Karlsruhe Institute of Technology

Institute for Data Processing and Electronics

Physics Program
Grand Vision

Frank Simon

FCC Physics Workshop, January 2024

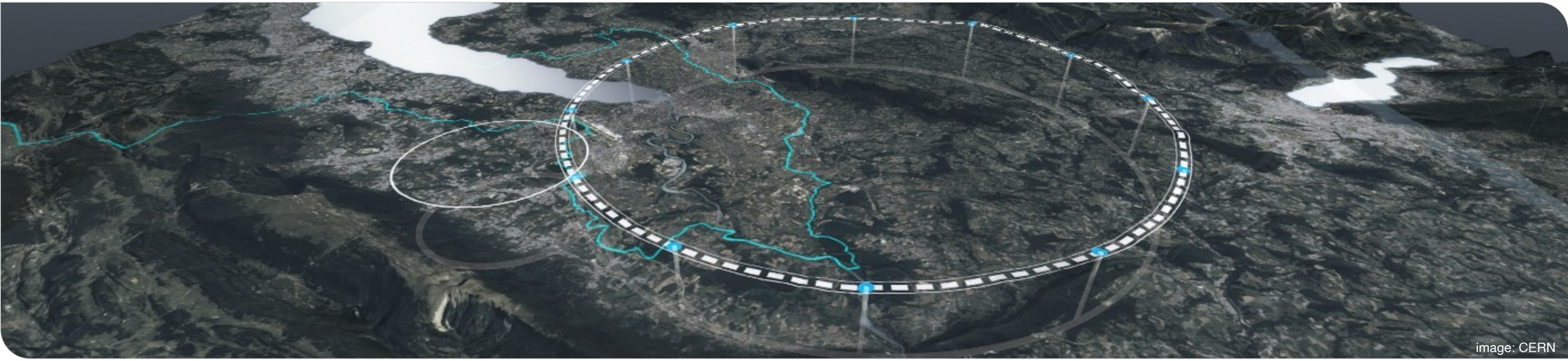

image: CERN

Disclaimer

- By construction, this talk is not free from bias - my own views and interpretations - also with the intent to trigger discussion!

The Physics Program of a ***Higgs***-*Top-Electroweak* Factory

as I have often framed it.

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A program of precision and discovery

The Higgs Boson

model-independent study
of all accessible couplings

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a precise measurement of its properties.
A possible window to new physics due to its high mass!

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New Particles

searches for weakly coupled new particles with high luminosity / high energy in a clean environment

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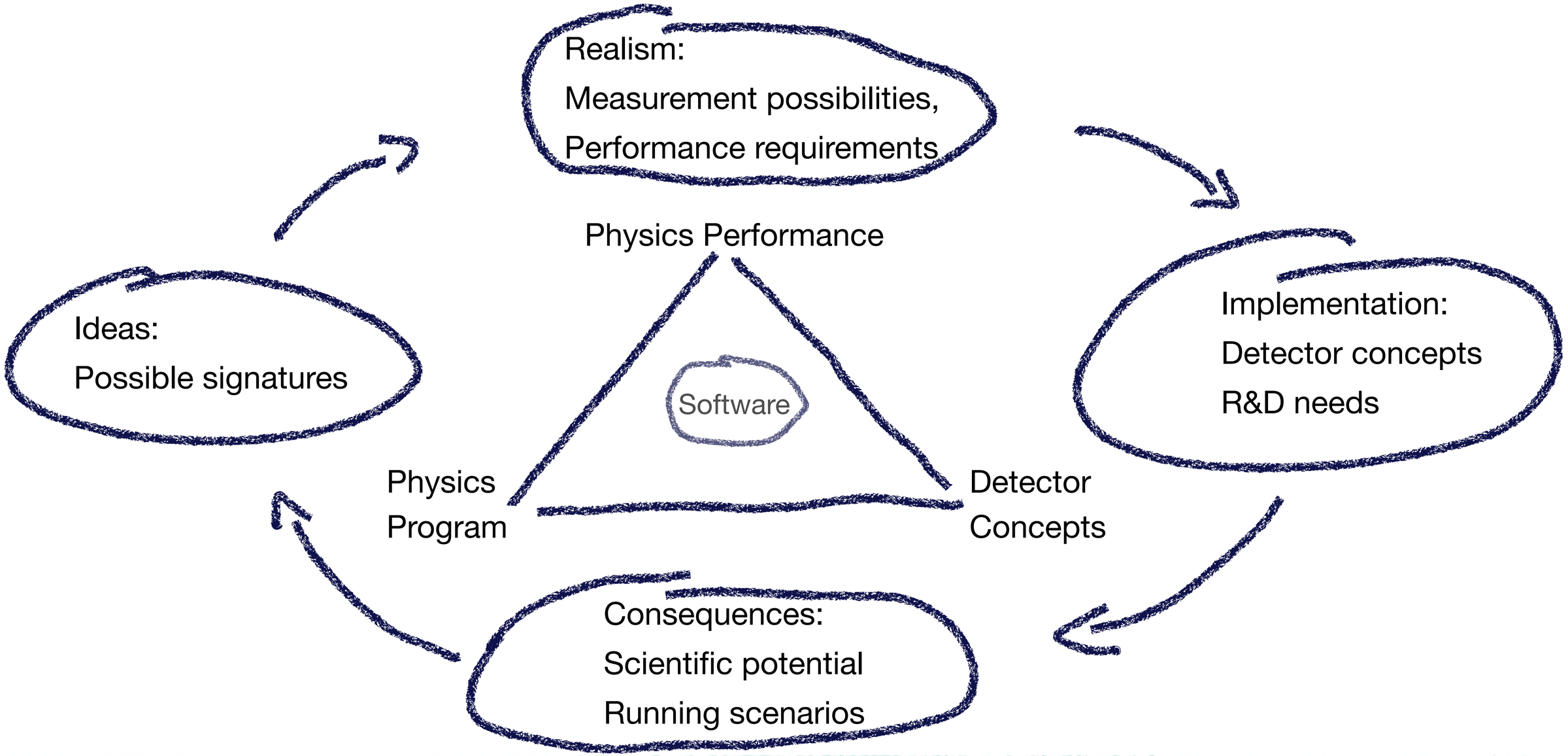
What we set out to do: Sharpening the Physics Case

My Summary Slide from 2 Years ago



Where we are today: The Physics Program of FCC-ee

After years of effort within the Feasibility Study

- The physics case has evolved substantially. Emphasis of the high-luminosity Z-pole program has increased - and the potential of this program is now much better understood.

  FCC-ee is not *just* a ***Higgs Factory*** - really a ***Higgs-Electroweak-Top Factory*** in the literal sense.

  This changes my picture: From Higgs-centric to two / three main pillars.

The Physics Program of a ***Higgs-Top-Electroweak*** Factory

How I see it today

Frank Simon (frank.simon@kit.edu)

The Physics Program of a ***Higgs-Top-Electroweak*** Factory

How I see it today

Karlsruhe Institute of Technology

Electroweak Pillar

Electroweak Precision & Discovery

Precision measurements as a probe of New Physics at high scales.

Flavour Physics

The next generation Flavour Factory: Solving flavour puzzles with extreme statistics (10x Belle II).

Direct Searches

Weakly coupled lighter BSM particles with high statistics.

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Precise and theoretically well-defined measurement of top quark mass.

Top as a BSM probe: Sensitivity due to high mass.

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The Higgs Width:

Connects higher-E pillars!

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The combination of all three pillars provides compelling discovery potential - and you need all three to cover the broadest possible range.

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None of this is new: Physics Thrusts mapped to Energy

Flashback to WS 2 Years ago

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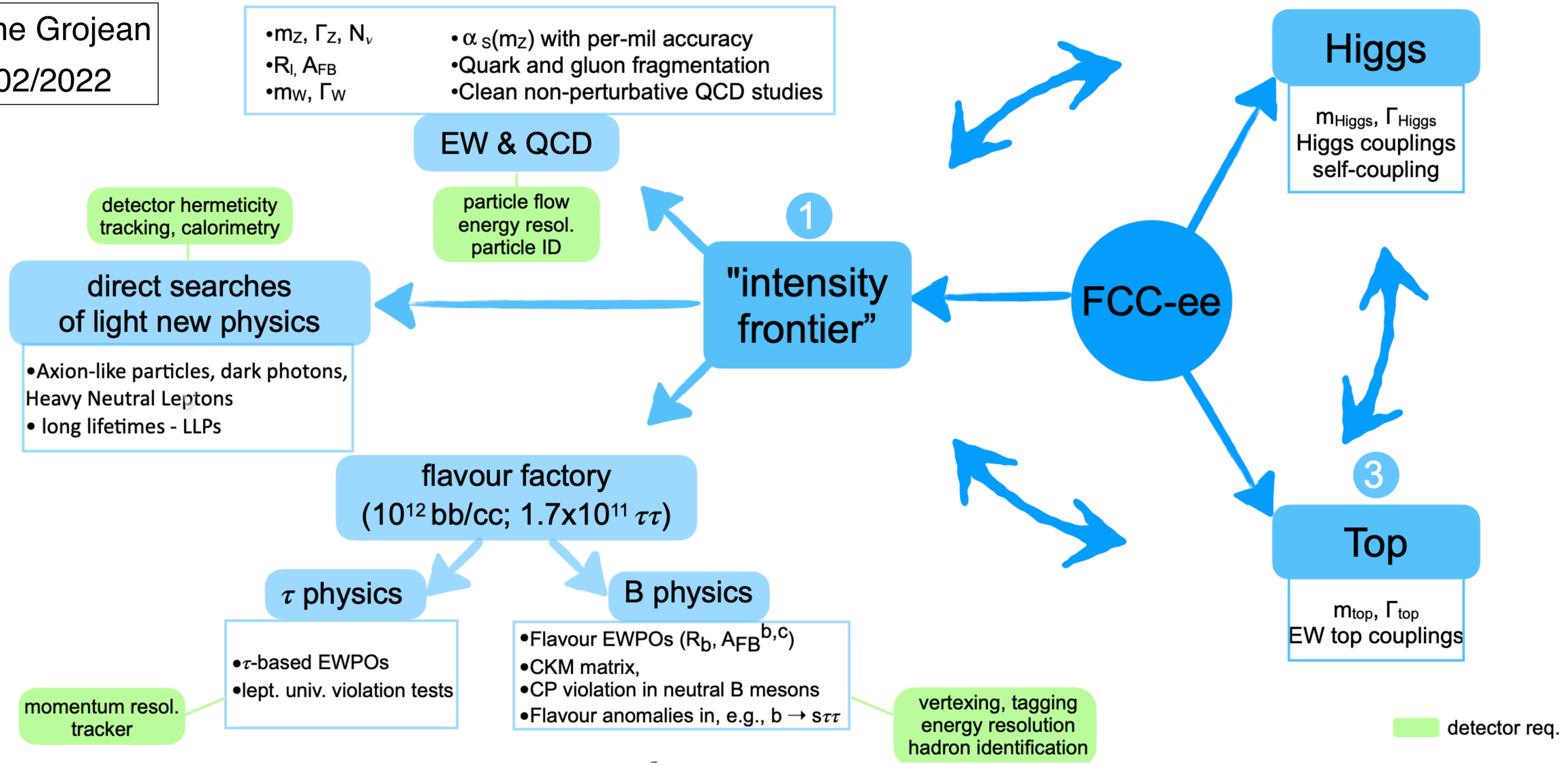
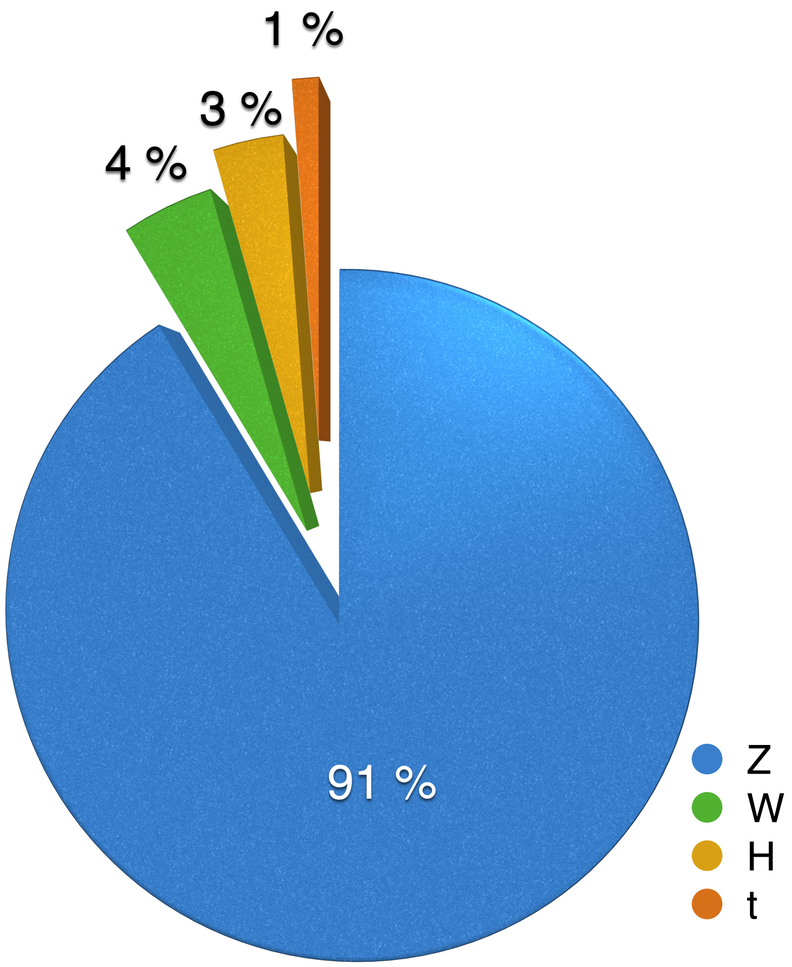
Christophe Grojean
Krakow, 02/2022



The Physics Program of FCC-ee

Seen through Integrated Luminosity & Running Time

Integrated luminosity



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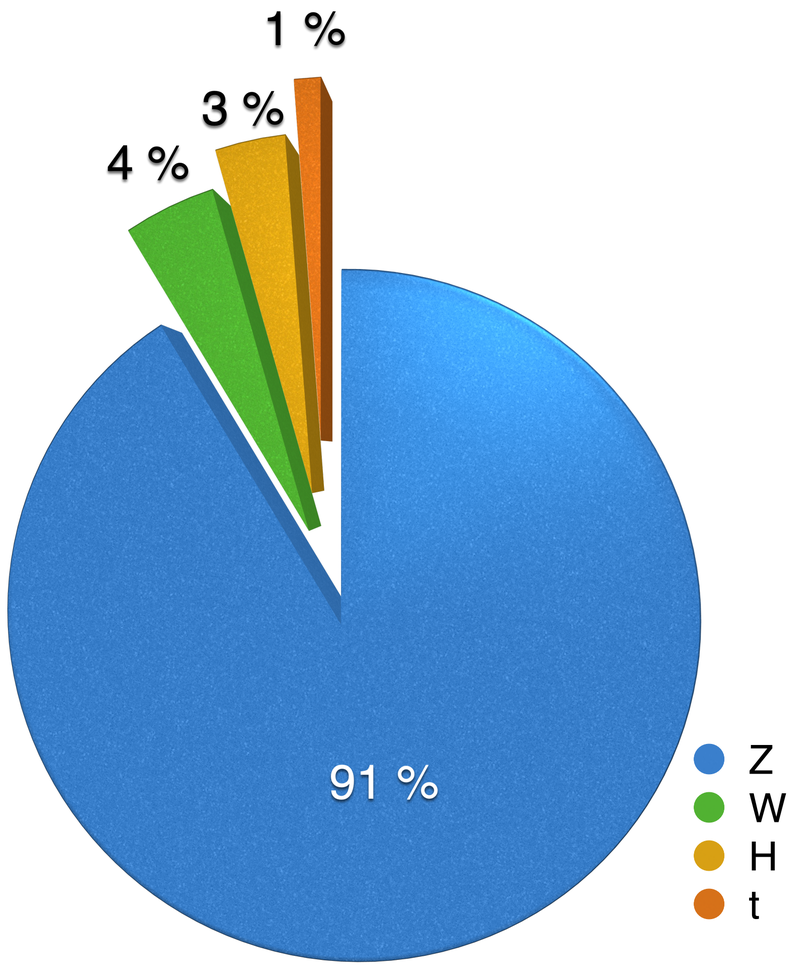
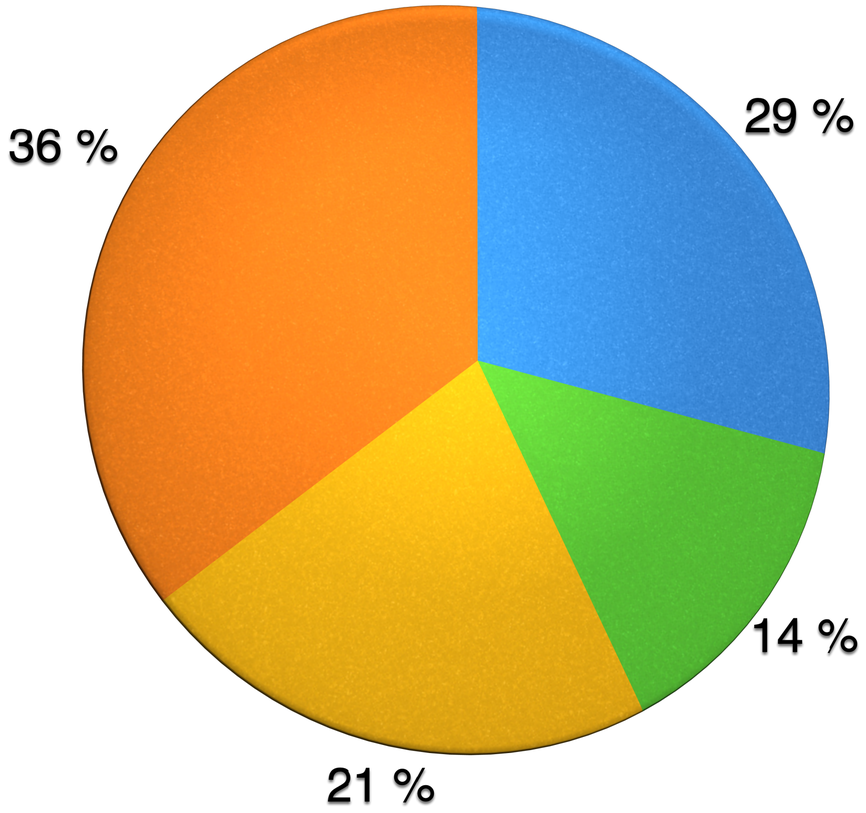


Running time:



35% of running time for electroweak & flavour

21% of running time for Higgs precision in ZH

36% of running time for Top (+ Higgs)

The Physics Program of FCC-ee

Flexibility & Opportunities

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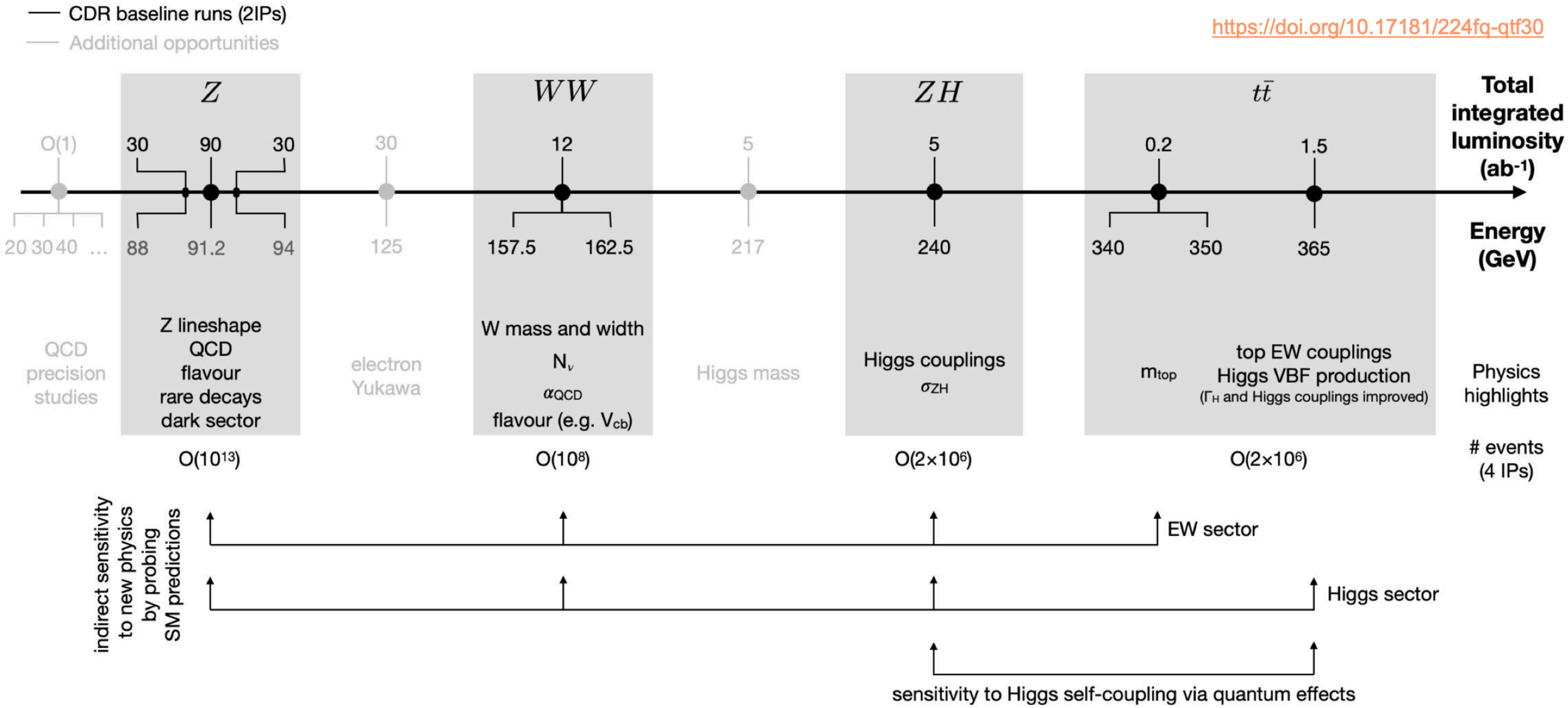
- The physics program is *not* static: Can react to developments - both on physics and on technology - in different ways: A highly *flexible* facility.

Christophe Grojean, Monday



Convincing the Community

Are we there yet?

Karlsruhe Institute of Technology

Frank Zimmermann, Monday, citing Fabiola Gianotti

FUTURE CIRCULAR COLLIDER

Why FCC ?

F. Gianotti

1) **Physics : best overall physics potential of all proposed future colliders; matches the vision of the 2020 European Strategy:** "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."

- ❑ FCC-ee : **ultra-precise** measurements of the Higgs boson, indirect exploration of next energy scale (~ x10 LHC)
- ❑ FCC-hh : **only** machine able to explore next **energy frontier** directly (~ x10 LHC)
- ❑ Also provides for heavy-ion collisions and, possibly, ep/e-ion collisions
- ❑ **4 collision points** → robustness; specialized experiments for maximum physics output

[…]

Is it feasible? Isn't it too ambitious?

-- Ongoing Feasibility Study showing spectacular progress

-- **FCC is big and audacious project, but so were LEP and LHC when first conceived** → they were successfully built and performed far beyond expectation → demonstration of capability of our community to deliver on very ambitious projects

-- FCC is the **best project for future of CERN** (for above reasons) → **we have to work to make it happen**

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The physics arguments in combination with the conclusion are not yet fully accepted in all parts of the community:

Make the case clearer, not just to the outside, but also to our peers!

Evolution of our View of FCC Physics

Very few selected impressions from the Workshop

Bringing the Power of Tera-Z into Focus

Discovery Potential at High Scales

- The Tera-Z program is not “just” the LEP program with higher statistics - today we also have more interpretation approaches [also applied to LEP measurements…]
  … and a very interesting set of experimental challenges!

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Sophie Renner, Tuesday

Question: what classes of models can/ cannot run into these at one loop?

Out of 2499 coefficients in dimension 6 SMEFT, 23 enter Z pole at tree level

$\{C_{HWB}, C_{HD}, C_{Hl}^{(1)}, C_{Hl}^{(3)}, C_{Hq}^{(1)}, C_{Hq}^{(3)}, C_{Hu}, C_{Hd}, C_{He}, C'_{ll}\}$

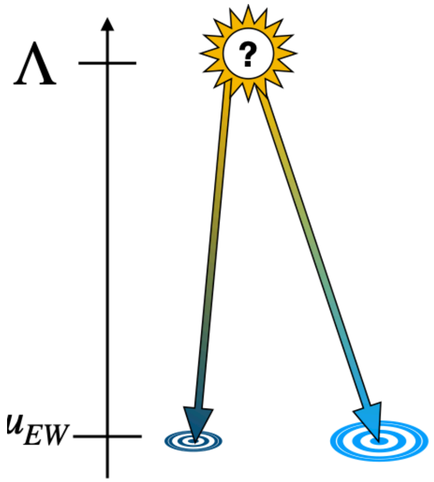
$\propto S$

$\propto T$

shift Z-fermion couplings

induces muon decay

$\Longrightarrow$ shifts G_F



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How much of the space of TeV-scale new physics will be explored by a Tera-Z run?

Sophie Renner, Tuesday

Within SMEFT

Not much: operators with non-zero flavour charges cannot run at one loop into Z pole operators (except by amounts ∝ small Yukawas)

In tree level UV completions

Possibly most: UV completions inevitably populate flavourless operators

But loopholes can be found which ensure cancellations in the RGEs

How generic are these loopholes? To be continued…

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Ben Stephanek, Tuesday

- In all models solving the hierarchy problem and/or flavor puzzle, there is NP coupled to the Higgs, making EWPT a powerful probe. But even without direct Higgs couplings, EWPTs unavoidably give strong bounds on a large class of operators via RG evolution.
- Because EWPT are much more flavor democratic, not even third family NP can hide. A future tera-Z machine will probe NP protected by the accidental symmetries of the SM in the 10-50 TeV range. In this sense, it seems clear that FCC-ee is the best way forward.

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Tera-Z as a Discovery Tool:
Discovering (or excluding) new physics up to scales of 50 TeV - with very high coverage.

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Revisiting the Higgs Program

Bringing more Realism to the Projections

Karlsruhe Institute of Technology

Nicolas Morange, Thursday

	HL-LHC (*)	FCC-ee
$\delta\Gamma_H / \Gamma_H$ (%)	SM (**)	1.3
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	0.17
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	0.43
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	0.61
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	1.21
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	1.01
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	0.74
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	4.3	9.0
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	1.8	3.9
$\delta g_{Htt} / g_{Htt}$ (%)	3.4	–
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–
$\delta g_{HHH} / g_{HHH}$ (%)	50	~40 (indirect)
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	< 1%

How do we get this ?

$$\Gamma_H \propto \frac{\sigma^2_{ZH}}{\sigma_{ZH,H(ZZ^*)}}$$

- Through $ZH \rightarrow ZZZ^*$
  - Most straightforward
  - Recoil analysis gives σ_{ZH} hence g_Z
  - Then ZZZ* gives BR(ZZ*) hence Γ_H
  - ~2-3% precision expected
- Through VBF
  - A bit more convoluted
  - Combine ZH cross-section, BR(bb), BR(WW*) at 240 GeV, and WW→H→bb at 365 GeV
  - 1-2% precision expected

$$\frac{\sigma(ZH \rightarrow bb)\sigma(ZH \rightarrow WW^*)}{\sigma(\nu\nu H \rightarrow bb)\sigma(ZH)^2} \propto \Gamma_H$$

- Seen a revival of concrete studies.

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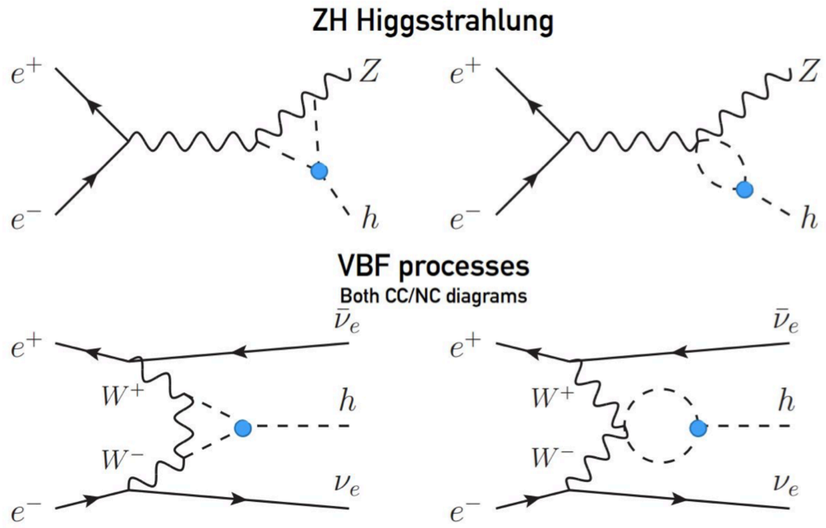
$$\frac{\sigma(ZH \to bb)\sigma(ZH \to WW^*)}{\sigma(\nu\nu H \to bb)\sigma(ZH)^2} \propto \Gamma_H$$

Getting a first (indirect) measurement of κ_λ

~ 24% with 4 IPs (combining 240 GeV and 365 GeV measurements



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Jan Eysermans, Thursday

Connecting to Big Questions

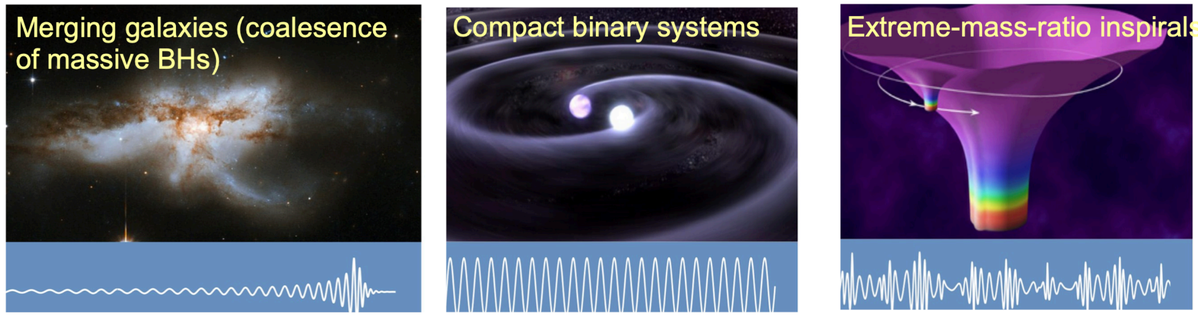
FCC-ee Discovery Stories in a bigger Context

Karlsruhe Institute of Technology

- Looking beyond particle physics:

Germano Nardini, Tuesday

With new instruments available on / before the time scale of FCC-ee, gravitational wave physics will also enter a new era



Comprehensive exploration of astrophysical objects, potential to discover (or bound) Stochastic Gravitational Wave Background

=> Links to BSM models - possible interplay with FCC-ee observables.

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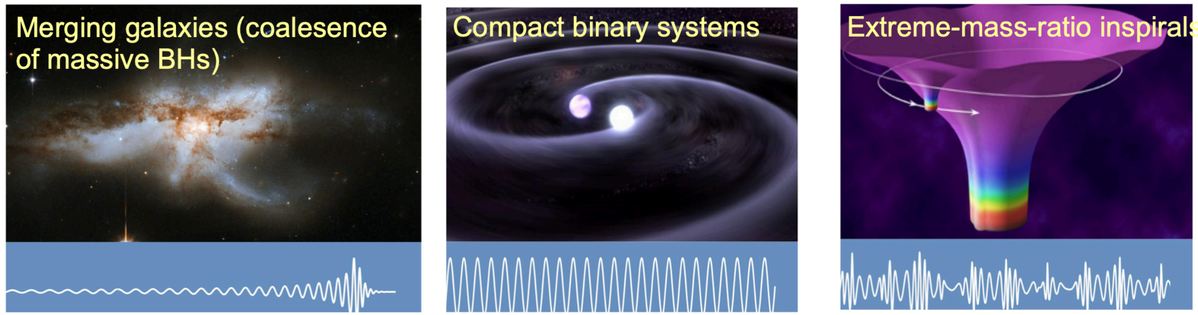

  Comprehensive exploration of astrophysical objects, potential to discover (or bound) Stochastic Gravitational Wave Background
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- Putting FCC-ee measurements in bigger contexts: Questions of Naturalness, electroweak phase transition in the early Universe, ….

  Oleksii Matsedonskyi, Tuesday

  Gauthier Durieux, Tuesday

  Ennio Salvioni, Thursday

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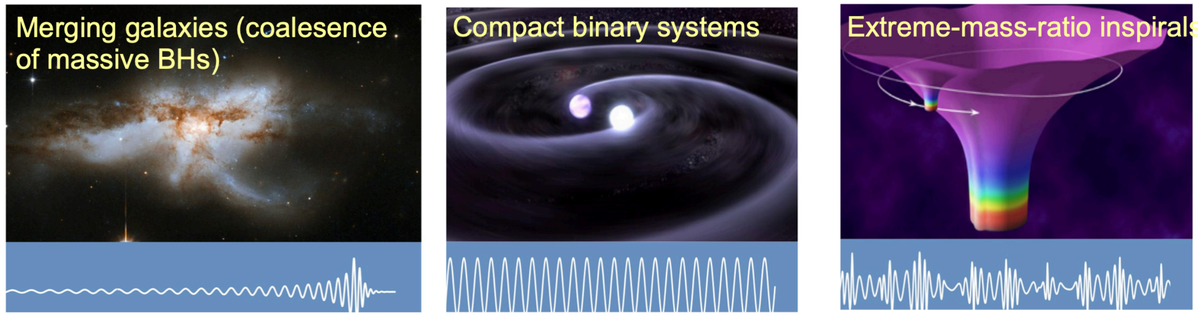

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Oleksii Matsedonskyi, Tuesday

Gauthier Durieux, Tuesday

Ennio Salvioni, Thursday

Giacomo Cacciapaglia , Thursday

Opportunities to tie this together into a global picture,

and to further understand the role all FCC-ee measurements can play in this!

…

Moving forward with the Physics Program of FCC-hh

Understanding the role of energy

- FCC-hh: Completing the Higgs program. A precise measurement of κ_λ

100 TeV	s ⊕
stat	3.0
syst	1.6
tot	**3.4**

80 TeV	s ⊕
stat	3.5
syst	1.6
tot	**3.8**

120 TeV	s ⊕
stat	2.6
syst	1.6
tot	**3.1**

=> more is better - but below 5% achievable with the right detector performance!

Michelangelo Mangano, Thursday

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S-channel resonances

	100 TeV	80 TeV	120 TeV
Q*	40	33	46
$Z'_{TC2} \to tt$	23	20	26
$Z'_{SSM} \to tt$	18	15	20
$G_{RS} \to WW$	22	19	25
$Z'_{SSM} \to ll$	43	36	50
$Z'_{SSM} \to TT$	18	15	20

- **10-15% reach increase at 120 TeV**
- **15-20% reach loss at 80 TeV**

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- **10-15% reach increase at 120 TeV**
- **15-20% reach loss at 80 TeV**

- For the key "guaranteed deliverables", the difference between 100 and 80 TeV is comparable to the detector performance projection uncertainties. The loss in rate is in the range of 20-30% for key observables, with minor impact on measurements that by and large tend to be systematics-dominated

  ➡ investing in detector performance is more effective than pushing the magnet technology 14→16 T

Michelangelo Mangano, Thursday

Wrapping Up

My Impressions

- The understanding of the *Physics Program* at FCC has made significant progress since the start of the FS.

  Have built a compelling scientific case for all energy stages of FCC-ee:

  FCC-ee now strongly stands on its own as a facility worth building.

Wrapping Up

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  Have built a compelling scientific case for all energy stages of FCC-ee:
  FCC-ee now strongly stands on its own as a facility worth building.

- We still have to do better in reaching out outside of our own bubble: Make the discovery potential of all FCC-ee stages, in particular that of the Z-pole, easily accessible to the community.

  Tell *discovery stories* that are not lost in technical, theoretical detail.
  Connected to interesting analysis and detector challenges.

Wrapping Up

My Impressions

- The understanding of the *Physics Program* at FCC has made significant progress since the start of the FS.

  Have built a compelling scientific case for all energy stages of FCC-ee:
  FCC-ee now strongly stands on its own as a facility worth building.

- We still have to do better in reaching out outside of our own bubble: Make the discovery potential of all FCC-ee stages, in particular that of the Z-pole, easily accessible to the community.

  Tell *discovery stories* that are not lost in technical, theoretical detail.
  Connected to interesting analysis and detector challenges.

Now we have to make it happen:

FCC-ee as the right next machine - with a broad, and *flexible* program of precision and discovery that fully stands on its own.

And opens up a path to the next energy frontier - scientifically, and through reusable infrastructure.

We need the whole community to do it!