Precision Measurements – Theory

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Istituto Nazionale di Fisica Nucleare

Outline

- Lots of interesting talks, discussions, results, comparisons, back-of-the-envelope calculations, arguments, etc.
- My apologies if I don’t do justice to / don’t get a chance to mention something that you presented/are working on...

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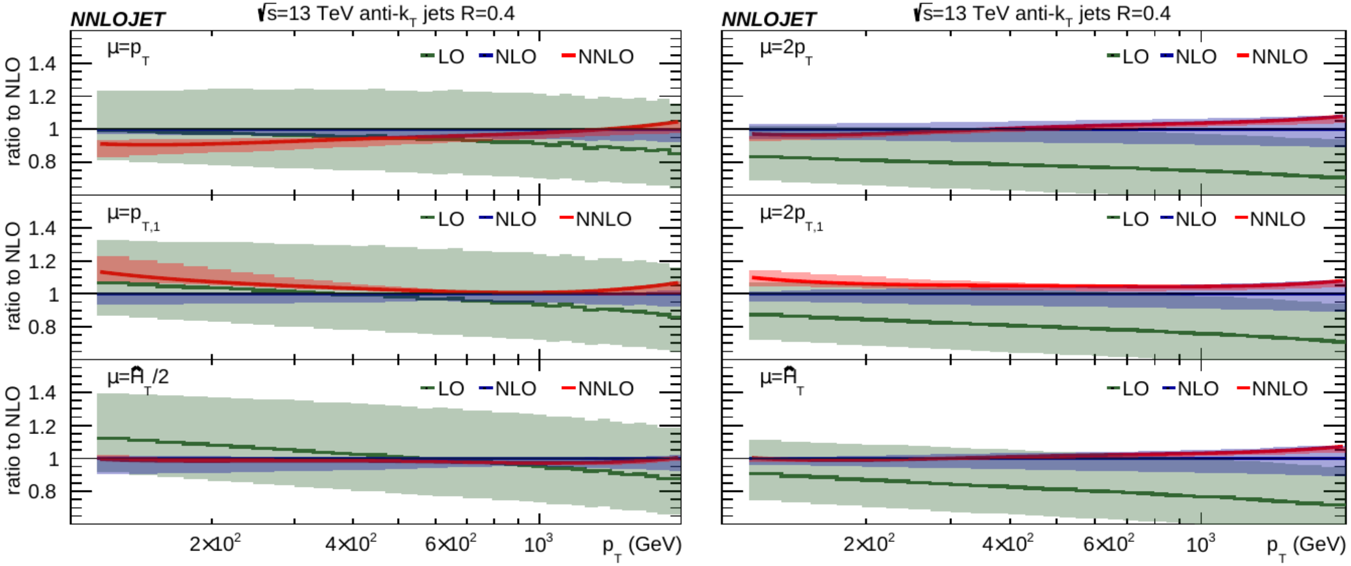
- Scale choices in inclusive jet production
- Improved estimates of theory uncertainties
- Multiloop-MC “Interface”
- Multiloop review
- Polarized dibosons
- LH2025 Wishlist

Scale choice for inclusive jet production



[Currie et al '18]

- Perturbative convergence of single jet inclusive production improves with "good" central scale choice.

Is this a reliable statement on perturbative convergence?
Or just accidental?

Talk by Terry

Scale choice for inclusive jet production

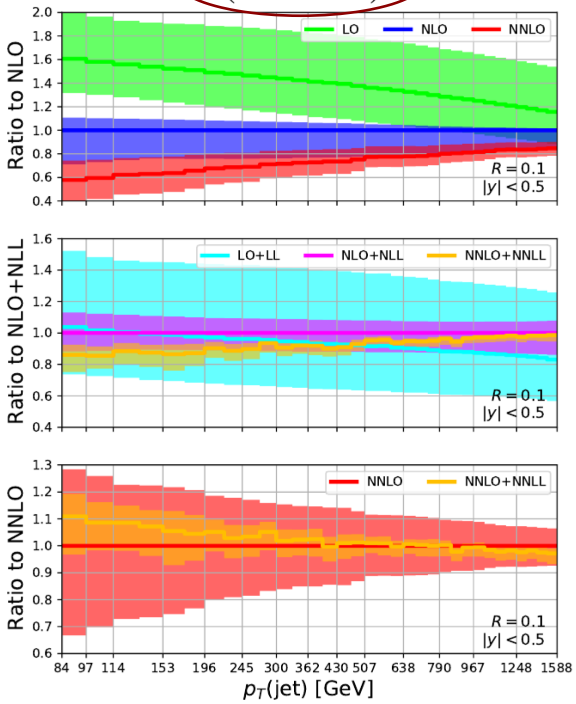
- NNLO + NNLL_R implemented in `STRIPPER` using fragmentation functions.

  [Generet et al ‘25]

For narrow jets:

- substantial corrections from resummation;
- improved perturbative convergence.

$\sigma(R = 0.1)$



Talk by Terry

Scale choice for inclusive jet production

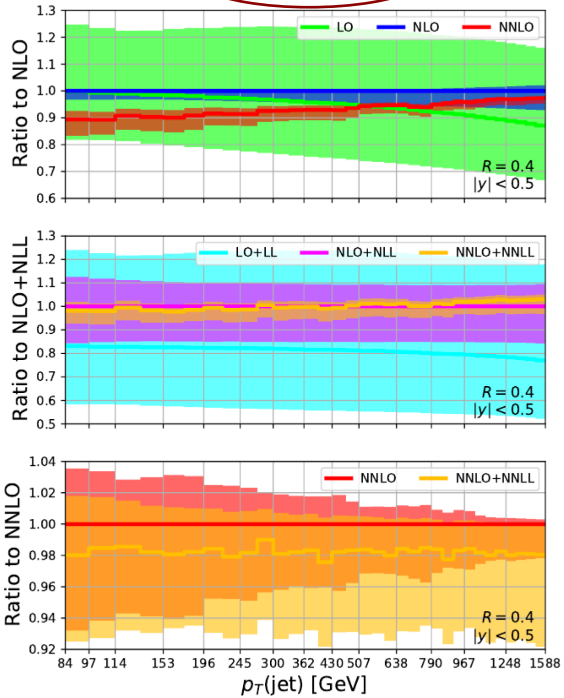
- NNLO + NNLL$_R$ implemented in `STRIPPER` using fragmentation functions.

  [Generet et al '25]

For mid-sized jets:

- smaller corrections from resummation.
- naive uncertainty increases (but more realistic)
- improved perturbative convergence.

$\sigma(R = 0.4)$



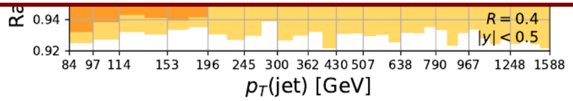
Talk by Terry

Scale choice for inclusive jet production

- N

What have we learned?

1. Resummation effects can be substantial even in regions where FO appears to converge well;
2. "Good behavior" of FO should be independent of the central scale choice;
3. Need a better means of estimating theory uncertainties which would capture effects of central scale choice, cancellations, etc.

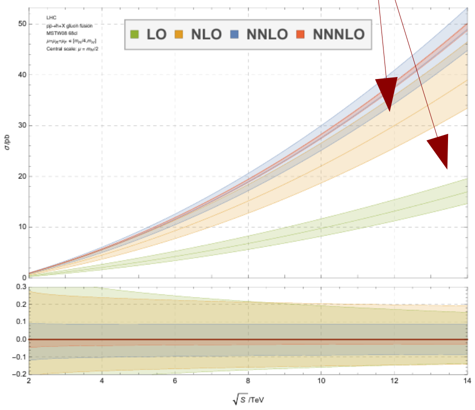


Talk by Terry

Theoretical Uncertainties

- Traditional scale variation frequently fails to capture missing higher (fixed) order corrections
  - Frequently explained *a posteriori*

    “Large color factors, new channels opening up,…”
- Especially true for uncertainties on shapes of distributions.



- Experimental uncertainties becoming comparable to those from theory (from advanced, challenging calculations).
- Reliable theoretical predictions should come with reliable uncertainties (ideally easily included in experimental analysis).

Theoretical Uncertainties

Requirements for theoretical uncertainties:

- Decrease with improved theoretical knowledge;
- Reflect uncertainty of current state-of-the-art predictions;

  (Current SotA might be accidentally close to all-order result, but uncertainty could still be large.);
- Correlated, e.g. in differential distributions ($\rightarrow$ uncertainties on shapes);
- Have statistical meaning;
- ...

[Tackmann ‘24]

See also [Cacciari, Houdeau, ‘11; Bonvini ‘20; Duhr, Huss, Mazeliauskas, Szafron ‘21] for “Bayesian approach”

Theoretical Nuisance Parameters

$$f(\alpha) = f_0 + f_1\,\alpha + f_2\,\alpha^2 + f_3\,\alpha^3 + \mathcal{O}(\alpha^4)$$

Talk by Frank

LO: $f(\alpha) = \hat{f}_0$

NLO: $f(\alpha) = \hat{f}_0 + \hat{f}_1\,\alpha$

NNLO: $f(\alpha) = \hat{f}_0 + \hat{f}_1\,\alpha + \hat{f}_2\,\alpha^2$

Calculated with much pain and effort.

Theoretical uncertainty

$\mathrm{N}^{1+1}\mathrm{LO}$: $f(\alpha, f_2) = \hat{f}_0 + \hat{f}_1\,\alpha + f_2\,\alpha^2$

$\mathrm{N}^{1+2}\mathrm{LO}$: $f(\alpha, f_2, f_3) = \hat{f}_0 + \hat{f}_1\,\alpha + f_2\,\alpha^2 + f_3\,\alpha^3$

$\mathrm{N}^{2+1}\mathrm{LO}$: $f(\alpha, f_3) = \hat{f}_0 + \hat{f}_1\,\alpha + \hat{f}_2\,\alpha^2 + f_3\,\alpha^3$

“One plus one is not two” – anonymous.

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Theoretical Nuisance Parameters

Talk by Frank

Unknown (but knowable) quantity $f_n(x, \theta_n)$

Physical parameters (partonic channels, number of colors/flavors, masses, kinematic distributions...)

TNPs

TNPs have true but unknown values such that $\hat{f}_n(x) = f_n(x, \hat{\theta}_n)$

(i.e. performing higher order calculations means fixing TNPs to true values)

Theoretical Nuisance Parameters

1. Derive TNP parametrization

Talk by Frank

Dependence of f on x encoded through TNPs.

- Explicit parametrization (e.g. color factors, partonic channels, …)
- From knowledge of limits
- Expansion in basis of complete orthogonal functions (with truncation → "uncertainty on uncertainty")

2. Constrain TNPs:

$$\theta_n = u_n \pm \Delta u_n$$

- Can fit to data…
- … but nice to have theory estimate.

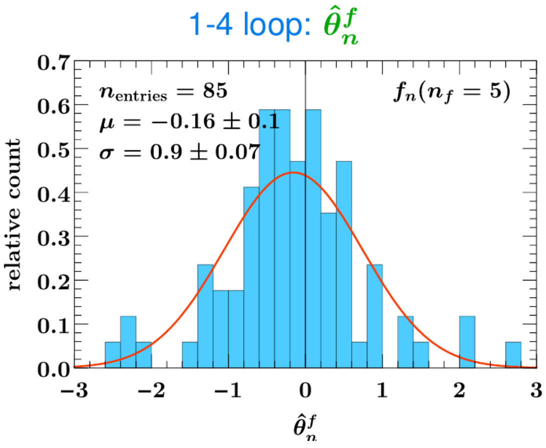
Theoretical Nuisance Parameters

Talk by Frank

Scalar series $f_n(\theta_n) = N_n\, \theta_n$ with normalization such that $|\hat{\theta}_n| \lesssim 1$

Impose $\theta_n = u_n \pm \Delta u_n = 0 \pm 1$ and model as a Gaussian.

Validation: using known 4-loop results for DY, ggH, $q\bar{q}H$



Theoretical Nuisance Parameters

Application to fixed-order computations

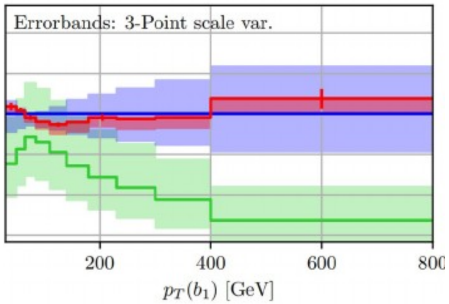
[Lim, Poncelet '24]

Talk by Rene

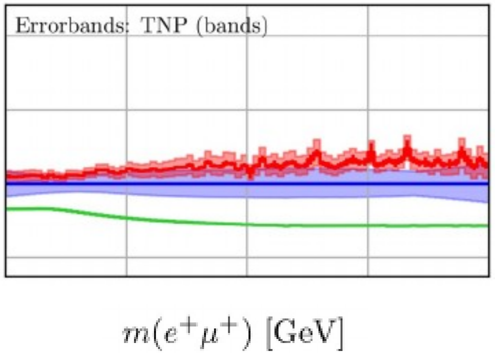
- Observe that (differential) k-factors ~ 1.
- Parametrize shape change using basis of Bernstein / Chebyshev polynomials

$$\frac{d\bar{\sigma}^{(N+1)}_{\mathrm{TNP}}}{d\bar{\sigma}^{(0)}} = \sum_{j=1}^{N} f_k^{(j)}\left(\vec{\theta}, x\right)\left(\frac{d\bar{\sigma}^{(j)}}{d\bar{\sigma}^{(0)}}\right)$$

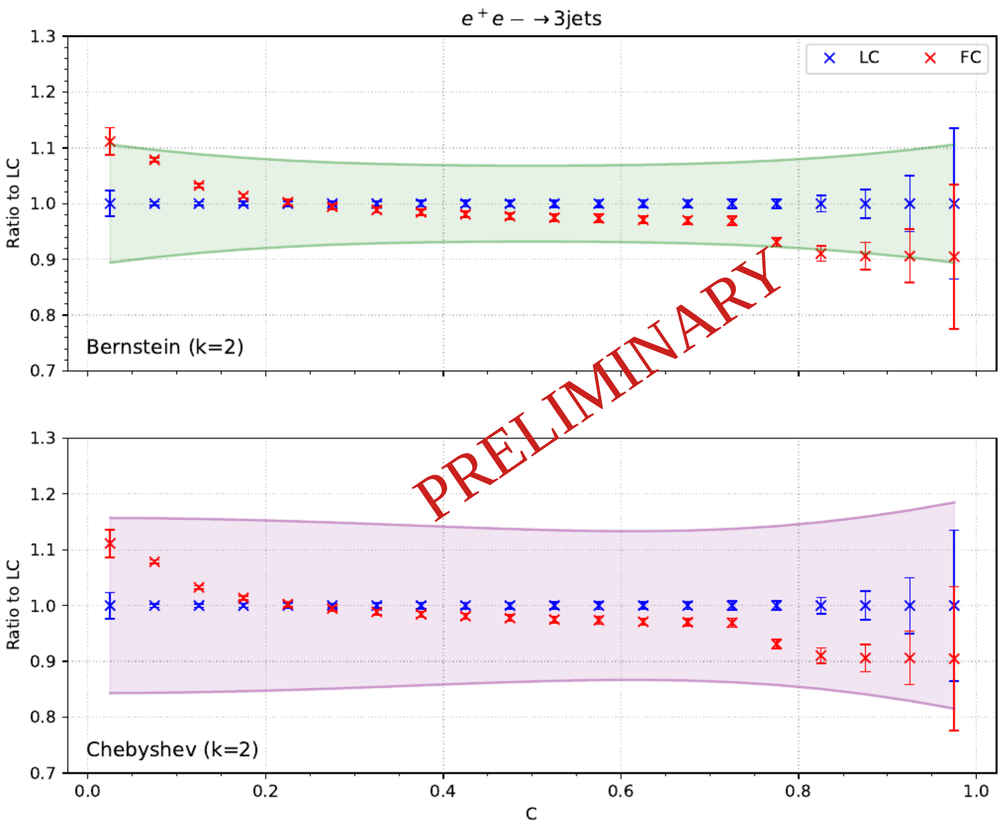
$pp \to t\bar{t} \to \ell\bar{\ell}\, 2b\mathrm{-jets},$



$pp \to ZZ^* \to e^+e^-\mu^+\mu^-$, LHC



TNPs in $e^+e^- \to$ 3 j



Use TNPs to parametrize uncertainties due to sub-leading color.

$$\frac{d\sigma^{SLC}TNP}{dx} = \frac{1}{N_c^2}\sum j = 1^N f_k^{(j)}(\vec{\theta}, x)\frac{d\sigma^{LC}}{dx}$$

Thanks to Simone and Matteo!

Multiloop-Monte Carlo “interface”

MC implementers

Multiloop calculators

What do they need?

What can they provide?

How to communicate this information?

Binoth LHA for one-loop calculation, but need to account for new information in higher order amplitudes.

Multiloop-Monte Carlo “interface”

Easy scenario: Suppose we can evaluate a matrix element for any (MC-generated) set of momenta.

$$\{p_i\} \to \mathcal{M}(\{p_i\}, \mu, \ldots \ldots)$$

“*This is completely trivial, we don’t need to discuss it at all.*” – me to Andreas, last Wednesday

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BUT

Momentum conventions, crossings for new partonic channels → analytic continuation, IR information → IR scheme, benchmark points, numerical precision and speed, estimations,...

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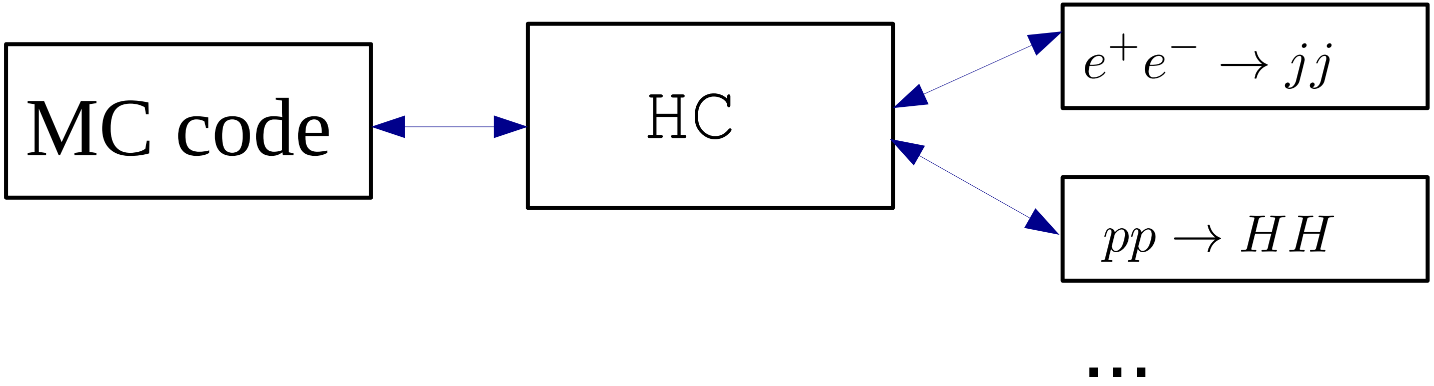
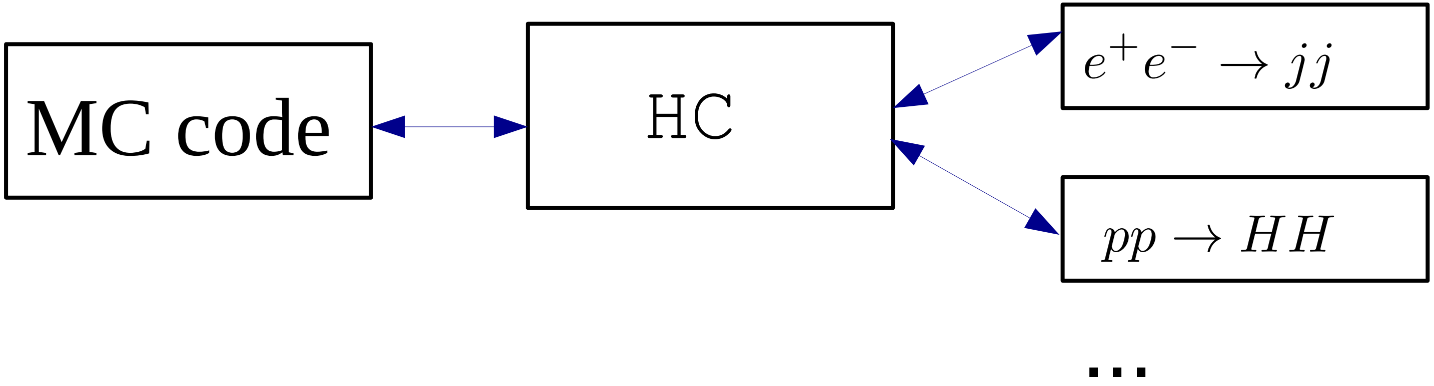
5 hours of discussion later...

Multiloop-Monte Carlo “interface”



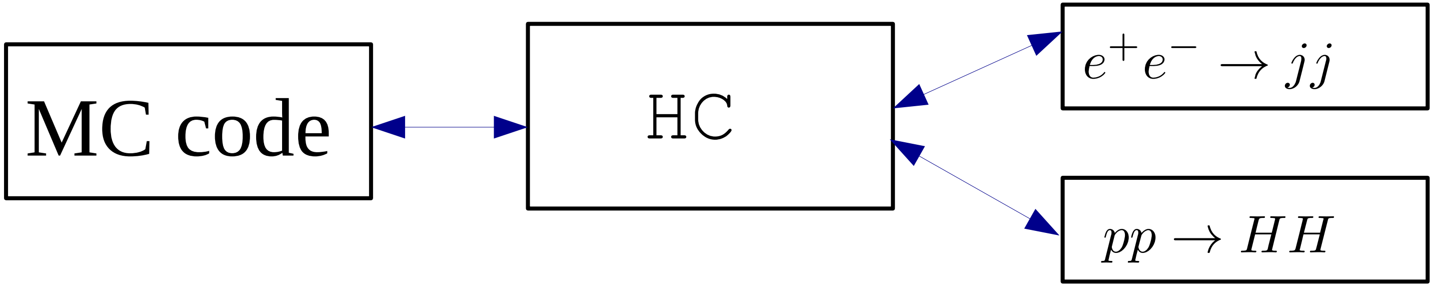
Proposed solution based on `HardCoded` library in `STRIPPER` (inspired by `OpenLoops`)

Multiloop-Monte Carlo "interface"



- Library of processes, each with own metadata: IR scheme, approximations, numerical accuracy, ...
- Passes IR-finite matrix element (including spin- and color-correlations) and information on IR poles to `HC`.

Multiloop-Monte Carlo “interface”



...

- `HC` organizes this into conventional form (e.g. $\overline{\text{MS}}$ IR scheme)
- MC code only needs to interface with `HC`:
  - Can change from `HC` conventions to own conventions independently of amplitude.
  - Obtain estimate of numerical accuracy, approximation information, etc from `HC`.

- Library of processes, each with own metadata: IR scheme, approximations, numerical accuracy, ...
- Passes IR-finite matrix element (including spin- and color-correlations) and information on IR poles to `HC`.

Multiloop-Monte Carlo "interface"

Initial implementation shared by Rene (with $e+e- \to jj$ @ 2 loops in library)

Work continuing after LH:

- Further processes ($pp \to HH$, $pp \to Zj$, $gg \to H$ @ 4 loops, ….) in library;
- Better understanding of requirements of different MC / possibilities from multiloop community;
- First public version in ~ 6 months …

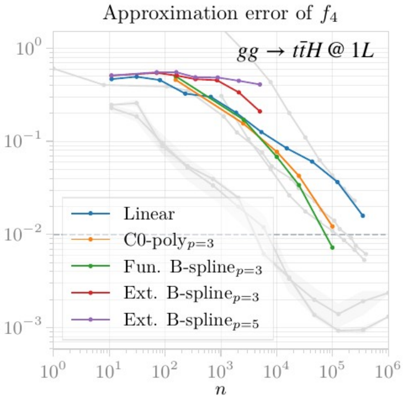
Hopefully streamline the implementation of multiloop amplitudes in MC codes (FO or PS).

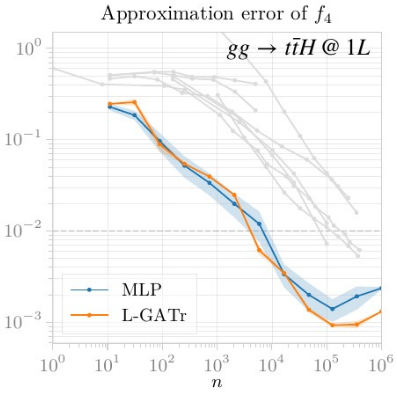
Multiloop-Monte Carlo “interface”

Difficult scenario: amplitudes only known at pre-determined set of points → grid interpolation

Recent study: Interpolate known 2→3 amplitudes at 0 and 1 loop using different methods. Talk by Matthias

[Bresó, Heinrich, Margerya, Olsson '24]

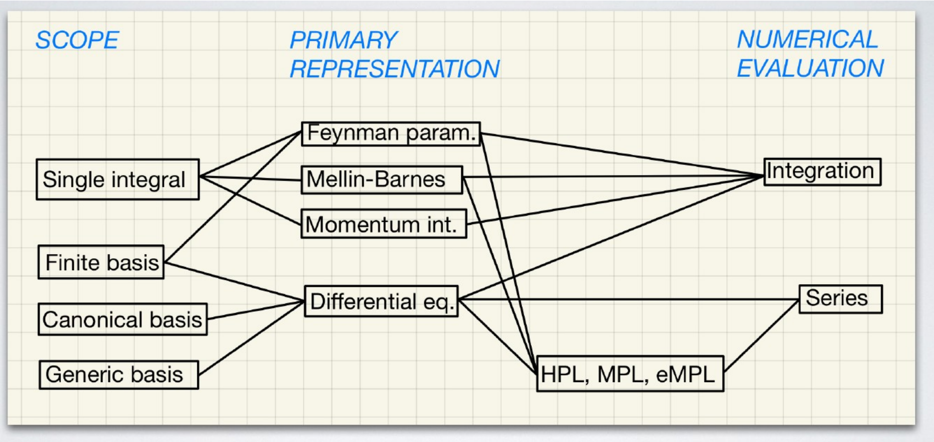




Open Questions

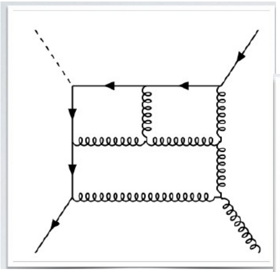
- Which method works best for a given use case?
- Which precision is required?
  (on amplitude / cross section)
- How to deal with uncertainties?
  (of input data; uncertainties due to interpolation)
- How can we incorporate parametric dependencies?
  (anomalous couplings, scale dependence, ...)
- ...

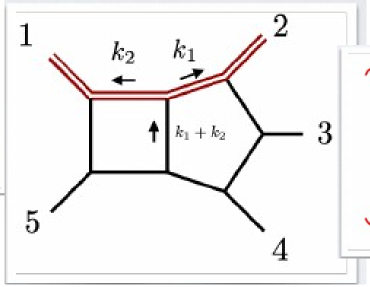
Multiloop review

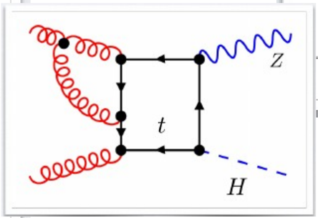


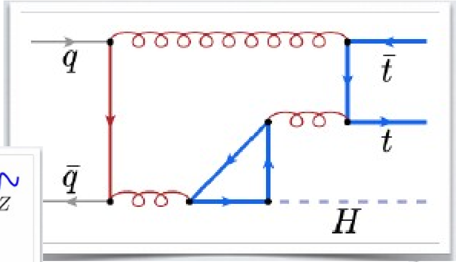
WHAT MAKES AMPLITUDES COMPLICATED ?

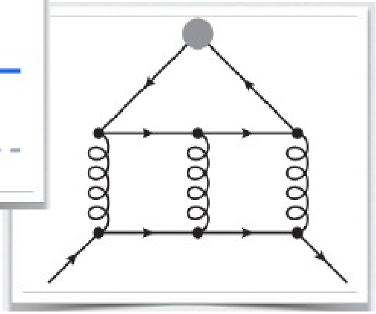
- Amplitudes become more difficult due to
  - Number of loops, number of legs
  - Number of scales
  - Massive propagators
  - Non-planar diagrams (subleading color)
- Complexity shows up in
  - Complexity of rational functions (combinatorics, higher degree denominators)
  - Functions space (multiple polylogs, elliptic, K3, more complicated Calabi-Yau)











Talk by Andreas

Polarized dibosons

- Precise Standard-Model predictions for polarised Z-boson pair production and decay at the LHC: arXiv:2505.09686
- NLO EW and QCD corrections to polarised same-sign WW scattering at the LHC: arXiv:2409.03620
- NLO EW corrections to polarised W^+W^- production and decay at the LHC: arXiv:2311.16031
- Polarised-boson pairs at the LHC with NLOPS accuracy: arXiv:2311.05220

- NNLO accuracy only very recently!
- Compared with PS.

- Interplay with SMEFT operators
  - include NLO corrections?
- Expect similar size corrections to SM? Depending on process / SMEFT operators?

Talk by Saptaparna

LH 2025 Wishlist

"Experimentalists wishlist" is one of the oldest LH institutions – extremely helpful snapshot of SotA and future prospects.

Les Houches 2023 - Physics at TeV Colliders: Report on the Standard Model Precision Wishlist

Alexander Huss[1] , Joey Huston[2] , Stephen Jones[3] , Mathieu Pellen[4] , Raoul Röntsch[5]

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[2] *Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA*

[3] *Institute for Particle Physics Phenomenology, Durham University, Durham DH1 3LE, United Kingdom*

[4] *Albert-Ludwigs-Universität Freiburg, Physikalisches Institut, Hermann-Herder-Straße 3, D-79104 Freiburg, Germany*

[5] *University of Milan and INFN Milan, Via Celoria 20133, Milan, Italy*

[hep-ph] 9 Apr 2025

Abstract

process	known	desired
$pp \to H$	$\mathrm{N^3LO_{HTL}}$ $\mathrm{NNLO_{QCD}^{(t,t\times b)}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}^{(HTL)}}$ $\mathrm{NLO_{QCD}}$	$\mathrm{N^4LO_{HTL}}$ (incl.)
$pp \to H + j$	$\mathrm{NNLO_{HTL}}$ $\mathrm{NLO_{QCD}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$	$\mathrm{NNLO_{HTL} \otimes NLO_{QCD} + NLO_{EW}}$ $\mathrm{N^3LO_{HTL}}$ $\mathrm{NNLO_{QCD}}$
$pp \to H + 2j$	$\mathrm{NLO_{HTL} \otimes LO_{QCD}}$ $\mathrm{N^3LO_{QCD}^{(VBF^*)}}$ (incl.) $\mathrm{NNLO_{QCD}^{(VBF^*)}}$ $\mathrm{NLO_{EW}^{(VBF)}}$	$\mathrm{NNLO_{HTL} \otimes NLO_{QCD} + NLO_{EW}}$ $\mathrm{N^3LO_{QCD}^{(VBF^*)}}$ $\mathrm{NNLO_{QCD}^{(VBF)}}$ $\mathrm{NLO_{QCD}}$
$pp \to H + 3j$	$\mathrm{NLO_{HTL}}$ $\mathrm{NLO_{QCD}^{(VBF)}}$	$\mathrm{NLO_{QCD} + NLO_{EW}}$ $\mathrm{NNLO_{QCD}^{(VBF^*)}}$
$pp \to VH$	$\mathrm{N^3LO_{QCD}}$ (incl.)$+ \mathrm{NLO_{EW}}$ $\mathrm{NLO_{gg\to HZ}^{(t,b)}}$	$\mathrm{N^3LO_{QCD}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$
$pp \to VH + j$	$\mathrm{NNLO_{QCD}}$ $\mathrm{NLO_{QCD} + NLO_{EW}}$	
$pp \to HH$	$\mathrm{N^3LO_{HTL} \otimes NLO_{QCD}}$ $\mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$
$pp \to HH + 2j$	$\mathrm{N^3LO_{QCD}^{(VBF^*)}}$ (incl.) $\mathrm{NNLO_{QCD}^{(VBF^*)}}$ $\mathrm{NLO_{EW}^{(VBF)}}$	$\mathrm{NLO_{QCD}}$
$pp \to HHH$	$\mathrm{NNLO_{HTL}}$	$\mathrm{NLO_{QCD}}$
$pp \to H + t\bar{t}$	$\mathrm{NLO_{QCD} + NLO_{EW}}$ $\mathrm{NNLO_{QCD}}$ (approx.)	$\mathrm{NNLO_{QCD}}$
$pp \to H + t/\bar{t}$	$\mathrm{NLO_{QCD} + NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$

3.3.7 $VV' + \geq 2j$

LH21 status: Full $\mathrm{NLO_{SM}}$ corrections ($\mathrm{NLO_{QCD}}$, $\mathrm{NLO_{EW}}$ and mixed NLO) available for W^+W^+jj [833, 834] and $ZZjj$ [835, 836]; $\mathrm{NLO_{QCD}}$ $+\mathrm{NLO_{EW}}$ known for $WZjj$ [837] and W^+W^-jj [838]; $\mathrm{NLO_{QCD}}$ corrections known for the EW production for all leptonic signatures in the vector-boson scattering approximation [839–845]; Same holds true for the QCD production modes [846–853]; $\mathrm{NLO_{QCD}}$ calculated for $WW + 3j$ [854];
All above computations matched to parton shower [855–863] (in the VBS approximation for EW production); $\mathrm{NLO_{EW}}$ to same-sign WW matched to parton/photon shower [864]. Comparative study at $\mathrm{NLO_{QCD}}$ and with parton-shower corrections for same-sign WW [865].

In Ref. [866], the final state $W^\pm W^\pm jjj$ has been computed at $\mathrm{NLO_{QCD}}$ matched to parton shower. This allows a better description of observables using the third jet (in addition to the two tagging jets), e.g. for jet veto in the central region in experimental analyses.

So far, most work in VBS has been focused on leptonic channels, but new results are becoming available for semi-hadronic and fully hadronic signatures. For example, the implementation of the $\mathrm{NLO_{QCD}}$ corrections matched to parton shower for $WZjj$ [863] in POWHEG has been extended to allow to consider the semi-leptonic and fully hadronic channels [867]. Results are shown for current and future possible hadron colliders up to 100 TeV. The spin-correlations and off-shell effects are also studied. Along the same line, Ref. [868] presented results at LO for the VBS production of $\ell\nu jjjj$ using a double-pole approximation.

In Ref. [869], full $\mathrm{NLO_{QCD}}$ +EW corrections have been presented for the W^+W^+jj, confirming the results of Ref. [833, 834]. In addition, the $\mathrm{NLO_{QCD}}$ corrections have been compared to those in the double-pole and VBS approximations.

One of the key properties of the VBS is that it is particularly sensitive to the longitudinal polarisations of heavy gauge bosons. In an effort to provide reliable predictions to experimental collaborations for the extraction of polarisation fractions, $\mathrm{NLO_{QCD}}$ +EW corrections have been

Providing full employment for theorists since 2005!

LH 2025 Wishlist

LH2025 wishlist will be the first to contain summaries/reviews of status of resummation and PS (partially included in previous lists but never systematically or extensively).

- Overdue as experimental and theory precision increase and measurements become more exclusive/kinematics dependent.
- Aim to complete review by summer 2026.
- Thanks to all who have volunteered!

THANKS!

Thanks to all participants for your contributions: talks, questions, comments, suggestions, calculations, results, estimates, discussions, arguments, …

Your engagement made our lives as conveners very easy!