

Physics at future e^+e^- colliders

Andrej Arbuzov

JINR, Dubna

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Outline

- 1 HEP
- 2 ESPP
- 3 Other projects
- 4 SM Physics
- 5 BSM
- 6 Outlook

Status of HEP

- HEP is a **great achievement** of mankind
- During the last decades, **remarkable experiments** have been carried out and the development of the **SM has been completed**
- Now HEP is in a **deep crisis**
- SM works **too good**, but it's certainly not the final story
- Discovering **physics beyond SM** is our hope, but we don't know how to do that for sure
- Big HEP projects become **too expensive**
- The logic of HEP development \Rightarrow new **e^+e^- collider**
- But we can even consider **“crazy” ideas**

The European Strategy for Particle Physics (ESPP)

May 21-22 dedicated ESPP Council session — upgrade of the strategy

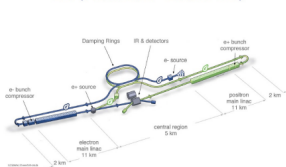
Major proposed colliders at CERN

e^+e^- colliders
("Higgs factories")

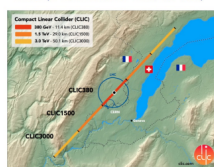
FCC- ee (e^+e^- , circular, 91 – 365 GeV)



LHC (e^+e^- , linear, 91 – 240, 550 GeV)



CLIC (e^+e^- , linear, 380 GeV, 1.5 TeV)



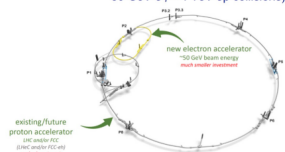
Intermediate projects

(Leave room (time, budget, resources) for further development of THE machine that can probe directly the energy frontier at the 10 TeV parton scale)

LHC3 (e^+e^- , circular, 91 – 230 GeV)



LHeC (ep, circular, electron ERL, 50 GeV e^- , > 1 TeV ep collisions)



slide from Karl Jakobs

Far future goal of HEP as seen by ESPP

Potential paths for 10 TeV parton-scale collisions

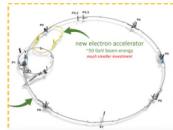
FCC-ee



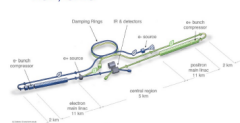
LEP3



LHeC



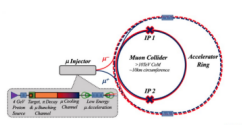
LCF, CLIC



PERLE



FCC-hh,
baseline 85 TeV (\rightarrow 120 TeV)
+ possibility for HI collisions



Muon Collider (3, 10 TeV)

R&D



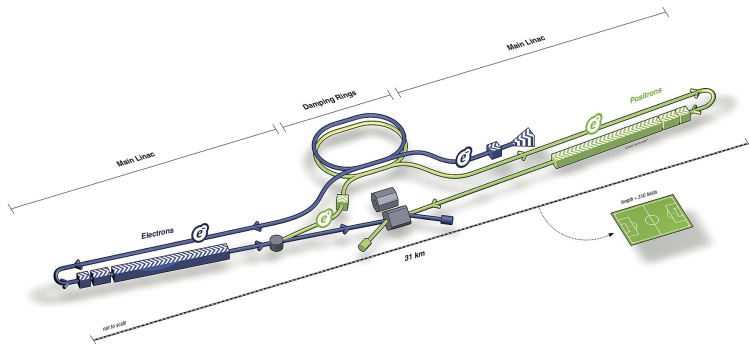
e^+e^- with improved acceleration technologies
LCF, C³ (\rightarrow 1 TeV), CLIC (1.5 TeV), HALHF, ...
 \rightarrow plasma acceleration for higher energies
(can $O(10)$ TeV be reached? on what timescale?)

slide from Karl Jakobs

* see talk by Lev Dudko on muon colliders

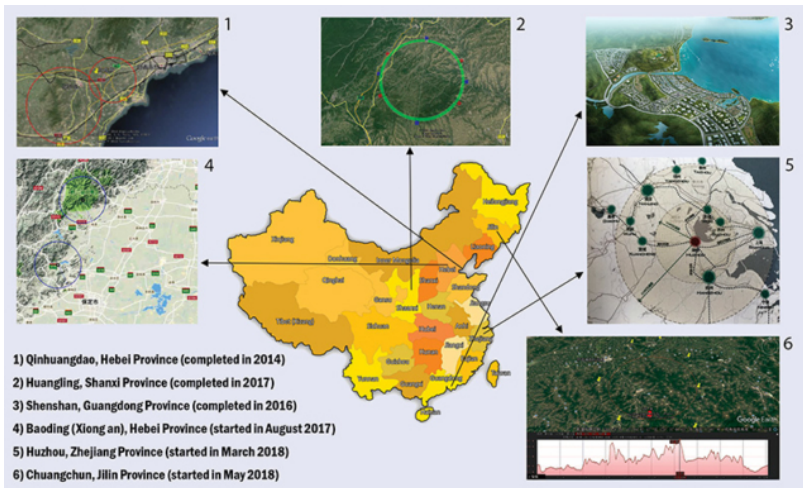
ILC in Japan?

from 240 GeV to 1 TeV collision energy



A good lesson for the community

CEPC in China?



As early as 2035?

[CDR '2018; TDR '2023]

Super Charm-Tau Factory Projects

Budker Institute of Nuclear Physics + Sarov and/or China

Colliding electron-positron beams with c.m.s. energies from 2 to 7 GeV with unprecedented high luminosity $10^{35} \text{cm}^{-2} \text{s}^{-1}$

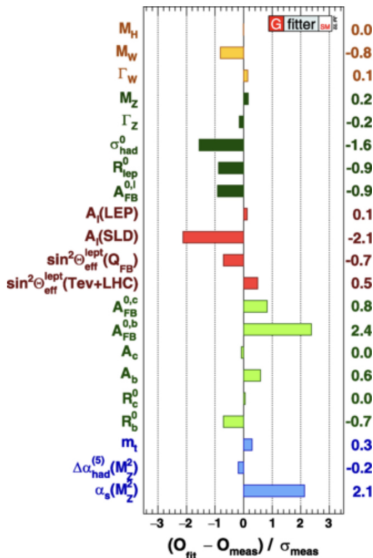
The electron beam will be longitudinally polarized

The main goal of experiments at the Super Charm-Tau Factory is to study the processes charmed mesons and tau leptons, using a data set that is 2 orders of magnitude more than the one collected by BESIII

Physics possibilities at future e^+e^- machines

- In-depth verification of the EW sector of the SM
- Unique possibilities for QCD at the different energy scales
- Searches for new physics of SMEFT and other types
- Photon-photon (+EW boson fusion) physics
- Properties of tau lepton
- Physics of (exotic) mesons
- N.B. Effective B-factory and Charm-tau factory

Where are we now with the SM



Core goals

Every improvement in determination of SM parameters is priceless

The **core physics goals** and possibilities are

- Study the Higgs boson properties including its selfinteraction, CP properties etc.
(see talk by Alexey Drutskoy)
- Top quark physics (need ~ 350 GeV) (see talks by Maxim Perfilov and Emil Abasov)
- Z (**Tera-Z factory!**) and W boson physics

Examples of EW precision measurements

Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_Z (MeV)	Z lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_Z (MeV)	Z lineshape	2495.2 ± 2.3	0.008	< 0.1	QED corr.
R_ℓ	Z peak	20.767 ± 0.025	0.0001	< 0.001	QED corr.
R_b	Z peak	0.21629 ± 0.00066	0.000003	< 0.00006	$g \rightarrow b\bar{b}$
$A_{FB}^{\mu\mu}$	Z peak	0.0171 ± 0.0010	0.000004	< 0.00001	E_{beam} meas.
N_ν	Z peak	2.984 ± 0.008	0.00004	0.004	Lumi meas.
N_ν	$e^+e^- \rightarrow \gamma Z(\text{inv.})$	2.92 ± 0.05	0.0008	< 0.001	–
$\alpha_s(m_Z)$	$R_\ell, \sigma_{\text{had}}, \Gamma_Z$	0.1196 ± 0.0030	0.00001	0.00015	New physics
$1/\alpha_{\text{QED}}(m_Z)$	$A_{FB}^{\mu\mu}$ at Z peak	128.952 ± 0.014	0.004	0.002	EW corr.
m_W (MeV)	WW threshold scan	80369 ± 13	0.3	< 1	QED corr.
$\alpha_s(m_W)$	B_{had}^W	$B_{\text{had}}^W = 67.41 \pm 0.27$	0.00018	0.00015	CKM matrix
m_t (MeV)	threshold scan	173200 ± 900	10	10	QCD

Table from [D. d'Enterria, “Physics case of FCC-ee” 2016]

Huge improvements with respect to LEP (+Tevatron+LHC) are due to:

- statistics
- detectors
- analysis techniques
- progress in theory

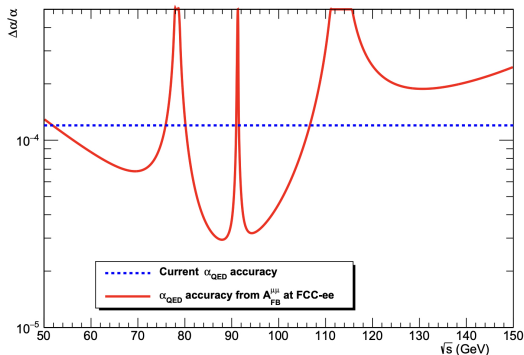
Weak mixing angle

An experimental precision better than 5×10^{-6} is therefore a robust target for the measurement of $\sin^2 \theta_W^{\text{eff}}$ at FCC-ee, corresponding to more than a **thirty-fold improvement** with respect to the current precision of 1.6×10^{-4} .

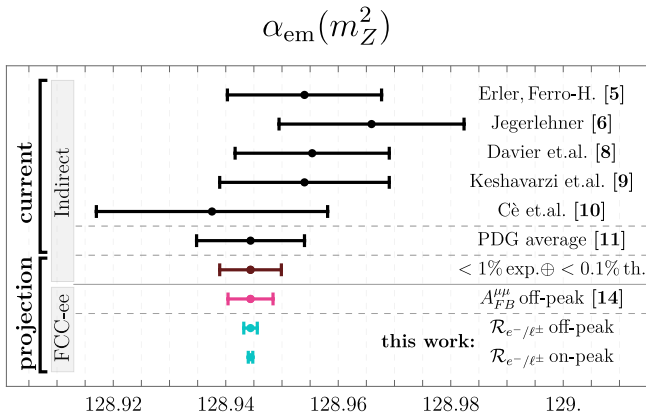
Individual measurements of leptonic and heavy quark couplings are achievable, with a factor of **several hundred improvement** on statistical errors and, with the help of detectors providing better particle identification and vertexing, by up to **two orders of magnitude** on systematic uncertainties.

[FCC Coll. EPJC'2019]

$\alpha_{\text{QED}}(m_Z^2)$ (I)



An experimental relative accuracy of 3×10^{-5} on $\alpha_{\text{QED}}(m_Z^2)$ can be achieved at FCC-ee, from the measurement of the muon forward-backward asymmetry at energies ~ 3 GeV below and ~ 3 GeV above the Z pole. The corresponding parametric uncertainties on other SM parameters and observables will be reduced. [FCC Coll. EPJC'2019]

$\alpha_{QED}(m_Z^2)$ (II)

A new method of $\alpha_{QED}(m_Z^2)$ extraction is proposed [M. Riebauer PRL 2025]

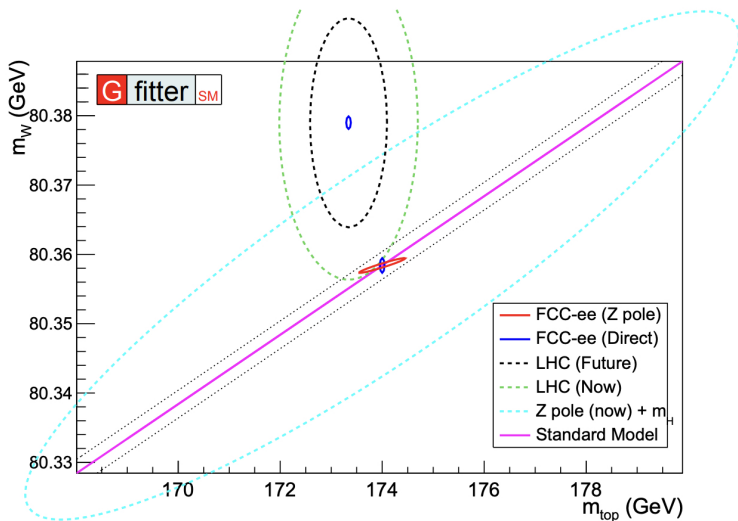
Z boson mass and width; R_l

Overall experimental uncertainties of **0.1 MeV** or better are achievable for the **Z mass and width** measurements at FCC-ee. The corresponding parametric uncertainties on $\sin^2 \theta_W^{\text{eff}}$ and m_W SM predictions are accordingly reduced to 6×10^{-7} and 0.12 MeV, respectively.

An absolute (relative) uncertainty of **0.001** (5×10^{-5}) on the ratio of the Z hadronic-to-leptonic partial widths (R_l) can be reached. The same relative uncertainty is expected for the ratios of the Z leptonic widths, which allows a stringent test of **lepton universality**.

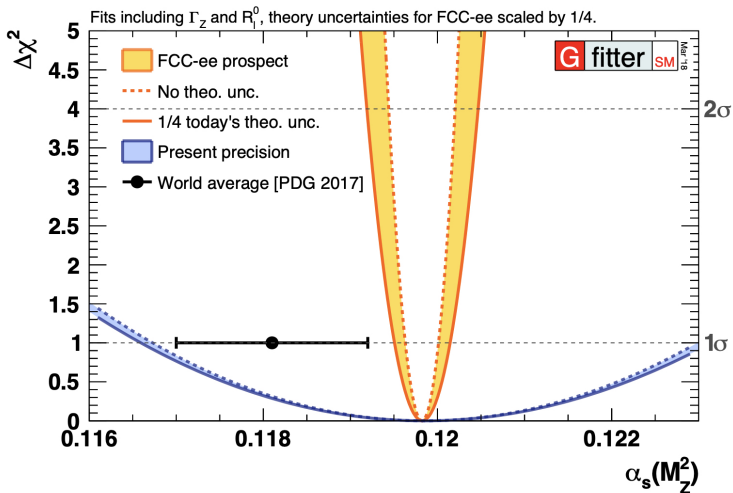
[FCC Coll. EPJC'2019]

Indirect SM measurements



[FCC Coll. EPJC'2019]

Alpha QCD



[FCC Coll. EPJC'2019]

SM for FCC-ee (CEPC): status and needs

Quantity	Current precision	FCC-ee stat. (syst.) precision	Required theory input	Theory status as of today	Needed theory improvement [†]
m_Z (MeV)	2.0	0.004 (0.1)	non-resonant $e^+e^- \rightarrow f\bar{f}$, initial-state radiation (ISR)	NLO, ISR logarithms up to 6 th order	NNLO for $e^+e^- \rightarrow f\bar{f}$
Γ_Z (MeV)	2.3	0.004 (0.012)			
$\sin^2 \theta_{\text{eff}}^\ell$	1.6×10^{-4}	$1.2 (1.2) \times 10^{-6}$			
m_W (MeV)	9.9	0.18 (0.16)	lineshape of $e^+e^- \rightarrow WW$ near threshold	NLO ($e^+e^- \rightarrow 4f$ or EFT framework)	NNLO for $e^+e^- \rightarrow WW$, $W \rightarrow f\bar{f}'$ in EFT setup
HZZ coupling	– *	0.1%	cross section for $e^+e^- \rightarrow ZH$	NLO EW plus partial NNLO QCD/EW	full NNLO EW
m_{top} (MeV)	290	4.2 (4.9)	threshold scan $e^+e^- \rightarrow t\bar{t}$	N ³ LO QCD, NNLO EW, resummations up to NNLL, $\mathcal{O}(30 \text{ MeV})$ scale uncert.	Matching fixed orders with resummations, merging with MC, α_S (input)

[FCC Coll., 2505.00272 [hep-ex]]

BSM searches

Assume **pessimistic scenario**: nothing new will be found at HL-LHC.
Then at a future e^+e^- collider we still have good perspectives for BSM searches. The main directions are

- Indirect searches: precision **electroweak & Higgs**
 - look for small deviations from SM predictions
 - sensitive to energy scales up to ~ 100 TeV
- Precision **top-quark** studies
 - run at $t\bar{t}$ threshold $\sqrt{s} \approx 365$ GeV
 - rely on stronger BSM connection to top quarks
- High-precision **flavour physics**
 - rare decay like $B \rightarrow K^* \tau^+ \tau^-$
 - advantage due to boosted B mesons, τ leptons etc.
- Direct searches for **feebly interacting particles**
 - search for light, weakly interacting particles (sterile ν , DM, etc.)
 - looking for missing energy or invisible decays, e.g., Z or H boson \rightarrow dark sector

SMEFT

Possible deviations from SM predictions in **differential** and inclusive observables to be fit within **SMEFT** extension of the SM by higher dim. operators

Remind three oblique Peskin–Takeuchi parameters used at LEP.
At a future machine one can (should) do a much more detailed study

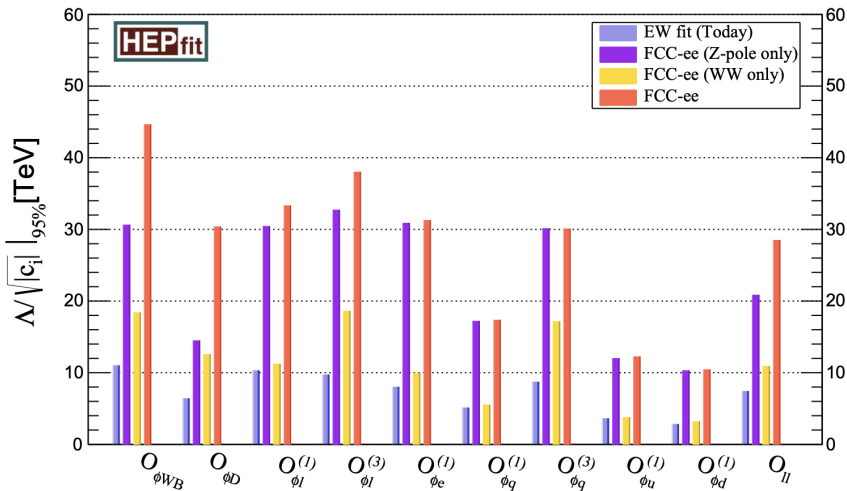
Scenarios of specific new physics models can be also verified,
e.g. with long-lived particles

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j \frac{C_j^{(8)}}{\Lambda^4} \mathcal{O}_j^{(8)} + \dots$$

N.B.1. Having polarised beams would help a lot

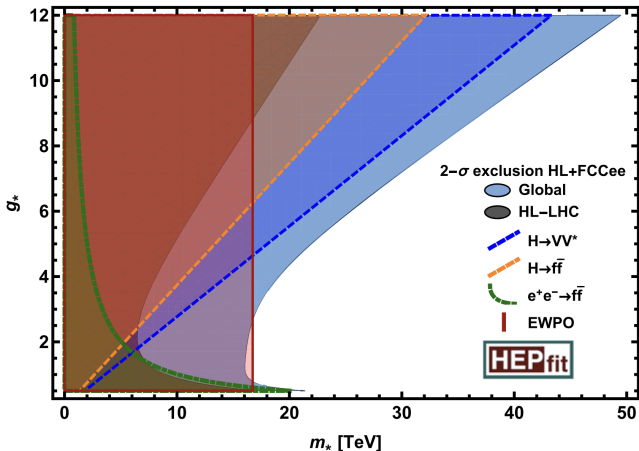
N.B.2. Higgs-EFT (**HEFT**) with non-linear gauge symmetry realisation has even more parameters

Sensitivity to new physics scale



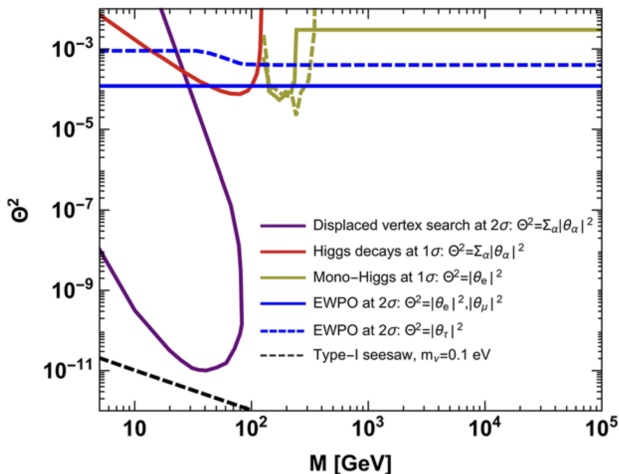
[FCC Coll. EPJC'2019]

Example: test of composite Higgs



[J. de Blas, EPC '2021]

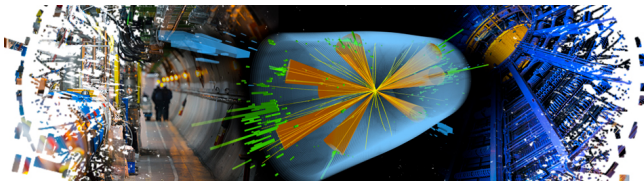
Example: search for sterile ν



[J. de Blas, EPC '2021]

Outlook

- A new high-energy e^+e^- collider is well motivated
- **Complementarity** to hadron-hadron and lepton-hadron machines is essential
- There are great possibilities for **progress in HEP**
- **New advances** in theory and experimental techniques are required
- **New (crazy) ideas** are welcome
- **Crisis is a time of opportunity!**



[picture: Copyright CNRS, CERN]



Electron is as inexhaustible as atom

— the motto for a future e^+e^- collider

Thank you for attention!