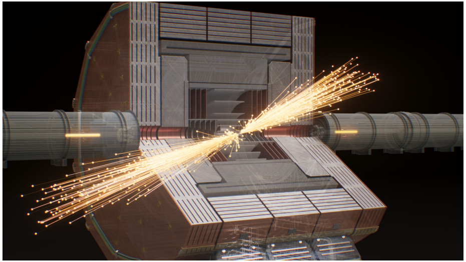
How to get histograms?

FCC Early Career Forum – FCC Beginner's Guide

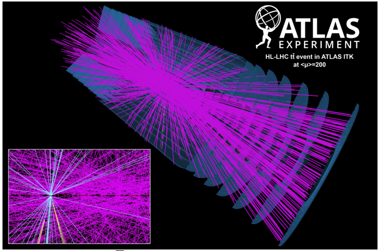
Armin Ilg[1]

[1]University of Zürich

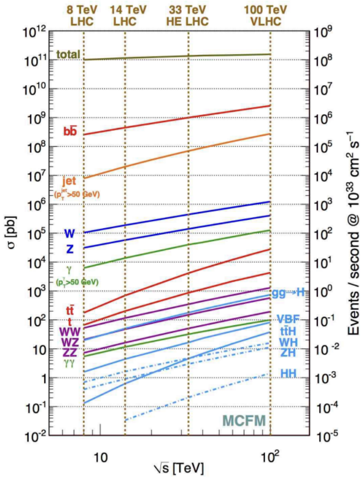
13.01.2025



Hadron collisions

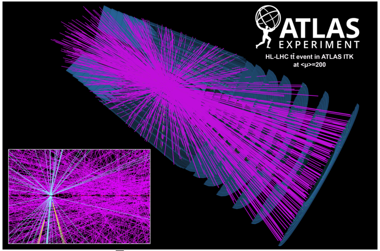


Simulated $t\bar{t}$ event in ATLAS ITk with pile-up of 200 (ATLAS Experiment © 2022 CERN).

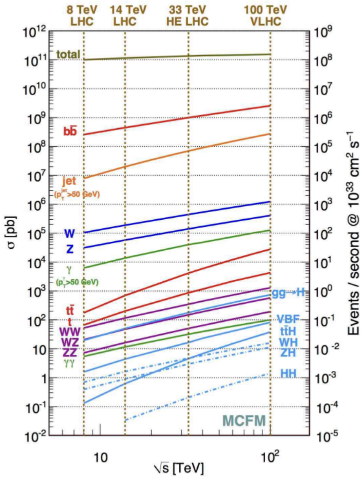


pp cross section.

- Actually a gluon and quark collider
  - → Initial state unknown
  - → High cross sections for colored states
- Huge total cross section
  - Pile-up
  - Triggering, readout, radiation damage...
- $\mathcal{O}(10^8)$ Higgses @ HL-LHC, $\mathcal{O}(10^{10})$ Higgses @ FCC-hh
- Directly produce heavy BSM particles



Simulated $t\bar{t}$ event in ATLAS ITk with pile-up of 200 (ATLAS Experiment © 2022 CERN).

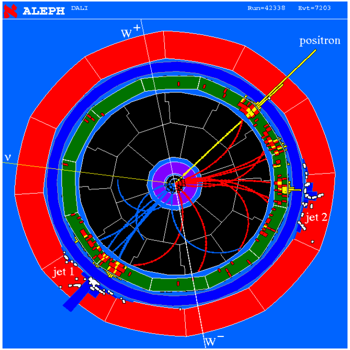


pp cross section.

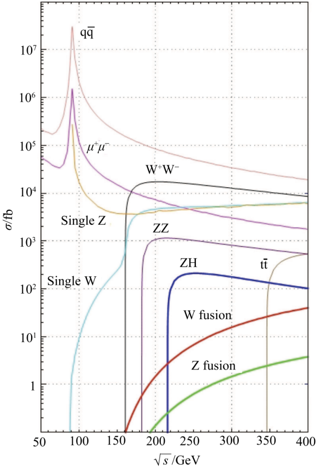
- Actually a gluon and quark collider
  - → Initial state unknown
  - → High cross sections for colored states
- Huge total cross section
  - Pile-up
  - Triggering, readout, radiation damage...
- $\mathcal{O}(10^8)$ Higgses @ HL-LHC, $\mathcal{O}(10^{10})$ Higgses @ FCC-hh
- Directly produce heavy BSM particles

→ *Looking for the needle in the haystack*

Lepton collisions



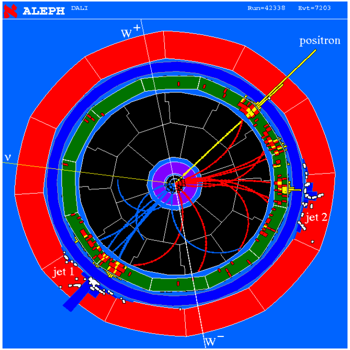
WW pair decay at LEP2, detected by ALEPH (source).



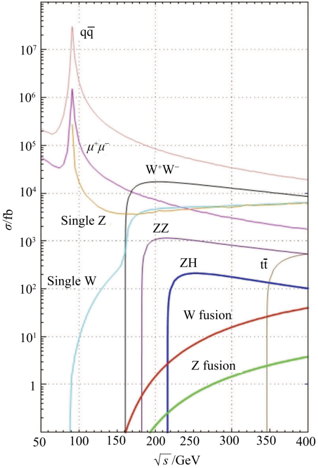
e^+e^- cross section [1].

- Collision of **point-like** particles
  $\rightarrow$ Initial E and p known
- No multijet (or QCD) background
  - No *total* line six orders of magnitues above the EW gauge bosons!
  - All collisions are interesting!
  - $\mathcal{O}(10^6)$ Higgses at e^+-e^- Higgs factories
  - Almost no pile-up
  - Lower radiation environment
- Especially sensitive to EW states
- Directly produce ligher BSM, indirect sensitivity through precision

Lepton collisions



WW pair decay at LEP2, detected by ALEPH (source).

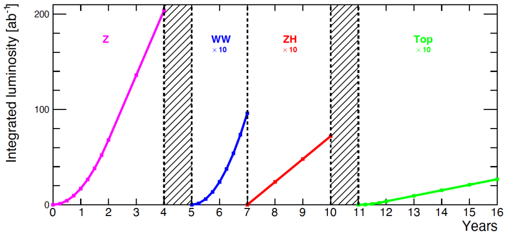


e^+e^- cross section [1].

→ *Measure a needlestack: How many needles and how pointed are they?*

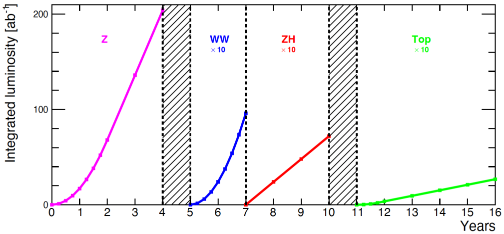
- Collision of **point-like** particles
  → Initial E and p known
- No multijet (or QCD) background
  - No *total* line six orders of magnitues above the EW gauge bosons!
  - All collisions are interesting!
  - $\mathcal{O}(10^6)$ Higgses at e^+-e^- Higgs factories
  - Almost no pile-up
  - Lower radiation environment
- Especially sensitive to EW states
- Directly produce ligher BSM, indirect sensitivity through precision

The Future Circular Collider (FCC) integrated programme



Possible FCC-ee run plan [2]

EW: $2.4 \cdot 10^8$ WW, $6 \cdot 10^{12}$ Z
Flavour: $O(10^{12})$ $b\bar{b}$, $c\bar{c}$, etc., $O(10^{11})$ $\tau\bar{\tau}$
H: $1.78 \cdot 10^6$ HZ, 125k WW $\rightarrow$ H
Top: $1.9 \cdot 10^6$ $t\bar{t}$



Possible FCC-ee run plan [2]

EW: $2.4 \cdot 10^8$ WW, $6 \cdot 10^{12}$ Z
Flavour: $O(10^{12})$ $b\bar{b}$, $c\bar{c}$, etc., $O(10^{11})$ $\tau\bar{\tau}$
H: $1.78 \cdot 10^6$ HZ, 125k WW $\rightarrow$ H
Top: $1.9 \cdot 10^6$ $t\bar{t}$

So what can be done with this many rather clean collisions?

Physics at the FCC-ee
A few highlights

Higgs physics

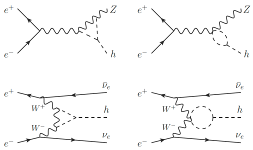
University of Zurich[UZH]

Shape of the **Higgs potential**:

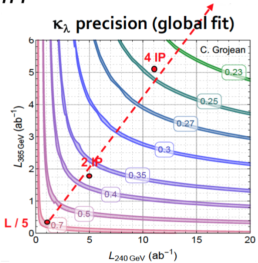
$$V(h) = \frac{m_H^2 h^2}{2} + \lambda_3 \nu h^3 + \lambda_4 \nu h^4$$

FCC-ee: Indirect measurement

- Probe a non-zero value for the Higgs self-coupling (λ_3) at better than 95% CL
- Accurate $t\bar{t}Z$ and Higgs couplings
  - $\rightarrow$ FCC-hh: measurement down to few % level in $gg \rightarrow HH$

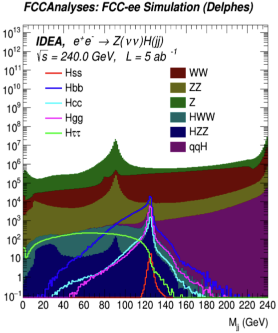


λ_3 in loops at FCC-ee [3].



C. Grojean

Yukawa couplings to third-generation quarks and τ and to W and Z established. Now looking at second generation (except μ, to be done at HL-LHC)



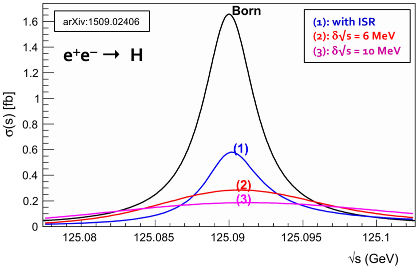
G. Marchiori, FCC Physics Workshop 2023.

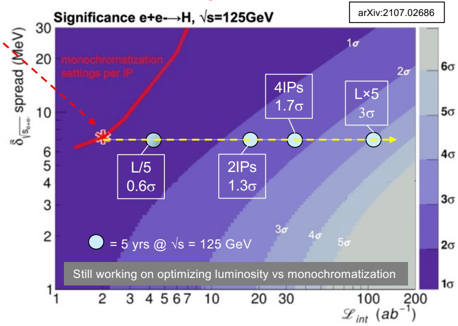
Z(→vv) H(→qq)	bb	cc	ss	gg
δμ/μ (%)	0.4	2.9	160	1.2

Discovery of c Yukawa coupling guaranteed, s not too far away

Gives mass to e, in nature everywhere! Unique to FCC-ee, in dedicated run at $\sqrt{s} = m_H$

- **One of the toughest challenges, which requires in particular, at √s = 125 GeV**
  - **Higgs boson mass prior knowledge to a couple MeV, requires at least the design lumi at √s = 240 GeV**
  - **Huge luminosity, achievable with with several years of running and possibly 4 IPs**
  - **√s monochromatisation : Γ_H (4.2 MeV) ≪ natural beam energy spread (~100 MeV)**
- **First studies indicate a significance of 0.4σ with one detector in one year**





P. Janot

EW and top physics

LEP1: $18 \cdot 10^6$ Z bosons

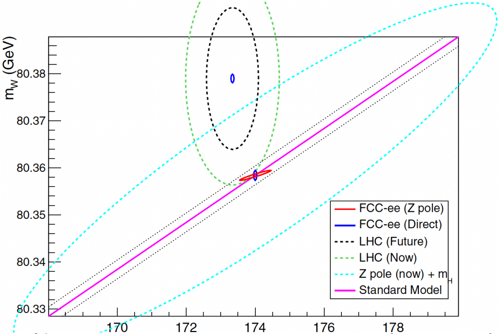
University of Zurich[UZH]

LEP1: $18 \cdot 10^6$ Z bosons

FCC-ee: $6 \cdot 10^{12}$ Z bosons $\rightarrow$ LEP1 programme in couple of minutes (LEP2 W stats in 90 min)

Observable	Present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_Z (keV)	$91{,}186{,}700 \pm 2200$	5	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	$2{,}495{,}200 \pm 2300$	8	100	From Z line shape scan Beam energy calibration
R^Z_ℓ ($\times 10^3$)	$20{,}767 \pm 25$	0.06	0.2–1.0	Ratio of hadrons to leptons acceptance for leptons
α_s (m_Z) ($\times 10^4$)	1196 ± 30	0.1	0.4–1.6	From R^Z_ℓ above [43]
R_b ($\times 10^6$)	$216{,}290 \pm 660$	0.3	< 60	Ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD [44]
σ^0_{had} ($\times 10^3$) (nb)	$41{,}541 \pm 37$	0.1	4	Peak hadronic cross-section luminosity measurement
N_ν ($\times 10^3$)	2991 ± 7	0.005	1	Z peak cross sections Luminosity measurement
$\sin^2\theta^{eff}_W$ ($\times 10^6$)	$231{,}480 \pm 160$	3	2–5	From $A^{\mu\mu}_{FB}$ at Z peak Beam energy calibration
$1/\alpha_{QED}$ (m_Z) ($\times 10^3$)	$128{,}952 \pm 14$	4	Small	From $A^{\mu\mu}_{FB}$ off peak [34]
$A^{b,0}_{FB}$ ($\times 10^4$)	992 ± 16	0.02	1–3	b-quark asymmetry at Z pole from jet charge
$A^{pol,\tau}_{FB}$ ($\times 10^4$)	1498 ± 49	0.15	< 2	τ Polarisation and charge asymmetry τ decay physics
m_W (MeV)	$80{,}350 \pm 15$	0.5	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan Beam energy calibration
α_s (m_W) ($\times 10^4$)	1170 ± 420	3	Small	From R^W_ℓ [45]
N_ν ($\times 10^3$)	2920 ± 50	0.8	Small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	$172{,}740 \pm 500$	17	Small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV)	1410 ± 190	45	Small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda^{SM}_{top}$	1.2 ± 0.3	0.1	Small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	$\pm 30\%$	0.5–1.5%	Small	From $E_{CM} = 365$ GeV run

Precision measurements at FCC-ee (FCC CDR)



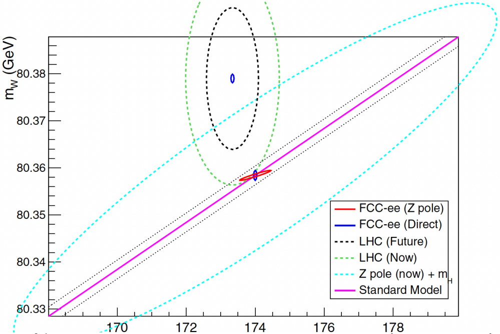
68% C.L contours of EW fit at FCC-ee (FCC CDR)

LEP1: $18 \cdot 10^6$ Z bosons

FCC-ee: $6 \cdot 10^{12}$ Z bosons $\rightarrow$ LEP1 programme in couple of minutes (LEP2 W stats in 90 min)

Observable	Present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_Z (keV)	91,186,700 ± 2200	5	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2,495,200 ± 2300	8	100	From Z line shape scan Beam energy calibration
R_ℓ^Z ($\times 10^3$)	20,767 ± 25	0.06	0.2–1.0	Ratio of hadrons to leptons acceptance for leptons
α_s (m_Z) ($\times 10^4$)	1196 ± 30	0.1	0.4–1.6	From R_ℓ^Z above [43]
R_b ($\times 10^6$)	216,290 ± 660	0.3	< 60	Ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD [44]
σ^0_{had} ($\times 10^3$) (nb)	41,541 ± 37	0.1	4	Peak hadronic cross-section luminosity measurement
N_ν ($\times 10^3$)	2991 ± 7	0.005	1	Z peak cross sections Luminosity measurement
$\sin^2\theta_W^{eff}$ ($\times 10^6$)	231,480 ± 160	3	2–5	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}$ (m_Z) ($\times 10^3$)	128,952 ± 14	4	Small	From $A_{FB}^{\mu\mu}$ off peak [34]
$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1–3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498 ± 49	0.15	< 2	τ Polarisation and charge asymmetry τ decay physics
m_W (MeV)	80,350 ± 15	0.5	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan Beam energy calibration
α_s (m_W) ($\times 10^4$)	1170 ± 420	3	Small	From R_ℓ^W [45]
N_ν ($\times 10^3$)	2920 ± 50	0.8	Small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	172,740 ± 500	17	Small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV)	1410 ± 190	45	Small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	0.1	Small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	0.5–1.5%	Small	From E_{CM} = 365 GeV run

Precision measurements at FCC-ee (FCC CDR)

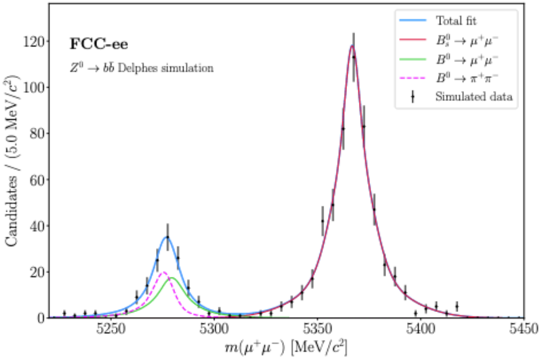


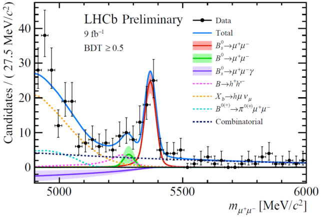
68% C.L contours of EW fit at FCC-ee (FCC CDR)

FCC-ee is a Higgs, EW and top factory!

Physics at the FCC-ee: Flavour physics

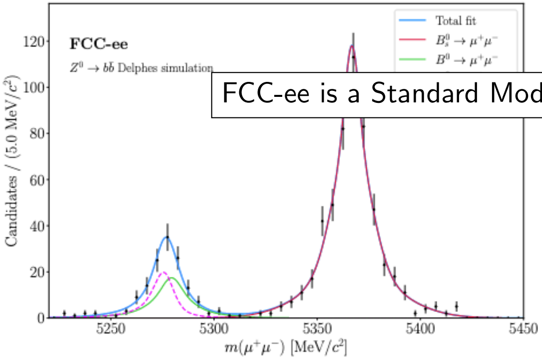
Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\overline{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	300	300	80	80	600	150



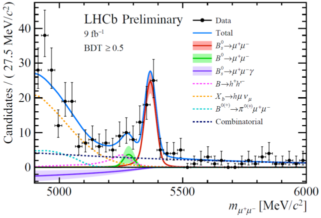


S. Monteil, FCC Flavours Workshop 2022

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\overline{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-ee	300	300	80	80	600	150



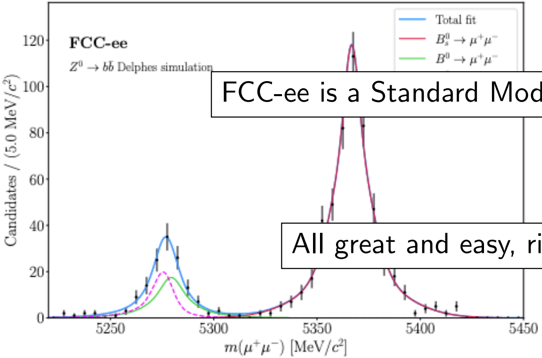
FCC-ee is a Standard Model factory!



S. Monteil, FCC Flavours Workshop 2022

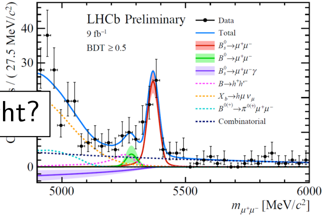
Physics at the FCC-ee: Flavour physics

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\overline{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	300	300	80	80	600	150

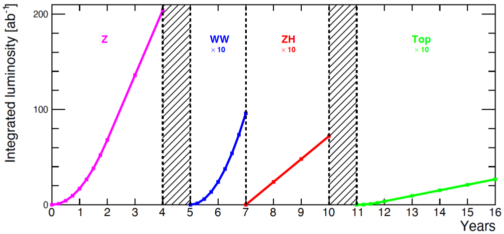


FCC-ee is a Standard Model factory!

All great and easy, right?



S. Monteil, FCC Flavours Workshop 2022



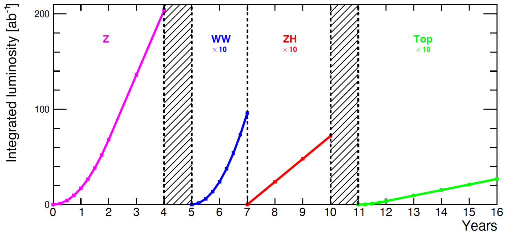
Possible FCC-ee run plan [2]

EW: $2.4 \cdot 10^8$ WW, $6 \cdot 10^{12}$ Z ← **challenging!**
Flavour: $O(10^{12})$ $b\bar{b}$, $c\bar{c}$, etc., $O(10^{11})$ $\tau\bar{\tau}$
H: $1.78 \cdot 10^6$ HZ, 125k WW → H
Top: $1.9 \cdot 10^6$ $t\bar{t}$

So what can be done with this many rather clean collisions?

Experimental challenges

- Need to match tiny statistical uncertainties with theoretical and experimental systematic uncertainties of $\mathcal{O}(10^{-4}\text{–}10^{-5})$!
- Event rate of $\sim 100\,\text{kHz}$ @ Z-pole → almost no pile-up, but want to read out every every single of these collisions with a very well defined efficiency!



Possible FCC-ee run plan [2]

EW: $2.4 \cdot 10^8$ WW, $6 \cdot 10^{12}$ Z ← **challenging!**
Flavour: $O(10^{12})$ $b\bar{b}$, $c\bar{c}$, etc., $O(10^{11})$ $\tau\bar{\tau}$
H: $1.78 \cdot 10^6$ HZ, 125k WW → H
Top: $1.9 \cdot 10^6$ $t\bar{t}$

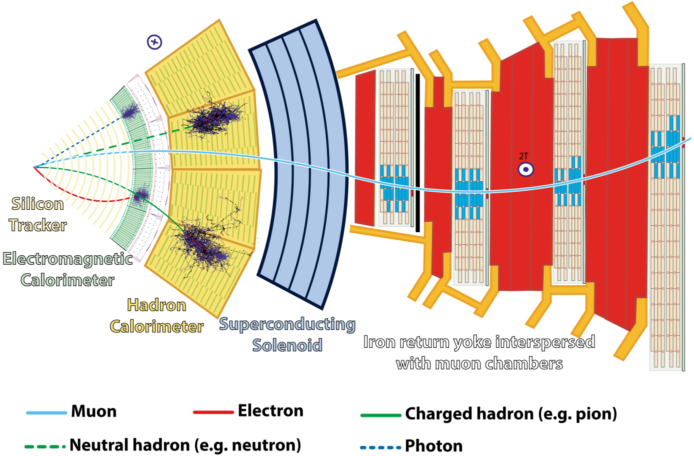
So what can be done with this many rather clean collisions?

Experimental challenges

- Need to match tiny statistical uncertainties with theoretical and experimental systematic uncertainties of $\mathcal{O}(10^{-4}$–$10^{-5})$!
- Event rate of $\sim$ 100 kHz @ Z-pole → almost no pile-up, but want to read out every every single of these collisions with a very well defined efficiency!

How are these challenges overcome experimentally?

Particle detection at colliders

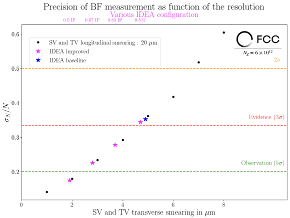


Particle detection in CMS (©2016 CERN).

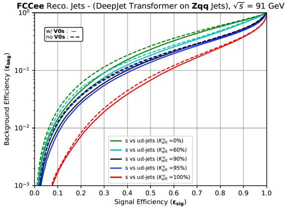
e^+e^- experiments similar structure. Main difference: First acc. magnets inside experiments!

For anything that has secondary vertices!

- b and c hadrons, taus, V0s, ...
- Reconstruct complex decay chains
- Particle lifetime measurements
- Efficient flavour tagging (b/c/g/**s**)



$B^0 \to K^{*0}\tau^+\tau^-$ [4]



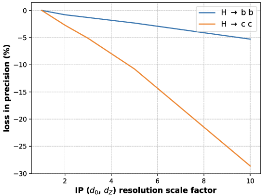
Secondary vertices for *s*-tagging [5]

Stringent requirements on vertex detector to limit syst. uncertainties:

→ Coverage down to $|\cos(\theta)| \lesssim 0.99$ and high reco. efficiency

→ $\sigma_{d_0} = a \oplus \frac{b}{p \sin^{3/2}\theta}$ with $a \approx 3\,\mu$m, $b \approx 15\,\mu$mGeV

- a given by sensor resolution → Small single-hit resolution, pixels
- b given by *multiple scattering* → Minimise material budget (number of radiation lengths X_0) in vertex and beam pipe

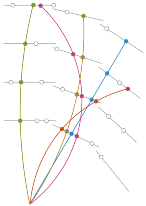


Impact of IP resolution on Yukawa coupling measurement (L. Gouskous)

University of Zurich[UZH]

Reconstruction of the charged particle trajectories

- Large radius due to lower momenta and B field limited to 2 (or 3?) T
- Precise angle determination in di-muons, $< 100\,\mu$rad
- Need for exquisite momentum resolution of $\sigma(1/p_{\mathrm{T}}) \approx a \oplus b/p_{\mathrm{T}}$, with $a \approx 3 \times 10^{-5}\,\mathrm{GeV}^{-1}$, $b \approx 0.6 \cdot 10^{-3}$
  - Again minimise the material budget
- Either some precise hits (silicon tracking) or many less precise hits (gaseous tracking)
  - Gaseous tracking benefitial to long-lived particle searches
- Precise tracks are important ingredient to *particle flow reconstruction*



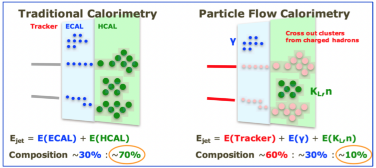
Visualisation of tracking [6].

EM calorimeter

- Supreme energy resolution for
  - $B_s \to D_s K$: Pions may require $5\%/\sqrt{E}$
  - Resolution on Higgs mass in $e^+e^- \to Z(\to e^+e^-)H$ almost as good as in $\mu^+\mu^-$ with $3\%/\sqrt{E}$ (M.T. Lucchino et al. [7])
  - $Z\nu_e\bar{\nu}_e$ coupling

Particle-flow reconstruction

- Optimise jet energy resolution by individually reconstructing each particle and using the best measurement for each (tracker, ECAL, HCAL)
- Needs transverse and longitudinal granularity



Particle flow calorimetry (M. Dam)

Hadronic calorimeter

- Sensitivity down to few 100 MeV
- Single hadron resolution of 25–50%$/\sqrt{E}$
- Particle Flow $\to$ Enough for jet resolution of $\sim$ 3–4 %

Particle identification: Distinguishing K, μ, π, e, γ

- Kaon ID for flavour tagging (s jets contain more kaons) and flavour physics
- γ/neutral hadron separation for particle flow reconstruction
- Background suppression in flavour physics (e.g $B_s^0 \to D_s K$ from $B_s^0 \to D_s \pi$)

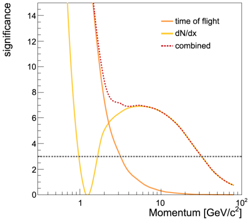
Drift chamber as tracker

- dE/dx and/or cluster counting (dN/dx)

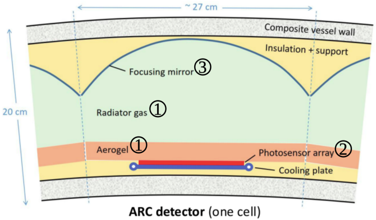
Timing measurement for time-of-flight

- $O(30)$ ps to get PID at low momenta (LGADs, MAPS, etc.). $O(100)\mathrm{m}^2$ of sensors needed

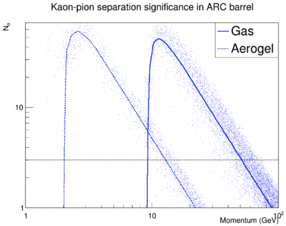
Ring imaging Cherenkov (RICH) detectors



Kaon-pion separation using drift chamber and TOF (F. Bedeschi [8])



Cell of ARC detector for FCC-ee (R. Forty)



Kaon-pion seperation in ARC (M. Tat)

Particle identification: Distinguishing K, μ, π, e, γ

University of Zurich[UZH]

- Kaon ID for flavour tagging (s jets contain more kaons) and flavour physics
- γ/neutral hadron separation for particle flow reconstruction
- Background suppression in flavour physics (e.g $B_s^0 \rightarrow D_s K$ from $B_s^0 \rightarrow D_s \pi$)

Drift chamber as tracker

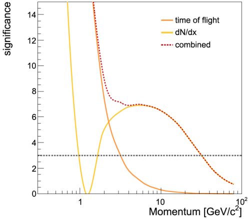
- dE/dx and/or cluster counting (dN/dx)

Timing measurement for time-of-flight

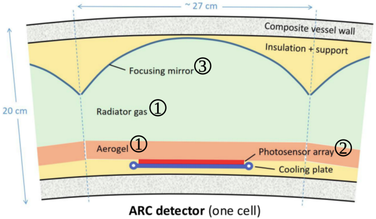
- $O(30)$ ps to get …)m^2 of sensors needed

Ring imaging Chere…

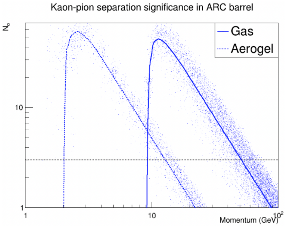
Let's build some detectors with these ingredients!



Kaon-pion separation using drift chamber and TOF (F. Bedeschi [8])



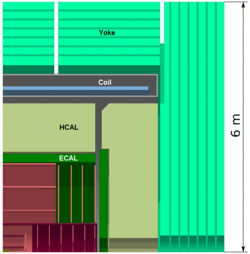
Cell of ARC detector for FCC-ee (R. Forty)



Kaon-pion seperation in ARC (M. Tat)

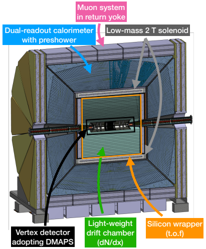
FCC-ee detector *concepts* + variations (RICH, different trackers, ...)

University of Zurich[UZH]



CLD [9, 10]/ILD' [11]

- ILC (→ CLIC) → FCC-ee (→ μCol)
- **Si vertexing** and Si tracking/TPC
- Highly-granular ECAL and HCAL, CALICE-like
- Solenoid coil outside calorimeter system



IDEA [12, 13]

- **Si vertexing**
- Drift chamber (down to 1.6% X_0, d$N_{\text{ion.}}$/dx)
- Silicon wrapper with T.O.F
- Crystal ECAL, light solenoid, dual-readout calorimeter
- μ-RWELL muon detector in return yoke

ALLEGRO [14]

- **Si vertexing**
- Drift chamber, silicon wrapper
- Noble liquid ECAL, Pb/W+LAr or W+LKr
- ECAL and solenoid coil in same cryostat
- CALICE-like or TileCal-like HCAL

How to concretise the detector designs?

University of Zurich[UZH]

A lot of work done for the feasibility study, but many points still open

- Requirements to the accelerator? (backgrounds, space constraints, etc.)
- Expected performance? What can we do with the particles we get?
- What next-gen detector technologies can benefit the FCC-ee physics program? Different detector concepts?

Feedback-loop

Sensor perf. $\xrightarrow[\text{sim.}]{\text{detector}}$ Subdetector perf. $\xrightarrow[\text{analysis}]{\text{sample}}$ physics perf. $\xrightarrow[\text{input}]{\text{theory}}$ sensor specification

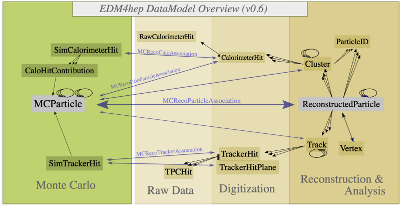
What you can do:

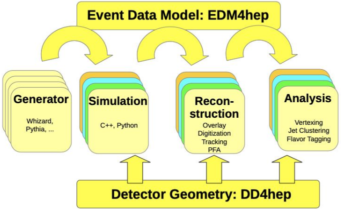
- Develop your new instrumentation, e.g. within the Detector R&D (DRD) collaborations
- Describe your detector (variants) in simulation, perform/implement/improve reconstruction
- Sample analysis: Study a process you're interested in, compare different detectors

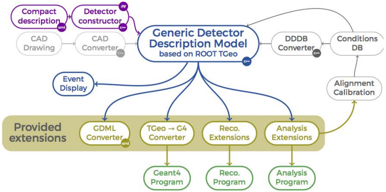
The common software vision: Key4hep

Key4hep is a huge ecosystem of software packages adopted by all future collider projects, complete workflow from generator to analysis

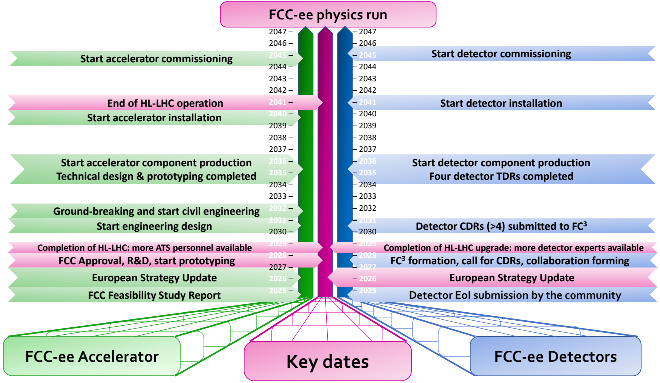
- Event data model: EDM4hep for exchange among framework components
  - Podio as underlying tool, for different collision environments
  - Including truth information
- Data processing framework: Gaudi
- Geometry description: DD4hep, ability to include CAD files
- Package manager: Spack: `source /cvmfs/sw.hsf.org/Key4hep/setup.sh`







Conclusions

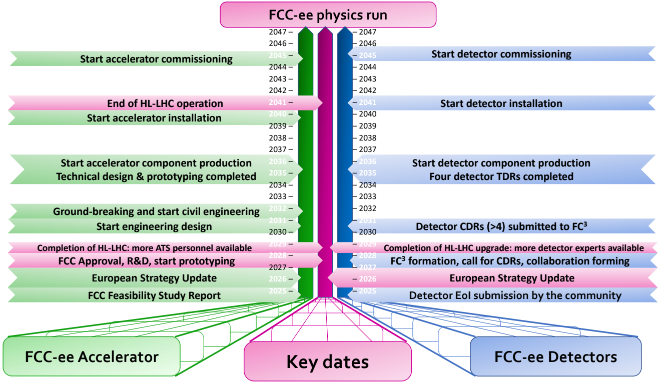


M. Benedikt, FCC Week 2023

- Huge room for contribution
- Four IPs able to accommodate novel detector ideas. Only general-purpose detector concepts so far

People often say "not much came out from LEP". That is completely wrong. What people forget is that LEP changed high-energy physics from a 10% to a 1% science.
- Former DG Herwig Schopper in CERN Courier

Conclusions



M. Benedikt, FCC Week 2023

- Huge room for contribution
- Four IPs able to accommodate novel detector ideas. Only general-purpose detector concepts so far

People often say "not much came out from LEP". That is completely wrong. What people forget is that LEP changed high-energy physics from a 10% to a 1% science.

- Former DG Herwig Schopper in CERN Courier → FCC-ee will lead us to ‰ and below!

Thanks!

Links to other good intro talks

University of Zurich[UZH]

- Mogens Dam and Nadia Pastrone @ Future Colliders for ECRs Workshop
- Mogens Dam @ CERN EP R&D day 2022

References I

University of Zurich[UZH]

[1] X. Mo, G. Li, M.-Q. Ruan, and X.-C. Lou, *Physics cross sections and event generation of e^+e^- annihilations at the CEPC*, Chinese Physics C **40** (2016) 033001, https://doi.org/10.1088/1674-1137/40/3/033001.

[2] B. Auchmann, et al., *FCC Midterm Report*, June, 2024.

[3] S. D. Vita, et al., *A global view on the Higgs self-coupling at lepton colliders*, Journal of High Energy Physics **2018** (2018), https://doi.org/10.1007/jhep02(2018)178.

[4] T. Miralles, *Sensitivity study of $B^0 \to K^{*0}\tau^+\tau^-$ at FCC-ee*, in *Proceedings of 20th International Conference on B-Physics at Frontier Machines — PoS(BEAUTY2023)*, p. , 060.
2024.

[5] F. Blekman, et al., *Jet Flavour Tagging at FCC-ee with a Transformer-based Neural Network: DeepJetTransformer*, 2024. https://arxiv.org/abs/2406.08590.

[6] S. Amrouche, et al., *The Tracking Machine Learning Challenge: Accuracy Phase*, pp. , 231–264.
Springer International Publishing, Nov., 2019.
https://doi.org/10.1007/978-3-030-29135-8_9.

[7] M. Lucchini, et al., *New perspectives on segmented crystal calorimeters for future colliders*, Journal of Instrumentation **15** (2020) P11005–P11005, https://doi.org/10.1088/1748-0221/15/11/p11005.

[8] F. Bedeschi, L. Gouskos, and M. Selvaggi, *Jet flavour tagging for future colliders with fast simulation*, The European Physical Journal C **82** (2022), https://doi.org/10.1140/epjc/s10052-022-10609-1.

[9] N. Bacchetta, et al., *CLD – A Detector Concept for the FCC-ee*, arXiv:1911.12230 [physics.ins-det].

[10] D. Dannheim, et al., *CERN Yellow Reports: Monographs, Vol 1 (2019): Detector Technologies for CLIC*, tech. rep., 2019.

[11] T. I. Collaboration and contact Ties Behnke, *The ILD detector at the ILC*, 2019. https://arxiv.org/abs/1912.04601.

University of Zurich[UZH]

[12] IDEA Collaboration, G. F. Tassielli, *A proposal of a drift chamber for the IDEA experiment for a future e^+e^- collider*, in *Proceedings of 40th International Conference on High Energy physics — PoS(ICHEP2020)*.
Sissa Medialab, Feb., 2021.

[13] FCC Collaboration, *FCC-ee: The Lepton Collider*, The European Physical Journal Special Topics **228** (2019) 261–623.

[14] M. Aleksa, et al., *Calorimetry at FCC-ee*, The European Physical Journal Plus **136** (2021) 1066.

[15] A. Ciarma, M. Boscolo, G. Ganis, and E. Perez, *Machine Induced Backgrounds in the FCC-ee MDI Region and Beamstrahlung Radiation*, Proceedings of the 65th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders **eeFACT2022** (2022) Italy, https://jacow.org/eefact2022/doi/JACoW-eeFACT2022-TUZAT0203.html.

[16] Boscolo,Manuela, et al., *Progress in the design of the future circular collider FCC-ee interaction region*, https://jacow.org/ipac2024/doi/jacow-ipac2024-tupc67.

[17] C. Neubüser, T. Corradino, G.-F. Dalla Betta, and L. Pancheri, *ARCADIA FD-MAPS: Simulation, characterization and perspectives for high resolution timing applications*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **1048** (2023) 167946, http://dx.doi.org/10.1016/j.nima.2022.167946.

[18] I. Peric, et al., *High-Voltage CMOS Active Pixel Sensor*, IEEE Journal of Solid-State Circuits **56** (2021) 2488–2502, http://dx.doi.org/10.1109/JSSC.2021.3061760.

[19] K. Mirbaghestan and A. Ilg, *Performance study of the IDEA Vertex Detector for FCC-ee*, 2024. https://zenodo.org/doi/10.5281/zenodo.14181210.

[20] M. Mager, *On the "bendable" ALPIDE-inspired MAPS in 65 nm technology*, 11, 2021. https://indico.ihep.ac.cn/event/14938/session/6/contribution/196. 2021 International Workshop on High Energy Circular Electron Positron Collider.

References III

[21] ALICE collaboration, *Technical Design report for the ALICE Inner Tracking System 3 - ITS3 ; A bent wafer-scale monolithic pixel detector*, tech. rep., CERN, Geneva, 2024.
https://cds.cern.ch/record/2890181.
Co-project Manager: Magnus Mager, magnus.mager@cern.chds.

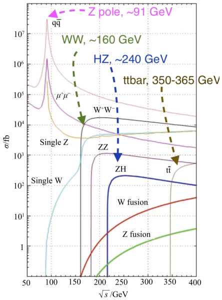
[22] D. Dannheim, et al., *Fine-pitch CMOS pixel sensors with precision timing for vertex detectors at future Lepton-Collider experiments and beyond*, https://cds.cern.ch/record/2914698.

FCC-ee collision environment at the Z pole

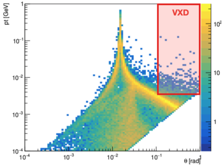
☺: e^+e^- collisions are *clean* - there's no QCD in the initial state

☹: Very high inst. luminosity of $140 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ thanks to 50 MHz bunch collision rate ($t_{BC} = 20\,\mathrm{ns}$)

- Very high rate of interesting events (200 kHz of Z) that need to be read out and saved (and simulated!)
- Considerable beam backgrounds, mainly from incoherent pairs
  - Hit rate of $\mathcal{O}(200\,\mathrm{MHz/cm^2})$ for innermost layer
  - → Trigger-less readout will be challenging
- "Pile-up" of 200 kHz/50 MHz = 0.004 at Z-pole
  - → Integrate over of a couple of bunch crossings?
  - → But need to check impact on uncertainties
  - Timing of $\mathcal{O}(\text{few ns} - 1\,\mu\mathrm{s})$
- $\mathcal{O}(1 \times 10^{14}\ 1\,\mathrm{MeV}\ n_{eq}\mathrm{cm}^{-2})$ and $\mathcal{O}(10\,\mathrm{MRad}/100\,\mathrm{kGy})$ per year



e^+e^- annihilation cross section [1]



Incoherent pairs at Z pole [15]