QCD/top physics in the era of future accelerators

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Introduction

- ✓ We had a lot of related talks …

Stefano Forte, Stefan Kluth, Fulvio Piccinini

  - ✓ Will not discuss EW physics (see talk by Fulvio Piccinini)

- ✓ This talk is about trying to guess what QCD may look like at FCCee

- ✓ … we can start by looking at the LHC today and extrapolate

- ✓ The situation at present is pretty amazing: we have many, more-precise calculations for a more complicated machine (LHC) than for e^+e^-!

- ✓ A brief LHC status:

  - ✓ Fully differential NNLO for 2->2 and 2->3.
  - ✓ N^3LO already exists for 2->1 processes.

On a 10-year timescale we can expect N^3LO calculations for the LHC, produced at scale

- ✓ These developments directly translate to e^+e^- :

- ✓ There are not as many e^+e^- implementations currently simply because there is no pressing need for them.

- ✓ The bottleneck at the LHC currently, and for the foreseeable future, is the calculation of multiloop amplitudes (translates directly to e^+e^-).

- ✓ Progress in multiloop amplitudes

  - ✓ Definition of the set of functions needed to describe such processes

  - ✓ Example 1: the description of massless 2->3 processes at NNLO required a new set of functions, the pentagon functions

    Papadopoulos, Tommasini, Wever ‘15
    Gehrmann, Henn, Lo Presti ‘16 ‘18

  - ✓ They evolved in a set which is fully useable for practical calculations

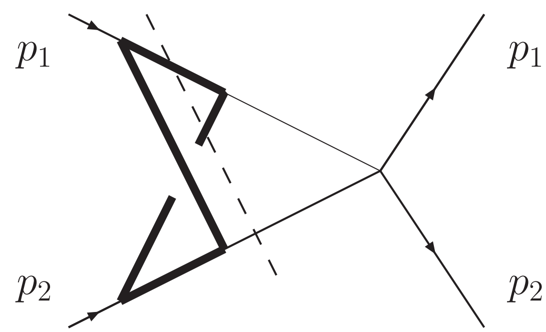
    Chicherin, Sotnikov ‘20

  - ✓ Approach currently being generalized up to V+4j at 2 loops

    Abreu, Chicherin, Ita, Page, Sotnikov, Tschernow, Zoia

- Example 2: Elliptic functions
  - These appear in multiscale problems
    - first such collider example was the NLO tt total inclusive cross-section).

Czakon, Mitov '08



  - These functions need to be systematized in order to have efficient algebra. Tremendous work ongoing.
- Computing amplitudes will become particularly tricky for multiscale processes (like different masses)
    - Likely only fully numeric calculations are feasible. But this is OK: for example, tt@LHC@2 loops is known numerically and not yet fully analytically.

Chen, Czakon, Poncelet '17

- Finally, even one-loop amplitudes for N^3LO calculation will require additional improvements

✓ What can we conclude from the discussion up to here?

By the time FCCee becomes operational many/most e^+e^- processes will have NNLO or N^3LO precision

✓ One should expect fully differential calculations, not just inclusive observables

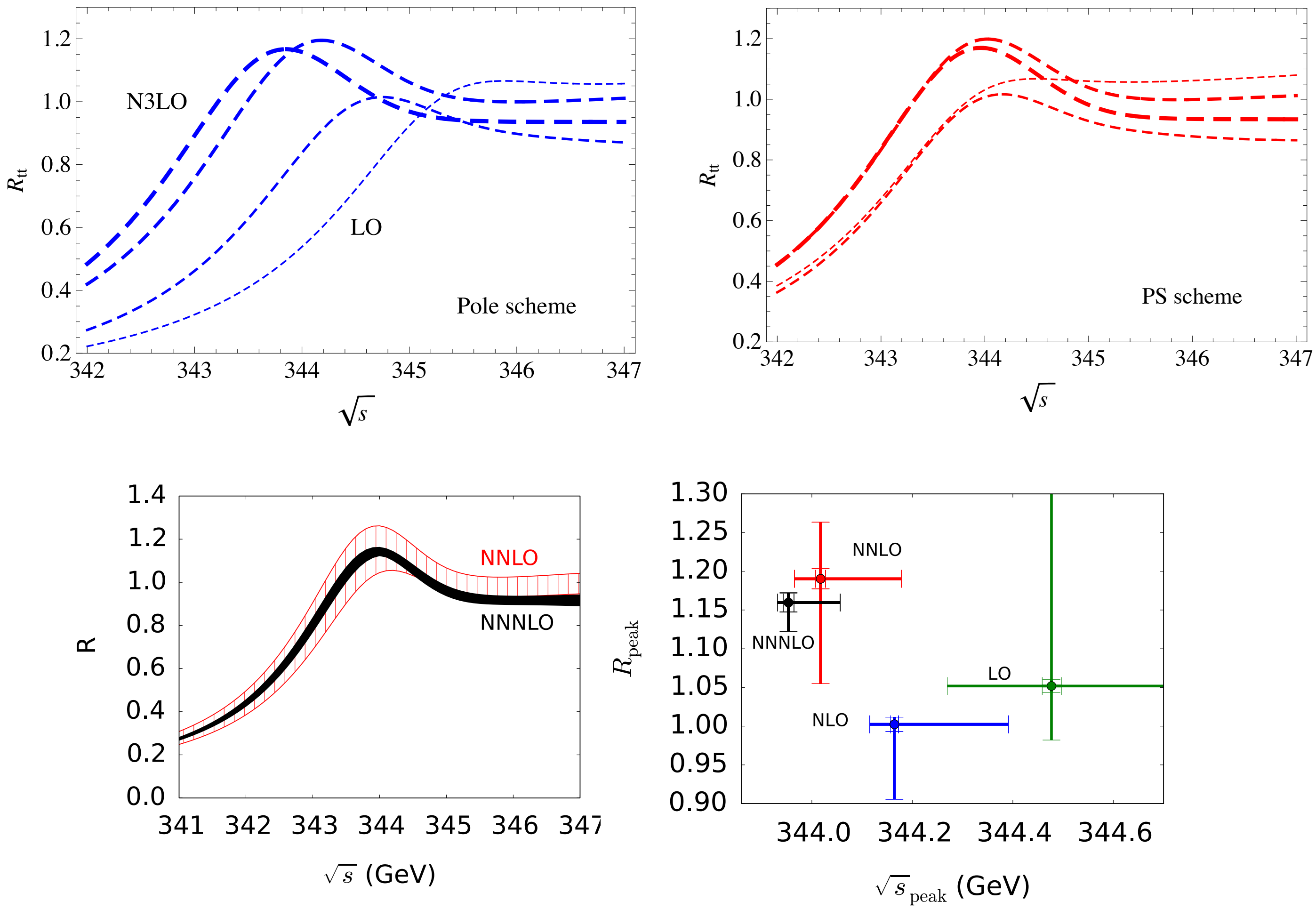
✓ This will be a huge progress relative to where we are today for e^+e^-

Overview of e^+e^- processes and their current status

Top quark pair production

- ✓ A major aim and potential major achievement for the FCCee
- ✓ A threshold scan allows a very precise measurement of the top quark mass, width and even its mass scheme.
- ✓ Theory known at N³LO in QCD

Beneke et al, ‘15



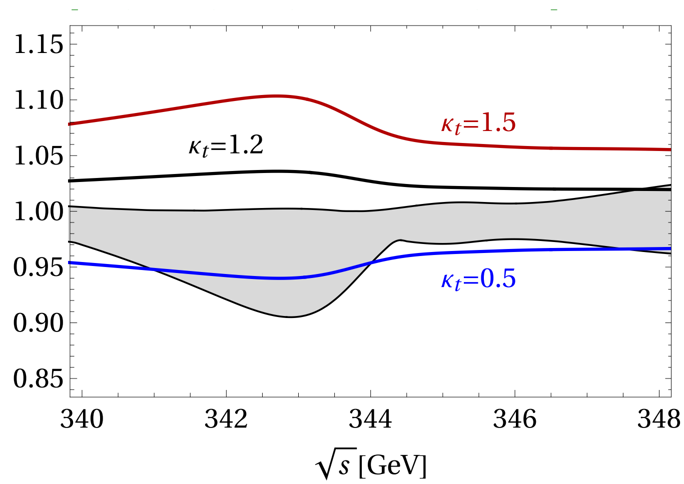
Top quark pair production

- ✓ Top Yukawa can also be constrained indirectly (albeit weakly).

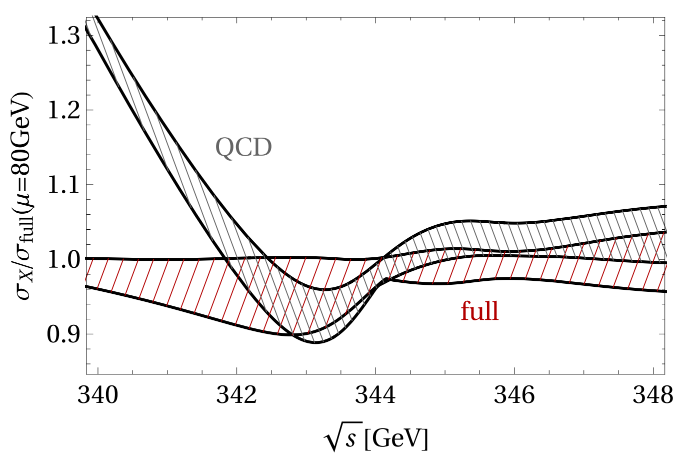
Nice connection to the talk by Gauthier Durieux

- ✓ Sensitivity to the top Yukawa coupling

Beneke et al, '17



- ✓ And NNLO EW corrections (EW+QED+non-resonant):



Top quark pair production

- ✓ Further prospects for ttbar at threshold:
  - ✓ A main remaining uncertainty is ISR
  - ✓ Going beyond N^3LO will likely require a multi-decade effort…
- ✓ Continuum top pair production
  - ✓ Essentially available only at NLO via MadGraph5 aMC@NLO, Whizard, …
  - ✓ No reason not to have full NNLO at present
- ✓ Note: the state of continuum b and c production is similar.
  - ✓ Single inclusive production at high p_T is known at NNLO (will revisit later in this talk)

Jet production and alpha_s

- ✓ 3-jet production at the LHC is known at NNLO (in full color)
- ✓ 3-jet is also known for e^+e^- at NNLO

Gehrmann-De Ridder, Gehrmann, Glover, Heinrich '07
Weinzierl '08
Del Duca, Duhr, Kardos, Somogyi, Szor, Trocsanyi, Tulipant '16

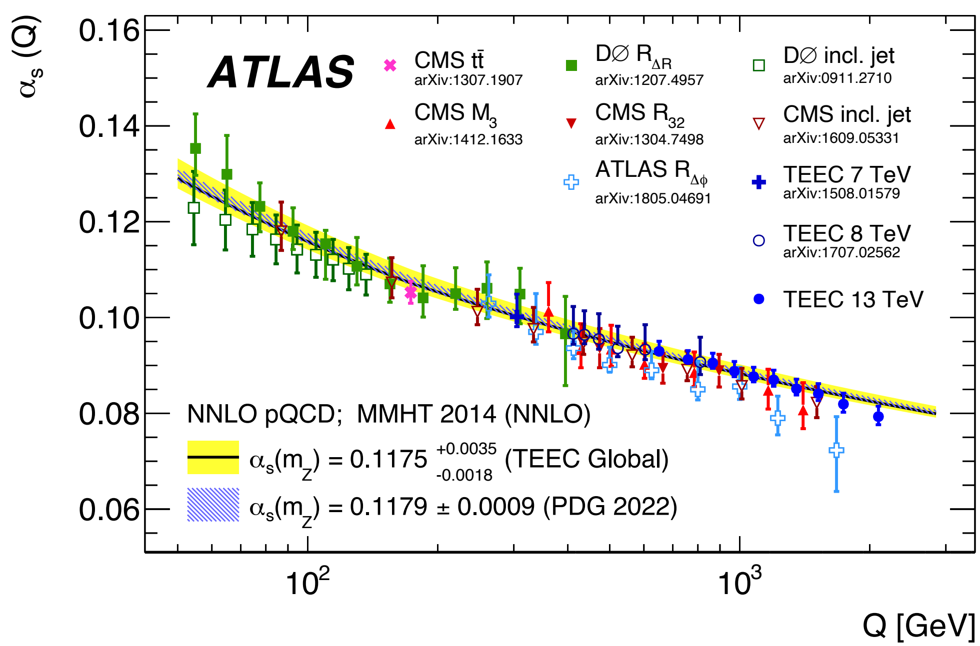
  - ✓ 4-jet at NNLO is doable (integrals were just derived for the LHC)

- ✓ Studies of jet substructure, jet algorithms, including flavor, has advanced tremendously during the lifetime of the LHC.
- ✓ Ultimately, N^3LO for 3 jet production at e^+e^- will likely be possible within a decade or so.
- ✓ Measurements of the strong coupling constant at e^+e^- will offer exciting possibilities

reviewed in talk by Stefan Kluth

- ✓ A remark: FCCee will only give us access to alpha_s at scales ~M_Z. This is unlike the LHC where the running of alpha_s has already been probed to 2 TeV or so with full NNLO precision.

ATLAS arXiv:2301.09351



Two selected aspects

we can learn from at future e^+e^- colliders

Terra Z

- ✓ Precision remeasurement of SM parameters and processes is going to be essential for the future precision program we all hope for.

- ✓ It is just like building a house: it can be only as good as the foundation it sits on.

- ✓ Zoltan Ligeti gave an exhaustive introduction to this. Let me just add couple of more examples:

  - ✓ B and D fragmentation measurements from LEP are rather limited.
  - ✓ Only a mixture of B mesons available
  - ✓ Only a single D meson measurement available
  - ✓ Quality of available data is currently a major limiting factor on heavy flavor production

- ✓ Another potential great benefit: measurements at different c.m. energies

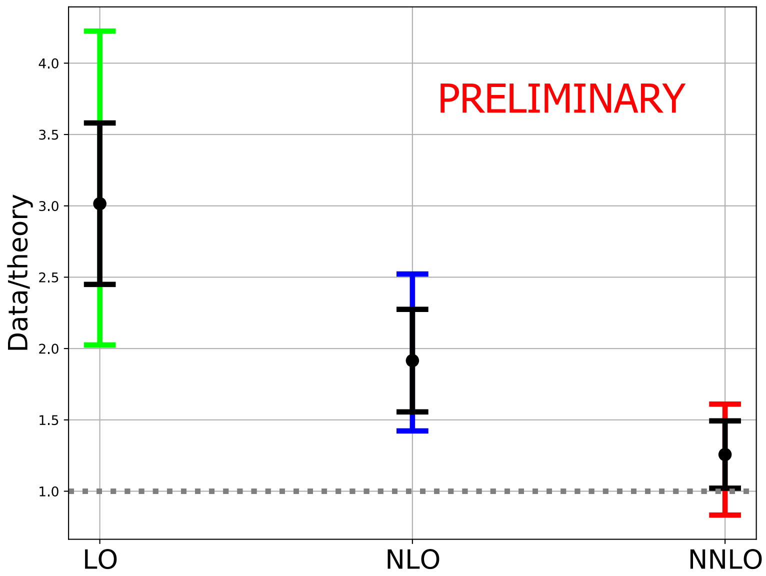
  - ✓ Measurements at higher energies (240GeV, 365 GeV) will be the first time we have high precision high-energy data to test precision DGLAP evolution for heavy flavors.

  - ✓ B fragmentation is currently restricted to $x>0.1 \sim m_Z/(2m_B)$. Higher c.m. energies will allow access to fragmentation measurements with $x<0.1$.

  - ✓ And a bigger lesson: acquiring confidence in treating small mass effects in unrelated processes (including muon colliders, how to properly treat the muon or electron mass – even in QED context, etc.).

Small mass effects

- ✓ Identified heavy flavor production (fragmentation) is among the basic processes QCD offers and has been measured at many colliders.
- ✓ e^+e^- the gold standard for such measurements (due to lack of pdf, clean environment and ease of directly relating the observable to the fragmentation function)
- ✓ Open B and D production have so far (in the last almost 30 years) been treated in FONLL (NLO+NLL).
- ✓ It has been a great success and a major step forward; its main limitation is a significant NLO scale uncertainty.
- ✓ NNLO calculations expected to improve this. Indeed, the Tevatron B-production anomaly completely disappears at NNLO



Czakon, Generet et al, to appear

Tevatron fiducial x-section for bb **at quark level**

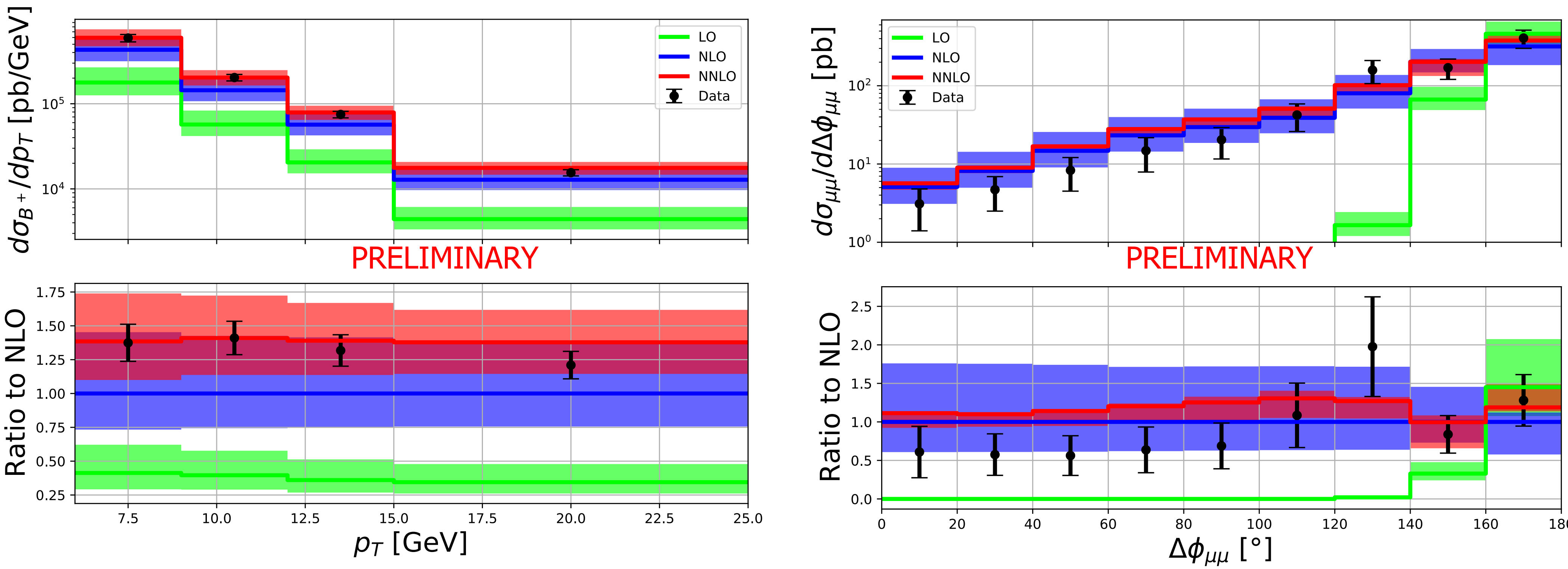
Could also be inferred from

Catani(a), Devoto, Grazzini, Kallweit, Mazzitelli ‘20

Small mass effects

- ✓ Full NNLO +resummation prediction for B mesons and their decays

Czakon, Generet et al, to appear



- ✓ At future e^+e^- machine we should expect this observable to be known to N^3LO.
- ✓ Uncertainties dominated by measurements of input parameters and treatment of mass effects.

Small mass effects

✓ Example: fitting LEP data is not trivial

arXiv:2210.06078

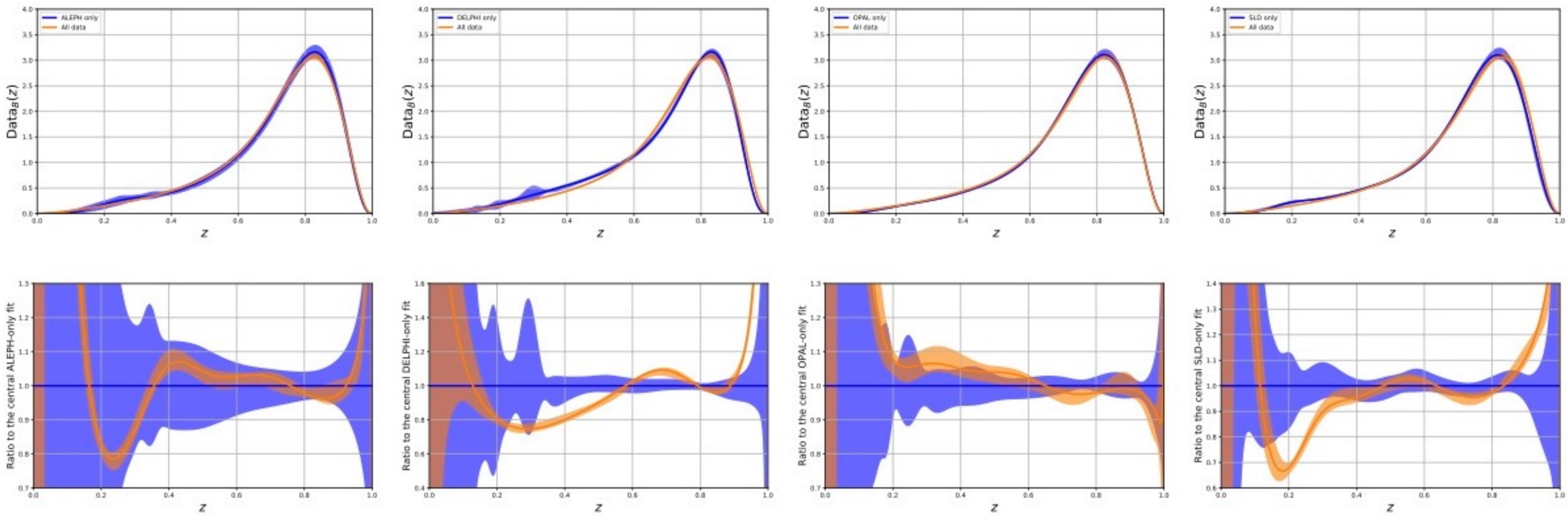


Figure 16. NPFF fits from one dataset at a time (blue) versus the combined fit (orange). The four datasets are (from left to right): ALEPH, DELPHI, OPAL and SLD.

HighTEA time

- ✓ A very legitimate question:
  - ✓ How do you make the above results available?
  - ✓ If I need a new prediction, where can I get it?
- ✓ There are just two options:
  - If there is a public code one can use it to compute what one needs
    - Problem 1: serious/huge CPU expense
    - Problem 2: is the user using the code correctly?

MCFM
MATRIX

  - No public code: ask the authors. Hope they are free and have spare CPU to use…
- ✓ Can one bypass all of these problems at once?

YES!

- ✓ The answer can be found here:

https://www.precision.hep.phy.cam.ac.uk/hightea/

✓ Dedicated website

https://www.precision.hep.phy.cam.ac.uk/hightea/

Centre for Precision Studies in Particle Physics

Research | People | Results | Top++ | HighTEA | Opportunities | ILC physics

high tea

HighTEA

(High-energy Theory Event Analyzer for collider processes)

- Publication (to appear)
- For the impatient: running HighTEA via Jupyter Notebook on Google Colab

The modern way of doing physics

This site is the public face of a novel approach for distributing and analyzing the results of fixed order NNLO calculations for LHC processes. Here are the main topics:

- The basic idea
- How it works
- Features
- Ways to access the library
- Our team
- Disclaimer

The basic idea

The idea behind HighTEA is very simple: existing calculations use Monte Carlo (MC) methods to integrate over the available phase space. Such MC samplings, called ***events***, are usually binned in histograms and then discarded.

While very powerful, such an approach to doing high-precision NNLO calculations has a serious drawback: it lacks

CAVENDISH HEP SEMINAR

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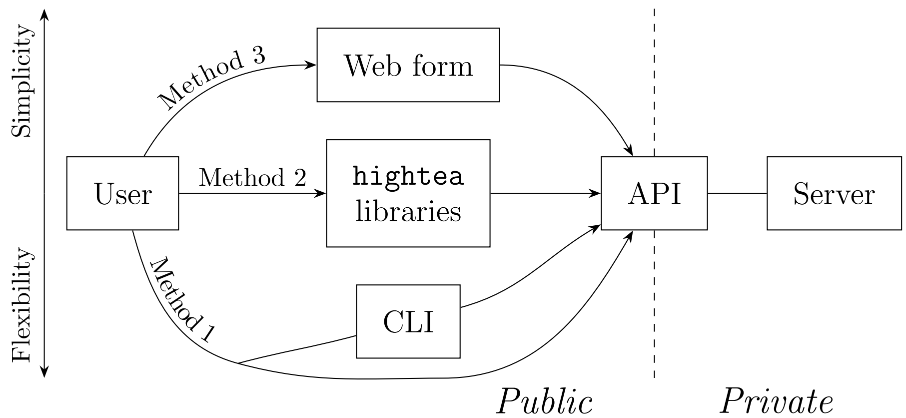
Czakon, Kassabov, Mitov, Poncelet, Popescu 2023

- ✓ What is HighTEA? A library of precomputed events + all the required infrastructure.
  - ✓ No specialized knowledge needed to fully use it
  - ✓ It allows the user to compute any infrared safe n-dimensional differential distribution in any process which has already been added to the library
  - ✓ The output of a HighTEA computation is a histogram, and the input is the histogram's specification.
  - ✓ Users can define their own kinematic variables and scales.
  - ✓ No need for major computing infrastructure (typically, a large cluster). Example: A quick calculation takes 50k CPUh; the most demanding ones – over 10M CPUh.
  - ✓ Predictions derived from HighTEA are very fast (~minutes).
  - ✓ All one needs is a computer (or a smart phone) and a free Google account.
- ✓ HighTEA's limitations
  - ✓ Only processes already included can be computed
  - ✓ Fixed statistics: fine bins will result in large MC uncertainty (estimate always provided)
  - ✓ Fixed parameters like LHC energy and particle masses.

✓ HighTEA's logic:



✓ Next:

✓ A webform (restricted functionality): https://www.hep.phy.cam.ac.uk/hightea/webform/

✓ Our Library implemented in Jupyter notebooks on Google Colab. Has full functionality. One needs a device and a free Google account https://colab.research.google.com/github/HighteaCollaboration/hightea-examples/blob/master/Start.ipynb

Conclusions

- ✓ Steady progress on NNLO and already N^{3}LO calculations for the LHC

- ✓ Future FCCee program will benefit from these developments

- ✓ Expect fully differential NNLO and N^{3}LO to be the standard for FCCee

- ✓ We need FCCee, among others, for (much) more precise measurements of basic SM parameters and processes.
  - ✓ This will be critical for the success of the future precision program.