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QCD with low-$\sqrt{s}$ runs at FCC-ee

(Selected topics)

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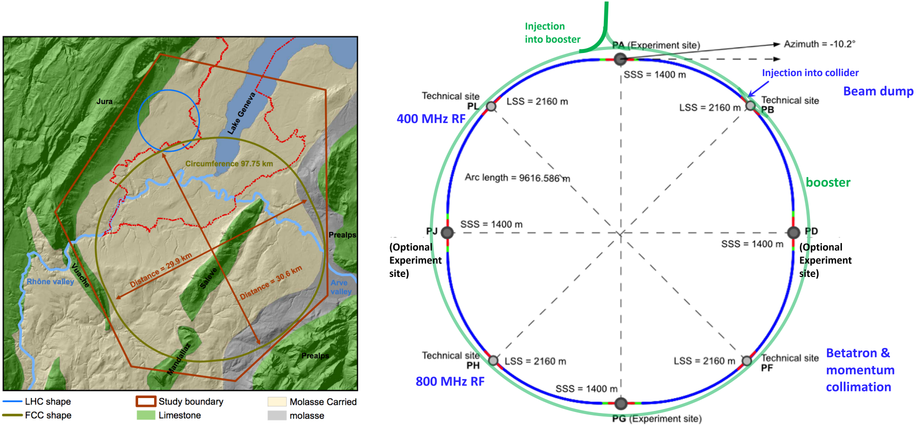
FCC-*ee*



Source: Ref. [1, 2].

- e^+e^- collider in CERN, 91 km [3] long, with 4 IPs.
- State of the art detector(s) design.
- Precision goals: 10^{-5} for EW, 10^{-3} for QCD observables.
- A lot of physics [4] **conceptually different from LEP physics**.

QCD tasks for FCC-*ee* era (experimental/pheno side)

- **Application of higher& even higher order pQCD and QCD×EW corrections, resummation/showers.**
- Studies of quark mass effects.
- Studies of exotic final states.
- **Better understanding of non-perturbative effects: hadronization, colour reconnection, etc.**.

How to approach those tasks?

Use various scales in pQCD.
Cross-section for a physical process with hard scale, Q_H, and heavy quark masses m_Q:

$$d\sigma \sim \mathrm{Hard}(Q_H, Q, m_Q) + \mathrm{Resum}(Q_H/Q, Q/m_Q, Q/\Lambda_{\mathrm{QCD}}) + \mathrm{NonPert}(\Lambda_{\mathrm{QCD}}/Q, m_Q/Q)$$

→ **Scale matters**.

To study

- Non-perturbative effects
- Quark masses
- Parton showers

Exploring the regions with different Λ_{QCD}/Q and m_Q/Q is a must.
Regions with larger Λ_{QCD}/Q and m_Q/Q are preferable: no reason to avoid the subject of study.

$\alpha_S(M_Z)$ from $e^+e^- \to$ *hadrons*

Determination[1]	Type	Data and procedure	Ref.
0.1175 ± 0.0025	Non-global fit +MChad	ALEPH 3-jet rate (NNLO+MChad)	[6]
0.1199 ± 0.0059		JADE 3-jet rate (NNLO+NLL+MChad)	[7]
0.1224 ± 0.0039		ALEPH event shapes (NNLO+NLL+MChad)	[8]
0.1172 ± 0.0051		JADE event shapes (NNLO+NLL+MChad)	[9]
0.1189 ± 0.0041		OPAL event shapes (NNLO+NLL+MChad)	[10]
$0.1164\,^{+0.0028}_{-0.0026}$	Global fit +anlhad	Thrust (NNLO+NLL+anlhad)	[11]
$0.1134\,^{+0.0031}_{-0.0025}$		Thrust (NNLO+NNLL+anlhad)	[12]
0.1135 ± 0.0011		Thrust (SCET NNLO+$\mathrm{N^3LL}$+anlhad)	[13]
0.1123 ± 0.0015		C-parameter (SCET NNLO+$\mathrm{N^3LL}$+anlhad)	[14]
0.11750 ± 0.00287	Global fit +MChad	EEC (NNLO+$\mathrm{N^2LL}$+MChad+NLO_{m_b})	[15]
0.11881 ± 0.00131		2-jet rate ($\mathrm{N^3LO}$+$\mathrm{N^3LL}$+MChad+$\mathrm{N^2LO}_{m_b}$)	[16]

Global fits and wide $\sqrt{s}$ range → best precision.
The discrepancy between the analytic and MC hadronization should be clarified.

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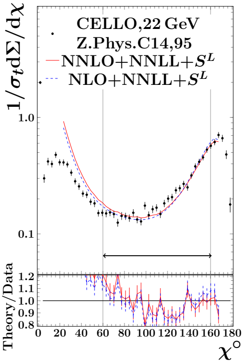
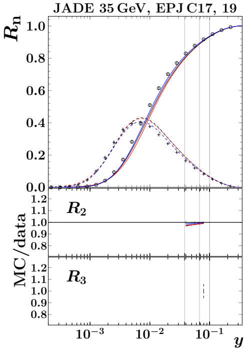
[1] Credits to Ref. [5]

Hadronization modeling in $e^+e^- \to hadrons$

- The modern MCEG models are for $\sqrt{s} \approx M_Z$, but not trustable for other energies[16][15] and lower scales.
- This is an artefact: the models were tuned with LEP data at $\sqrt{s} \approx M_Z$ or LHC data, where the tuning does not give very certain results.





- The recent efforts to re-use the PETRA, TRISTAN and PEP data [17] had limited success due to huge data uncertainties.

With enough data away from Z peak, MCEG models can be re-tuned to describe the hadronization better at all energies.

Solution: away from Z peak …to lower energies

The data collected at $M_Z < \sqrt{s}$ also can be used for the hadronization studies. However,

- The data with $M_Z < \sqrt{s} < 2M_W$ contains large radiative return.
- The data with $2M_W < \sqrt{s}$ has large contributions from $e^+e^- \to VV$ or even $e^+e^- \to ZH$, which cannot be fully decoupled from the $e^+e^- \to Z/\gamma \to hadrons$. The removal of "background" from those processes are the dominant systematic uncertainties at LEP. Theory predictions for $e^+e^- \to (Z, \gamma, VV, ZH) \to hadrons$ seems to be in a very distant future.

The only range with theoretically clean signal with precise $e^+e^- \to hadrons$ predictions is $M_\Upsilon \leq \sqrt{s} < M_Z$.

Historically collected data

Accelerator	Energy range, GeV	Luminosity, pb^{-1}	Eligible multihadron events, $\times 10^3$
TRISTAN	$50 - 64$	900 [18]	$\approx$ 110 [19]
PETRA	$12 - 47$	760 [20]	$\approx$ 200 [21, 20]
PEP	29	315 [22]	144 [22]

Table: Estimate of the number of eligible hadronic events at TRISTAN, PETRA, and PEP. The numbers for PETRA were estimated by multiplication of the JADE numbers from Ref. [20] by 4, i.e. assuming the numbers for the MARK-J, TASSO and CELLO experiments are reasonably close. The numbers for TRISTAN were estimated scaling the numbers from Ref. [19] to the total luminosity.

There are even less data available for reanalysis.

An extension of FCC-e^+e^- physics program for MCEGs

Proposed extension of the FCC-e^+e^- program with datataking in range $\sqrt{s} = 40 - 91\,\mathrm{GeV}$

FCC-e^+e^- $=$ Higgs factory $+$ SuperLEP

$+$ SuperTRISTAN $+$ SuperPEP $+$ SuperPETRA

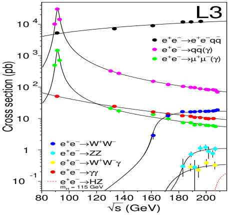
Two **non-excluding** options are available to get to $\sqrt{s} = 40 - 91\,\mathrm{GeV}$:

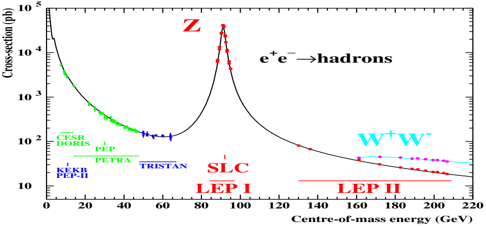
- Dedicated runs: runs with lowered beam energy.
- $e^+e^-\gamma$: γ tagging of radiative events $e^+e^- \rightarrow hadrons + \gamma$.

Measurements in focus: event shapes, jets, (heavy flavour) fragmentation functions, hadron multiplicities for MC tunes.

$e^+e^-\gamma$ vs. dedicated runs in short

- Dedicated: Perfect, background-free data, fast to collect supersedes data collected at **all** previous colliders within days. Requires efforts.
- $e^+e^-\gamma$: Lower data quality and numerous issues. But with and advanced FCC-*ee* detector this option can be extremely valuable.





A perfect scenario: dedicated runs with ≈ 10 equidistant energy points in range $40-91$ GeV with 10^8-10^9 events each and the use of all $e^+e^-\gamma$ events.

Historical example of $e^+e^-\gamma$ vs. dedicated runs

Clear differences between the precision of results with e.g. α_s extraction.
OPAL [23]:

$0.1182 \pm 0.0015(\mathrm{stat.}) \pm 0.0038(\mathrm{exp.syst.}) \pm 0.0070(\mathrm{hadr.}) \pm 0.0062(\mathrm{theory.})(\mathit{NLO})$

vs JADE [9]:

$0.1172 \pm 0.0006(\mathrm{stat.}) \pm 0.0020(\mathrm{exp.syst.}) \pm 0.0035(\mathrm{hadr.}) \pm 0.0030(\mathrm{theory.})(\mathit{NNLO} + \mathit{NLLA})$

	Year	Type	$\sqrt{s}$	Hadr. unc.	Exp. syst. unc .
JADE	2008	Low energy run	12-46	0.0035	0.0020
OPAL	2007	$e^+e^-\gamma$	10-45	0.0070	0.0038

The boring and obvious conclusion – the data and results from dedicated runs were better.

Ups and downs: $e^+e^-\gamma$ extrapolation from LEP

Type	$\sqrt{s}'$ (GeV)	$\langle\sqrt{s}'\rangle$ (GeV)	Lumi (pb^{-1})	Selection Eff. (%)	Purity (%)	# Sel. Evts	FCC-ee, estimation
Reduced Centre-of-Mass Energy	30–50	41.4	142.4	48.3	68.4	1247	0.9×10^9
	50–60	55.3	142.4	41.0	78.0	1047	0.7×10^9
	60–70	65.4	142.4	35.2	86.0	1575	1.1×10^9
	70–80	75.7	142.4	29.9	89.0	2938	2.1×10^9
	80–84	82.3	142.4	27.4	90.5	2091	1.5×10^9
	84–86	85.1	142.4	27.5	87.0	1607	1.1×10^9
Z pole	91.2	91.2	8.3	98.5	99.8	248 100	3.1×10^{12}

Table: Properties of the hadronic data samples collected from ISR/FSR by the L3 experiment [24] and estimated number of events that could be similarly obtained at FCC-ee with the expected 100 ab^{-1} at the Z pole.

5×10^9 events for $\sqrt{s} = 30 - 80\,\text{GeV}$ collected during $\approx$ 10 years.

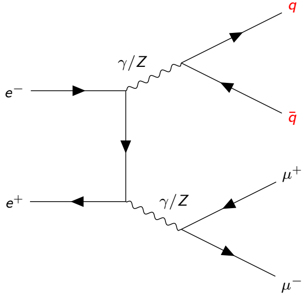
Ups and downs: $e^+e^-\gamma$ MC studies

MC studies can give some clues about the feasibility. Processes modeled with **Sherpa 3.0.1**

- $e^+e^- \to q\bar{q}$
- $e^+e^- \to q\bar{q}\gamma$
- $e^+e^- \to \tau^+\tau^-$
- $e^+e^- \to \tau^+\tau^-\gamma$
- $e^+e^- \to \tau^+\tau^-\tau^+\tau^-$
- $e^+e^- \to q\bar{q}e^+e^-$
- $e^+e^- \to q\bar{q}\mu^+\mu^-$
- $e^+e^- \to q\bar{q}\tau^+\tau^-$
- $e^+e^- \to q\bar{q}\nu\bar{\nu}$
- $\gamma\gamma \to$ *hadrons* (several)

and passed through Delphes fast simulation for IDEA. Output is a subject for selection.

Parton/hadron level quantity of interest: $m(q\bar{q})/m(HFS)$



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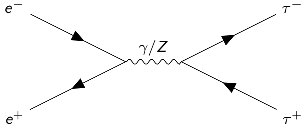

- **Select on particle/detector level → look at composition of selected events.**
- **Selection implies assumptions on the event.**

Ups and downs: $e^+e^-\gamma$ MC studies selections

Selection

- a) Enough visible hadrons[2] in the final state in the detector acceptance range, requiring that the total visible energy $E_{\rm vis}$ deviates a little from the $2 \times E_{\rm beam}$. In addition, a well isolated high-energy[3] photon with energy E_γ is registered in the detector. The HFS without the photon is clustered into two jets which should satisfy the triangle condition, see Eq.3 in Ref. [**?**] for details[4]. This selection aims to select wide-angle high-energy FSR/ISR events and reconstruct the kinematics of these events correctly.
- b) Enough visible hadrons in the final state in the detector acceptance range, requiring that the total visible energy E_{vis} deviates a little from the $2 \times E_{\rm beam} - |P_{\rm vis,z}|$, where $P_{\rm vis,z}$ is the longitudinal component of the total visible momenta. The later condition implies an existence of a single ISR photon radiated parallel to the beam and not registered in the detector, which is almost completely responsible for the momenta imbalance in the event [5]. The events should also fail the criterion a). This selection is designed to select events with FSR/ISR photons collinear to the beam direction and reconstruct the kinematics of these events correctly.
- c) Enough visible hadrons in the final state in the detector acceptance range, requiring that the total visible energy $E_{\rm vis}$ deviates a little[6] from the $2 \times E_{\rm beam}$, and that the thrust vector direction is contained within the detector acceptance range[7]. The events should also fail the criterion a). This selection is aimed at selecting events without significant FSR/ISR and reconstruct the kinematics of these events correctly.

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[2] at least five tracks or calorimeter objects

[3] at least 10 GeV

[4] The photon energy can be also estimated clustering the remaining HFS into two jets j_1 and j_2 and using from the sinus theorem

$$E_{\gamma,triangle} = 2 \times E_{beam} \times \frac{|\sin j_1 \wedge j_2|}{|\sin j_1 \wedge j_2| + |\sin j_1 \wedge \gamma| + |\sin j_2 \wedge \gamma|.}$$

E_γ should lie in the $[E_{\gamma,triangle} - 10GeV, E_{\gamma,triangle} + 5GeV]$ interval. The photon should be isolated from the jets such that $min(j_1 \wedge \gamma, j_2 \wedge \gamma) > 0.5$.

[5] Therefore the requirement ($\vec{P}_{\rm vis} \wedge beam < 3^\circ$ or $\vec{P}_{\rm vis} \wedge beam > 177^\circ$) is imposed.

[6] less than 5 GeV

[7] $|\cos\theta_T| < 0.9$

Ups and downs: $e^+e^-\gamma$ MC studies results

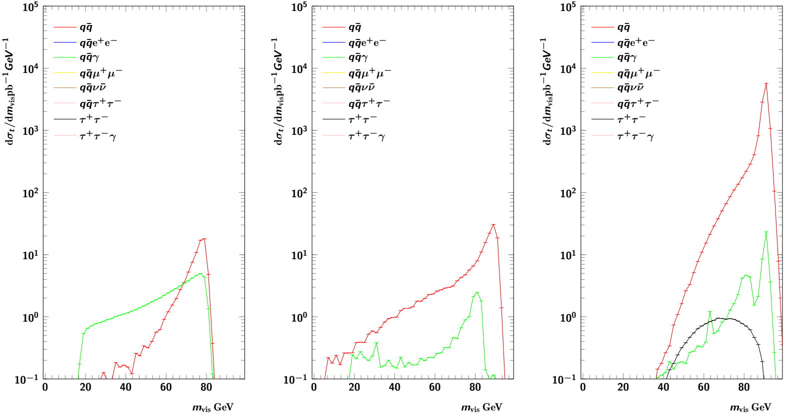

Figure: Distribution of the invariant mass of the visible HFS for the events that passed the selection criteria. The photon is excluded from the HFS mass calculation. All the final states but $\boldsymbol{q\bar{q}}$, $\boldsymbol{q\bar{q}\gamma}$ and $\boldsymbol{\tau^+\tau^-}$ are strongly suppressed by the selection requirements. The full visible signal in the detector will be the sum of the displayed processes. Left: Event passed selection $\boldsymbol{a}$. The selection assumptions on kinematics are correct for $\boldsymbol{q\bar{q}\gamma}$ "signal" samples What does "correct" mean?. Center: Event passed selection $\boldsymbol{b}$. The selection assumptions on kinematics are correct for $\boldsymbol{q\bar{q}}$ "signal" samples with collinear radiation idem. Right: Event passed selection $\boldsymbol{c}$. The selection assumptions on the kinematics are correct for $\boldsymbol{q\bar{q}}$ "signal" samples with negligible radiation idem.

Ups and downs: $e^+e^-\gamma$ MC studies results

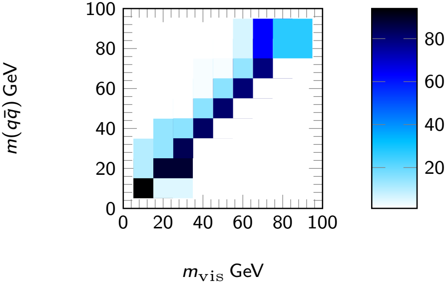

Figure: Correlation of the $m(q\bar{q})$ and the mass of the HFS on the detector level for the $\mathrm{e^+e^-} \to \mathrm{hadrons} + \gamma_{FSR}$ events passed selection *a* The values are normalized across the x axis and the colour coding scale is given in %.

The "resolution" is a couple of GeV → bin size for combination of events should be of the same order, e.g. $5GeV$.

Ups and downs: $e^+e^-\gamma$ MC studies conclusions

- More or less the purity and the accessible range of centre-of-mass energy is restricted by physics even with the state-of-the art detectors.
- With tight selection and enough statistics one can get reasonably large and pure event samples in the region $\sqrt{s} = 20 - 60\,\mathrm{GeV}$.
- MC studies are ongoing: more backgrounds, higher statistics, etc.

Ups and downs: dedicated runs

No detector amendments needed.	=0€ extra for detector construction
Running time for dedicated runs would be some weeks with lower energy consumption.	≈?€ extra for running
The changes of beam energies would require readjustments of some magnets (but not the main ring).	Some manpower and time (a week?)
The data is of same type as the data at and above Z and would fit into any software/analysis for higher energy.	≈0€ extra for computing and physics

Costs in terms of money, time and manpower expected to be tiny, but should be evaluated more carefully.

Ups and downs: dedicated runs machine parameters

- The work on the feasibility of machine settings is ongoing.
- Calculations kindly provided by Katsunobu Oide for $\sqrt{s} = 40, 60 GeV$.
- Also: lower requirements for beam energy spread, beam energy, etc.

FCC-ee collider parameters for Z and $E_{\text{beam}} = 30\,\text{GeV}$, Nov. 28, 2024.
SR: symchrotron ratioation, IB: +intrabeam scattering, BS: +beamstrahlung

Beam energy	[GeV]	45.6	30	20
Layout		PA31-3.0		
# of IPs		4		
Circumference	[km]	90.658728		
Bend. radius of arc dipole	[km]	10.021		
Energy loss / turn	[GeV]	0.0390	0.0072	0.0014
SR power / beam	[MW]	50	9.3	1.8
Beam current	[mA]	1294		
Colliding bunches / beam		11200	60000	60000
Colliding bunch population	[10^{11}]	2.18	0.407	0.407
Hor. emittance at collision ε_x	[nm]	0.70	0.48	0.86
Ver. emittance at collision ε_y	[pm]	2.3	0.98	1.71
Lattice hor. emit. $\varepsilon_{x,\text{lattice}}$ (SR/IB/BS)	[pm]	1.05 / - / -	0.31 / 0.54 / 0.48	0.14 / 0.93 / 0.86
Lattice ver. emittance $\varepsilon_{y,\text{lattice}}$	[pm]	1.05	0.53	1.06
Arc cell		Long 90/90		
Momentum compaction α_p	[10^{-6}]	28.66		
Arc sext families		75		
$\beta^*_{x/y}$	[mm]	130 / 0.7		
Transverse tunes $Q_{x/y}$		218.145 / 222.220		
Chromaticities $Q'_{x/y}$		+2 / +5		
Energy spread (SR/IB/BS) σ_δ	[%]	0.039 / - / 0.121	0.026 / 0.032 / 0.061	0.017 / 0.046 / 0.0598
Bunch length (SR/IB/BS) σ_z	[mm]	4.70 / - / 14.6	2.4 / 3.0 / 5.8	1.9 / 5.1 / 6.6
RF voltage 400/800 MHz	[GV]	0.103 / 0		0.05
Harm. number for 400 MHz		121200		
RF frequency (400 MHz)	MHz	400.787129		
Synchrotron tune Q_s		0.0340	0.0436	0.0371
Long. damping time	[turns]	1181	4140	14000
RF acceptance	[%]	1.41	2.36	2.09
Energy acceptance (DA)	[%]	±1.0		
Beam crossing angle at IP θ_x	[mrad]	±15		
Crab waist ratio	[%]	50		
Beam-beam ξ_x/ξ_y[a]		0.0032 / 0.1009	0.0054 / 0.1010	0.0061 / 0.1052
Piwinski angle $(\theta_x \sigma_{z,\text{BS}})/\sigma^*_x$		22.3	10.9	9.4
Lifetime (q + BS + lattice)	[sec]	10900	61000	59000
Lifetime (Touschek)	[sec]	-	6100	7100
Lifetime (lum)[b]	[sec]	1320	1930	3100
Luminosity / IP	[10^{34}/cm^{2}s]	145	102	65

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[a] incl. hourglass.

[b] only the energy acceptance is taken into account for the cross section, no beam size effect.

Ups and downs: dedicated runs timescale

$\sqrt{s}$ (GeV)	Time (days) to collect 10^9 hadronic events	
	$\mathcal{L} = \mathcal{L}(91\text{ GeV})$	$\mathcal{L} \propto \sqrt{s}$
80	6	7
70	13	17
60	15	22
50	12	22
40	8	18

Table: Time needed to collect 10^9 hadronic events in dedicated runs at given CM energy assuming instant luminosity $\mathcal{L}$ is the same as at Z peak and is equal to 4.6 $pb^{-1}s^{-1}$ or alternatively assuming the scaling $\mathcal{L} \propto \sqrt{s}$ [25].

We are discussing weeks of datataking.

Ups and downs: dedicated runs

- Estimation of time to change energy by the accelerator experts is 1 week.
- → 10 points will take 3 months just to switch the energies is **a luxury**.

→ A more humble, but still extendable suggestion: **two runs at 40 GeV and 60 GeV**. Total runtime: 6-8 weeks. Preferably **in the first year of running** to be able to use results for MC tunes, calibration, etc of further analyses.

Conclusions

- The best $\sqrt{s}$ range for QCD studies in e^+e^- collisions as of now is $M_\Upsilon < \sqrt{s} \leq M_Z$ and FCC-*ee* can provide data in this range.
- The feasibility studies for the low-energy runs at FCC-*ee* are in a well developed state, feedback from accelerator experts, MC studies, etc. The contribution to European Strategy is under way.
- The current proposal, which takes into account the time constraints and machine capabilities is to have two runs at $\sqrt{s} = 40\,\mathrm{GeV}$ and $\sqrt{s} = 60\,\mathrm{GeV}$ to collect 10^9 per run and complement those data with the data from ISR/FSR events. In case of the imminent success those data taking options can be extended with more energy points and/or higher statistics.

Backups and discussion

Methodology of measurements of QCD observables: $e^+e^-\gamma$ vs. dedicated runs

$e^+e^-\gamma$

- Measure γ energy.
- Calculate the CM boost assuming γ comes from ISR/FSR.
- Alternatively to the points above do a kinematic fit of the hadronic final state to gen the energy of γ.
- Boost the event to the calculated CM.
- Calculate observables from the boosted hadronic final state.

Dedicated

- Make sure the CM energy is close to nominal using cuts.
- Calculate observables from hadronic final state.

The measurement of γ and the boost procedure bring additional uncertainties. The performance of these methods could be insufficient for the desired accuracy of the measurements.

$e^+e^-\gamma$ vs. dedicated runs: Point 3

- There will be enough data from $e^+e^-\gamma$ anyway.

- Not really and not of good quality, see L3 [26] and OPAL [23] at LEPI:

Type	$\sqrt{s}$, GeV	$\langle\sqrt{s}\rangle$, GeV	Int. Lumi (pb)	Selection Eff.(%)	Purity(%)	Sel. Events
Reduced Centre-of-Mass Energy	30–50	41.4	142.4	48.3	68.4	1247
	50–60	55.3	142.4	41.0	78.0	1047
	60–70	65.4	142.4	35.2	86.0	1575
	70–80	75.7	142.4	29.9	89.0	2938
	80–84	82.3	142.4	27.4	90.5	2091
	84–86	85.1	142.4	27.5	87.0	1607
Z pole	91.2	91.2	8.3	98.5	99.8	248100

$$\alpha_S(M_Z)_{41\text{ GeV}} = 0.1418 \pm 0.0053(\text{stat.}) \pm 0.0030(\text{exp.syst.}) \pm 0.0055(\text{hadr.}) \pm 0.0085(\text{theory.})(NLO)$$
$$\alpha_S(M_Z)_{55\text{ GeV}} = 0.1260 \pm 0.0047(\text{stat.}) \pm 0.0056(\text{exp.syst.}) \pm 0.0066(\text{hadr.}) \pm 0.0062(\text{theory.})(NLO)$$

. . . V.S.

$$\alpha_S(M_Z)_{91\text{ GeV}} = 0.1210 \pm 0.0008(\text{stat.}) \pm 0.0017(\text{exp.syst.}) \pm 0.0040(\text{hadr.}) \pm 0.0052(\text{theory.})(NLO)$$

E_γ [GeV]	Events	$\sqrt{s'}_{Mean}$[GeV]	Background [%]		
			Non-rad. MH		$\tau\tau$
			Likelihood	Isolated tracks	
10-15	1560	78.1± 1.7	6.0± 0.7	6.2± 0.9	0.9± 0.2
15-20	954	71.8± 1.9	3.1± 0.5	4.9± 0.8	1.0± 0.3
20-25	697	65.1± 2.0	2.6± 0.6	6.3± 1.1	0.9± 0.4
25-30	513	57.6± 2.3	5.1± 1.1	7.9± 1.4	1.1± 0.5
30-35	453	49.0± 2.6	4.5± 1.1	9.6± 1.6	0.7± 0.4
35-40	376	38.5± 3.5	5.2± 1.2	13.1± 1.9	0.8± 0.5
40-45	290	24.4± 5.3	10.4± 2.3	12.9± 1.7	0.8± 0.5

$$\alpha_S(M_Z)_{comb} = 0.1182 \pm 0.0015(\text{stat.}) \pm 0.0038(\text{exp.syst.}) \pm 0.0070(\text{hadr.}) \pm 0.0062(\text{theory.})(NLO)$$

+specific problems: hadronization, systematics, statistics.

Bibliography I

[1] Alipour Tehrani, N. and others,
FCC-ee: Your Questions Answered,
CERN Council Open Symposium on the Update of European Strategy for Particle Physics, Blondel, A. and Janot, P. (eds.).
(2019).
Also in preprint 1906.02693.
`arXiv:1906.02693`.

[2] Agapov, I. and others,
Future Circular Lepton Collider FCC-ee: Overview and Status,
Snowmass 2021.
(2022).
Also in preprint 2203.08310.
`arXiv:2203.08310`.

[3] FCC, Abada, A. and others,
FCC Physics Opportunities: Future Circular Collider Conceptual Design Report Volume 1.
Eur. Phys. J. C **79**, 474 (2019).

[4] FCC, Abada, A. and others,
FCC-ee: The Lepton Collider: Future Circular Collider Conceptual Design Report Volume 2.
Eur. Phys. J. ST **228**, 261 (2019).

[5] G.P. Salam,
The strong coupling: a theoretical perspective,
in From My Vast Repertoire . . . : Guido Altarelli's Legacy, eds. Levy, Aharon and Forte, Stefano and Ridolfi, Giovanni, pp. 101–121.
2019,
doi:10.1142/97898132380530_007.

Bibliography II

[6] G. Dissertori et al.,
Precise determination of the strong coupling constant at NNLO in QCD from the three-jet rate in electron-positron annihilation at LEP.
Phys. Rev. Lett. **104**, 072002 (2010).
`arXiv:0910.4283`.

[7] JADE Collaboration, J. Schieck et al.,
Measurement of the strong coupling α_S from the three-jet rate in e^+e^- - annihilation using JADE data.
Eur. Phys. J. **C73**, 2332 (2013).
`arXiv:1205.3714`.

[8] G. Dissertori et al.,
Determination of the strong coupling constant using matched NNLO+NLLA predictions for hadronic event shapes in e^+e^- annihilations.
JHEP **08**, 036 (2009).
`arXiv:0906.3436`.

[9] JADE Collaboration, S. Bethke et al.,
Determination of the Strong Coupling α_s from hadronic Event Shapes with $\mathcal{O}(\alpha_s^3)$ and resummed QCD predictions using JADE Data.
Eur. Phys. J. **C64**, 351 (2009).
`arXiv:0810.1389`.

[10] OPAL Collaboration, G. Abbiendi et al.,
Determination of α_s using OPAL hadronic event shapes at $\sqrt{s} = 91 - 209\,\text{GeV}$ and resummed NNLO calculations.
Eur. Phys. J. **C71**, 1733 (2011).
`arXiv:1101.1470`.

Bibliography III

[11] R.A. Davison and B.R. Webber,
Non-Perturbative Contribution to the Thrust Distribution in e+ e- Annihilation.
Eur. Phys. J. **C59**, 13 (2009).
`arXiv:0809.3326`.

[12] T. Gehrmann, G. Luisoni and P.F. Monni,
Power corrections in the dispersive model for a determination of the strong coupling constant from the thrust distribution.
Eur. Phys. J. **C73**, 2265 (2013).
`arXiv:1210.6945`.

[13] R. Abbate et al.,
Thrust at N^3LL with power corrections and a precision global fit for $\alpha_S(M_Z)$.
Phys.Rev. **D83**, 074021 (2011).
`arXiv:1006.3080`.

[14] A. Hoang et al.,
Precise determination of α_s from the C-parameter distribution.
Phys. Rev. **D91**, 094018 (2015).
`arXiv:1501.04111`.

[15] A. Kardos et al.,
Precise determination of $\alpha_S(M_Z)$ from a global fit of energy–energy correlation to NNLO+NNLL predictions.

Eur. Phys. J. **C78**, 498 (2018).
`arXiv:1804.09146`.

[16] A. Verbytskyi et al.,
High precision determination of α_s from a global fit of jet rates.
JHEP **08**, 129 (2019).
`arXiv:1902.08158`.

Bibliography IV

[17] C. Bierlich et al.,
Robust Independent Validation of Experiment and Theory: Rivet version 3.
SciPost Phys. **8**, 026 (2020).
`arXiv:1912.05451`.

[18] Kuroda, S.,
TRISTAN accelerator: Operation in 1994,
3rd Workshop on TRISTAN Physics at High Luminosities, pp. 404–408.
(1996).

[19] TOPAZ, Adachi, I. and others,
Measurements of in $\mathrm{e}^+\mathrm{e}^-$ annihilation at $\sqrt{s} =$ 53.3-GeV and 59.5-GeV.
Phys. Lett. B **227**, 495 (1989).

[20] JADE, Schieck, J. and Bethke, S. and Biebel, O. and Kluth, S. and Movilla Fernandez, P. A. and Pahl, C.,
Measurement of the strong coupling from the four-jet rate in $\mathrm{e}^+\mathrm{e}^-$ annihilation using JADE data.
Eur. Phys. J. C **48**, 3 (2006).
`arXiv:0707.0392`.
[Erratum: Eur.Phys.J.C 50, 769 (2007)].

[21] TASSO, Braunschweig, W. and others,
Experimental Study of Jet Masses in $\mathrm{e}^+\mathrm{e}^-$ Annihilation at $c.m.$ Energies Between 12-GeV and 43.5-GeV.
Z. Phys. C **45**, 11 (1989).

[22] Allaby, J. V. and others,
The Mac Detector.
Nucl. Instrum. Meth. A **281**, 291 (1989).

Bibliography V

[23] OPAL, G. Abbiendi et al.,
Measurement of α_s with Radiative Hadronic Events.
Eur. Phys. J. **C53**, 21 (2008).
`arXiv:0902.1128`.

[24] L3, Achard, P. and others,
Studies of hadronic event structure in $\mathrm{e}^{+}\mathrm{e}^{-}$ annihilation from 30-GeV to 209-GeV with the L3 detector.
Phys. Rept. **399**, 71 (2004).
`arXiv:hep-ex/0406049`.

[25] Zimmermann, Frank,
Private communication, 2024.

[26] L3 Collaboration, P. Achard et al.,
Studies of hadronic event structure in $e^{+}e^{-}$ annihilation from 30 GeV to 209 GeV with the L3 detector.
Phys. Rept. **399**, 71 (2004).
`arXiv:hep-ex/0406049`.