Jet(s) with the CoLoRFulNNLO framework

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Motivation:

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Two-loop amplitude calculations are turning into mature age.

Examples:

- Specialized conferences, workshops: LoopFest, Amplitude, Feynman Memorial Meeting,...
- More and more papers addressing the case of five parton amplitudes at two-loop
- ...


ANNA GRAND HOTEL
BALATON2018 - FEYNMAN MEMORIAL MEETING
16-19.09.2018

Motivation:

As en masse production of two-loop amplitudes become more and more realistic: we need general frameworks for all the other parts of the NNLO computation too!

The orthodox (old fashioned) way of doing NNLO:

- A process of potential interest was picked
- The two-loop amplitude was being calculated [timeframe: ~ O(1) year]
- Meanwhile a fortran code was written or tailored from previous calculation to be suitable for the actual process
- Sewing pieces together and running it

And this is completely fine!

Motivation:

… As far as:

- Two-loop amplitude calculations take a lot of time
- Enough manpower to work from scratch/heavily modifying existing code
- Do not care about heavy debugging sessions
- …

If these are of concern it is much better to develop a general framework for NNLO computations.

Frankly, it can be screwed up a million places…

Motivation:

Ideally an NNLO framework should contain:

- General purpose phase space generator
  Not to build phase space by hand process by process
- Contains all necessary subtraction terms
  To be suitable for any process
- Capable of detecting all singular regions
  Not to hunt down singular regions by hand
- General facilities for histograms
  Using a format widely used and flexible, e.g.: YODA
- Scalable computation
  Should run on multicore up to HPC
- Local subtractions
  To improve stability and avoid severe numeric cancellations

Motivation:

The CoLoRFulNNLO framework has

- General purpose phase space generator ✅
  Not to build phase space by hand process by process
- Contains all necessary subtraction terms ✅
  To be suitable for any process
- Capable of detecting all singular regions ✅
  Not to hunt down singular regions by hand
- General histogramming facilities ✅
  Using a format widely used and flexible, e.g.: YODA
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  Should run on multicore up to HPC
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The CoLoRFulNNLO Framework

In CoLoRFulNNLO scheme no sector selector function is used

$\Longrightarrow$ all subtraction terms are defined in the whole phase space

$\Longrightarrow$Subtraction terms can develop singularities not only in their respective limit:

C_{ir} develops singularity in the limit of $\mathcal{C}_{irs}$

C_{irs} develops singularity in the limit of $\mathcal{C}_{ir}$

$$\left|\mathcal{M}^{\mathrm{RR}}\right|^2 - \cdots - C_{ir} - \cdots - C_{irs} - \ldots + C_{ir}C_{irs} \ldots$$

This is to remove oversubtraction

The CoLoRFulNNLO Framework

Because of delicate cancellations between various sub'n terms special care is needed when setting up parametrization

$\Longrightarrow$ 3-particle Sudakov parameters should go to the 2-particle Sudakov parameters in the respective limit.

Also, naive crossing does not work for the 3-particle Sudakov parameters. x_a can vanish in the bulk of RR phase space.

An elaborate choice has to be made for the 3-particle Sudakov parameters.

For further discussion see the talk and video of Gabor's talk at *Subtracting Infrared Singularities Beyond NLO*

MCCSM (Monte Carlo for the CoLoRFulNNLO Method):

CoLoRFulNNLO is just a possible scheme to do and organize NNLO computations $\Longrightarrow$ a numerical program is needed which implements it:

MCCSM:

Main features:

- Fully general
- Can treat radiation from both the final and initial state
- As input it only needs the matrix elements (and spin- and/or color correlated ones)
- Can be used with any PDF provider
- Computation with an arbitrary number of different scales at the same time
- Automatic calculation of PDF and scale uncertainties
- Several built-in checks to test ingredients

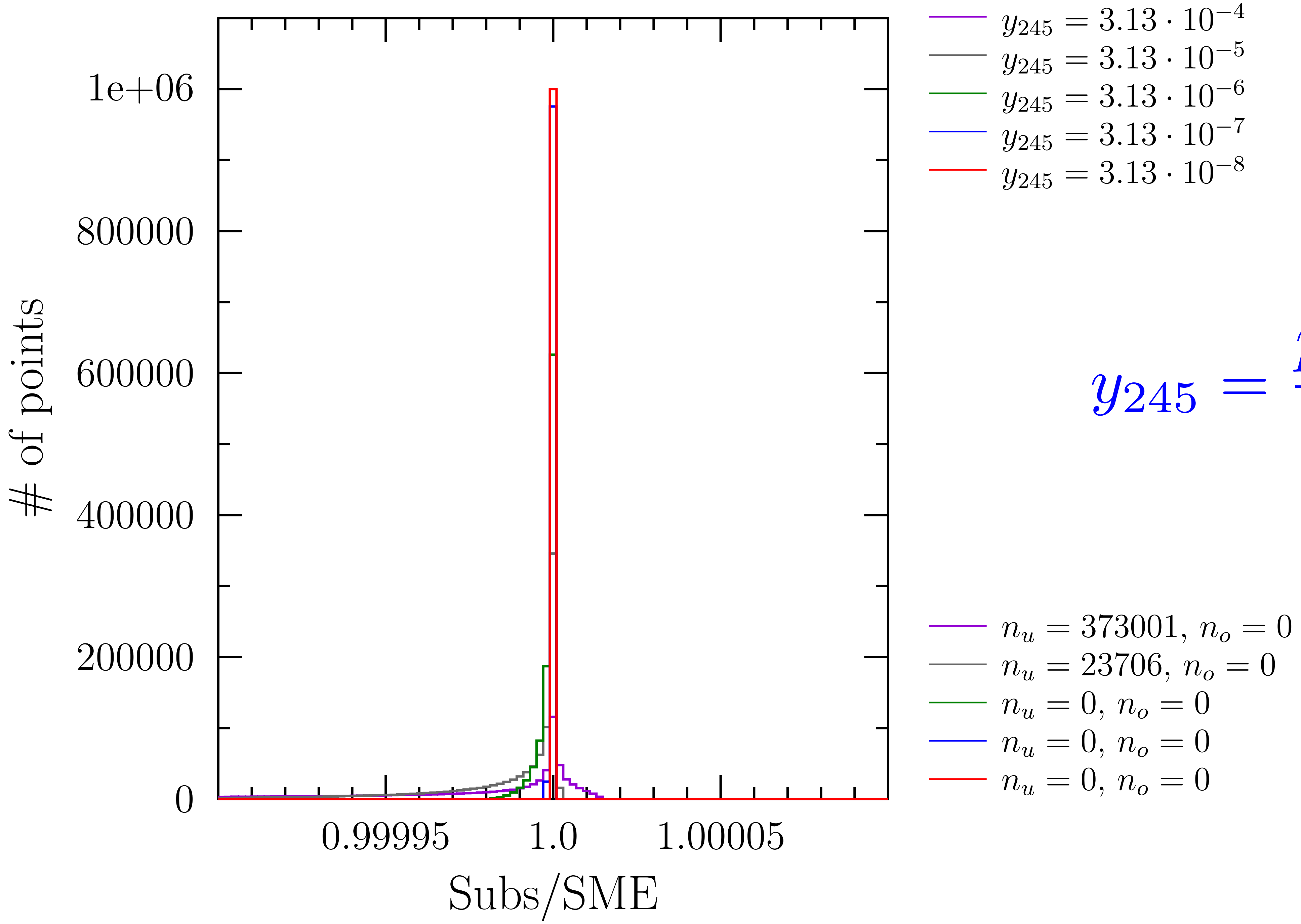
MCCSM:

Checking individual sub'n terms in the deep limit using quad precision:

```
iterm:     2 , g (1) -> g (1) || g (5)  ,  g (4) -> 0
UBorn: g  g  -> H
iexp=   2   1  , CSirs/RR=   0.894408622478533567923909543699053
iexp=   1   0  , CSirs/RR=   0.989656569458498378248160412268579
iexp=   0   0  , CSirs/RR=   0.998984087183573407744664784713080
iexp=   0   0  , CSirs/RR=   0.999899087219586988949483197210863
iexp=  -1   0  , CSirs/RR=   0.999989931061646012227618371658314
iexp=  -2  -1  , CSirs/RR=   0.999998993821207819442106652116466
iexp=  -3  -1  , CSirs/RR=   0.999999899404817688781093779226699
iexp=  -4  -2  , CSirs/RR=   0.999999989941200358268994615024347
iexp=  -5  -2  , CSirs/RR=   0.999999998994142768111304483657964
iexp=  -6  -3  , CSirs/RR=   0.999999999899414995753473129857948
iexp=  -7  -3  , CSirs/RR=   0.999999999989941522310943063961619
iexp=  -8  -4  , CSirs/RR=   0.999999999998994152949658537282741
iexp=  -9  -4  , CSirs/RR=   0.999999999999899415328433346439495
iexp= -10  -5  , CSirs/RR=   0.999999999999989941546867811958159
iexp= -11  -5  , CSirs/RR=   0.999999999999998993598252544730358
iexp= -12  -6  , CSirs/RR=   0.999999999999999902186411799426160
iexp= -13  -6  , CSirs/RR=   0.999999999999999929668481837946967
iexp= -14  -7  , CSirs/RR=   0.999999999999999789102229897554873
iexp= -15  -7  , CSirs/RR=   0.999999999999999821792914993393278l
iexp= -16  -8  , CSirs/RR=    1.00000000000000651192770454333835
```

MCCSM:

Checking rate of cancellation in multiple phase space points:



$$y_{245} = \frac{p_{245}^2}{Q^2}$$

The CoLoRFulNNLO/MCCSM Framework

The CoLoRFulNNLO framework was originally created for e^+e^- collisions with the following results achieved:

- EEC and Oblateness: Phys.Rev.Lett. 117 (2016) no.15, 152004: Del Duca, Duhr, AK, Somogyi and Trócsányi

- JCEF: Phys.Rev. D94 (2016) no.7, 074019: Del Duca, Duhr, AK, Somogyi, Szőr, Trócsányi and Tulipánt

- NNLL+NNLO for EEC: Eur.Phys.J. C77 (2017) no.11, 749: Tulipánt, AK and Somogyi

- α_S from EEC @ N^2LL+N^2LO: Eur.Phys.J. C78 (2018) no.6, 498: AK, Kluth, Somogyi, Tulipánt and Verbytskyi

Towards Hadronic Initial States

The CoLoRFulNNLO scheme is extended to accommodate LHC processes.

Colored initial states make a huge difference: radiation can also come from them! $\Longrightarrow$ We need more subtractions

The scheme is fully implemented in the MCCSM numerical code.

To set foot on LHC land two processes were chosen having key importance:

- $W^{\pm}$ production
- Higgs production in gluon-gluon fusion

The kinematics is special ($2 \to 1$) but perfect to test new subtractions.

Preliminary Results for the LHC:

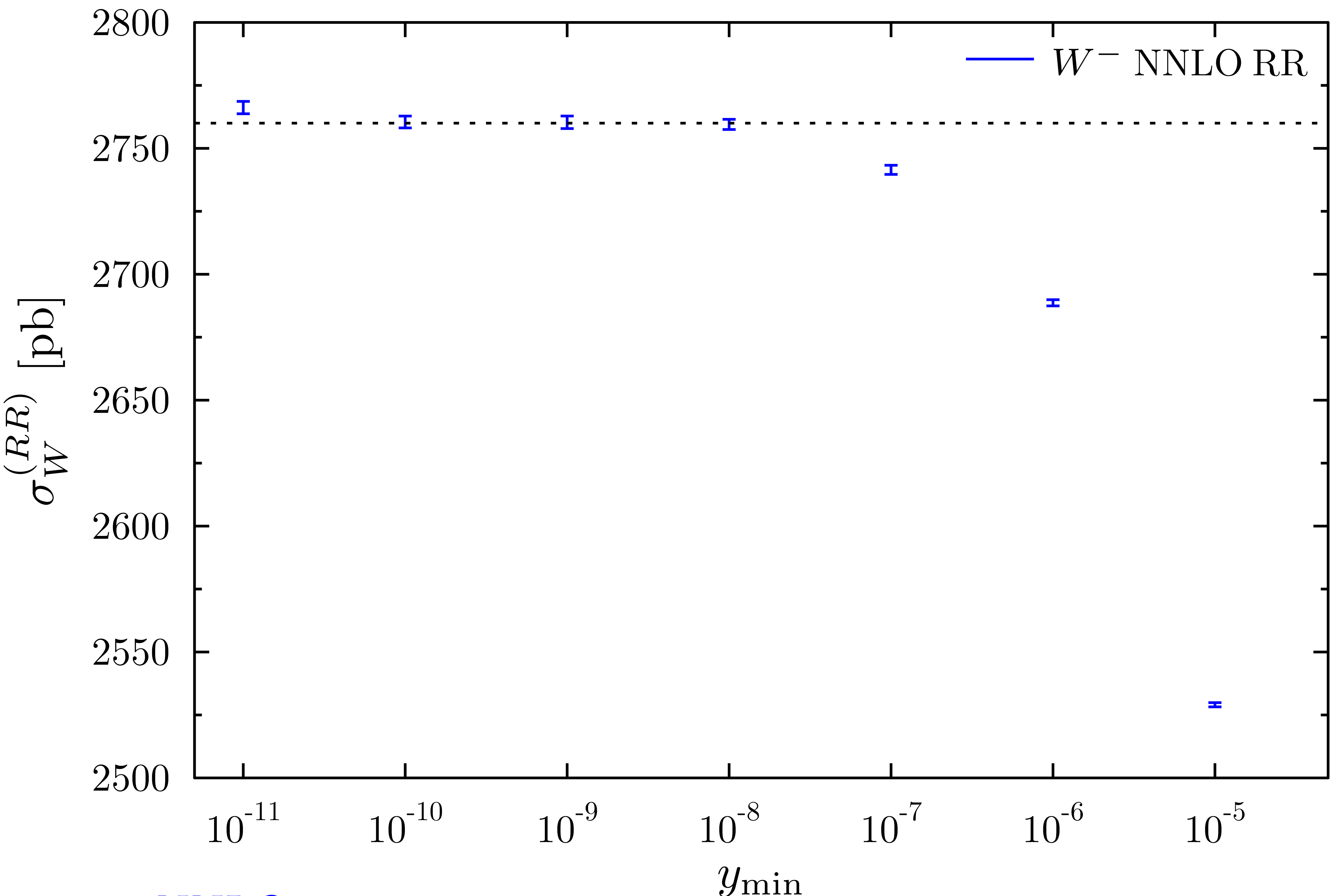
- Every computation beyond LO has a technical cutoff parameter: determining how close we allow particles to get to each other.

$$y_{\mathrm{min}} = \min_{i,\,j} \frac{(p_i + p_j)^2}{Q^2} > y_{\mathrm{cut}}$$

where y_{cut} is between 10^{-6} and 10^{-8}.

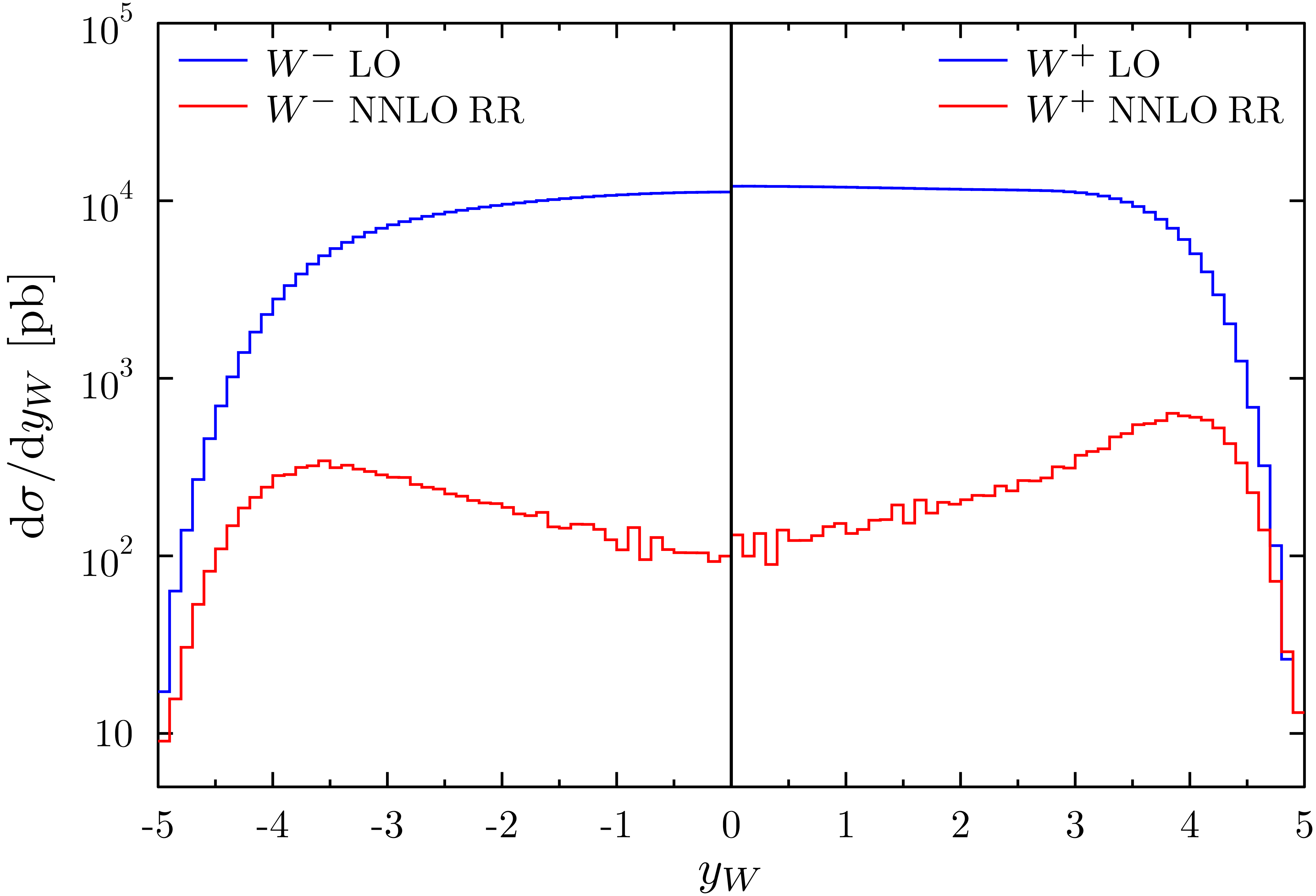
- Note that this is not a slicing but a technical cutoff parameter.
- It is necessitated by floating point arithmetics.
- If the sub'n terms are correct the dependence upon y_{cut} should go away as it is decreased.
- The minimal possible value of y_{cut} depends on the floating point arithmetics

Saturation for W Production:



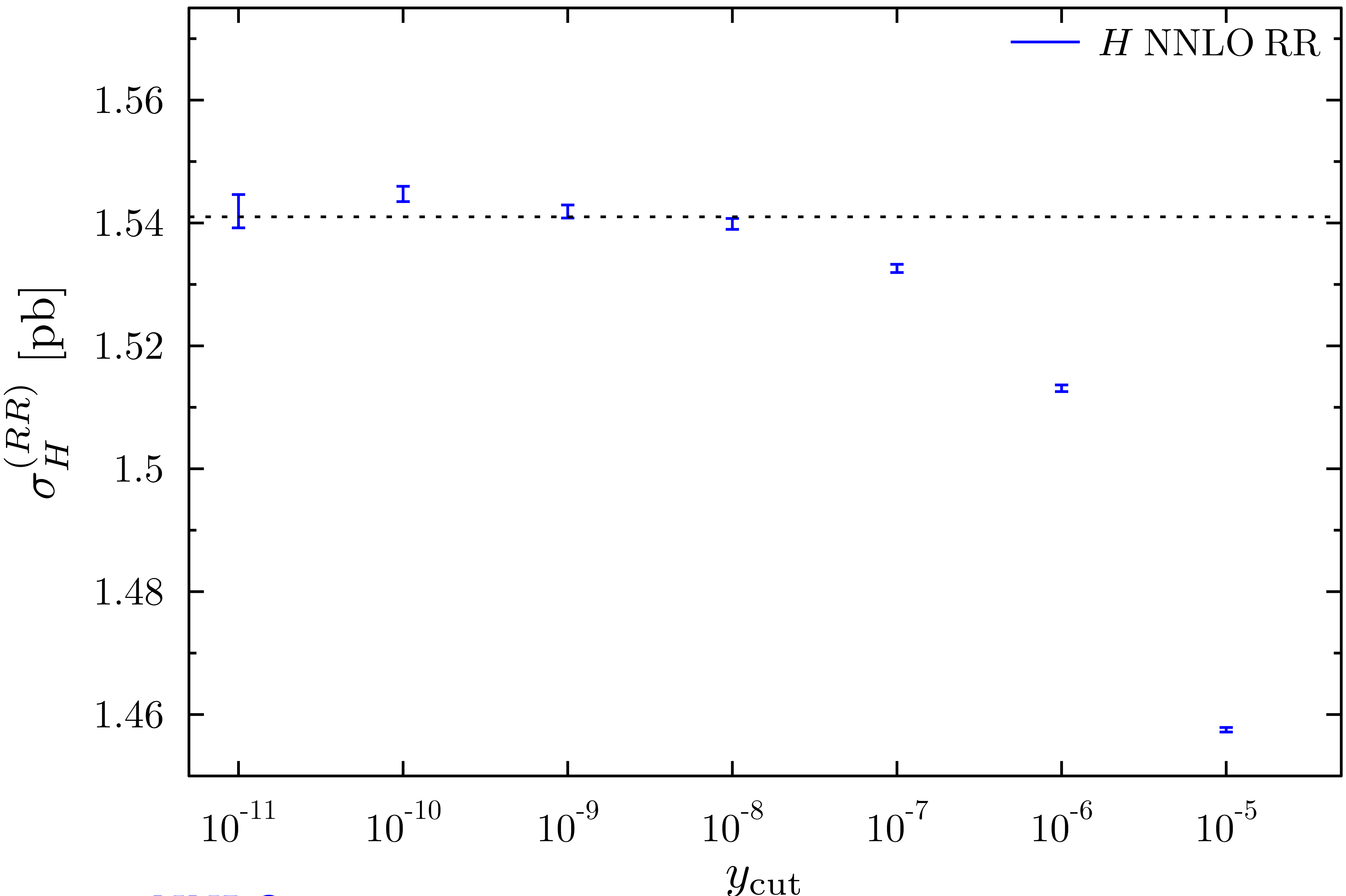
$\sigma_{\mathrm{RR}}^{\mathrm{NNLO}}$ as a function of phase space cutoff parameter

Rapidity Distribution of W:



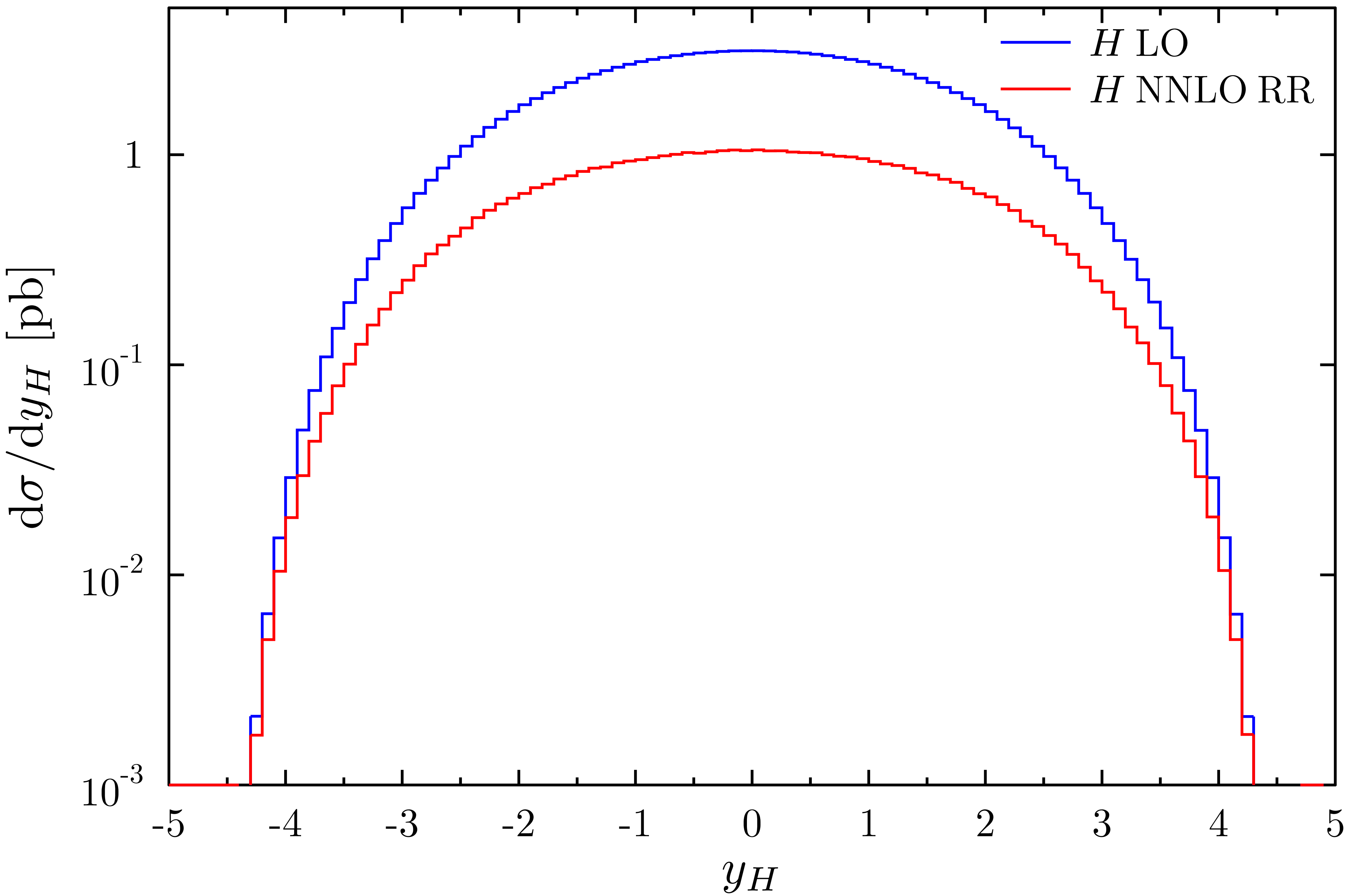
Note that this is only one contribution (RR). To get the total NNLO correction we need two more contributions.

Saturation for Higgs Production:



$\sigma_{\rm RR}^{\rm NNLO}$ **as a function of phase space cutoff parameter**

Rapidity Distribution of the Higgs:



Note that this is only one contribution (RR). To get the total NNLO correction we need two more contributions.

What can be done with jets at NNLO?

work done in collaboration with
G. Somogyi and Z. Trócsányi

Based upon: arXiv:1807.11472

What Can Be Done With Jets at NNLO?

Nowadays there is a lot of activity around jets, naming a few:

- Jet substructure
- Filtering, pruning, filtri-pruning
- Fat jets
- Deep learning
- …

The NNLO calculation of these observables is quite challenging!

Soft-Dropped Observables

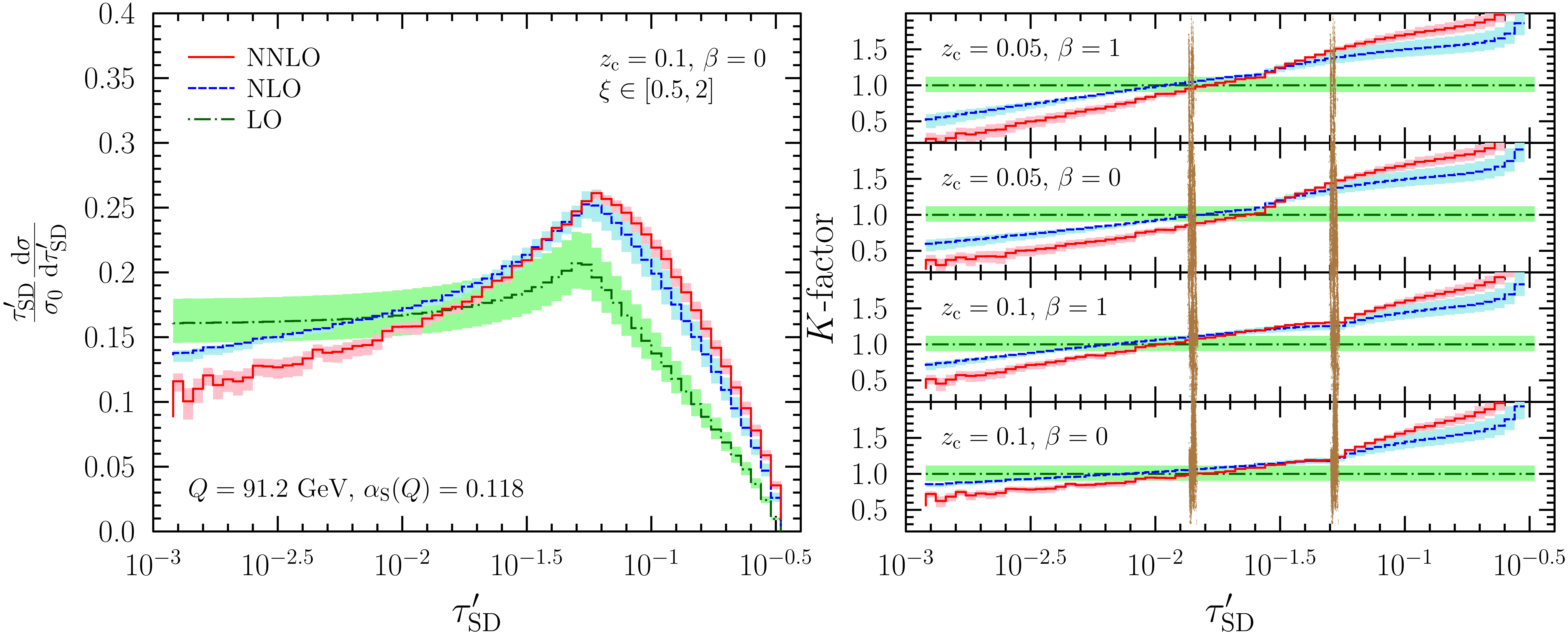
Different sub'n term groups have different phase space mappings from the RR PS to the Born/Real one per phase space point $\Longrightarrow$ the analysis has to be run several times.

In the analysis there is not just a jet clustering but we have to store all the pseudojets to undo mergings

Undoing mergings, removing soft content, recomputing observables all take much time!

Numerics is very-very challenging for these very complicated observables!

Soft-Dropped Thrust



Soft-dropped thrust distribution for z_c=0.1, β=1 and K-factors for different (z_c, β) pairings

For details see Zoltán Trócsányi's talk from yesterday!

Summary

- The CoLoRFulNNLO method is extended to hadronic initial states.
- Stability and cancellation of kinematic singularities are demonstrated with W and Higgs-production.
- The robustness of the method is demonstrated on calculating soft-dropped observables in electron-positron annihilation.
- Have to apply the method even to 2→2 processes.
- Have to integrate the subtraction terms.

Thank you for your attention!