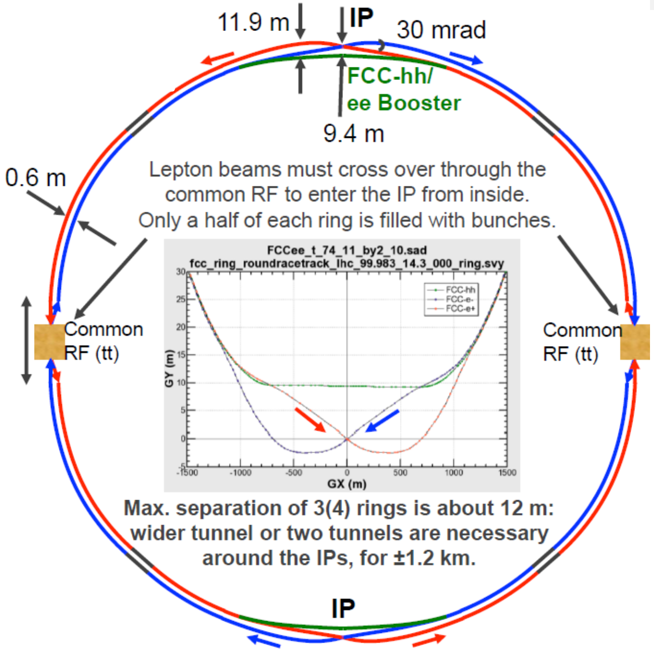
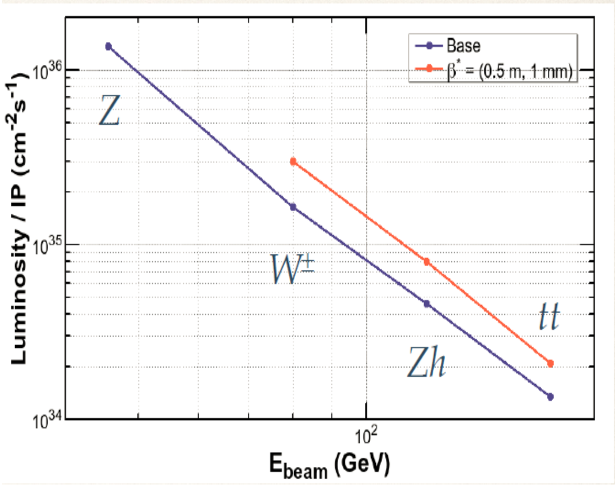
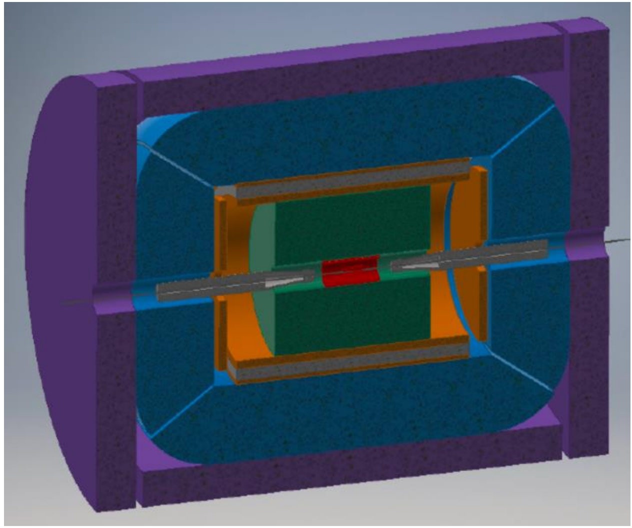
FCC-ee Physics and Experiments

-- News at this FCC week
-- Status
-- Towards the CDR
-- Run plan







20 talks and 400 minutes.

Patrick Janot	**FCC-ee (History, motivation, overview of present status of design study and issues, run plan)**
Paolo Azzurri	**Electroweak physics at the Z and W – experimental capabilities**
Fulvio Piccinini	**Status and prospects for precision electroweak calculations**
Alain Blondel	**Beam polarization (longitudinal vs transverse) and energy calibration**
Markus Klute	**Higgs physics at FCC-ee**
Patrizia Azzi	**Top physics at FCC-ee**
Stephane Monteil	**Flavour physics (c, b, LFV)**
David d'Enterria	**QCD and gamma-gamma**
Maurizio Pierini	**Search for New Physics at the FCC-ee**
Mogens Dam	**FCC-ee detector requirements and specific designs**
Emilia Leogrande	**Detector design II (CLIC adaption)**
Georgios Voutsinas	**Experimental environment and luminosity measurement (experimental side of MDI)**
Jonathan R. Ellis	**Complementarity between FCC-ee and FCC-hh for BSM Searches**
Christophe Grojean	**Higgs physics synergies**
David d'Enterria	**QCD synergies**
Oliver Fischer	**An example of synergy in BSM physics: right-handed neutrinos**
Jiayin Gu EFT	**global fit of Higgs couplings at ee colliders**
Dario Mueller	**Implications of a leptoquark explanation of the anomalous magnetic moment of the muon for the FCC-ee**
Janusz Gluza	**Present status on numerical calculation of complete 2-loop EWPOs and 3-loop prospects**
Sven Heinemeyer	**Precision Observables at FCC-ee: Status and Future**

2013 European Strategy: There is a strong scientific case for an electron positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded

An e+e- in the energy range **Z - WW - H - $t\bar{t}$** is a **must do**

The FCC-ee offers the best luminosity and center-of-mass definition
in addition it is obviously a possible first step towards a 100 TeV pp collider.

The idea was (re)born in 2011 as Higgs Factory; the 2102 ICFA beam dynamics workshop recommended that a conceptual design report would be necessary.

This is what we are doing: The FCC design study was launched in Feb. 2014

FCC-ee: discovery machine, not «just» measurements!

Today we do not know how nature will surprise us. A few things that FCC-ee could discover :

EXPLORE 10 TeV energy scale (and beyond) with Precision Measurements

-- ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass)

$m_{Z,}$ m_W, m_{top} , $\sin^2 \theta_w^{eff}$, R_b , α_{QED} (m_z) α_s (m_z; m_W; m_τ), Higgs and top quark properties

DISCOVER a violation of flavour conservation or universality

-- ex FCNC (Z --> $\mu\tau$, $e\tau$) in 5 10^{12} Z decays.

+ flavour physics (10^{12} bb events)

DISCOVER dark matter as «invisible decay» of H or Z

DISCOVER very weekly coupled particle in 5-100 GeV energy scale

such as: Right-Handed neutrinos, Dark Photons etc…

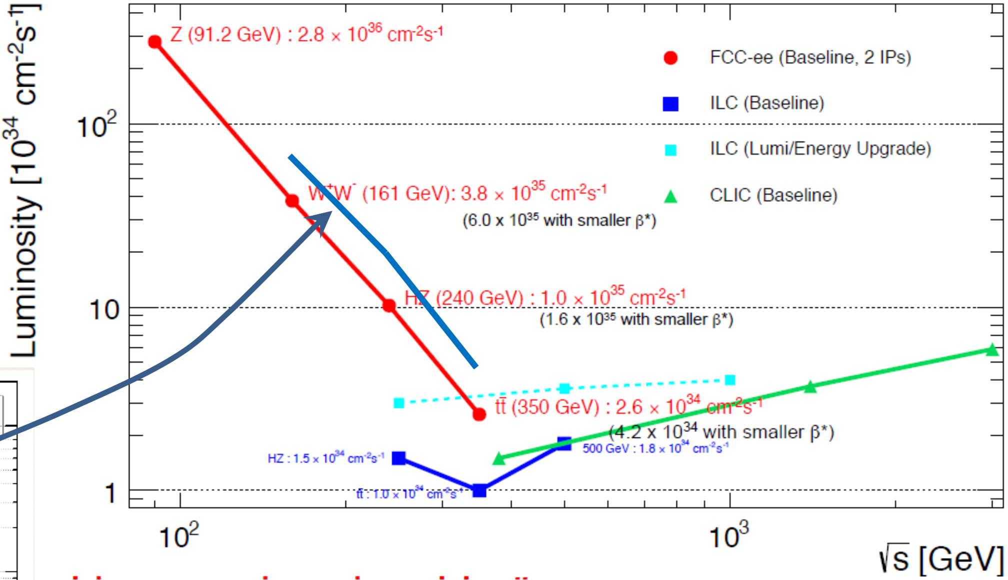
«Study the properties of the Higgs boson and other particles with unprecedented precision»

-- High (integrated) luminosity at the requested E_{cm} *)
-- Clean environment
-- Precise knowledge of the center-of-mass energy and of the luminosity
-- Precise detectors offering plenty of redundency (and more than one)

√s (GeV)	Z	WW	HZ	top
Lumi (ab^{-1}/year)	15, then 30	4	1	0.3
Events/year	1.5×10^{12}	1.5×10^{7}	2.0×10^{5}	2.0×10^{5}
Physics goal	150 ab^{-1}	10 ab^{-1}	5 ab^{-1}	1.5 ab^{-1}

*) note that maximum E_{cm} requested is ~20 GeV above the top pair threshold, 365-370 GeV

- Run at $\sqrt{s}$ ~ 91.2 GeV (Z), ~161 GeV (W), ~240 GeV (Higgs), ~350 GeV (top and Higgs)



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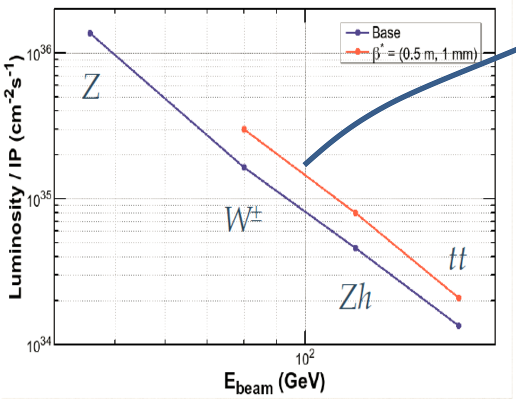
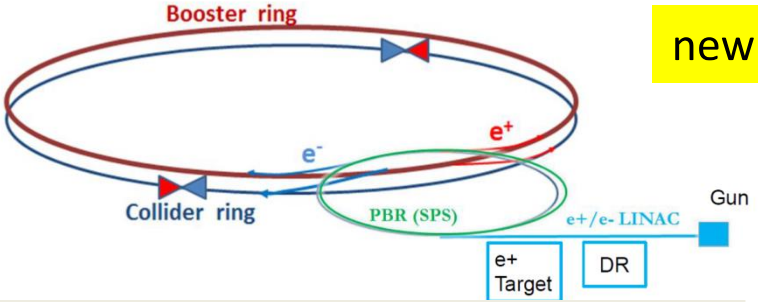




new

Welcome the possible increase by factor 1.6 wrt the baseline! → impact on necessary running time. And… we can take more…

top-up injection for high duty factor assume 0.6

- Run plan with 2 IP and the baseline optics (and the β^*=1mm optics)

√s (GeV)	Z	WW	HZ	top	
Lumi (ab^{-1}/year)	15, then 30	4 (6)	1 (1.6)	0.3 (0.45)	
Events/year	1.5×10^{12}	1.5×10^{7}	2.0×10^{5}	2.0×10^{5}	
Physics goal	150 ab^{-1}	10 ab^{-1}	5 ab^{-1}	1.5 ab^{-1}	
Runtime (years)	6	2 (1-2)	5 (3)	5 (3)	18 (13.5)

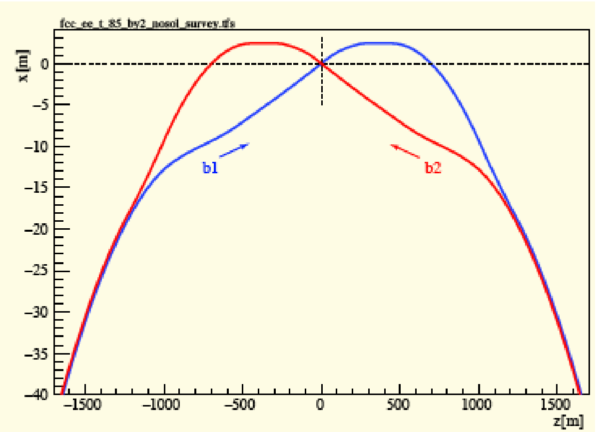
- Numbers of years are soft numbers that can be revised and negotiated (β^*, # IPs)

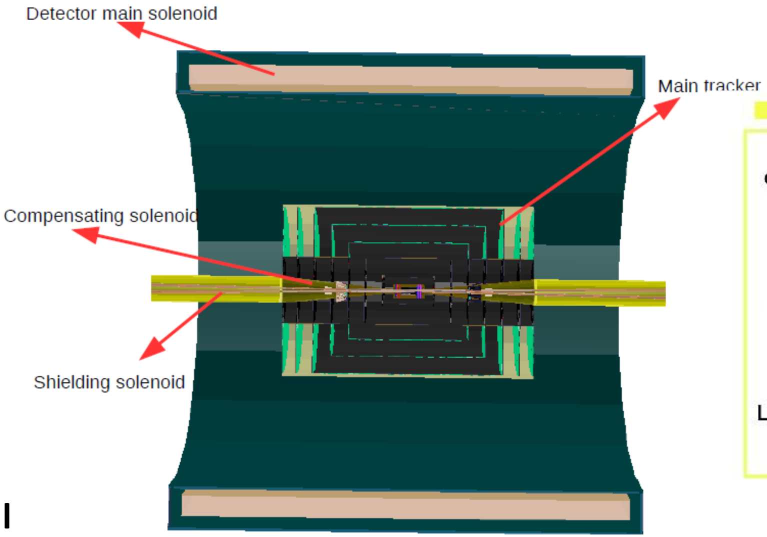
numbers in blue were shown (almost) by M.Benedikt, F. Zimmermann

there exist two detector concepts for linear colliders
ILD based on TPC tracker and SiD(CLIC-SiD) based on all-silicon tracker
+ new IDEA for FCC-ee (and CEPC) based on drift chamber

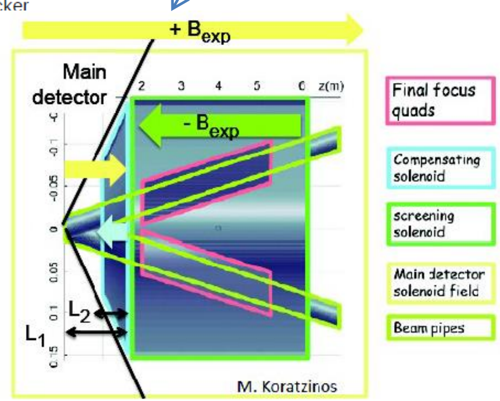
MDI: Clean experimental conditions

Beams pass at angle inside exp. solenoid





100 mrad

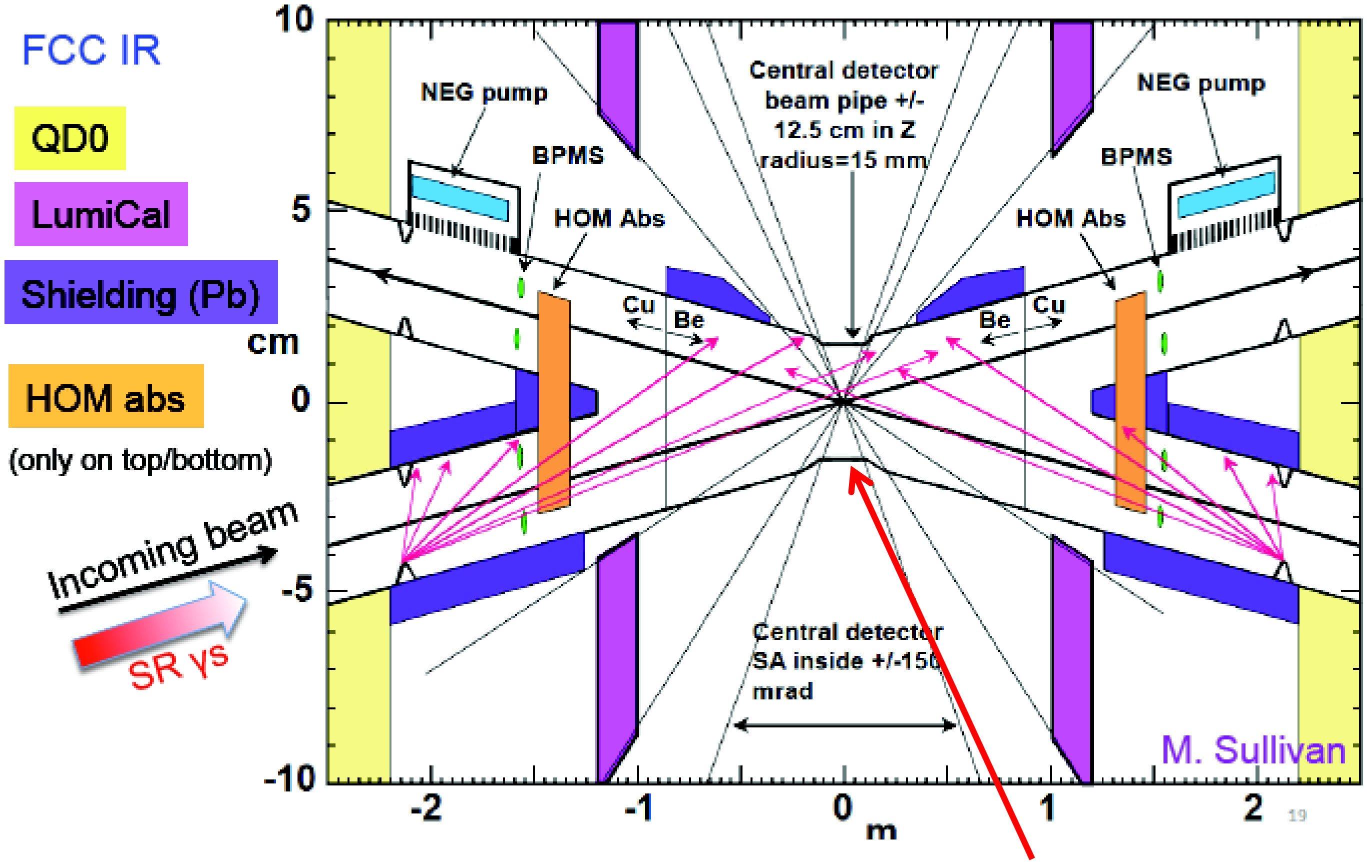


Asymmetric geometry works very well to limit synchrotron radiation to LEP levels (Voutsinas)

Pile-up is less than 10^{-3}

delicate insertion magnet system
challenging magnets... (keep all below 100 mrad)

FCC IR

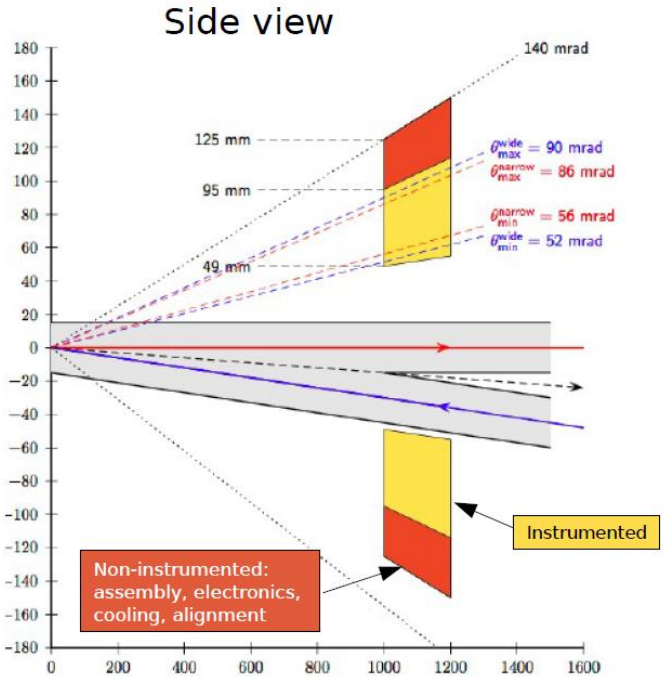


detailed layout of the IR

Beam pipe radius at IP is 15mm ☺

LumiCal geometry

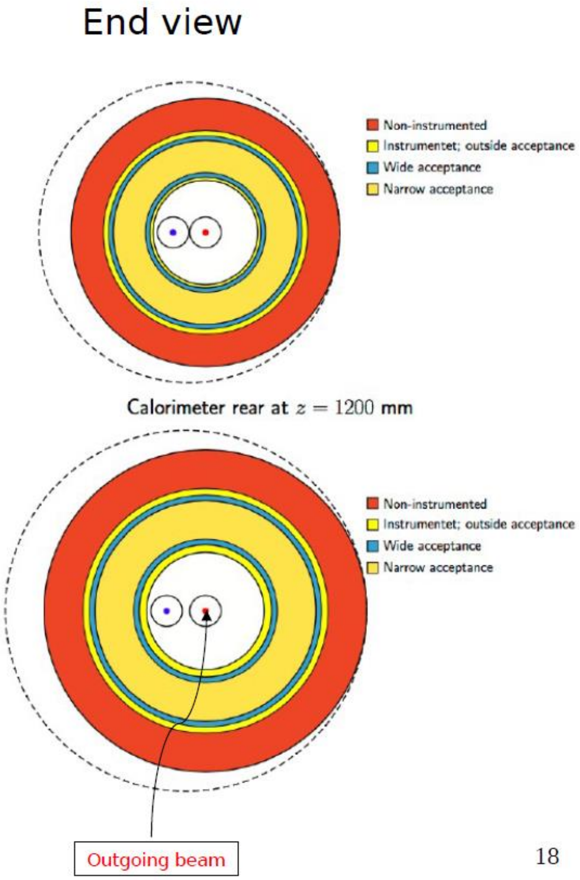
Luminosity measurement challenging: L* is small.



Cross section: σ = 23 nb

Geometric precision needed for absolute normalization to 10^{-4}

- δz = 50 μm
- δr_{min} = 1.6 μm
- δr_{max} = 5.8 μm



A

Beam Polarization and Energy calibration

We have concluded that first priority is to achieve transverse polarization
in a way that allows continuous beam calibration by resonant depolarization
(energy measurement every ~10 minutes on 'monitoring' single bunches)

- **This is a unique feature of circular e+e- colliders**
- baseline running scheme defined with monitoring bunches, wigglers, polarimeter
- the question of the residual systematic error requires further studies of the relationship between spin tune, beam energy at IRs, and center-of-mass energy

➔ **target is O(±100keV) at Z and W pair threshold energies (averaged over data taking)**

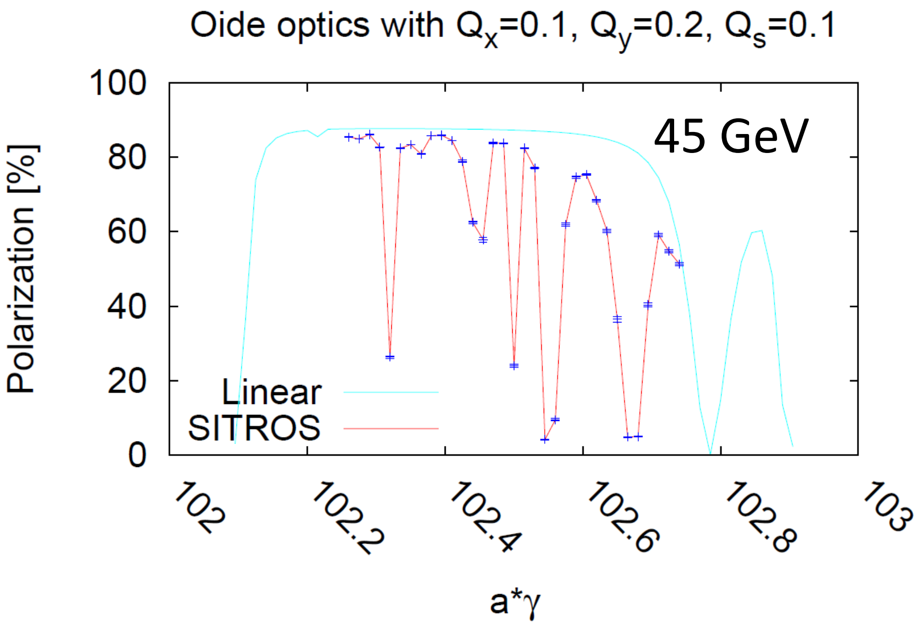
'Do we want longitudinal polarization'?

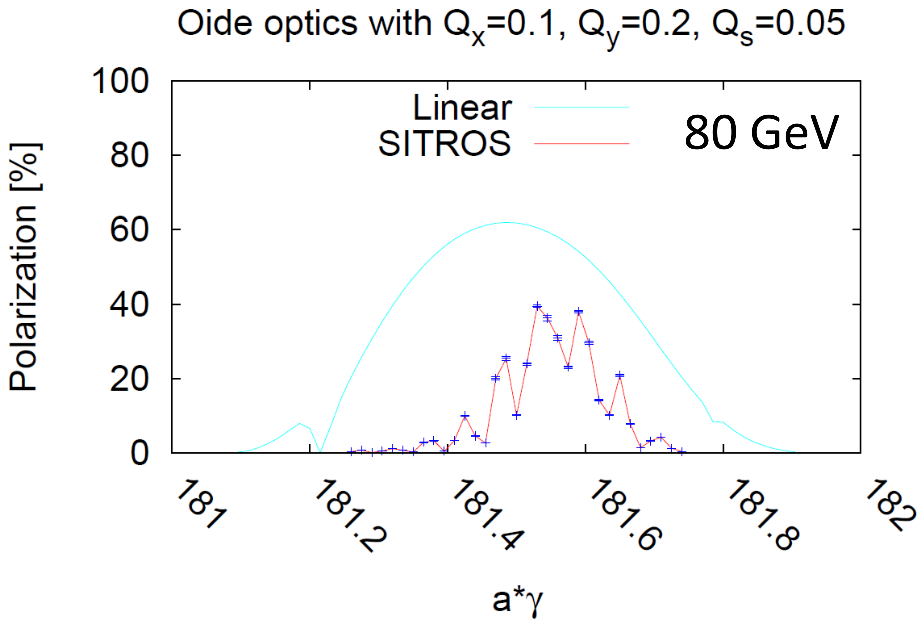
➔ **lower priority**

at Z, W, top: no information that we cannot obtain otherwise
from unpolarized A_{FB} asymmetries or final state polarization (top, tau)

+ too much loss of luminosity in present running scheme to provide gain in precision.

Beam Polarization and Energy calibration





At the Z obtain excellent polarization level
but too slow for polarization in physics
need wigglers for Energy calibration

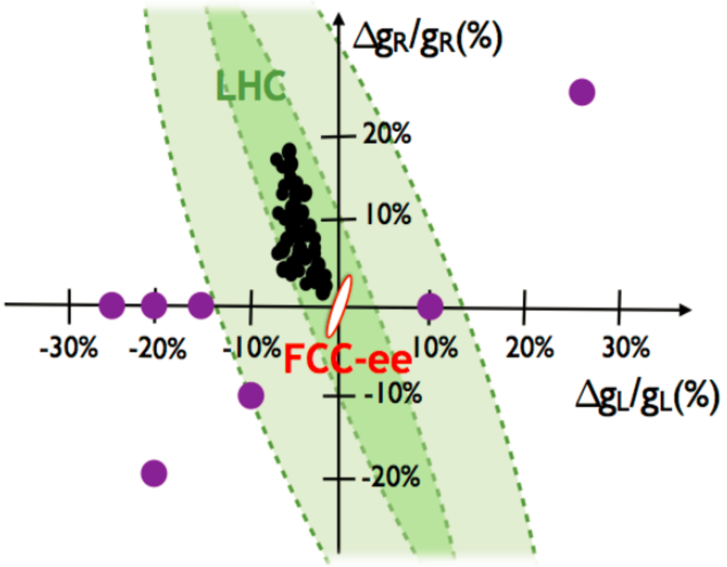
At the W expecation similar to LEP at Z
→ enough for energy calibration

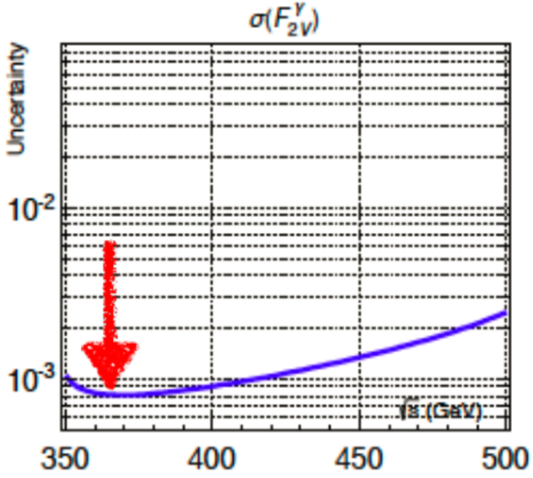
Simulations by Eliana Gianfelice

observable	Physics	Present precision		FCC-ee stat Syst Precision	FCC-ee key	Challenge
M_Z MeV/c2	Input	91187.5 ±2.1	Z Line shape scan	0.005 MeV <±0.1 MeV	E_cal	QED corrections
Γ_Z MeV/c2	$\Delta\rho$ (T) (no $\Delta\alpha$!)	2495.2 ±2.3	Z Line shape scan	0.008 MeV <±0.1 MeV	E_cal	QED corrections
$R_l = \frac{\Gamma_h}{\Gamma_l}$	α_s, δ_b	20.767 (25)	Z Peak	0.0001 (2-20)	Statistics	QED corrections
N_ν	Unitarity of PMNS, sterile ν's	2.984 ±0.008	Z Peak Z+γ(161 GeV)	0.00008 (40) 0.001	->lumi meast Statistics	QED corrections to Bhabha scat.
R_b	δ_b	0.21629 (66)	Z Peak	0.000003 (20-60)	Statistics, small IP	Hem. correlations
A_{LR}	$\Delta\rho$, ε_3, $\Delta\alpha$ (T, S)	$\sin^2\theta_w^{eff}$ 0.23098(26)	Z peak, Long. polarized	$\sin^2\theta_w^{eff}$ ±0.000006	4 bunch scheme	Design experiment
A_{FB}^{lept}	$\Delta\rho$, ε_3, $\Delta\alpha$ (T, S)	$\sin^2\theta_w^{eff}$ 0.23099(53)		$\sin^2\theta_w^{eff}$ ±0.000006	E_cal & Statistics	
M_W MeV/c2	$\Delta\rho$, ε_3, ε_2, $\Delta\alpha$ (T, S, U)	80385 ± 15	Threshold (161 GeV)	0.3 MeV <0.5 MeV	E_cal & Statistics	QED corections
m_{top} MeV/c2	Input	173200 ± 900	Threshold scan	~10 MeV	E_cal & Statistics	Theory limit at 50 MeV?

ELECTROWEAK COUPLINGS OF THE TOP QUARK(2)

- Large statistics and final state polarization allow a full separation of the ttZ/γ couplings with **NO need for polarization in the initial state.**
- **Optimal $\sqrt{s}$= 365-370 GeV**





- Fit includes conservative assumptions detector performance
- Theory uncertainty on production mechanism dominates

FCC-ee expected precision of order 10^{-2} to 10^{-3}

FCC-ee Detectors

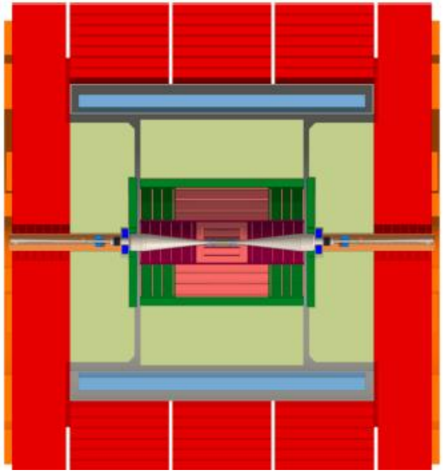
News on this front:

Emilia Leogrande

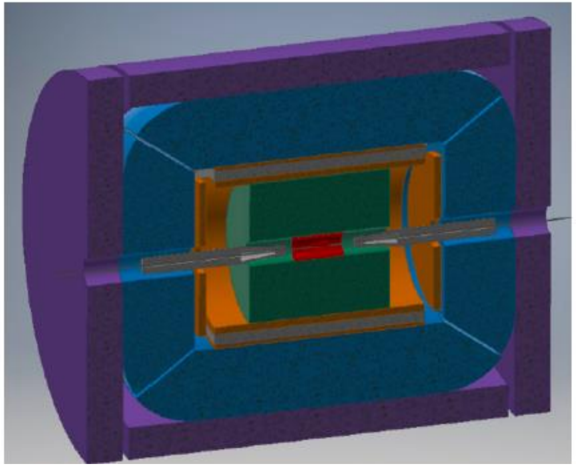
-- EP-LCD group at CERN has undertaken the adaption of CLIC-SID detector for FCC-ee

-- new IDEA, detector specifically designed for FCC-ee (and CEPC)

"CLIC-detector revisited"



"IDEA"



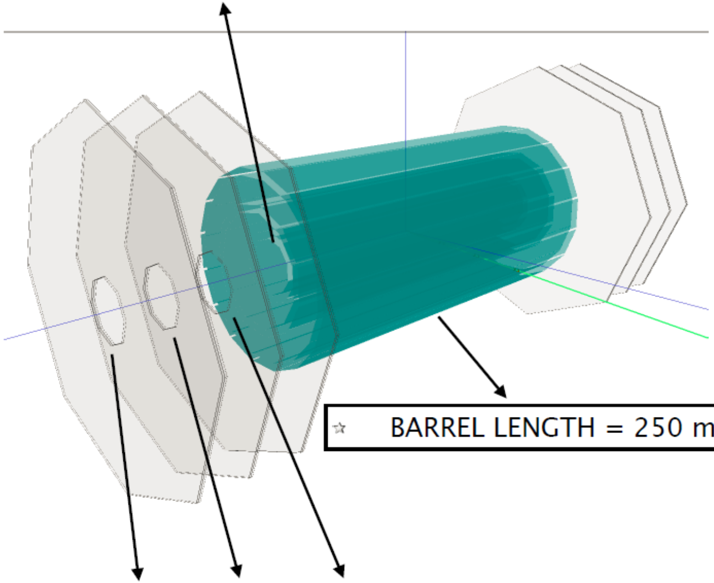
- Vertex detector: ALICE **MAPS**
- Tracking: MEG2
- Si Preshower
- Ultra-thin solenoid (2T)
- Calorimeter: DREAM
- Equipped return yoke

Detector layout/ Vertex

CLIC to FCC
changeover
mostly straightforward.
Main changes
-- smaller beam pipe
-- smaller Bfield
→ larger radius
-- CW operation,
need to increase cooling
→ thicker detectors

Work in progress
performance to come soon

☆ INNER LAYER closer to the beam pipe
☆ depends on beam-induced background



☆ BARREL LENGTH = 250 mm

☆ DISKS INNER RADIUS closer to the beam pipe

Scale all the barrel layers*

double layer radius [mm]	CLIC	FCC
1st	31–33	17–19
2nd	44–46	37–39
3rd	58–60	57–59

*layer thickness may need to be increased to accommodate water cooling

Disks to replace spirals
(no need for air flow)

	double disk z [mm]
1st	159–161
2nd	229–231
3rd	299–301

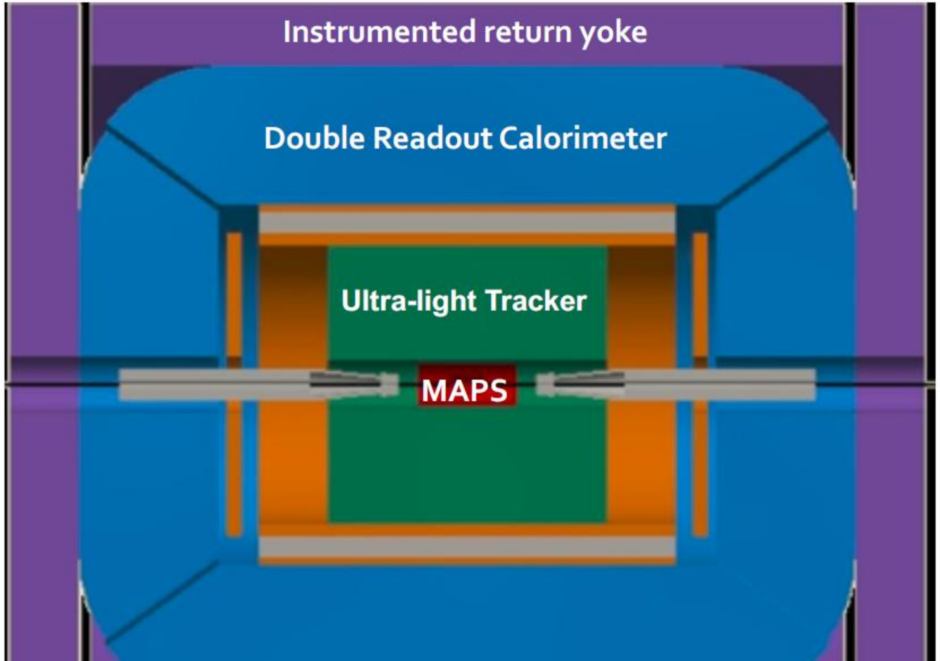
FCC-ee Detectors: IDEA

FCC-ee Detector Requirements

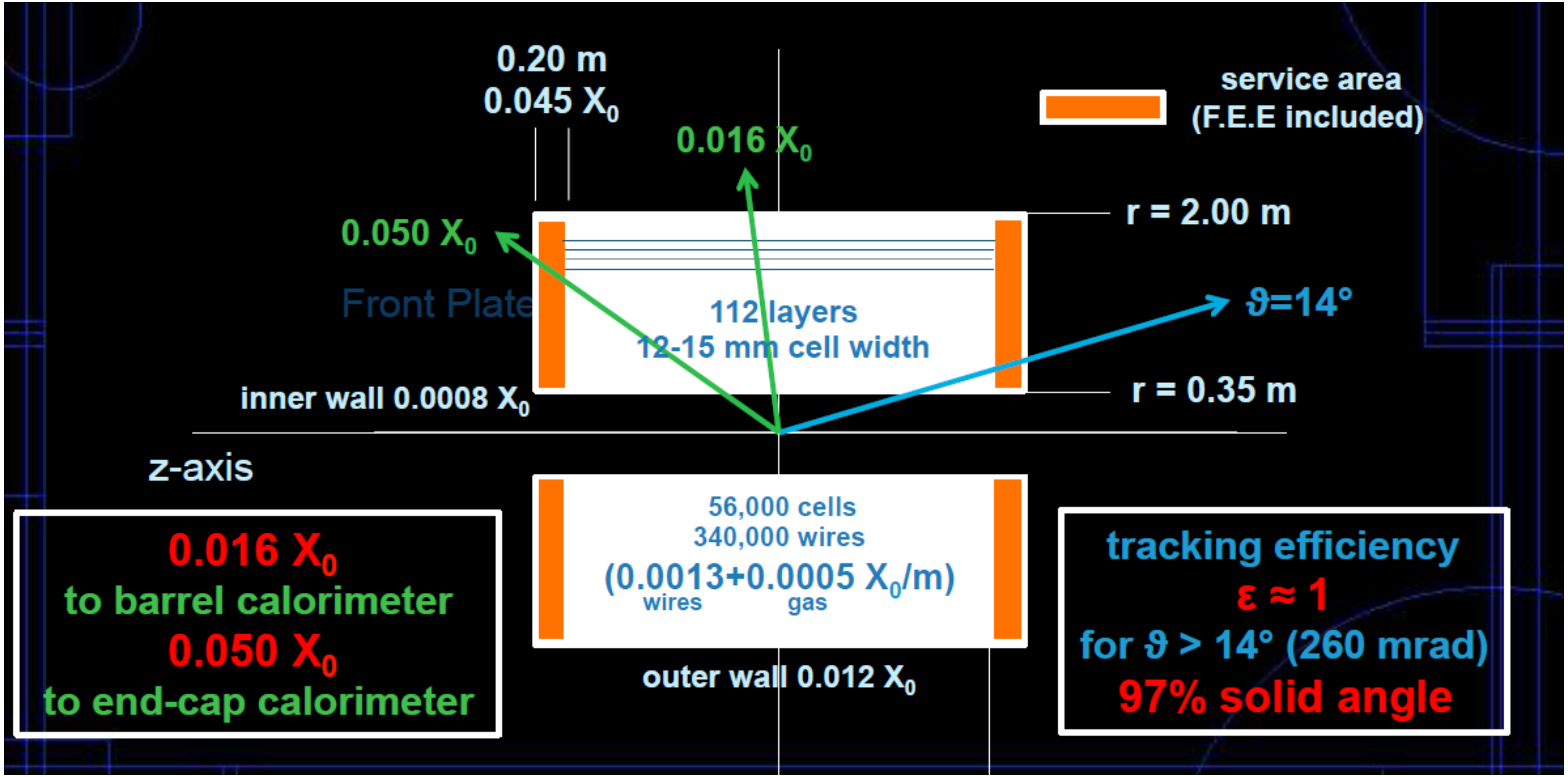
Momentum resolution	Jet Energy	Impact parameter resolution
$\sigma_{1/p} = 3 \times 10^{-5}\,\mathrm{GeV}^{-1}$	$\delta E/E \simeq 30\% / \sqrt{E}\ (\mathrm{GeV})$	$\sigma_{d_0} = a \oplus \frac{b}{p \sin^{3/2}\theta}$; $a \simeq 5\,\mu\mathrm{m}$; $b \simeq 15\,\mu\mathrm{m\,GeV}$

- Vertex detector, MAPS
- Ultra-light drift chamber with PID
- Pre-shower counter
- Double read-out calorimetry
- 2 T solenoidal magnetic field
- Possibly instrumented return yoke

- Or possibly surrounded by large tracking volume (R ≃ 8m) for very weakly coupled (long-lived) particles

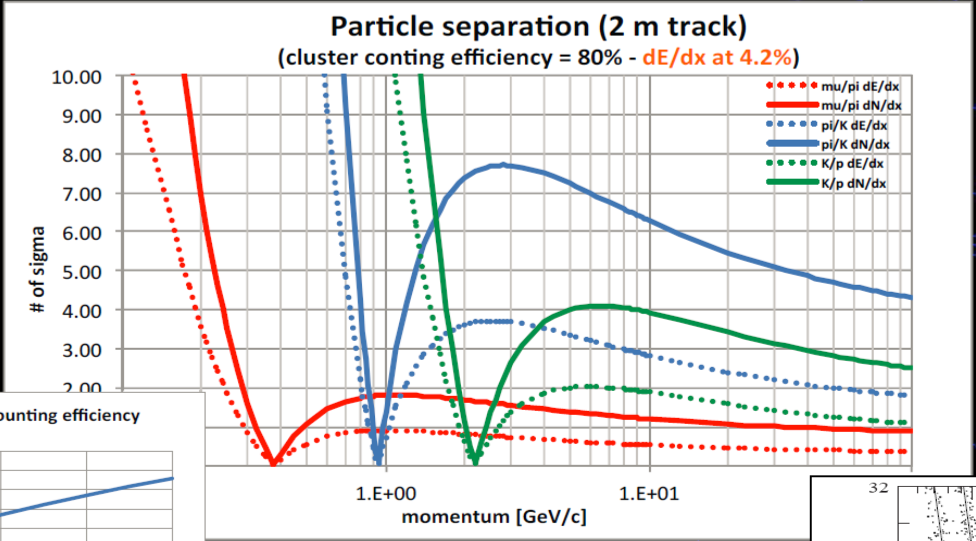


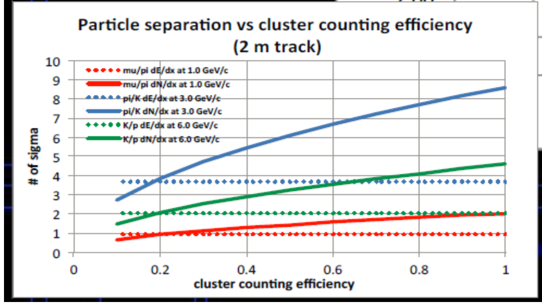
IDEA -- Choice of tracker : He-C4H10 drift chamber 12mm drift cells

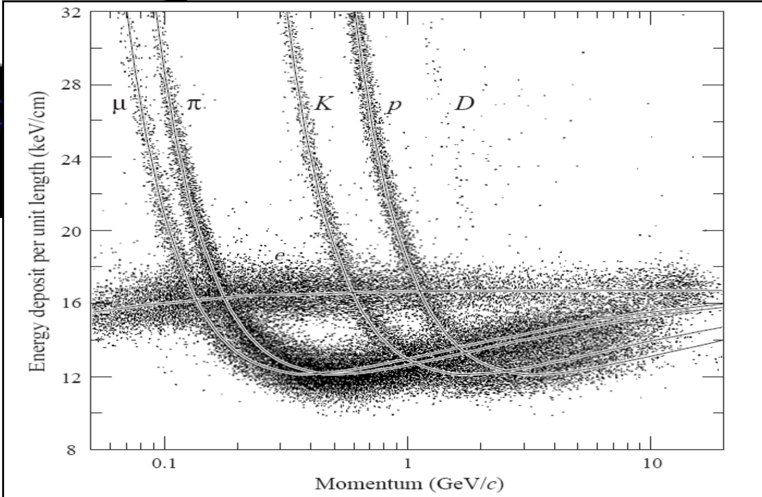


fast and precise, low material dE/dx. need to check tracking efficiencies, simulations on going

Drift Chamber Particle Id.







FCC-ee discovery potential

Today we do not know how nature will surprise us. A few things that FCC-ee could discover :

EXPLORE 10 TeV energy scale (and beyond) with Precision Measurements

-- ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass)

$m_{Z,}$ m_W, m_{top} , $\sin^2\theta_w^{eff}$, R_b , α_{QED} (m_z) α_s $(m_z\, m_W\, m_\tau)$, Higgs and top quark couplings

DISCOVER a violation of flavour conservation or universality

-- ex FCNC (Z --> $\mu\tau$, $e\tau$) in 5 10^{12} Z decays.

+ flavour physics (10^{12} bb events)

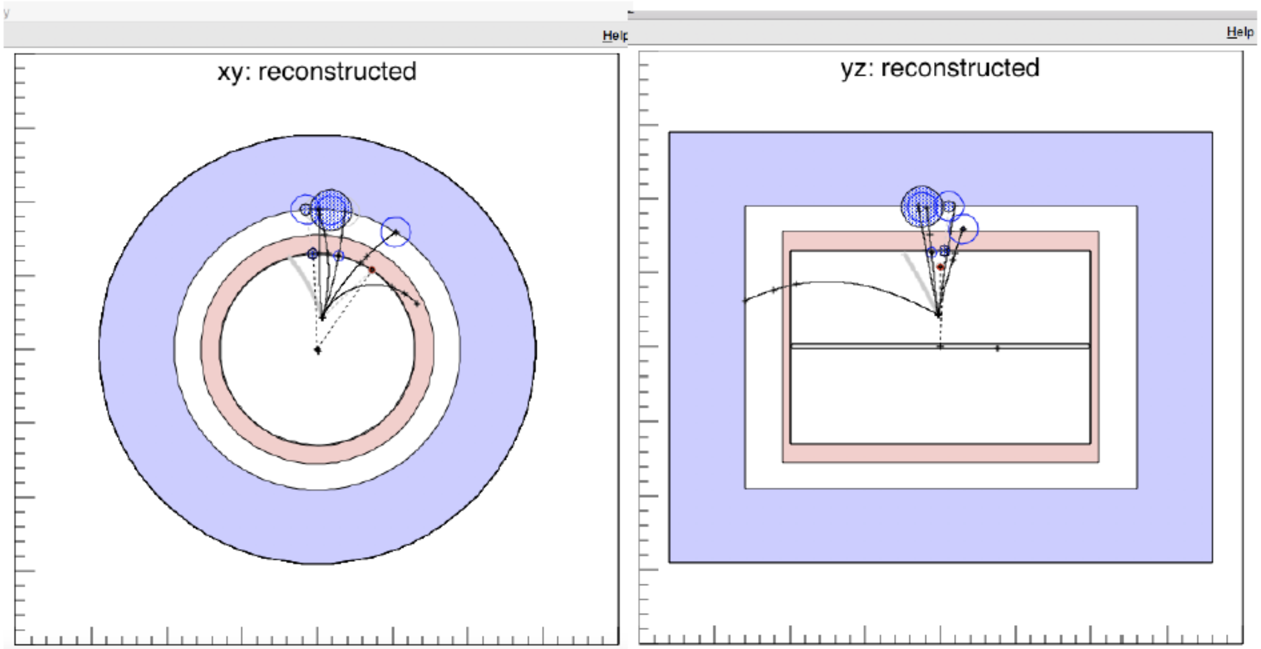
DISCOVER dark matter as «invisible decay» of H or Z

DISCOVER very weekly coupled particle in 5-100 GeV energy scale

such as: Right-Handed neutrinos, Dark Photons etc…

Simulation of heavy neutrino decay in a FCC-ee detector

See presentation by O. Fischer.

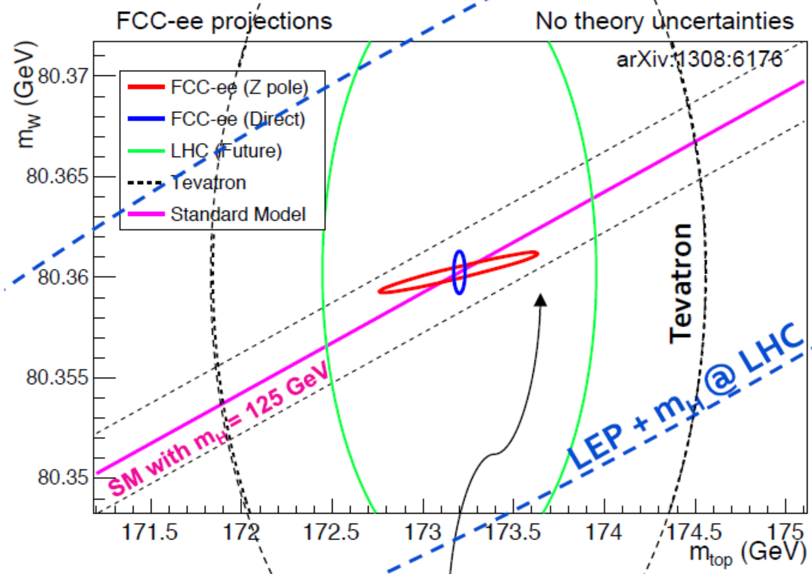


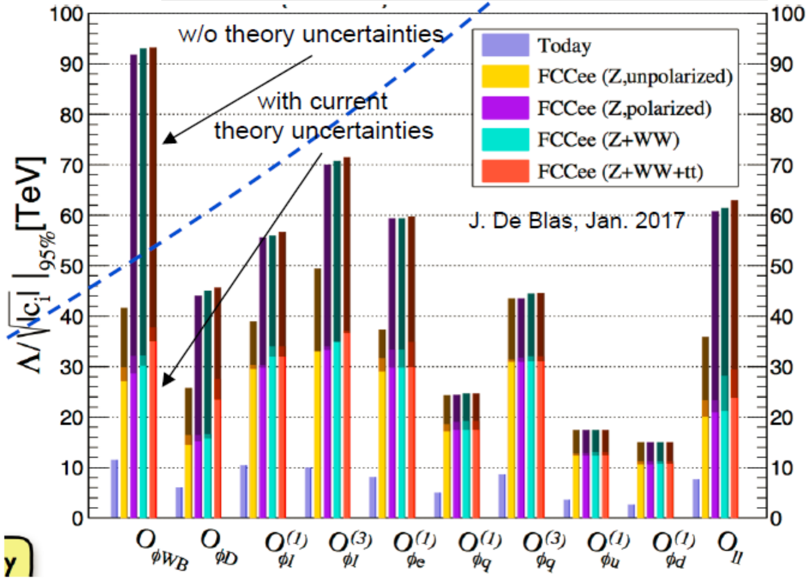
what is the background to this? No trigger needed – we will not lose it!

Global Fit and sensitivity to new physics

- **Combining all EW measurements**
  - In the context of the SM … and beyond

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$





Without m_Z (α_{QED})@FCC-ee, the SM line would have a 2.6 (1.8) MeV width

FCC-ee sensitivity severely drops without POLARIZATION + STATISTICS (and improved theory calculations)

Today: Λ > 5-10 TeV

After FCC-ee: Λ > 50-100 TeV ?

Synergetic with FCC-hh

Theoretical limitations

FCC-ee

SM predictions (using other input)

$M_W = 80.3593 \pm 0.0002 \pm 0.0001 \pm 0.0003$

$0.0005 \pm 0.0001 \pm 0.0000\ M_H \pm 0.0040_{\text{theo}}$

$\sin^2\theta^{\ell}_{\text{eff}} = 0.231496 \pm 0.0000015 \pm 0.000001 \pm 0.000006$

$0.000006 \pm 0.0000014 \pm 0.000000 \pm 0.000047_{\text{theo}}$

Experimental errors at FCC-ee will be 20-100 times smaller than the present errors.

BUT can be typically 10 -30 times smaller than present level of theory errors

Will require significant theoretical effort and additional measurements!

the above explains why we want the top running – and high Z statistics.

Freitas, Heinemeyer, Jadach, Gluza … need for 3 loop calculations for the future!

Suggest including manpower for theoretical calculations in the project cost.

Theoretical uncertainties for electroweak and Higgs-boson precision measurements at the FCC-ee

Conveners: A. Freitas[1], S. Heinemeyer[2],
Contributors: M. Beneke[3], A. Blondel[4], A. Hoang[5], P. Janot[6], J. Reuter[7], C. Schwinn[8], and S. Weinzierl[9]

Intrinsic uncertainties: ⇒ always a limiting factor!

Quantity	FCC-ee	Current intrinsic unc.		Projected unc.
M_W [MeV]	1	4	$(\alpha^3, \alpha^2\alpha_s)$	1
$\sin^2\theta^\ell_{\rm eff}$ $[10^{-5}]$	0.6	4.5	$(\alpha^3, \alpha^2\alpha_s)$	1.5
Γ_Z [MeV]	0.1	0.5	$(\alpha^2_{\rm bos}, \alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2)$	0.2
R_b $[10^{-5}]$	6	15	$(\alpha^2_{\rm bos}, \alpha^3, \alpha^2\alpha_s)$	7
R_l $[10^{-3}]$	1	5	$(\alpha^2_{\rm bos}, \alpha^3, \alpha^2\alpha_s)$	1.5

J. Gluza

Look into the future. Bookkeeping with three loops

$Z \to b\bar{b}$			
Number of topologies	1 loop	2 loops	3 loops
	1	$14 \to^{A} 7 \to^{B}$ **5**	$211 \to^{A} 84 \to^{B}$ **50**
Number of diagrams	15	$2383 \to^{A,B}$ **1114**	$490387 \to^{A,B}$ **120187**
Fermionic loops	0	371	116091
Bosonic loops	15	2012	374296
Planar	1T/15D	13T/2250D	186T/426753D
Non-planar	0	1T/133D	25T/63634D

$Z \to e^+e^-, \ldots$			
Number of topologies	1 loop	2 loops	3 loops
	1	$14 \to^{A} 7 \to^{B}$ **5**	$211 \to^{A} 84 \to^{B}$ **50**
Number of diagrams	14	$2012 \to^{A,B}$ **880**	$397690 \to^{A,B}$ **91271**
Fermionic loops	0	301	92397
Bosonic loops	14	1711	305293
Planar	1	13	186
Non-planar	0	1	25

Genuine virtual loops (aITALC, qgraf, FeynArts).

(A) - no tadpoles, no product of lower loops, (B) - symmetry included

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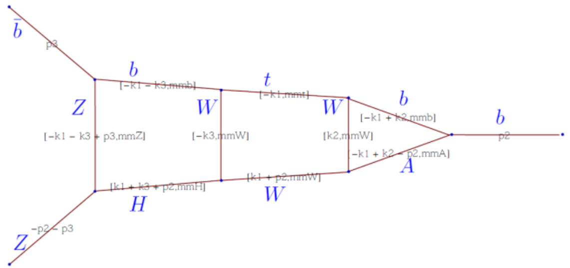
such as:

MB: ϵ^0**[8-dim]**, $1/\epsilon$**[7-dim]**; SD: ϵ^0**[8-dim]** , $1/\epsilon$**[7-dim]**;



Some examples

PHYSICS COMPLEMENTARITY

Higgs Physics -- ee → ZH fixes Higgs width and HZZ coupling ,
-- FCC-hh gives huge statistics of HH events for Higgs self-coupling

Search for Heavy Physics
-- ee gives precision measurements (m_Z m_W to < 0.5 MeV, m_{top} 10 MeV, etc…)
sensitive to heavy physics up to … 100 TeV
-- FCC-hh gives access to direct observation

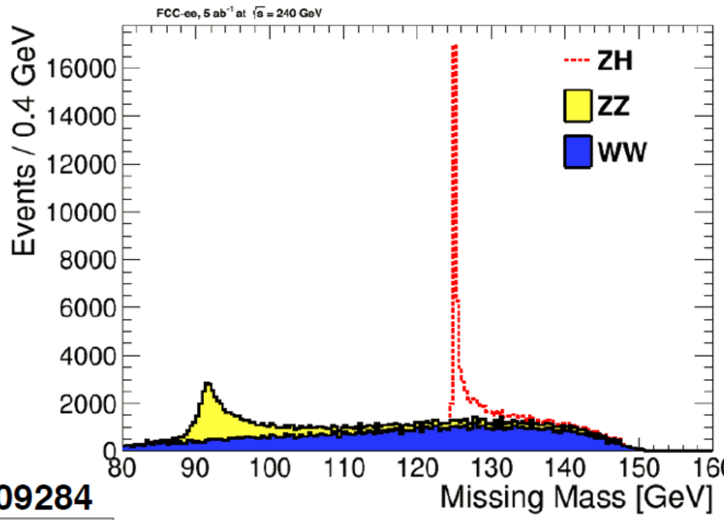
QCD -- ee gives $\alpha_s \pm 0.0002$ in several ways
also H→gg events (gluon fragmentation!)
-- ep provides tructure functions and $\alpha_s \pm 0.0003$
-- all this improves the signal and background predictions
for new physics signals at FCC-hh

Heavy Neutrinos -- ee: powerful and clean, but flavour-blind
-- hh and eh more difficult, but potentially flavour sensitive

BSM Higgs Studies

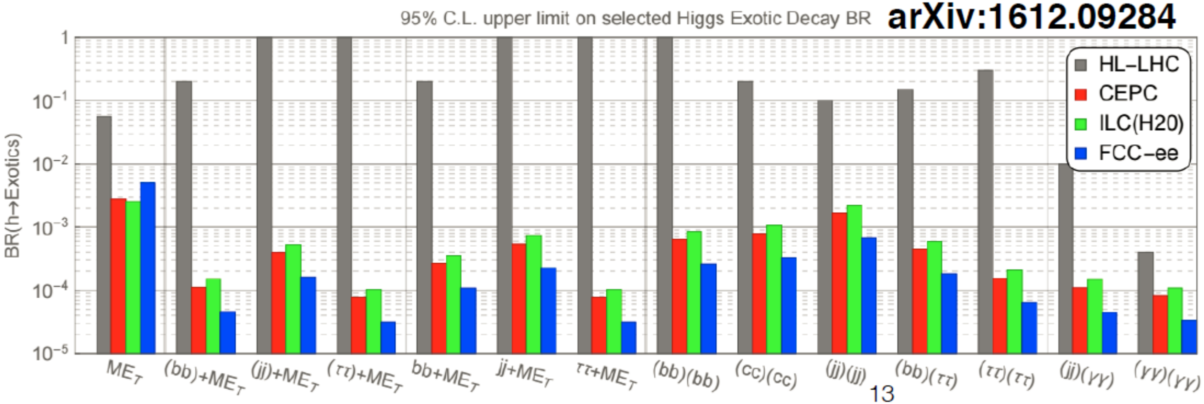
➡ **Example: Higgs to invisible decays**

- follows ZH cross section measurement
- for visualization BR(H->inv) = 100%
- 95%CL upper limit using $5ab^{-1}$ is 0.44%
- study published using leptonic Z decays in Eur. Phys. J. C (2017) 77: 116
- hadronic Z decays under study. Shows similar performance

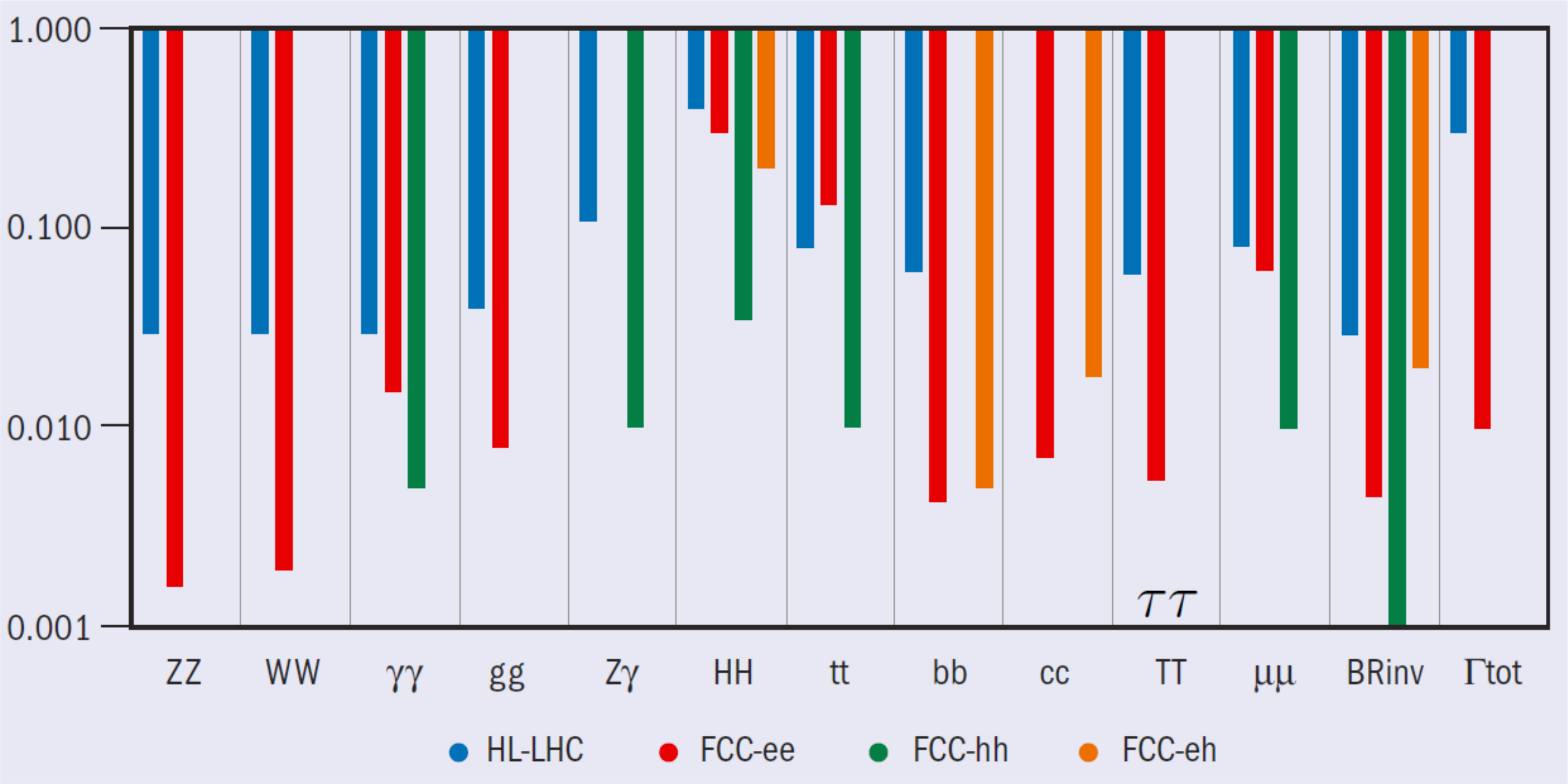


➡ **Incredible opportunities for BSM Higgs searches**

arXiv:1612.09284



To summarise the Higgs programme...

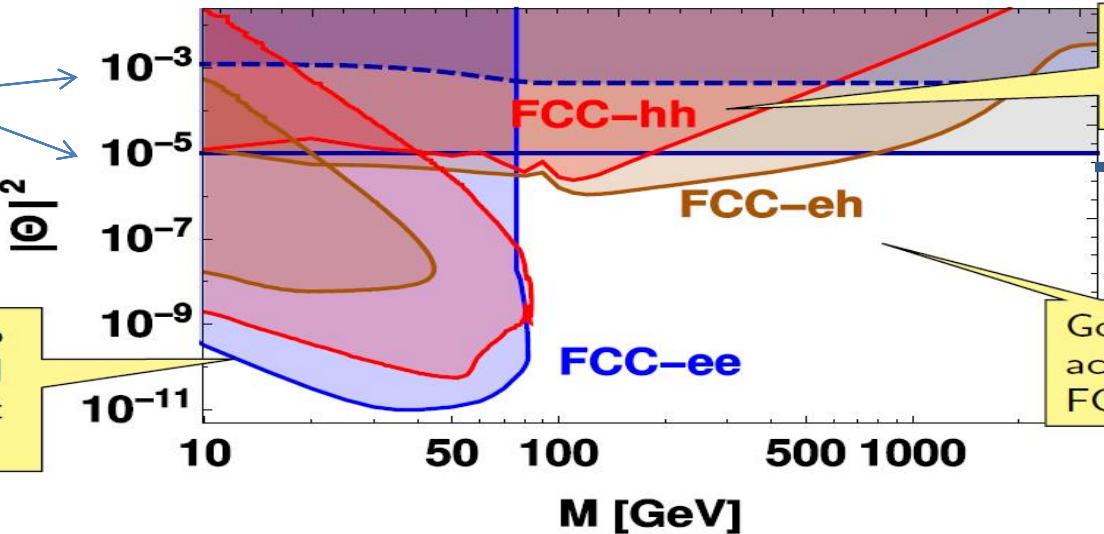


hh, eh precisions assume ee measurements esp. for Htt and HHH

Summary

Another example of Synergy and complementarity

- Systematic assessment of heavy neutrino signatures at colliders.
- First looks at FCC-hh and FCC-eh sensitivities.
- Golden channels:
  - **FCC-hh:** LFV signatures and displaced vertex search
  - **FCC-eh:** LFV signatures and displaced vertex search
  - **FCC-ee:** Indirect search via EWPO and displaced vertex search



FCC-hh able to test all flavour combinations.

to > 40TeV

Best sensitivity to $|\theta|^2$ from displaced vertex searches at the FCC-ee.

Good sensitivity reach from FCC-hh & FCC-eh.

detailed study required for all FCCs – especially FCC-hh to understand feasibility at all

CONCLUSIONS

-- The study of FCC-ee Physics and Experiments is going hand-in-hand with the accelerator study

-- The Physics is fantastic (and so is the team :-)). There are still many optimizations to do!
Collaboration for the detectors is now gearing up with CLIC group and CEPC.

-- The collaboration with theory for ideas, concepts and calculations is strong

-- We are gearing up to prepare the CDR!

PHYSICS WITH VERY HIGH ENERGY

e^+e^- COLLIDING BEAMS

CERN 76-18
8 November 1976

L. Camilleri, D. Cundy, P. Darriulat, J. Ellis, J. Field,
H. Fischer, E. Gabathuler, M.K. Gaillard, H. Hoffmann,
K. Johnsen, E. Keil, F. Palmonari, G. Preparata, B. Richter,
C. Rubbia, J. Steinberger, B. Wiik, W. Willis and K. Winter

ABSTRACT

This report consists of a collection of documents produced by a Study Group on Large Electron-Positron Storage Rings (LEP). The reactions of

Did these people suspect that we would be running HL-LHC in that tunnel >**60 years later?**

Let's not be SHY!

CDR Vol. 5 Outline

- Vol. 5 "FCC-ee: Physics & Experiments"
  - Introduction (running plan, history, motivation, ...)
  - Electroweak physics with Z's and W's
  - Higgs physics
  - Top quark physics
  - QCD and $\gamma\gamma$ physics
  - Flavours
  - BSM (Physics behind precision, global fits, direct searches)
  - MDI and experimental environment
  - Polarization and beam energy measurement
  - Detector designs
  - Summary and outlook

5 – Lepton Collider Comprehensive

Experiment

- Each of the "physics" sections will contain
  - The theory counterpart (e.g., the quest for precision calculations)
  - The requirements on detectors (geometry, acceptance, resolution, tolerances)
  - The requirements on accelerator (luminosity, polarization, E_{beam} knowledge)

Synergy and complementarity

FCC-ee is a very powerful precision machine covering considerable new territory, with discovery potential in its own right.

There are presently four proposals for e+e- colliders covering the H and top (and Z, WW) {ILC, CLIC} and {FCC-ee, CEPC}.*) There is a consensus that physics needs such a machine
FCC-ee is unique for its precision and luminosity at the W,Z,H.

Only the circular machines come with a tunnel, cryo, etc… for a 100 TeV «ultimate» step
Synergy : cost (ee+hh) < cost (ee) + cost (hh)

The Physics of the hadron collider is quite complementary but in many cases it benefits from the ee measurements in ways that should be quantified further in the 2d Physics Workshop
Complementarity:
Physics (ee+hh+ ep) > Physics(ee) + Physics (hh) + Physics (ep) >> Physics (ee), (hh), (ep)

*) we are starting to work together, but one could do more!

Physics and Experiments Studies Coordination

Physics Studies coordination
A. Blondel, P. Janot (EXP), C. Grojean, M. McCullough, J. Ellis (TH)

EW Physics with Z's and W's
R. Tenchini, F. Piccinini
S. Heinemeyer, A. Freitas

Higgs properties
M. Klute, K. Peters
S. Heinemeyer, A. Freitas

Top quark physics
P. Azzi (F. Blekman)
S. Heinemeyer, A. Freitas

Synergies with FCC-hh physics, LC studies, LEP legacy

QCD and $\gamma\gamma$ physics
D. d'Enterria
P. Skands

Flavours physics
S. Monteil
J. Kamenik

New physics
M. Pierini, C. Rogan
M. McCullough

Global Analysis Synergies
J. Ellis

Physics software
C. Bernet, B. Hegner,
C. Helsens

Synergy with FCC-hh, LC, LHC

Online selection & DAQ
C. Leonidopoulos
E. Perez

Polarization, $\sqrt{s}$ measurement
A. Blondel
J. Wenninger

Joint with FCC-ee Accelerator

MDI, Exp'tal environment
M. Boscolo
N. Bacchetta

Adapt (to) the interaction region
Joint with FCC-ee Accelerator

Detector designs
A. Cattai, G. Rolandi,
M. Dam

Synergy with LC and CEPC
Set constraints on designs
to match statistical precision
Propose detector designs

Challenges

Readout electronics

- Few ns beam crossing time:
  - To maintain backgrounds (off-momentum particles, etc) at a tolerable level, need **very fast readout** (one or few crossings)
  - Continous beam:
    - No power pulsing possible: heat dissipation, how to maintain mechanical stability

Control of geometry to few µm

- For increased acceptance in tight geometry suggest **conical layout** of monitors
  - Need detailed plan for mechanical assembly
- Heat dissipation:
  - Need detailed plan for cooling

High integrated rate particularly at low radii

- Possible need for radiation tolerant sensors and electronics

FCC-ee group (Copenhagen) invited to join ILC FCAL Collaboration for discussion of forward instrumentation issues