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NLO/MC tools

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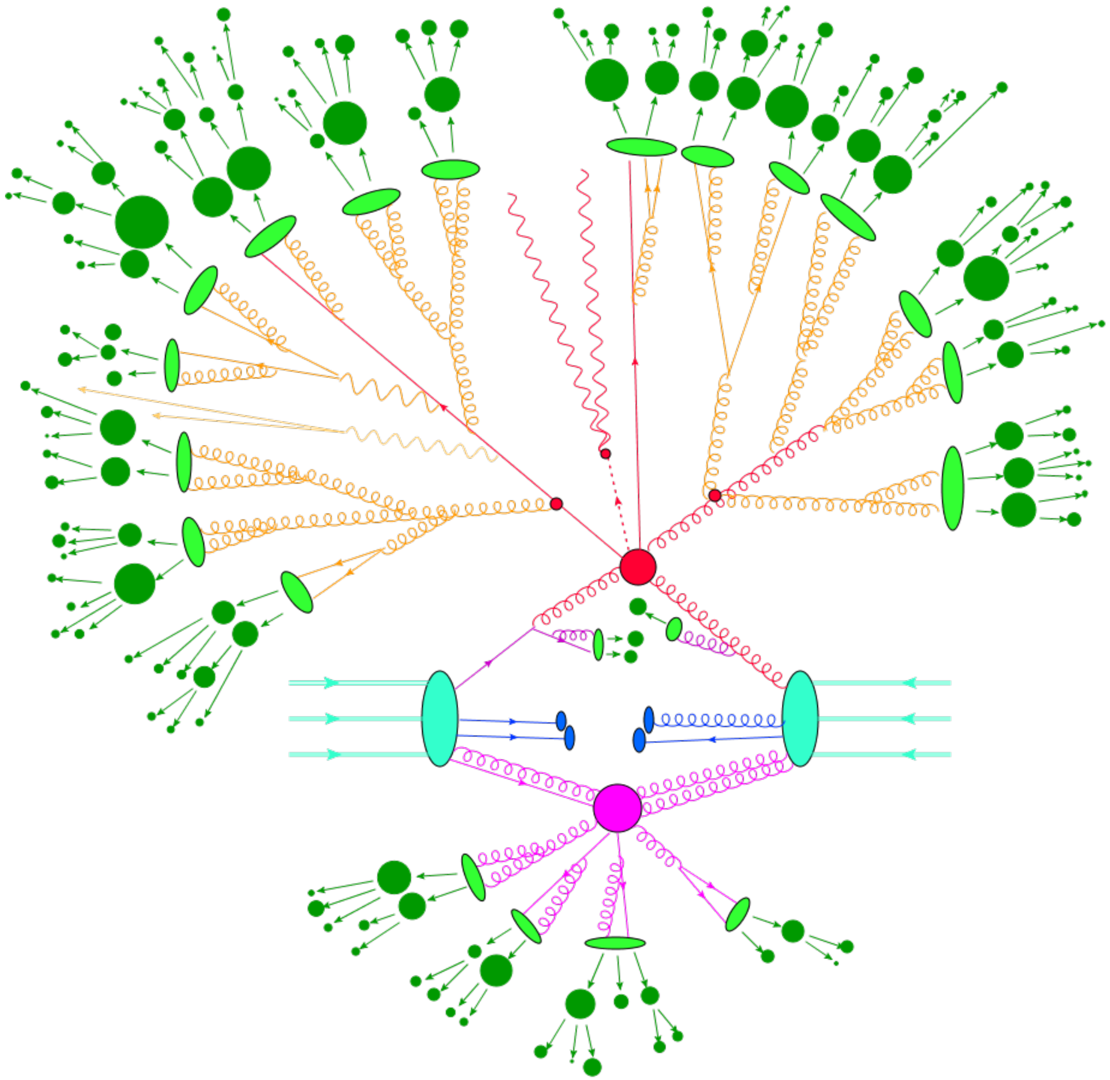
FNSNF
FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

The full picture



Proton
Parton distribution function

Hard scattering (perturbative)

Parton shower
(still perturbative)

Hadronization
(non-perturbative)

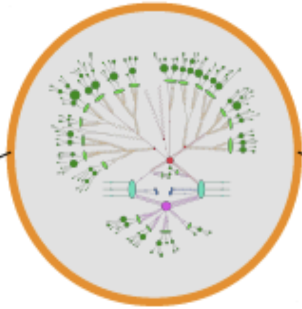
Hadron-decay

Beam remnants

Multi-parton interactions

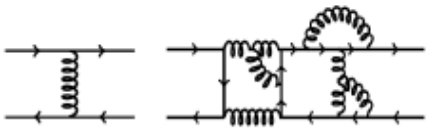
+ many protons in one bunch
→ more than one p-p interaction

The full picture

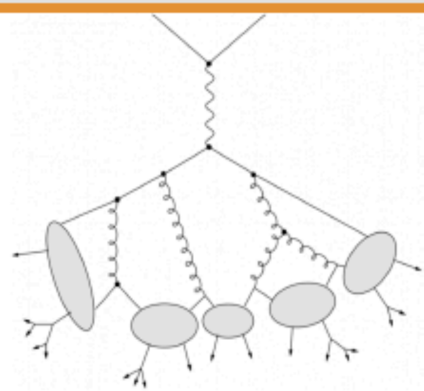


Partonic hard scattering
–
Fixed order expansion

$$\sigma = \sigma_0(1 + c_1\alpha_s + c_2\alpha_s^2 + ...)$$

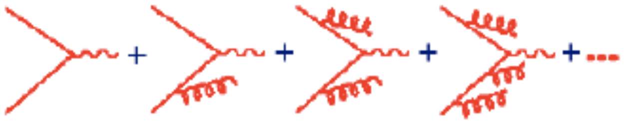


Parton shower / Hadronization
Event generation



Resummation

$$\alpha_s \ln(Q/Q_T) \sim 1$$



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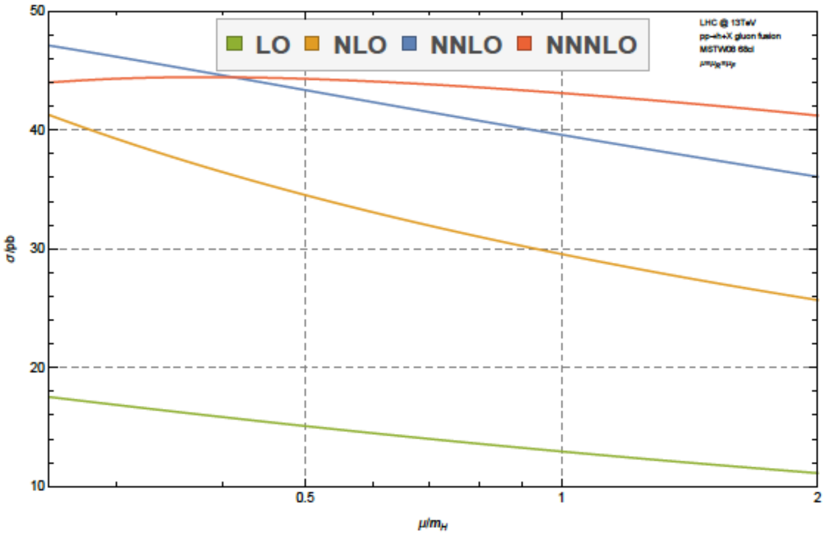
Fixed order expansion

- Higher order corrections mandatory for reliable corrections
- **Example:** Higgs production in gluon fusion



- Large corrections from higher orders
- Strong dependence on ren./fac. Scale
- Unreliable estimation of theoretical uncertainties

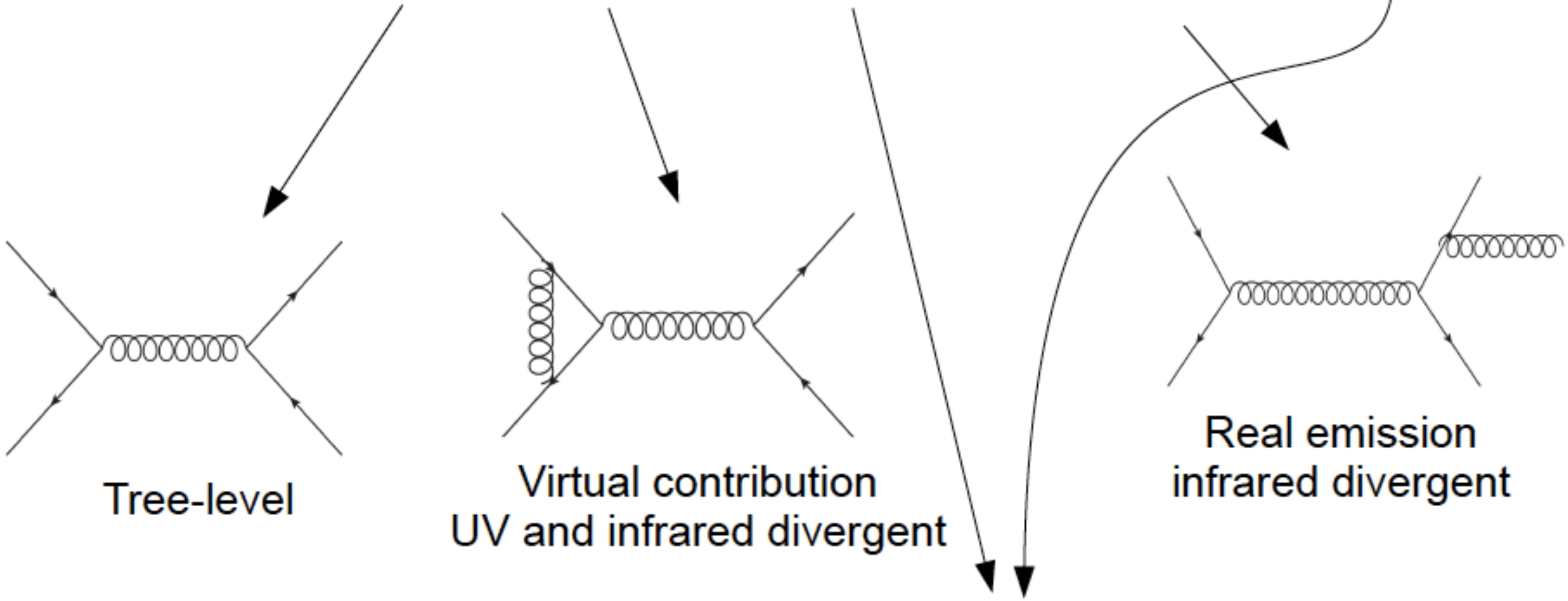
[Anastasiou,Duhr,Dulat,Herzog,Mistlberger '15]

Many relevant LHC processes yield NLO QCD corrections ~10-100%

➡ **Need precise predictions to confirm/disprove SM !**

The structure of NLO

$$\sigma_{NLO} = \int_n \left(d\sigma^B + d\sigma^V + \int_1 d\sigma^A\right) + \int_{n+1} \left(d\sigma^R - d\sigma^A\right)$$



Subtraction terms: Needed to cancel infrared singularities numerically.
Idea: Add zero in suitable way to cancel infrared singularities from real emission.

Automating NLO corrections

- Increasing complexity required development of automated software tools for **numerical** calculations

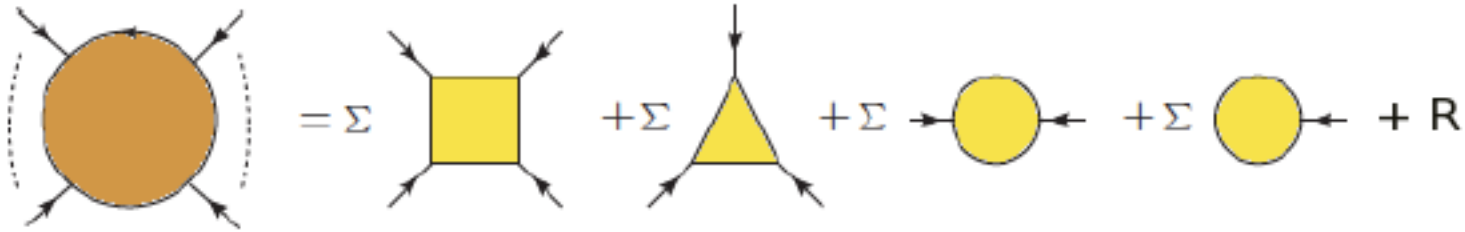
- Development of tools for NLO calculations (QCD)
  Main bottleneck: **Virtual one-loop contribution**

"I designed a program that allows me to run the entire plant from my computer. By the way, how's the weather back there?"

- ✓ it saves time
- ✓ avoids human mistakes
- ✓ allows to reuse building blocks
- ✓ easier to handle for the user
- ✓ not necessary to understand all details
- ✓ multipurpose

- Selection of excellent tools for different ingredients of one-loop calculations available

Virtual one loop corrections



Unique basis of scalar **boxes**, **triangles**, **bubbles** and **tadpoles**, all master integrals known analytically

Reduction of tensor integrals to scalar integrals

Reduction at the integral level (Passarino-Veltman) (analytical or numerical)

[Passarino,Veltman]
[Denner,Dittmaier]
[Binoth et al]

Collier [Denner,Dittmaier,Hofer]
Golem95 [Binoth et al],PJFry [Fleischer et al] + in-house

Reduction on the integrand level (suited for numerical approach)

[Ossola, Papadopulos,Pittau]
[Ellis,Giele,Kunszt,Melnikov]

Integrand reduction

$$\text{Integrand:} \quad A(\bar{q}) = \frac{N(q)}{\bar{D}_0 \bar{D}_1 \cdots \bar{D}_{m-1}}$$

$$N(q) = \sum_{i_0<i_1<i_2<i_3}^{m-1} \left[d(i_0i_1i_2i_3) + \tilde{d}(q;i_0i_1i_2i_3)\right] \prod_{i\neq i_0,i_1,i_2,i_3}^{m-1} D_i + \sum_{i_0<i_1<i_2}^{m-1} \left[c(i_0i_1i_2) + \tilde{c}(q;i_0i_1i_2)\right] \prod_{i\neq i_0,i_1,i_2}^{m-1} D_i$$
$$+ \sum_{i_0<i_1}^{m-1} \left[b(i_0i_1) + \tilde{b}(q;i_0i_1)\right] \prod_{i\neq i_0,i_1}^{m-1} D_i + \sum_{i_0}^{m-1} \left[a(i_0) + \tilde{a}(q;i_0)\right] \prod_{i\neq i_0}^{m-1} D_i$$

$\tilde{a}, \tilde{b}, \tilde{c}, \tilde{d}$ spurious terms, vanish upon integration, parametric form known

- **Coefficients** can be obtained by applying **suitable cuts** (i.e. setting propagators on-shell) [Cutkosky][Bern,Dixon,Dunbar,Kosower],[Britto,Cachazo,Feng]
- **Process independent** form, but **process dependent** coefficients
- **Polynomial fitting** allows to determine all coefficients
- Only need to evaluate **numerator function N(q)** on the cuts [Ossola,Papadopoulos,Pittau],[Ellis,Giele,Kunszt,Melnikov]

-> Suitable for algorithmic, numerical implementation

Cuttools [Ossola,Papadopoulos,Pittau], **Samurai** [Mastrolia,Ossola,Reiter,Tramontano], **Ninja** [Mastrolia,Mirabella,Ossola,Peraro], **many in-house solutions...**

NLO revolution

- Both version of reduction yield fast and stable results
- Remaining scalar integrals can be evaluated using integral libraries (e.g. **QCDLoop** [Ellis,Zanderighi], **OneLoop** [vanHameren])
- **Note:** Reduction does not care how integrand is provided -> Both **unitarity** inspired methods as well as **Feynman diagrammatic** approach has been proven to be successful in challenging applications
- Healthy diversity in available tools using different methods: **unitarity methods, Feynman diagrams, recursion relations, algebraic approach, numerical approach**

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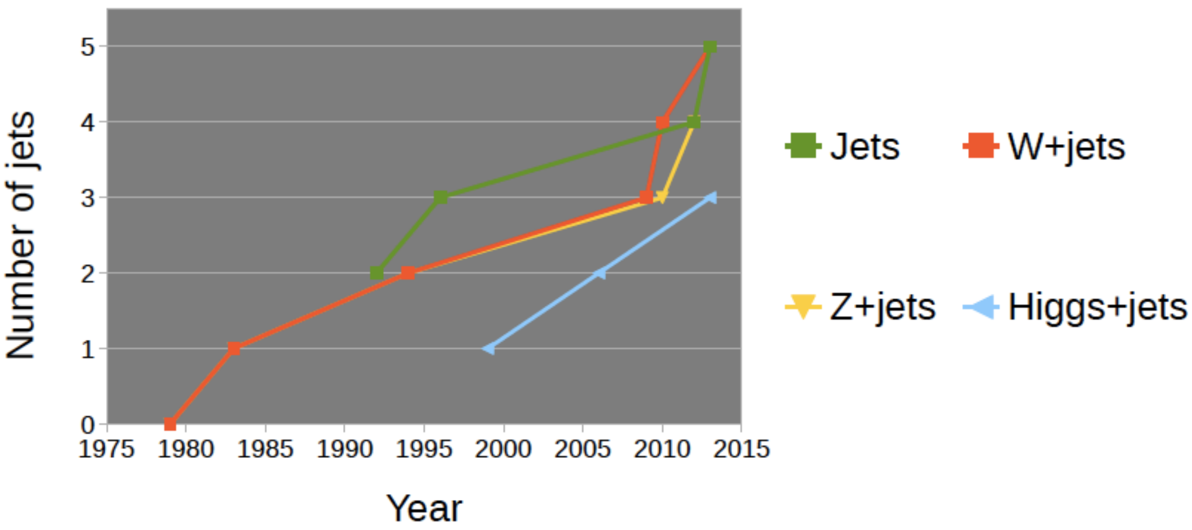
NLO revolution

Various general purpose tools like:
BlackHat, GoSam, Helac-NLO, Madgraph5_aMC@NLO, Njet, OpenLoops, Recola...

Tools based on process list:
MCFM, VBFNLO,...

Analytical tools:
Feynarts, FormCalc, Looptools,...



Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$jet	WWjet completed by Dittmaier/Kallweit/Uwer [4, 5]; Campbell/Ellis/Zanderighi [6]. ZZjet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti [7]
2. $pp \to$ Higgs+2jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi [8]; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier [9, 10]
3. $pp \to V\,V\,V$	ZZZ completed by Lazopoulos/Melnikov/Petriello [11] and WWZ by Hankele/Zeppenfeld [12] (see also Binoth/Ossola/Papadopoulos/Pittau [13])
4. $pp \to t\bar{t}\,b\bar{b}$	relevant for $t\bar{t}H$ computed by Bredenstein/Denner/Dittmaier/Pozzorini [14, 15] and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek [16]
5. $pp \to V$+3jets	calculated by the Blackhat/Sherpa [17] and Rocket [18] collaborations
Calculations remaining f[illegible] Les H[illegible]s 2005	
6. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$ computed by Bevilacqua/Czakon/Papadopoulos/Worek [19]
7. $pp \to VV\,b\bar{b}$,	re[illegible]evant for VBF $\to H \to VV$, $t\bar{t}H$
8. $pp \to VV$+2jets	[illegible]nt for VBF $\to H \to VV$ [illegible]BF [illegible]ributions calculated by (Boz[illegible]äger/Oleari/Zeppenfeld [20–22]
NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	$q\bar{q}$ char[illegible] ca[illegible]ed by Golem collaboration [23]
NLO calculations added to list in 2009	
10. $pp \to V$+4 jets	top pair production, va[illegible]s new physics signatures
11. $pp \to Wb\bar{b}j$	top, new physics signatures
12. $pp \to t\bar{t}t\bar{t}$	various new physics signatures
Calculations beyond NLO added in 2007	
13. $gg \to W^*W^*\ \mathcal{O}(\alpha^2\alpha_s^3)$	backgrounds to Higgs
14. NNLO $pp \to t\bar{t}$	normalization of a benchmark process
15. NNLO to VBF and Z/γ+jet	Higgs couplings and SM benchmark
Calculations including electroweak effects	
16. NNLO QCD+NLO EW for W/Z	precision calculation of a SM benchmark

done!

Table 1: The updated experimenter's wishlist for LHC processes

Subtraction methods

Infrared structure of amplitude is **universal** and **process independent**

➡ Construct terms that are simpler as real emission ME with the correct IR limit

$\int_{n+1} \left(d\sigma^R - d\sigma^A\right)$ finite !, $\int_1 d\sigma^A$ Has to be calculated analytically (IR divergencies cancel against virtuals)

- **(Phase space slicing)**
  Divide PS in singular/nonsingular regions, replace ME in sing region.

- **Residue subtraction (FKS)** [Frixione,Kunszt,Signer]
  -> MadFKS

- **Dipole formalism** [Catani,Seymour][Catani,Dittmaier,Seymour,Trocsanyi]
  -> Amegic++,AutoDipole, Helac-Phegas, Herwig++, MadDipole

- **Antenna subtraction** [Kosower][Daleo et al][Gehrmann et al]

Interface to Monte Carlo Programs

- Interface via **Binoth-Les-Houches-Accord (BLHA)**

- Step 1: MC writes an **order file**

```
CorrectionType QCD
AmplitudeType Loop
2 -2 -> 1 -1
2 -2 -> 2 -2
```

- Step 2: OLP writes a **contract file**

```
CorrectionType QCD | OK
AmplitudeType Loop | OK
2 -2 -> 1 -1 | 0
2 -2 -> 2 -2 | 1
```

- Virtual amplitude called from within the MC during runtime (Sherpa,Powheg,Herwig++, MG5_aMC@NLO,Whizard,...)

Event generator and parton shower

General purpose event generators:

- Combine ME's, PS, hadronization and soft underlying physics in one simulation
- Different showers, different prescription of matching/merging, different hadronization models, etc.. -> **Herwig++, MadGraph, Pythia, Sherpa**

Parton shower (PS):

✓ Good approximation in soft/collinear regions
X Bad approximation in hard regions
Herwig++, MC@NLO, Pythia, Sherpa, Vincia,...

Matrix element (ME):

X Bad description in soft/collinear regions due to logarithmic enhancement
✓ Describes hard regions and regions of large angles very well

Combine ME + PS to obtain good description in soft/collinear and hard region
LO merging: Combination of several ME's lead to double counting

- General prescription to avoid double counting: **CKKW, CKKW-L,MLM,...**
  [Catani,Krauss,Kuhn,Webber],[Loennblad],[Loennblad,Prestel],[Hamilton,Richardson,Tully]
  [Hoeche,Krauss,Schumann,Siegert]....

NLO + PS

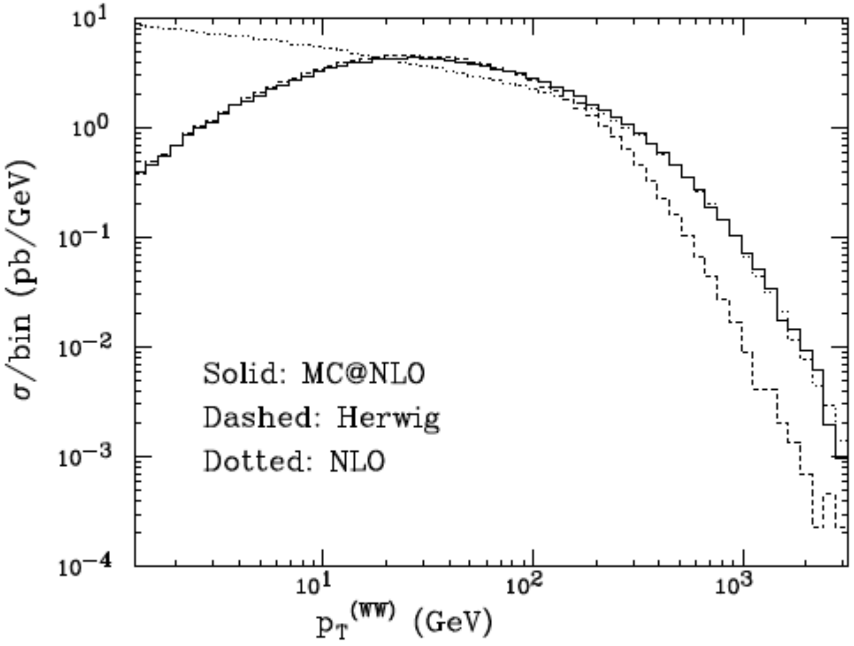
NLO matching:

- Combining NLO ME's +PS
- Both contain NLO contributions (double counting between LO+PS and NLO real emission)
- NLO matching: General description to obtain NLO+PS result without double counting
  MC@NLO,Powheg,+variants

NLO merging:

- Merges multiple NLO ME's + multiple LO ME's to the PS
  FxFx, MEPS@NLO,UNLOPS,...
  [Frederix,Frixione][Lavesson,Loennblad]
  [Loennblad,Prestel][Platzer]
  [Gehrmann,Hoeche,Krauss,Schoenherr,Siegert]

$pp \to W^+W^-$



[Frixione,Webber '02]

Note: Differences in approaches and methods of merging, matching scale, introduce theoretical uncertainties

Electroweak corrections at NLO

- Electroweak corrections important for Run 2

- NLO corrections mostly small for total cross section, but easily supersede QCD corrections in high pT tail
  (mostly due to incomplete cancellation of large logarithms)
  -> interesting region for new physics

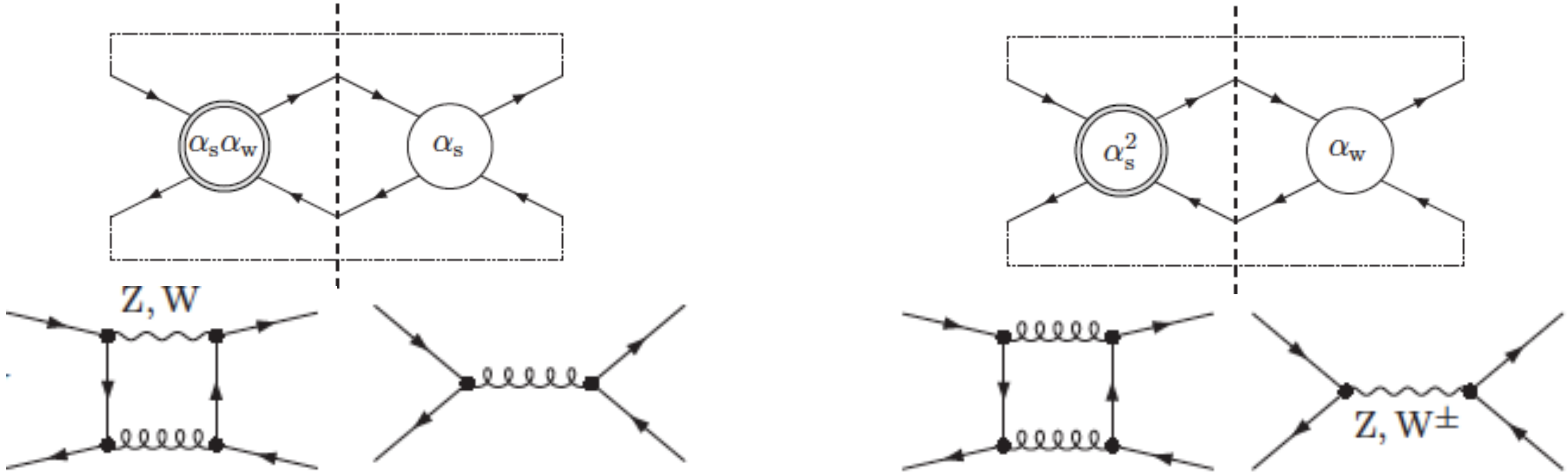
✓ Reduction strategies can applied to EW calculations without modification

BUT:

- Computation much more involved due to increased number of diagrams (photon/W/Z)
- In general mixing between QCD and EW corrections
  Need to sum up ALL contributions at a given order

Electroweak corrections at NLO

Simplest example: **Dijet production** [Dittmaier,Huss,Speckner]



- Need to sum up all possible contributions at a given order
- Conceptually clear, but subtle difficulties (different types of loop diagrams, subtraction terms proportional to interference term, etc..)

Conclusions

- Tremendous progress in NLO calculations within the last decade
- Calculation of NLO corrections highly automated
- So far mostly focused on QCD, but EW corrections field of highly active research
- Fixed order calculations mostly not sufficiently precise, inclusion of parton shower mandatory
- NLO + PS is the standard for LHC processes
- Next step: Automation of NNLO calculations....