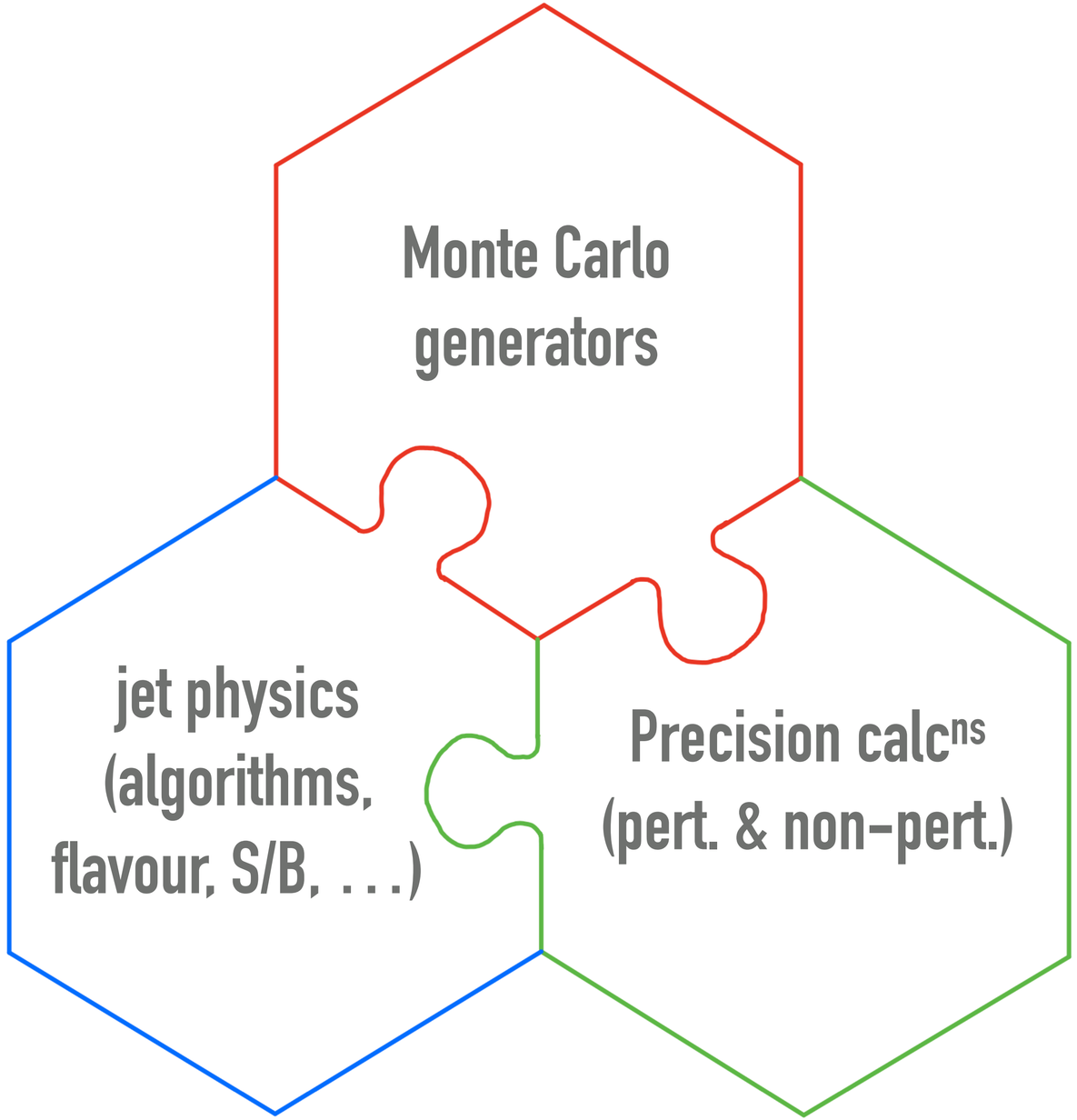
Precision calculations for future e+e– colliders: targets and tools

P. Monni (CERN) on behalf of the workshop committee

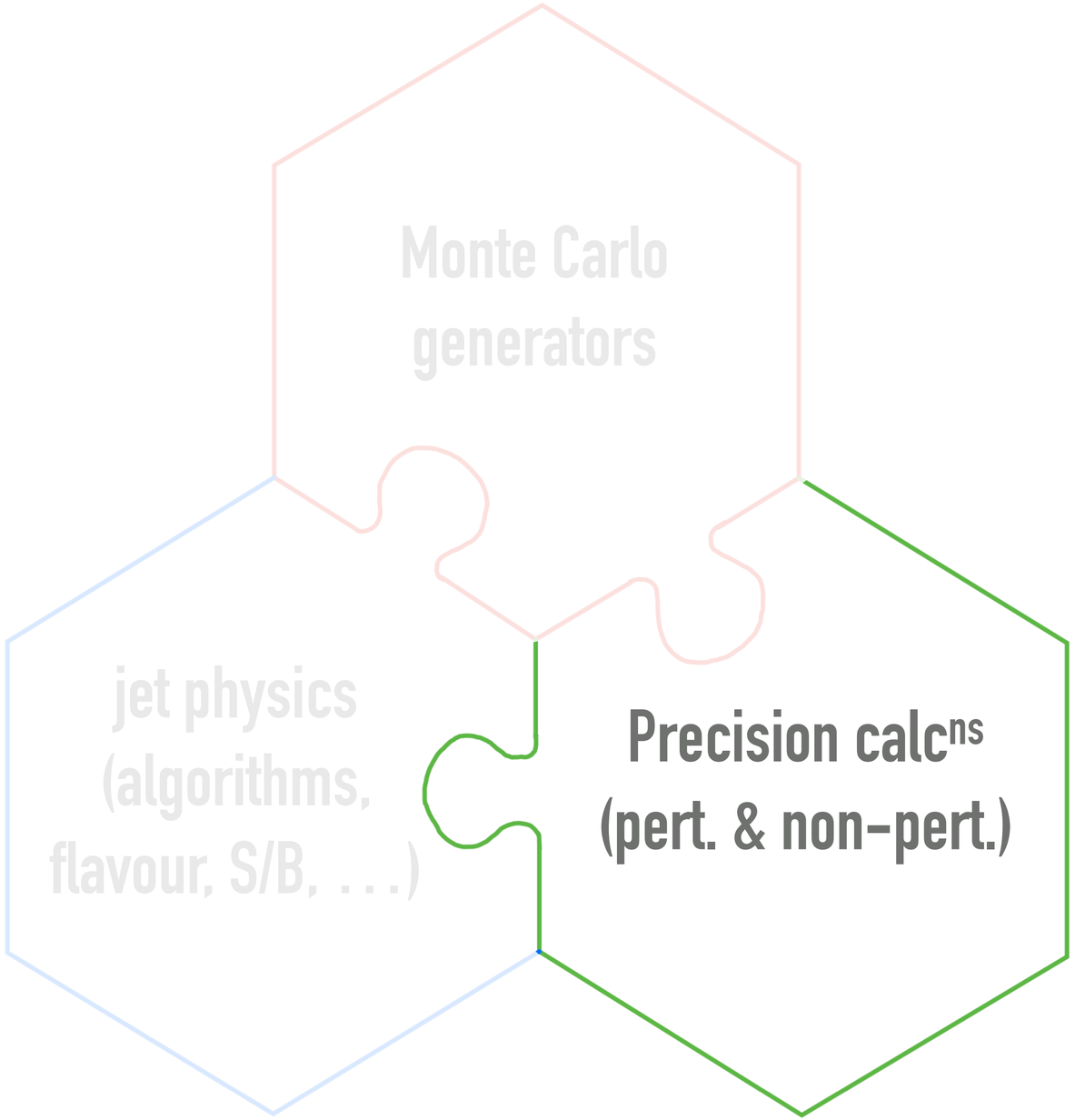
FCC Physics Programme meeting - 12 July 2022

QCD (and SM) aspects of FCC-ee



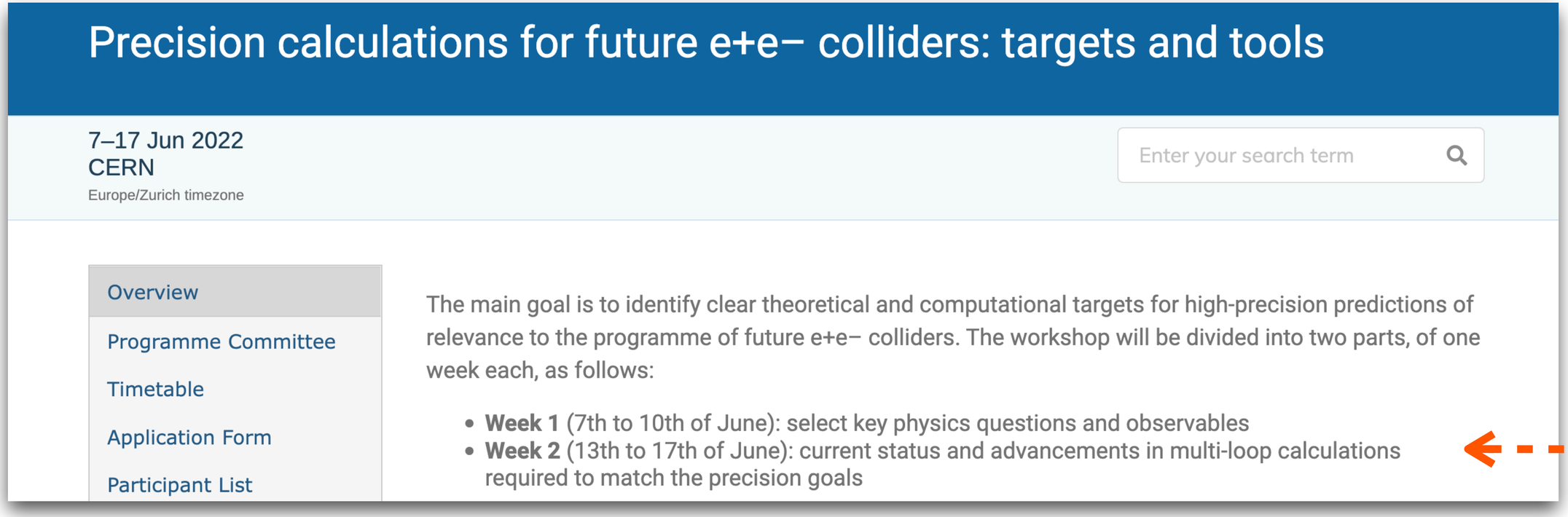
Reaching the precision foreseen at FCC(ee) poses outstanding challenges on theory calculations. Evolution in many areas is required to meet the goals

QCD (and SM) aspects of FCC-ee



This talk reviews mainly QCD aspects, EW corrections will be discussed tomorrow in A. Freitas' talk [link]

Goal of the workshop



- 227 registered participants, of which 40-50 attending in person

- 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

Targets: main objectives and observables of the FCCee programme

Tuesday, 7 June

12:45 → 13:00 Welcome — 15m — 4/3-006 - TH Conference Room

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)

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

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))

17:00 → 19:00 Reception — 2h — 500/1-201 - Mezzanine

Z pole physics

Wednesday, 8 June

10:00 → 11:00 Coffee Break — 1h — 4/2-011 - TH common room

12:20 → 17:10 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)

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))

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)

ISR (QED) and top-pair physics

Thursday, 9 June

10:00 → 11:00 Coffee Break — 1h — 4/2-011 - TH common room

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))

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

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))

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)

Higgs and QCD (jets)

Friday, 10 June

10:00 → 11:00 Coffee Break — 1h — 4/2-011 - TH common room

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

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))

15:30 Summary of week 1 — 20m — 4/3-006 - TH Conference Room

WW physics

Tools: state of the art analytical and numerical techniques

13:00 → 17:00 **Talks and discussions: multi-loop computational techniques** 4/3-006 - TH Conference Room

13:00 **Latest IBP reduction techniques** 40m 4/3-006 - TH Conference Room

The talk will review the status and future prospects of IBP reduction techniques. The importance and impact of finite-field based calculations, analytic reconstruction, multivariate partial fractioning and syzygys should be discussed.

Speaker: Tiziano Peraro (University of Bologna and INFN)

Tiziano_Peraro.pdf

14:00 **Modern calculation techniques for multi-scale loop amplitudes** 40m 4/3-006 - TH Conference Room

The talk will review modern techniques to compute multi-leg/loop amplitudes, as well
numerical techniques will be compared.

Speaker: Vasily Sotnikov (University of Zurich (UZH))

Sotnikov_CERN_ee_...

15:00 Coffee break

15:30 **OpenLoops @ 2 loops**

The talk will discuss the status and future prospects for the numerical calculation of t
applications to future e+e- colliders.

Speaker: Max Zoller (PSI)

Zoller_CERN_ee_20...

13:00 → 17:00 **Talks and discussions: multi-loop computational techniques** 4/3-006 - TH Conference Room

13:00 **Numerical calculations using pySecDec** 40m 4/3-006 - TH Conference Room

The talk will discuss recent multi-loop calculations with PySecDec, highlighting how these calculations and the technology adopted can be exploited for multiloop computations at future e+e- colliders (e.g. EW corrections and reactions involving quark masses).

Speakers: Vitalii Ivanovych Maheria, Vitalii Maheria

magerya-futurecolli...

14:00 **Feynman parametrization and numerical integration** 40m 4/3-006 - TH Conference Room

The talk will discuss the status of the calculation of electroweak pseudo-observables, as well as the methodology to evaluate Feynman-parameter integrals numerically, with a focus on the Mellin-Barnes method. The prospects for future applications at future e+e- machines will be highlighted.

Speakers: Janusz Gluza (University of Silesia (PL)), Janusz Gluza (U. Silesia)

CERN_TH_MB_2022...

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

15:30 **Mixed QCD-EW corrections to neutral-current Drell-Yan** 40m 4/3-006 - TH Conference Room

The talk will discuss the recent calculations of QCD-EW corrections to Drell-Yan, highlighting how these calculations and the technology adopted can be exploited for multiloop computations at future lepton colliders.

Speaker: Narayan Rana (INFN Milan)

Rana_FCCee.pdf

13:00 → 17:00 **Talks and discussions: multi-loop computational techniques** 4/3-006 - TH Conference Room

13:00 **Local unitarity: perspectives for future lepton colliders** 40m 4/3-006 - TH Conference Room

The talk will discuss the status and future prospects of the Loop-Tree Duality approach for the calculation of higher-order corrections to cross sections relevant for future e+e- colliders (both for QCD and EW corrections).

Speaker: Valentin Hirschi (CERN)

FCC_ee_workshop_...

14:00 **Integrand subtraction & numerical integration** 40m 4/3-006 - TH Conference Room

The talk will discuss the status and future prospects of integrand-subtraction methods to construct locally finite two-loop amplitudes, focusing on applications to future e+e- colliders.

Speaker: Charalampos Anastasiou

HPFCee_Anastasio...

Coffee break 30m 4/2-011 - TH common room (...

Analytic methods for multi-loop calculations 40m 4/3-006 - TH Conference Room

The talk will discuss the recent calculations of EW corrections to Drell-Yan and of the four-loop form factor, highlighting how these calculations and the technology adopted can be exploited for multiloop computations at future lepton colliders.

Speaker: Andreas von Manteuffel (Michigan State University)

manteuffel-ee-2020....

13:00 → 17:40 **Talks and discussions: multi-loop computational techniques**

13:00 **Numerical evaluation of QCD virtual corrections with top quarks in e+e- collisions** 40m 4/3-006 - TH Conference R...

The talk will discuss recent multi-loop calculations involving heavy quarks, highlighting how these calculations and the technology adopted can be exploited for multiloop computations at future e+e- colliders.

Speaker: Long Chen

Chen_FCCeeWorks...

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

https://indico.cern.ch/event/1155782/

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

15:30 **Elliptic integrals** 40m 4/3-006 - TH Conference Room

The talk will discuss the current understanding of elliptic integrals and future prospects in the context of multiloop calculations for future e+e- colliders. The talk will cover both the aspect of the analytic calculation of this class of integrals as well as their numerical evaluation.

Speaker: Stefan Weinzierl (Universität Mainz)

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13:00 → 17:00 **Talks and discussions: multi-loop computational techniques** 4/3-006 - TH Conference Room

13:00 **DiffExp and Feynman parameter integration** 40m 4/3-006 - TH Conference Room

The talk will discuss the status and applications of the generalized power-series solution of differential equations (e.g. DiffExp, CAESAR), highlighting how this technology can be exploited for multiloop computations at future lepton colliders.

Speaker: Martijn Hidding (Uppsala University)

Talk_FCCee.pdf

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

14:30 **The AMFlow approach** 40m 4/3-006 - TH Conference Room

The talk will discuss the status and applications of the AMFlow method to the calculation of IBP systems and the solution of differential equations for master integrals. The talk will highlight how this technology can be exploited for multiloop computations at future lepton colliders.

Speaker: Xiao Liu (University of Oxford)

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Precision physics at the Z pole

- **Numbers are given here for FCC-ee (best prospects)** [From P. Janot's talk]

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, ...)

- Theory crucial in 3 ways: measurement/calibration (e.g. QED ISR); interpretation of results (EWPO); parametric uncertainties (i.e. couplings, masses)

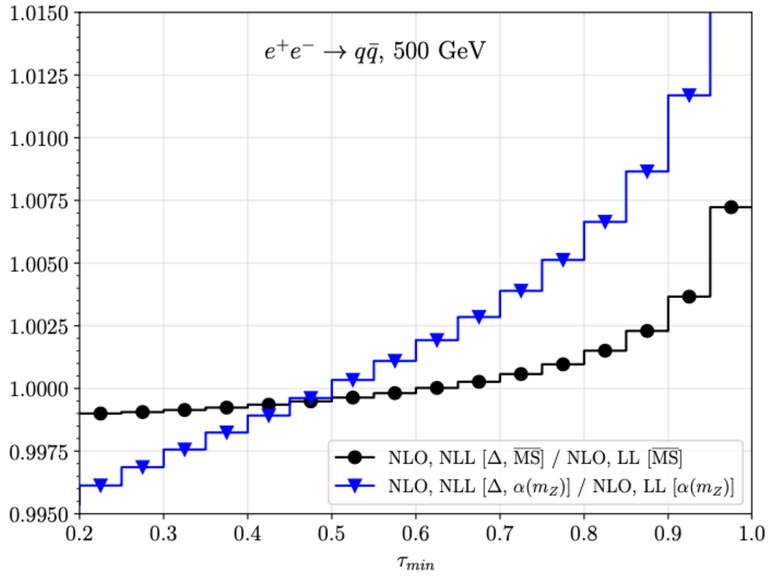
- In an optimistic scenario, consider statistical uncertainties as the ultimate target

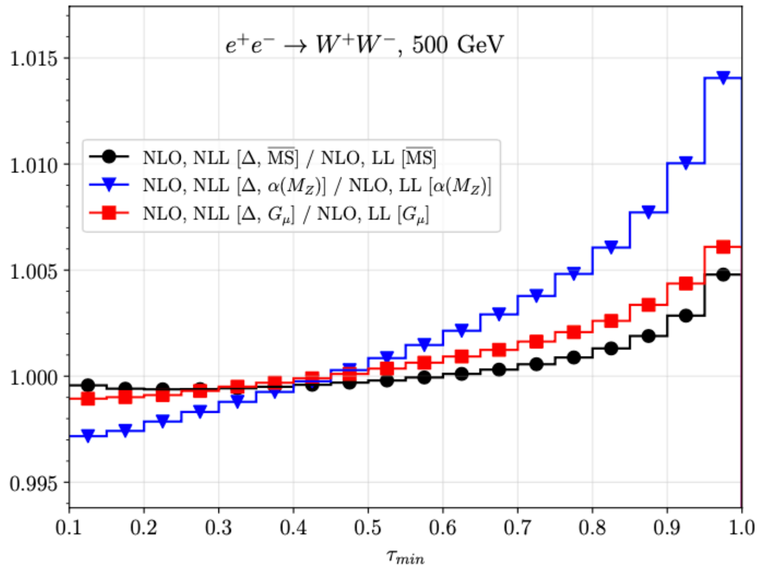
Initial state radiation and collinear factorisation

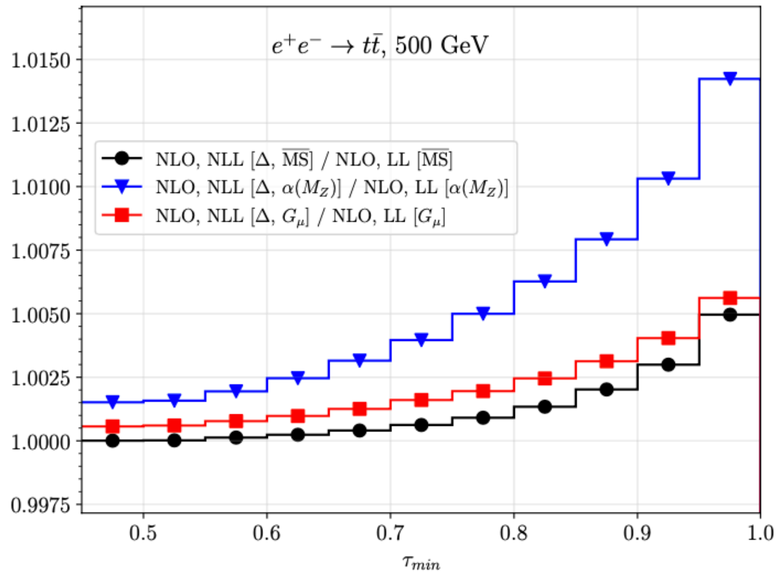
- Modelling of QED ISR central in FCCee (Z pole physics, WW, tt thresholds, ZH,…)
- Recently important progress in formulating collinear factorisation (as opposed to YFS) beyond LO/LL.

  E.g. NLL/NLO corrections to total rates ($\tau_{\min} = \frac{M^2}{s}$)

NLL sizeable (% level)
and proc./obs. dependent
(Also large renormalisation scheme dep.)







[From S. Frixione's talk (plot from Bertone et al. '22)]

Initial state radiation and collinear factorisation

- More progress needed in coming years:
  - NNLL coll. factorisation needed to improve further (within reach with modern perturbative techniques, but tough)
  - Simultaneous resummation at all-orders of soft (non-collinear) and collinear logarithms (traditionally two approaches used - YFS / coll. factorisation). Potentially relevant in studies at the ttbar threshold
  - Exclusive implementation in (accurate) MCPS's (several tools exist, important to explore how to improve logarithmic accuracy in view of recent developments in QCD)

Precision physics at the Z pole

- **Numbers are given here for FCC-ee (best prospects)** [From P. Janot's talk]

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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)
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R_b ($\times 10^6$)	216290 ± 660	0.3	?	< 60 ?	QCD (gluon radiation, gluon splitting, fragmentation, decays, ...)

- Theory crucial in 3 ways: measurement/calibration; interpretation of results; parametric uncertainties
- QCD uncertainties concern all three categories

Precision physics in Z → jets

- Main challenges from EW aspects: EWPO Z → qq+X @ 3 loops EW and beyond, beam calibration [$e^+e^- \to e^+e^-$, $\mu^+\mu^-$, $\gamma\gamma$ @ NNLO EW - still beyond reach]

- Also high potential for precision QCD studies: α_S, gauge structure and spin correlations in multi-jet final states, non-perturbative dynamics, HQ asymmetries, fragmentation functions, τ decays (α_S), …

  - Typical example: R_b, A_{FB} requires QQg and qqg(→ QQ) @ 2 loops with m_b dependence

- Significant progress needed for multi-jet final states (both fixed-order and resummations)

  - Examples:

    - 3 jets @ N^{3}LO QCD

    - 4 & 5 jets at NNLO QCD

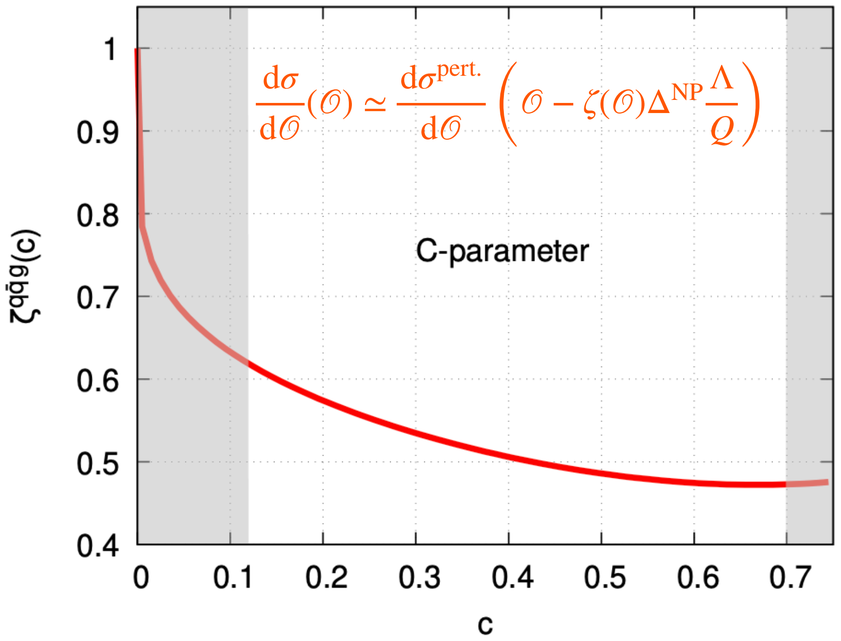
Possibly already achievable in the next few years thanks to multi-scale techniques developed for LHC calc^{ns}

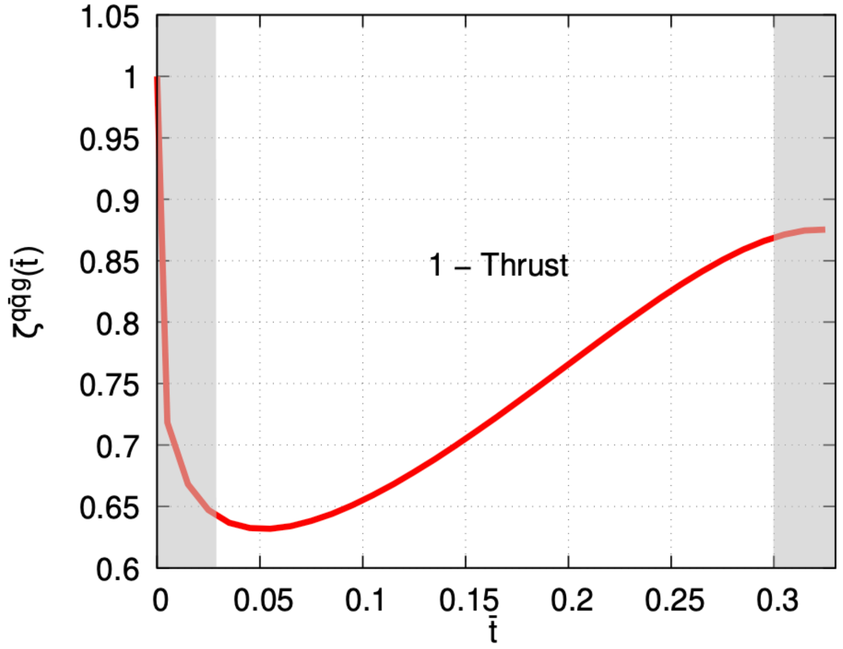
- Many new directions are under investigation: e.g. prospects for numerical approaches to calculate total rates at N$^{(2/3)}$LO (also for EW corrections) look very promising (e.g. Feynman parameters; local unitarity, AMFlow, …). Further progress is needed to control kinematic distributions precisely

The elephant in the room: hadronisation

- Better understanding of hadronisation in jet observables appears to be essential to control differential distributions (event shapes, jet rates, jet substructure). Serious limitation of TH accuracy
- Possible avenues (possibly in combination - deserves further thoughts):
  - techniques to calculate leading corrections as $1/Q$ expansion (at higher energies)
  - new observables with reduced NP sensitivity (LHC jet substructure technology may help)

[From A. Banfi's & P. Nason's talks]

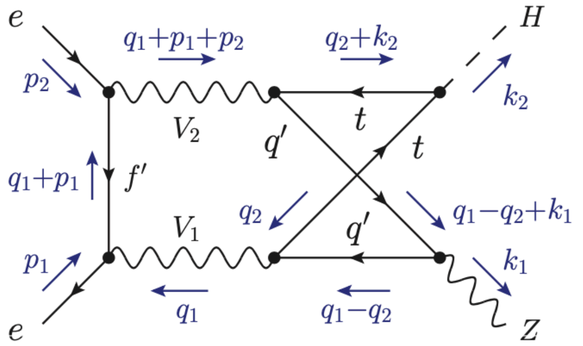




e.g. Recently first steps in understanding linear (1/Q) corrections in multi-jet final states (e.g. event shapes or jet rates in $e^+e^- \to 3$ jets)

Higgs physics

- Experimental precision approaching 0.1% in many cases at ZH threshold
- Example: **total cross section will be measured with precision in the range 0.2%-0.5%**. Necessary ingredients:
  - $e^+e^- \to Z\,H,\ H\,\nu\,\nu\ (e^+e^-)$ @ 2 loops EW (hard at the moment)
  - **Mixed QCD⊗EW @ 2 loops under control**: combination of kinematic expansions and new numerical techniques (fast evaluation of amplitudes)



[From L. L. Yang's talk]

Gong, Li, Xu, **LLY**, Zhao: 1609.03955

$\sqrt{s}$ (GeV)	$\mathcal{O}(m_t^2)$	$\mathcal{O}(m_t^0)$	$\mathcal{O}(m_t^{-2})$	$\mathcal{O}(m_t^{-4})$
240	81.8%	16.2%	1.4%	0.4%
250	81.7%	16.1%	1.5%	0.5%
300	80.0%	15.2%	2.1%	1.1%
350	69.7%	12.6%	2.7%	2.1%
500	137%	18.6%	17.3%	31.1%

E.g. $1/m_t$ expansion below $s \sim (2\,m_t)^2$, and $m_H^2, m_Z^2 \ll s, m_t^2$ elsewhere. Such methods could help in EW corr^n too

Hadronic Higgs decays

[From J. List's talk]

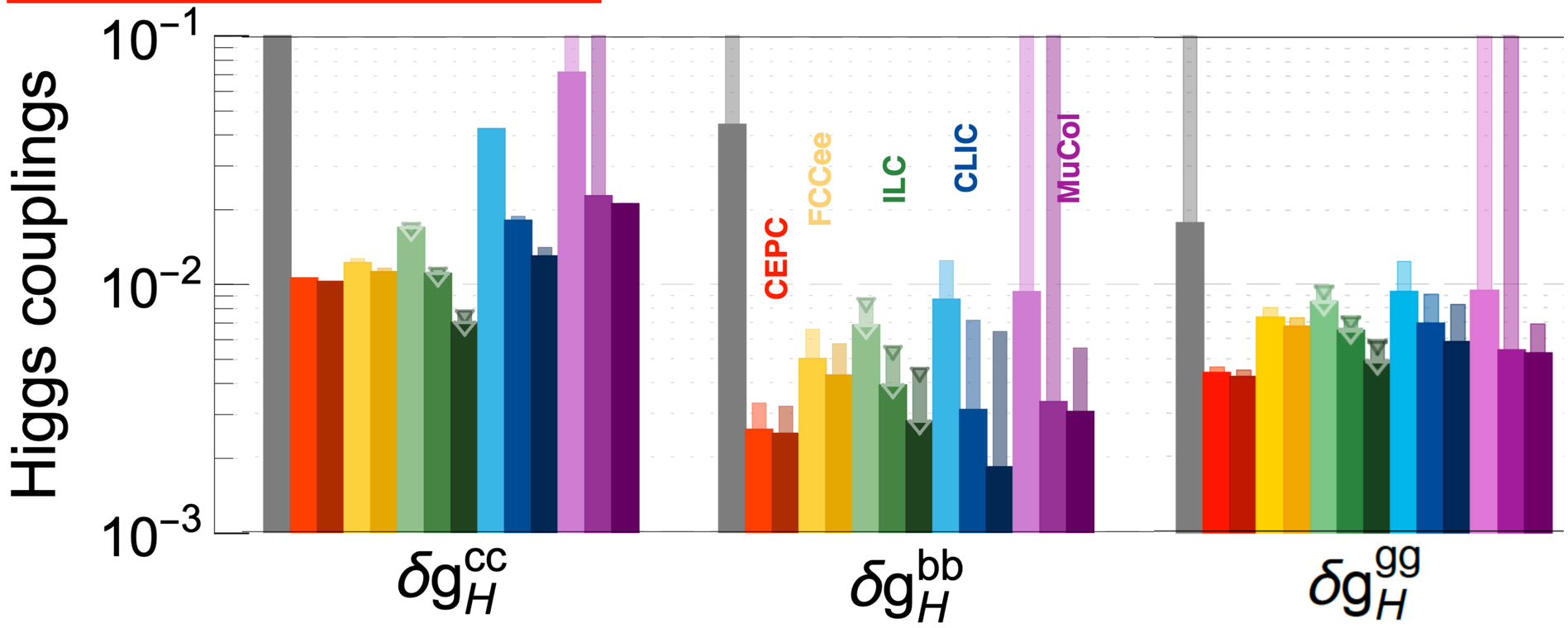
Higgs decay to jets

…in SMEFT fit

preliminary Snowmass fit result:
- recall: neither intrindic theory nor parametric uncertainties included

future estimates (on Γ_{partial}) from arXiv:1906.05379:

decay	intrinsic	para. m_q	para. α_s	para. M_H
$H \to b\bar{b}$	$\sim 0.2\%$	0.6%	$< 0.1\%$	–
$H \to c\bar{c}$	$\sim 0.2\%$	$\sim 1\%$	$< 0.1\%$	–
$H \to gg$	$\sim 1\%$		0.5% (0.3%)	–



Projected reduction of TH uncertainties (total rates) within reach of current technology

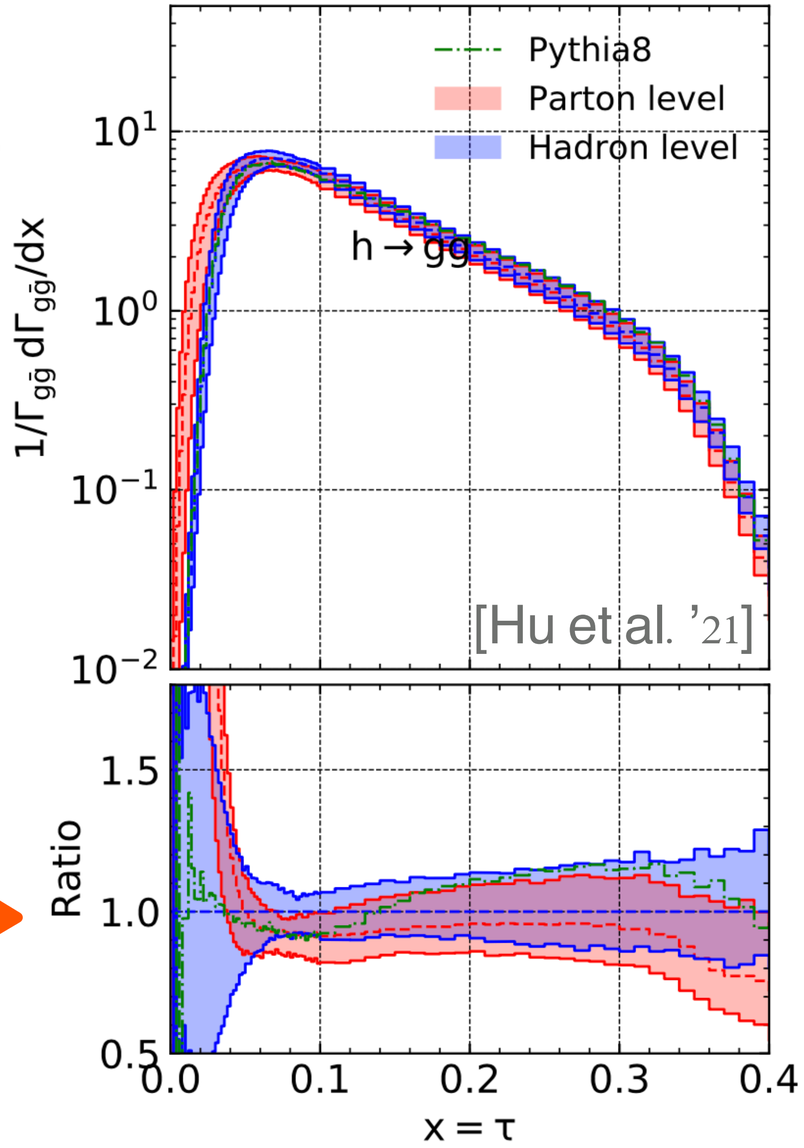
Hadronic Higgs decays

$$T = \max_{\vec{n}} \frac{\sum_i |\vec{n} \cdot \vec{p}_i|}{\sum_i |\vec{p}_i|}$$

$$\tau = 1 - T$$

- Accuracy significantly lower for differential distributions (e.g. potential sensitivity to light-quark Yukawa couplings)
- N³LO (+resummations) probably achievable in the coming decade, sufficient to reduce perturbative uncertainties at the ~% level
- However, hadronisation remains a great bottleneck
  - E.g. thrust distribution in H → gg decays (NNLO+PS in the plot)

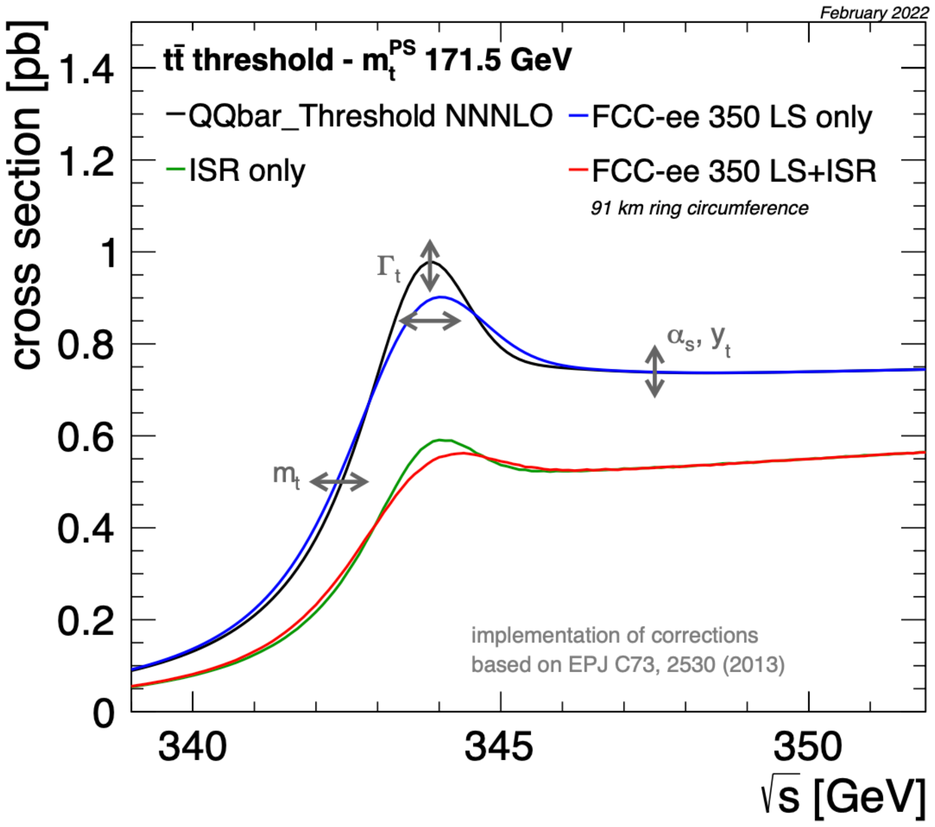
Same considerations as for Z → jets: developments in MC technology also crucial to improve on this aspects



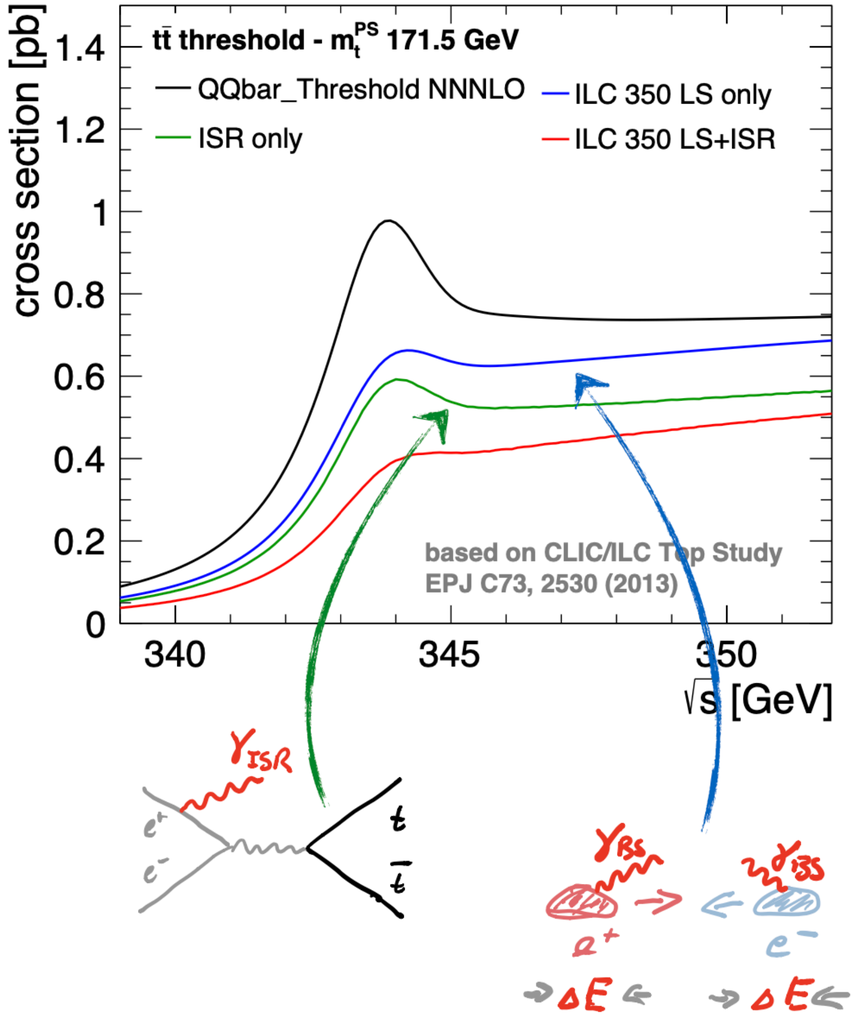
Top physics

- Huge potential from threshold scan: up to per-mille accuracy on cross section & asymmetries
- Great challenge for theory to match experimental precision ("intrinsic" and parametric unc.s)

[From F. Simon's talk]



FCC vs ILC



Top physics: threshold

[Many thanks to M. Beneke and M. Vos for helpful exchanges]

- PNRQCD predictions known to N^{3}LO (also including EW+non-resonant effects @ NNLO)
- Uncertainty in top mass (potential subtracted) ~ 40 MeV (Beneke et al.). Exp. target 20 MeV
  - Some improvements already from matching of N^{3}LO+NNLL (ongoing, NNLL from Hoang et al.)
  - Ultimately N^{4}LO in PNRQCD needed (currently out of reach) and NLL ISR QED (including soft limit)

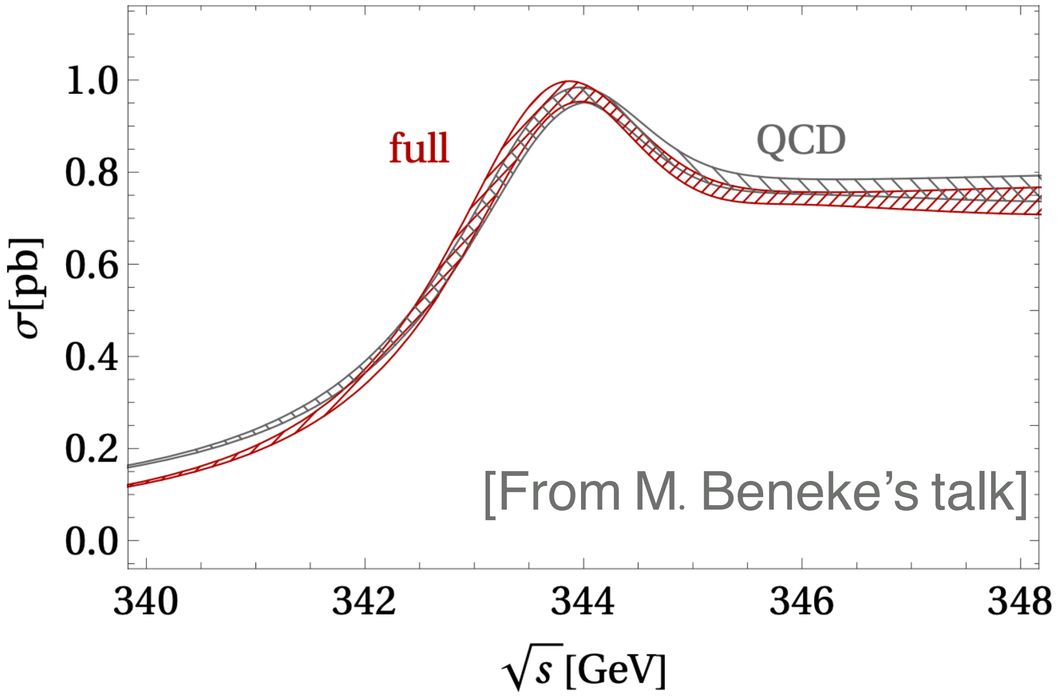
$$\mathcal{L}_{\rm QCD}\,[Q(h,s,p),\ g(h,s,p,us)] \qquad \mu > m$$

$$\downarrow$$

$$\mathcal{L}_{\rm NRQCD}\,[Q(s,p),\ g(s,p,us)] \qquad mv < \mu < m$$

$$\downarrow$$

$$\mathcal{L}_{\rm PNRQCD}\,[Q(p),\ g(us)] \qquad \mu < mv$$



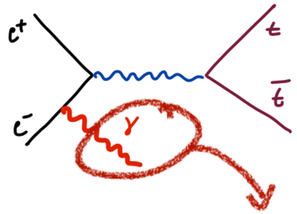
Top physics: continuum

[Many thanks to M. Beneke and M. Vos for helpful exchanges]

- 360-380 GeV and radiative events requires matching of continuum and threshold calculations. Available at NNLL+NNLO (Boronat et al.), still needs a careful assessment of uncertainties

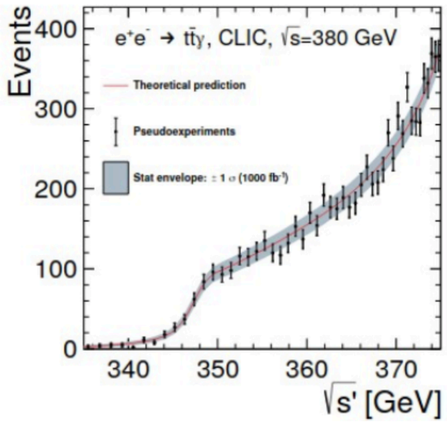
- Continuum: target is 0.1% on cross section. NNLO QCD available (Chen et al.) but 2 loop EW is large! N^{3}LO QCD + NNLO EW necessary in the end, probably feasible (with a lot of work) in the coming decade(s).

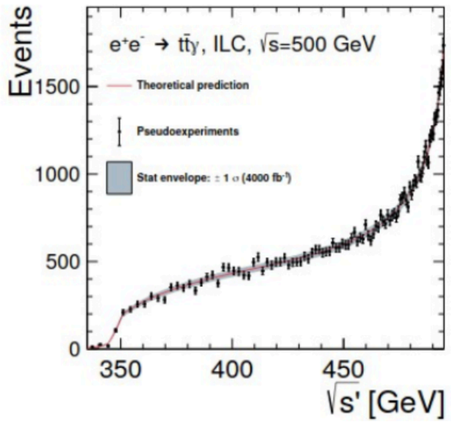
- A new(er) idea to measure the top mass in a theoretically well-defined scheme in high-energy running above the threshold



matched NNLO + NNLL calculation, luminosity spectrum folded in explicitly; Extraction of short distance MSR mass

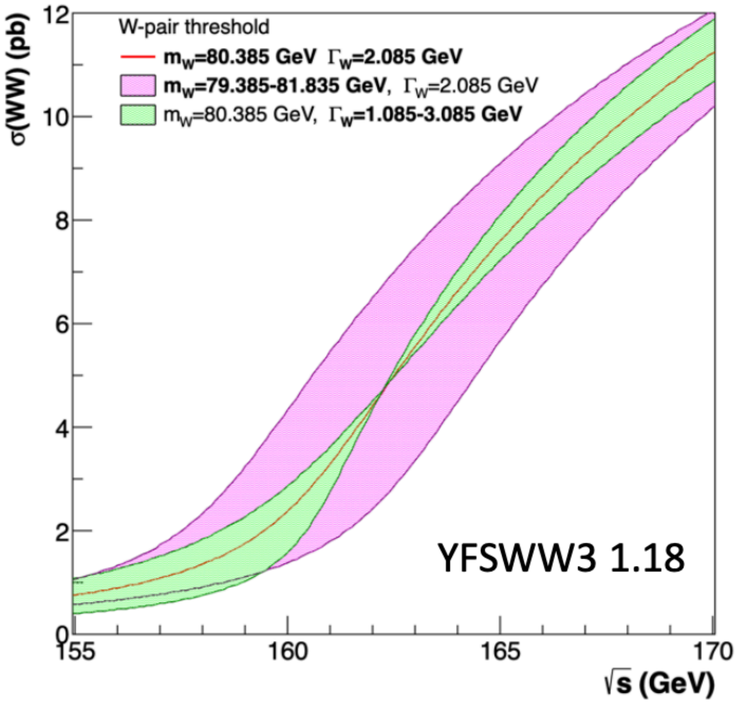
cms energy	CLIC, $\sqrt{s} = 380$ GeV		ILC, $\sqrt{s} = 500$ GeV	
luminosity [fb^{-1}]	500	1000	500	4000
statistical	140 MeV	90 MeV	350 MeV	110 MeV
theory	46 MeV		55 MeV	
lum. spectrum	20 MeV		20 MeV	
photon response	16 MeV		85 MeV	
total	150 MeV	110 MeV	360 MeV	150 MeV

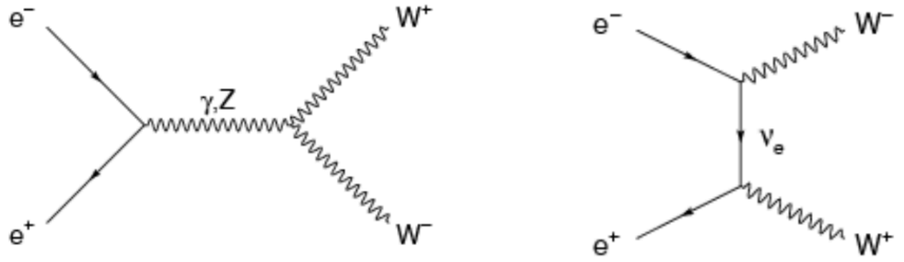




WW threshold (and above)

- Precise extraction of TGCs and W mass & width: e.g. δm_W~few MeV (statistical error ~ 0.5 MeV!)





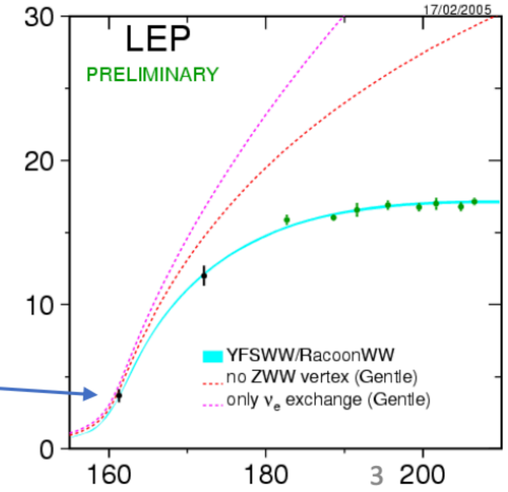
[From P. Azzurri's talk]

WW cross section rise $\beta = \sqrt{1 - 4m_W^2/s}$ driven by t-channel production

Extract the W mass inverting the m_W dependence

$$\sigma(m_W, E) \qquad m_W = \sigma^{-1}(E)$$

$$\Delta m_W = \left(\frac{d\sigma}{dm_W}\right)^{-1} \Delta\sigma$$



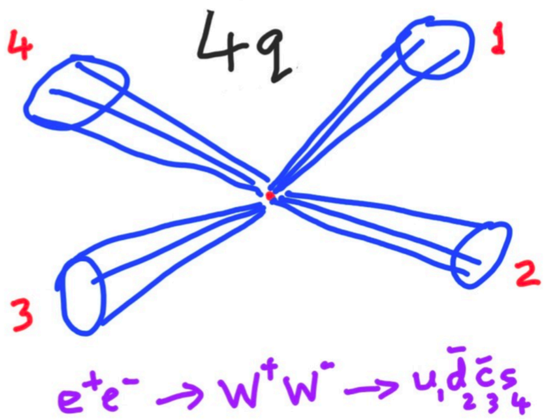
ALEPH Phys.Lett.B 401 (1997) 347 with 10/pb $m_W = 80.14 \pm 0.34$ GeV

stat extrapolation to 10/ab $\Longrightarrow$ $\Delta m_W = 0.34$ MeV

WW threshold (and above)

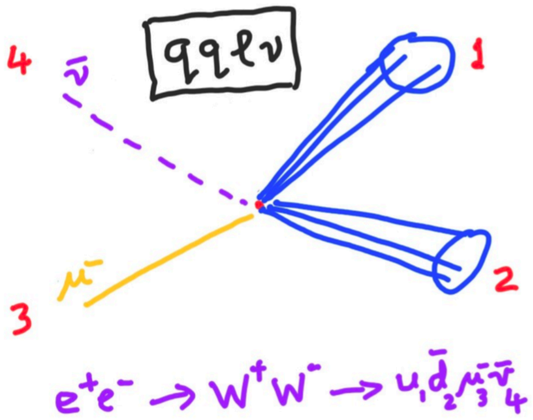
- Theory modelling enters differently in different signatures/channels. To be precisely assessed
  - Control over QED ISR (discussed earlier); EFT resonant aspects near threshold
  - Signal & background: 2f (calibration), 4f final states ($e^+e^- \to qqev$ particularly relevant)
  - Colour reconnection in hadronic channels (more generally MC generators)

fully hadronic $q\bar{q}q\bar{q}$



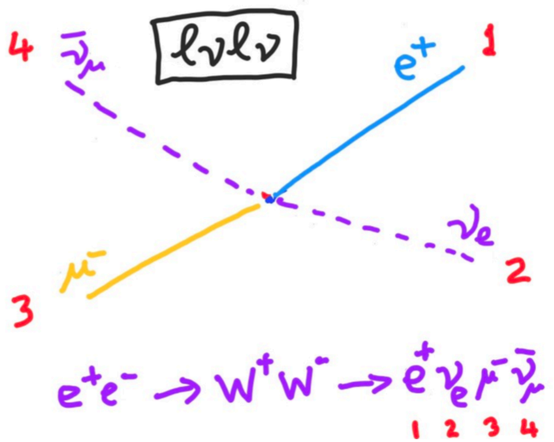
$B_h^2 = 45.4\%$

semi-leptonic $q\bar{q}\ell\nu_\ell$



$6B_\ell B_h = 43.9\%$

fully leptonic $\ell\nu_\ell\ell'\bar{\nu}_{\ell'}$



$9B_\ell^2 = 10.6\%$

[From G. Wilson's talk]

Outlook

- Astounding experimental programme at FCCee, drastic reduction of statistical (and systematic) uncertainties: theory precision likely to be among the main bottlenecks

- Many/all areas of theory calculations need to be involved, this workshop mainly covered the field of Feynman integrals calculations

  - Most challenges are technical in nature: hard calculations, currently beyond reach but likely to be achieved with natural evolution of the field in the coming decade(s), and a large amount of work

  - Some conceptual issues, which need significant breakthroughs in the years to come: non-perturbative QCD (hadronisation, colour reconnection); EFT (e.g. Coulomb) effects in MC generators, …

- Short term plan: try to collect targets into a “shopping list” to be shared with the community (input from all speakers and many participants); iterate workshop on other TH areas in coming years (e.g. MC generators, jets & resummations,…)