 2009 !