Precision calculations for e+e- colliders: future directions

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Summary of Precision calculations for future e+e– colliders: targets and tools

https://indico.cern.ch/event/1140580/

Organisation committee: S. Abreu, J. Alcaraz, J. Alimena, P. Azzi, D. D'Enterria, A. Freitas, G. Heinrich, A. Huss, M. Mangano, M. McCullough, P. Monni, J. Usovitsch, M. Vos

Snowmass CSS Workshop — 19th of July 2022

Targets . . .

13:00 → 17:00 **Talks and discussions: key physics questions and observables** — 4/3-006 - TH Conference Room

13:00 **Possibilities and precision goals at the Z pole** — 40m — 4/3-006 - TH Conference Room

The talk will review the physics potential of future lepton (e+e-) colliders at the Z pole, highlighting in particular the electroweak measurements that rely heavily on theory inputs, such as precision calculations. Primary examples are Z-pole measurements of EW parameters, as well as EW precision observables.

Speaker: Patrick Janot (CERN)

PrecisionGoalsZPo...

14:00 **Status of theory calculations for Z-pole observables** — 40m — 4/3-006 - TH Conference Room

The talk will review the status of theory calculations for Z pole precision observables, and highlight the requirements to match the foreseen experimental precision. Moreover, it will compare the EW pseudo-observables and EFT-parameterisation approaches to carry out precision physics at the Z pole.

Speaker: Ayres Freitas

FCee_freitas.pdf

15:00 **Coffee break** — 30m — 4/2-011 - TH common room (...

15:30 **Possibilities and precision goals for QCD measurements** — 40m — 4/3-006 - TH Conference Room

The talk will review the physics potential of future lepton (e+e-) colliders at the Z pole, highlighting in particular the QCD measurements that rely heavily on theory inputs, such as precision calculations. Primary examples are Z-pole measurements of the strong coupling constant, hadronic decay rates of W/Z/tau, as well as (mulit-)jet measurements.

Speaker: Stefan Kluth (Max Planck Society (DE))

precisionQCD.pdf

Z pole

QCD measurements

13:00 → 17:50 **Talks and discussions: key physics questions and observables** — 4/3-006 - TH Conference Room

13:00 **Initial state QED radiation aspects for future lepton colliders** — 40m — 4/3-006 - TH Conference Room

The talk will discuss the latest progress in the description of QED corrections to the initial state, such as the application and limitations of collinear factorisation to beamstrahlung and YFS approaches. This talk highlights the necessary steps to achieve the precision demanded by future lepton collider experiments.

Speaker: Stefano Frixione (INFN)

eeisr.pdf

14:00 **TH colloquium** — 1h — 4/3-006 - TH Conference Room

https://indico.cern.ch/event/1124737/

15:00 **Coffee break** — 30m — 4/2-011 - TH common room (...

15:30 **Theory aspects in top-pair production** — 40m — 4/3-006 - TH Conference Room

The talk will review the status of theory calculations for tt production at threshold energies and above at future lepton colliders, and highlight the requirements to match the foreseen experimental precision.

Speaker: Martin Beneke (Technische Universitaet Muenchen (DE))

cern.pdf

16:30 **Experimental possibilities at and above the top-pair threshold** — 40m — 4/3-006 - TH Conference Room

The talk will review the physics potential of future lepton (e+e-) colliders at the tt threshold and above, highlighting in particular the experimental targets and those measurements that rely heavily on theory inputs, such as precision calculations.

Speaker: Frank Simon (Max-Planck-Institut fuer Physik)

TopPhysicsExperi...

ISR

Top

13:00 → 18:30 **Talks and discussions: key physics questions and observables** — 4/3-006 - TH Conference Room

13:00 **Experimental constraints on Higgs properties** — 40m — 4/3-006 - TH Conference Room

The talk will review the physics potential of future lepton (e+e-) colliders for Higgs production, e.g. Higgs-strahlung (e e -> HZ) and VBF (e e -> H v v (W W -> H)), highlighting in particular the experimental targets and those measurements that rely heavily on theory inputs, such as precision calculations.

Speaker: Jenny List (Deutsches Elektronen-Synchrotron (DE))

jlist_eehiggs_2206...

14:00 **Theory precision for Higgs observables** — 40m — 4/3-006 - TH Conference Room

The talk will review the status of theory calculations for H production, e.g. Higgs-strahlung (e e -> HZ) and VBF (e e -> H v v (W W -> H)), and Higgs decays at future lepton colliders, and highlight the requirements to match the foreseen experimental precision.

Speaker: Li Lin Yang

2022-06-09 FCC-ee...

15:00 **Coffee break** — 30m — 4/2-011 - TH common room (...

15:30 **Non-perturbative aspects of QCD jet observables** — 40m — 4/3-006 - TH Conference Room

The talk will review the current understanding of non-perturbative (linear) corrections to final state observables at lepton colliders, such as event shapes and jet rates. The prospects for new calculations needed at future e+e- machines should be highlighted in view of the accuracy required at these experiments.

Speaker: Paolo Nason (Max Planck Society (DE))

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16:30 **Prospects for precision QCD jet calculations** — 40m — 4/3-006 - TH Conference Room

This talk will review calculations for multi-jet production in e+e- collisions; emphasizing the precision targets and prospects for new calculations needed at future colliders, and whether these can be achieved with state-of-the-art technology.

Speaker: Andrea Banfi (University of Sussex)

banfi_CERN_22.pdf

Higgs

QCD: jets and NP

13:00 → 17:10 **Talks and discussions: key physics questions and observables** — 4/3-006 - TH Conference Room

13:00 **Precision electroweak physics above the Z pole** — 40m — 4/3-006 - TH Conference Room

The talk will review the physics potential of future lepton (e+e-) colliders for EW precision physics above the Z pole, highlighting in particular the experimental targets and those measurements that rely heavily on theory inputs, such as precision calculations.

Speaker: Graham Wilson

Wmass_GWW_CER...

14:00 **Coffee break** — 30m — 4/2-011 - TH common room (...

14:30 **W properties at the pair-production threshold** — 40m — 4/3-006 - TH Conference Room

This talk will review the physics potential of future lepton (e+e-) colliders for EW precision physics at the WW threshold, highlighting in particular the experimental targets for the measurement of the W-boson mass and width.

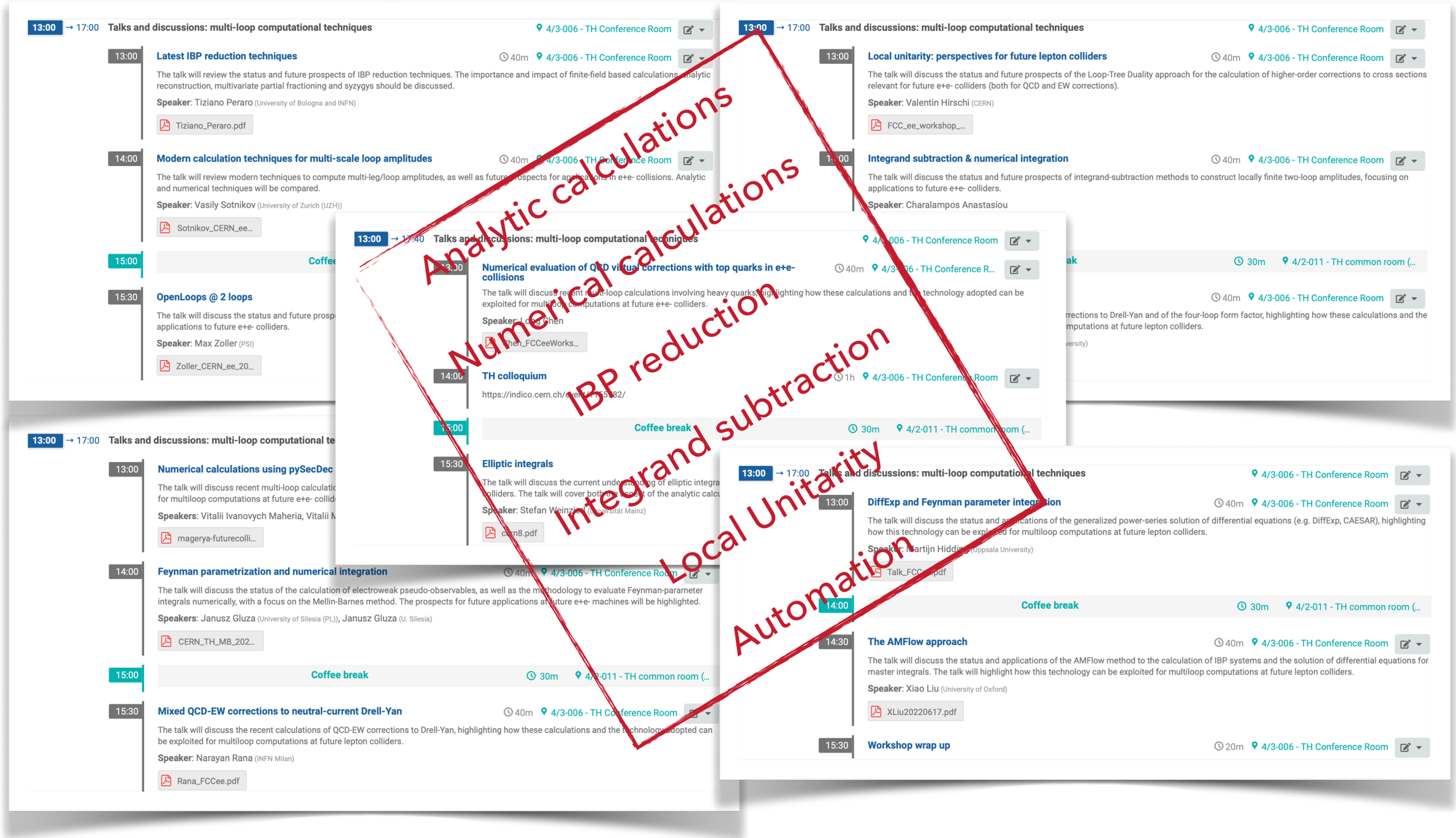
Speaker: Paolo Azzurri (Universita & INFN Pisa (IT))

azzurriCERNPrecisi...

15:30 **Summary of week 4** — 20m — 4/3-006 - TH Conference Room

Above Z pole, WW

… and Tools (for multi-loop calculations)



- ✓ 222 participants (50 in person), mix of theory and experiment especially on week 1
- ✓ We are aiming at producing a shopping list of important target and calculations, collecting input from the speakers/participants of the workshop

First target & Template: Z-pole physics

Summary: Theory inputs for Z lineshape observables

- **Numbers are given here for FCC-ee (best prospects)**

Observables	Present value	FCC-ee stat.	FCC-ee current syst.	FCC-ee ultimate syst.	Theory input (not exhaustive)
m_Z (keV)	91187500 ± 2100	4	100	10 ?	Lineshape QED unfolding Relation to measured quantities
Γ_Z (keV)	2495500 ± 2300 [*]	4	25	5 ?	Lineshape QED unfolding Relation to measured quantities
σ^0_{had} (pb)	41480.2 ± 32.5 [*]	0.04	4	0.8	Bhabha cross section to 0.01% $e^+e^- \to \gamma\gamma$ cross section to 0.002%
N_ν ($\times 10^3$) from σ_{had}	2996.3 ± 7.4	0.007	1	0.2	Lineshape QED unfolding $(\Gamma_{\nu\nu}/\Gamma_{\ell\ell})_{SM}$
R_ℓ ($\times 10^3$)	20766.6 ± 24.7	0.04	1	0.2 ?	Lepton angular distribution (QED ISR/FSR/IFI, EW corrections)
$\alpha_s(m_Z)$ ($\times 10^4$) from R_ℓ	1196 ± 30	0.1	1.5	0.4 ?	Higher order QCD corrections for Γ_{had}
R_b ($\times 10^6$)	216290 ± 660	0.3	?	< 60 ?	QCD (gluon radiation, gluon splitting, fragmentation, decays, ...)

- **And also sophisticated and state of the art MC generators (signal and backgrounds)**
  - **Plus, maybe, redefined EW Precision Parameters (EWPP) and extraction procedures ?**

P. Janot — Precision Calculations for future e^+e^- Colliders, 7 June 2022 — [*] https://arxiv.org/abs/1912.02067 — 20

- ✓ Take statistical uncertainties as ultimate target
- ✓ Theory enters in several ways, e.g.:
  - ✓ Calibration: Initial State Radiation (ISR)
  - ✓ Parametric uncertainties: masses and couplings
  - ✓ Interpretation of results: ElectroWeak Precision Observables (EWPO)

First target & Template: Z-pole physics

✓ What experimentalists are asking from theory:

Theory and experiment at the Z pole

- **Tasks for theory**
  - **Identify observables/parameters that contain sensitivity to new phenomena**
    - Via loops in γ, Z, W propagators (flavour universal), e.g., S, T, U @LEP/SLC
    - Via boxes and vertices (flavour dependent), e.g., δ_b @ LEP/SLC
    - Via direct long distance propagator effects (universality violation): e.g., new Z'
    - Via mixing with known particles, e.g., Z'/Z mixing, ν/N mixing, …
  - **Develop high-precision SM procedures to extract these parameters from measurements**
    - Precise (maybe not universal?) QED/QCD Monte Carlo / radiator for ISR/FSR/IFI, …
  - **Perform high-precision calculations of these observables/parameters in the SM**
    - Precise multi-loop calculations with, e.g., m_Z, G_F, $\alpha_{QED}(0)$ as basic inputs
      - ➔ Also requires high-precision theory to extract ancillary quantities from experimental measurements
        $\alpha_{QED}(m_Z)$, $\alpha_S(m_Z)$, m_{top} , m_b, m_H, etc. to reduce parametric uncertainties
  - **Develop sophisticated MC event generators for direct tests of the theoretical prediction**
    - Also needed to remove detector acceptance and selection inefficiencies

First target & Template: Z-pole physics

Summary

28/28

- Electroweak precision tests require theory input for **measurements of pseudo-observables** (BRs, widths, masses, cross-sections, ...) and their **SM/BSM interpretation**
- **Future e^+e^- colliders** improve precision by 1–2 orders of magnitude
- Theory progress needed both for **fixed-order loop corrections** as well as **MC tools**
- Model-independent description of BSM effects through **EWPOs** (for leading Z-pole term) and **SMEFT operators**
- Accurate description of non-resonant terms (backgrounds) requires a **gauge-invariant framework**, **SM corrections**, and accounting of **BSM effects**

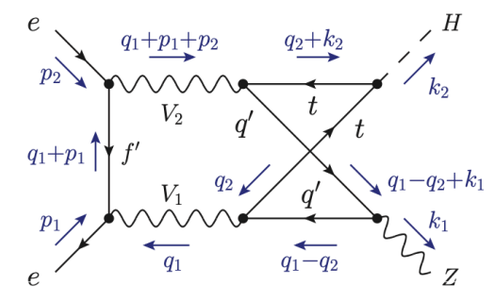
[talk by Ayres Freitas]

Initial State Radiation

- ✓ Talk by S. Frixione, based on Snowmass 21 contribution 2203.12557
- ✓ Model QED ISR: crucial for any measurement at lepton collider
- ✓ Process/Observable dependent
- ✓ NLL description gives sizeable correction
- ✓ More progress needed, build on recent developments in QCD:
    - ✓ NNLL description collinear radiation: within reach
    - ✓ All-order resummation of soft and collinear logarithms (e.g. ttbar threshold)
    - ✓ Implementation in accurate Monte Carlo codes: several tools exist, must be improved

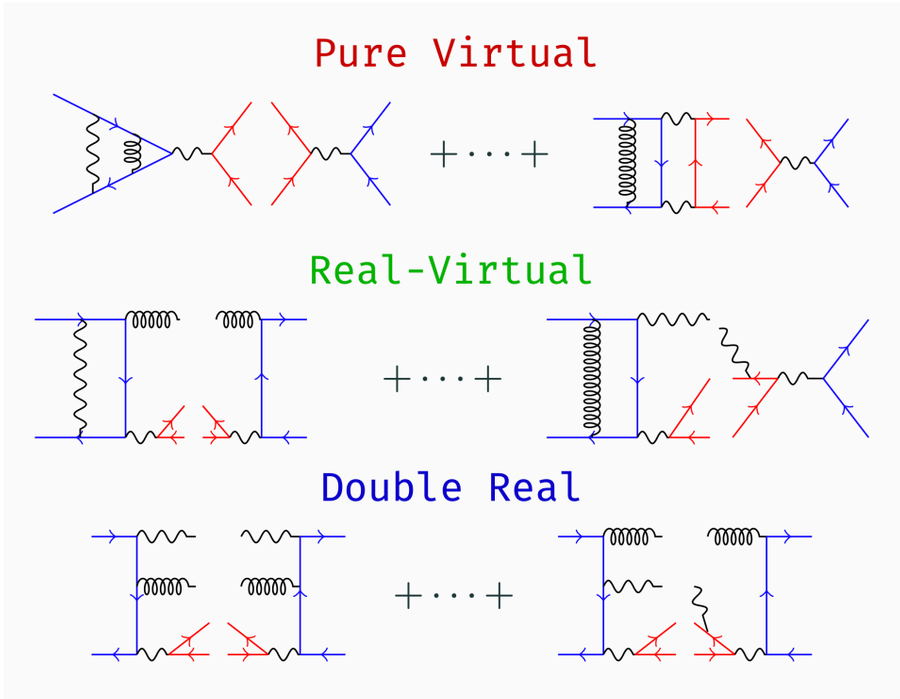
Fixed order: different types of processes/observables

1. Numbers: masses and other SM parameters (ρ, ...)
2. Multi-leg processes: QCD corrections to $e^+e^- \to n$ jets/photons
3. Multi-scale (e.g., masses) processes: (Mixed QCD-) EW corrections
4. Combination of the above: $e^+e^- \to t\bar{t}H$, ...



[EW corrections to ZH, talk by Yang]

- ✓ Multi-loop calculations:
  - ✓ Reduce amplitudes to minimal set of Feynman integrals
  - ✓ Compute Feynman integrals
  - ✓ Combine real and virtual corrections



[Mixed QCD-EW correction to DY, talk by Rana]

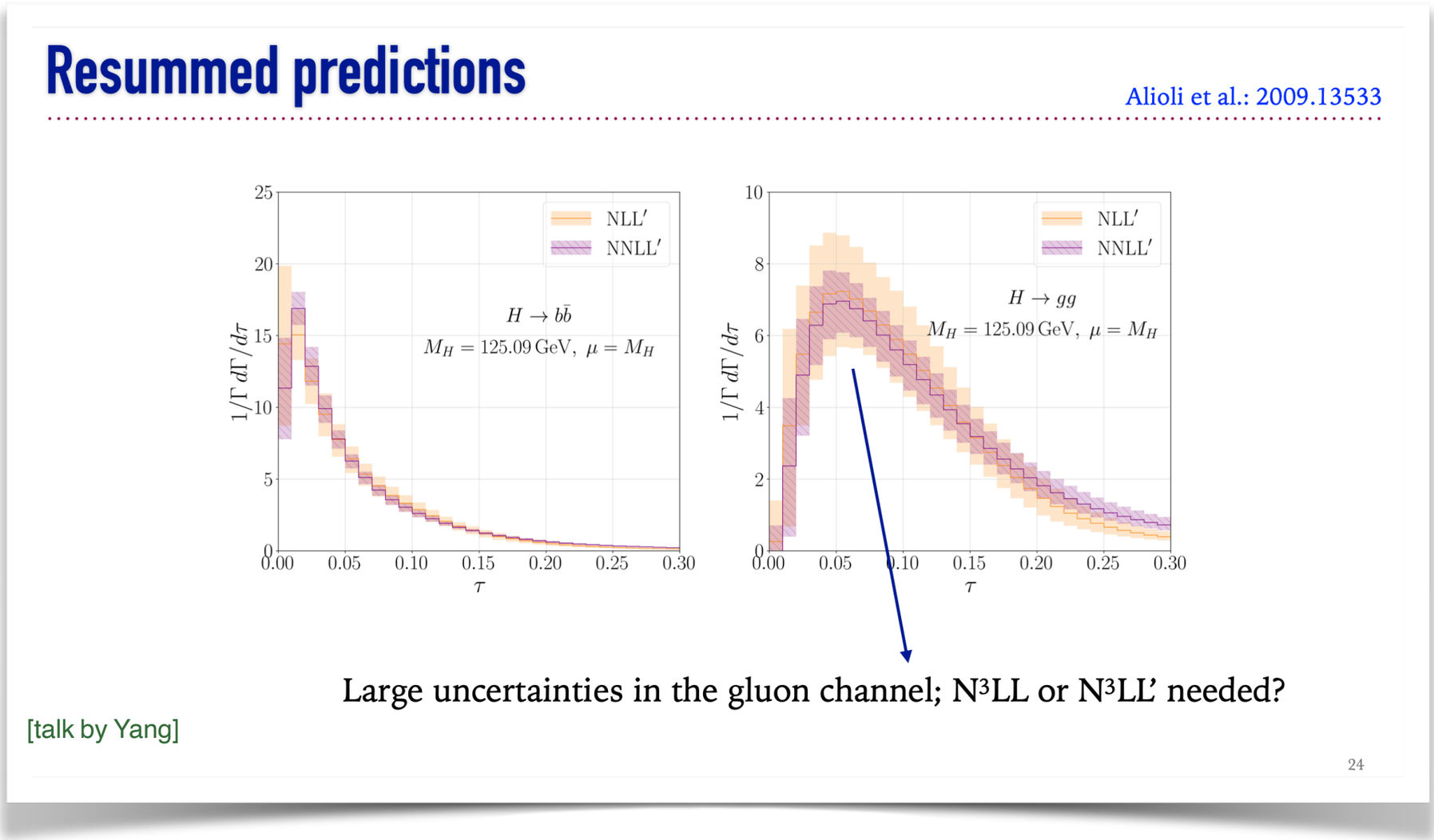
Fixed order: different types of processes/observables

- ✓ Choose right tool for each job:
  - ✓ Fully numerical: slow evaluation but generic, ideal for type 1. [talks by Maheria, Gluza, Liu]
  - ✓ Analytic calculations: fast evaluation but hard to get, ideal for type 2. [talks by Sotnikov, Peraro, von Manteuffel, Weinzierl]
  - ✓ Semi-analytic calculations, expansions: process specific, easier than full analytic, ideal for type 3. [talks by Chen, Rana, Hidding]
- ✓ New directions:
  - ✓ Combine real and virtual: progress in Loop/Tree duality, integrand subtraction [talks by Hirschi, Anastasiou]
  - ✓ Towards automation: progress in OpenLoops2 [talk by Zoller]

- ✳ Build on new developments in LHC calculations and new ideas from neighbouring fields (amplitudes, pure mathematics, …)
- ✳ FCee targets: very challenging, but substantial progress achievable with current tools (e.g., QCD corr. $e^+e^- \to 4$ jets at 2 loops vs EW corr. $e^+e^- \to H\nu\bar{\nu}$ at 2 loops)

Resummation

- ✓ Fixed-order calculations insufficient, need to resum large logarithms
  - ✓ e.g., event-shape distributions in Higgs physics

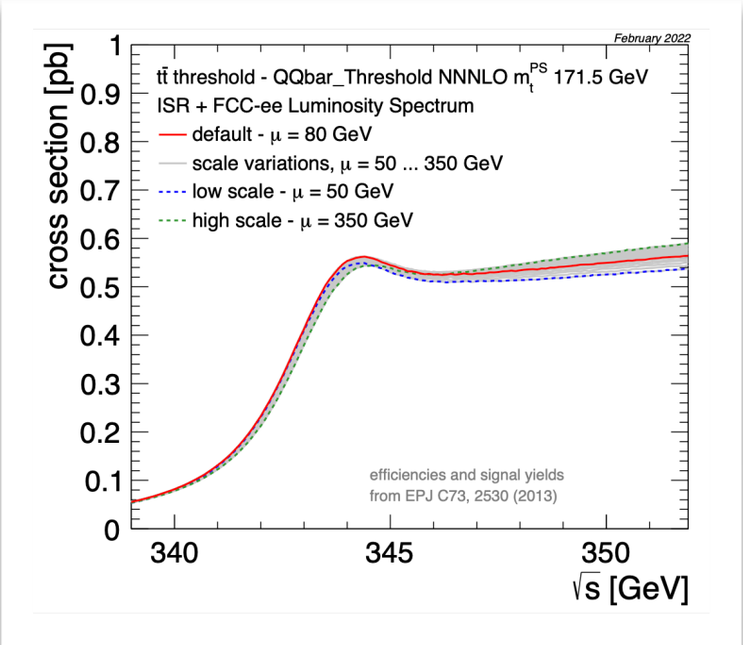


- ✓ Required resummation achievable in the coming decade, sufficient to reduce perturbative uncertainties at the ~% level

Beyond standard perturbation theory — Top Physics

[talks by Beneke and Simon]

- ✓ e^+e^- colliders are precision tools for top quark physics (few permille/percent -level on cross section)



- A challenge for theory: Understanding parameters on a level comparable to expected experimental precision. Theory is a / the leading systematic for many measurements - for the mass it is the leading uncertainty overall.

➪ Advances in theory directly translate into improvements of overall precision.

- ✓ pNRQCD known to N^{3}LO (also including EW+non-resonant effects @ NNLO)
- ✓ TH uncertainty in top mass ~ 40MeV (Beneke et al.) while EXP target is 20MeV
  - ✓ matching of N^{3}LO+NNLL (ongoing, NNLL from Hoang et al.)
  - ✓ NLL ISR QED, including soft limit
  - ✓ N^{4}LO in pNRQCD needed (currently out of reach)

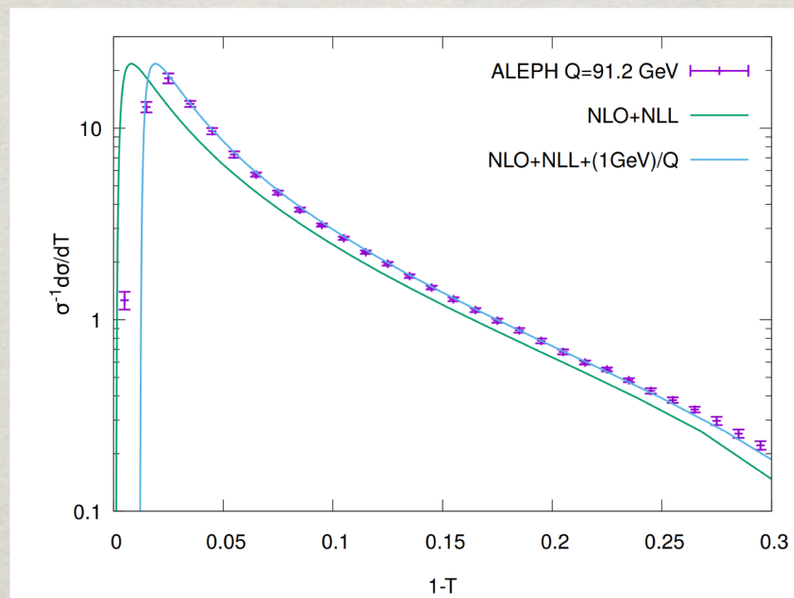
New challenges — NP effects

- ✓ Jet Physics: Non-Perturbative corrections are serious limitation of TH accuracy!

  [talks by Kluth, Nason and Banfi]

  - ✓ Better understanding of hadronisation (for even shapes, jet rates, jet substructure)

[from A. Banfi]



- Central hadrons with momenta ~1GeV give rise to a 1/Q suppressed shift of perturbative distributions of jet observables (~10% at LEP energies)

[Dokshitzer Webber hep-ph/9704298]

  - ✓ Compute new observables with reduced NP sensitivity

  - ✓ First steps in understanding linear 1/Q corrections in multi-jet final states: see P.Nason's talk for preliminary results

Conclusion and outlook

- Future lepton colliders to bring drastic reduction of experimental uncertainties
- Theory precision likely to be among main bottlenecks
- Many technical challenges, with some calculations currently beyond reach: build upon tools developed for LHC calculations, new ideas and a lot of work
- Some conceptual issues, such as Non-Perturbative corrections to hadronisation
- Not covered here in detail but very important: Monte Carlo generators for both QCD and QED, resummation, jets and parton showers, …
- Collect theory targets into a shopping list to develop and motivate theory community
- New editions of the workshop focusing on other important theory aspects (MC, resummation, …): we encourage everyone to attend!

THANK YOU!