FCC Physics, Experiments, Detectors (PED)

PED Summary

This project is supported from the European Union's Horizon 2020 research and innovation programme under grant agreement No 951754.

Physics, Experiments, Detectors (PED): Summary

❑ Outline

- **Monday: Vision and strategy**
  - Why, how, when ?
- **Tuesday, Wednesday: Implementation**
  - What has been done ?
  - What can be your contribution ?
    - ➔ Software
    - ➔ Detectors
    - ➔ Luminosity and √s measurements
    - ➔ Physics studies
- **Wednesday: Convincing the world**
  - Round table
    - ➔ Is the FCC physics case sharp enough?

(*) EPOL and MDI sessions in the Accelerator summary

Monday	Tuesday				Wednesday		
Plenary	Parallel 1	Parallel 2	Parallel 3	Parralel 4	Parallel 1	Parallel 2	Parallel 3
Campus Cordeliers	CICSU Jussieu				Campus Cordeliers		Réfectoire Cordeliers
FARABOEUF	Room 105	Room 107	Room 109	Room 116	ROUSSY	PASQUIER	
	FCCee accelerator FCCIS WP2	Phy Programme/ Performance	FCCIS WP4 Socio Econom		FCC hh accelerator	PED: EPOL	FCCIS WP3 Placement
Plenary session	T. Raubenheimer	S. Jadach			G. Apollinari	E. Gianfelice	F. Eder
L. Rivkin	*Coffee break*				*Coffee break*		
Coffee break Plenary session	FCCee accelerator FCCIS WP2	Phy Programme/ Performance	SRF Directions for R&D		Technology	PED: Detector Concepts	Civil Engineering
B. Heinemann	M. Minty	F. Blekman	O. Brunner			F. Gaede	F. Bordry
Lunch break	*Lunch break*				*Lunch break*		
Plenary session	FCCee injector FEB	Phy Programme/ Performance	Technology SRF	ISC meeting CLOSED	FCCee accelerator	PED: Detector Concepts	FCCIS WP5
	A. Grudiev	G. Cacciapaglia	A.M. Valente	F. Gianotti	A. Faus-Golfe	S. Gascon-Shotkin	M. Chrzaszcz
J. Mnich	*Coffee break*				*Coffee break*		
Coffee break	FCCee injector FEB	Phy Programme/ Performance	Technology SRF	ISC meeting CLOSED	FCCee accelerator	TI Geodesy and survey	FCCIS WP5 M. Chalmers
Plenary session	I. Chaikovska	M. Chamizo Llatas	T. Proslier	F. Gianotti	F. Carlier	A. Wieser	FCCIS WP5
M. Lamont					Early Career	ICB meeting	Raubenheimer

The scientific vision

C. Grojean

- ❑ **After the Higgs boson discovery**

> The LHC has revolutionised our views on the particle world.
> It didn't find (yet) any BSM physics.
> But its results have forced us to think differently about BSM physics.
>
> G. Giudice@DESY'22

My key message

- The days of "guaranteed" discoveries or of no-lose theorems in particle physics are over, at least for the time being ....
- .... but the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU, ...)
- This simply implies that, more than for the past 30 years, future HEP's progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias

MLM@Aspen'14

We need a broad, versatile and ambitious programme that
1. sharpens our knowledge of already discovered physics (e.g., Higgs)
2. pushes the frontiers of the unknown in the intensity and energy frontiers

— FCC-ee+eh+hh combine these different aspects —

more PRECISION, more ENERGY for more SENSITIVITY to New Physics

Be it light and too feebly interacting, or too heavy, or leading to too soft final states
… and therefore could not be discovered at the LHC

The Strategy

F. Gianotti

- **The 2020 update of the European Strategy for Particle Physics didn't say otherwise**

"An electron-positron Higgs factory is the highest priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy."

"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update."

⬇

FCC Feasibility Study (FS) launched in 2021:
- To be carried out in 2021-2025 → input to the next Strategy update
- Mid-term review in Autumn 2023
- Will cover the integrated programme (FCC-ee followed by FCC-hh)

Program funding approved by CERN Council

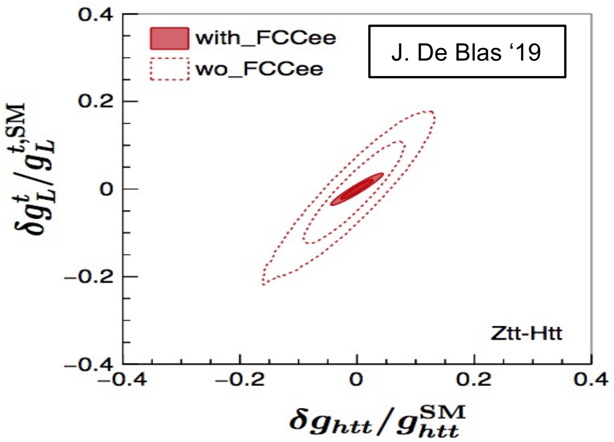
FCC, the ultimate Higgs laboratory

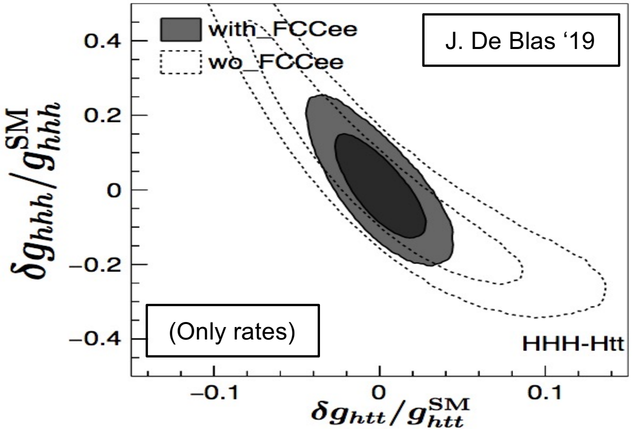
C. Grojean

- The Higgs provides a very good reason why we need both e^+e^- **AND** pp colliders
  - FCC-ee measures g_{HZZ} to 0.2% (absolute, model-independent, standard candle) from σ_{ZH}
    - Fixes all other couplings (HL-LHC/FCC-hh/FCC-ee)
  - FCC-hh produces over 10^{10} Higgs bosons
    - (1^{st} standard candle →) $g_{H\mu\mu}$, $g_{H\gamma\gamma}$, $g_{HZ\gamma}$, Br_{inv}
  - FCC-ee measures ttZ couplings ($e^+e^- \to$ tt)
    - Another standard candle
  - FCC-hh produces 10^8 ttH and 2. 10^7 HH pairs
    - (2^{nd} standard candle →) g_{Htt} and g_{HHH}

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

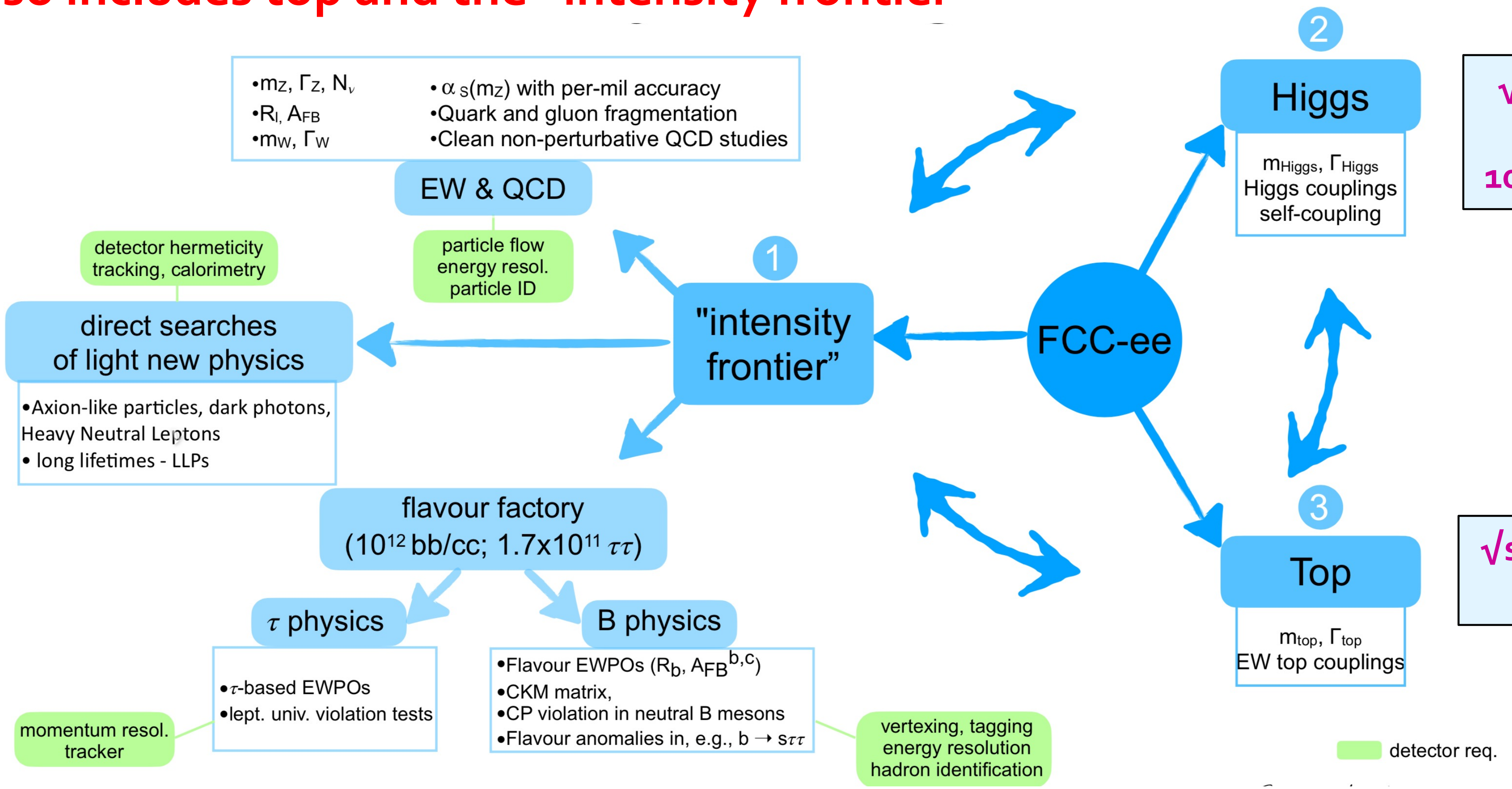
Unreachable by high-energy lepton colliders

FCC-ee, much more than a Higgs factory

C. Grojean

- FCC-ee also includes top and the "intensity frontier"

$\sqrt{s} \sim m_Z$, $> 2m_W$
5×10^{12} Z
Few 10^8 W



$\sqrt{s}$ = 240, 365 GeV
10^6 HZ events
10^5 WW → H events

$\sqrt{s}$ = 340 → 365 GeV
10^6 tt events

- **Amazingly rich field of studies, with exploration opportunities unique to FCC-ee**
  - **Imposes a whole new level of requirements to detectors, theory calculations, collider operation, ..**

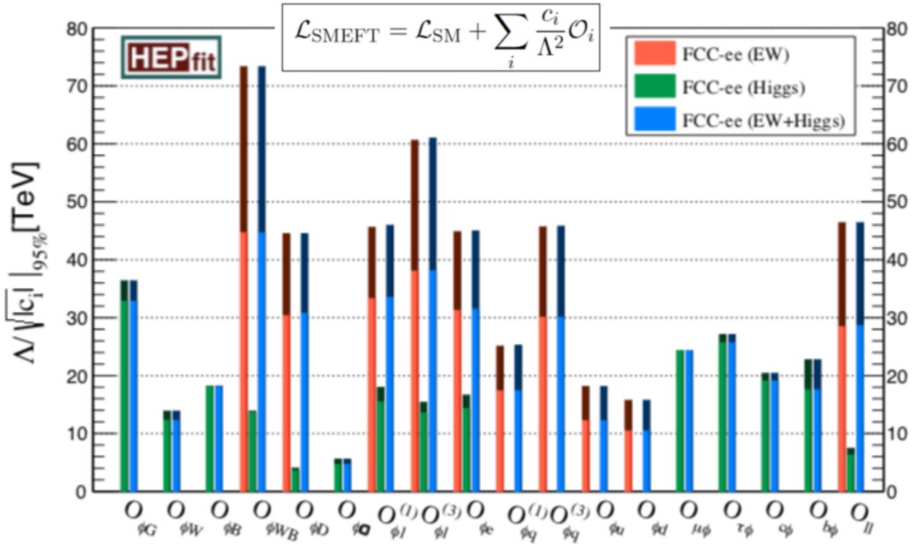
FCC, the infinity machine

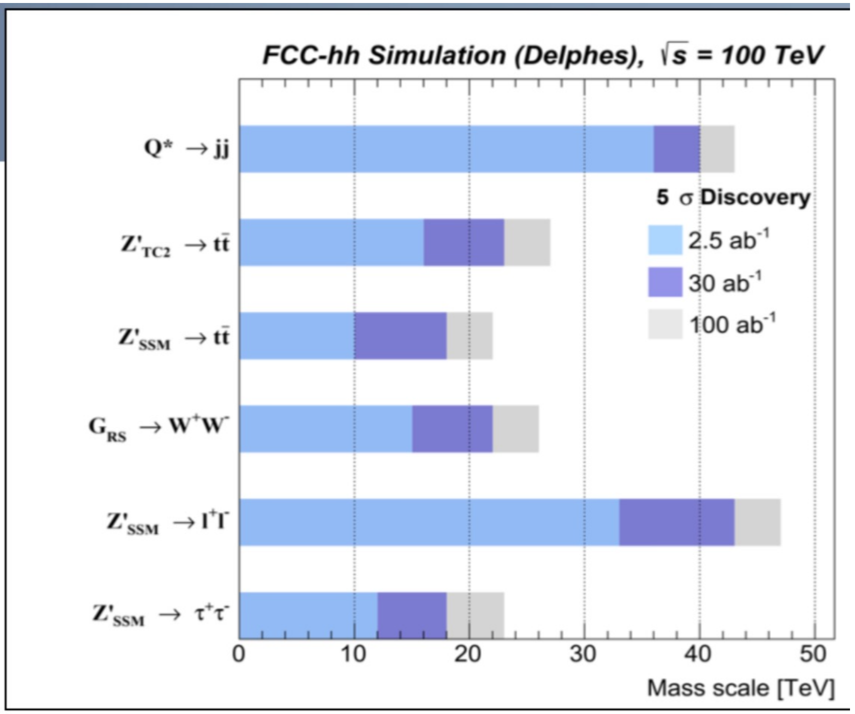
F. Gianotti

- **Astounding heavy physics reach, indirectly with FCC-ee, directly with FCC-hh**

Physics potential: examples

FCC-ee sensitivity to "interaction scales" of new physics from EW and Higgs measurements (dark: no theory uncertainty)





… and gluinos up to 20 TeV and stops up to 10 TeV ….

The precision expected with the FCC multidimensional approach will allow a multitude of new physics models to be rejected, thus strongly limiting the field of possible new physics interpretations, and will provide a clearer vision of what to look for, either at the 10 TeV energy scale (or beyond) with FCC-hh and elsewhere, or for light particles with much weaker couplings.

FCC, a general purpose particle observatory

T. You

- Explore the (BSM) origins of the laws of our universe in a wide-ranging physics programme
  - Rather than yet another expensive search for supersymmetry

FCC as an origins explorer (and possibly, origins identifier)

- **Origin of matter**
  - EW phase transition, CP violation, baryogenesis, etc.
- **Origin of the Higgs**
  - BSM in post-naturalness era, supersymmetry, compositeness, etc.
- **Origin of flavour**
  - BSM flavour models, B anomalies, g-2, etc.
- **Origin of dark matter**
  - Including dark sectors more generally
- **Origin of neutrinos**
  - BSM neutrino models, neutrino portal, etc.
- **Origin of the Standard Model**
  - SM is an EFT of an underlying UV theory that it originates from: SMEFT (or HEFT)

Timescales

M. Benedikt

- Timescales define the highest priority goals for PED during the feasibility study
  - Focus: Set the scene for the FCC-ee proto-collaborations
    - Sharpen the physics case : Have we discovered everything that FCC can discover?
      - ➔ Identify open questions, observables, BSM models
      - ➔ Optimize collider operation (what lumi at what √s?)

M. McCullough

    - Match (exp. and th.) syst. uncertainties to statistical precision
      - ➔ Complete case studies of benchmark physics processes
      - ➔ Development of state-of-the-art physics tools
      - ➔ Detector requirements and plans for theoretical calculations
      - ➔ Measurement of the centre-of-mass energy (EPOL)

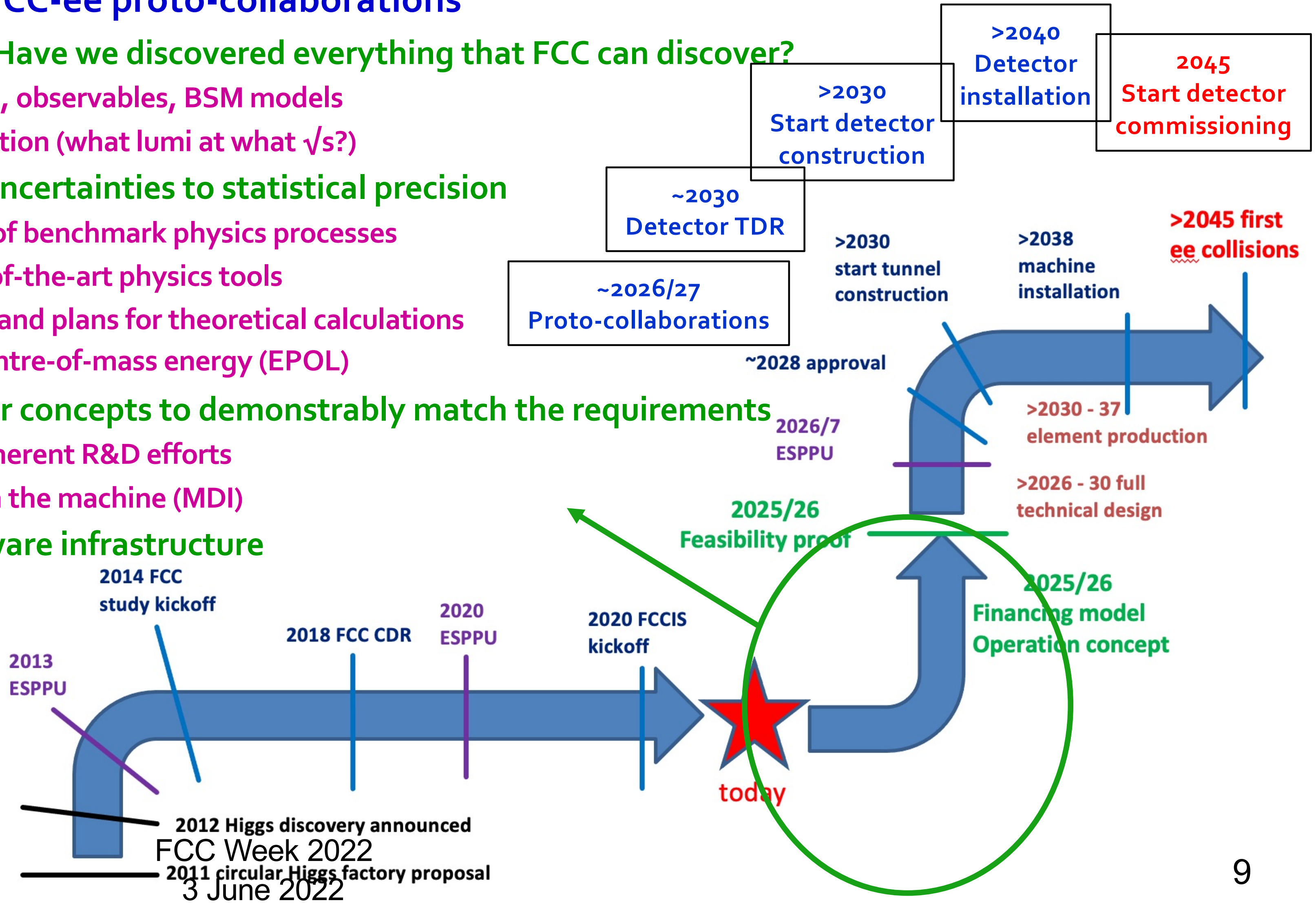
A. Blondel

    - Benchmark several detector concepts to demonstrably match the requirements
      - ➔ Provide guidance to coherent R&D efforts
      - ➔ Optimize interface with the machine (MDI)

F. Sefkow

G. Ganis

    - Develop the common software infrastructure
    - Build the community
    - Convince the world

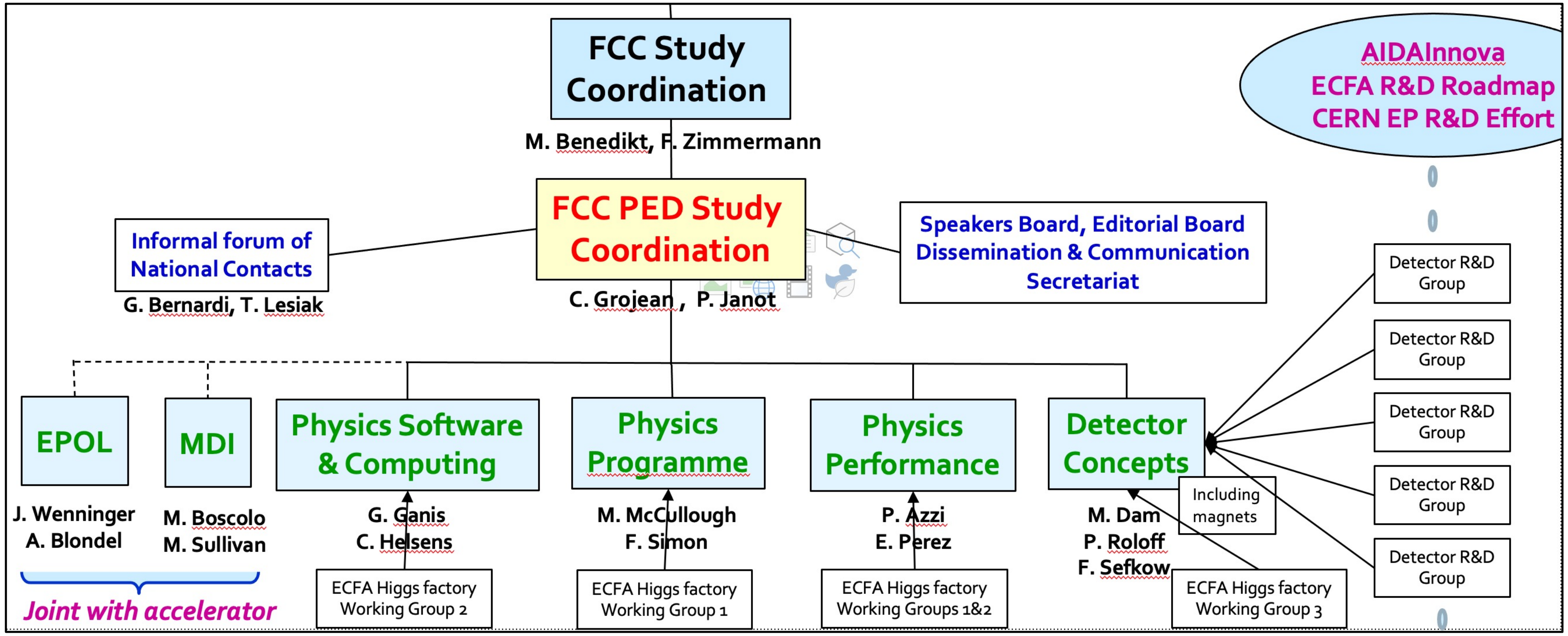


A lot to do in a few years…
The challenges arise from the richness of the physics programme

P. Janot

Build the community

- The new management team is at work towards reaching the highest priority goals



  - Links with ECFA Higgs factory working groups is essential and timely
    - They allow a fruitful collaboration / communication with linear collider community

- Mission: pass the baton to the young generation and start the knowledge transfer
  - It was a pleasure to see young faces presenting talks in the parallel sessions

Software: Huge progress, lots to do

G. Ganis, V. Volkl, C. Helsens

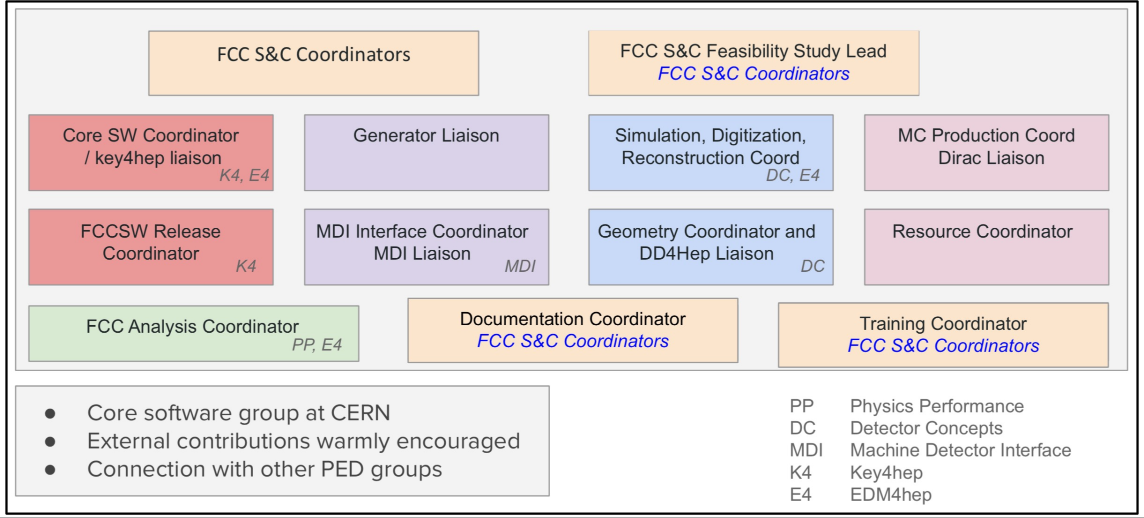
- The underlying tissue that connects physics studies, detector concepts, detector R&D
  - All possible synergies in the community are exploited
    - The software framework will be common to all FCC experiments
    - The software framework (and content) is developed in a common effort
      - ➔ LHC, FCC (ee and hh), ILC, CLIC, CEPC, EIC, … (+ECFA)
  - Ongoing priorities : you can contribute in many places
    - Subdetector plug & play technology, to optimize detector concept simulation
    - Use / optimisation of reconstruction tools developed in linear collider studies
    - Feedback on the analysis framework
    - Develop an event visualisation tool
  - New group structure being put in place
    - Address challenges, build community
  - Support from FCC community needed
    - Small CERN core group to lead the effort

Benefits of this collaborative approach already visible key4hep, edm4hep, dd4hep

Synergies with:

Detector concepts

Physics performance

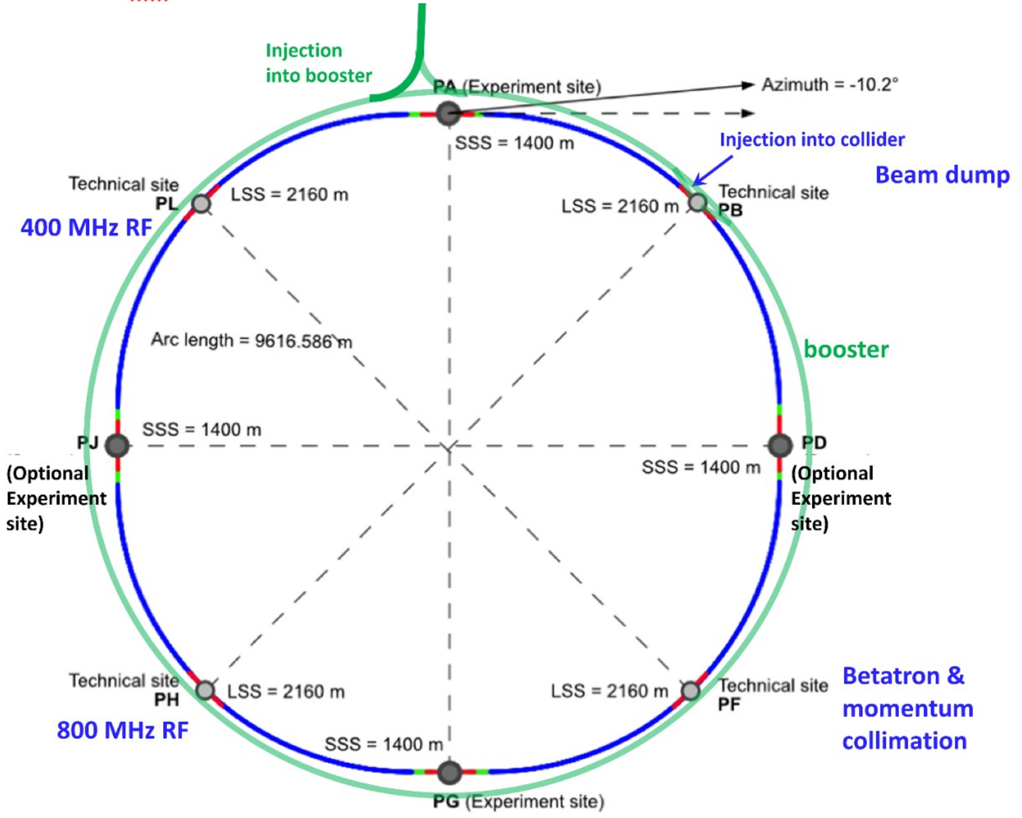


Detectors: Important development

new layouts and assignments of straight sections

injection-tunnel near PA; 400 MHz RF in PL; 4 exp. caverns for both

FCC-ee **4-fold periodicity, synergies ee & hh** **FCC-hh**



- **New layout with fourfold superperiodicity**
  - Compatible with two or four experiments
  - FCC-ee greatly benefits from having four interaction point
    - More data, sooner
    - Redundancy brings systematic robustness
      - ➔ Lesson from m_Z measurement at LEP
    - Better physics coverage with different detector technologies and abilities

Coherent sets of detector requirements?

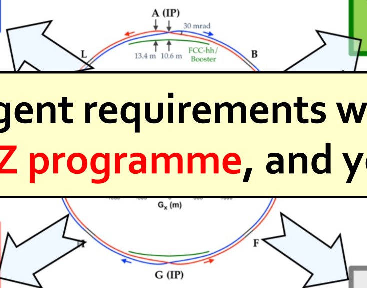
M. Dam

- **Offering four interaction regions is of great interest to cover all requirements**
  - **And to motivate different designers, with different favourite technology**

"Higgs Factory" Programme
- Momentum resolution of $\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5}$ GeV^{-1} commensurate with $\mathcal{O}(10^{-3})$ beam energy spread
- Jet energy resolution of 30%/√E in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

LC-inspired.
Update from physics studies ongoing

Ultra Precise EW Programme & QCD
- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. $\Gamma_{had}/\Gamma_{\ell}$) to 10^{-5}
- Momentum resolution "as good as we can get it"
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from μμ)
- Stability of B-field to 10^{-6} : stability of √s meast.



It is not unlikely that the most stringent requirements will come from the intensity frontier
Just pick up a case study in the TeraZ programme, and you'll make a unique contribution

Heavy Flavour Programme
- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time measts.
- ECAL resolution at the few %/ √E level for inv. mass of final states with π^0s or γs
- Excellent π^0/γ separation and measurement for tau physics
- PID: K/π separation over wide momentum range for b and τ physics

Feebly Coupled Particles - LLPs
Benchmark signature: Z → νN, with N decaying late
- Sensitivity to far detached vertices (mm → m)
  - Tracking: more layers, continous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths ⇒ extended detector volume
- Precise timing for velocity (mass) estimate
- Hermeticity

Example: Calorimetry
- High EM precision vs
- High granularity vs
- High stability vs
- Cost vs
- Particle ID vs …

N. Morange
LAr Calorimetry

Example: Tracking
- Transparency vs
- Segmentation vs
- Momentum resolution vs
- Time resolution vs
- Power consumption vs
- Particle ID vs
- Acceptance definition vs …

A. Besson
Silicon tracking

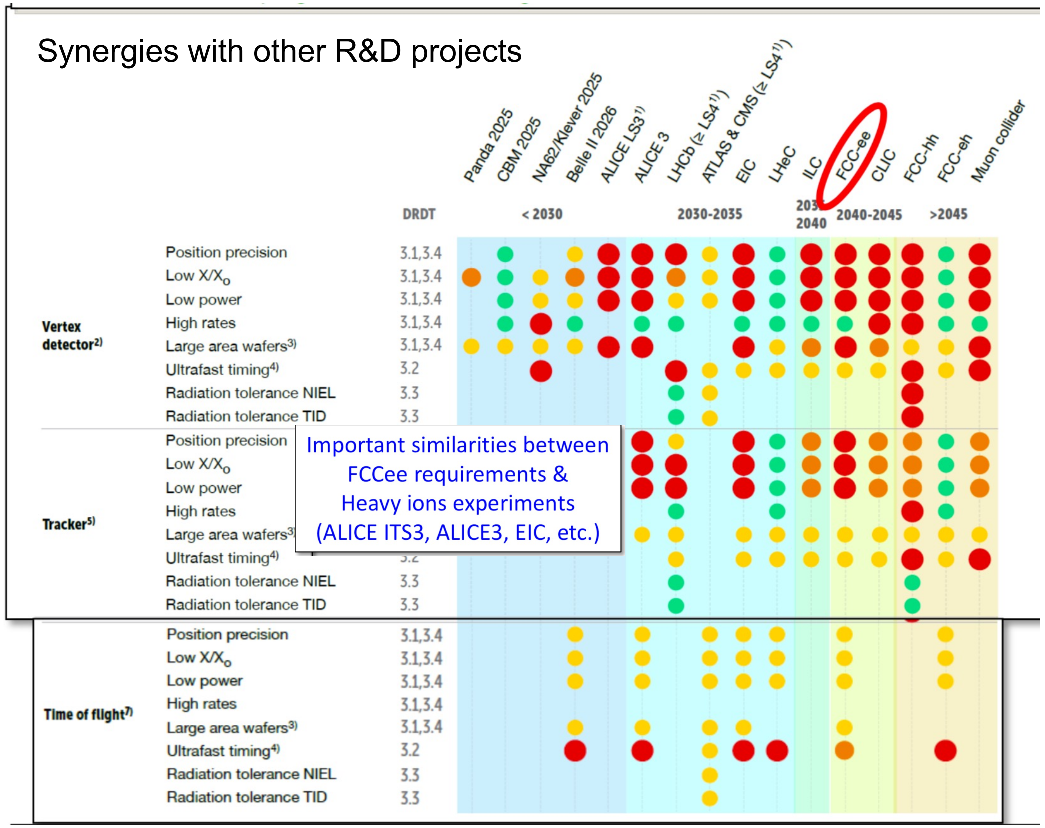
- **Calls for at least four detector concepts to be benchmarked during the FS (tough!)**
  - **Which in turn will provide guidelines for R&D efforts**

Guide detector R&D

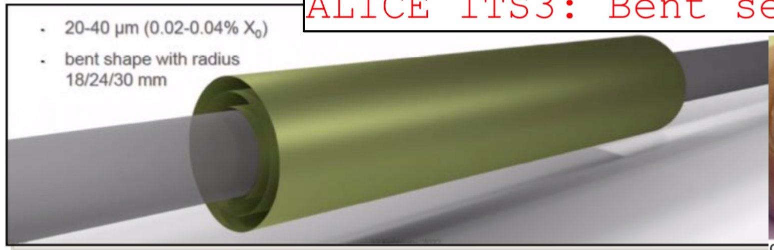
A. Besson

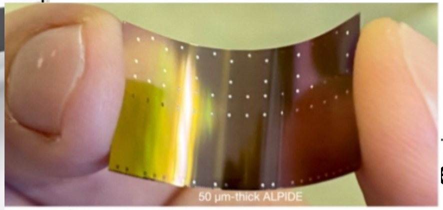
N. Morange

- Silicon tracking and vertexing



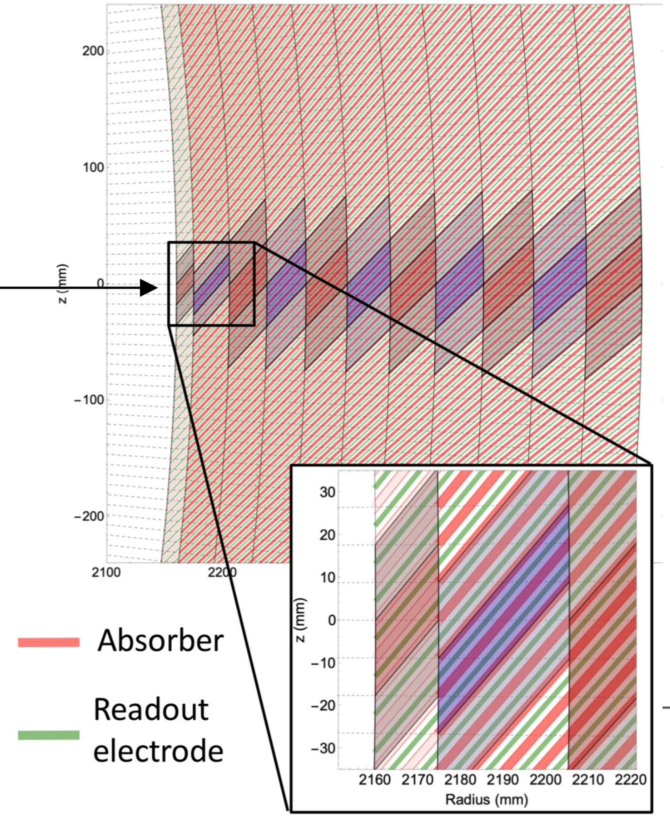
ALICE ITS3: Bent sensors



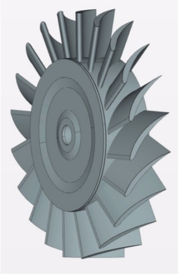


Courtesy of Magnus Mager, CERN

- High-granularity LAr Calorimetry
  - Reaching 10 times ATLAS granularity !
    - Barrel: Inclined readout/absorber planes
      - ➔ 11 longitudinal compartments
    - Endcap: Turbine wheel like geometry?



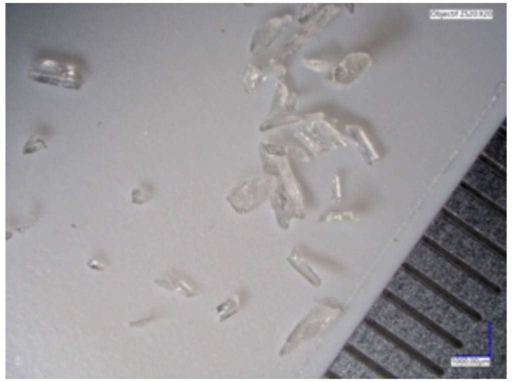
Endcaps

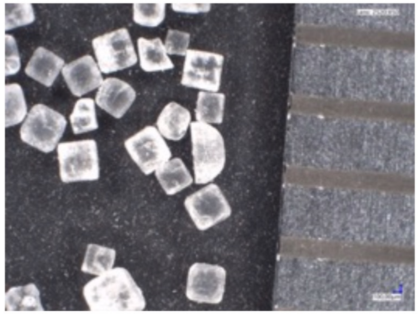


Inspire innovative R&D: GRAiNITA

J. Lefrançois

- **Idea #1: use small crystal grains of $ZnWO_4$**
  - Similar as growing salt grains (sea water+sun)
  - Excellent energy resolution (~2%/√E)
  - Much less expensive than big monocrystals
    - Scintillation light collected by WLS optical fibres



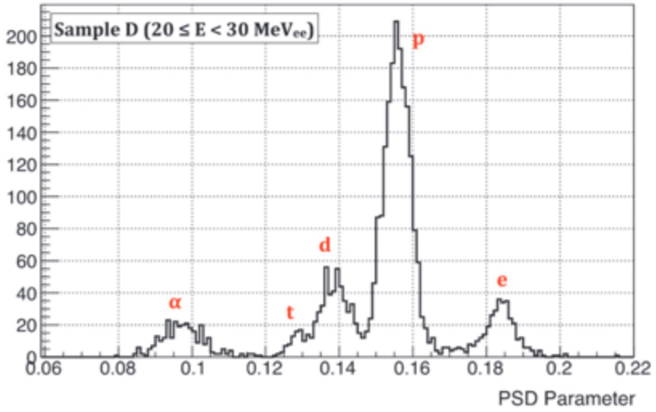


For comparison kitchen salt 0.5mm

- **Idea #2: Use fast and slow scintillation light components for PID**
  - Example: CSI crystals

$$\text{PSD parameter} = \frac{Q(T_2) - Q(T_1)}{Q(T_2)}.$$

Where Q =charge integrated from 0 to T and T1=2μsec T2=4 μsec
20-30 MeV electron and proton are easily identified



Hope: this built-in particle ID may be used to determine the e/h ratio, as is done for scintillation and Cerenkov light in dual readout calorimeters

- **Next step: simulation of the pulse to evaluate the precision of the method**
  - Or even data from past BGO RD52 test beam campaigns ?

F. Bedeschi

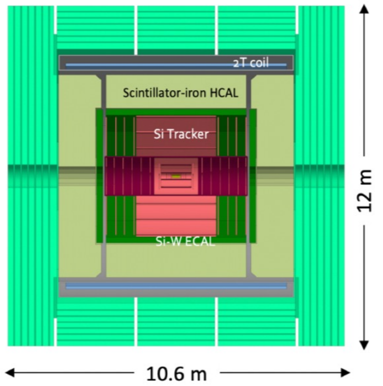
Quick overview of possible detector concepts

M. Dam

- Might (or might not) be adapted to the FCC-ee detector requirements
  - Simulation studies will tell us more – here again, plenty of room for individual contribution

A. Sailer

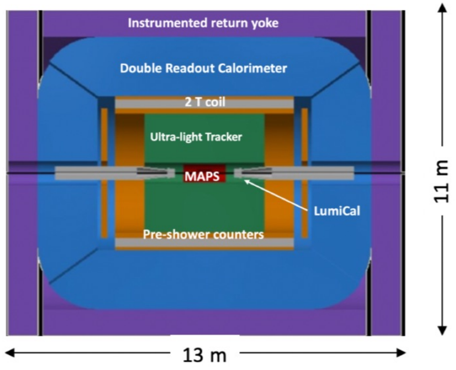
CLD



- Well established design
  - ILC -> CLIC detector -> CLD
- Engineering needed to make able to operate with continous beam (no pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations?
  - σ_p/p, σ_E/E
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?
  - …
- Robust software stack
  - Now ported (wrapped) to FCCSW

P. Giacomelli

IDEA

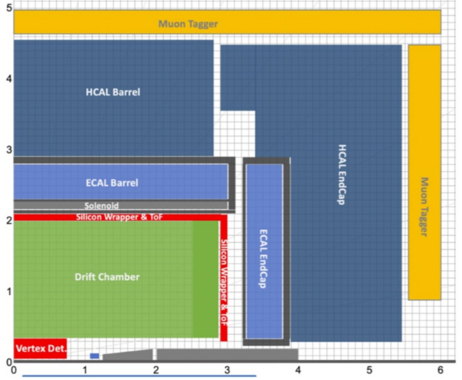


- Less established design
  - But still ~15y history: 4th Concept
- Developed by very active community
  - Prototype construction / test beam compains
  - Italy, Korea,…
- Is IDEA really two concepts? Or will it be?
  - w, w/o crystals : EM resolution long. segmentation

  Maybe even GRAiNITA ?
- Software under active development
  - Being ported to FCCSW

Noble Liquid ECAL based

M. Aleksa

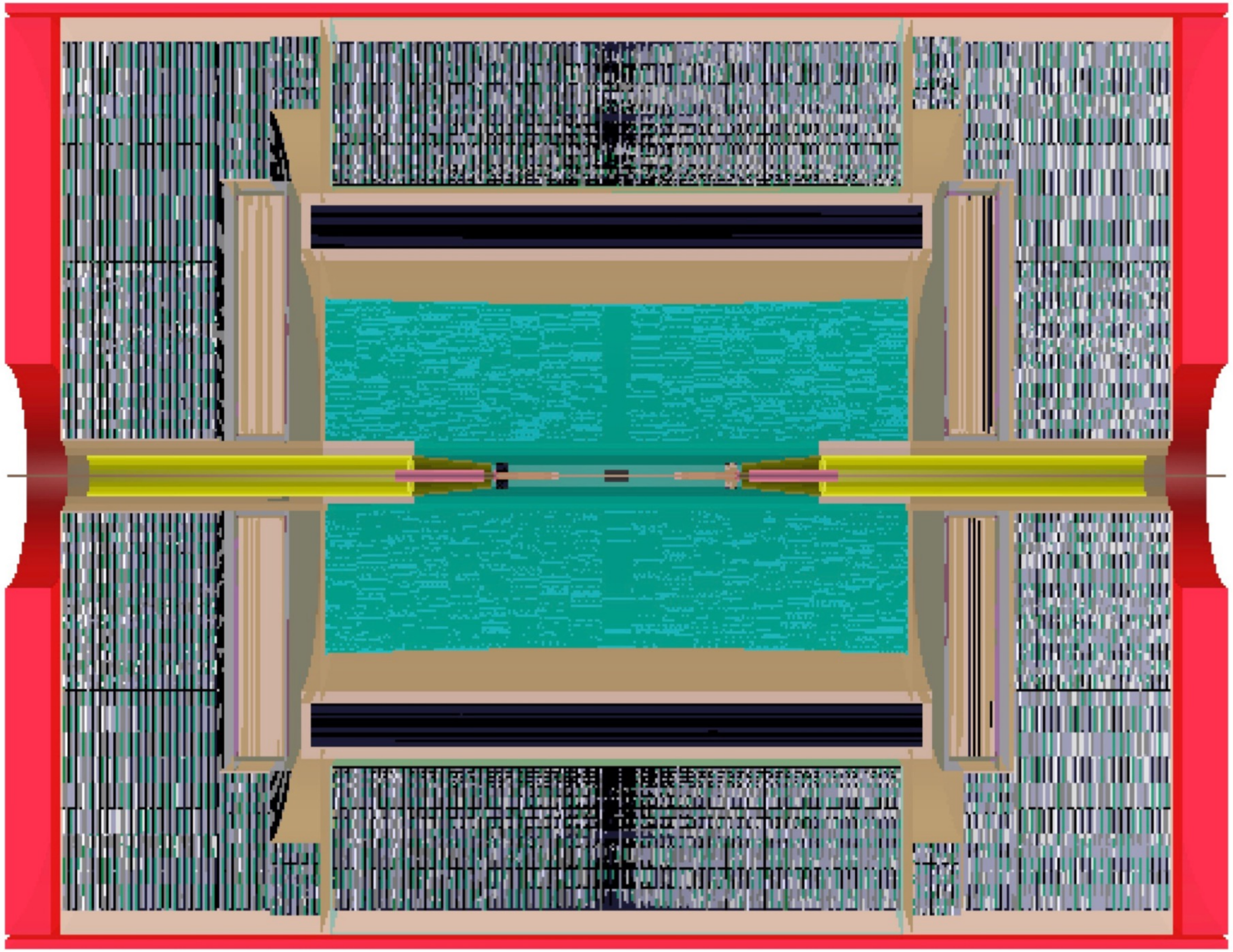


- A design in its infancy
- High granul Noble Liquid ECAL is the core
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies
- Full simulation of ECAL available in FCCSW

And now, plug and play in FCCSW !

M. Aleksa

- **Detector Concept 1** with noble-liquid ECAL and TileCal HCAL has been implemented into key4hep (J. Faltova link)
- Ready for **plug-n-play** – e.g. simulations with drift chamber or Si tracker are possible …
- **Clustering** can be used from FCC-hh calorimeter (sliding window, topo cluster), also plan to integrate CLUE algorithm (k4Clue, see talk by V. Volkl yesterday, link)
- **Particle flow**: Pandora being made available in key4hep via wrapper (k4pandora, see talk by V. Volkl yesterday, link)

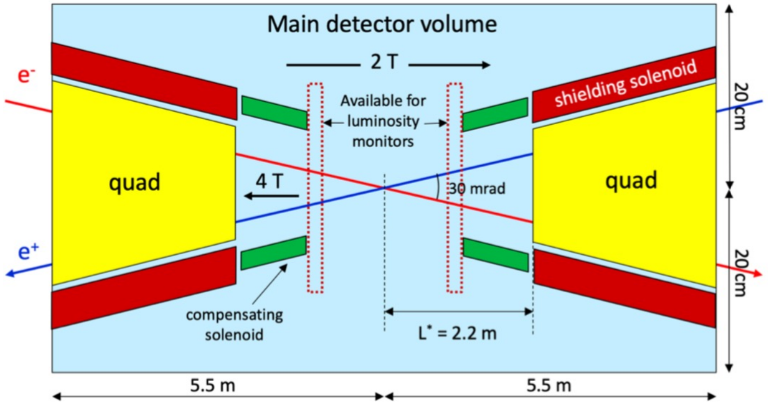


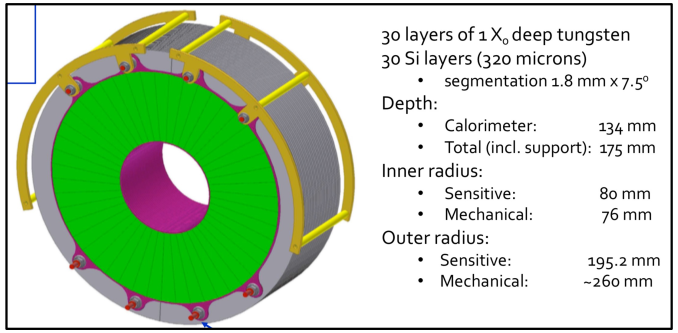
Luminosity measurement with low-angle $e^+e^- \rightarrow e^+e^-$

M. Dam

❑ A considerable detector challenge & an opportunity to contribute decisively

- Very ambitious FCC-ee absolute normalisation goal of 10^{-4} (experiment AND theory)
  - ❑ Best at LEP was OPAL at 3.4×10^{-4} with their second generator monitors and a huge analysis effort
- Compared to LEP, the FCC-ee LumiCals are placed in a much more complicated position
  - ❑ Just above z=1 m from the IP, right inside the general detector volume
- Challenges
  - ❑ Detector geometry to be controlled to $\mathcal{O}$(1 μm) in radius [4.4 μm achieved in OPAL]
    - Can in principle produce each (half) sensor layer from a single 10 inch Si wafer
  - ❑ Distance between two monitors to be controlled to $\mathcal{O}$(100 μm) [100-140 μm achieved in OPAL]
    - Tolerances refer to the sensitive layer(s) that determine the scattering angle
  - ❑ CDR LumiCal design squeezed from two sides
    - Stay away from beam pipe + stay inside 150 mrad cone
    - Visible cross section rather small: 14 nb compared to 30 nb for $Z \rightarrow q\bar{q}$
  - ❑ No engineering design perfromed for CDR LumiCals
    - Electronics, cooling, …
    - Mechanics: assembly, tolerances, support, …
      - How to construct adequate support without protruding further into detector region
      - …





❑ FCC contribution to the FCAL R&D collaboration?

W. Lohmann

- **Designed LumiCal for ILC and CLIC, but activity would benefit from a boost !**

Alternative case study: $e^+e^- \rightarrow \gamma\gamma$ at large angle
- **Theoretically clean : 10^{-5} accuracy possible**
- **Statistical precision of 2×10^{-5}**
- **Background from large angle $e^+e^- \rightarrow e^+e^-$**

√s measurement with resonant depolarisation

A. Blondel

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

factor 500-75 more precise than LEP

~40 times more precise than CDF

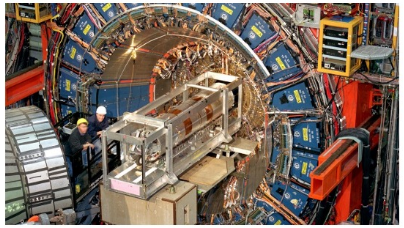
➔ Improvement by factor 10-1000 on a long list of EW precision measurements.
e.g. W mass down to ±250 keV, Z mass and width ±4 keV, $\sin^2\theta_W^{eff} \pm 2.10^{-6}$ etc..
➔ explore new physics at 10-100 TeV scale, or 10^{-5} mixing with known particles.

The goal of the group is to demonstrate that a feasible program of measurements and procedures in the operation and data taking of the accelerator will allow a determination of the centre-of-mass energy that matches the precision offered by the high luminosities. **(and centre-of-mass energy spread)**

… and beyond FCC-ee !

Measurements with physics events

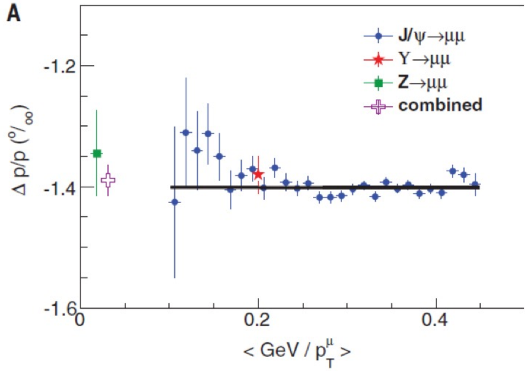
- For example $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$
- Not much done since CDR studies
  - A lot to do and learn here



Recent CDF: m_W (MeV)= 80'433.5 $\pm$ 6.4 $_{stat}$ $\pm$ 6.9$_{syst}$ (10^{-4} precision)
-- « could hint at new physics » and surely created a buzz!
-- precision measurements as broad exploration of new physics in quantum corrections, or mixing (SUSY, Heavy neutrinos, etc..)
(-- questions because inconsistent with previous measurements)

CDF measurement is remarkable in two ways:

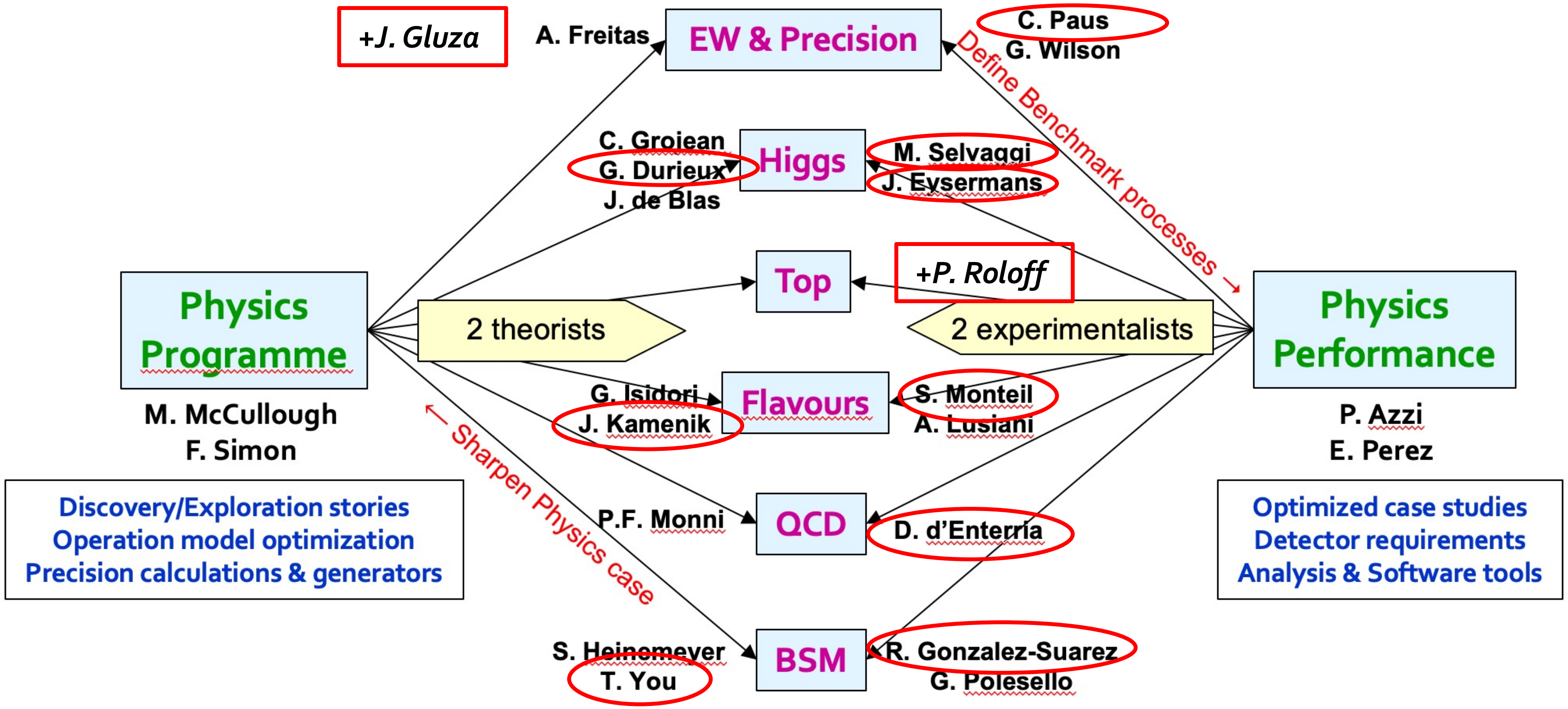
1. relies for the precise calibration on J/ψ, ϒ, Z masses
   all measured in e+e- colliders… (VEPP-4M, Doris, LEP= using resonant depolarization!
2. (after 10 years of work)
   systematic errors similar to statistical precision



The credo of precision physics at FCC-ee

Speaking of physics …

- The team of physics group (young) conveners has now been assembled and is at work!



- They presented the programme of their group and a list of opportunities for contribution
  - This is not summary-talk material – look at the slides to pick the contribution you like best (*)

(*) and even propose new ones !

Your choice will be good, no matter what!

Not just an advertising slide
I am speaking from experience

- The work you'll do will be both interesting and rewarding
  - It'll be guided by physics first principles
    - Feynman graphs, matrix element, symmetries, …
  - It'll be entirely new (though at time guided by past experience and CDR estimates)
    - Who worked with 10^{12} Z's before? By the way, how do we do that?
  - You'll carry out a physics study from the beginning to the end
  - You'll have to find original solutions to reduce sensitivity to uncertainties (exp, th)
    - E.g., by making ancillary independent measurements, by inventing new variables, …
  - You'll reduce accordingly the demands on detectors or on theory with clever tricks
    - And you'll be thanked for that
  - You'll contribute, without even noticing, to the development of physics tools
    - Which will then benefit others, through the common software framework
  - Finally, you'll come up with a publication of your work
    - With your sole name on it (or maybe with that of a few colleagues in your team)

A few highlights – focussing on what is new

- The work is restarting ~ now
  - With fresh physicists
  - With brand new (and evolving) software
  - With an important load of knowledge to be transferred
  - With a speed proportional to the number of new people involved

    - Do not expect Feasibility Study Report materiel here
      - ➔ Not even Mid-Term Review material yet

The most important message is that the new generation starts committing to the work and owning the FCC project

EW&Precision: Higher-order calculations of EWPOs

J. Gluza

- **First full two-loop calculations of the Z total width Γ_Z in the Standard Model**

Dubovyk et al, https://doi.org/10.1016/j.physletb.2018.06.037

	$\Gamma_e, \Gamma_\mu, \Gamma_\tau$	$\Gamma_{\nu_e}, \Gamma_{\nu_\mu}, \Gamma_{\nu_\tau}$	Γ_d, Γ_s	Γ_u, Γ_c	Γ_b	Γ_Z
Born	81.142	160.096	371.141	292.445	369.56	2420.2
$\mathcal{O}(\alpha)$	2.273	6.174	9.717	5.799	3.857	60.22
$\mathcal{O}(\alpha\alpha_s)$	0.288	0.458	1.276	1.156	2.006	9.11
$\mathcal{O}(N_f^2\alpha^2)$	0.244	0.416	0.698	0.528	0.694	5.13
$\mathcal{O}(N_f\alpha^2)$	0.120	0.185	0.493	0.494	0.144	3.04
$\mathcal{O}(\alpha^2_{bos})$	0.017	0.019	0.058	0.057	0.167	0.505

the bosonic 2-loop corrections shift the value of Γ_Z by 0.51 MeV

Will require three- or four-loop calculations (!)

To meet projected exp. uncertainty (0.025 MeV)

(This uncertainty may still decrease …)

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Table 3 Measurement of selected precision measurements at FCC-ee, compared with present precision. Statistical errors are indicated in boed phase. The systematic uncertainties are initial estimates, aim is to improve down to statistical errors. This set of measurements, together with those of the Higgs properties, achieves indirect sensitivity to new physics up to a scale Λ of 70 TeV in a description with dim 6 operators, and possibly much higher in specific new physics (non-decoupling) models

Observable	Present value ± error	FCC-ee stat.	FCC-ee syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}$ ($\times 10^6$)	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)$ ($\times 10^3$)	128952 ± 14	**3**	Small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z ($\times 10^3$)	20767 ± 25	**0.06**	0.2–1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ ($\times 10^4$)	1196 ± 30	**0.1**	0.4–1.6	From R_ℓ^Z above
σ^0_{had} ($\times 10^3$) (nb)	41541 ± 37	**0.1**	4	Peak hadronic cross section Luminosity measurement
N_ν ($\times 10^3$)	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b ($\times 10^6$)	216290 ± 660	**0.3**	< 60	Ratio of $b\bar{b}$ to hadrons

J. Kamenik, S. Monteil

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

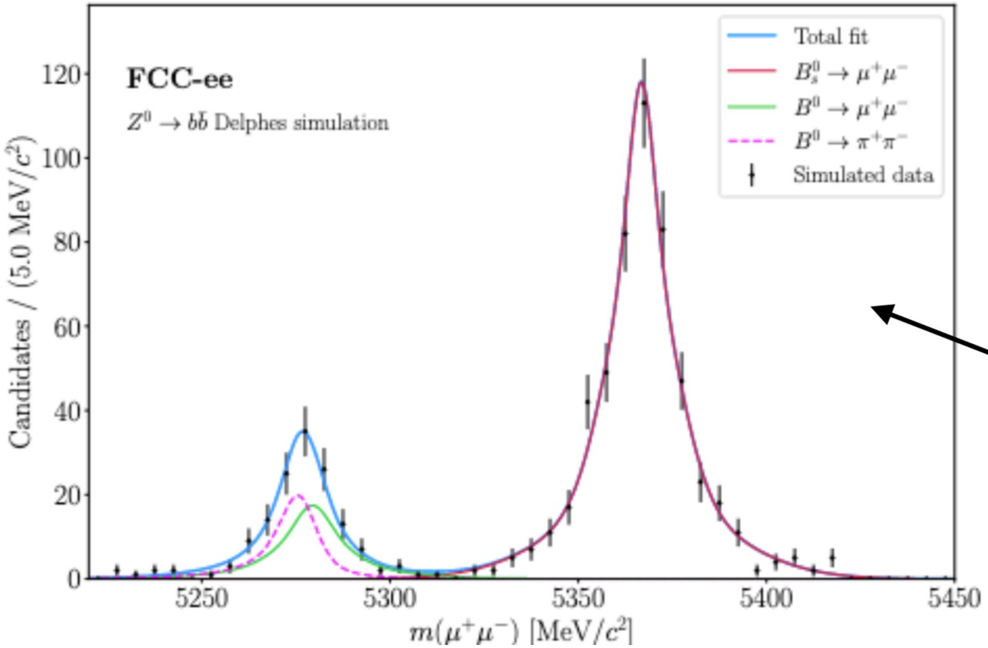
Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

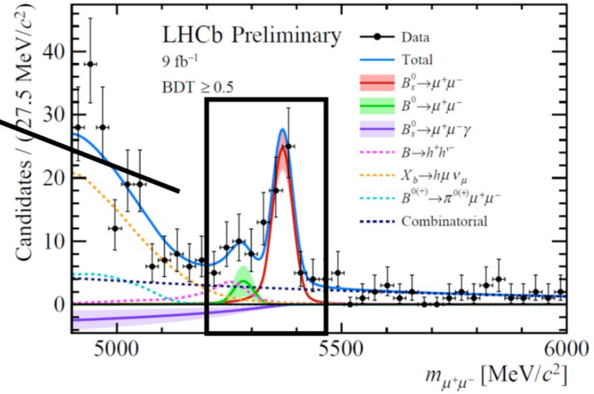
Make CP violation studies possible for very rare B decays?

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 $B^0_d/B^0_s \to \mu^+\mu^-$

Exquisite tracking from the IDEA drift chamber



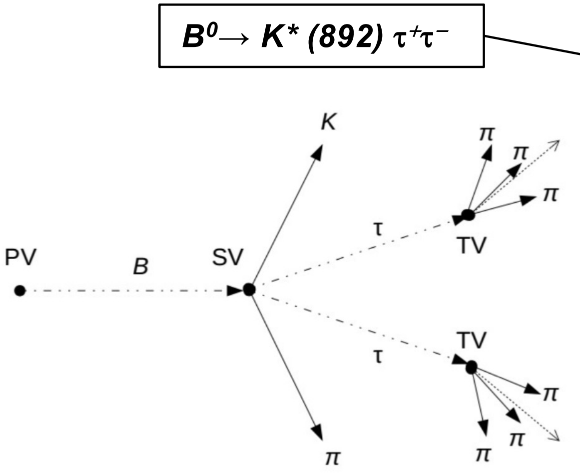


Complete case study required

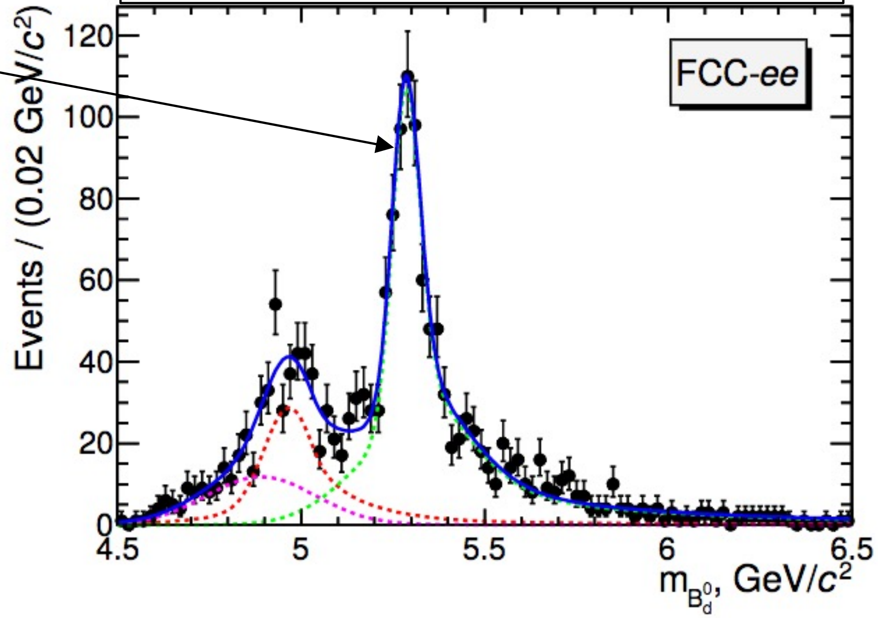
Flavours: Complete studies may bring surprises

T. Mirales

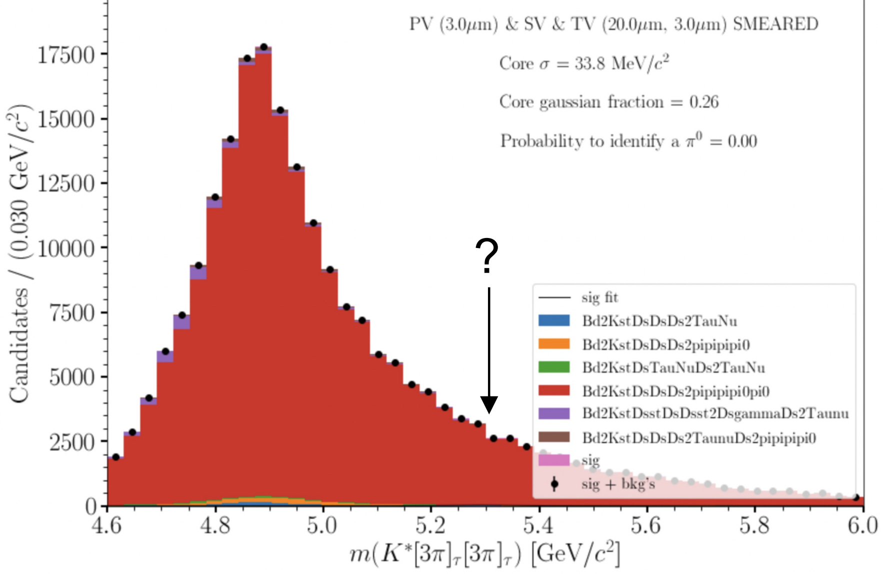
- Revisit the $B^0 \to K^*(892)\,\tau^+\tau^-$ flagship channel towards detector requirements



CDR: ~1000 events, little background



Now: ~200 events, overwhelming bkgd

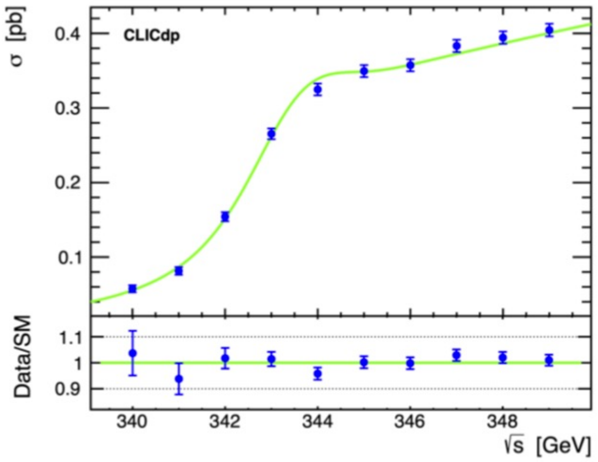


- **Dominant background (unexpected kinematic conspiracy):** $B^0 \to K^{*0} D_s D_s (D_s \to \pi\pi\pi\pi^0\pi^0)$
  - Work is in progress to find a solution to reject this (and other) background(s)
    - ➔ Stay tuned !

Top: Optimisation of the top-pair threshold scan

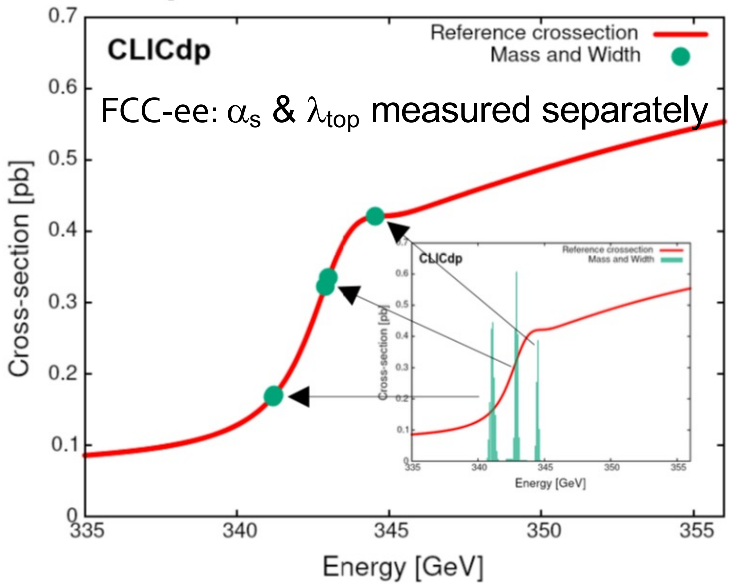
P. Roloff

CDR **Baseline scenario:**

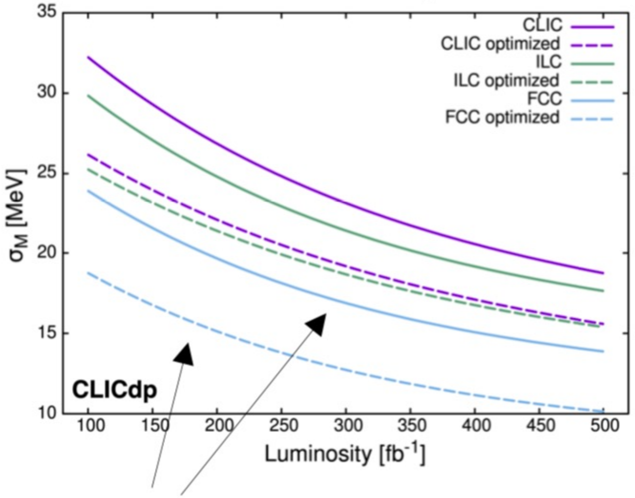


10 points of 10 fb^{-1} each

Optimised for mass & width:



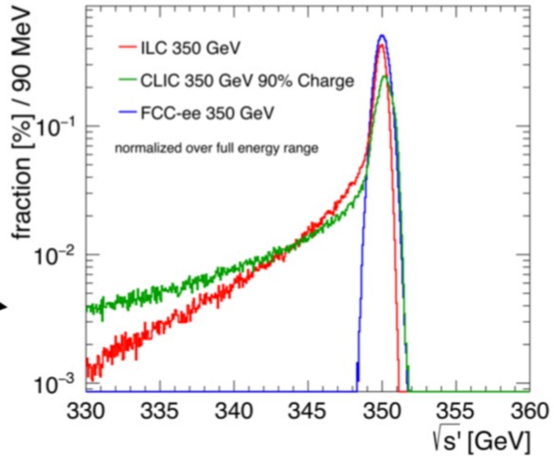
Precision on top mass:



FCC-ee

- Optimisation of quantity and centre-of-mass energy for the individual cross section measurements
→ 25% better statistical precision on top mass compared to 10 equidistant measurements

- Main difference between colliders: luminosity spectra

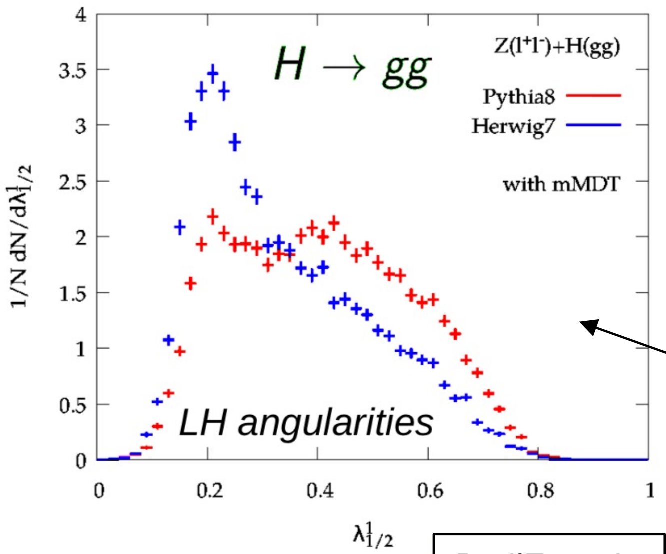


JHEP **07**, 070 (2021)

Physics Tools: Flavour-tagging algorithm

❑ Input Features

- Kinematic Variables
  - Features derived from the momentum of each jet-constituent
- Displacement Variables
  - Observables related to the longitudinal and transverse displacement of the jet-constituents
  - More **relevant** to identify **b & c jets**
- Identification Variables
  - Nature of each particle using the PF reconstruction and PID using ToF & dN/dx
  - **PID** important to identify **s jets**

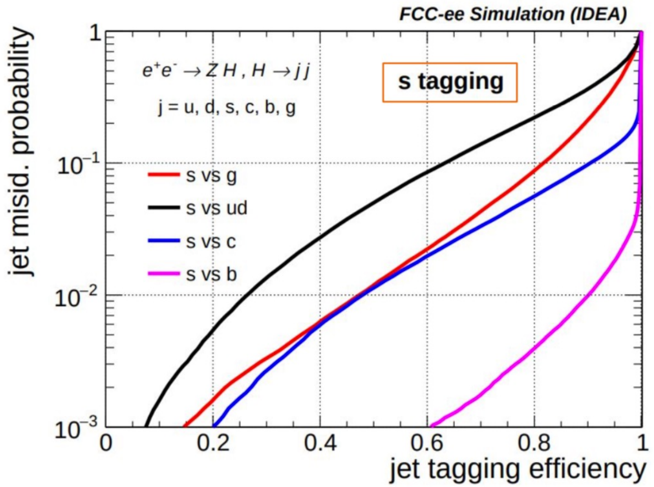


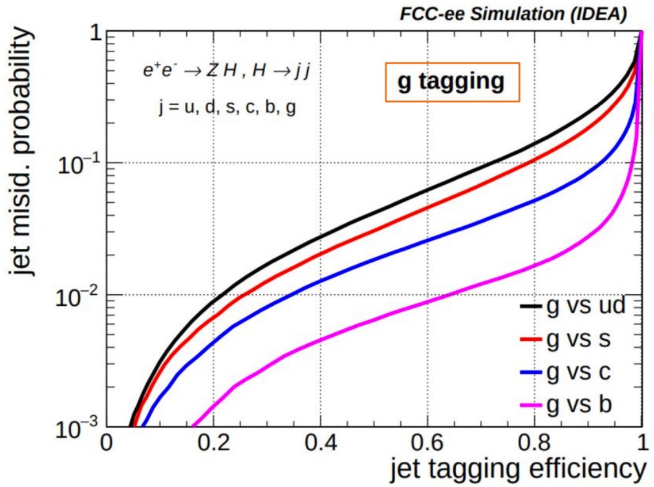
D. d'Enterria

3 pixel layers
PID: dN/dx + ToF (30ps)

Performance

K. Gautam





40% Z→ ss for 1% Z → uu, dd

40% H → gg for 0.1% H → cc
0.01% H → bb

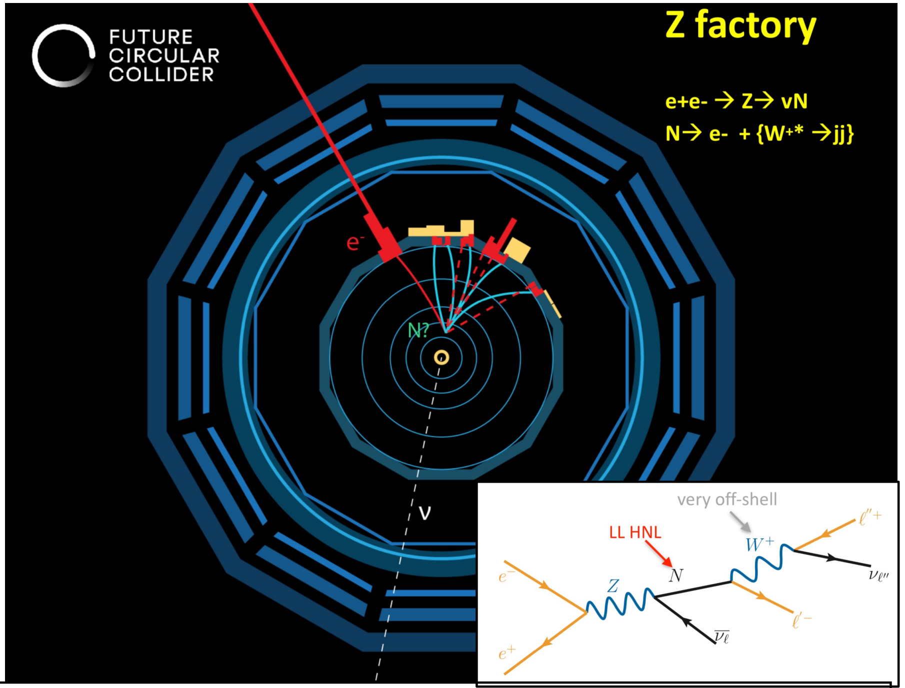
Allow for several additional EW measurements in the strange sector
Never done at LEP / SLC

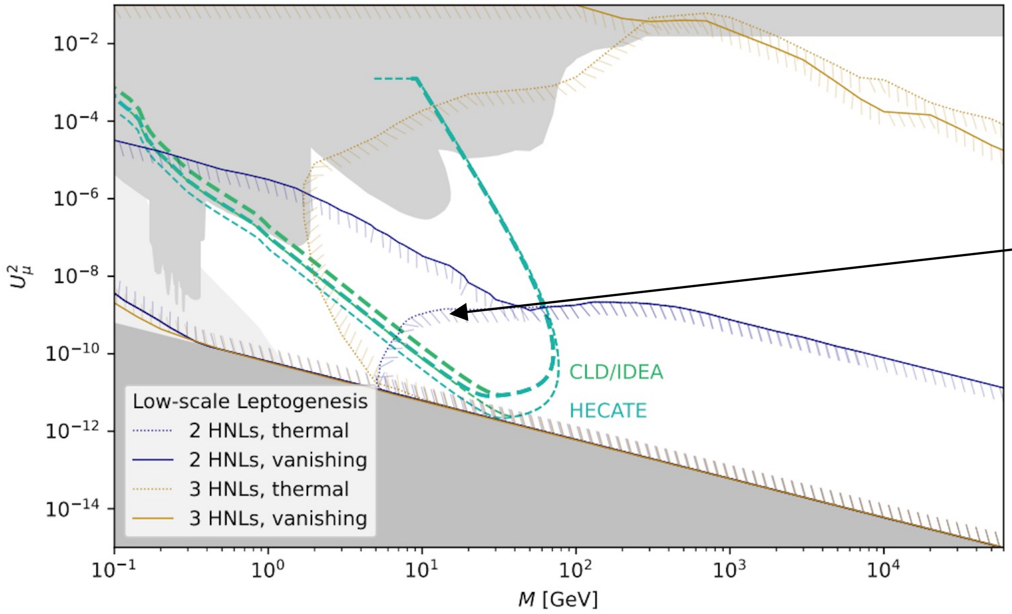
Allow for gluon fragmentation studies with a pure H → gg sample
e.g., with a tag-and-probe selection

BSM: Direct search for feebly interacting light particles

- Fully exploit the intensity frontier to look for
  - Heavy neutral leptons (HNL)
  - Action-like particles (ALPs)
  - Higgs boson with exotic decays to LLPs
- Realistic case studies in FCCSW, with background
  - To possibly design (large) detectors with LLP in mind

J. Alimena
S. Kulkarni





- If HNL signal is detected
  - Design optimal variables to disentangle Dirac from Majorana HNL
    - Different angular distributions
    - Different polarisation distribution
  - More to come soon – stay tuned !

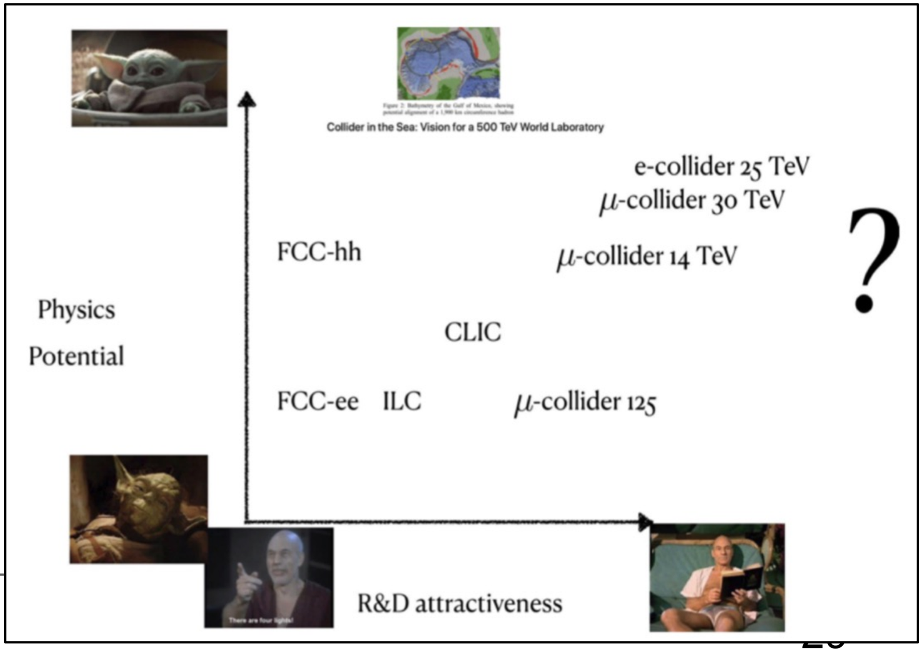
Convincing the community, convincing the world

- **The physics prospects of FCC appear to me vast**
  - **They seem to be addressing some of the most important questions in nature**
    - Exploiting maximally the complementarities and synergies of both the intensity and energy frontiers
- **But this view is not shared by all : The CERN research director told us (Feb. 2022)**

> I strongly believe that we have to strengthen and sharpen our physics arguments
> - Just higher precision is not enough! Sharpen the physics case for FCC!
> - What are the connections to the really big fundamental questions and miracles of the Universe?

- **Possible hints for an explanation**
  - **In the Snowmass presentation (Monday), this plot was shown**
    - The FCC-ee physics potential is not appreciated / understood
    - The FCC R&D is not felt attractive
    - The FCC-ee and FCC-hh are not part of a single project
  - **In this talk, FCC-hh, CLIC, μ coll. were called BSM colliders**
    - The FCC-ee is, consequently, viewed as a SM collider?
      - → Precision frontier sensitivity
      - → Feebly interacting particles

      Not on par with energy frontier



Convincing the community, convincing the world

- A round table was organised on Wednesday by Matthew Chalmers with this topic
  - "Is the FCC physics case sharp enough?"
    - Panelists: Rebeca Gonzalez Suarez – Bruno Mansoulié – Oliver Buchmueller – Patrice Verdier

- Rebeca summarized the FCC physics case in a creative and effective manner
  - The panelists were then asked to give (and explain) their opinion about it
    - "I think the FCC physics case is very strong and very sharp"
    - "The FCC physics is compelling – I am fully supportive"
    - "The FCC scientific case is great – we are lucky to be able to think of such a project"

These are very strong and positive statements

- The FCC physics case seems to need no specific sharpening
  - The rest of the discussion went on to understand what is not convincing about the FCC
    - Which in turn will help us to tune our message to the community and to the world

Convincing the community, convincing the world

Young physicists not excited about "A repeat of LEP and LHC".

The timescales are such that it is not obvious to maintain a community for so long

Maintain other collider projects – be it at the R&D level : Diversity is important

Recruiting the best students have become much harder.

Competition with new developments in fundamental physics, which may give faster returns
Gravitational waves, Quantum technology, …

Compare expected FCC scientific outcomes (and timescales) with other projects in the discipline
HL-LHC, DUNE, CTA, LSST, DARKSIDE/DARWIN …

Put FCC in the bigger picture: where is high-energy physics heading to?
How does it articulate with cosmology ? With other physics domains ?

How are we going to avoid the SSC fate?

Importance for young physicists to take ownership of the project, to engage with interesting and rewarding work

Flow of the project
2045 … 2070 …
And that's it ?

Find easy-to-remember slogans and killer apps about FCC

Change the name: "Future" sounds like it will not happen. It IS happening.
"Circular" automatically recalls "Linear"
Make the name concrete and unescapable

Convincing the community, convincing the world

- A number of suggestions were already made yesterday to improve the "convincing"
  - We should think of what was said and come with a message that addresses all concerns
    - "FCC: Your questions answered" is a title that is already taken
      - → But we can happily give up the copyright
  - We should not by shy in emphasising the immense breadth and richness of the program
    - Very lively and diverse program for FCC-ee, with changes almost every year
    - Tremendous high-energy prospects for FCC-hh
    - Challenging R&D for FCC-ee and FCC-hh detectors, in order to approach the frontiers
    - More scientific topics that one can imagine, with likely O(10^4) publications (starting now)
    - Program conducted by O(10) separate experiments, addressing the full range of HEP
  - Certainly, we should start putting more efforts in spreading the word
    - Within the community and outside