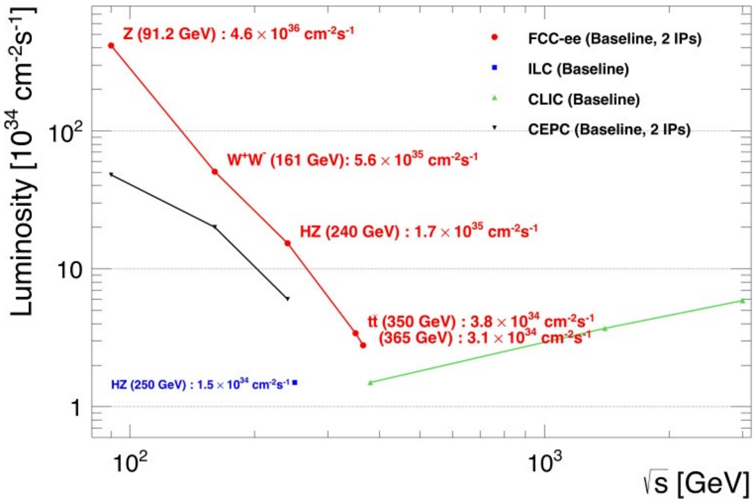
Physics studies at FCC-ee

Gabriella Gaudio
on behalf of the FCC-ee group
August, 29th 2022

FCC-ee key elements: dedicated working points

FCC-ee: The Lepton Collider, Eur. Phys. J. Spec. Top. 228 (2019)

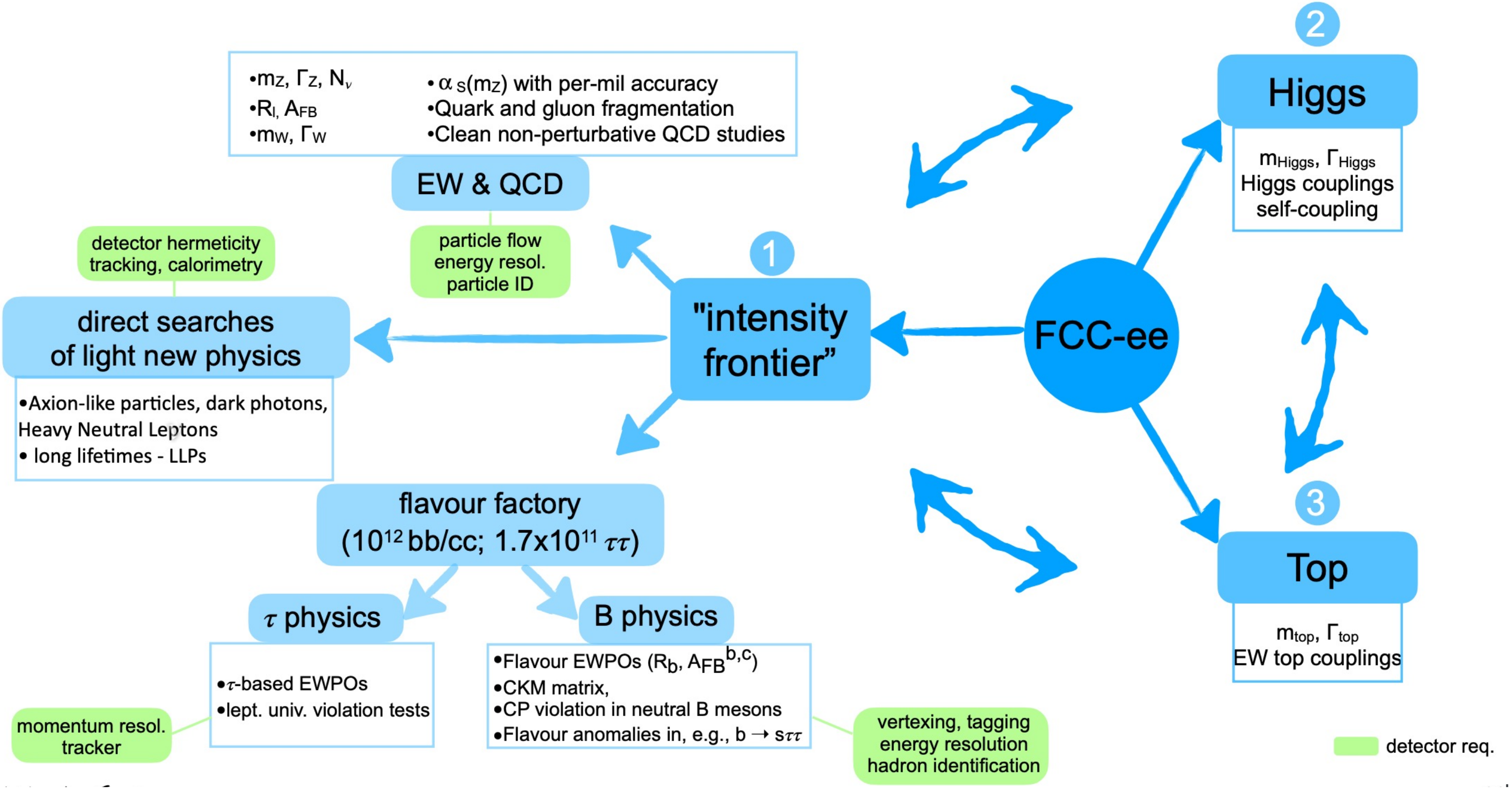


Working point	Z, years 1-2	Z, later	WW	HZ	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163	240	340-350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	115	230	28	8.5	0.95	1.55
Lumi/year (ab^{-1}, 2 IP)	24	48	6	1.7	0.2	0.34
Physics Goal (ab^{-1})	150		10	5	0.2	1.5
Run time (year)	2	2	2	3	1	4
Number of events	5×10^{12} Z		10^8 WW	10^6 HZ + 25k WW → H	$10^6 t\bar{t}$ +200k HZ +50k WW → H	

Staged physics programs with 4 working points

- **Z-pole**: Tera Z sample for very high precision measurements
- **WW threshold**: W mass and width
- **HZ**: Higgs precision physics
- **tt threshold**: t mass and width

FCC-ee physics in a nutshell



C.Grojean FCC Week 30.5.22

FCC-ee key elements

High Statistics

Precise center-of-mass
energy determination

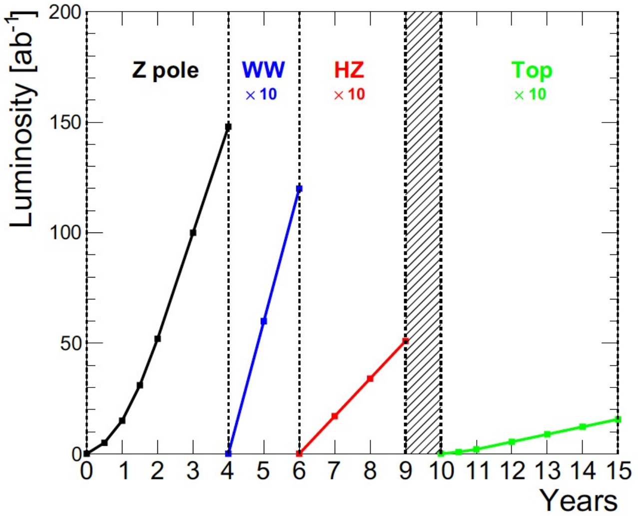
Clean environments

FCC-ee key elements

High Statistics

Precise center-of-mass energy determination

Clean environments



- Reduce statistical errors
- Allow for extremely precise global consistency check of the SM through electroweak precision observables measurements
- Check for deviation from SM prediction $\Longrightarrow$ hint of BSM physics

FCC-ee key elements

High Statistics

Precise center-of-mass energy determination

Clean environments

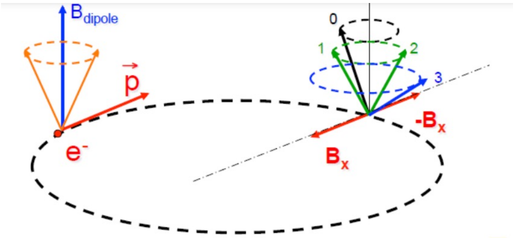
Transverse beam polarization provides beam energy calibration by resonant depolarization

Resonant depolarization is the cornerstone of the precision programme of FCC-ee

factor 500-75 more precise than LEP

~40 times more precise than CDF

➔ Improvement by factor 10-1000 on a long list of EW precision measurements.
e.g. W mass down to ±250 keV, Z mass and width ±4 keV, $\sin^2\theta_W^{eff} \pm 2.10^{-6}$ etc..
➔ explore new physics at 10-100 TeV scale, or 10^{-5} mixing with known particles.



$$\nu = \frac{g_e - 2}{2}\frac{E}{mc^2} = \frac{E_b}{0.44065686(1)}$$

ν is the spin tune

A. Blondel FCC Week 30.5.22

FCC-ee key elements

High Statistics

Precise center-of-mass energy determination

Clean environments

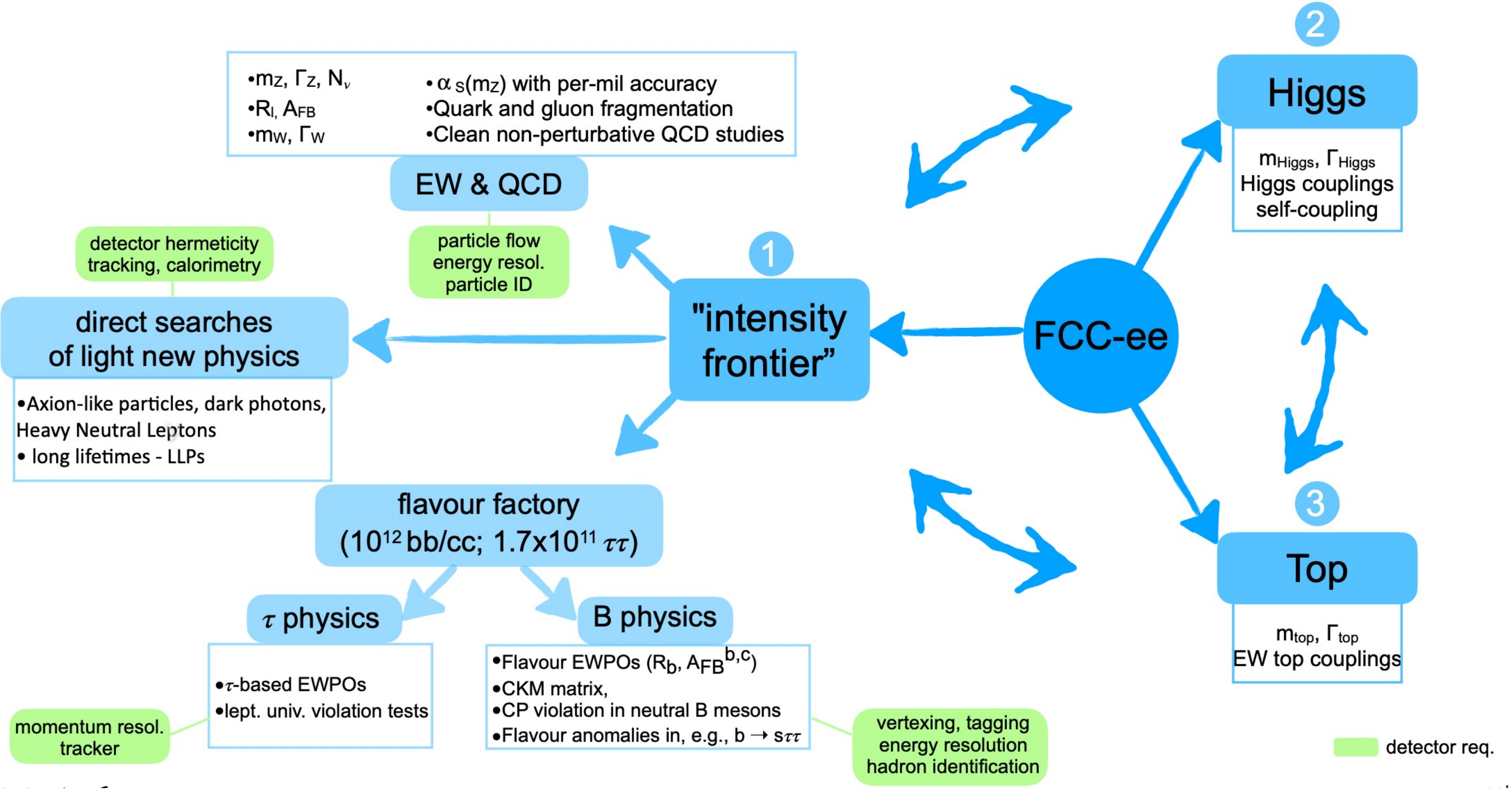
Higher luminosity but higher number of bunches wrt LEP
⟹ **intensity/bunch mostly the same as LEP**

The **asymmetric e^+e^- beam lines** around the FCC-ee interaction regions are designed to minimize synchrotron radiation in the detectors.

From simulation:
the occupancy in a typical vertex detector is found to be smaller than 10^{-5} at the Z pole, and a few 10^{-4} at 365 GeV

FCC-ee physics in a nutshell

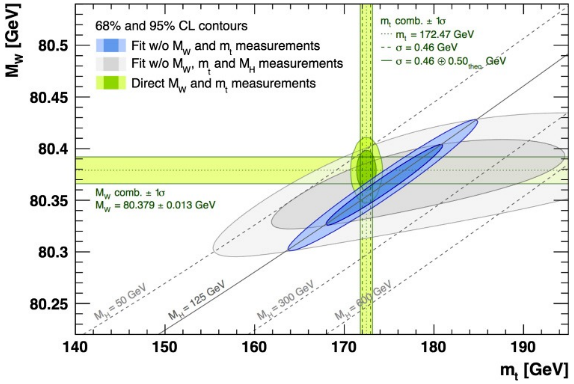
C.Grojean FCC Week 30.5.22

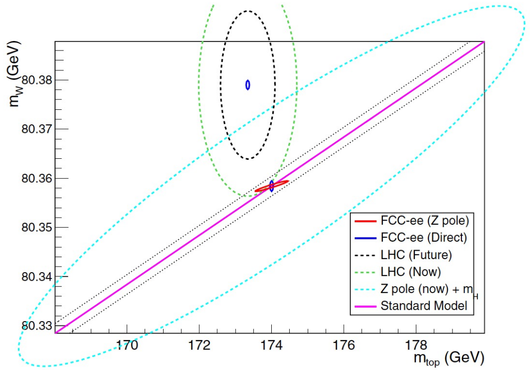


Electroweak Precision Observable

Observable	Present value	±	error	FCC-ee (statistical)	FCC-ee (systematic)
m_Z (keV/c^2)	91 186 700	±	2200	5	100
Γ_Z (keV)	2 495 200	±	2300	8	100
R_ℓ^Z ($\times 10^3$)	20 767	±	25	0.06	1
$\alpha_s(m_Z)$ ($\times 10^4$)	1196	±	30	0.1	1.6
R_b ($\times 10^6$)	216 290	±	660	0.3	<60
σ^0_{had} ($\times 10^3$) (nb)	41 541	±	37	0.1	4
N_ν($\times 10^3$)	2991	±	7	0.005	1
$\sin^2\theta_W^{eff}$($\times 10^6$)	231 480	±	160	3	2–5
$1/\alpha_{QED}(m_Z)$($\times 10^3$)	128 952	±	14	4	Small
$A_{FB}^{b,0}$ ($\times 10^4$)	992	±	16	0.02	<1
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498	±	49	0.15	<2
m_W (keV/c^2)	803 500	±	15 000	600	300

+FCC-ee





P. Janot FCC Week 30.5.22

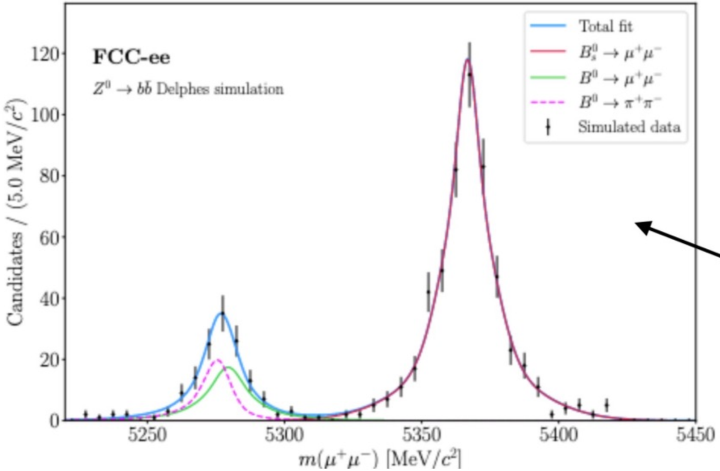
- FCC-ee combines advantages from LHCb and Belle2, with 10 × larger stat than Belle II

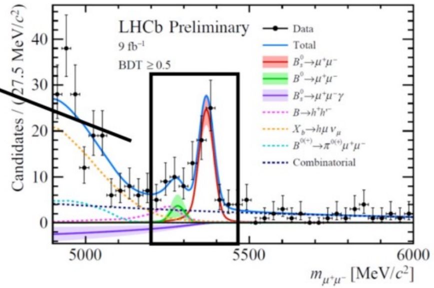
Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

Make CP violation studies possible for very rare B decays?

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	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

Much higher rate and better separation for $B^0_d/B^0_s \to \mu^+\mu^-$



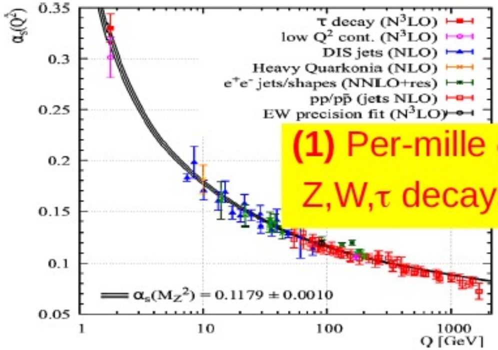


Complete case study required

QCD @FCC-ee

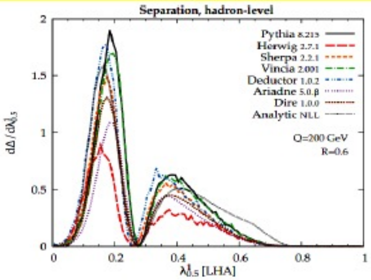
- The precision needed to fully exploit all future ee, pp, ep, eA, AA SM and BSM programs requires precise control of pQCD and non-pQCD physics

F. Giuli's talk on Tuesday



(1) Per-mille α_s via hadronic Z,W,τ decays, evt shapes...

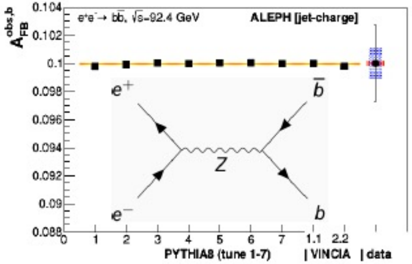
(2) N^nLO+N^nLL jet structure Ultimate g/q/Q discrimination

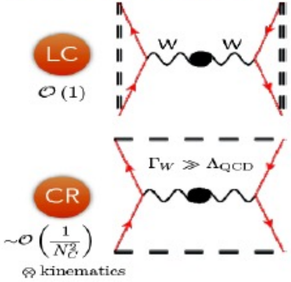


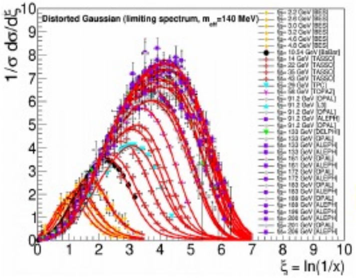
(3) Reduced PS+hadroniz. uncert. of EWPOs

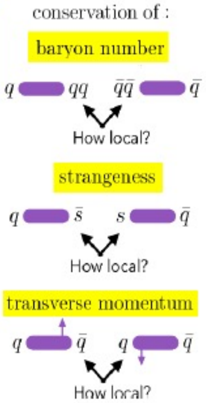
(4) <<1% control of colour reconnection

(5) High-precision hadronization:







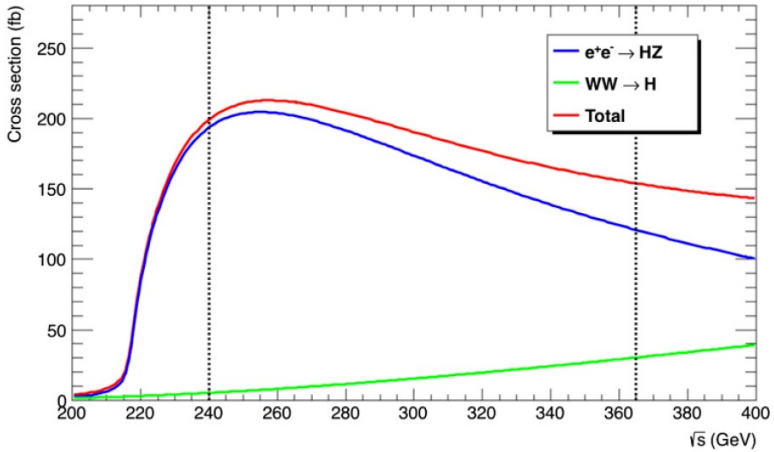


Higgs Physics @ Fcc-ee (hh)

P. Janot FCC Week 30.5.22

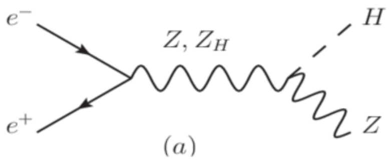
Collider	HL-LHC	$FCC\text{-}ee_{240\to365}$	FCC-INT	
Lumi (ab^{-1})	3	5 + 0.2 + 1.5	30	
Years	10	3 + 1 + 4	25	
g_{HZZ} (%)	1.5	0.18 / 0.17	0.17/0.16	ee
g_{HWW} (%)	1.7	0.44 / 0.41	0.20/0.19*	ee
g_{Hbb} (%)	5.1	0.69 / 0.64	0.48/0.48	ee
g_{Hcc} (%)	SM	1.3 / 1.3	0.96/0.96	ee
g_{Hgg} (%)	2.5	1.0 / 0.89	0.52/0.5	ee
$g_{H\tau\tau}$ (%)	1.9	0.74 / 0.66	0.49/0.46	ee
$g_{H\mu\mu}$ (%)	4.4	8.9 / 3.9	0.43/0.43	pp
$g_{H\gamma\gamma}$ (%)	1.8	3.9 / 1.2	0.32/0.32	pp
$g_{HZ\gamma}$ (%)	11.	– / 10.	0.71/0.7	pp
g_{Htt} (%)	3.4	10. / 3.1	1.0/0.95	pp
g_{HHH} (%)	50.	44./33. 27./24.	3-5	pp
Γ_H (%)	SM	1.1	0.91	ee
BR_{inv} (%)	1.9	0.19	0.024	pp
BR_{EXO} (%)	SM (0.0)	1.1	1	ee

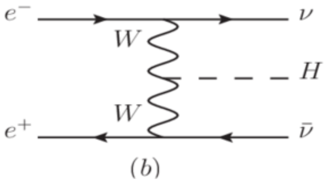
* g_{HWW} includes also ep



FCC-ee / FCC-hh complementarity is outstanding

$$\delta g_{HXX}/g_{HXX} < 5\% \quad per\ \Lambda \sim 1TeV$$





Higgs Physics @ Fcc-ee (hh)

P. Janot FCC Week 30.5.22

Collider	HL-LHC	FCC-ee$_{240\to365}$	FCC-INT	
Lumi (ab^{-1})	3	5 + 0.2 + 1.5	30	
Years	10	3 + 1 + 4	25	
g_{HZZ} (%)	1.5	0.18 / 0.17	0.17/0.16	ee
g_{HWW} (%)	1.7	0.44 / 0.41	0.20/0.19*	ee
g_{Hbb} (%)	5.1	0.69 / 0.64	0.48/0.48	ee
g_{Hcc} (%)	SM	1.3 / 1.3	0.96/0.96	ee
g_{Hgg} (%)	2.5	1.0 / 0.89	0.52/0.5	ee
$g_{H\tau\tau}$ (%)	1.9	0.74 / 0.66	0.49/0.46	ee
$g_{H\mu\mu}$ (%)	4.4	8.9 / 3.9	0.43/0.43	pp
$g_{H\gamma\gamma}$ (%)	1.8	3.9 / 1.2	0.32/0.32	pp
$g_{HZ\gamma}$ (%)	11.	– / 10.	0.71/0.7	pp
g_{Htt} (%)	3.4	10. / 3.1	1.0/0.95	pp
g_{HHH} (%)	50.	44./33. 27./24.	3-5	pp
Γ_H (%)	SM	1.1	0.91	ee
BR$_{inv}$ (%)	1.9	0.19	0.024	pp
BR$_{EXO}$ (%)	SM (0.0)	1.1	1	ee

* g_{HWW} includes also ep

FCC-ee / FCC-hh complementarity is outstanding

$$\delta g_{HXX}/g_{HXX} < 5\% \quad per\ \Lambda \sim 1TeV$$

Model-independent total Higgs production cross-section σ_H measurement from

$$e^+e^- \to ZH \to (l^+l^-)H$$

Model-independent Higgs mass m_H measurement from system recoiling against the l^+l^- system

Model-independent Higgs to Z coupling g_{HZZ} and Higgs width Γ_H measurement from relation between σ_H, m_H and g_{HZZ} in

$$e^+e^- \to (Z \to l^+l^-)(H \to ZZ)$$

$$\sigma_{HZ} \times \Gamma(H \to ZZ)/\Gamma_H$$

BSM @ FCC-ee

BSM searches @FCC-ee is a very important topic

Indirect measurements

- High precision and high statistics will allow for new physics discovery as deviation from Standard Model expectation
  - particle with too high mass and/or with too feebly couplings can still contribute to loops or modify BR
  - Precise information on the parameters provide guidance to model(s) to interpret deviations

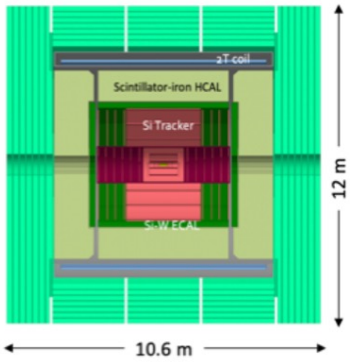
Direct search

- LLP searches with displaced vertices
- Rare/forbidden decays
- ALP
- Massive Neutrinos
- ...

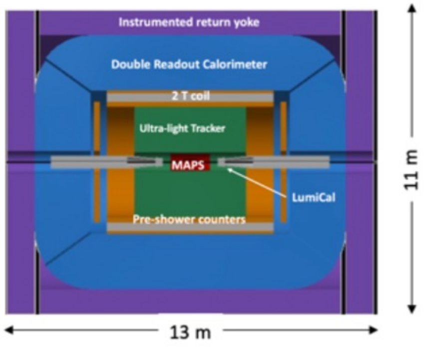
integrated ee + hh project can better cope with BSM search

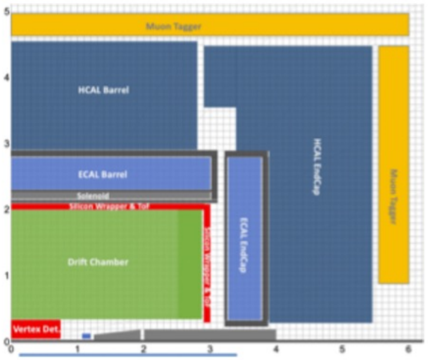
Detector Concepts

CLD	IDEA	Noble Liquid ECAL based



CDR





new

- ILC -> CLIC detector -> CLD
- Full Si vtx + tracker; CALICE-like calo; large coil, muon system

- Si vtx ; ultra light drift chamber with powerful PID; compact, light coil; monolitic parallel fibers, dual readout calo; muon system
- Possibly augmented by crystal ECAL

- High granularity ECAL
  - Pb+Lar (or W+LKr)
- Drift chamber (or Si) tracker; CALICE-like HCAL; muon sys.
- Coil in same cryostat as LAr

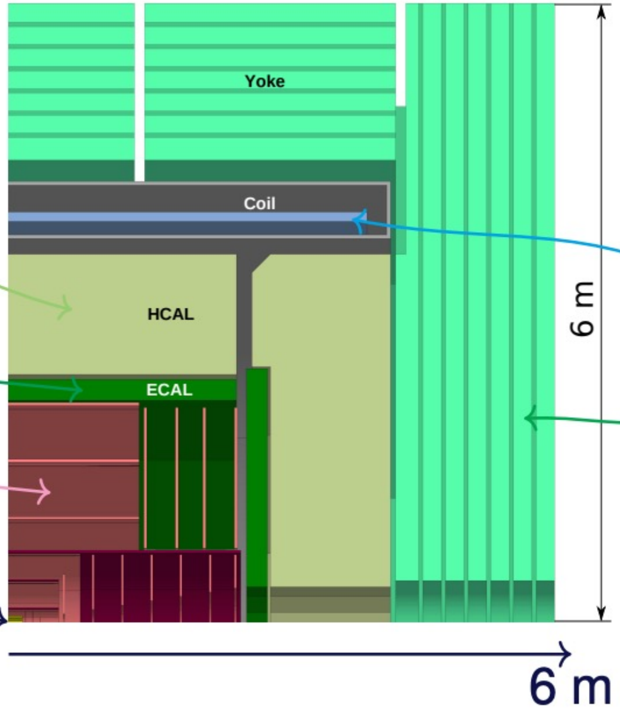
CLD detector concept

General purpose detector for Particle Flow reconstruction [1]

Calice-like Calorimeter

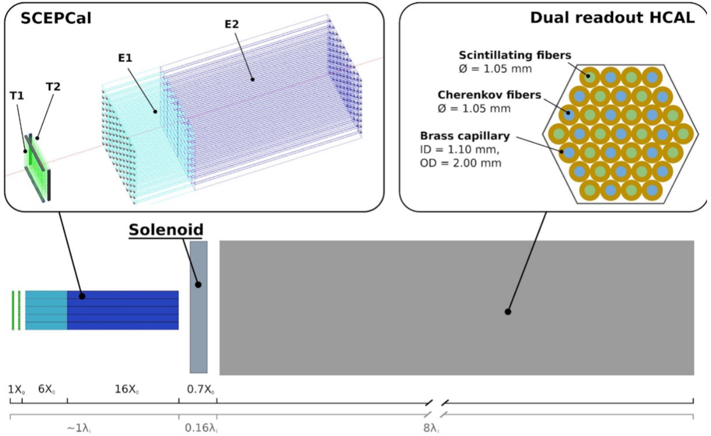
- Steel–Scintillator HCal with 3 cm cell-size
- Silicon–Tungsten ECal with 5 mm cell-size
- Silicon Tracker, mostly 50 μm pitch strips
- Vertex Detector with 25 μm pixels

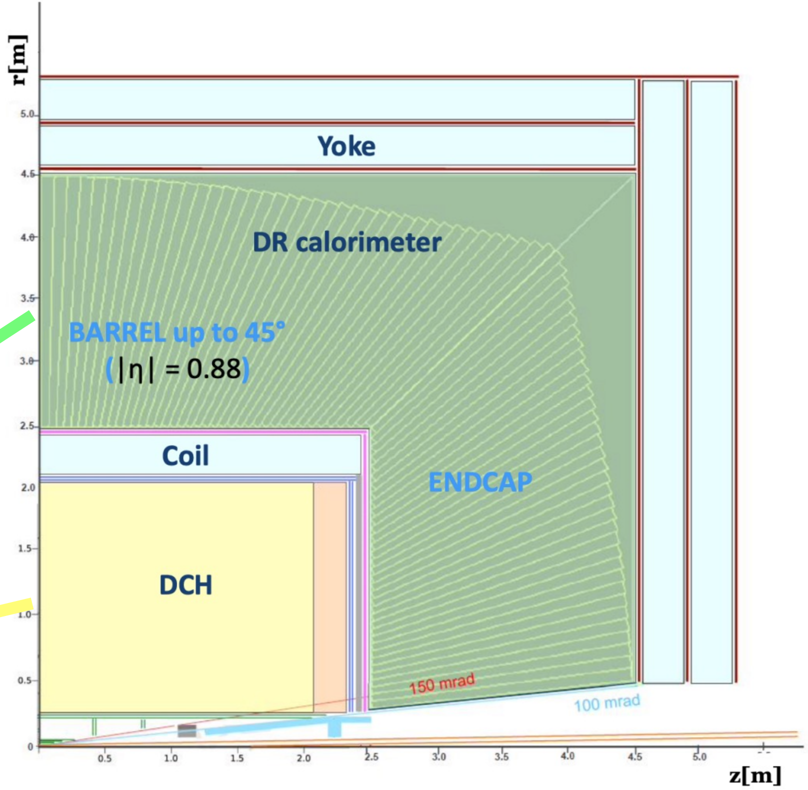
Full Si tracker



- Superconducting Solenoid of 2 T
- Iron Yoke with RPCs for Muon ID

IDEA detector concept

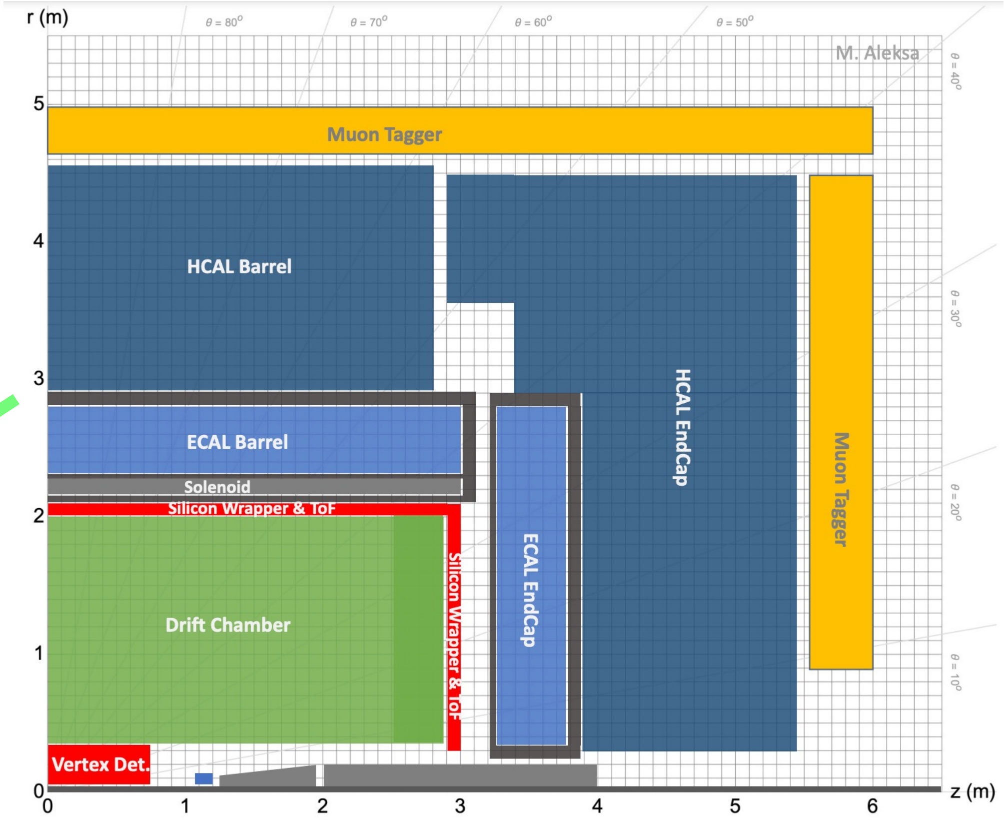




- monolitic parallel fibers, dual readout calorimeter
- EM Dual Readout Crystal section as an option

ultra light drift chamber

Liquid Noble Gas ECAL based detector concept



- Noble Liquid + Pb or W for ECAL
- High Granular HCAL

Detector Performance Requirements

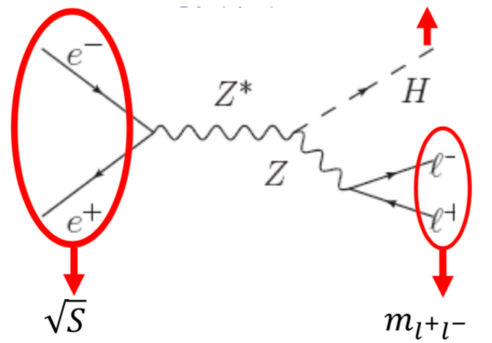
Physics Process	Measured Quantity	Critical Detector	Required Performance
$ZH \to \ell^+\ell^- X$	Higgs mass, cross section	Tracker	$\Delta(1/p_T) \sim 2 \times 10^{-5}$
$H \to \mu^+\mu^-$	$BR(H \to \mu^+\mu^-)$		$\oplus 1 \times 10^{-3}/(p_T \sin\theta)$
$H \to b\bar{b},\ c\bar{c},\ gg$	$BR(H \to b\bar{b},\ c\bar{c},\ gg)$	Vertex	$\sigma_{r\phi} \sim 5 \oplus 10/(p \sin^{3/2}\theta)\ \mu m$
$H \to q\bar{q},\ VV$	$BR(H \to q\bar{q},\ VV)$	ECAL, HCAL	$\sigma_E^{jet}/E \sim 3-4\%$
$H \to \gamma\gamma$	$BR(H \to \gamma\gamma)$	ECAL	$\sigma_E \sim 16\%/\sqrt{E} \oplus 1\%$ (GeV)

$\Delta(1/p_T)$ high precision measurement at the end of tracker

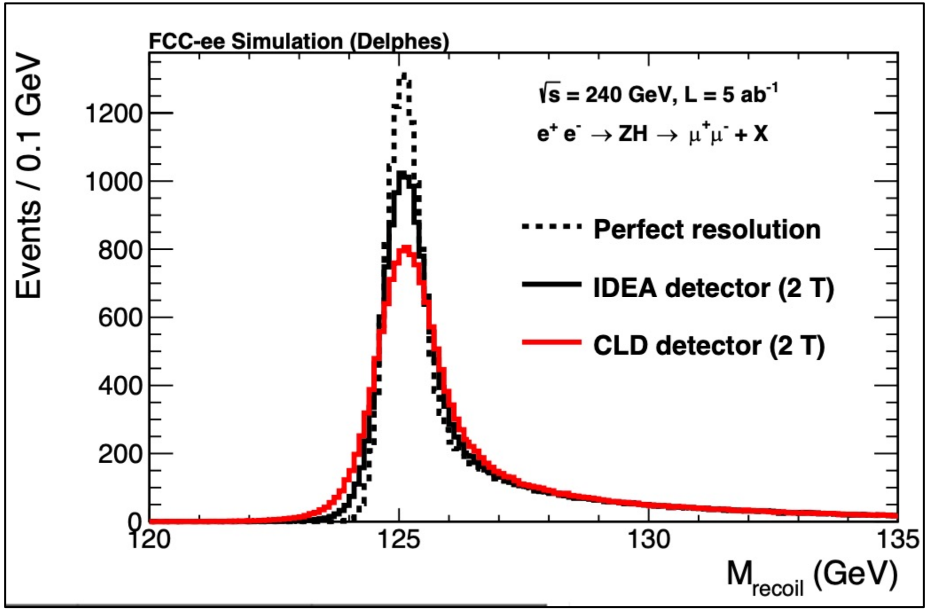
$\sigma_{r\Phi}$ requires finely segmented vertex detector

Challenging requirements for detector materials

Higgs mass from recoil mass in Z(μμ)H events



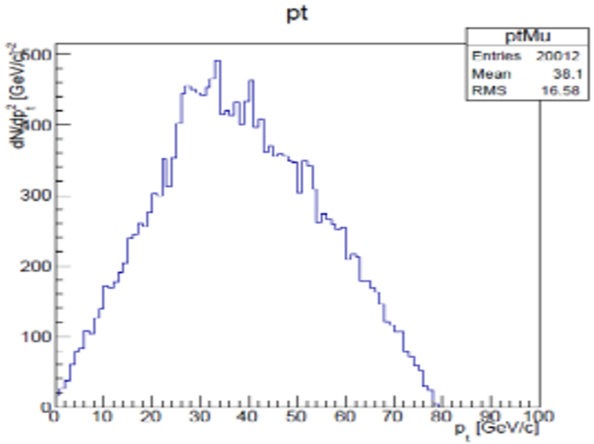
$$m^2_{\text{recoil}} = (\sqrt{s} - E_{l\bar{l}})^2 - p^2_{l\bar{l}} = s - 2E_{l\bar{l}}\sqrt{s} + m^2_{l\bar{l}}$$



Recoil mass affected by :
- The beam energy spread
- The momentum resolution (and the ISRs for the tail)

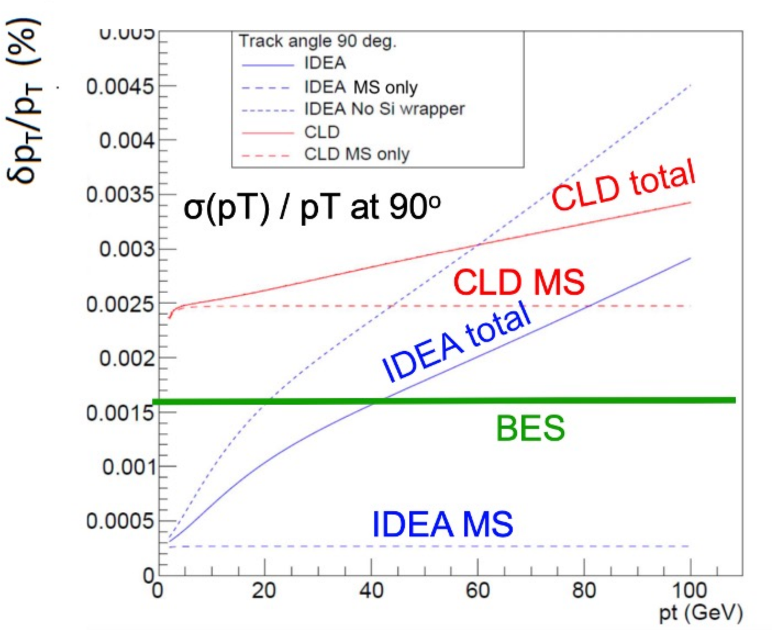
Model-independent Higgs cross-section measurement

Momentum resolution



Ideally: σ(p) / p ≈ rel. BES

BES inherent to the machine.
~ 0.16% at 240 GeV
(~ 0.13% at the Z)



Muons in ZH events have rather small p_T
Transparency more relevant than asymptotic resolution

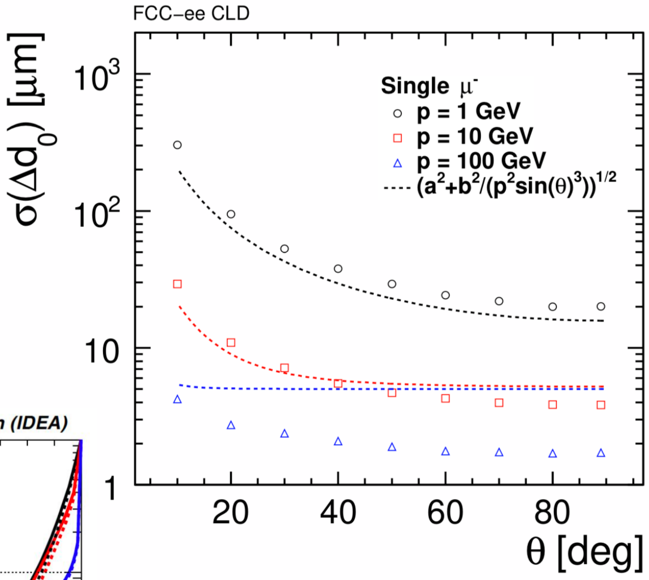
Vertex Detection Parameters

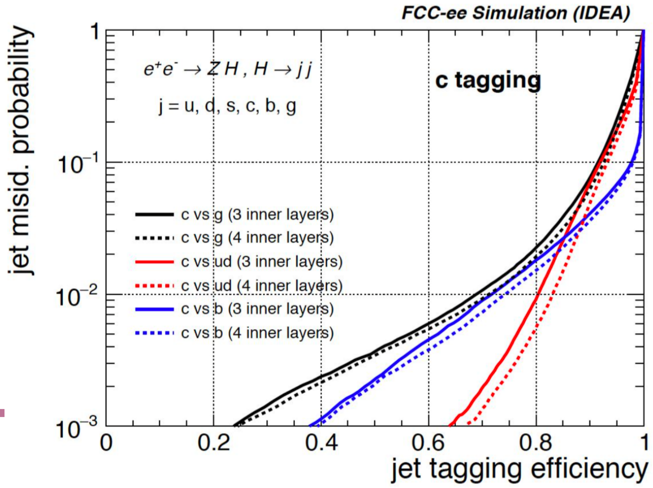
Secondary vertices identification, **key to b-, c- and τ- tagging**

- Measurement of **Higgs couplings to b, c, g**
- Measurement of **V_{cb} from WW** events
- Measurement of **EW HF observables** Rb, Rc, A_{FB} c)

Precise (PV)/SV/TV reco for Flavour physics

- Time-dependent CPV measurements
- Unobserved/rare decays: $B \rightarrow K^*\tau\tau$
- Lifetime measurements
  - Measurement of the t-lifetime





$$\sigma_{d_0} = a \oplus \frac{b}{p \sin^{3/2}\theta}$$

$$a \simeq 5\,\mu\mathrm{m}; \quad b \simeq 15\,\mu\mathrm{m\,GeV}$$

Detector Performance Requirements

Physics Process	Measured Quantity	Critical Detector	Required Performance
$ZH \to \ell^+\ell^- X$	Higgs mass, cross section	Tracker	$\Delta(1/p_T) \sim 2 \times 10^{-5}$
$H \to \mu^+\mu^-$	$\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\oplus 1 \times 10^{-3}/(p_T \sin\theta)$
$H \to b\bar{b},\ c\bar{c},\ gg$	$\mathrm{BR}(H \to b\bar{b},\ c\bar{c},\ gg)$	Vertex	$\sigma_{r\phi} \sim 5 \oplus 10/(p \sin^{3/2}\theta)\ \mu\mathrm{m}$
$H \to q\bar{q},\ VV$	$\mathrm{BR}(H \to q\bar{q},\ VV)$	ECAL, HCAL	$\sigma_E^{\mathrm{jet}}/E \sim 3-4\%$
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\sigma_E \sim 16\%/\sqrt{E} \oplus 1\%$ (GeV)

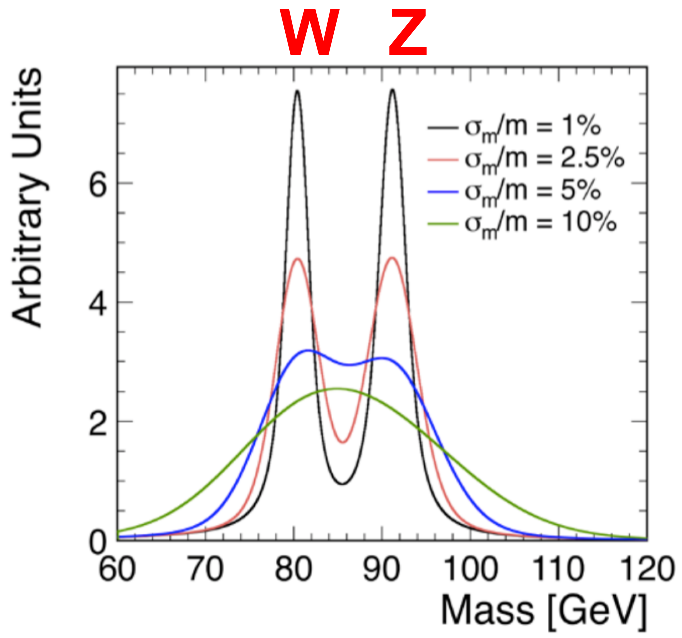
Fair $\sigma_{EM} \sim$ 10-20% /$\sqrt{E}$ sufficient for Higgs physics
$\sigma_{jets} \sim$ 30-40% /$\sqrt{E}$ to clearly identify W, Z, H in 2 jets decays
Transverse granularity < 1 cm for π_0 from τ and HF

Calorimeter performance

Jet energy: $\delta E_{jet}/E_{jet} \simeq 30\% / \sqrt{E}$ [GeV]

Jet final state will be dominant at FCC-ee
- higher BR
- clean environment

Disantangling W and Z peak
e.g. Separation of νvH from WW fusion and HZ



At $\delta E/E \simeq 30\% / \sqrt{E}$ [GeV], detector resolution comparable to Γ_W and Γ_Z

ECAL performance

e+e- →HZ physics constraints

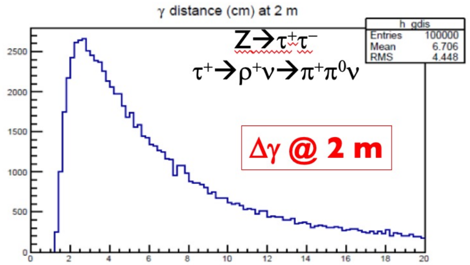
H→ $\gamma\gamma$ ➔ ECAL resolution

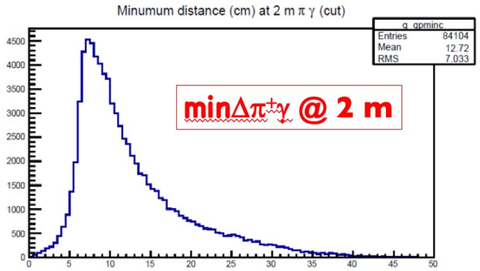
As good as possible – at least $20\%/\sqrt{E}$ + 1%

for HF physics 3%/√E is required

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

technology	a	b	c
CALICE	15%	-	1%
Fiber DR	10%	-	1%
Lar	9%	-	-
Crystal	3-5%	-	0.5%





- π^0 important in tau and HF physics
  - No π^0: 35% τ → l (e, μ) νν + 20% τ→(1,3)$\pi^{\pm}$ lν
  - 1 π^0: 28% τ→(1,3) $\pi^{\pm}\pi^0$lν
  - 2 –3π^0: 10% τ→$\pi^{\pm}$ (2,3) π^0lν
- High granularity/Pre-shower → π^0 identification
- Overlap with π^+ may require longitudinal segmentation

Outlook

FCC-ee will allow for a very reach physics programs

It's both a precise machine and an "intensity frontier" machine

Complementarity with FCC-hh is one of the key elements

A lot of activity ongoing in all aspects of the project (accelerator, detector, physic studies, theoretical calculation, ...) we need all of them