Take home message from the 1^{st} FCC-France Workshop

S. Muanza: CPPM Marseille, CNRS-IN2P3 & AMU

First FCC-CPPM Meeting

November 27, 2019

Selected Talks Grouped into 3 Themes

1^{st} FCC-France Workshop

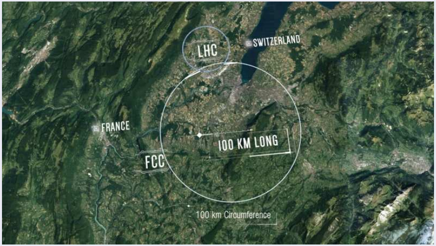
- Organizers: IN2P3 + CEA Joint Committee
- Where & when: At LPNHE Paris, on 14-15 November 2019
- Attendance: 87 participants
- "Kick-off meeting"

Physics Panorama at the LHC

- Big discovery: a neutral SM-like Higgs boson, ATLAS & CMS (2012)
- Standard Model (SM):
  - Theoretically: complete, could technically be extrapolated up-to the Planck scale
  - Experimentally: alive and kicking, still resisting most tests at accelerators!
- Beyond the Standard Model (BSM):
  - No signs of it at the energy frontier (SUSY, Z', W', LQ, ED, ALP, Composite Higgs,...)
  - Hints from low energy:
    - Long standing tension of $(g-2)_\mu$,... TBC (soon?)
  - Hints from Flavor Physics:
    - Renormalizable SM needs BSM to explain neutrino masses ($(B-L)$ violation or ν_R)
    - Tensions wrt SM in B-Physics: LFU (B decays to 2^{nd} gen. via charged or neutral currents)
    - CKM phase unsufficient source of CPV to explain baryon asymmetry in the universe
  - Hints from astrophysics & cosmology:
    - Need BSM to explain Cold Dark Matter (galaxies rotation curves, large structure formation,...)
    - Need BSM to explain Dark Energy (accelerated expansion of the universe)

The Concept

- FCC stands for "Future Circular Collider"
- The most ambitious endeavour to both perform precison studies of SM and to search for BSM in the post-LHC era
- Integrated strategy:
  - First: FCC-ee
  - Then: FCC-hh and FCC-eh (plus ions)
  - Exploring both energy and intensity frontiers



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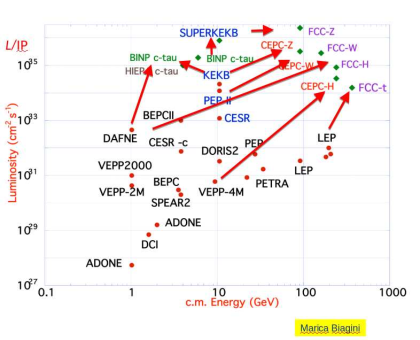

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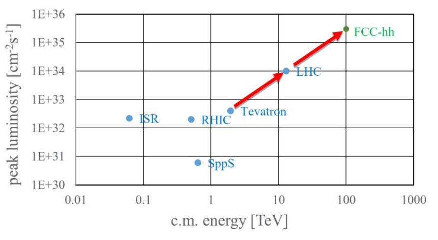

In Practice

- Collaboration:
  - 136 Institutes from 34 countries, plus 25 private companies (support from EU through H2020)
  - CNRS (IN2P3, LAPP Annecy), CEA (IRFU Saclay, INAC-SBT Grenoble), CETU (Bron), CEREMA (Bron), Mines Paris Tech
- Long term project: 2035-2090
- Requires huge investments:
  - Tunnel: ≈ 5.4 MChF
  - FCC-ee: ≈ 6.2 MChF (ILC: ≈ 7 MChF, $CLIC_{380}$: $\approx 6-7$ MChF)
  - FCC-hh: ≈ 17.0 MChF

First Step FCC-ee

- Baseline: 2 IPs, 15 years of operation (incl. shutdowns)
- "Tera-Z factory": $\sqrt{s} = M_Z \implies N_{exp} = 5 \times 10^{12}$ Z bosons
  - Measure: $\alpha_S(M_Z)$ at 0.01%
- "Oku-W": $\sqrt{s} = 157.5 - 162.5\ GeV \gtrapprox 2 \times M_W \implies N_{exp} = 10^8$ W boson pairs
  - Measure: M_W at 0.5 MeV, Γ_W at 1.2 MeV
- "Clean Higgs Factory": $\sqrt{s} = 240\ GeV \gtrapprox M_H + M_Z \implies N_{exp} = 10^6\ e^+e^- \to HZ$
  - Measure: g_{HZZ} at 0.17%, Γ_H at 1.6%, g_{HHH} at 34%
- "Clean Top Factory": $\sqrt{s} = 350 - 365\ GeV \gtrapprox 2 \times M_t \implies N_{exp} = \times 10^6\ t\bar{t}$
  - Measure: $g^{vector}_{Zt\bar{t}}$ at 0.5%, $g^{axial}_{Zt\bar{t}}$ at 1.5%
- Progress needed on theoretical precision: (see talk by C. Grojean)

More theory work needed to match EXP uncertainties

	experimental accuracy			intrinsic theory uncertainty		
	current	ILC	FCC-ee	current	current source	prospect
ΔM_Z[MeV]	2.1	–	0.1			
$\Delta\Gamma_Z$[MeV]	2.3	1	0.1	0.4	$\alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2$	0.15
$\Delta \sin^2\theta^\ell_{eff}[10^{-5}]$	23	1.3	0.6	4.5	$\alpha^3, \alpha^2\alpha_s$	1.5
$\Delta R_b[10^{-5}]$	66	14	6	11	$\alpha^3, \alpha^2\alpha_s$	5
$\Delta R_\ell[10^{-3}]$	25	3	1	6	$\alpha^3, \alpha^2\alpha_s$	1.5

Need TH results to fully exploit Tera-Z

and to avoid Tera-Z=Giga-Z=Mega-Z

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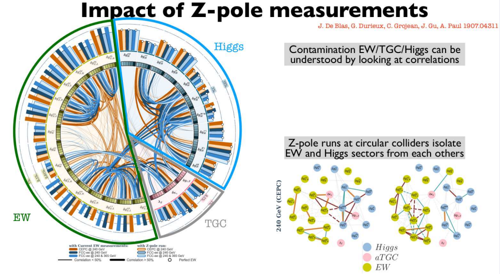

FCC-ee: Heavy Flavors vs Global Panorama

- No direct signs of BSM at LHC Run 2 implies a gap above the SM!
- Disappointing, but not surprising (talk by G. Isidori): else we should have seen deviations in EWPO, or Flavors, or CPV

$$A(\psi_i \rightarrow \psi_j + X) = A_0 \left[\frac{c_{SM}}{M_W^2} + \frac{c_{NP}}{\Lambda^2} \right]$$

$$\mathscr{L}_{NP\text{-}EFT} = \mathscr{L}_{SM} + \Sigma_i \frac{c_{NP}}{\Lambda^{d-4}} O_i^{d\geq 5}$$

FCC-ee: Heavy Flavors for Indirect Searches

- $N_{exp} = 5 \times 10^{12}$ Z bosons, means unprecedented stat. of B-hadrons, C-hadrons, $\tau-$leptons

$$\left.\begin{matrix}\Lambda_{NP}\\ c_{NP}\end{matrix}\right|_{N_Z\ [\text{LEP}]} \rightarrow \left.\begin{matrix}18 \times \Lambda_{NP}\\ 0.003 \times c_{NP}\end{matrix}\right|_{10^5 \times N_Z\ [\text{FCC-ee}]}$$

$$\left.\begin{matrix}\Lambda_{NP}\\ c_{NP}\end{matrix}\right|_{\frac{b\underline{b}}{\tau\underline{\tau}}\ [\text{Belle}]} \rightarrow \left.\begin{matrix}5.6 \times \Lambda_{NP}\\ 0.03 \times c_{NP}\end{matrix}\right|_{10^3 \times \frac{b\underline{b}}{\tau\underline{\tau}}\ [\text{FCC-ee}]}$$

- Note: B and τ at FCC-ee are much more boosted than in current B-factories
  - Measure: LFV in B and τ decays
- See also detector requirements in the talk by S. Monteil

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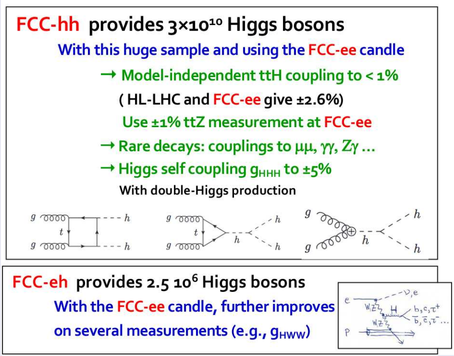
FCC-hh & FCC-eh

- Baseline: 2 IPs, 25 years of operation (incl. shutdowns)
- Dedicated runs:
  - FCC-eh: to discrease the proton PDF systematic uncertainty
  - FCC-ions
- See talk by P. Janot



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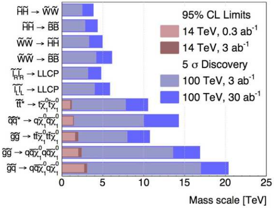
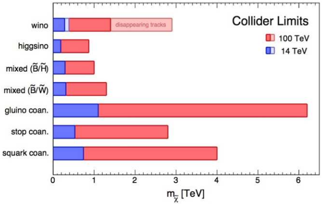
SUSY and WIMP Dark Matter at FCC-hh





- From DM relic abundance : $M_{\mathrm{WIMP}} \leq 1.8 \text{ TeV} \left(\frac{g^2}{0.3}\right)$
  - FCC-hh can find (or rule out) lot's of weakly interacting massive DM candidates.

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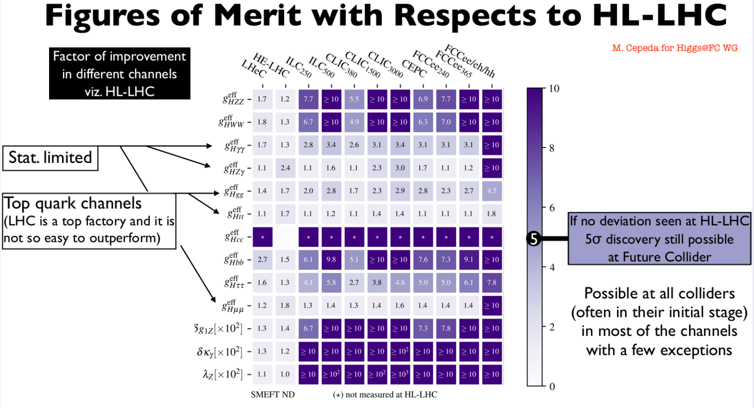

	LHeC	HE-LHC	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
g^{eff}_{HZZ}	1.7	1.2	7.7	≥ 10	5.5	≥ 10	≥ 10	6.9	7.7	≥ 10	≥ 10
g^{eff}_{HWW}	1.8	1.3	6.7	≥ 10	4.9	≥ 10	≥ 10	6.3	7.0	≥ 10	≥ 10
$g^{eff}_{H\gamma\gamma}$	1.7	1.3	2.8	3.4	2.6	3.1	3.4	3.1	3.1	3.1	≥ 10
$g^{eff}_{HZ\gamma}$	1.1	2.4	1.1	1.6	1.1	2.3	3.0	1.7	1.1	1.2	≥ 10
g^{eff}_{Hgg}	1.4	1.7	2.0	2.8	1.7	2.3	2.9	2.8	2.3	2.7	4.5
g^{eff}_{Htt}	1.1	1.7	1.1	1.2	1.1	1.4	1.4	1.1	1.1	1.1	1.8
g^{eff}_{Hcc}	⋆		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
g^{eff}_{Hbb}	2.7	1.5	6.1	9.8	5.1	≥ 10	≥ 10	7.6	7.3	9.1	≥ 10
$g^{eff}_{H\tau\tau}$	1.6	1.3	4.1	5.8	2.7	3.8	4.8	5.0	5.0	6.1	7.8
$g^{eff}_{H\mu\mu}$	1.2	1.8	1.3	1.4	1.3	1.4	1.6	1.4	1.4	1.4	≥ 10
$\delta g_{1Z}[\times 10^2]$	1.3	1.4	6.7	≥ 10	≥ 10	≥ 10	≥ 10	7.3	7.8	≥ 10	≥ 10
$\delta\kappa_\gamma[\times 10^2]$	1.3	1.2	≥ 10	≥ 10	≥ 10	≥ 10	$\geq 10^2$	≥ 10	≥ 10	≥ 10	≥ 10
$\lambda_Z[\times 10^2]$	1.1	1.0	≥ 10	$\geq 10^2$	≥ 10	$\geq 10^2$	$\geq 10^3$	≥ 10	≥ 10	≥ 10	≥ 10

FCC-ee

- Beyond baseline: 4 IPs are under study
- Possibility to further improve $\sqrt{s}$ and especially L using ERL
- There will be at least 1 detector tailored for Flavor Physics
- See talks by P. Giacomelli, T. Guillemin,...

INFN Istituto Nazionale di Fisica Nucleare

Detector requirements

- $\Delta p_t/p_t^2 \sim 2\text{-}4 \times 10^{-5}$ (GeV^{-1})
- Extremely light tracker
- $\sigma(E)/E \sim 10\%/\sqrt{E}$ EM energy resolution
- $\sigma(E)/E \sim 30\%/\sqrt{E}$ jet energy resolution
- Flavour tagging
  - Decay length
  - Jet kinematic variables
  - Semi-leptonic decays
- Hadron calorimeter with particle flow capability
- Excellent b/c separation over a large p range
- PID for π^{+-} separation from other particles
- Low energy π^0 reconstruction
- Very accurate knowledge of the beam spread

Being revised now

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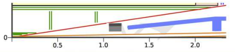
Vertex detector

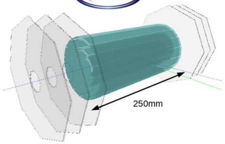
Requirements

Fast readout (one full frame read-out in less than ~ 85 μsec), low power consumption (< 20 mW/cm^2), low material budget (0.15% X_0), single point resolution of: ~ 5 μm

Today: ALICE ITS* (5 μm spatial resolution, > 100 kHz readout, 0.3-1% X_0, 41-27 mW/cm^2)
Tomorrow: Exploit what is being done (e.g. ARCADIA - INFN project).

5 MAPS layers:
R = 1.7 - 2.3 - 3.1 cm
Pixel size: 20 x 20 μm^2
R = 32 - 34 cm
Pixel size: 50 x 100 μm^2





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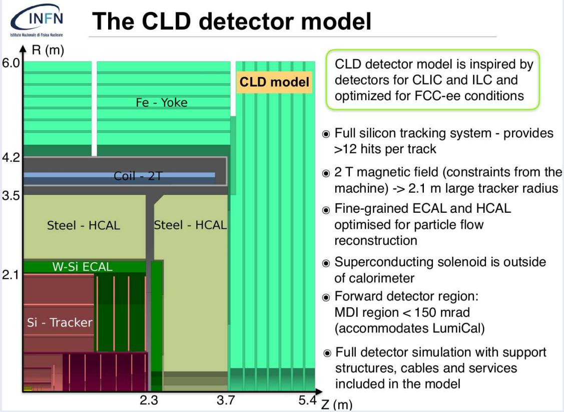

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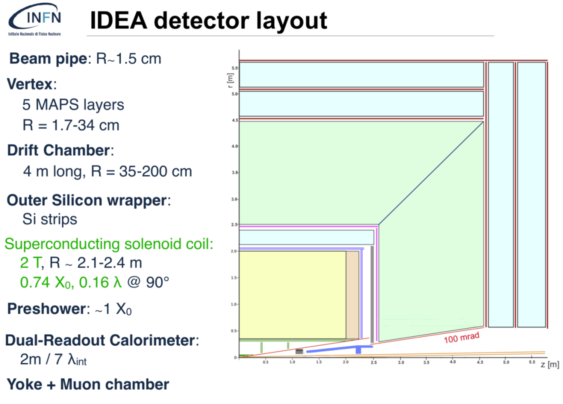

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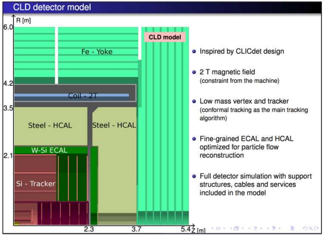
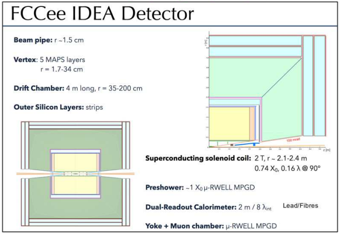
So far: Two detector concepts for the CDR

See P. Giacomelli's presentation

- It was demonstrated that detectors satisfying requirements are feasible
  - Physics performance, beam backgrounds, invasive MDI, event rates, ...
    - With two rather complementary designs (tracker / calo technologies, magnets, cost, ...)





- It is quite likely that these two concepts will not be the final answer
  - And we might need detectors for four IP, with newest technologies – lots of R&D and fun work ahead.

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Liquid Argon and Scintillating tile calorimeters for FCC-hh *

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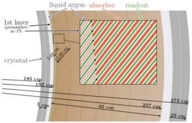
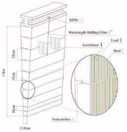
- Liquid Argon calorimeter is a unique technology to sustain radiation up to ≃ 5 x 10^{18} neq/cm² and 500 GRad
  - Straight inclined structure design with 8 longitudinal segmentations
    $\Delta\eta \times \Delta\phi \simeq 0.01(0.025) \times 0.01(0.025)$ in ECAL(HCAL) /10 ATLAS
  - → Engineering challenge to develop multilayer PCB electrodes, and high density feedthrough for readout outside the cold volume
  - → Interest for low mass cryostat
    - Also for magnets, ex. IDEA design with calorimeters outside of magnet
  - Time resolution is limited, pile-up effect need simulation?
- Scintillating tile + WLS + SiPM can sustain radiation for barrel Had. Calo.
  - Vertical design /4 ATLAS granularity



LAr Calo. concept

FCC-pp requirements
Jet energy resolution similar to current ATLAS (≃ x 2 e-e)

	η_{min}	η_{max}	a	c	$\Delta\eta$	$\Delta\phi$	Fluence	Dose	Material	Mix	Seg.
Unit			$\%\sqrt{\mathrm{GeV}}$	%			cm^{-2}	MGy			
EMB	0	1.5	10	0.7	0.01	0.009	5×10^{15}	0.2	LAr/Pb/PCB	1/0.47/0.28	8
EMEC	1.5	2.5	10	0.7	0.01	0.009	3×10^{16}	4	LAr/Pb/PCB	1/0.75/0.6	6
EMF	2.5	4	10	0.7	0.025	0.025			LAr/Cu/PCB	1/50/6	6
	4	6	30	1	0.025	0.025	5×10^{18}	5000	LAr/Cu/PCB	1/50/6	6
HB	0	1.26	50	3	0.025	0.025	3×10^{14}	0.006	Sci/Pb/Fe	1/1.3/3.3	10
HEB	0.94	1.81	50	3	0.025	0.025	3×10^{14}	0.008	Sci/Pb/Fe	1/1.3/3.3	8
HEC	1.5	2.5	60	3	0.025	0.025	2×10^{16}	1	LAr/Cu/PCB	1/5/0.3	6
HF	2.5	4	60	3	0.05	0.05	5×10^{18}	1000	LAr/Cu/PCB	1/200/6	6
	4	6	100	10	0.05	0.05	5×10^{18}	1000	LAr/Cu/PCB	1/200/6	6



Tile Calo. concept

* *See talk of T. Guillemin*

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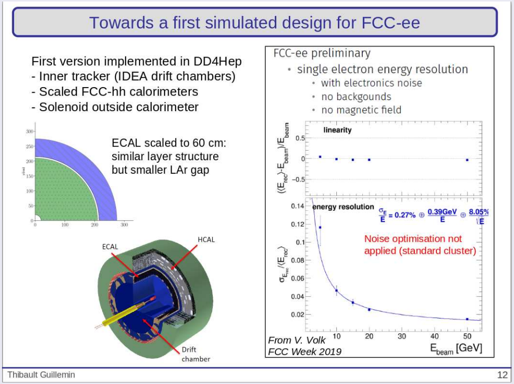

BACK-UP