Automation of NLO computations using the FKS subtraction method

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in collaboration with

Stefano Frixione, Fabio Maltoni & Tim Stelzer

JHEP **0910** (2009) 003 [arXiv:0908.4272 [hep-ph]]

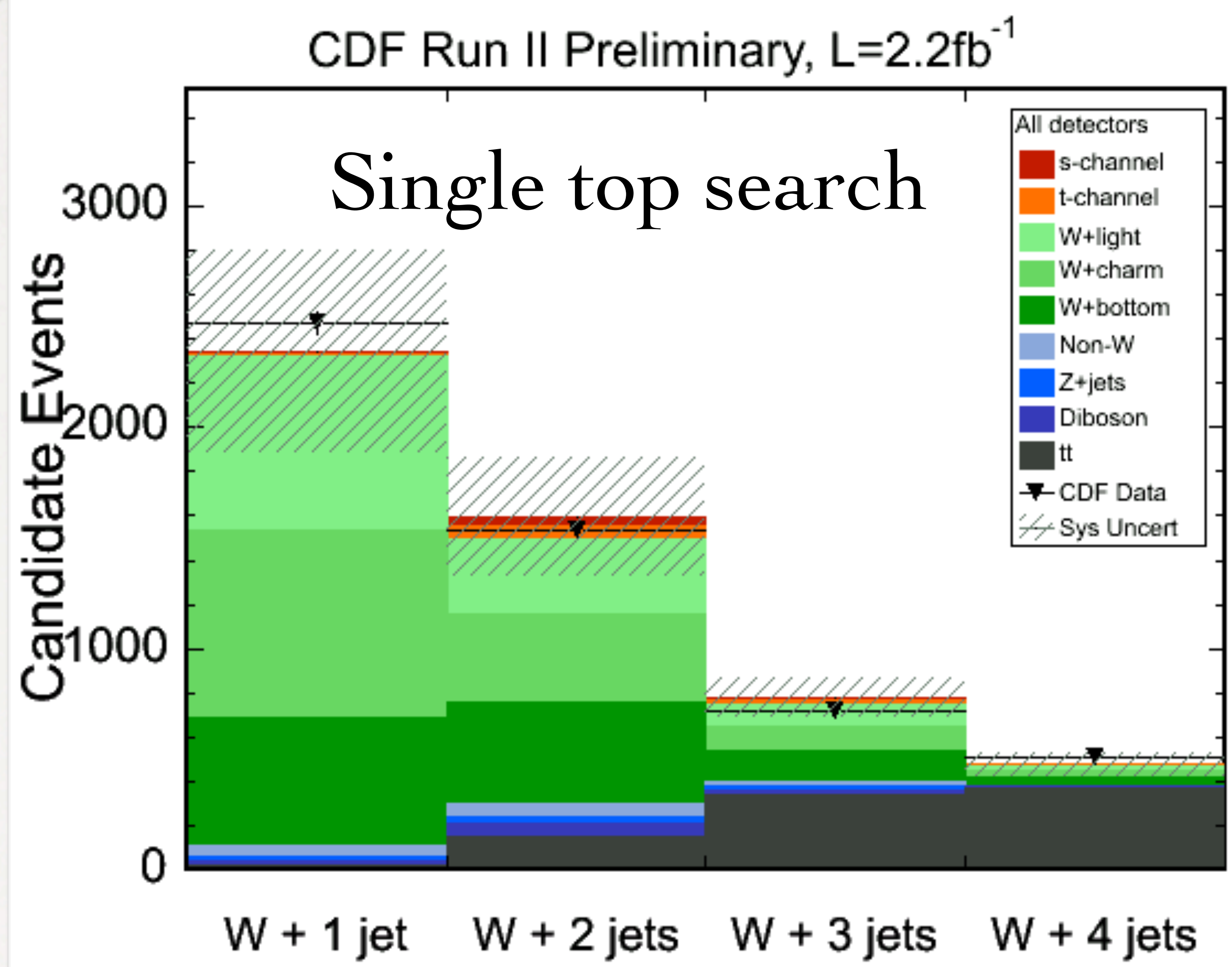
PSI, Villigen, April 15, 2010

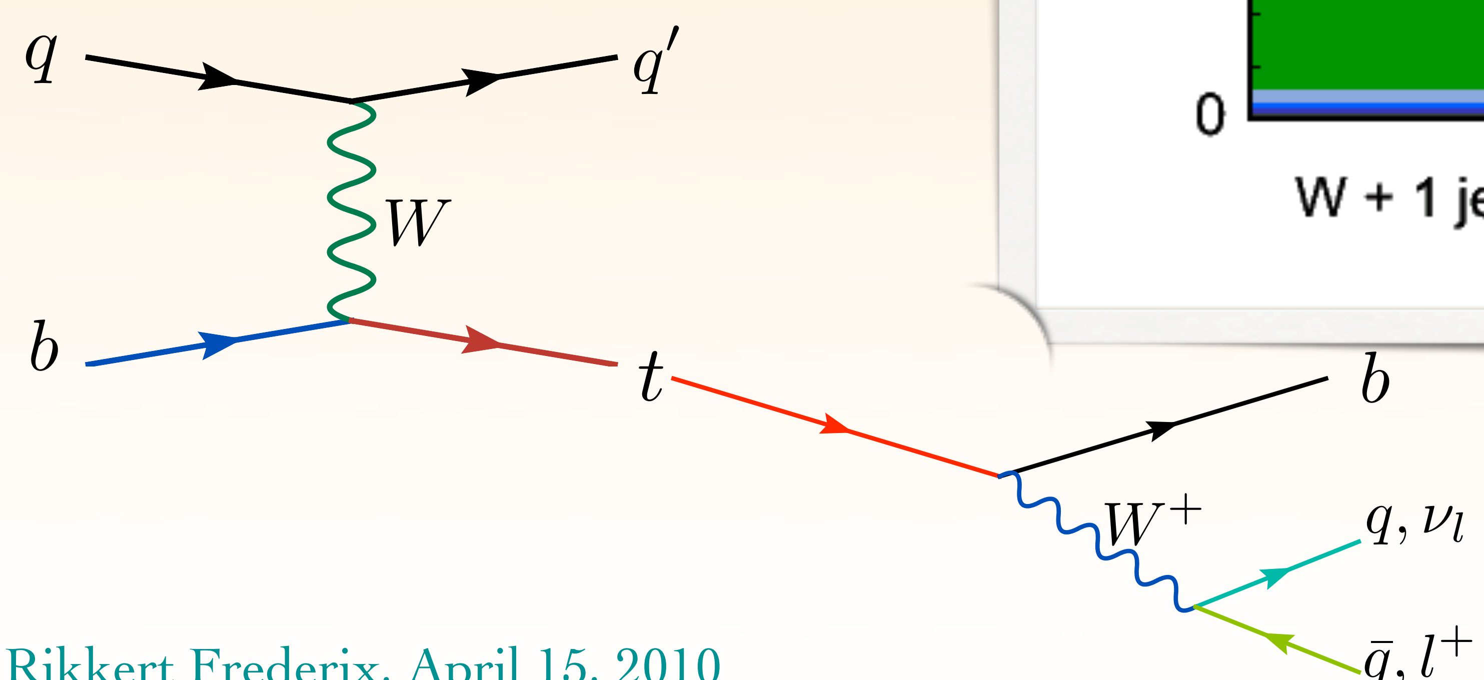
Contents

- Motivation
  - Example in single top production
- The FKS subtraction
  - Automated in MadFKS
- Some results for MadFKS standalone (i.e. without virtual corrections)
- Results in collaboration with BlackHat and Rocket: e^+e^- -> 2, 3, 4 and 5 jets at NLO

Why NLO?

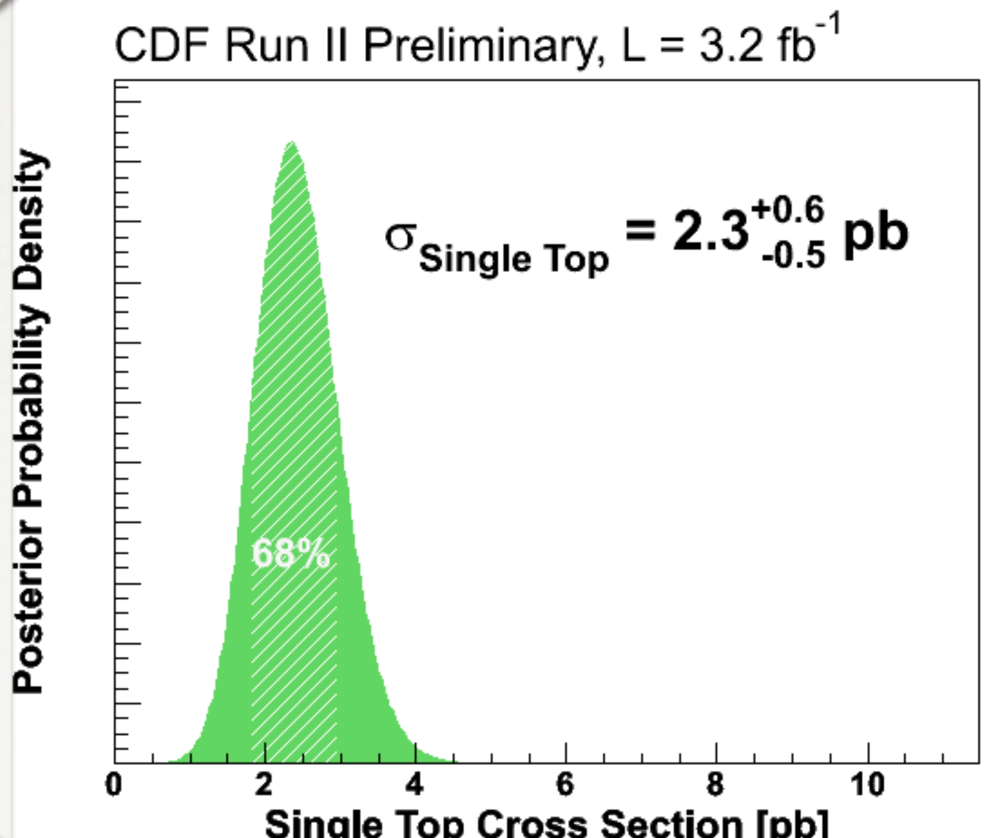
- Theoretical predictions are crucial in the search for signals events in large backgrounds samples





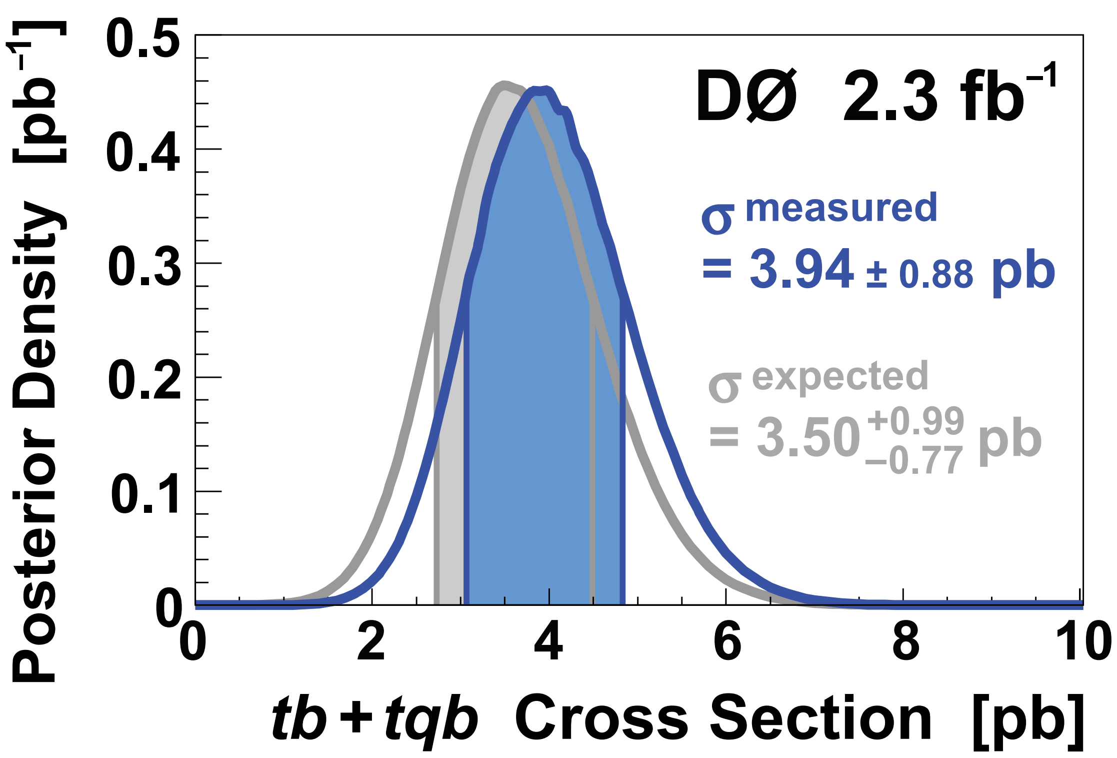
Observation at the Tevatron!

- CDF
  m_t=175 GeV



arXiv: 0903.0885

- DØ
  m_t=170 GeV

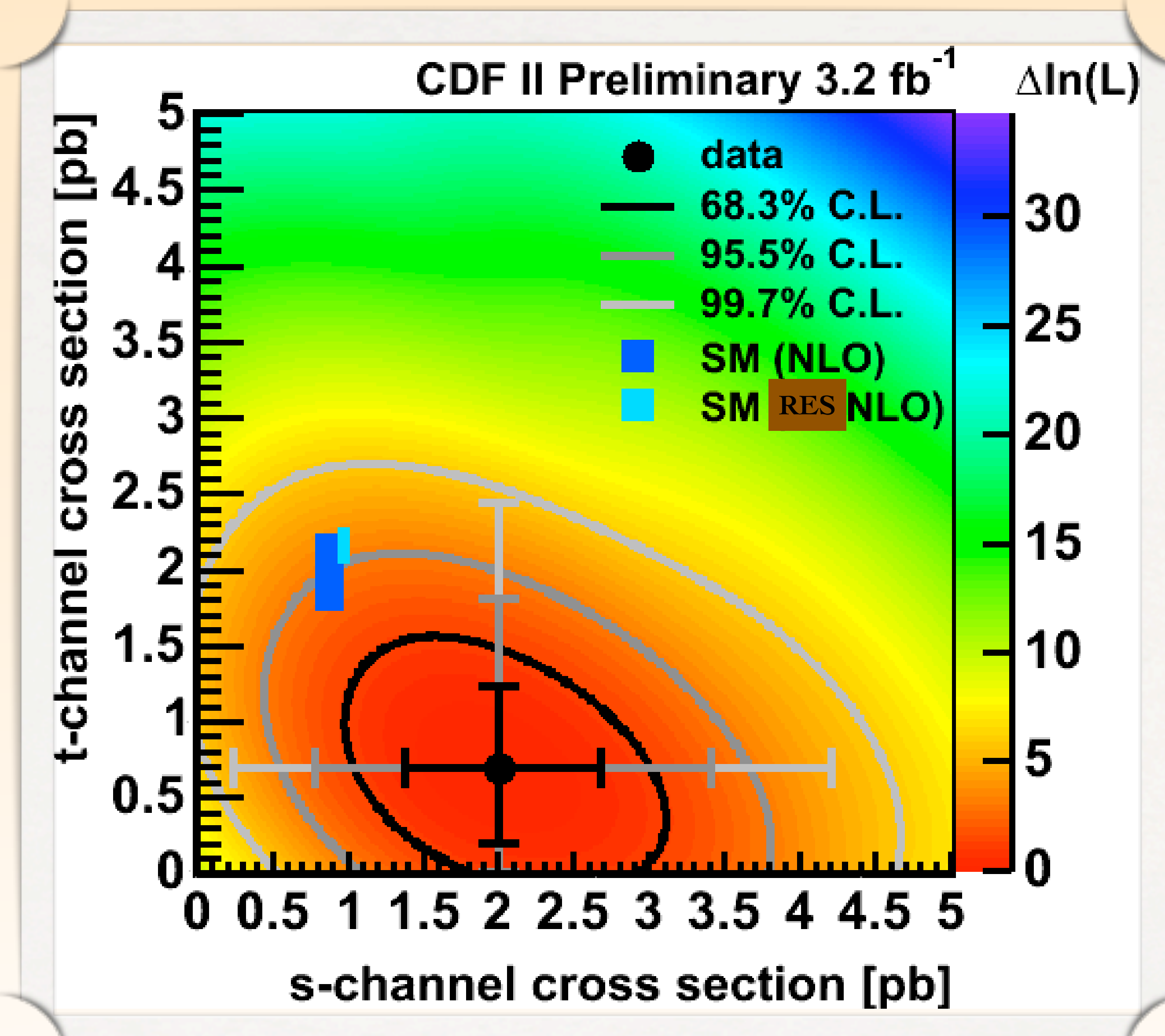


arXiv: 0903.0850

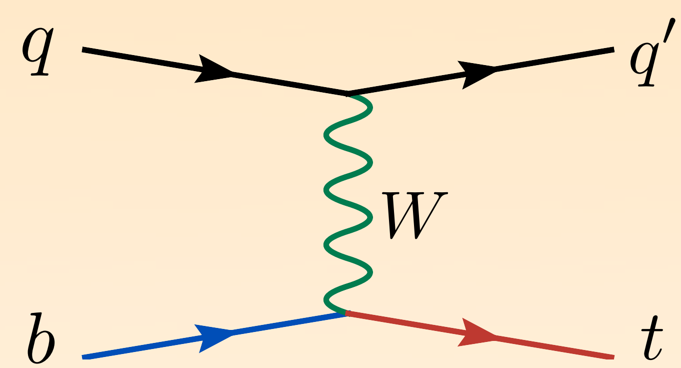
Reliable predictions are crucial!

(March 4, 2009)

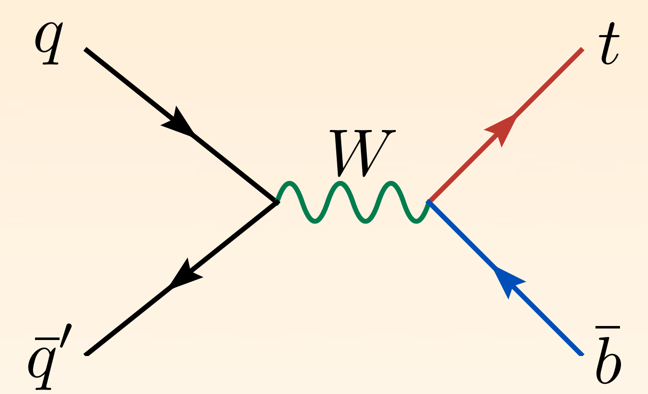
DISCREPANCY?



CDF note 9716



t-channel



s-channel

- New Physics?
- Statistical fluctuation?
- Mistake in the (theoretical) predictions?

NLO corrections

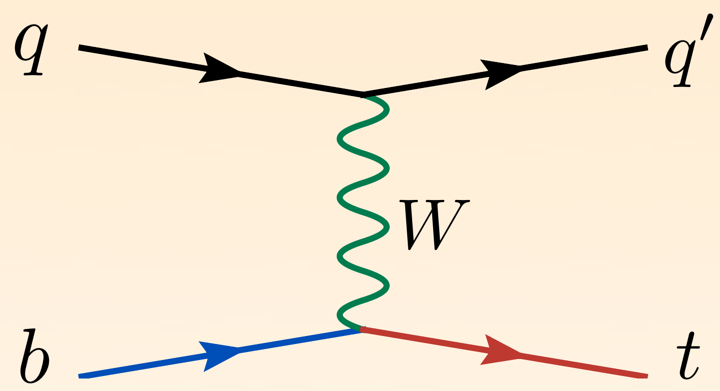
- NLO (in QCD) corrections are needed for a good theoretical understanding of processes at (hadron) colliders
- They improve the theory predictions for
  - Absolute normalization; corrections can be very large
  - Reduce the renormalization scale dependence
  - Shapes of distributions

W+n jets	LO	NLO
n=1	16%	7%
n=2	30%	10%
n=3	42%	12%

Table by Daniel Maitre

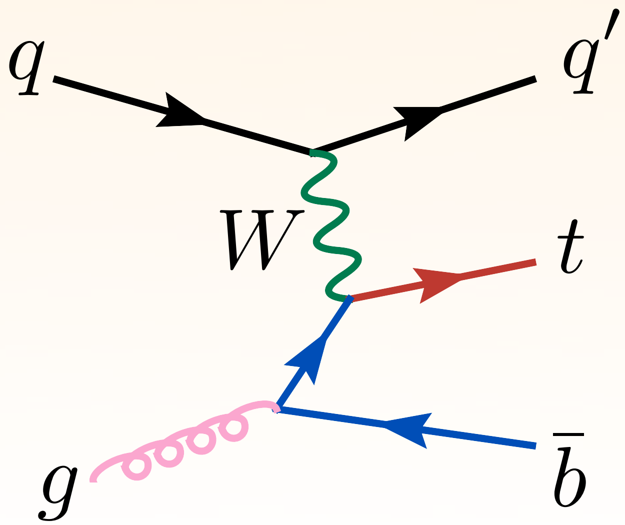
T-CHANNEL SINGLE TOP

- t-channel single top production has a (heavy) bottom quark in the initial state



“2 → 2”

- There is an equivalent description with a gluon splitting to a bottom quark pair



“2 → 3”

T-CHANNEL SINGLE TOP

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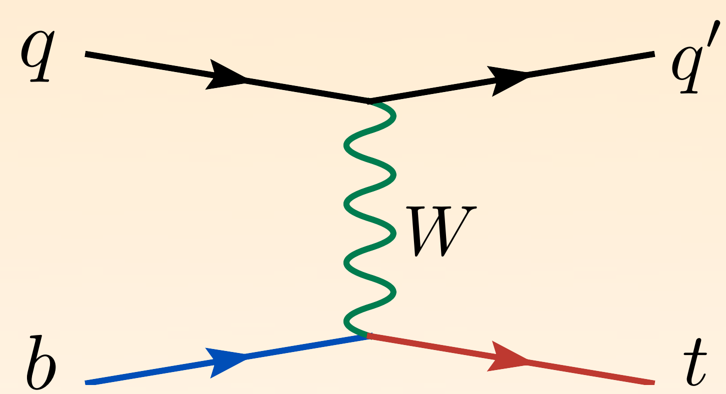

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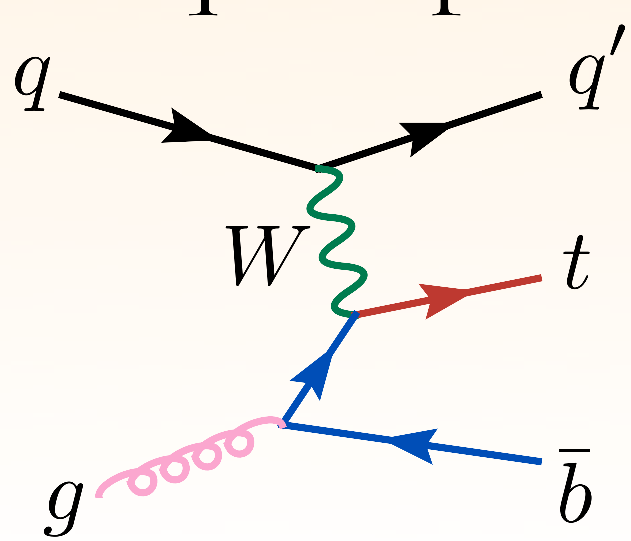
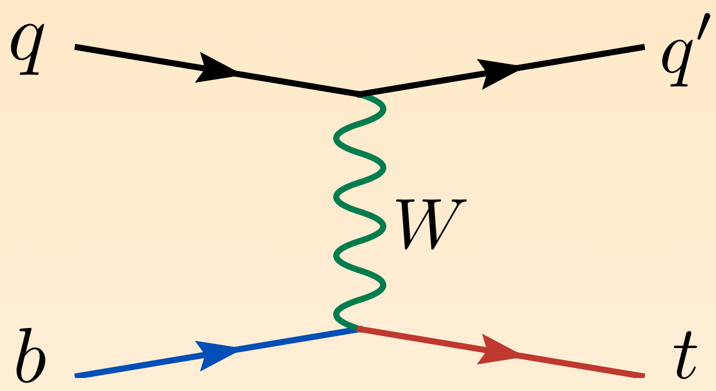
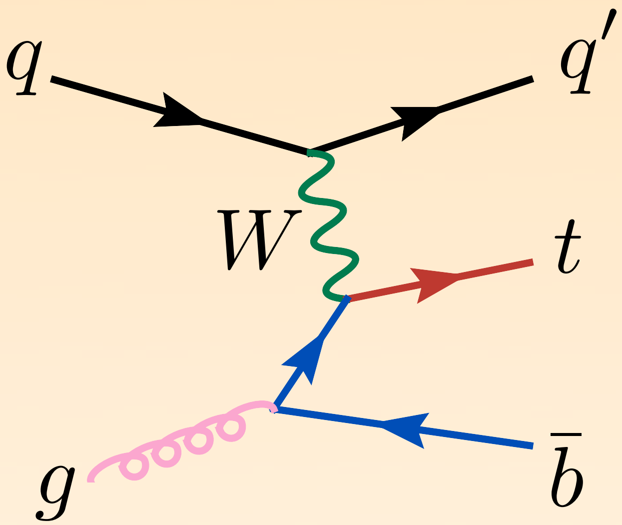


"2 → 3"

"spectator bottom quark"

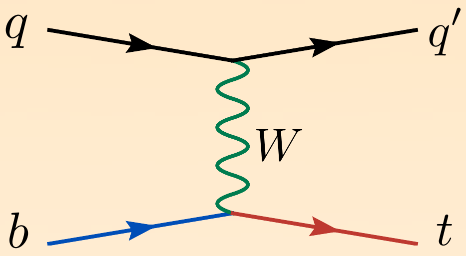
Which is 'better'?





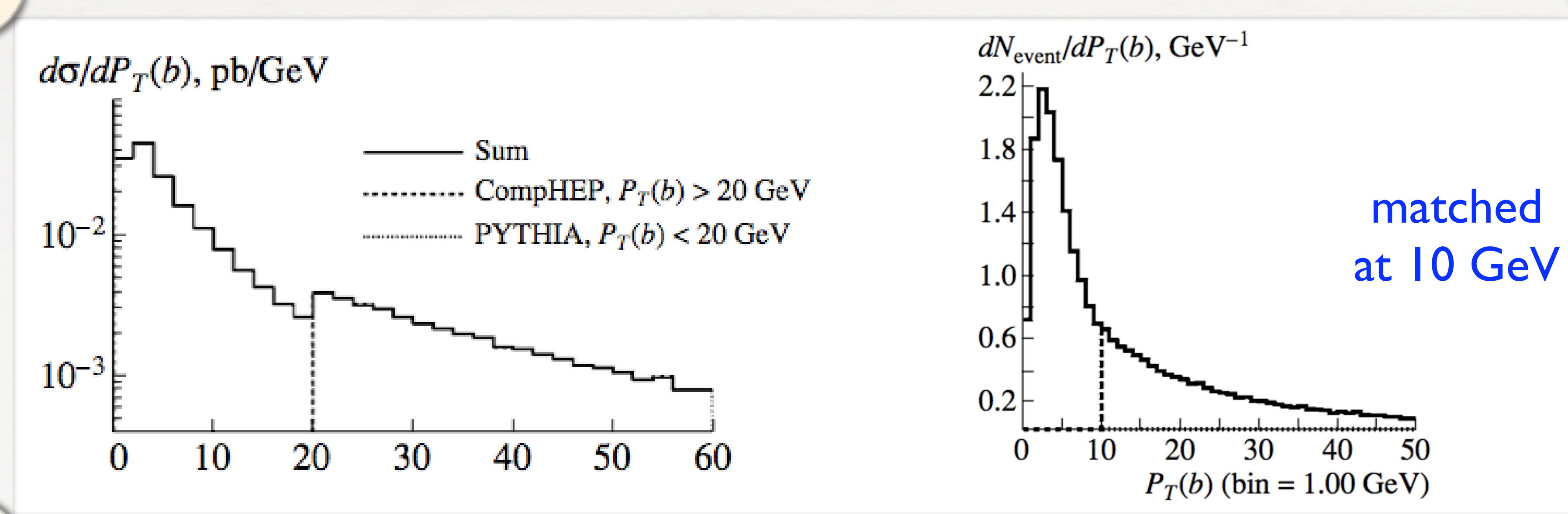
- Equivalent at all orders, but differences arise when perturbative series is truncated
- Differences at fixed order are due to large logarithms associated to spectator b quark: resummed in PDF for $2 \to 2$, but explicit (including other non-log contributions) in $2 \to 3$
  - Uses $2 \to 2$ when interested in total rate, use $2 \to 3$ when spectator b quark is important.

Need for matching in the 5F ($2 \to 2$) approach



- At LO, no final state b quark
- At NLO, effects related to the spectator b only enter at this order and not well described by corresponding MC implementations
- "Effective NLO approximation": separate regions according to $p_T(b)$ and use (N)LO 5F ($2 \to 2$)+ shower below and LO 4F ($2 \to 3$) above

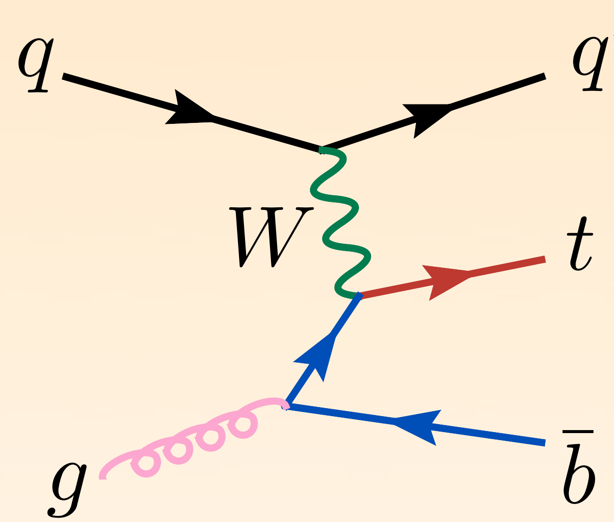
Boos et al., Phys. At. Nucl. 69, 1317 (2006)



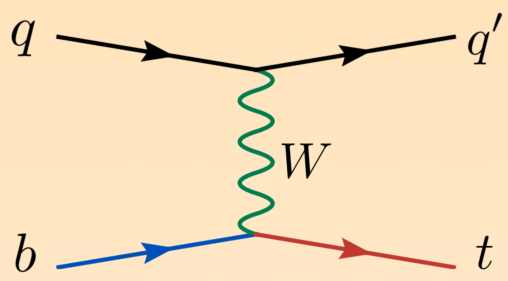
- Ad hoc matching well motivated, but theoretically unappealing

Four-flavor scheme

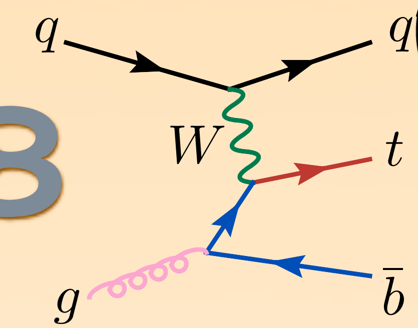
- Use the 4-flavor ($2 \to 3$) process as the Born and calculate NLO
  - Much harder calculation due to extra mass and extra parton
  - Spectator b for the first time at NLO
  - Compare to 5F ($2 \to 2$) to asses logarithms and applicability



Campbell, RF, Maltoni & Tramontano
PRL **102** (2009) 182003 [arXiv:0903.0005 [hep-ph]];
JHEP **0910** (2009) 042 [arXiv:0907.3933 [hep-ph]]



2 → 2 vs 2 → 3



- The NLO calculations are in agreement for the total rate:

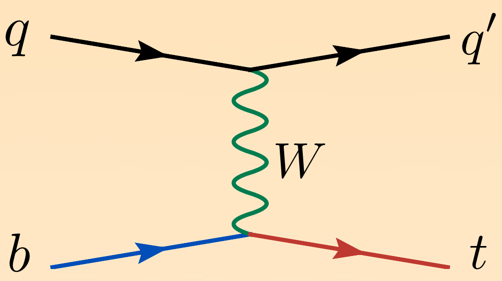
$\sigma^{\rm NLO}_{\rm t-ch}(t+\bar{t})$	$2 \to 2$ (pb)					$2 \to 3$ (pb)				
Tevatron Run II	1.96	$^{+0.05}_{-0.01}$	$^{+0.20}_{-0.16}$	$^{+0.06}_{-0.06}$	$^{+0.05}_{-0.05}$	1.87	$^{+0.16}_{-0.21}$	$^{+0.18}_{-0.15}$	$^{+0.06}_{-0.06}$	$^{+0.04}_{-0.04}$
LHC (10 TeV)	130	$^{+2}_{-2}$	$^{+3}_{-3}$	$^{+2}_{-2}$	$^{+2}_{-2}$	124	$^{+4}_{-5}$	$^{+2}_{-3}$	$^{+2}_{-2}$	$^{+2}_{-2}$
LHC (14 TeV)	244	$^{+5}_{-4}$	$^{+5}_{-6}$	$^{+3}_{-3}$	$^{+4}_{-4}$	234	$^{+7}_{-9}$	$^{+5}_{-5}$	$^{+3}_{-3}$	$^{+4}_{-4}$

Fac. & Ren. scale

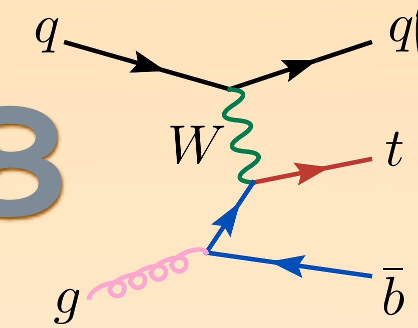
PDF

top mass

b mass



2 → 2 vs 2 → 3



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$\sigma^{\rm NLO}_{\rm t-ch}(t+\bar{t})$	$2\to 2$ (pb)	$2 \to 3$ (pb)
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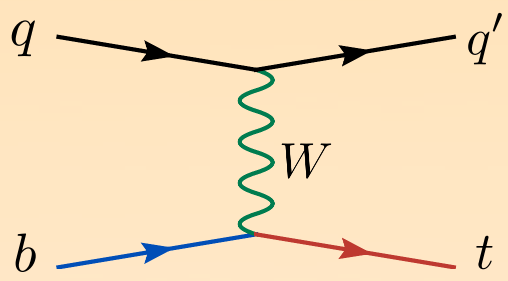
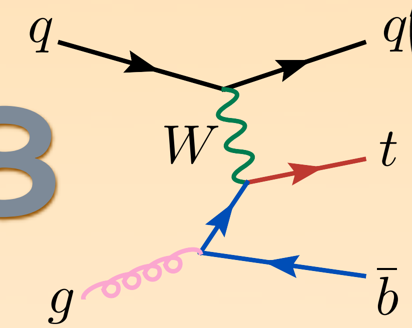
LHC (10 TeV)	$130\;^{+2}_{-2}\;^{+3}_{-3}\;^{+2}_{-2}\;^{+2}_{-2}$	$124\;^{+4}_{-5}\;^{+2}_{-3}\;^{+2}_{-2}\;^{+2}_{-2}$
LHC (14 TeV)	$244\;^{+5}_{-4}\;^{+5}_{-6}\;^{+3}_{-3}\;^{+4}_{-4}$	$234\;^{+7}_{-9}\;^{+5}_{-5}\;^{+3}_{-3}\;^{+4}_{-4}$

- Already at NLO the two schemes are in agreement
  - Also distributions for top and light jet are very similar
- 2 → 3 contains much more ‘information’...



2 → 2 vs 2 → 3



- ... however the acceptance of the spectator bottom quark changes significantly:

Effectively LO →

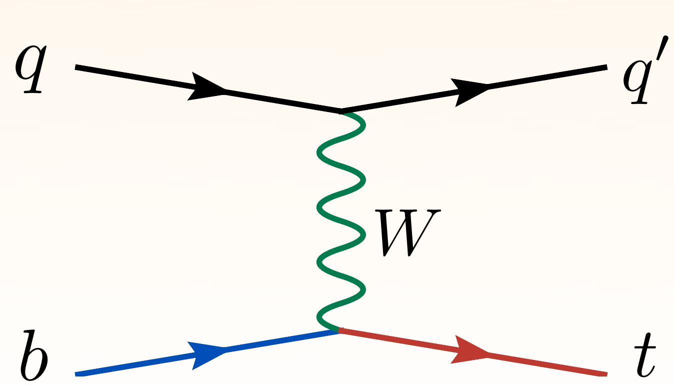
Calculation	Acceptance
2 → 2 "@ NLO"	19.7 + 7.1 - 4.5 %
2 → 3 @ NLO	29.9 + 1.0 - 2.0 %
CDF (as input)	17.6%
DØ (as input)	31.6%

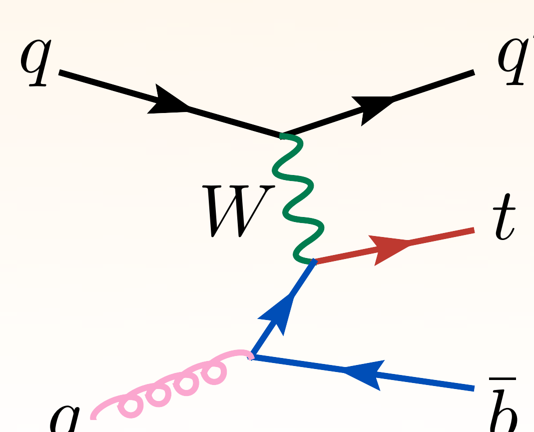
"Acceptance" is defined as the ratio of events with a hard central spectator b quark over the inclusive cross section:

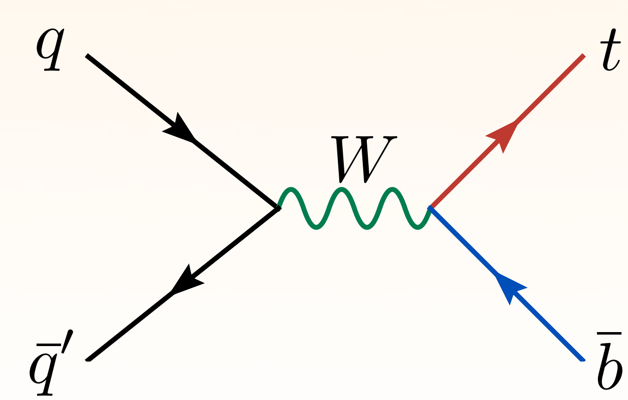
$$\frac{\sigma(|\eta(b)| < 2.5,\ p_T(b) > 20\ \text{GeV})}{\sigma_{\text{inclusive}}}$$

Consequences for single top observation?

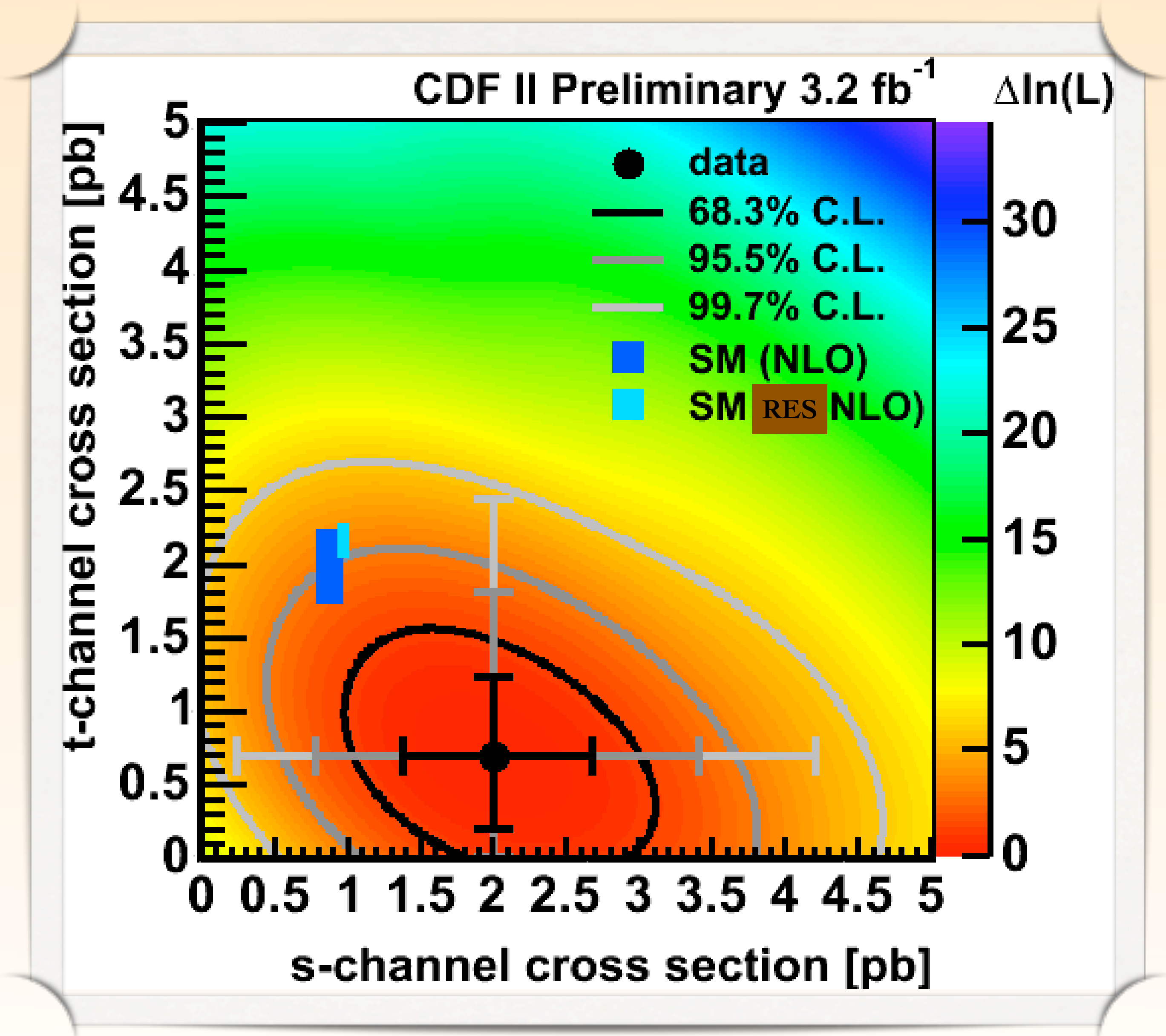
- Difficult to say a priori...
- Naively:
  - No change in total cross section (s + t channel)
  - Measured t channel goes up, s channel goes down
    - More events that were considered s channel before are in fact t channel, because more t channel events have also a spectator b quark







S AND T CHANNEL SEPARATION AT CDF



CDF note 9716

- This explains (part of) this 2 sigma deviation
- We are in contact with CDF single top group to address this issue

Why automate?

- To save time

  NLO calculations can take a long time. It would be nice to spend this time doing phenomenology instead.

- To reduce the number of bugs in the calculation

  Having a code that does everything automatically will be without* bugs once the internal algorithms have been checked properly.

- To have all processes within one framework

  To learn how to use a new code for each process is not something all our (experimental) colleagues are willing to do.

The NLO contributions

$$\sigma^{\mathrm{NLO}} = \int_{m+1} \mathsf{d}^{(d)}\sigma^{R} + \int_{m} \mathsf{d}^{(d)}\sigma^{V} + \int_{m} \mathsf{d}^{(4)}\sigma^{B}$$

‘Real emission’
NLO corrections

‘Virtual’ or ‘one-loop’
NLO corrections

‘Born’ or ‘LO’
contribution

Automation of virtual corrections

- BlackHat
  Berger, Bern, Dixon, Febres Cordero, Forde, Ita, Kosower & Maitre
- Rocket
  Ellis, Melnikov, Schulze & Zanderighi
- Cuttools (in Helac-1Loop)
  Ossola, Papadopoulos & Pittau (& Van Hameren)
- Golem
  Binoth, Guffanti, Guillet, Heinrich, Karg, Kauer, Pilon, Reiter & Sanguinetti
- and many others...
  Lazopoulous, Kilian, Kleinschmidt, Winter, Kunszt, Giele, Denner, Dittmaier...

IR divergence (of the real emission)

$$\sigma^{\text{NLO}} = \int_{m+1} \mathsf{d}^{(d)}\sigma^R + \int_m \mathsf{d}^{(d)}\sigma^V + \int_m \mathsf{d}^{(4)}\sigma^B$$

- Real emission -> IR divergent
- (UV-renormalized) virtual corrections -> IR divergent
  - After integration, the sum of all contributions is finite (for infrared-safe observables)
  - To see this cancellation the integration is done in a non-integer number of dimensions: Not possible with a Monte-Carlo integration

Subtraction terms

$$\sigma^{\mathrm{NLO}} = \int_{m+1} \mathsf{d}^{(d)}\sigma^R + \int_m \mathsf{d}^{(d)}\sigma^V + \int_m \mathsf{d}^{(4)}\sigma^B$$

Subtraction terms

$$\sigma^{\rm NLO} = \int_{m+1} \mathsf{d}^{(d)}\sigma^R + \int_m \mathsf{d}^{(d)}\sigma^V + \int_m \mathsf{d}^{(4)}\sigma^B$$

⇓

$$\sigma^{\rm NLO} = \int_{m+1} \left[d^{(4)}\sigma^R - d^{(4)}\sigma^A\right] + \int_m \left[d^{(4)}\sigma^B + \int_{\rm loop} d^{(d)}\sigma^V + \int_1 d^{(d)}\sigma^A\right]_{\epsilon=0}$$

- Include subtraction terms to make real emission and virtual contributions separately finite

- All can be integrated numerically

Automation of subtraction schemes

- Catani-Seymour dipole subtraction *Catani & Seymour 1997; Catani, Dittmaier, Seymour & Trocsanyi 2002.*
  - implemented by various groups *Seymour & Tevlin; RF, Gehrmann & Greiner; Hasegawa, Moch & Uwer; Gleisberg & Krauss; Czakon, Papadopoulos & Worek*
- Nagy-Soper dipoles *Nagy & Soper 2007;*
  - implementation in progress *Robens & Chung.*
- FKS subtraction *Frixione, Kunzst & Signer 1996.*
  - implemented in MadFKS *RF, Frixione, Maltoni & Stelzer* and the POWHEG BOX *Alioli, Nason, Oleari & Re.*
- No automation available for other methods (such as Antenna subtraction)

FKS subtraction

- FKS subtraction: Frixione, Kunszt & Signer 1996. Standard subtraction method in MC@NLO and POWHEG, but can also be used for 'normal' NLO computations
- Also known as "residue subtraction"
- Based on using plus-distributions to regulate the infrared divergences of the real emission matrix elements

FKS for beginners

- Easiest to understand by starting from real emission:

$$d\sigma^R = |M^{n+1}|^2 d\phi_{n+1}$$

- $|M^{n+1}|^2$ blows up like $\frac{1}{\xi_i^2}\frac{1}{1-y_{ij}}$ with $\begin{array}{l} \xi_i = E_i/\sqrt{\hat{s}} \\ y_{ij} = \cos\theta_{ij} \end{array}$
- Partition the phase space in such a way that each partition has at most one soft and one collinear singularity

$$d\sigma^R = \sum_{ij} S_{ij} |M^{n+1}|^2 d\phi_{n+1} \qquad \sum_{ij} S_{ij} = 1$$

- Use plus distributions to regulate the singularities

$$d\tilde{\sigma}^R = \sum_{ij} \left(\frac{1}{\xi_i}\right)_+ \left(\frac{1}{1-y_{ij}}\right)_+ \xi_i (1-y_{ij}) S_{ij} |M^{n+1}|^2 d\phi_{n+1}$$

FKS FOR BEGINNERS

$$d\tilde{\sigma}^R = \sum_{ij} \left(\frac{1}{\xi_i}\right)_+ \left(\frac{1}{1-y_{ij}}\right)_+ \xi_i (1-y_{ij}) S_{ij} |M^{n+1}|^2 d\phi_{n+1}$$

- Definition plus distribution

$$\int d\xi \left(\frac{1}{\xi}\right)_+ f(\xi) = \int d\xi \, \frac{f(\xi)-f(0)}{\xi}$$

- One event has maximally three counter events:
  - Soft: $\xi_i \to 0$
  - Collinear: $y_{ij} \to 1$
  - Soft-collinear: $\xi_i \to 0 \qquad y_{ij} \to 1$

FKS for beginners

$$d\tilde{\sigma}^R = \sum_{ij} \left(\frac{1}{\xi_i}\right)_{\xi_{cut}} \left(\frac{1}{1-y_{ij}}\right)_{\delta_O} \xi_i (1-y_{ij}) S_{ij} |M^{n+1}|^2 d\phi_{n+1}$$

- Definition plus distribution

$$\int d\xi \left(\frac{1}{\xi}\right)_{\xi_{cut}} f(\xi) = \int d\xi \, \frac{f(\xi) - f(0)\Theta(\xi_{cut} - \xi)}{\xi}$$

- One event has maximally three counter events:
  - Soft: $\xi_i \to 0$
  - Collinear: $y_{ij} \to 1$
  - Soft-collinear: $\xi_i \to 0 \quad y_{ij} \to 1$

Subtraction terms

$$\sigma^{\rm NLO} = \int_{m+1} \left[d^{(4)}\sigma^R - d^{(4)}\sigma^A \right] + \int_m \left[d^{(4)}\sigma^B + \int_{\rm loop} d^{(d)}\sigma^V + \int_1 d^{(d)}\sigma^A \right]_{\epsilon=0}$$

- This defines the subtraction terms for the reals
- They need to be integrated over the one-parton phase space (analytically) and added to the virtual corrections
    - these are process-independent terms proportional to the (color-linked) Borns
- All formulae can be found in the MadFKS paper, arXiv:0908.4247

MadFKS

- Automatic FKS subtraction within the MadGraph/ MadEvent framework
- Given the (n+1) process, it generates the real, all the subtraction terms and the Born processes
- For a NLO computation, only the finite parts of the virtual corrections are needed from the user
- Phase-space integration deals with the (n) and (n+1) body processes at the same time, or separately
- Phase-space generation for the (n)-body is the same as in standard MG. It has been heavily adapted to generate (n+1)-body emission events at the same time

MadFKS

- Color-linked Borns generated by MadDipole

  RF, Gehrmann & Greiner

- Any physics model: massive particles have only soft singularities, which are spin independent: MadFKS works also for BSM physics, e.g. squarks, gluinos
- Interface to link with the virtual corrections following the proposal for the Binoth-Les Houches Accord
  - Standardized way to link to other virtual corrections

Optimization

- Each phase space partition can be run completely independently of all the others -> genuine parallelization
- MadFKS uses the symmetry of the matrix elements to reduce the number of phase space partitions:
  - adding multiple gluons does not increase the complexity of the subtraction structure
- Within each phase space partition: usual MadGraph 'Single diagram enhanced multi-channel' phase space integration, using the Born diagrams
- Born amplitudes are computed only once for each event, and used for the Born and collinear, soft and soft-collinear (integrated) counter events and for the multi-channel enhancement

δ_O	$a_S = b_S$	$\xi_{cut} = \xi_{\max}$	$\xi_{cut} = 0.3$	$\xi_{cut} = 0.1$	$\xi_{cut} = 0.01$
		useenergy=.true.			
2	1.0	3.5988 ± 0.0146	3.6173 ± 0.0122	3.6190 ± 0.0140	3.6126 ± 0.0141
	1.5	3.6085 ± 0.0126	3.5942 ± 0.0143	3.5956 ± 0.0115	3.5989 ± 0.0133
	2.0	3.6127 ± 0.0121	3.6122 ± 0.0158	3.6020 ± 0.0147	3.5956 ± 0.0144
0.6	1.0	3.6196 ± 0.0142	3.6012 ± 0.0139	3.5888 ± 0.0142	3.5833 ± 0.0130
	1.5	3.5941 ± 0.0123	3.6012 ± 0.0139	3.6009 ± 0.0138	3.6047 ± 0.0114
	2.0	3.6066 ± 0.0120	3.6111 ± 0.0117	3.6053 ± 0.0110	3.5950 ± 0.0150
0.2	1.0	3.6350 ± 0.0151	3.5927 ± 0.0145	3.5813 ± 0.0128	3.5811 ± 0.0146
	1.5	3.6020 ± 0.0119	3.6086 ± 0.0133	3.6104 ± 0.0127	3.5993 ± 0.0119
	2.0	3.5815 ± 0.0140	3.5966 ± 0.0136	3.5938 ± 0.0121	3.6079 ± 0.0125
0.06	1.0	3.6053 ± 0.0202	3.5998 ± 0.0181	3.5988 ± 0.0122	3.6088 ± 0.0165
	1.5	3.6144 ± 0.0161	3.5986 ± 0.0140	3.5847 ± 0.0119	3.5884 ± 0.0126
	2.0	3.5990 ± 0.0166	3.6016 ± 0.0158	3.6014 ± 0.0147	3.6191 ± 0.0133
		useenergy=.false.			
2	1.0	3.6078 ± 0.0164	3.6149 ± 0.0162	3.6145 ± 0.0158	3.6085 ± 0.0140
	1.5	3.5695 ± 0.0156	3.5841 ± 0.0180	3.5975 ± 0.0165	3.5986 ± 0.0142
	2.0	3.5921 ± 0.0125	3.6260 ± 0.0211	3.6034 ± 0.0134	3.6007 ± 0.0149
0.6	1.0	3.5891 ± 0.0199	3.5786 ± 0.0164	3.6084 ± 0.0232	3.5956 ± 0.0151
	1.5	3.6083 ± 0.0152	3.5944 ± 0.0136	3.6040 ± 0.0123	3.6018 ± 0.0147
	2.0	3.5838 ± 0.0141	3.5633 ± 0.0154	3.5964 ± 0.0129	3.5920 ± 0.0158
0.2	1.0	3.5976 ± 0.0171	3.5790 ± 0.0166	3.5702 ± 0.0155	3.6155 ± 0.0132
	1.5	3.5804 ± 0.0163	3.5925 ± 0.0136	3.6012 ± 0.0137	3.6091 ± 0.0138
	2.0	3.5978 ± 0.0148	3.5749 ± 0.0144	3.5825 ± 0.0128	3.5902 ± 0.0145
0.06	1.0	3.6122 ± 0.0170	3.5942 ± 0.0158	3.5743 ± 0.0146	3.5962 ± 0.0167
	1.5	3.6064 ± 0.0198	3.5977 ± 0.0136	3.6047 ± 0.0115	3.5886 ± 0.0123
	2.0	3.5971 ± 0.0169	3.6018 ± 0.0136	3.5991 ± 0.0148	3.6040 ± 0.0148

Table 1: Cross section (in pb) and Monte Carlo integration errors for the $(n+1)$-body process $e^+e^- \to Z \to u\bar{u}ggg$. See the text for details.

- Our 'benchmark process': e^+e^- -> Z -> uubar ggg
- Results are independent of internal (non-physical) parameters
- Also the integration uncertainty is independent of the choice for the internal parameters
- run-time: 1-4 minutes for each integration channel

δ_O	$a_S = b_S$	$\xi_{cut} = \xi_{\max}$	$\xi_{cut} = 0.3$	$\xi_{cut} = 0.1$	$\xi_{cut} = 0.01$
		useenergy=.true.			
	1.0	3.5988 ± 0.0146	3.6173 ± 0.0122	3.6190 ± 0.0140	3.6126 ± 0.0141
2	1.5	[illegible]	[illegible]	[illegible]	[illegible]
	2.0	[illegible]	[illegible]	[illegible]	[illegible]
	1.0	3.6196 ± 0.0142	3.6012 ± 0.0139	3.5888 ± 0.0142	3.5833 ± 0.0130
0.6	1.5	3.5941 ± 0.0123	3.6012 ± 0.0139	3.6009 ± 0.0138	3.6047 ± 0.0114
	2.0	[illegible]	3.6111 ± 0.0117	3.6053 ± 0.0110	3.5950 ± 0.0150
	1.0	3.6350 ± 0.0151	3.5927 ± 0.0145	3.5813 ± 0.0128	3.5811 ± 0.0146
0.2	1.5	3.6020 ± 0.0119	[illegible]	[illegible]	3.5993 ± 0.0119
	2.0	3.5815 ± 0.0140	[illegible]	[illegible]	3.6079 ± 0.0125
	1.0	3.6053 ± 0.0202	[illegible]	[illegible]	3.6088 ± 0.0165
0.06	1.5	3.6144 ± 0.0161	[illegible]	[illegible]	3.5884 ± 0.0126
	2.0	3.5990 ± 0.0166	3.6016 ± 0.0158	3.6014 ± 0.0147	3.6191 ± 0.0133
		useenergy=.false.			
	1.0	3.6078 ± 0.0164	3.6149 ± 0.0162	3.6145 ± 0.0158	3.6085 ± 0.0140
2	1.5	3.5695 ± 0.0156	3.5841 ± 0.0180	3.5975 ± 0.0165	3.5986 ± 0.0142
	2.0	3.5921 ± 0.0125	3.6260 ± 0.0211	3.6034 ± 0.0134	3.6007 ± 0.0149
	1.0	3.5891 ± 0.0199	3.5786 ± 0.0164	3.6084 ± 0.0232	3.5956 ± 0.0151
0.6	1.5	3.6083 ± 0.0152	3.5944 ± 0.0136	3.6040 ± 0.0123	3.6018 ± 0.0147
	2.0	3.5838 ± 0.0141	3.5633 ± 0.0154	3.5964 ± 0.0129	3.5920 ± 0.0158
	1.0	3.5976 ± 0.0171	[illegible]	[illegible]	[illegible]
0.2	1.5	3.5804 ± 0.0163	3.5925 ± 0.0136	[illegible]	[illegible]
	2.0	3.5978 ± 0.0148	3.5749 ± 0.0144	[illegible]	[illegible]
	1.0	3.6122 ± 0.0170	3.5942 ± 0.0158	[illegible]	[illegible]
0.06	1.5	3.6064 ± 0.0198	3.5977 ± 0.0136	3.6047 ± 0.0115	3.5886 ± 0.0123
	2.0	3.5971 ± 0.0169	3.6018 ± 0.0136	3.5991 ± 0.0148	3.6040 ± 0.0148

Table 1: Cross section (in pb) and Monte Carlo integration errors for the $(n+1)$-body process $e^+e^- \to Z \to u\bar{u}ggg$. See the text for details.

Six-fold increase of the statistics:

3.6007 ± 0.0053

3.6086 ± 0.0051

- Our 'benchmark process': e+e- -> Z -> uubar ggg
- Results are independent of internal (non-physical) parameters
- Also the integration uncertainty is independent of the choice for the internal parameters
- run-time: 1-4 minutes for each integration channel

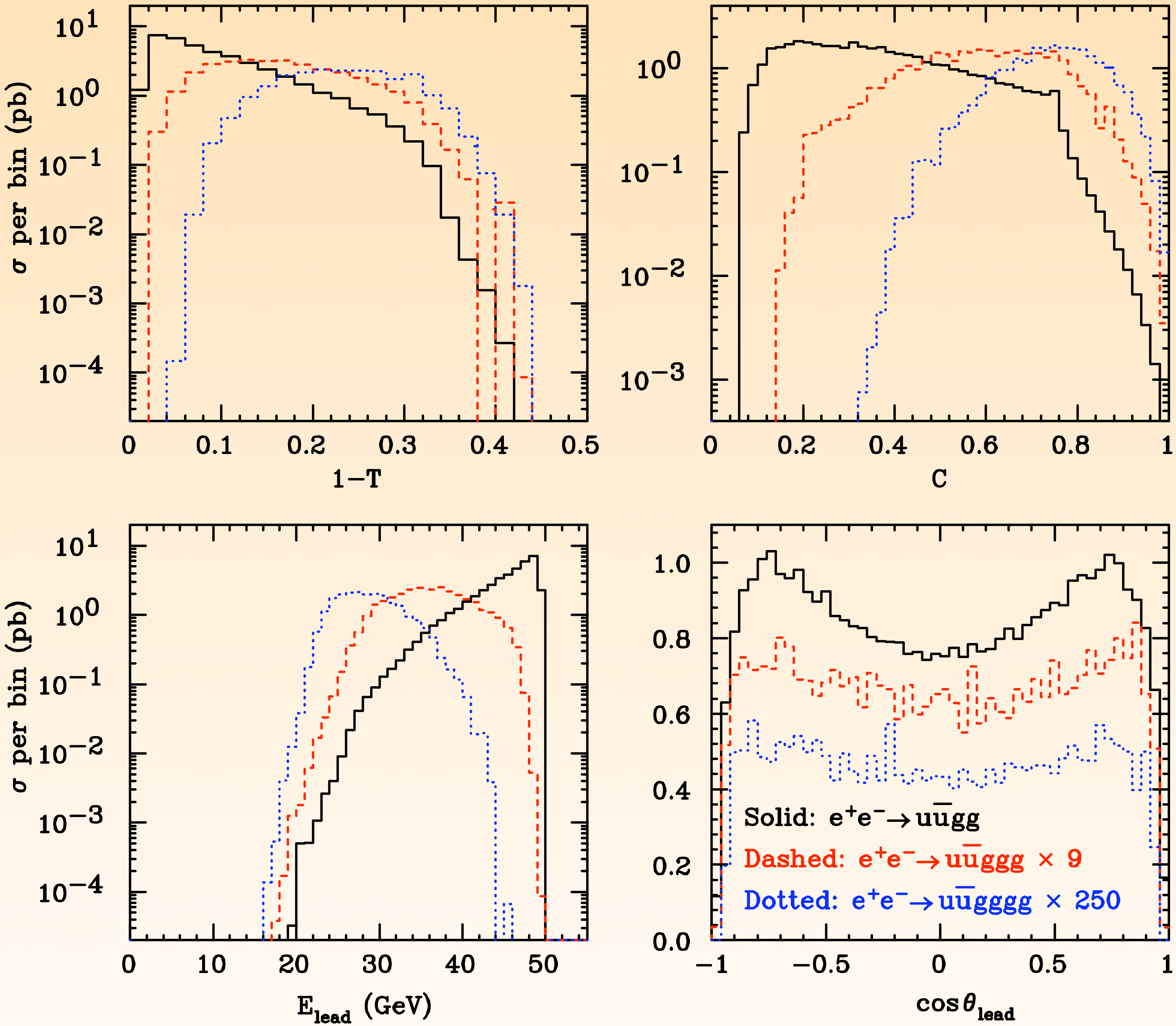
$(n+1)$-body process	cross section	$\overline{N}_{\rm FKS}$	iterations $\times$ points	$N_{\rm ch}$	ϵ
$e^+e^- \to Z \to u\bar{u}gg$	$(0.4144 \pm 0.0006\ (0.15\%))\times 10^2$	3	10×50k	6	0.536
$e^+e^- \to Z \to u\bar{u}ggg$	$(0.3601 \pm 0.0014\ (0.38\%))\times 10^1$	3	10×50k	18	0.167
$e^+e^- \to Z \to u\bar{u}gggg$	$(0.8869 \pm 0.0054\ (0.61\%))\times 10^{-1}$	3	10×350k	52	0.031
$e^+e^- \to \gamma^*/Z \to jjjj$	$(0.1801 \pm 0.0002\ (0.12\%))\times 10^3$	14	10×50k	56	0.520
$e^+e^- \to \gamma^*/Z \to jjjjj$	$(0.1529 \pm 0.0004\ (0.26\%))\times 10^2$	30	10×50k	328	0.171
$e^+e^- \to \gamma^*/Z \to jjjjjj$	$(0.3954 \pm 0.0015\ (0.38\%))\times 10^0$	55	10×350k	2450	0.033
$e^+e^- \to Z \to t\bar{t}gg$	$(0.1219 \pm 0.0003\ (0.24\%))\times 10^{-1}$	3	10×10k	6	0.899
$e^+e^- \to Z \to t\bar{t}ggg$	$(0.1521 \pm 0.0013\ (0.83\%))\times 10^{-2}$	3	10×10k	18	0.708
$e^+e^- \to Z \to t\bar{t}gggg$	$(0.1108 \pm 0.0031\ (2.76\%))\times 10^{-3}$	3	10×20k	52	0.427
$e^+e^- \to Z \to t\bar{t}b\bar{b}g$	$(0.1972 \pm 0.0024\ (1.23\%))\times 10^{-4}$	4	10×10k	16	1.000
$e^+e^- \to Z \to t\bar{t}b\bar{b}gg$	$(0.2157 \pm 0.0029\ (1.34\%))\times 10^{-4}$	5	10×10k	120	0.824
$e^+e^- \to Z \to \tilde{t}_1\bar{\tilde{t}}_1ggg$	$(0.3712 \pm 0.0037\ (1.00\%))\times 10^{-8}$	3	10×10k	18	0.764
$e^+e^- \to Z \to \tilde{g}\tilde{g}ggg$	$(0.1584 \pm 0.0020\ (1.23\ \%))\times 10^{-1}$	2	10×10k	9	0.753
$\mu^+\mu^- \to H \to gggg$	$(0.1404 \pm 0.0005\ (0.34\ \%))\times 10^{-7}$	1	10×50k	2	0.559
$\mu^+\mu^- \to H \to ggggg$	$(0.2575 \pm 0.0018\ (0.69\ \%))\times 10^{-8}$	1	10×50k	4	0.165
$\mu^+\mu^- \to H \to gggggg$	$(0.1186 \pm 0.0008\ (0.70\ \%))\times 10^{-9}$	1	10×350k	9	0.031

- Compared to the Born, the error is only 1.9-4.5 times larger with the same statistics*

* 2 exceptions; ttbbg: 7 & ttgggg: 9

Further optimization (not yet used)

- The results presented here do not use possible optimization related to
  - using the Monte Carlo to sum over the helicities of the external particles:
    - simple to implement with explicit sum of the two FKS partons
    - also possible with MC sum over FKS partons, but slightly more complicated
  - Diagram information is only used for defining the integration channels: use recursive relations for the rest?



- Sqrt(s)=100 GeV
- ren. & fac. scales equal to Z mass
- kt jet clustering with $Y_{cut}=(10\ \mathrm{GeV})^2$
- **Finite part of virtual correction not included**

- Same runs as in the table: no 'smoothing' of the plots
- fine binning, and smooth results

Full NLO

- Of course, to get the total NLO results the finite parts of the virtual corrections should be included as well
- Binoth Les Houches interface available
- Working interfaces to BLACKHAT and ROCKET for the finite part of the virtual corrections
- *Many thanks to Daniel Maitre and Giulia Zanderighi*

Binoth-Les Houches Accord

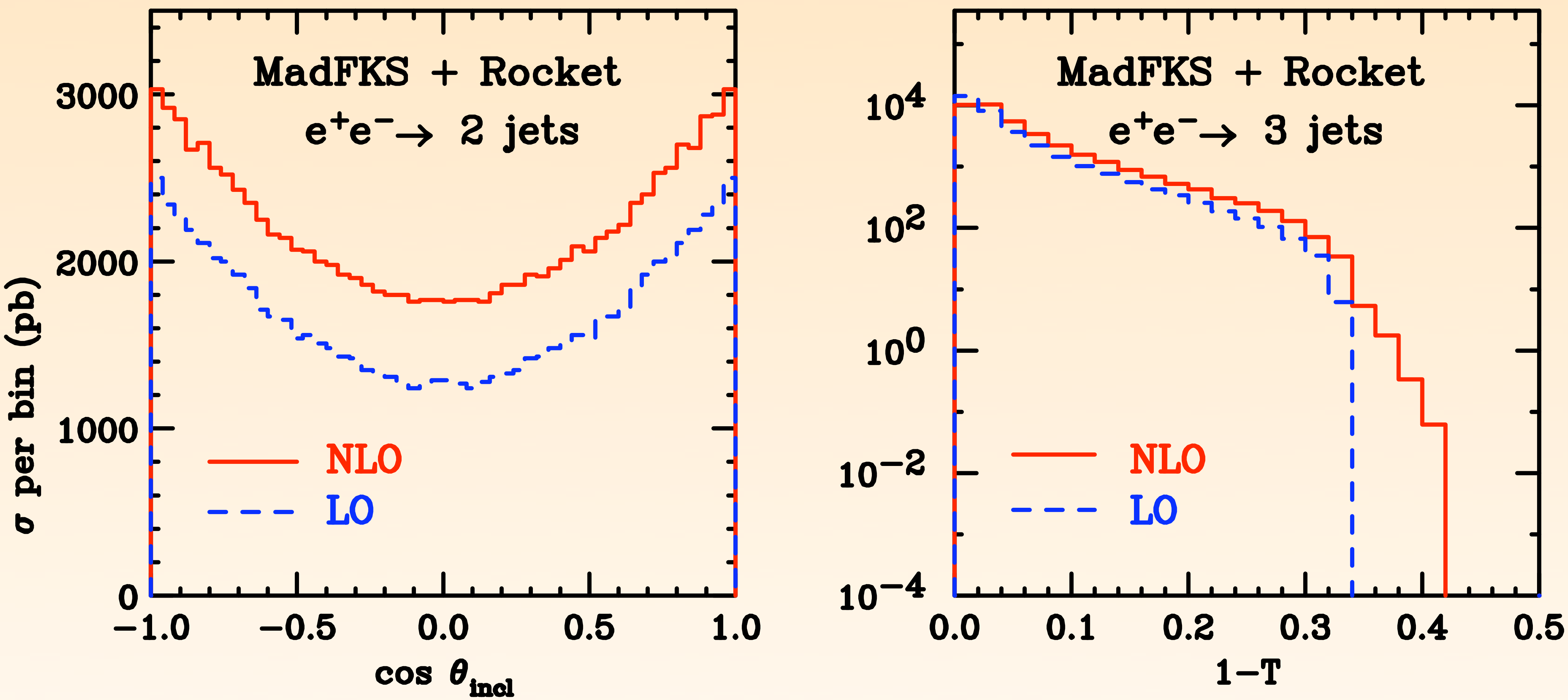
"Dedicated to the memory of, and in tribute to, Thomas Binoth, who led the effort to develop this proposal for Les Houches 2009"

- **Initialization phase**
  MC code communicates basic information about the process to the OLP. OLP answers if it can provide the loop corrections.

- **Run-time phase**
  MC code queries the OLP for the value of the one-loop contributions for each phase-space point.

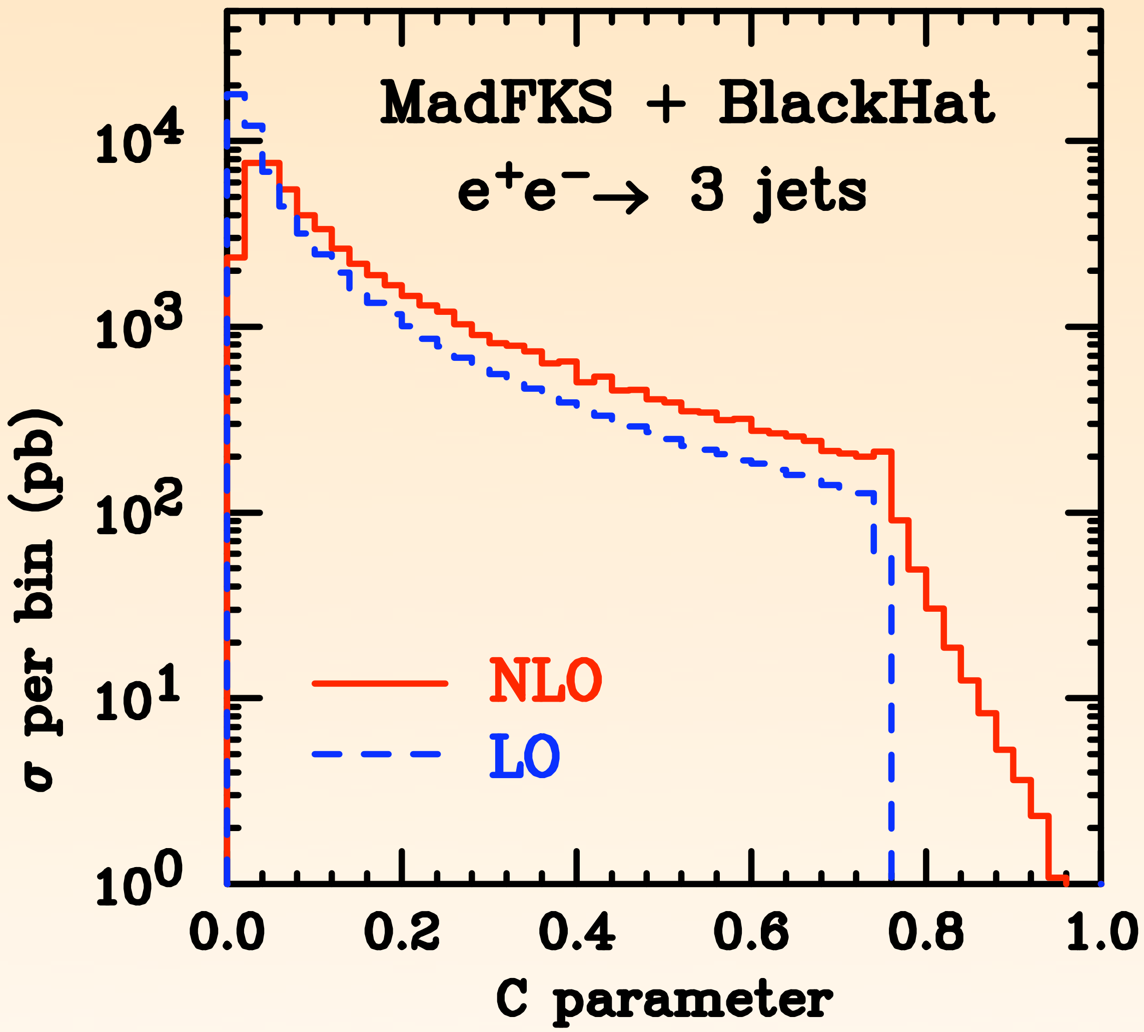
arXiv:1001.1307 [hep-ph]

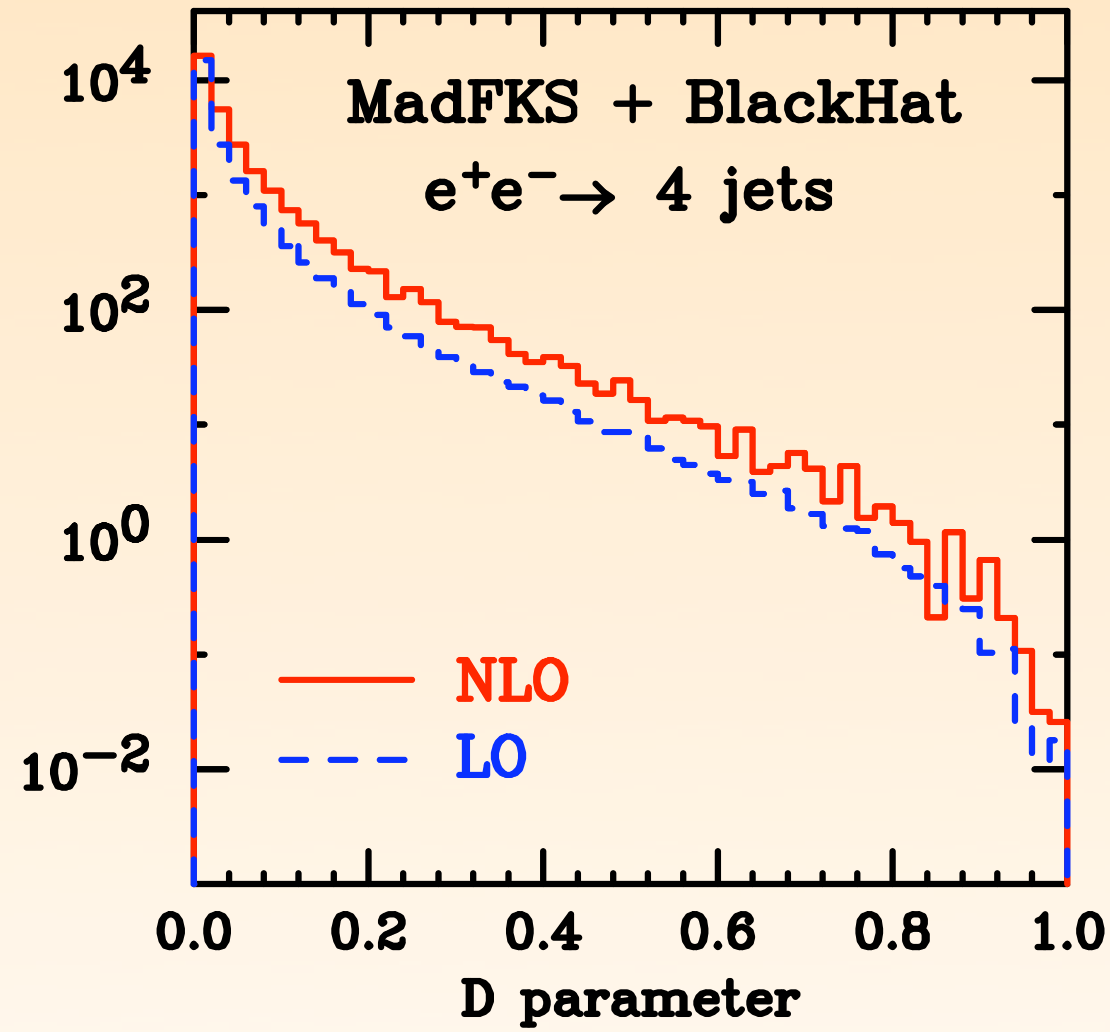
MadFKS + Rocket



- Inclusive angle between jets and electron direction and Thrust distribution

MadFKS + BlackHat



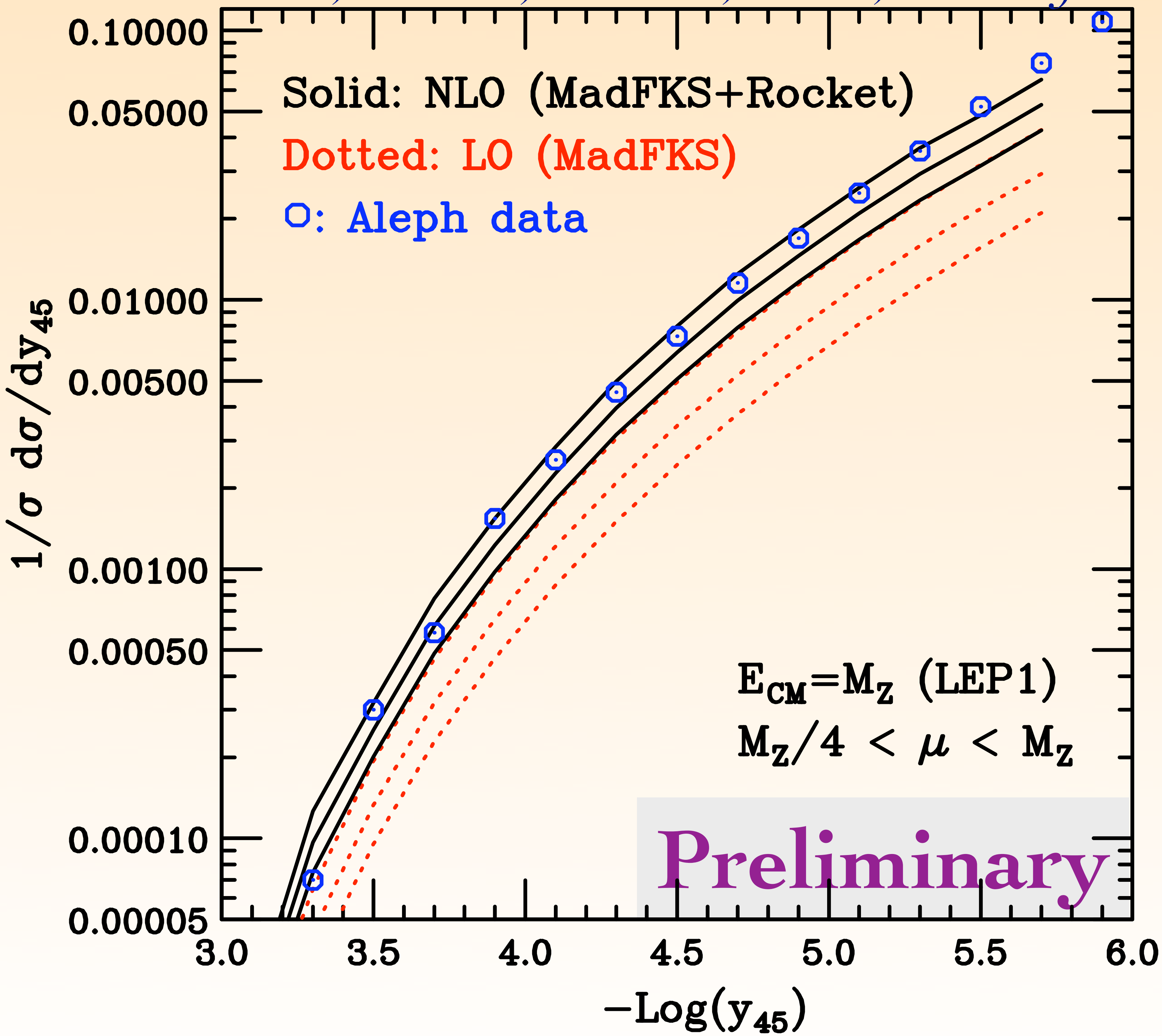


- C and D parameters for 3 and 4 partons at LO respectively

Preliminary result

- e+e- to 5 jets at NLO
- MadFKS + Rocket
- Results checked with MadFKS + BlackHat

RF, Frixione, Melnikov, Stelzel, Zanderighi



To conclude

- NLO corrections are needed for precision phenomenology and to understand all features of the experimental data
- For any QCD NLO computation (SM & BSM) MadFKS takes care of:
  - Generating the Born, real emission, subtraction terms, phase-space integration and overall management of symmetry factors, subprocess combination etc.
- External program(s) needed for the (finite part of the) loop contributions (so far working with BlackHat and Rocket)
  - Other codes/programs/groups more than welcome!
- With the shower subtraction terms, interface to showers to generate automatically unweighted events at NLO is in testing phase