Experimental challenges at future colliders

CHIPP Strategy Update Workshop
ECR Discussion

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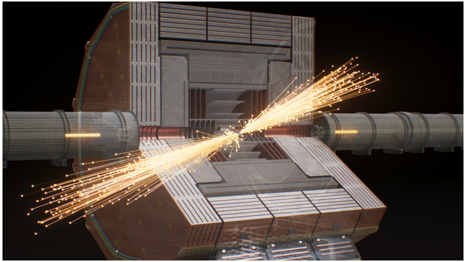
04.02.2025



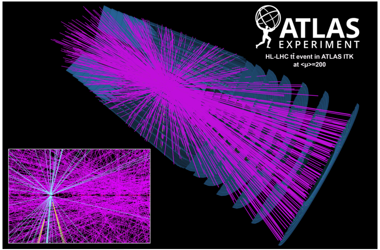
Different challenges at different colliders

Factors:

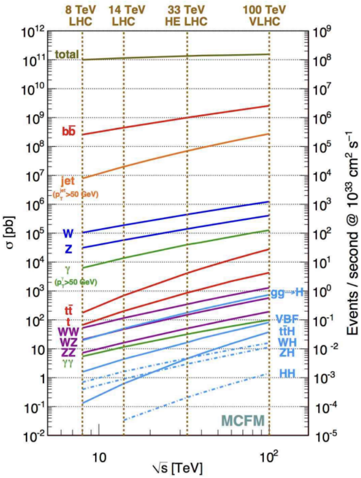
- Type of particles being collided (e^+e^-, e^-p, e^-h, pp, hh, $\mu^+\mu^-$, $\gamma\gamma$, ...)
- Centre-of-mass energy
- Luminosity
- Asymmetry (HALHF or Belle II)
- Hermetic or forward only

Will focus on FCC-ee experimental challenges, but also show differences at linear colliders, muon colliders, and FCC-hh

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

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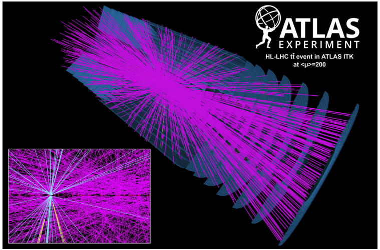

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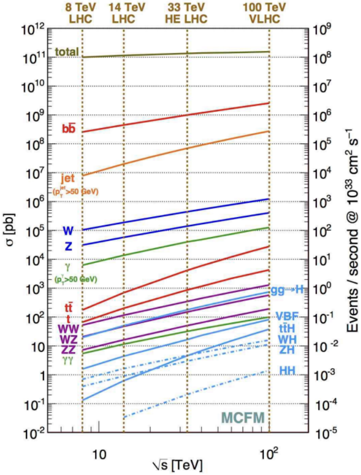

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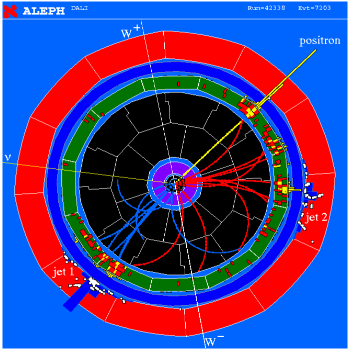
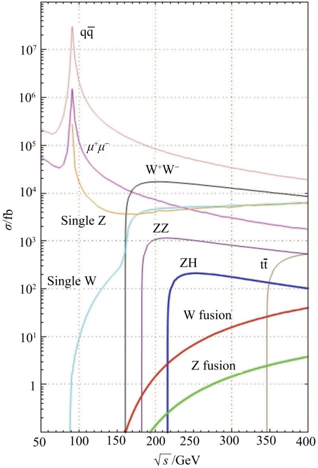
→ *Looking for the needle in the haystack*

Lepton collisions



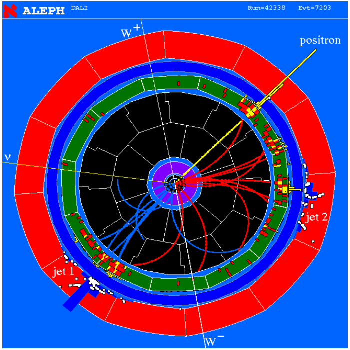
WW pair decay at LEP2, detected by ALEPH (source).



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

- Collision of **point-like** particles
  → 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



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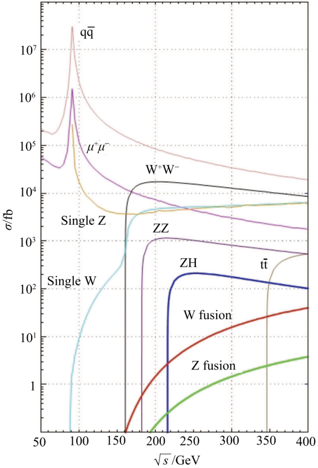

e^+e^- cross section [1].

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

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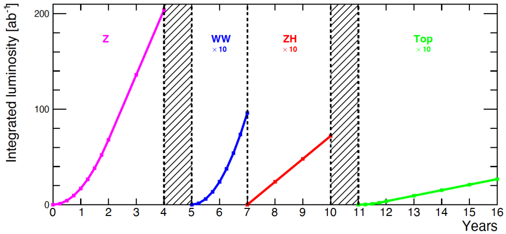
The Future Circular Collider (FCC) integrated programme



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., $O(10^{11})$ $\tau\bar{\tau}$
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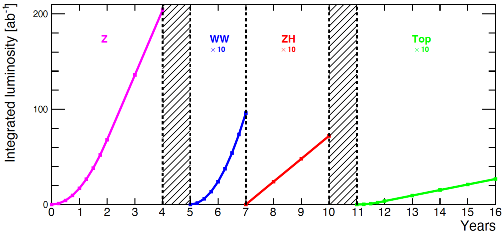

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So what can be done with this many rather clean collisions?

Physics at the FCC-ee
A few highlights

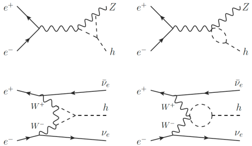
Higgs physics

Shape of the **Higgs potential**:

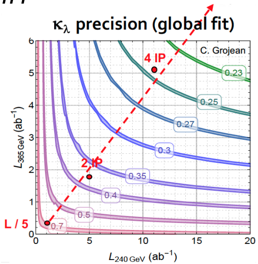
$$V(h) = \frac{m_H^2 h^2}{2} + \lambda_3 \nu h^3 + \lambda_4 \nu h^4$$

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
  - → FCC-hh: measurement down to few % level in $gg \to HH$

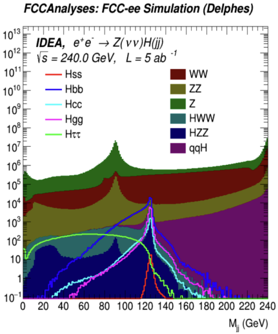


λ_3 in loops at FCC-ee [3].



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

EW and top physics

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

EW and top physics

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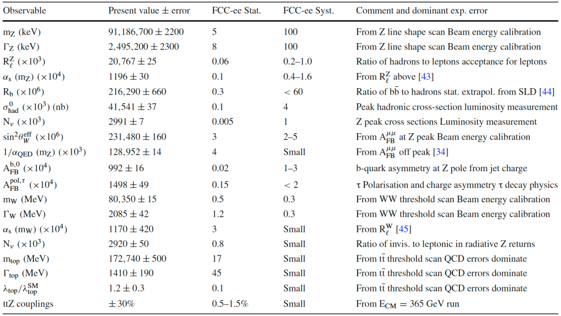
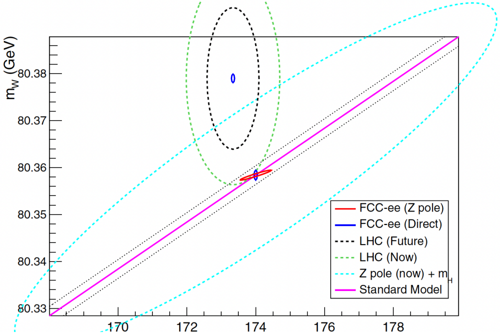
FCC-ee: $6 \cdot 10^{12}$ Z bosons → LEP1 programme in couple of minutes (LEP2 W stats in 90 min)



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_ℓ^Z ($\times 10^3$)	$20{,}767 \pm 25$	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_ℓ^Z 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_{had}^0 ($\times 10^3$) (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
$\sin^2\theta_W^{eff}$ ($\times 10^6$)	$231{,}480 \pm 160$	3	2–5	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}$ (m_Z) ($\times 10^3$)	$128{,}952 \pm 14$	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)	$80{,}350 \pm 15$	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_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)	$172{,}740 \pm 500$	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
$\lambda_{top}/\lambda_{top}^{SM}$	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)

EW and top physics

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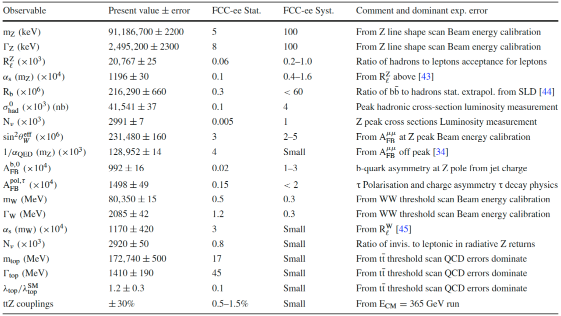

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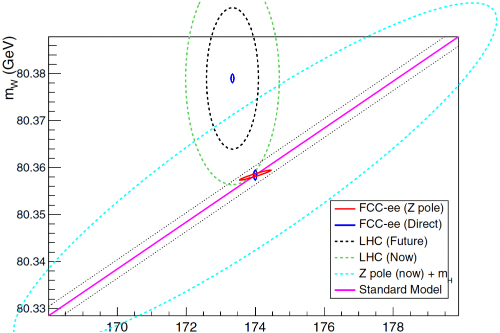
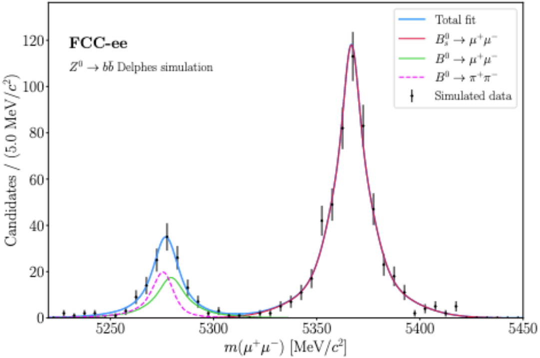


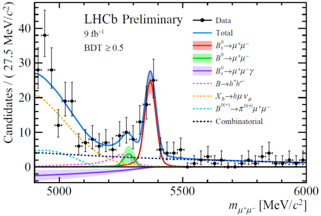
68% C.L contours of EW fit at FCC-ee (FCC CDR)

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_s^0 / $\overline{B}_s^0$	Λ_b / $\overline{\Lambda}_b$	$c\bar{c}$	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

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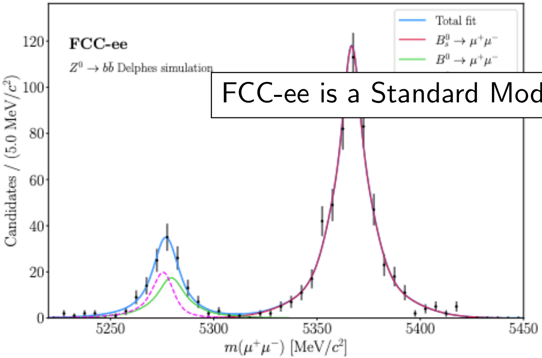
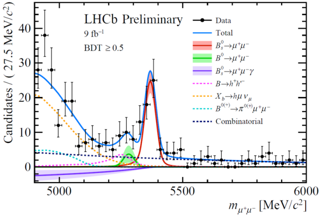


FCC-ee is a Standard Model factory!



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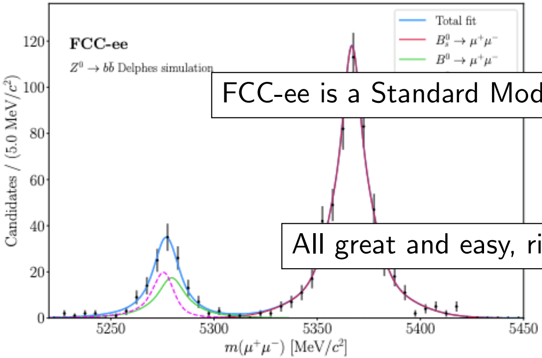

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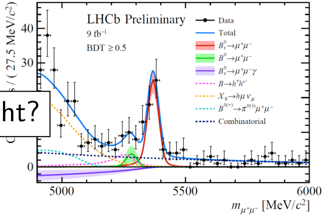
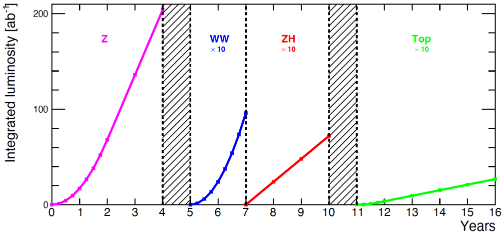


All great and easy, right?

S. Monteil, FCC Flavours Workshop 2022

The Future Circular Collider (FCC) integrated programme



Possible FCC-ee run plan [2]

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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 $\sim 100\,\mathrm{kHz}$ @ Z-pole → almost no pile-up, but want to read out every every single of these collisions with a very well defined efficiency!

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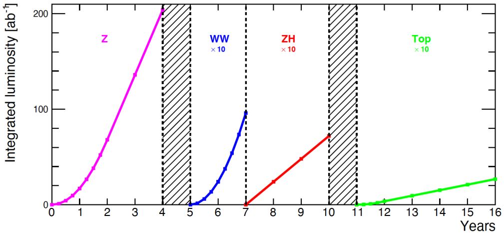

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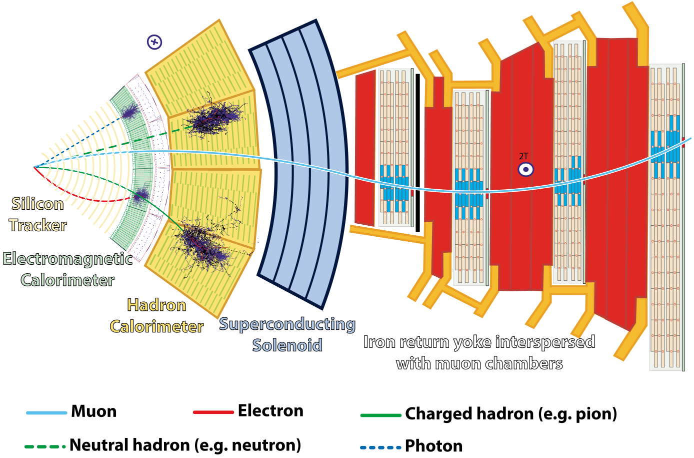
How are these challenges overcome experimentally?

Particle detection at colliders



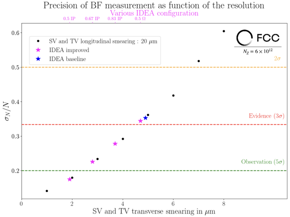
Particle detection in CMS (©2016 CERN).

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

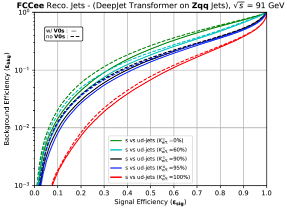
Vertex detector

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]



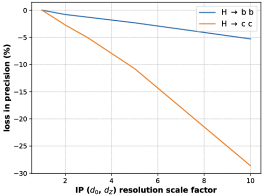
Secondary vertices for *s*-tagging [5]

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

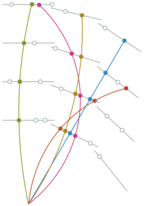


Impact of IP resolution on Yukawa coupling measurement (L. Gouskous)

Tracking

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].

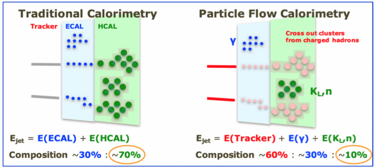
Calorimetry

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 $25\text{–}50\%/\sqrt{E}$
- Particle Flow → 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 $B_s^0 \rightarrow D_s K$ from $B_s^0 \rightarrow D_s \pi$)

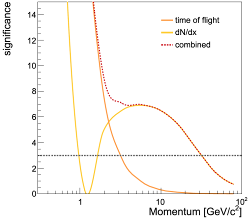
Drift chamber as tracker

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

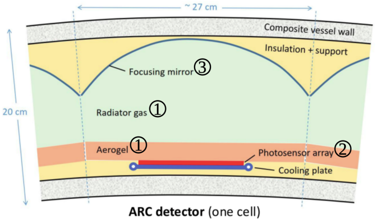
Timing measurement for time-of-flight

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

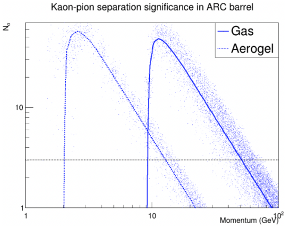
Ring imaging Cherenkov (RICH) detectors



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

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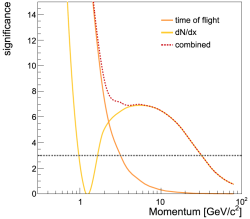
Timing measurement for time-of-flight

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

Let's build some detectors with these ingredients!

Ring imaging Cherenkov (RICH) detectors



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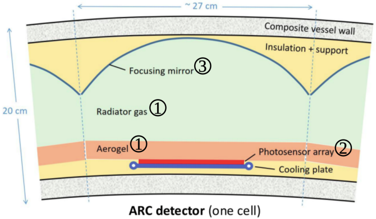

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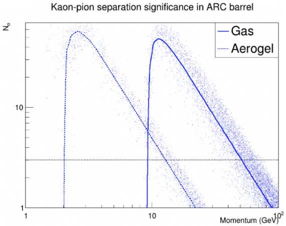
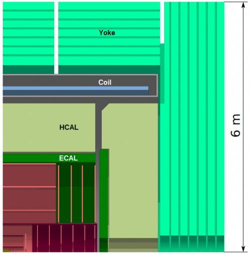


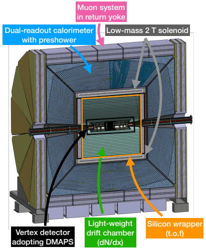
Kaon-pion seperation in ARC (M. Tat)

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



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



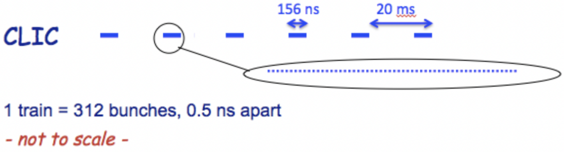
IDEA [12, 13]

- **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

Differences at linear e^+e^- colliders



Bunch structure at CLIC [15]

No continuous bunch collisions as in circular colliders

→ Allows to power off on-detector electronics in-between bunch trains → Makes cooling easier

→ Need $\mathcal{O}(5\,\text{ns})$ time resolution to deal with beam backgrounds

→ Time-projection-chamber as tracker is feasible, since number of primary ions is limited (period between bunch trains). At FCC-ee: Extremely challenging

→ 1-2 orders of magnitude less radiation damage

Circular colliders better at low $\sqrt{s}$, linear better at high $\sqrt{s}$

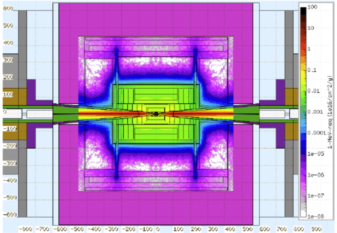
→ Linear collider experiments optimised for larger momenta
  - Larger B fields of 4 T at CLIC (limited to 2 T at Z pole), smaller tracker
  - Larger depth of hadronic calorimeter

- Smaller beam pipe at FCC-ee, but cooled

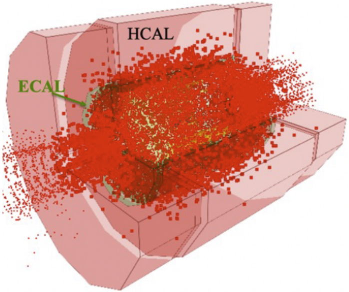
Differences at 3 or 10 Tm_{e}V muon colliders N. Pastrone

Main challenges:

- Intense beam-induced background (muons constantly decaying into detector)
  - → Very complex machine-detector interface design
  - → Radiation levels at HL-LHC levels or ∼ 1 order above
  - → Timing to suppress beam induced background hits
- "HL-LHC detectors with amazing timing and better resolution" or "FCC-ee detectors with amazing timing"
- High-energy shower containment, measurment of very high-momentum particles



	Vertex Detector	**Inner Tracker**	**Outer Tracker**
Cell type	pixels	macropixels	microstrips
Cell Size	25 µm × 25 µm	50 µm × 1 mm	50 µm × 10 mm
Sensor Thickness	50 µm	100 µm	100 µm
Time Resolution	30 ps	60 ps	60 ps
Spatial Resolution	5 µm × 5 µm	7 µm × 90 µm	7 µm × 90 µm



FCC-hh (check [16] for details)

Not so difficult

FCC-hh (check [16] for details)

Take ATLAS

FCC-hh (check [16] for details)

Take ATLAS, strap two LHCb's to it on both sides

FCC-hh (check [16] for details)

Take ATLAS, strap two LHCb's to it on both sides, reconstruct events with pile-up of 1000

FCC-hh (check [16] for details)

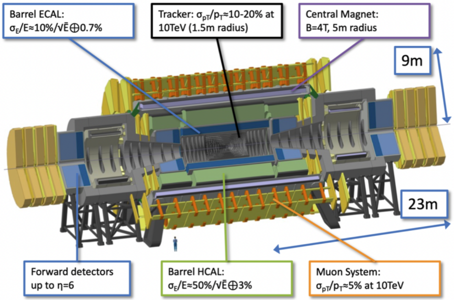
Take ATLAS, strap two LHCb's to it on both sides, reconstruct events with pile-up of 1000, make it sustain 100 times more radiation than HL-LHC (10^{18} NIEL)

FCC-hh (check [16] for details)

Take ATLAS, strap two LHCb's to it on both sides, reconstruct events with pile-up of 1000, make it sustain 100 times more radiation than HL-LHC (10^{18} NIEL), extend forward coverage

FCC-hh (check [16] for details)

Take ATLAS, strap two LHCb's to it on both sides, reconstruct events with pile-up of 1000, make it sustain 100 times more radiation than HL-LHC (10^{18} NIEL), extend forward coverage, you're done


Barrel ECAL: $\sigma_E/E \approx 10\%/\sqrt{E} \oplus 0.7\%$

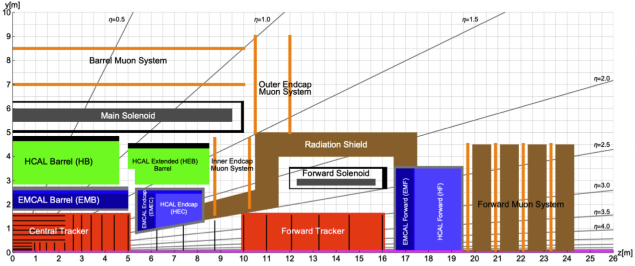
Tracker: $\sigma_{p_T}/p_T \approx$10-20% at 10TeV (1.5m radius)

Central Magnet: B=4T, 5m radius

Forward detectors up to $\eta=6$

Barrel HCAL: $\sigma_E/E \approx 50\%/\sqrt{E} \oplus 3\%$

Muon System: $\sigma_{p_T}/p_T \approx 5\%$ at 10TeV



Conclusions

Lots of challenges for all proposed colliders.

If approved, the next 5 years will be the time in which the collaborations for the next generation of collider experiments will be formed.

Huge room for contribution, innovation, and crazy ideas...

Conclusions

Lots of challenges for all proposed colliders.

If approved, the next 5 years will be the time in which the collaborations for the next generation of collider experiments will be formed.

Huge room for contribution, innovation, and crazy ideas... from you!

Thanks!

Links to other good intro talks

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

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`https://jacow.org/eefact2022/doi/JACoW-eeFACT2022-TUZAT0203.html`.

How to concretise the detector designs?

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

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

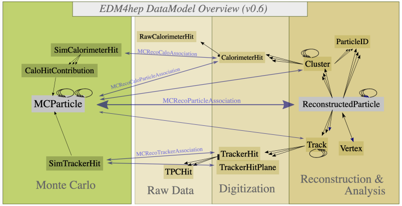
What you can do:

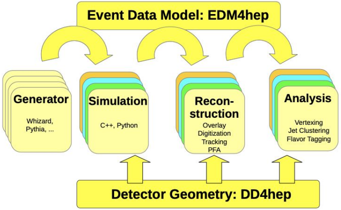
- Develop your new instrumentation, e.g. within the Detector R&D (DRD) collaborations
- Describe your detector (variants) in simulation, perform/implement/improve reconstruction
- Sample analysis: Study a process you're interested in, compare different detectors

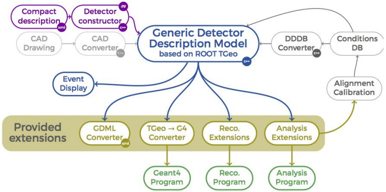
The common software vision: Key4hep

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`







FCC-ee collision environment at the Z pole

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

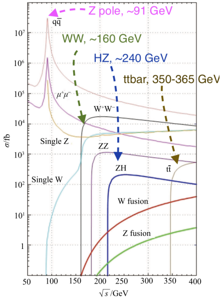
☹: Very high inst. luminosity of $140 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ thanks to 50 MHz bunch collision rate ($t_{\mathrm{BC}} = 20\,\mathrm{ns}$)

- 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

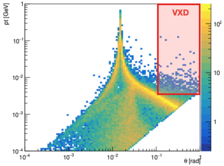
  → Trigger-less readout will be challenging
- "Pile-up" of 200 kHz/50 MHz = 0.004 at Z-pole

  → Integrate over of a couple of bunch crossings?

  → But need to check impact on uncertainties
  - Timing of $\mathcal{O}(\text{few ns} - 1\,\mu\text{s})$
- $\mathcal{O}(1 \times 10^{14}$ 1 MeV $n_{\mathrm{eq}}\mathrm{cm}^{-2})$ and $\mathcal{O}(10\,\mathrm{MRad}/100\,\mathrm{kGy})$ per year



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

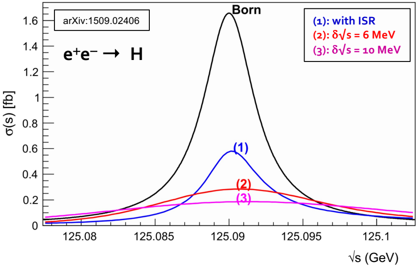


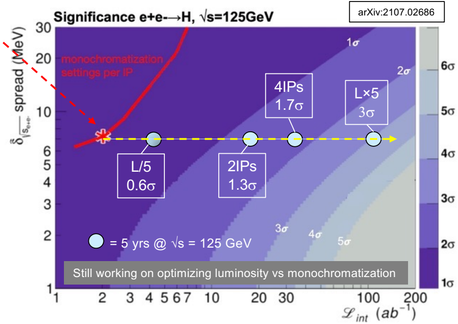
Incoherent pairs at Z pole [17]

Higgs physics bonus: Electron Yukawa

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