NNLO W Pair Production at the LHC: Status Report

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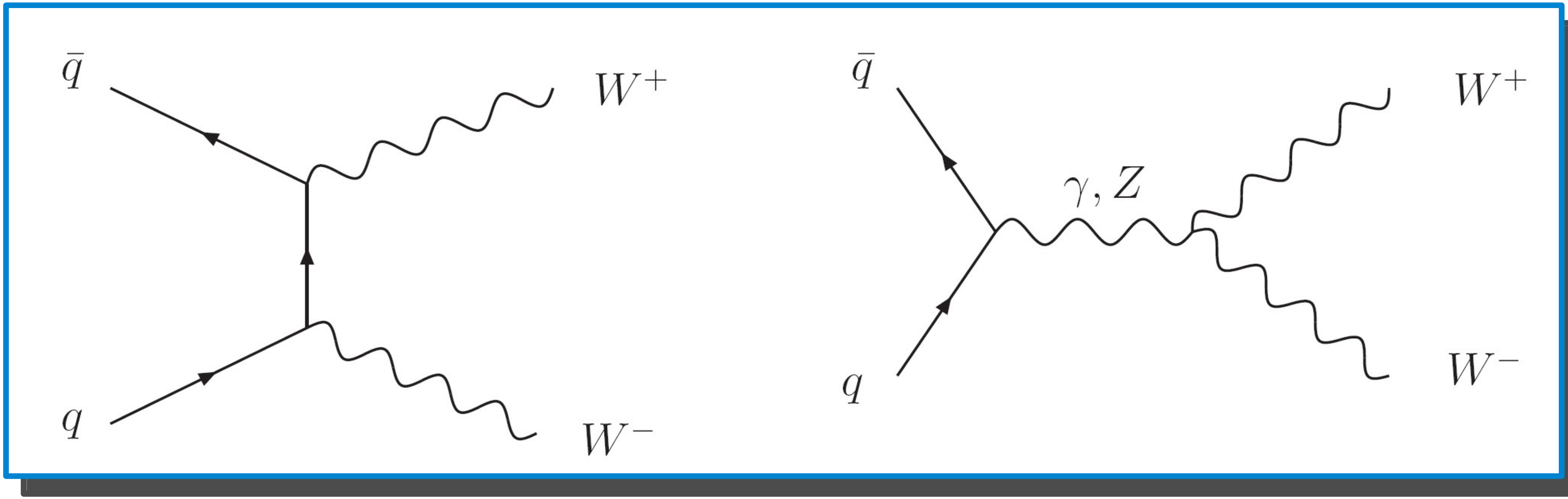
Outline

- Introduction and a bit of history
- Motivation for computing the NNLO corrections
- Classification of the radiative corrections
- Some computational details regarding the double-virtual corrections (2-loop)
- Outlook

The process at LO

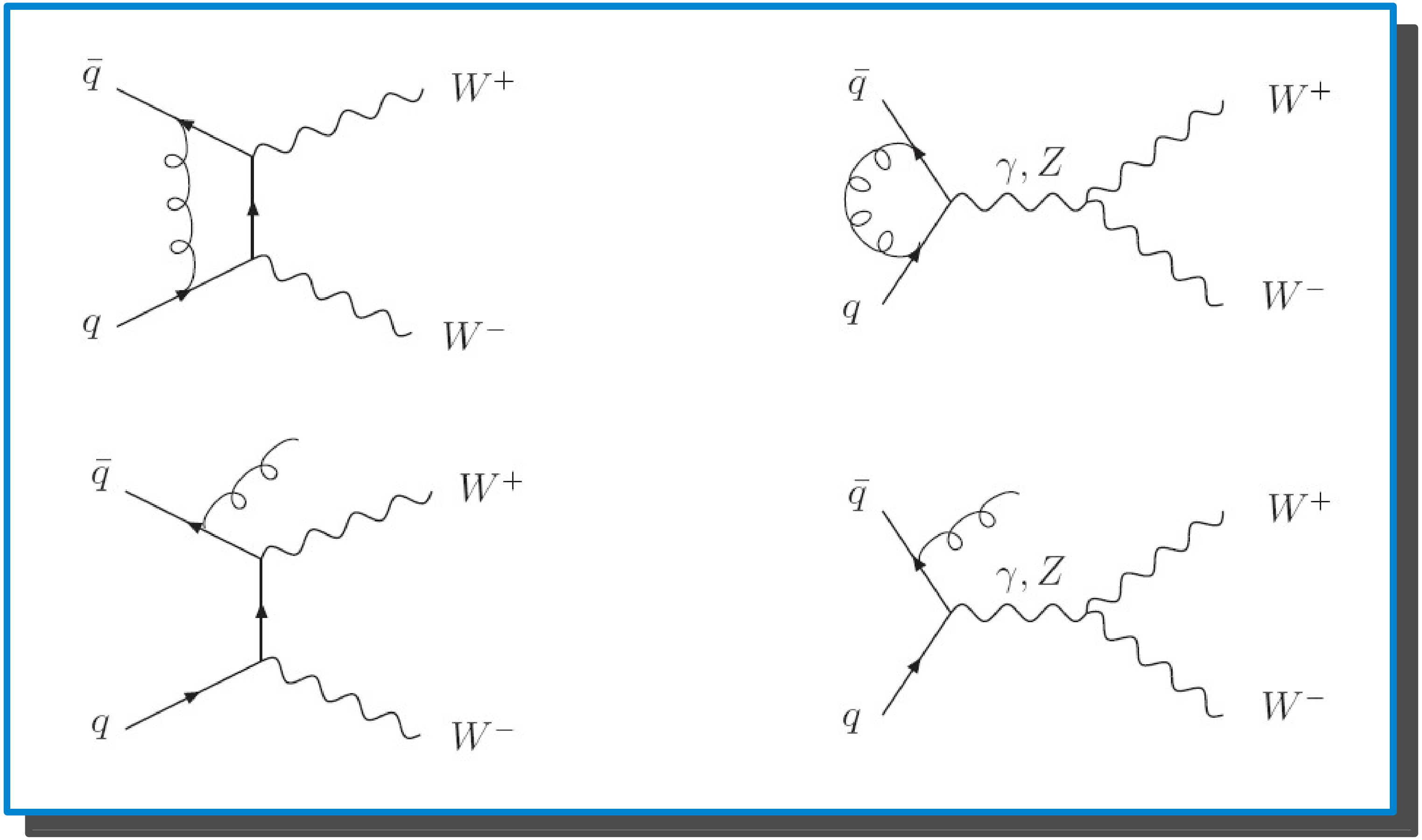
W Pair Production in the quark-anti-quark annihilation channel
$2 \rightarrow 2$ process with **massive** particles



LO Calculation — Brown, Mikaelian ('79)

CERN Discovery of W and Z bosons ('83)

… and at NLO



NLO Calculation

Ohnemus ('91); Frixione ('93)
Ohnemus('94)
Dixon, Kunszt, Signer ('98,'99)
Campbell, K. Ellis ('99)

Why to NNLO?

W pair production important as a **signal** in searches for **New Physics.** Testing ground for non-abelian structure of SM, triple gauge couplings, γWW, ZWW

TEVATRON

$$\sigma(p\bar{p} \rightarrow W^+W^-) =$$

$$14.6^{+5.8}_{-5.1}(\text{stat})\ ^{+1.8}_{-3.0}(\text{syst}) \pm 0.9(\text{lum})\ \text{pb}$$ CDF

$$13.8^{+4.3}_{-3.8}(\text{stat})\ ^{+1.2}_{-0.9}(\text{syst}) \pm 0.9(\text{lum})\ \text{pb}$$ DØ

$\sqrt{s} = 2$ TeV ($p\bar{p}$)	W^+W^-	
	MRS98	CTEQ5
Born [pb]	10.0	10.3
Full [pb]	13.0	13.5

Theory

Campbell, Ellis ('99)

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LHC

	fb^{-1}	$\sigma(pp \rightarrow WW + X)$ [pb]	SM NLO
ATLAS 7TeV	4.6	$51.9 \pm 2.0(stat) \pm 3.9(syst) \pm 2.0(lumi)$	$44.7^{+2.1}_{-1.9}$
CMS 7TeV	4.9	$52.4 \pm 2.0(stat) \pm 4.5(syst) \pm 1.2(lumi)$	–
CMS 8TeV	3.5	$69.9 \pm 2.8(stat) \pm 5.6(syst) \pm 3.1(lumi)$	$57.3^{+2.4}_{-1.6}$

MCFM NLO+CT10

CMS 7 TeV WW: CMS PAS SMP-12-005 ATLAS 7 TeV WW: arXiv: 1211.6096

Vincenzo Lombardo LAPP/CNRS

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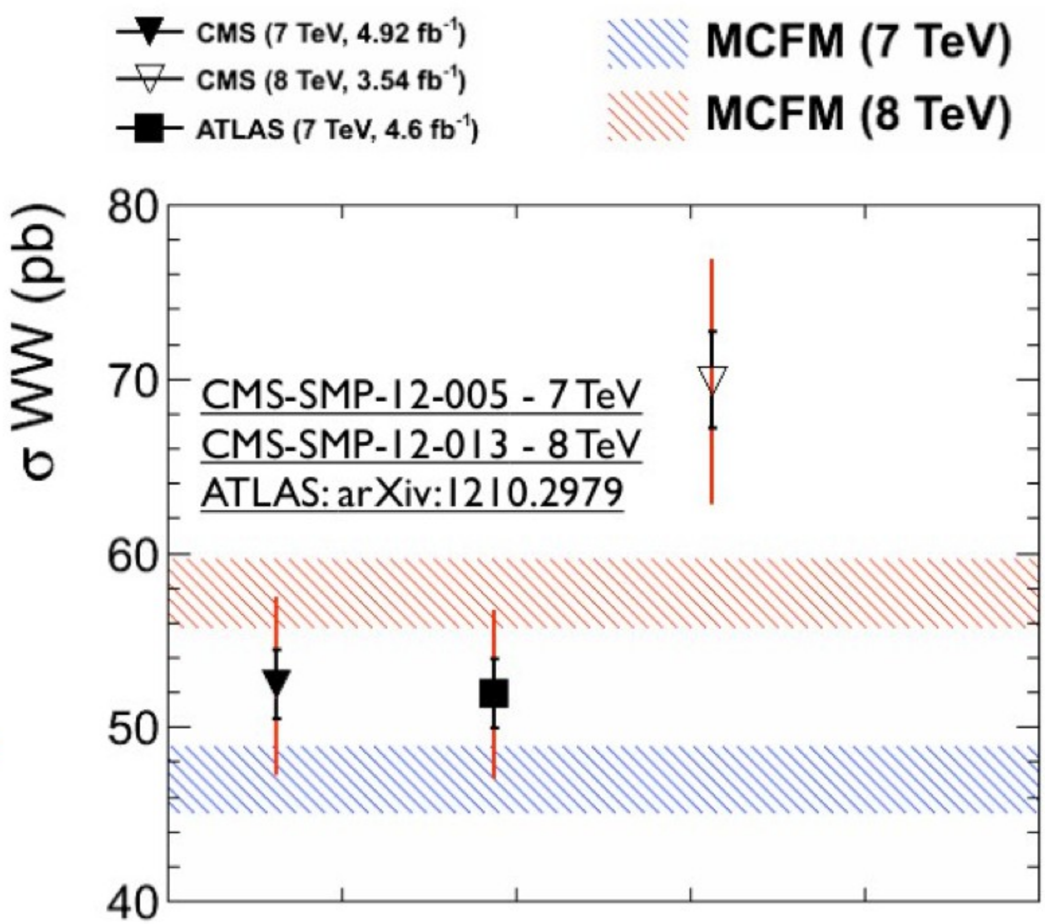
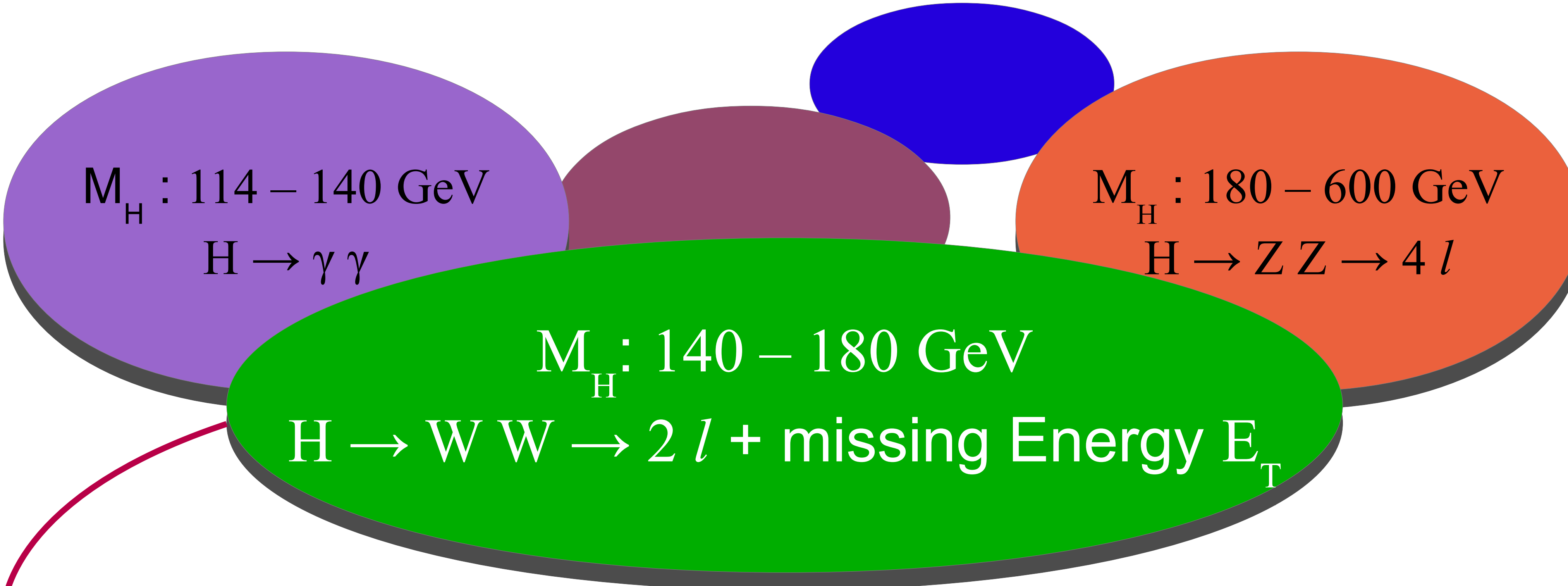
LHC



D. Evans @ HCP2012

Why to NNLO?

Higgs discovery channels:



- Pick up the signal process
- Avoid or suppress the usually large **background**
- Accurate theoretical predictions for both signal and background

→ Main background (irreducible): W pair production

Size of higher order corrections

- qq→WW

70% enhancement at NLO. With a jet veto the enhancements fall to 20-30%

Dixon, Kunszt, Signer ('98, '99)

- loop induced gg→WW

Contributes to the quark annihilation channel at $\mathcal{O}(\alpha_s^2)$.
Enhanced by the **large gluon flux.** After Higgs search cuts it increases the background by 30%, with no cuts by 5%

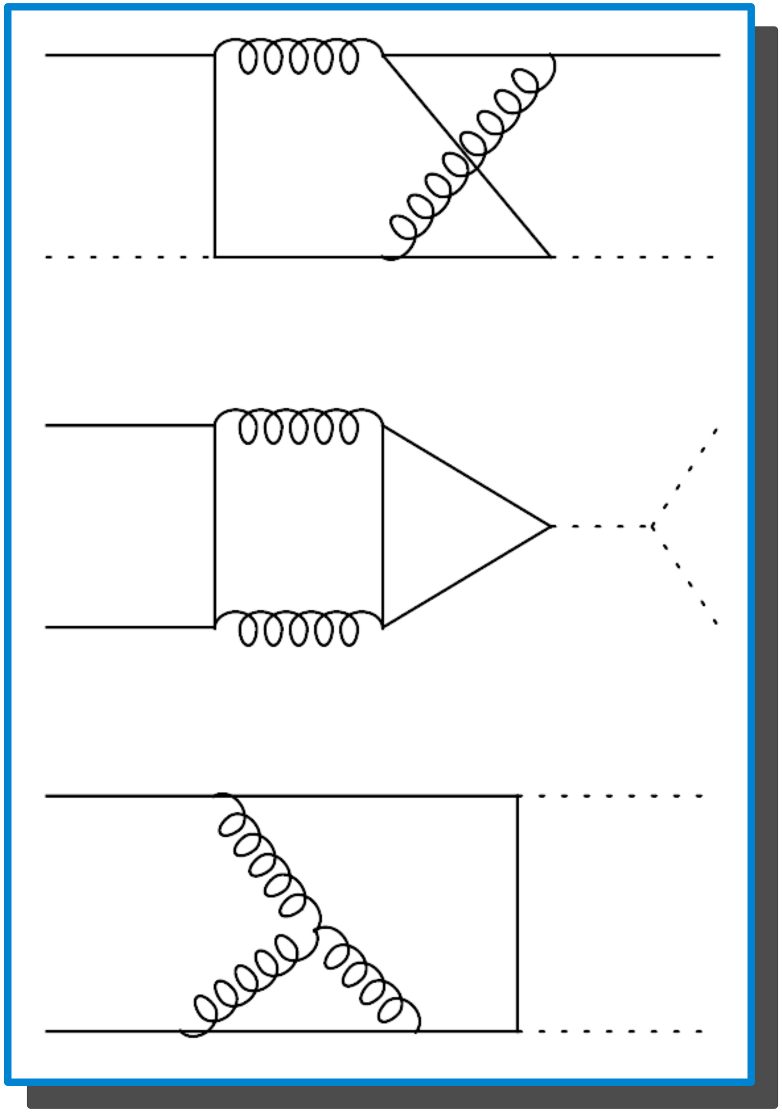
Glover, van der Bij ('89); Kao, Dicus ('91)
Binoth, Ciccolini, Kauer, Krämer ('05)
Duhrssen, Jackobs, v. d. Bij, Marquard ('05)

- EW corrections

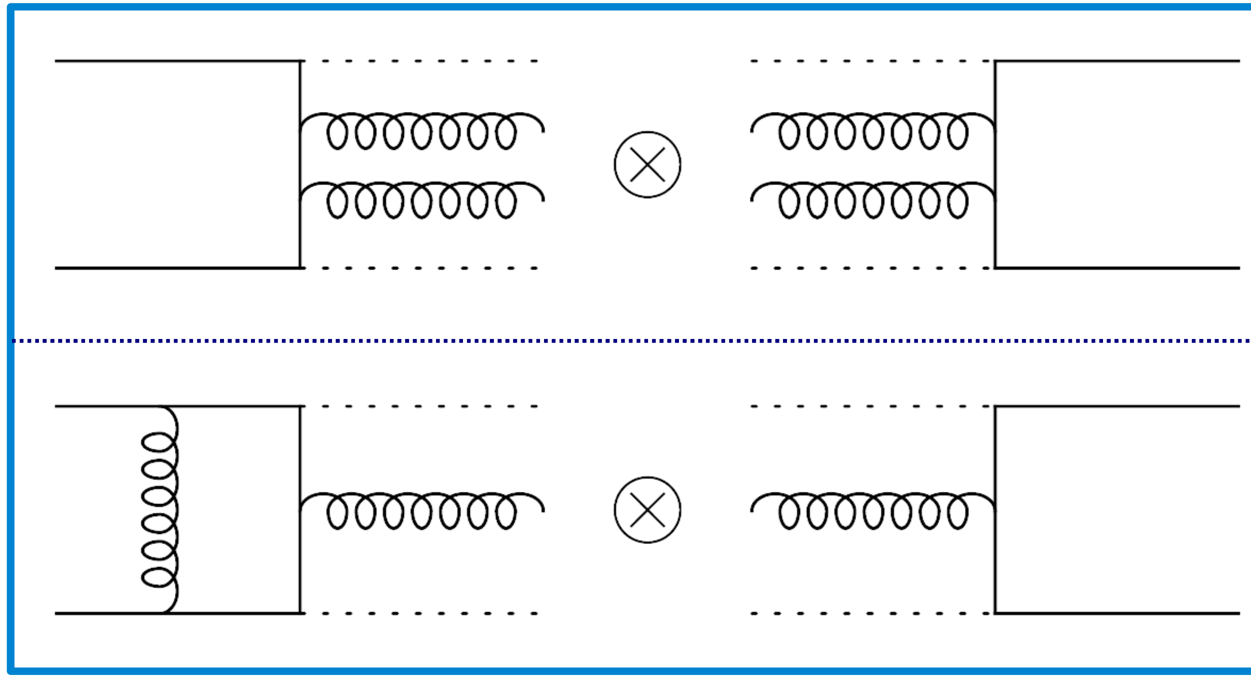
Accomando, Denner, Kaiser ('05)

See also recent: Gehrmann, Tancredi Weihs ('13); Dawson,Lewis, Zeng ('13)
Baglio, Ninh and Marcus M. Weber ('13)

Type of corrections at NNLO

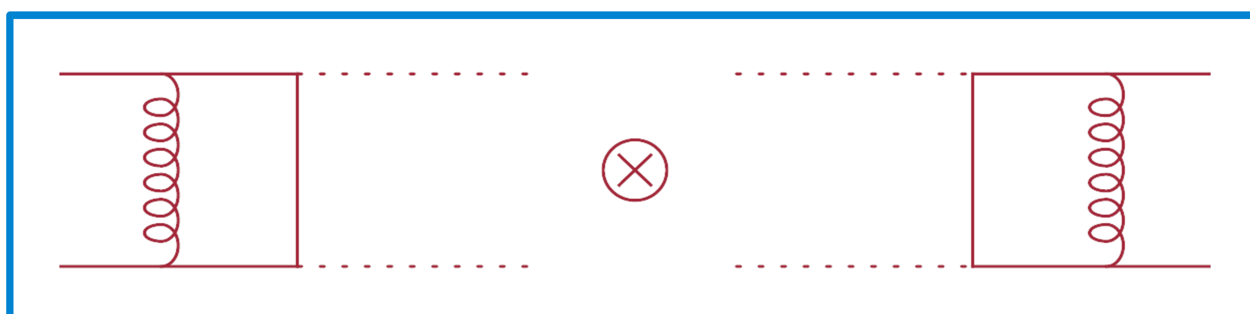


Double-Real



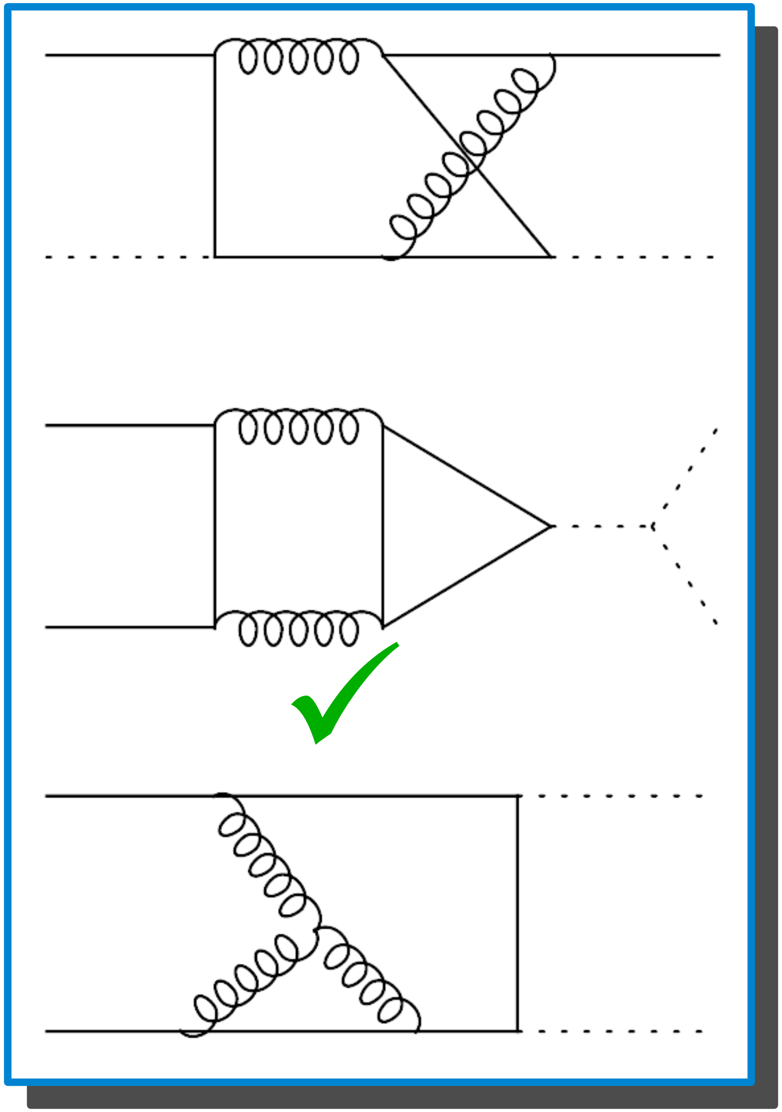
Virtual-Real

Double-Virtual



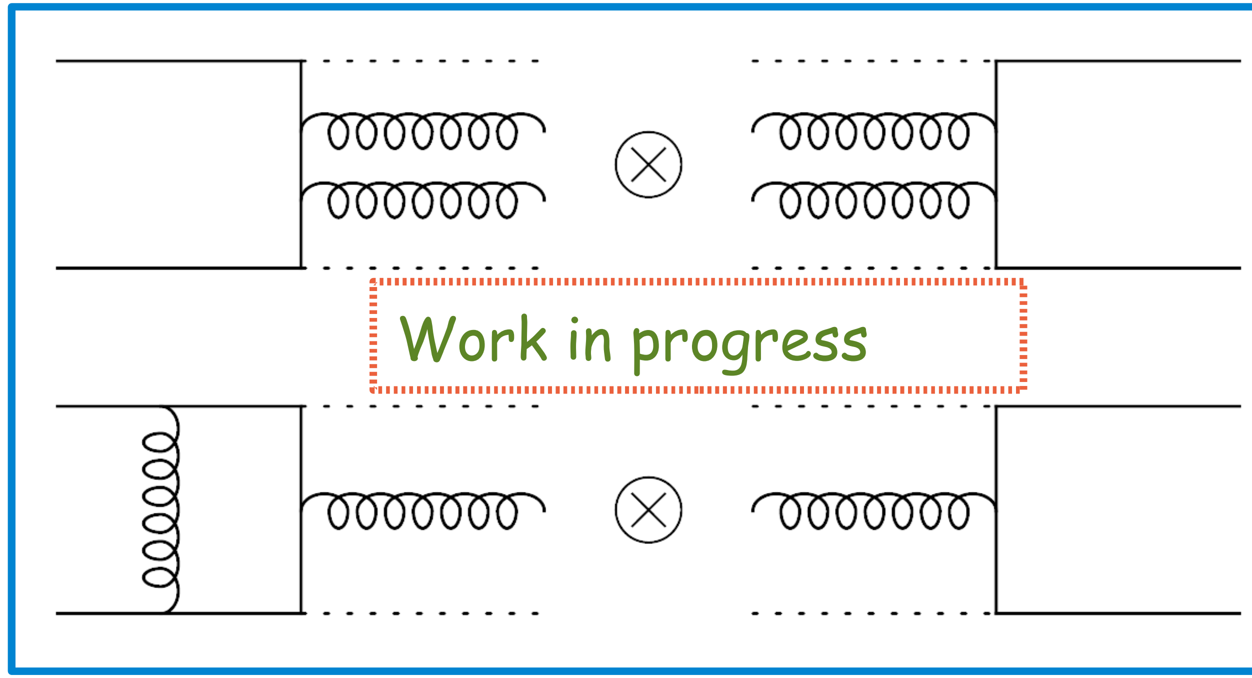
(one loop) x (one loop)*

Type of corrections at NNLO

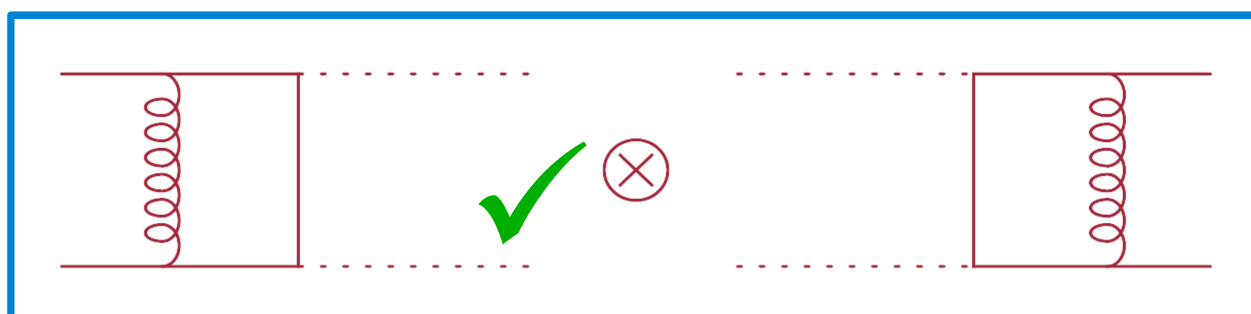


Double-Virtual

Double-Real



Virtual-Real



(one loop) x (one loop)*

Focus on double-virtual corrections:

The difficult part here is to compute the
2-loop Feynman Integrals.

We do that in a semi-analytic/semi-numeric way:
We use a combination of:

- Mellin-Barnes representations technique for computing the integrals in the high energy limit
- A deep mass expansion
- A numerical differential equations solution

Caffo, Czyz, Laporta, Remiddi ('98)

Mellin-Barnes recipe

Do a reduction a la Laporta into Masters, then starting from the Feynman parameters representation of a master, “walk” the following steps:

- produce representations (**MBrepresentation.m**)
- analytically continue in ε to the vicinity of 0 and expand in mass (**MB.m, MBasymptotics.m**)
- perform as many as possible integrations using Barnes lemmas (**BarnesRoutines.m**)
- resum the remaining integrals by transforming into harmonic series (**Xsummer**)
- resum remaining constants by high-precision numerical evaluation (**quadprec.m**) and fit them to a transcendental basis (**PSLQ**)

Software needed

MBrepresentation.m (G.C., Czakon)

Produces representations for **multi**-loop, **planar** or **non-planar**, **scalar** or **tensor** integrals of any **rank**!

MB.m (Czakon)

Determination of contours, analytic continuation, expansion in a chosen parameter, numerical integration

barnesroutines.m (Kosower)

Barnes' lemmas

XSummer (Moch, Uwer)

Evaluation of harmonic sums

PSLQ (Bailey)

Fitting to a transcendental basis

quadprec.m (Czakon)

High precision numerical evaluation with up to 64 digits

The deep mass expansion

Assume that any master integral can be written as:

$$\mathrm{M}_i = \sum_{m,n,l} \mathrm{Coeff}_{(i;n,l,m)}(x)\ \epsilon^m\ m_s^n\ \log^l(m_s)$$

$$m_s = M_W^2 / s$$

One can also express the derivative of a master (with respect to the mass) in terms of master integrals:

$$m_s \frac{d}{dm_s} \mathrm{M}_i(m_s, x, \epsilon) = \sum_j \mathrm{C}_{ij}(m_s, x, \epsilon) \mathrm{M}_j(m_s, x, \epsilon)$$

Determine this way the Coeff's

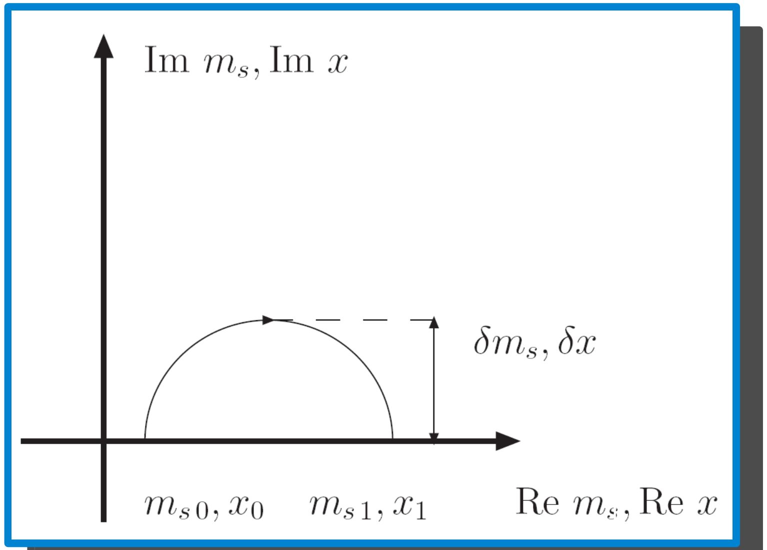
Numerical differential equations solution

- Compute the high energy asymptotics of the master integrals obtaining the leading behaviour of the amplitude
- Determine the coefficients of the mass expansions using differential equations in m_s obtaining the power corrections

$$m_s \frac{d}{d m_s} M_i(m_s, x, \epsilon) = \sum_j C_{ij}(m_s, x, \epsilon) M_j(m_s, x, \epsilon)$$

- Evaluate the expansions for $m_s \ll 1$ to obtain the desired numerical precision of the boundaries
- Evolve the functions from the boundary point with differential equations first in m_s and then in x (**ZVODE**)

Brown, Byrne, Hindmarsh ('89)



Differential equations: specifics

- Find the optimal set of masters
- Solve the differential equations for a grid of points
- Run numerical checks (e.g. use different contours) and control errors.
- Interpolate
- Renormalise

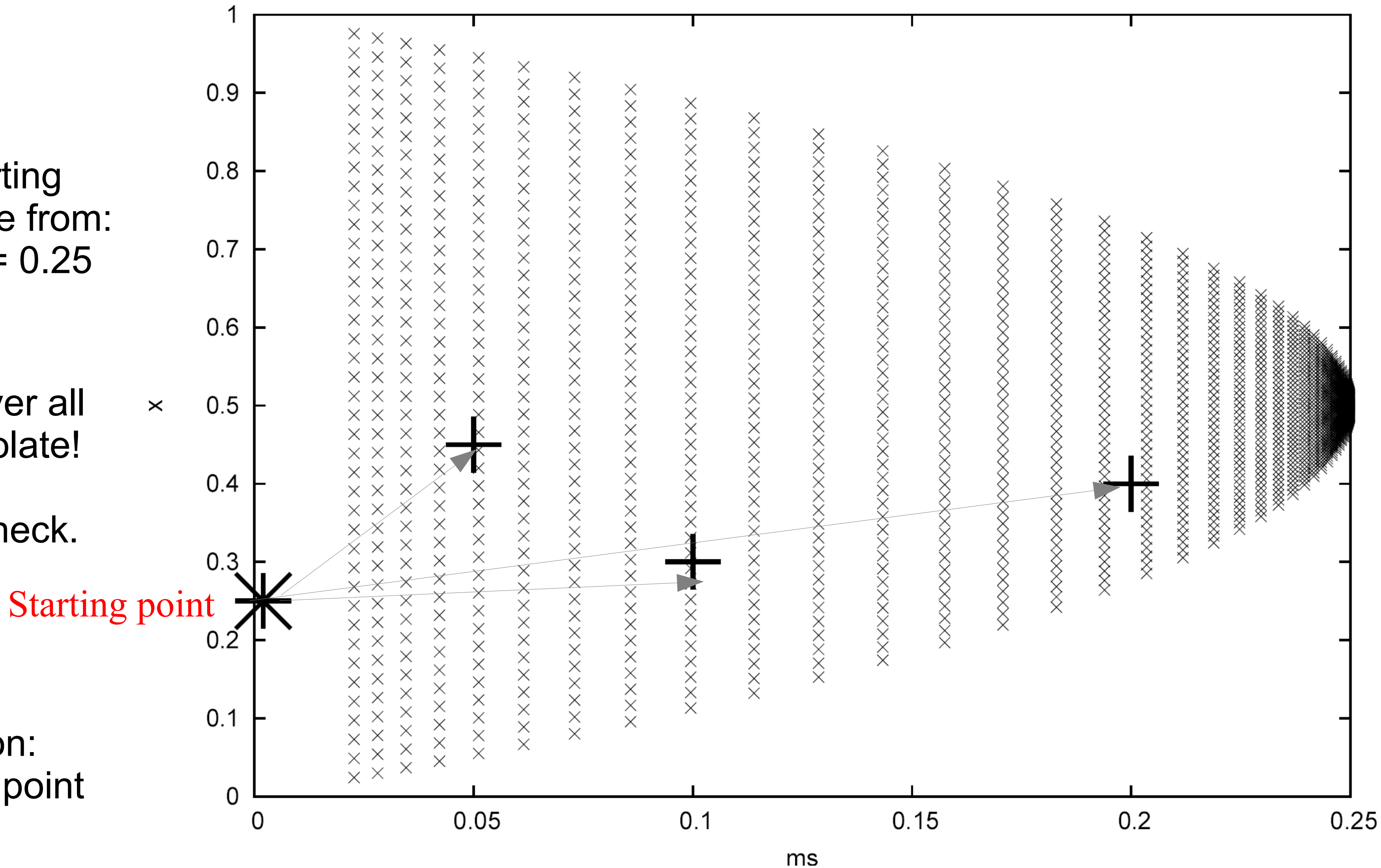
Phase space and evolution

Make a grid:
1600 points

Pick up a starting point to evolve from:
ms=0.002, x = 0.25

Once you cover all points, interpolate!
Use different contours to check.

Quad precision:
~15 mins per point



Have already run for all 1600 points and for 3 different contours

Conclusions and Outlook

- We have computed the 2-loop virtual corrections
- We are making fast progress in computing the double-real corrections
- We hope that in a matter of few months we will be able to present the total cross-section for the quark-anti-quark-annihilation channel for LHC energies