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:

- The previous talk: Two-loop five-gluon helicity amplitudes by Hartanto and references therein
- Chawdhry, Lim and Mitov: Two-loop five-point massless QCD amplitudes with IBP, arXiv:1805.09182
- ....

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
- Contains all necessary subtraction terms
- Capable of detecting all singular regions
- General histogramming facilities
- Parallelizable
- Local subtractions for stability

The CoLoRFulNNLO Framework

The CoLoRFulNNLO framework has

- General purpose phase space generator ✅
- Contains all necessary subtraction terms ✅
- Capable of detecting all singular regions ✅
- General histogramming facilities ✅
- Parallelizable ✅
- Local subtractions for stability ✅

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 being 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 ($2 \rightarrow 1$) but perfect to test new subtractions.

Preliminary Results for the LHC:

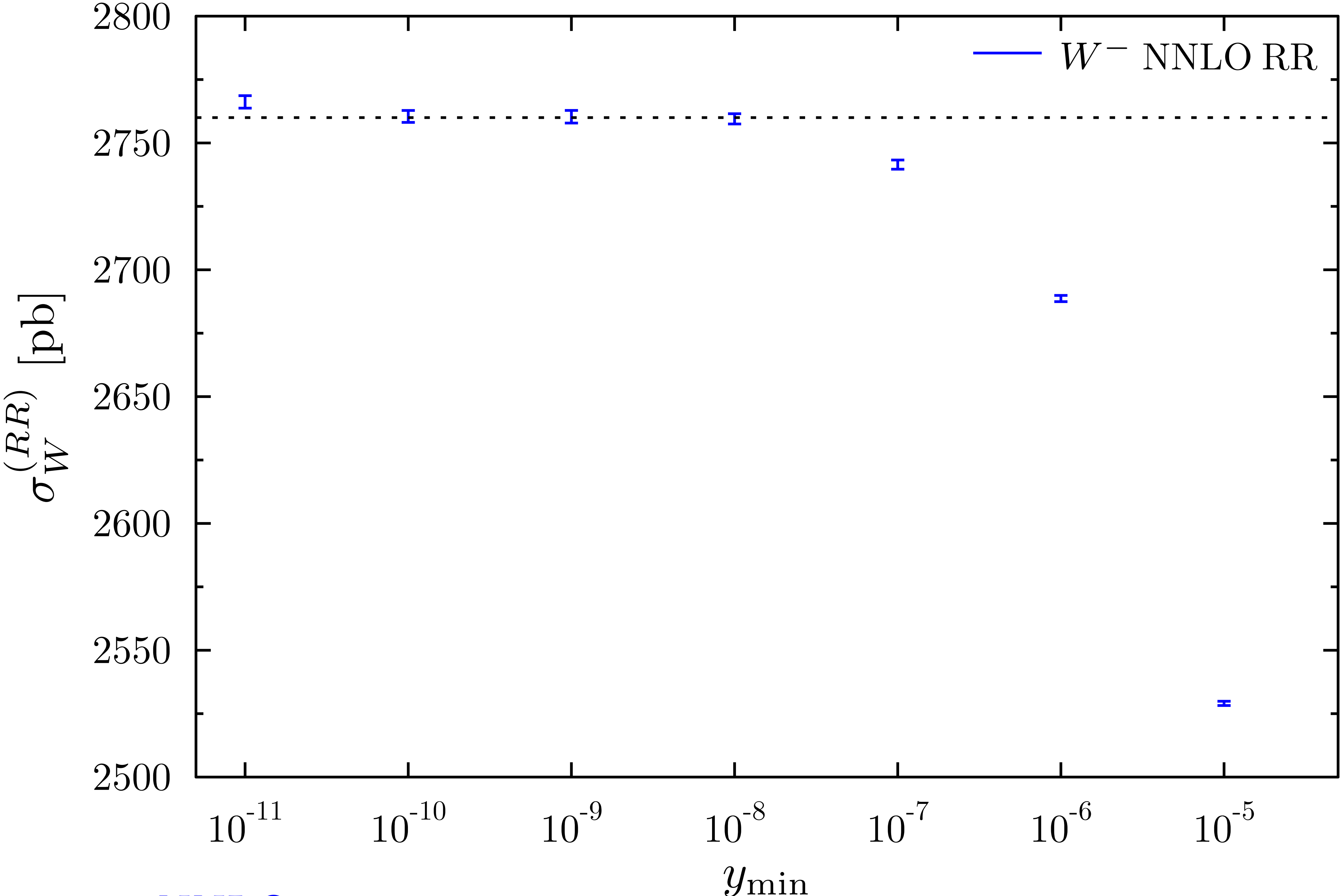
- Every computation beyond LO has a technical cutoff parameter: determining how close we allow particles to get to each other.

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

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

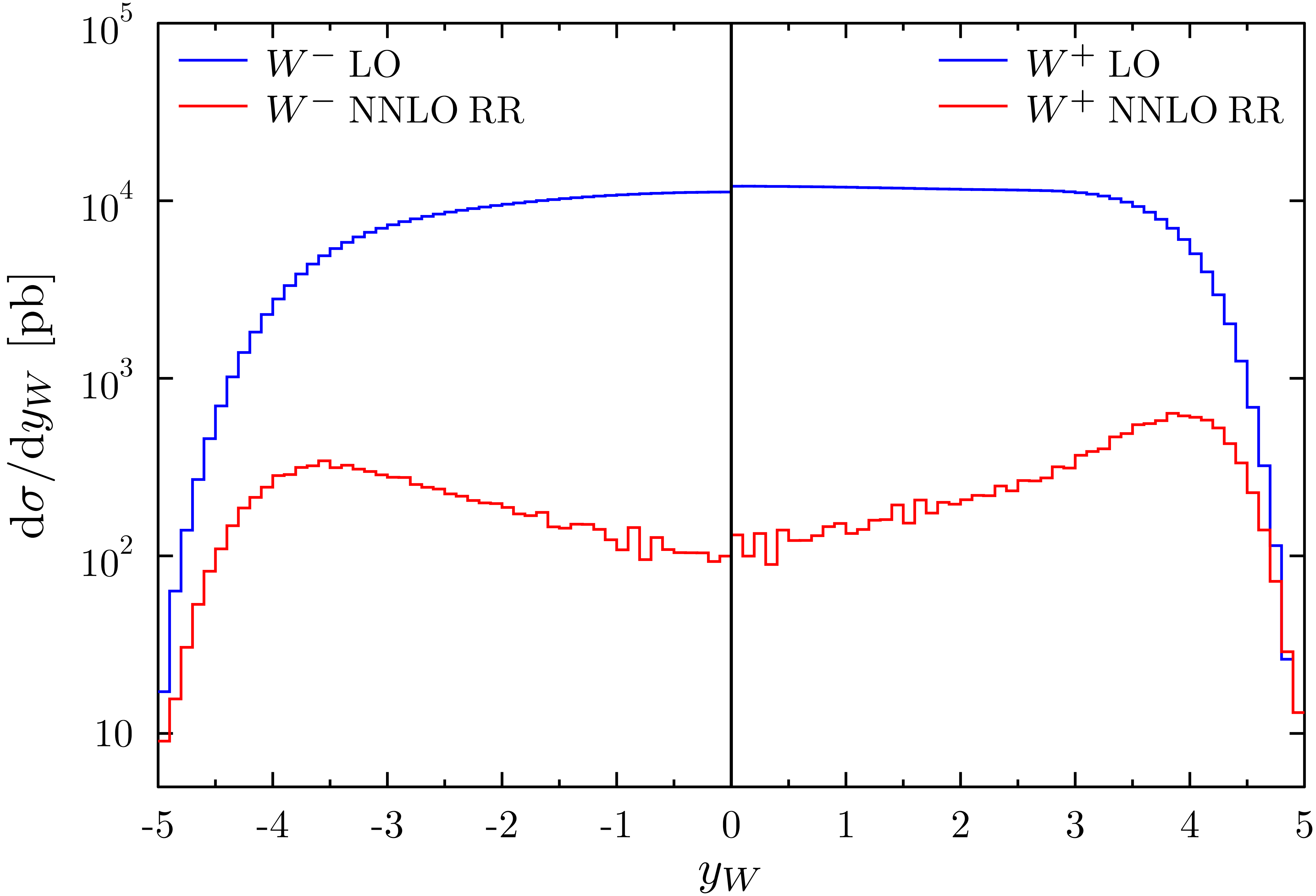
- Note that this is not a slicing but a technical cutoff parameter.
- It is necessitated by floating point arithmetics.
- If the subterms are correct the dependence upon y_{cut} should go away as it is decreased.
- The minimal possible value of y_{cut} depends on the floating point arithmetics

Saturation for W Production:



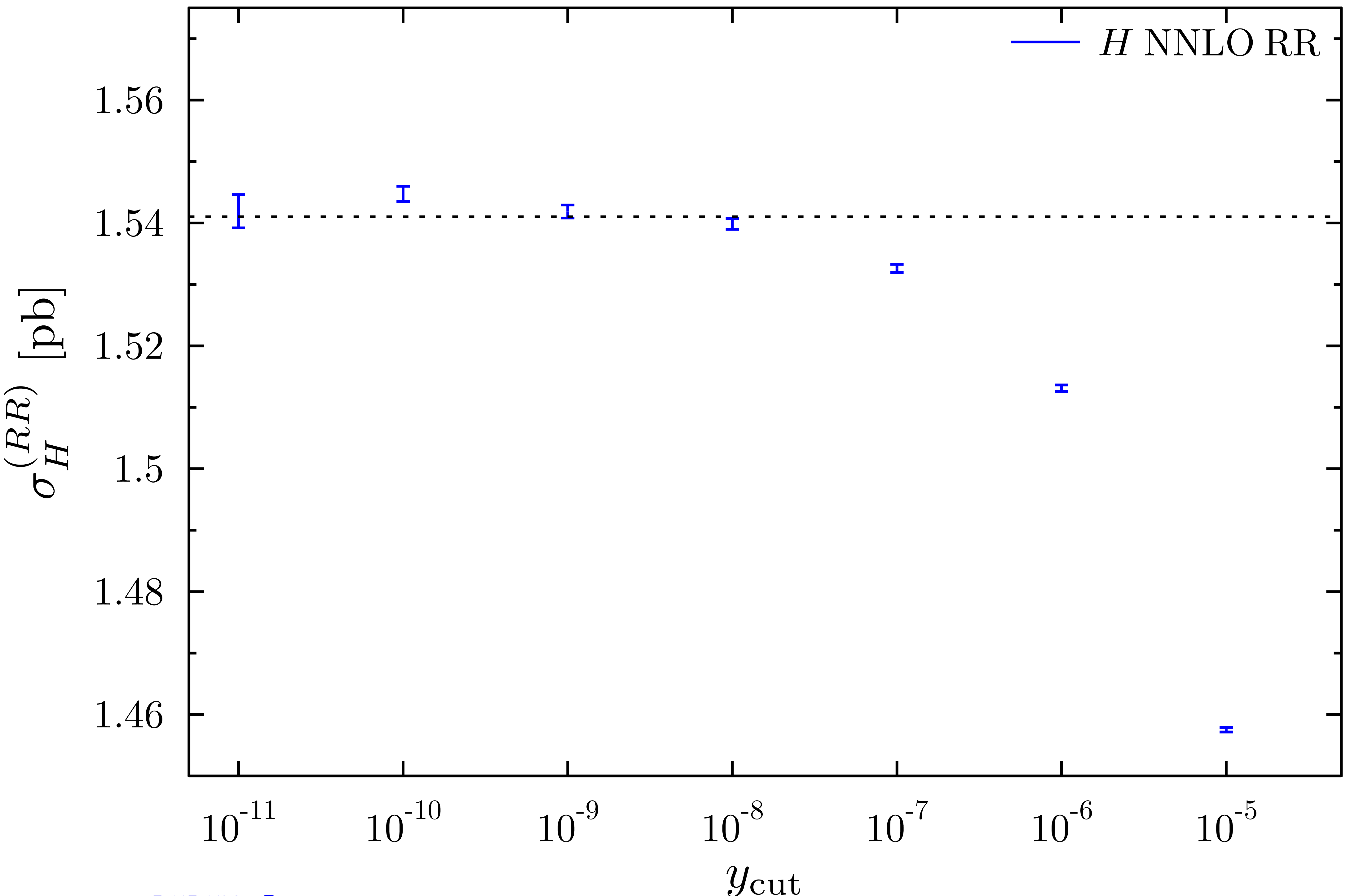
$\sigma_{\mathrm{RR}}^{\mathrm{NNLO}}$ **as a function of phase space cutoff parameter**

Rapidity Distribution of W:



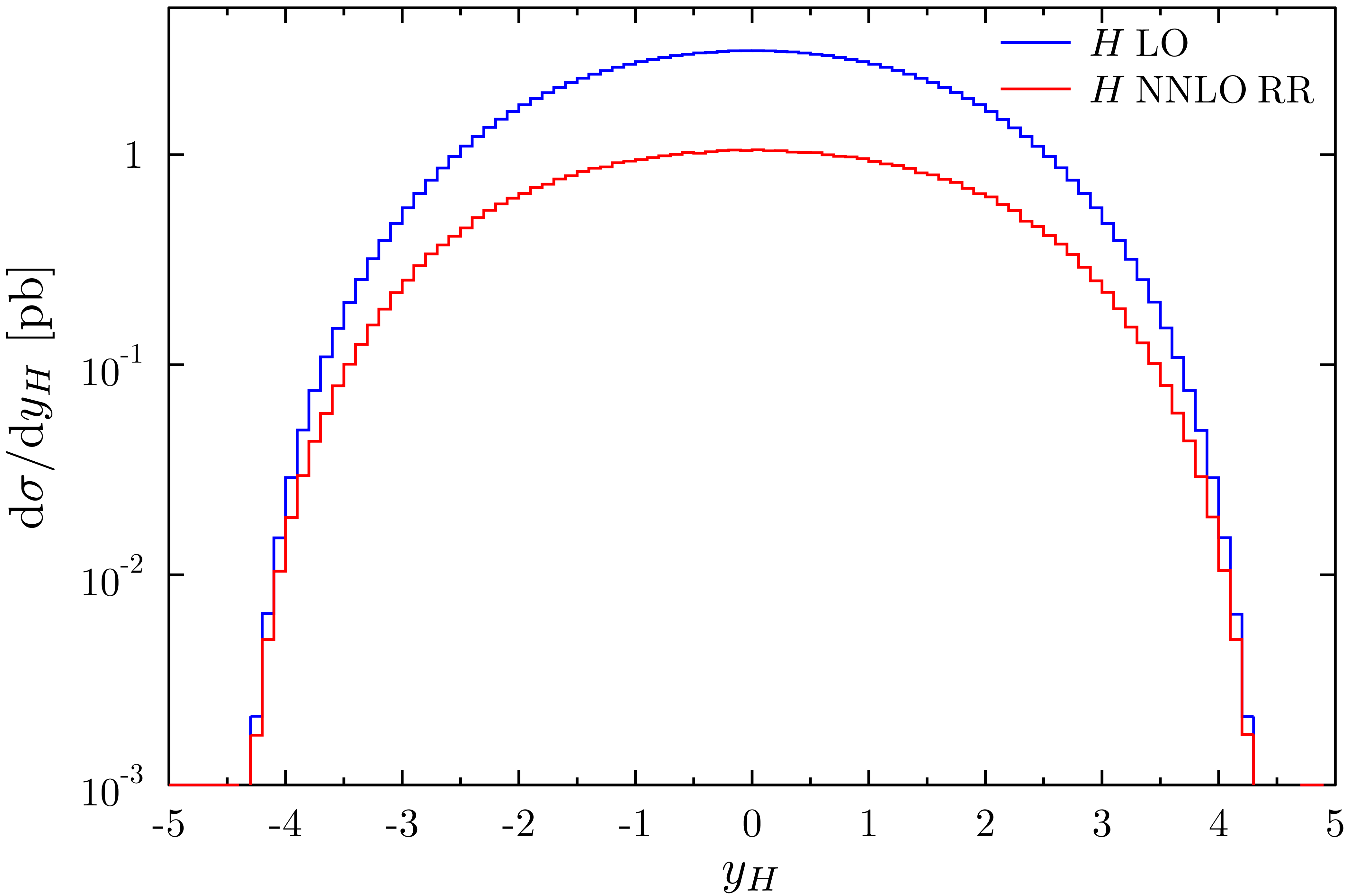
Note that this is only one contribution (RR). To get the total NNLO correction we need two more contributions.

Saturation for Higgs Production:



$\sigma_{\text{RR}}^{\text{NNLO}}$ 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
- ...

An NNLO calculation is complex: it uses several different PS mappings per PS points $\Longrightarrow$ analysis have to be run several times per PS point

Range of observables can be limited if numerics is slow...

In the following we consider soft-dropped observables

Soft-Dropped Observables

This kind of grooming is introduced by

Larkoski, Marzani, Soyez and Thale, JHEP 1405 (2014) 146

Applied to jets produced in lepton collisions by

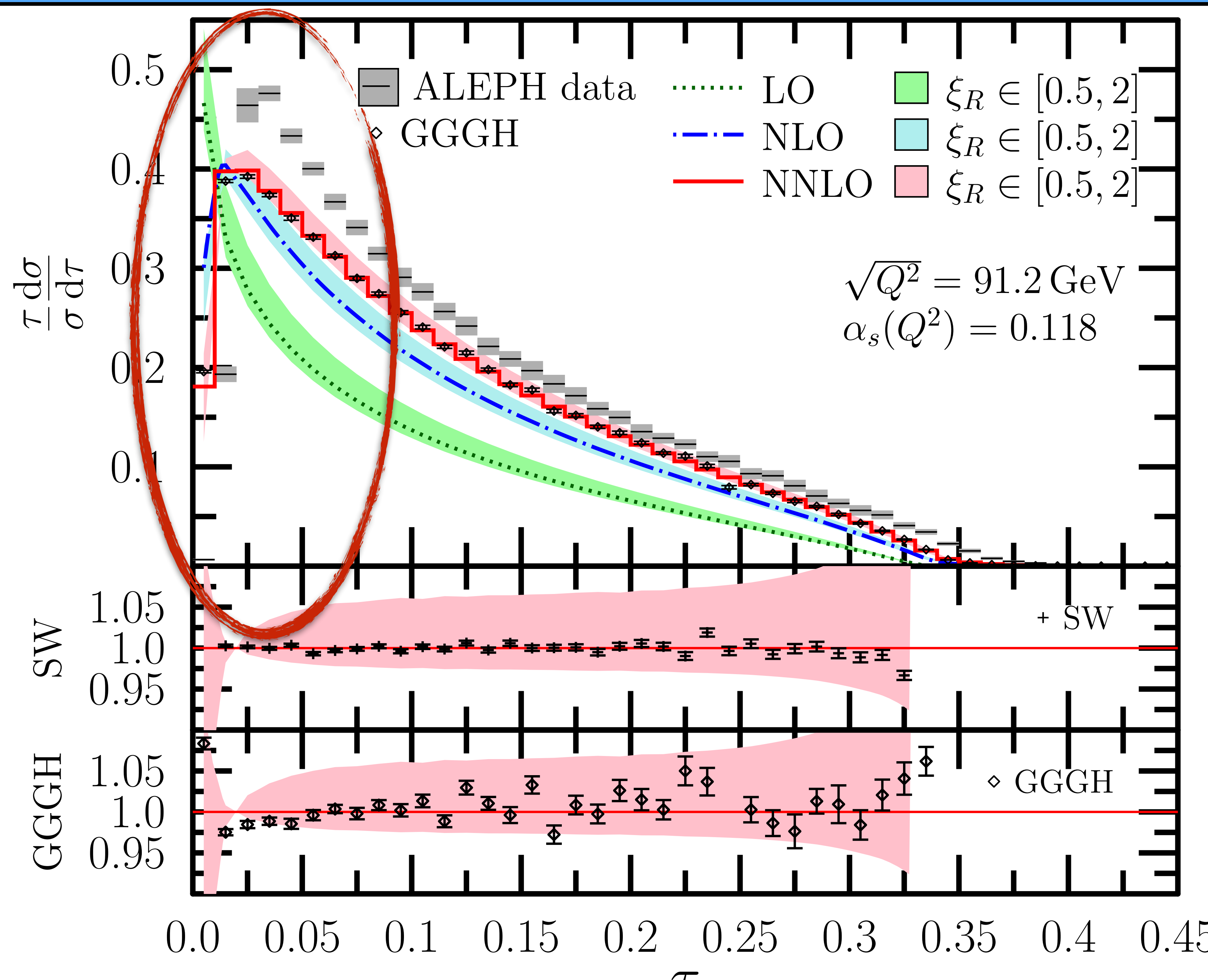
Frye, Larkoski, Schwartz, and Yan, JHEP 1607 (2016) 064

and applied to thrust, hemisphere jet and narrow jet mass in

Baron, Marzani, Theeuwes, JHEP 1808 (2018) 105

The idea is (roughly): where the event shape distribution peaks the hadronization corrections are large (vast majority of events is here!). These are tough to estimate $\Longrightarrow$ Try to get rid of as much hadronization as possible without affecting the cross section.

Soft-Dropped Observables



Thrust (1-T) distribution peaking where hadronization is important

Soft-Dropped Observables

Alternatively, can be thought of soft-dropped observables as a proof of concept for a NNLO scheme because these are tough to calculate:

Having a jet with radius R, undoing the last merging and evaluating the relation:

$$\frac{\min\left[E_i, E_j\right]}{E_i + E_j} > z_{\rm cut}\left(\frac{1-\cos\theta_{ij}}{1-\cos R}\right)^{\beta/2} \text{ or } z_{\rm cut}\left(1-\cos\theta_{ij}\right)^{\beta/2}$$

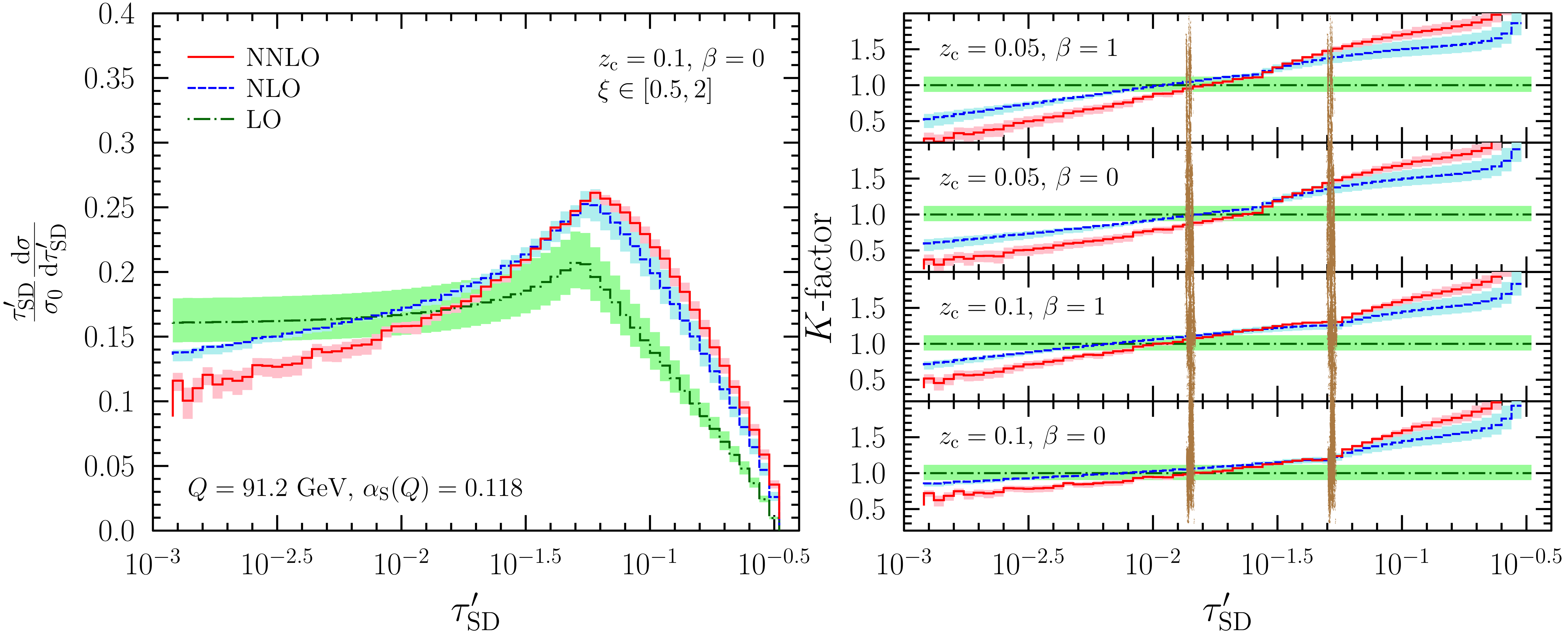
If False: softer pseudojet is dropped and continue with harder one

If True: there is no soft content to be stripped off

For details, see Baron et al., JHEP 1808 (2018) 105

The analysis is far from trivial: jet clustering with storing all the intermediate pseudojets than perform the soft-dropping

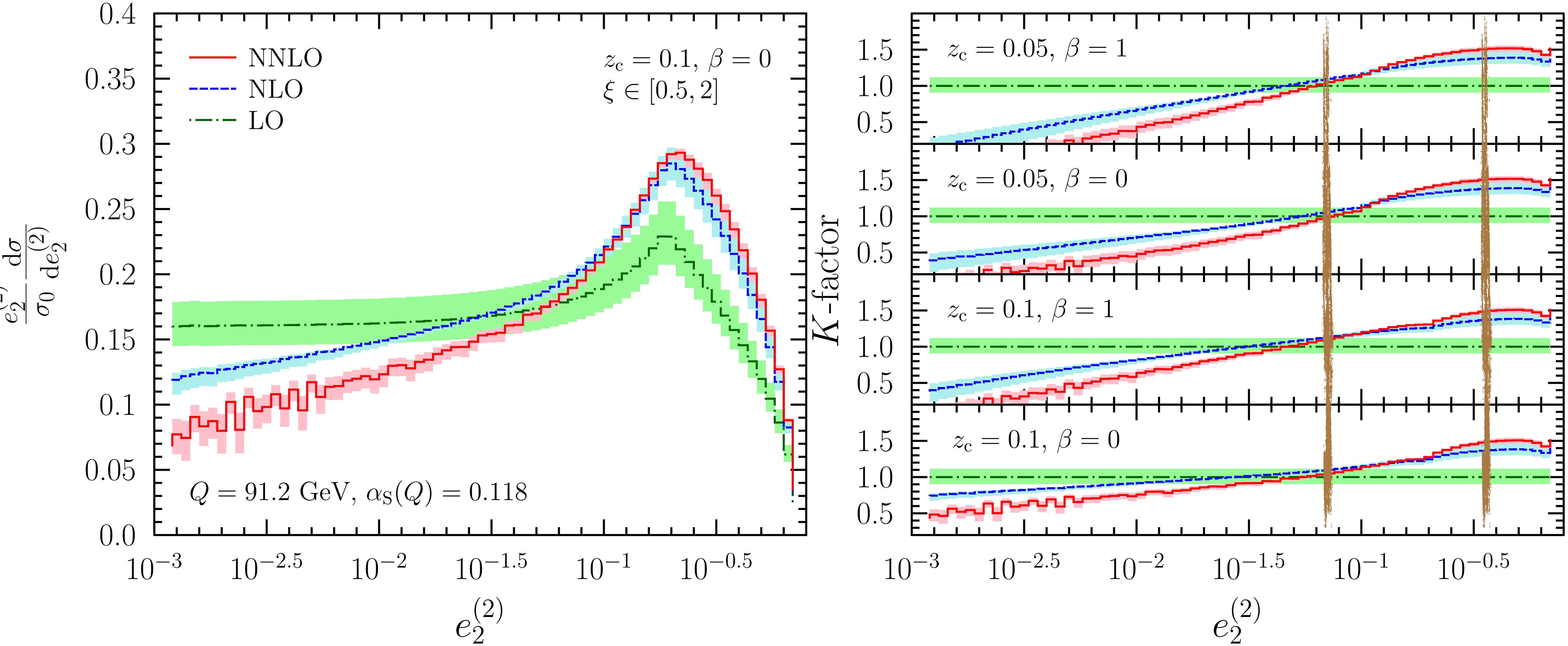
Soft-Dropped Thrust



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

For all cases there is a region with good perturbative stability and modest contribution from hadronization.

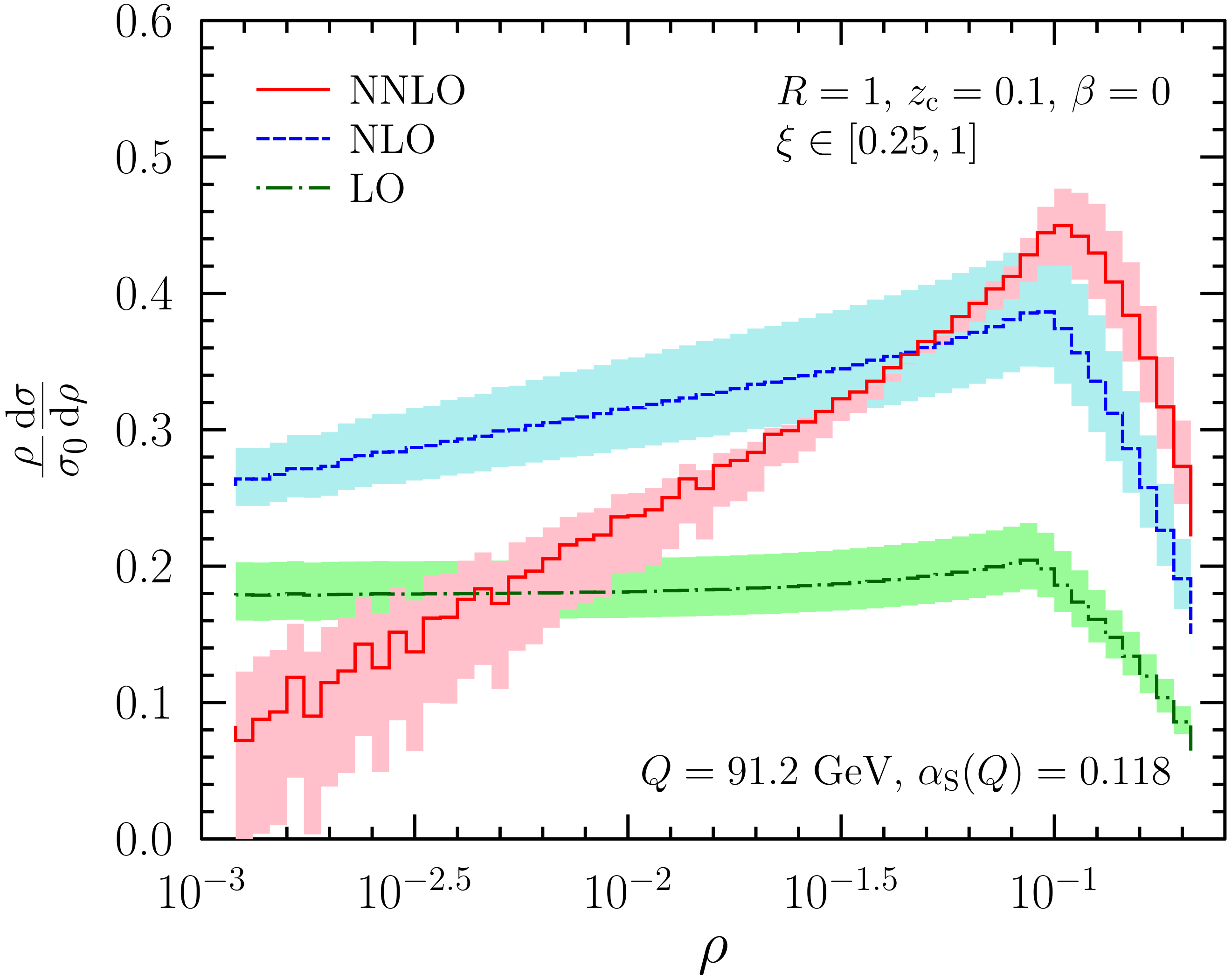
Soft-Dropped Hemisphere Mass

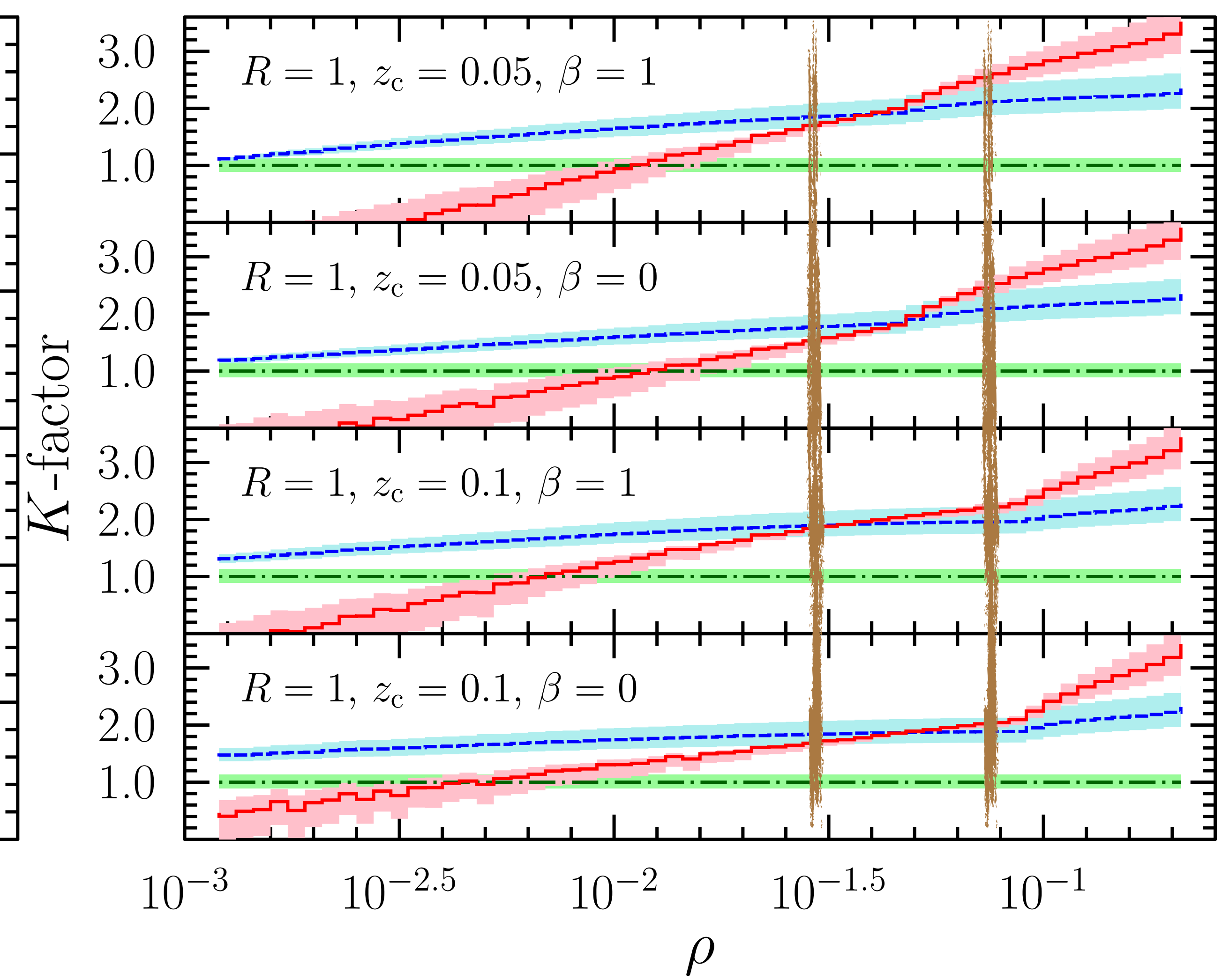


Soft-dropped hemisphere mass distribution for z_c=0.1, β=1 and K-factors for different (z_c, β) pairings

For all cases there is a region with good perturbative stability and modest contribution from hadronization.

Soft-Dropped Narrow-Jet Mass





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

For all cases there is a region with good perturbative stability and modest contribution from hadronization.

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.
- A suggestion is given for soft-dropped parameters could be used to extract α_S from soft-dropped event shapes.
- Have to apply the method even to 2→2 processes.
- Have to integrate the subtraction terms.

Thank you for your attention!