Région Autonome Vallée d'Aoste
Regione Autonoma Valle d'Aosta
Assessorat de l'Éducation et de la Culture
Assessorato Istruzione e Cultura

CERN

A perspective on future colliders

Les Rencontres de Physique de la Vallée d'Aoste
La Thuile
15 Marzo 2025

Michelangelo Mangano
CERN TH

Outline

- The science goals of a future collider
- The criteria driving the choice of a future collider
- Focus on FCC, CERN’s proposed Future Circular Collider facility
    - physics programme
    - technical challenges and status of the project

All of this in the context of the ongoing (2025-26)
Update of the European Strategy for Particle Physics

2012

Contents lists available at SciVerse ScienceDirect
Physics Letters B
www.elsevier.com/locate/physletb

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

Contents lists available at SciVerse ScienceDirect
Physics Letters B
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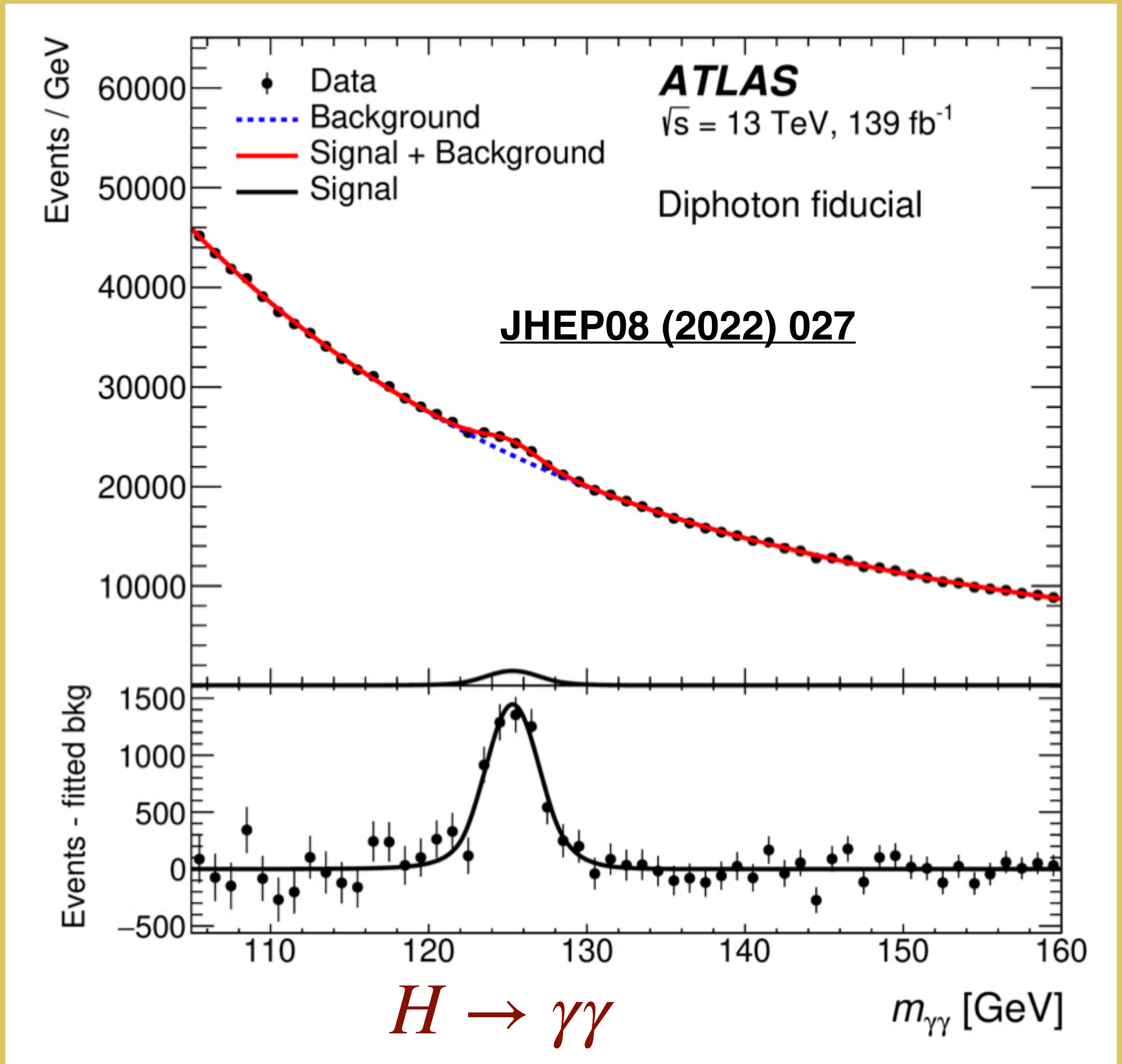
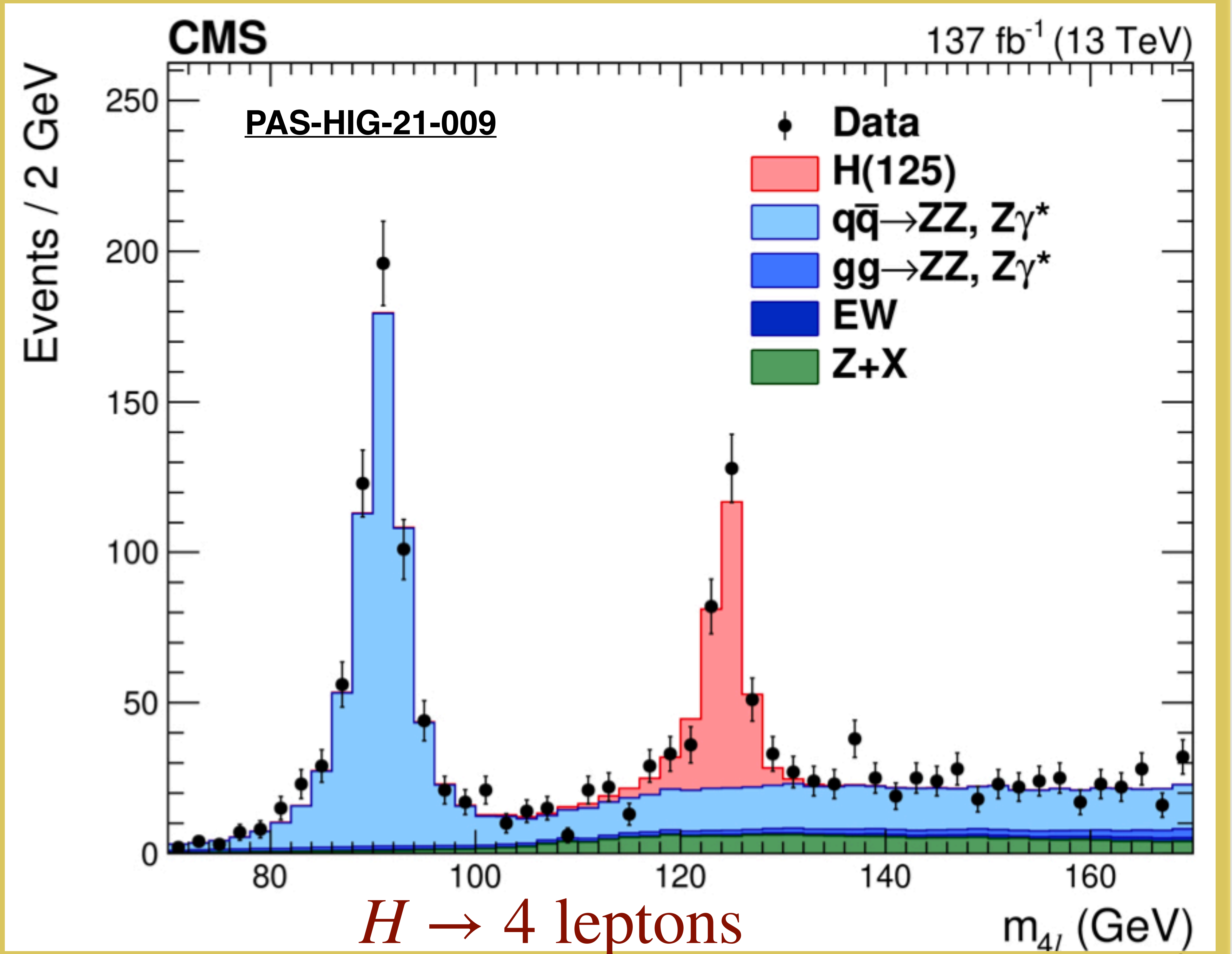
Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *

2023





Why future colliders, beyond the LHC ?

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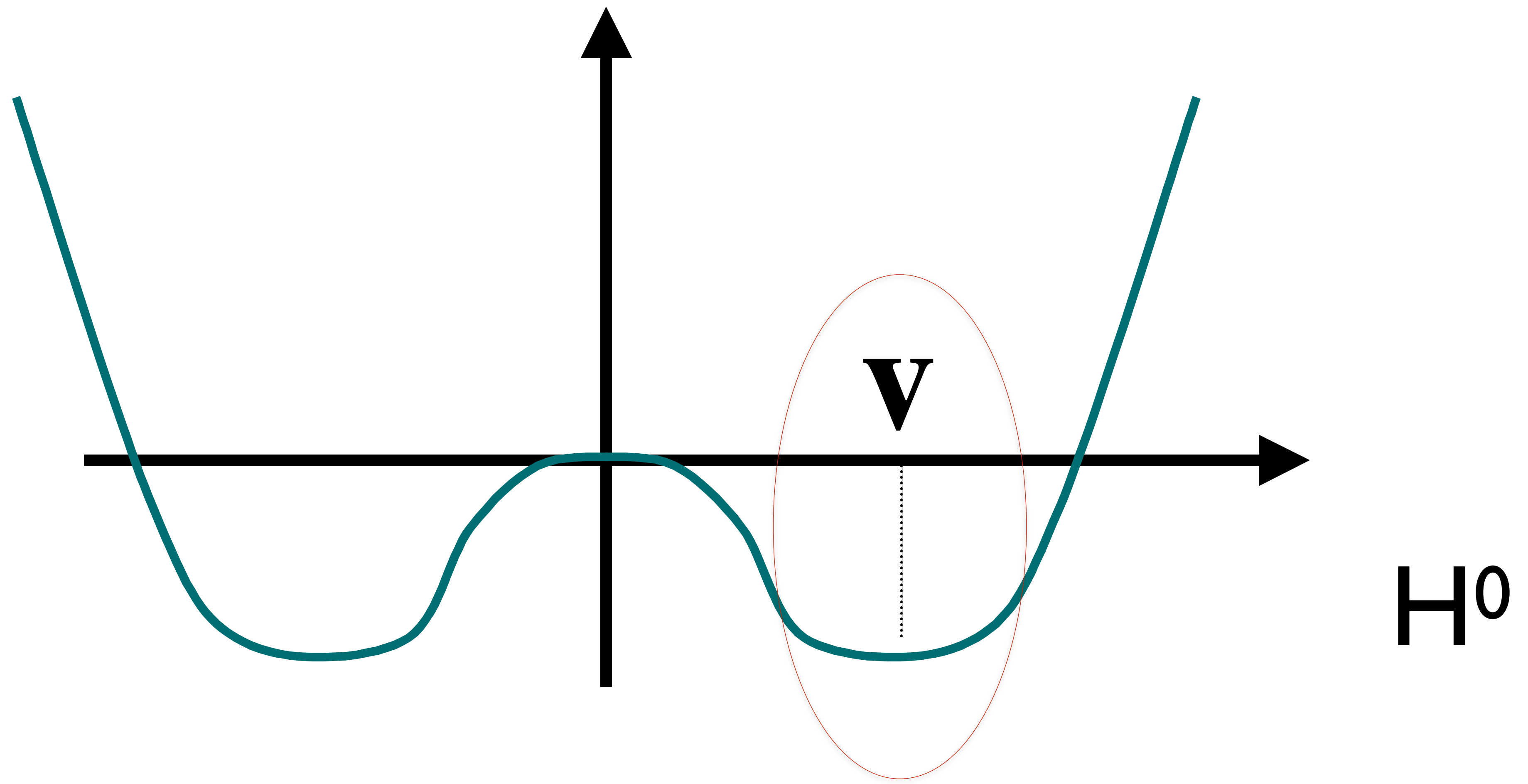
because we are not done !



$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

Where does this come from?

The Higgs mechanism* , as implemented in the SM (*á la Weinberg, 1967*), provides the *minimal* set of *ingredients* required to enable a consistent breaking of the EW symmetry.

* Higgs, Brout, Englert, Guralnik, Hagen, Kibble 1964

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Eg, *is m_H calculable from 1^{st} principles*?

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a historical example: superconductivity

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- The relation between the Higgs phenomenon and the SM is similar to the relation between superconductivity and the Landau-Ginzburg theory of phase transitions: a quartic potential for a bosonic order parameter, with negative quadratic term, and the ensuing symmetry breaking. If superconductivity had been discovered after Landau-Ginzburg, we would be in a similar situations as we are in today: an experimentally proven phenomenological model. But we would still lack a deep understanding of the relevant dynamics.

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- For superconductivity, this came later, with the identification of e^-e^- Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in both cases we have no clue as to what is the dynamics that generates the Higgs potential. With Cooper pairs it turned out to be just EM and phonon interactions. With the Higgs, none of the SM interactions can do this, and **we must look beyond.**

examples of possible scenarios

- **BCS-like**: the Higgs is a composite object … m_H can be calculated like the pion mass in QCD

- **Supersymmetry**: the Higgs is a fundamental field and
  - $\lambda^2 \sim g^2+g'^2$, it is not arbitrary (MSSM, w/out susy breaking, has one parameter less than SM!)
  - potential is fixed by susy & gauge symmetry
  - EW symmetry breaking (and thus m_H and λ) determined by the parameters of SUSY breaking

- …

other important questions in particle physics are still open

- What's the origin of
  - DM,
  - neutrino masses,
  - the baryon asymmetry of the Universe,
  - the flavour structure and hierarchy,
  - …

hints or answers to these may come from a vast multitude of experiments … but for all we know today, only colliders can shed light on the issue of the origin of the Higgs

Other important open issues on the Higgs sector

- Is the Higgs the only (fundamental?) scalar field, or **are there other Higgs-like states** (e.g. $H^{\pm}$, A^0, $H^{\pm\pm}$, ... , EW-singlets, ...) ?
  - Do all SM families get their mass from the **same** Higgs field?
  - Do I_3=1/2 fermions (up-type quarks) get their mass from the **same** Higgs field as I_3=–1/2 fermions (down-type quarks and charged leptons)?
  - Do Higgs couplings conserve flavour? $H \to \mu\tau$? $H \to e\tau$? $t \to Hc$?
- Is there a deep reason for the apparent metastability of the Higgs vacuum?
- Is there a relation among Higgs/EWSB, baryogenesis, Dark Matter, inflation?
- What happens at the EW phase transition (PT) during the Big Bang?
  - what's the order of the phase transition?
  - are the conditions realized to allow EW baryogenesis?

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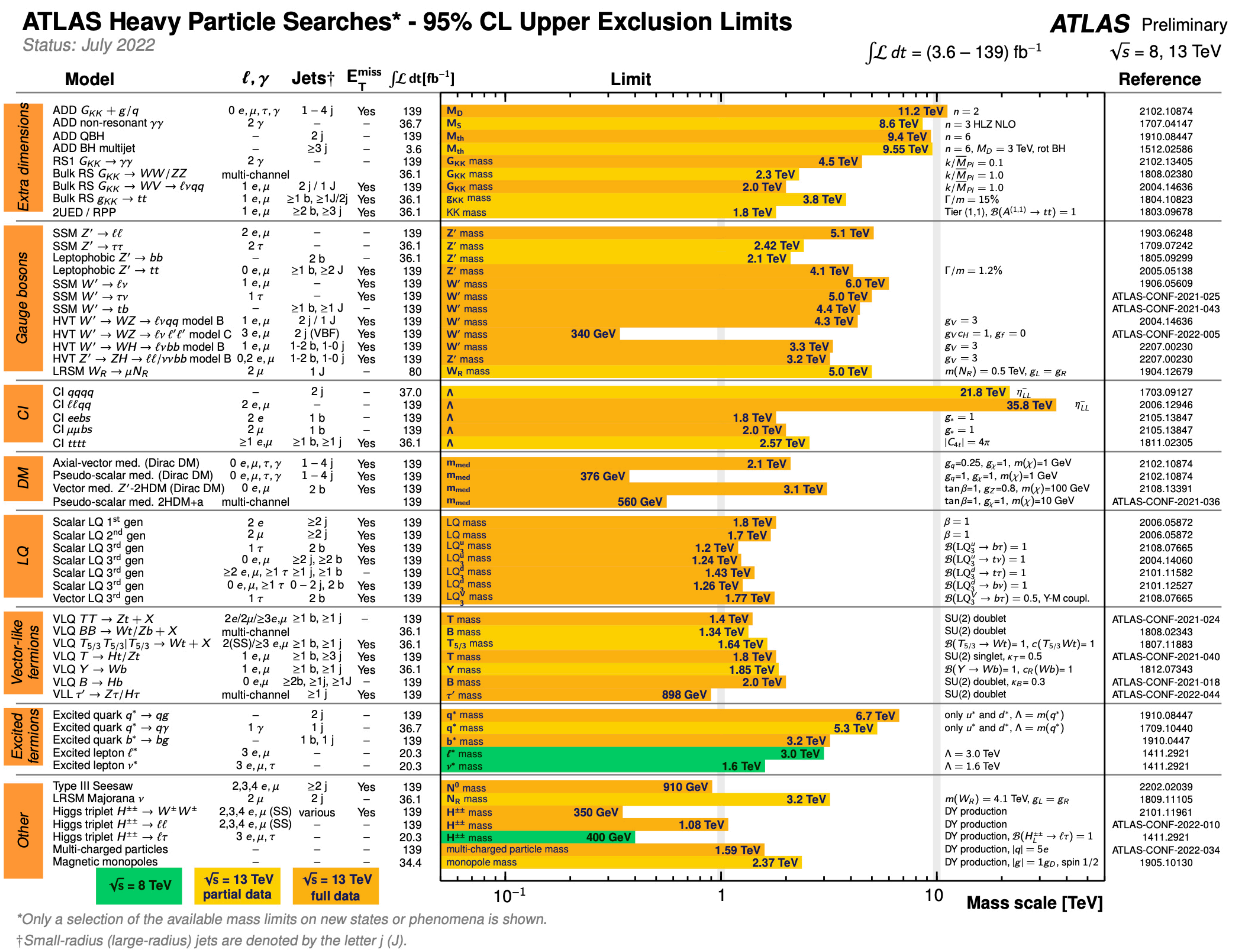
➡ the Higgs discovery does not close the book, it opens a whole new chapter of exploration, based on precise measurements of its properties,
which can only rely on a future generation of colliders

So far, no *conclusive* signal of physics beyond the SM



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we can’t, but that’s not the right question to ask …

progress towards answering questions like the origin of EWSB or of flavour requires a multitude of probes and perspectives, whose interplay and role cannot be anticipated as it will ultimately depend on what is the actual underlying framework.

What features will allow the next accelerator facility to drive this progress?

The physics programme of future colliders should build on 3 pillars

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- The guaranteed deliverables
  - improved measurements of fundamental constants and parameters (eg H couplings)
  - deeper exploration of dynamics of SM interactions, eg
    - EW symmetry breaking and flavour phenomena
    - QCD non-perturbative dynamics
  - *push further the boundary between* ***established*** *facts (e.g. quarks and Higgs are pointlike* ***at scales*** *of (1-10 TeV)$^{-1}$) and* ***conjectures*** *(e.g. quarks and Higgs* ***are*** *pointlike)*

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- The exploration and discovery potential
  - higher precision/sensitivity and higher energy !!
- Conclusive answers to important questions, like
  - Is DM a thermal WIMP ?
  - What was the nature of the EW phase transition ?
  - Does the origin of neutrino masses lie at the TeV scale ?
  - Are the Higgs potential and mass defined by physics at the few-TeV scale ?
  - are there BSM sources of CPV below the few-TeV scale ?

What’s on the table?

Future Circular Collider

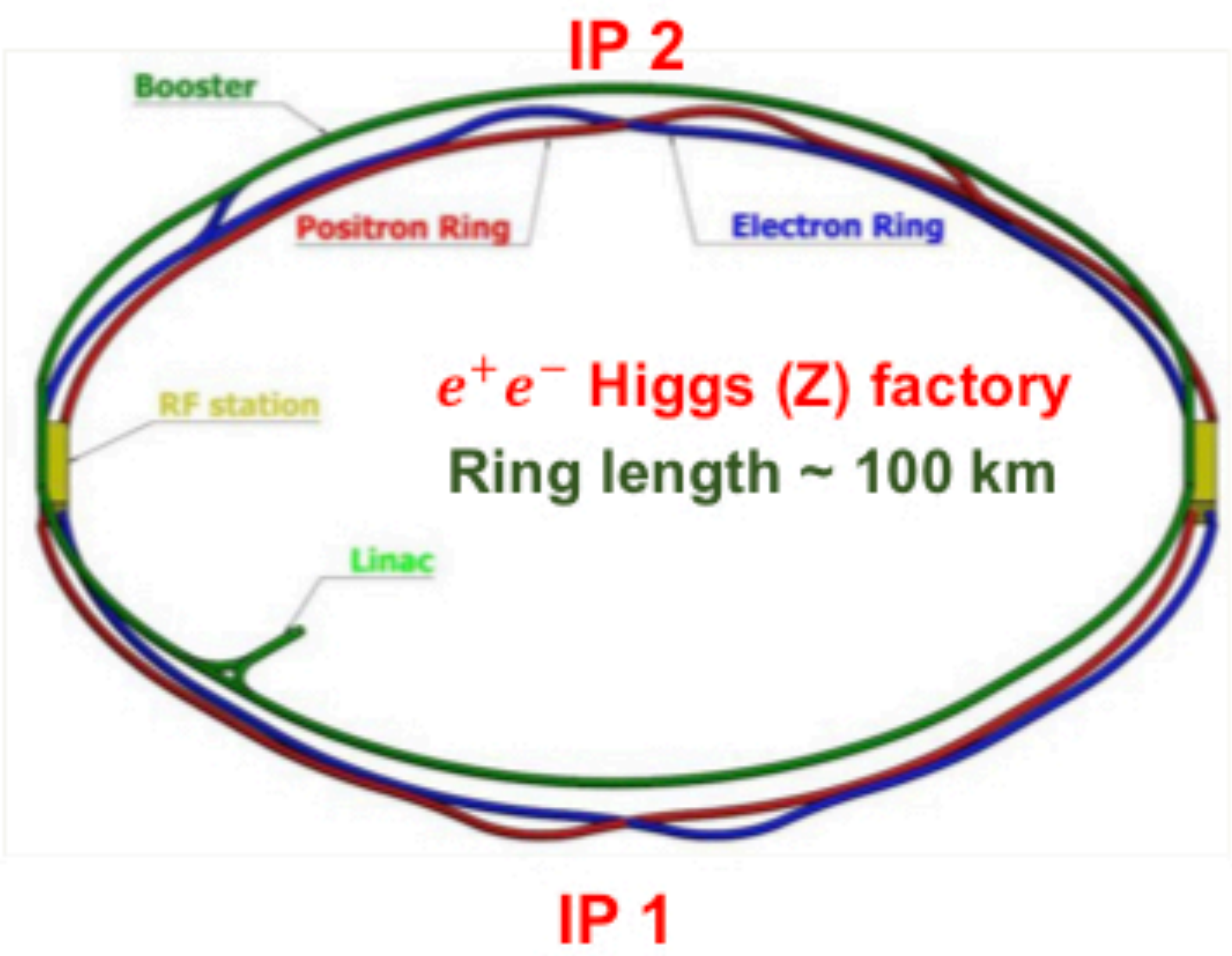
http://cern.ch/fcc

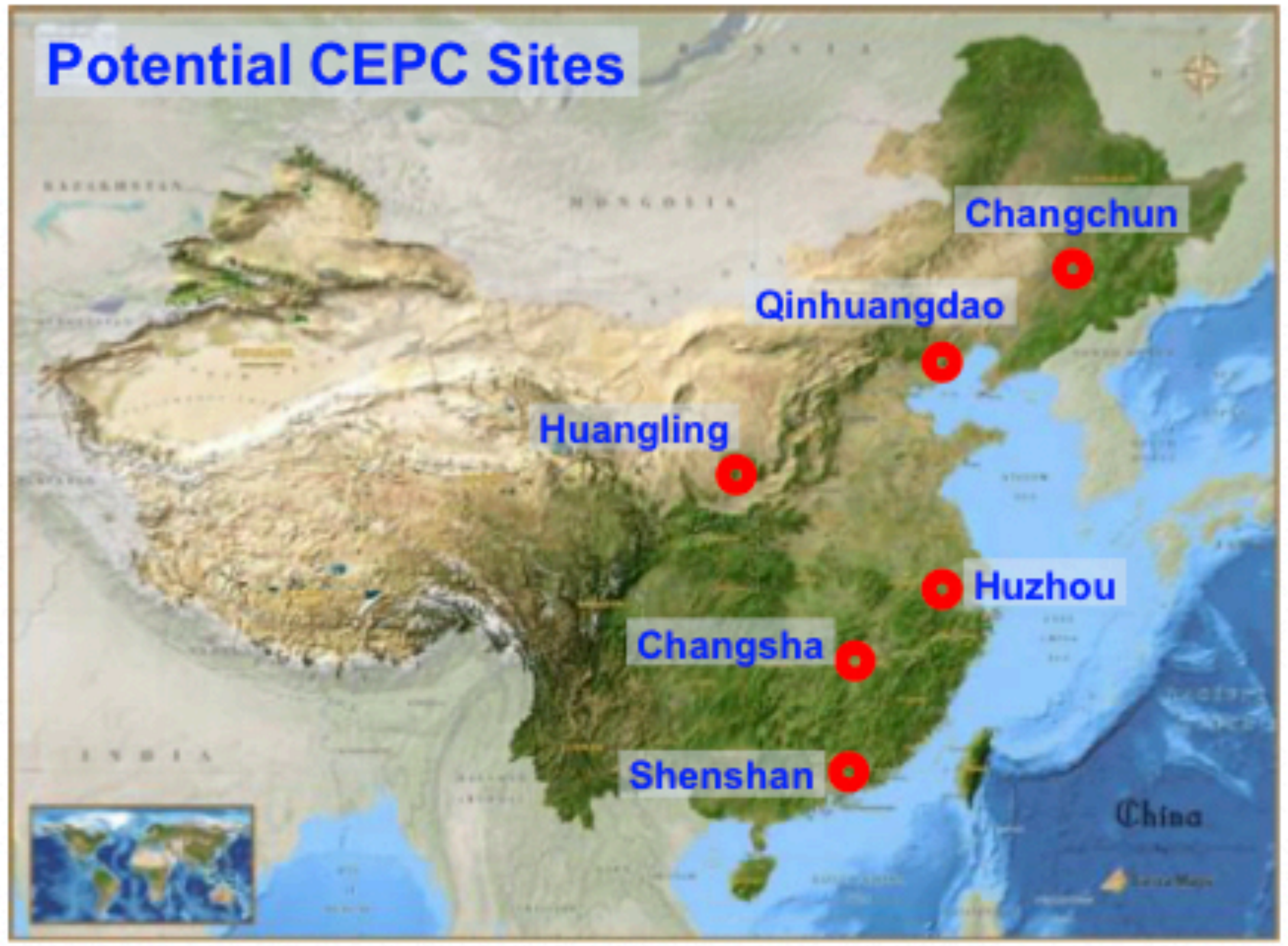
90.7 km tunnel

- FCC-ee: e^+e^- @ 91, 160, 240, 365 GeV
- FCC-hh: pp @ 84 TeV with Nb_3Sn 14 T dipoles
- FCC-eh: $e_{60\mathrm{GeV}}\ p_{50\mathrm{TeV}}$ @ 3.5 TeV

Circular electron-positron Collider

- The CEPC aims to start operation in 2030’s, as a Higgs (Z / W) factory in China.
- To run at $\sqrt{s}$ ~ 240 GeV, above the **ZH** production threshold for ≥1 M Higgs; at the **Z** pole for ~Tera Z; at the **W^+W^-** pair and possible $t\bar{t}$ pair production thresholds.
- Higgs, EW, flavor physics & QCD, probes of physics BSM.
- Possible *pp* collider (SppC) of $\sqrt{s}$ ~ 50–100 TeV in the far future.





[link to CDR]

Linear ee colliders

e^+e^- @ 250, 350, 500 GeV

e^+e^- @ 380 GeV, 1.5 & ~3 TeV

Future Multi-TeV e^+e^- colliders, from plasma wakefield acceleration

The ALEGRO collaboration

https://www.lpgp.u-psud.fr/icfaana/alegro

https://arxiv.org/pdf/1901.08436.pdf

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Table 2.4: LWFA single stage parameters operating at a plasma density of $n_0 = 10^{17}$ cm^{-3}.

Plasma density (wall), n_0[cm^{-3}]	10^{17}
Plasma wavelength, λ_p[mm]	0.1
Plasma channel radius, r_c[μm]	25
Laser wavelength, λ[μm]	1
Normalized laser strength, a_0	1
Peak laser power, P_L[TW]	34
Laser pulse duration (FWHM), τ_L[fs]	133
Laser energy, U_L[J]	4.5
Normalized accelerating field, E_z/E_0	0.14
Peak accelerating field, E_L[GV/m]	4.2
Plasma channel length, L_c[m]	2.4
Laser depletion, η_{pd}	23%
Bunch phase (relative to peak field)	$\pi/3$
Loaded gradient, E_z[GV/m]	2.1
Beam beam current, I[kA]	2.5
Charge/bunch, $eN_b = Q$[nC]	0.15
Length (triangular shape), L_b[μm]	36
Efficiency (wake-to-beam), η_b	75%
e^-/e^+ energy gain per stage [GeV]	5
Beam energy gain per stage [J]	0.75

peak accelerating field: 4.2 GeV/meter

Example parameter sets for 0.25, 1, 3, 30 TeV center-of-mass LWFA-based colliders.

Energy, center-of-mass, U_{cm}[TeV]	0.25	1	3	30
Beam energy, $\gamma mc^2 = U_b$[TeV]	0.125	0.5	1.5	15
Luminosity, $\mathcal{L}[10^{34}$ s^{-1}cm^{-2}]	1	1	10	100
Beam power, P_b[MW]	1.4	5.5	29	81
Laser repetition rate, f_L[kHz]	73	73	131	36
Horiz. beam size at IP, σ_x^*[nm]	50	50	18	0.5
Vert. beam size at IP, σ_y^*[nm]	1	1	0.5	0.5
Beamstrahlung parameter, Υ	0.5	2	16	2890
Beamstrahlung photons, n_γ	0.6	0.5	0.8	2.8
Beamstrahlung energy spread, δ_γ	0.06	0.08	0.2	0.8
Disruption paramter, D_x	0.07	0.02	0.05	3.0
Number of stages (1 linac), N_{stage}	25	100	300	3000
Distance between stages [m]	0.5	0.5	0.5	0.5
Linac length (1 beam), L_{total}[km]	0.07	0.3	0.9	9.0
Average laser power, P_{avg}[MW]	0.3	0.3	0.6	0.17
Efficiency (wall-to-beam)[%]	9	9	13	13
Wall power (linacs), P_{wall}[MW]	30	120	450	1250

Linear Collider Vision

Linear Collider White Papers for the 2025 update of the ESPP

https://agenda.linearcollider.org/event/10624/program

The Linear Collider Facility (LCF) at CERN

Contact persons: Jenny List*, Steinar Stapnes†

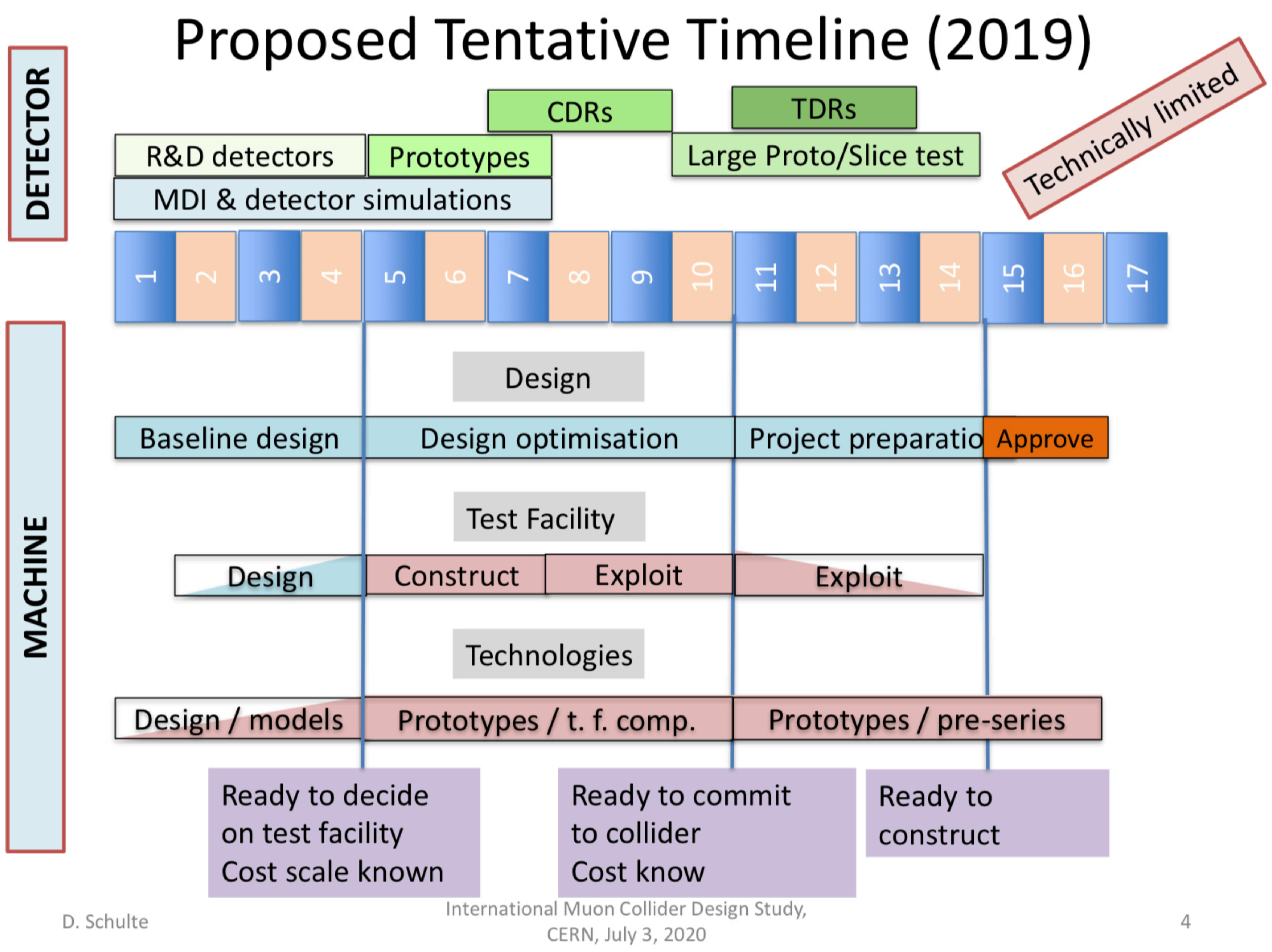
* DESY, † CERN

https://agenda.linearcollider.org/event/10624/attachments/40242/63940/LCF4CERN_10pager_v2.pdf

beyond, with muons (circular)

=> International Muon Collider Design Study* recently set up

Kick-off meeting: https://indico.cern.ch/event/930508/



* *building on 2 decades of preliminary work, notably within the US Muon Accelerator Program (MAP)*

Further options on the table, relying on re-use of LHC tunnel:

- LEP3 (upgrade of LEP2 to 240 GeV)
- HE-LHC (LHC w. new 14 T Nb_3Sn dipoles ~ 24 TeV
- LHeC (ep collider)

To be considered in the ESPPU discussion for scenarios where the FCC tunnel is not feasible — not covered in the following

Non-baseline scenarios for FCC-hh, relying on magnet technologies **less** challenging that the baseline

- 6 T NbTi dipoles => 36 TeV
- 12 T Nb_3Sn dipoles => 72 TeV

.. or **more** challenging that the baseline

- 20 T HTS dipoles => 120 TeV

See material at the end

Remarks on colliders' cross comparisons

- Discovery-reach comparison among different colliders is by and large subjective
  - statements like *"collider A is more/less/as powerful as collider B"* are often of limited value and possibly misleading, unless they refer to the performance for specific new-physics scenarios and observables
- Studies/discovery prospects presented by the proponents of various colliders typically focus on new-physics scenarios best suited for discovery at their preferred collider … nothing wrong with that … but interpretation requires a grain of salt …
- An important criterion to evaluate is the extent to which a facility can, in the course of its full evolution, answer to questions it raises (eg directly discover the origin of indirect evidence for new physics)

Example:

Sequential Z' reach: comparison across colliders, direct vs indirect reach

Indirect observation through EW precision observables **Direct observation**

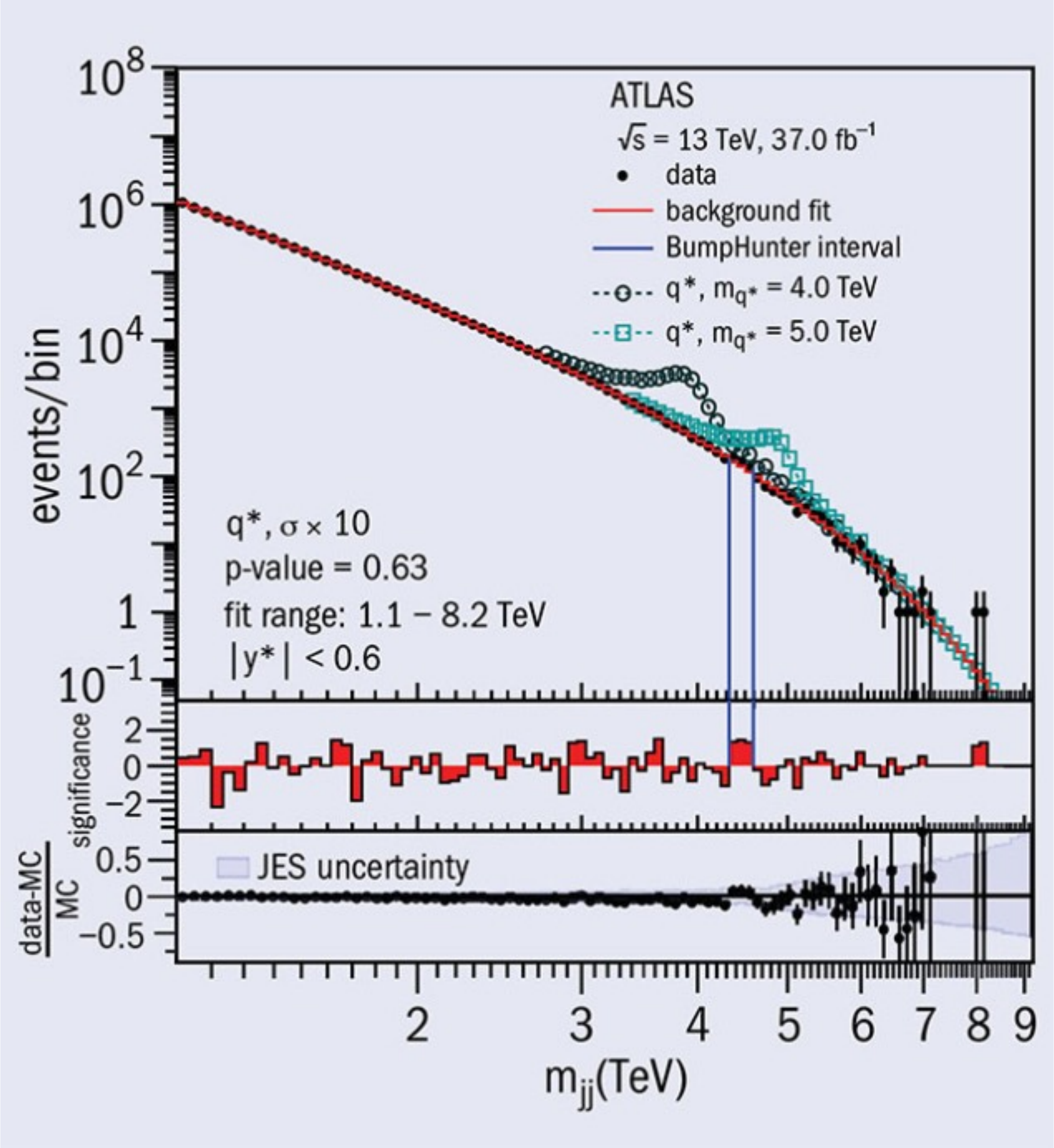
Machine	Type	$\sqrt{s}$ (TeV)	$\int$ Ldt (ab^{-1})	Source	Z' Model	5σ (TeV)	95% CL (TeV)
HL-LHC	pp	14	3	RH [395]	$Z'_{SSM} \to$ dijet	4.2	**5.2**
				ATLAS [396]	$Z'_{SSM} \to l^+l^-$	$\boxed{6.4}$	**6.5**
				CMS [397]	$Z'_{SSM} \to l^+l^-$	–	**6.8**
				EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**6**
ILC250, CLIC380 or FCC-ee	e^+e^-	0.25	2	ILC [398]	$Z'_{SSM} \to f^+f^-$	4.9	**7.7**
				EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**7**
HE-LHC	pp	27	15	EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**11**
				ATLAS [396]	$Z'_{SSM} \to e^+e^-$	12.8	**12.8**
ILC	e^+e^-	0.5	4	ILC [398]	$Z'_{SSM} \to f^+f^-$	8.3	**13**
				EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**13**
CLIC	e^+e^-	1.5	2.5	EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**19**
Muon Collider	$\mu^+\mu^-$	3	1	IMCC [392]	$Z'_{Univ}(g_{Z'} = 0.2)$	10	**20**
ILC	e^+e^-	1	8	ILC [398]	$Z'_{SSM} \to f^+f^-$	14	**22**
				EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**21**
CLIC	e^+e^-	3	5	EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**24**
FCC-hh	pp	100	30	RH [395]	$Z'_{SSM} \to$ dijet	25	**32**
				EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**35**
				EPPSU [399]	$Z'_{SSM} \to l^+l^-$	$\boxed{43}$	**43**
Muon Collider	$\mu^+\mu^-$	10	10	IMCC [392]	$Z'_{Univ}(g_{Z'} = 0.2)$	$\boxed{42}$	**70**

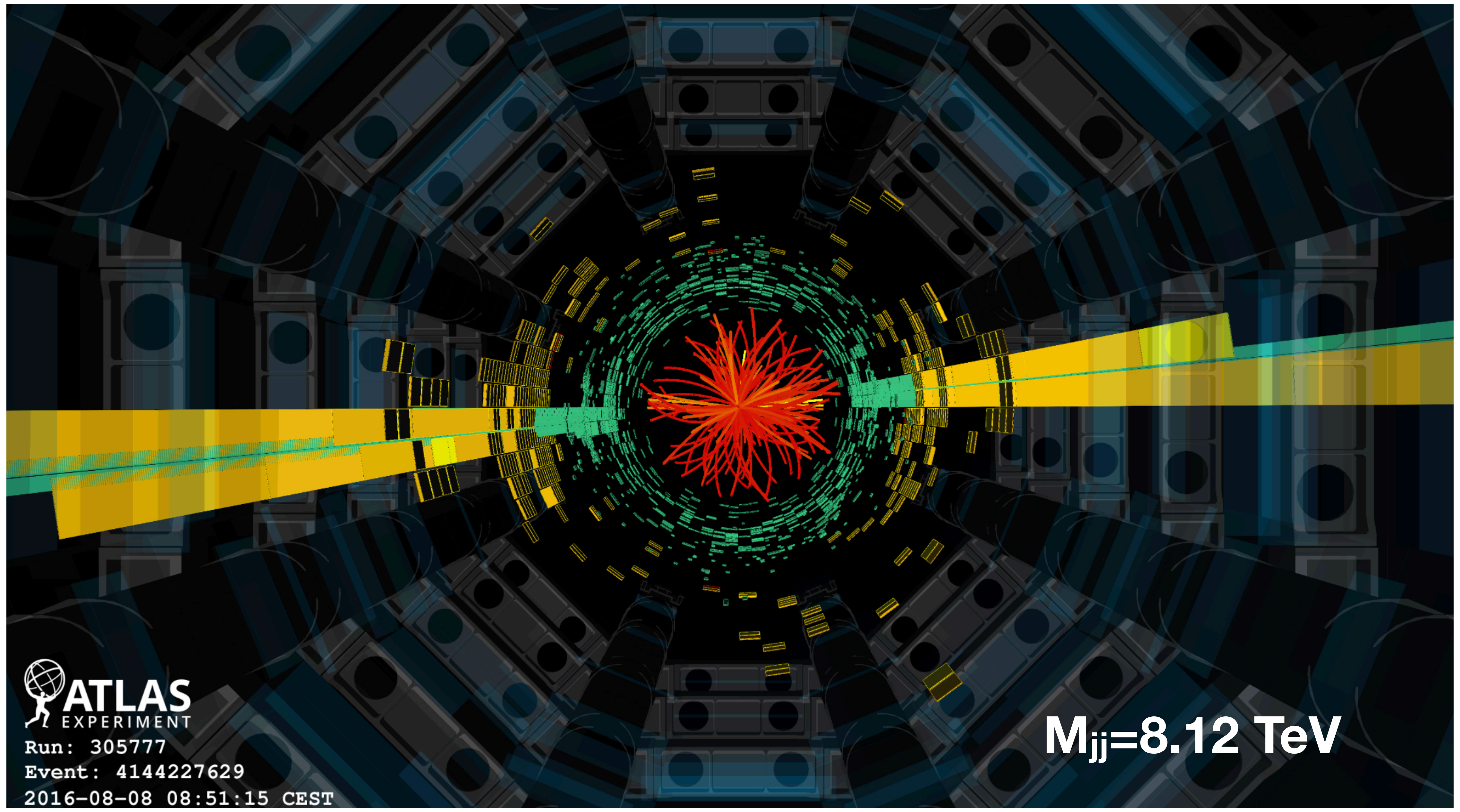
Table 2-14. *For each collider we list the operating point and mass reach, for 5σ discovery and 95% CL exclusion, of the SSM Z' model taken from Refs. [395, 399, 396, 397, 398], and the mass reach of the universal Z' model with a coupling $g_{Z'} = 0.2$ from Refs. [392, 384] that we determined from Fig. 2-32.*

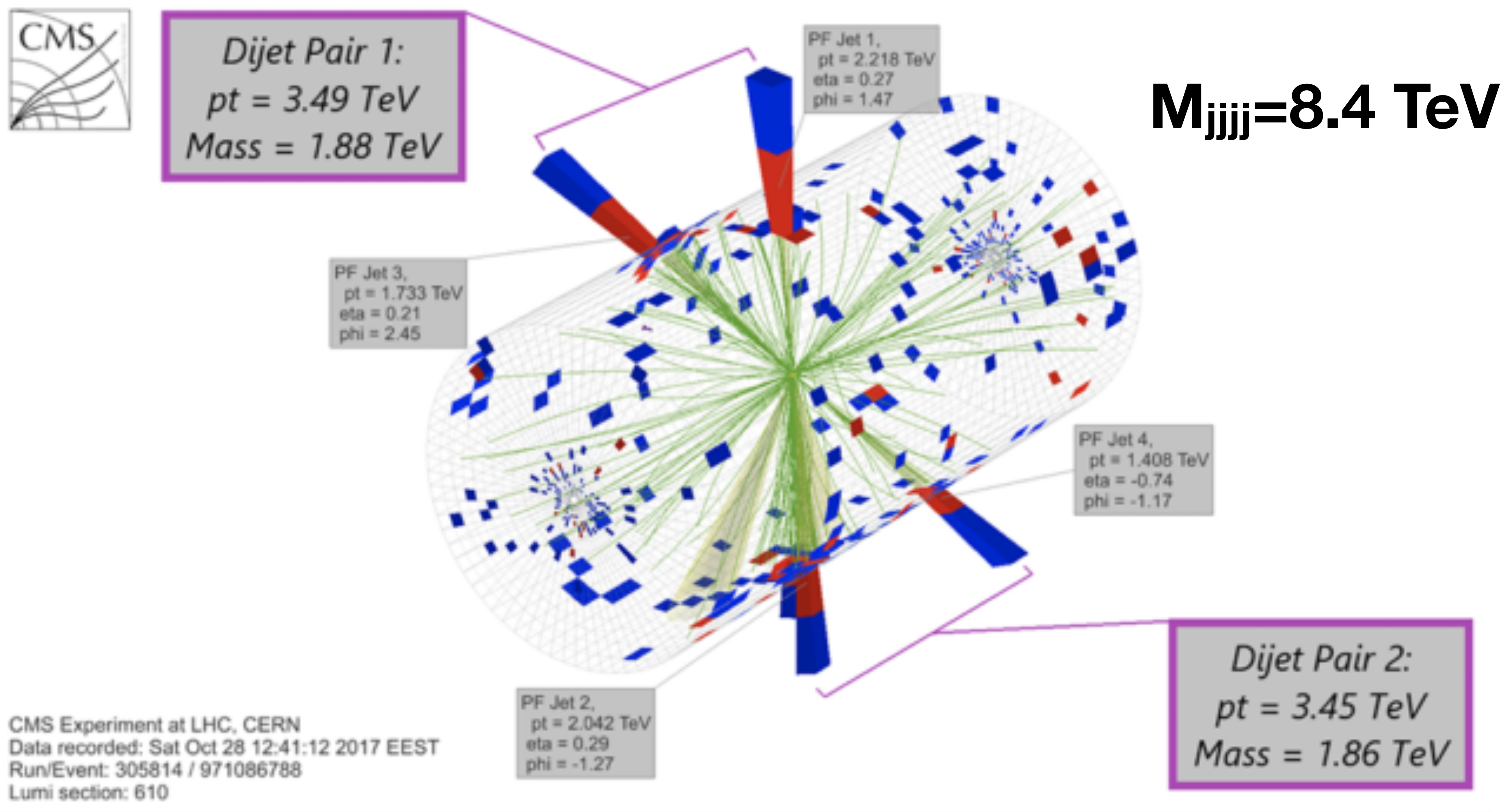
> ***“All options for a 10 TeV pCM collider are new technologies under development and R&D is required before we can embark on building a new collider”***
>
> *P5 Report (2023), p. 17*

The 10 TeV pCM holy Grail: how far are we from it, really?

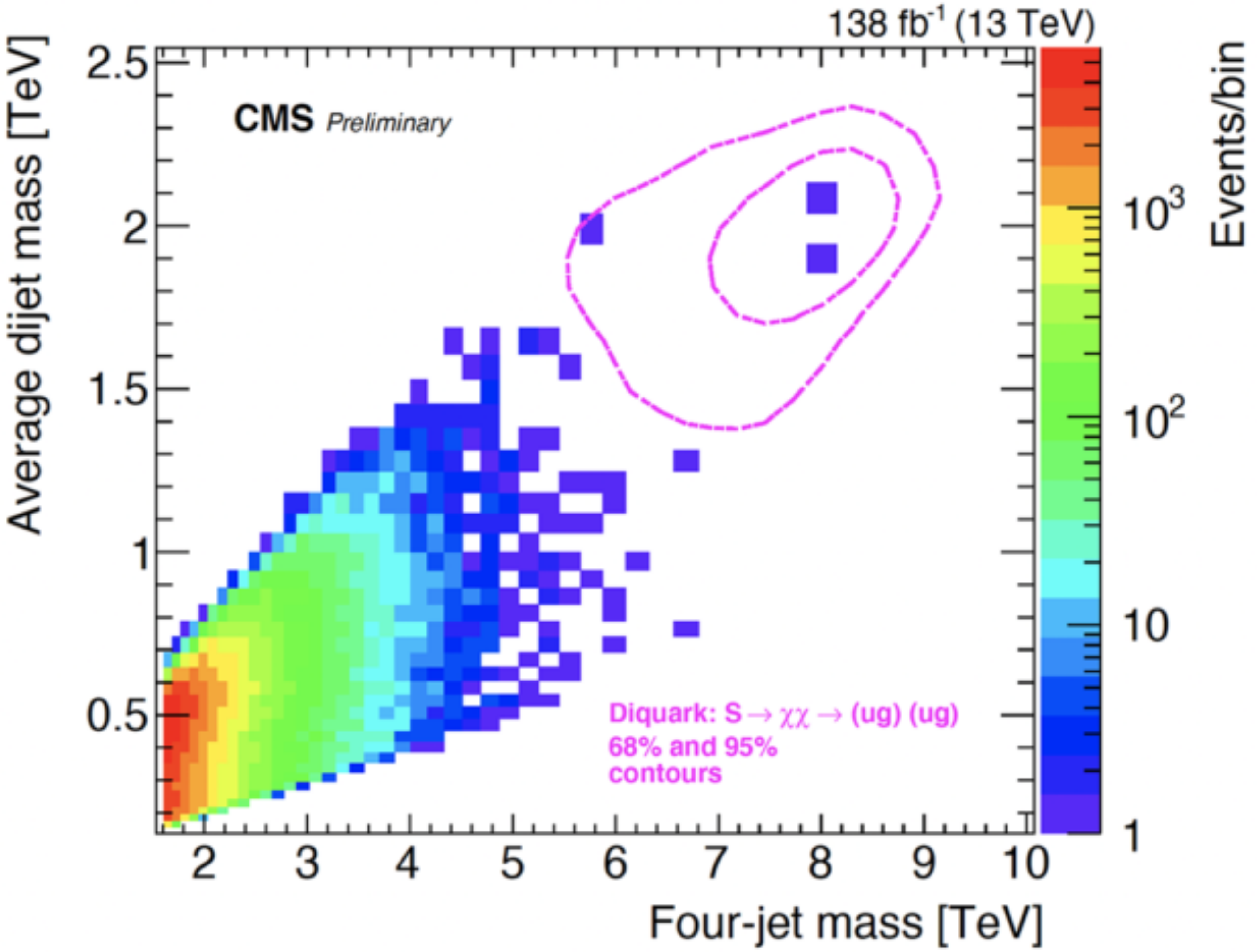
not much actually, already at the LHC







https://arxiv.org/abs/1911.03947



- **Why FCC** : The breadth, synergies and complementarities offered by the FCC integral programme (ee+hh) offer the best promise to fulfill these goals
    - *Complementarity/synergy between ee and hh, but also within the individual ee and hh programs*

Follow some examples of how FCC-ee and FCC-hh will play hand in hand

The absolutely unique statistical power of circular e+e– colliders

$e^+e^- \to Z$	$e^+e^- \to WW$	$\tau(\leftarrow Z)$	$b(\leftarrow Z)$	$c(\leftarrow Z)$	$e^+e^- \to tt$
$5\ 10^{12}$	10^8	$3\ 10^{11}$	$1.5\ 10^{12}$	10^{12}	10^6

=> O(10^5) larger statistics than LEP at the Z peak and WW threshold

Flavour statistics from Z decays:

S. Monteil, FCC PED Week 2023

Working point	Lumi. / IP [10^{34} cm^{-2}.s^{-1}]	Total lumi. (2 IPs)	Run time	Physics goal
Z first phase	100	26 ab^{-1} /year	2	
Z second phase	200	52 ab^{-1} /year	2	150 ab^{-1}

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

Additional bonus wrt B factory: (i) Lorentz boost (ii) B hadrons not accessible at the Y(4S,5S) thresholds

The absolutely unique power of pp $\rightarrow$H+X:

- the extraordinary statistics that, complemented by the per-mille e^+e^- measurement of eg BR($H\rightarrow ZZ^*$), allows
  - the sub-% measurement of rarer decay modes
  - the ~5% measurement of the Higgs trilinear selfcoupling

- the huge dynamic range (eg pt(H) up to several TeV), which allows to
  - probe d>4 EFT operators up to scales of several TeV
  - search for multi-TeV resonances decaying to H, or extensions of the Higgs sector

	$gg\rightarrow H$	VBF	WH	ZH	ttH	HH
N_{100}	24×10^9	2.1×10^9	4.6×10^8	3.3×10^8	9.6×10^8	3.6×10^7
N_{100}/N_{14}	180	170	100	110	530	390

$N_{100} = \sigma_{100\,\mathrm{TeV}} \times 30\ \mathrm{ab}^{-1}$

$N_{14} = \sigma_{14\,\mathrm{TeV}} \times 3\ \mathrm{ab}^{-1}$

Higgs couplings after FCC-ee / hh

	HL-LHC	FCC-ee	FCC-hh
$\delta\Gamma_H / \Gamma_H$ (%)	SM	**1.3**	tbd
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**	tbd
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**	tbd
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**	tbd
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**	tbd
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**	tbd
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	**0.74**	tbd
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	4.3	9.0	**0.65 (*)**
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	1.8	3.9	**0.4 (*)**
$\delta g_{Htt} / g_{Htt}$ (%)	3.4	~10 (indirect)	**0.95 (**)**
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–	**0.9 (*)**
$\delta g_{HHH} / g_{HHH}$ (%)	50	~44 (indirect)	**< 5**
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	**< 1%**	**$BR_{inv} < 0.025\%$**

NB

$BR(H\to Z\gamma,\gamma\gamma) \sim O(10^{-3}) \Rightarrow$ **$O(10^7)$ evts for $\Delta_{stat}\sim\%$**

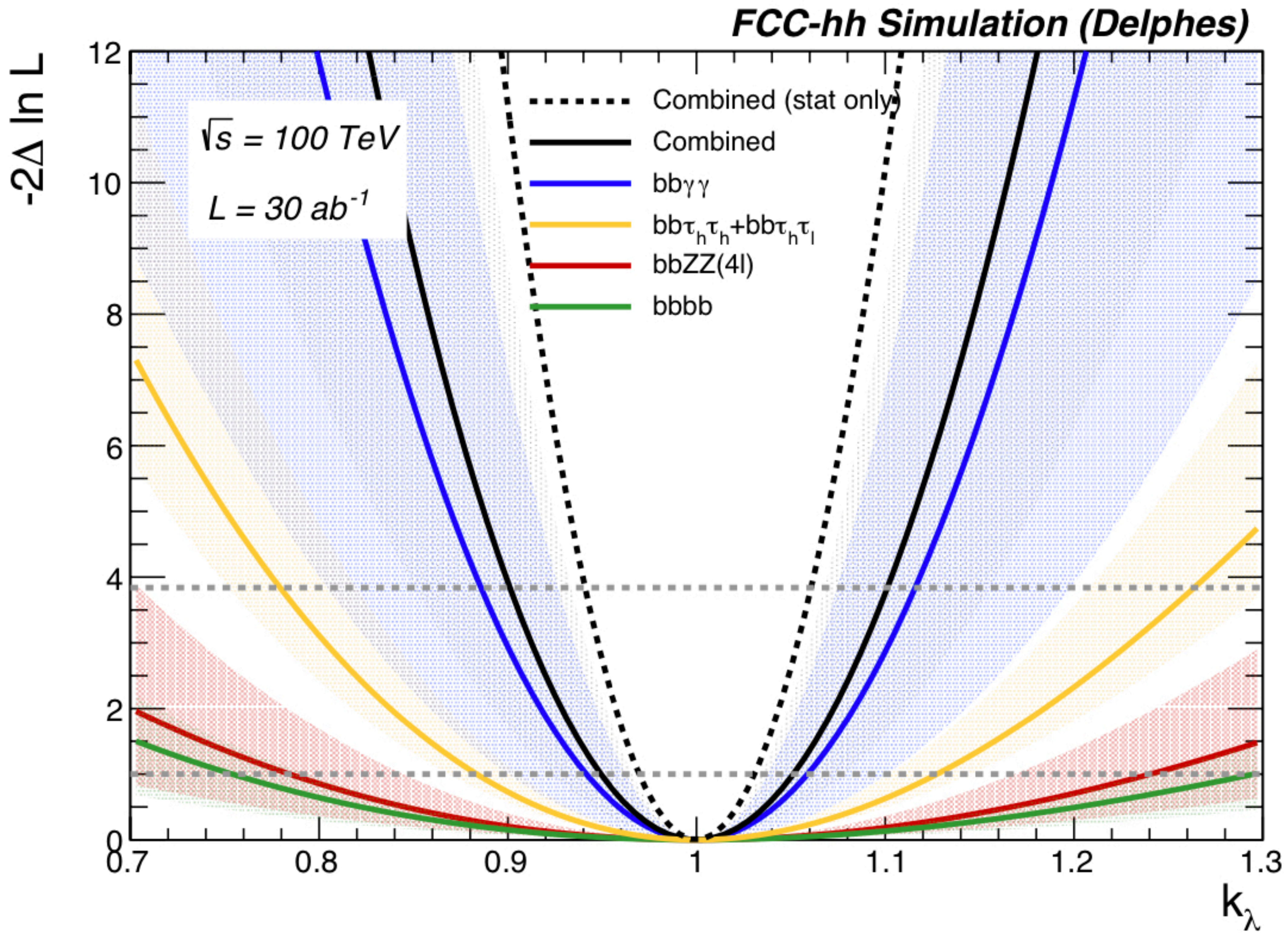
$BR(H\to\mu\mu) \sim O(10^{-4}) \Rightarrow$ **$O(10^8)$ evts for $\Delta_{stat}\sim\%$**

pp collider is essential to beat the % target, since no proposed ee collider can produce more than $O(10^6)$ H's

* From BR ratios wrt $B(H\to ZZ^*)$ @ FCC-ee

** From $pp\to ttH$ / $pp\to ttZ$, using $B(H\to bb)$ and ttZ EW coupling @ FCC-ee

The Higgs self-coupling



Being updated towards the March 31 submissions to the ESPPU => heading towards the 1% level experimental stat+systematics !!

MLM, Ortona, Selvaggi https://arxiv.org/abs/2004.03505

Figure 13. Expected negative log-Likelihood scan as a function of the trilinear self-coupling modifier $\kappa_\lambda = \lambda_3/\lambda_3^{SM}$ in all channels, and their combination. The solid line corresponds to the scenario II for systematic uncertainties. The band boundaries represent respectively scenario I and III. The dashed line represents the sensitivity obtained including statistical uncertainties only, under the assumptions of scenario I.

Det performance/systematics scenarios

I. Target det performance: LHC Run 2 conditions
II. Intermediate performance
III. Conservative: extrapolated HL-LHC performance, with today's algo's (eg no timing, etc)

2019

	@68% CL	scenario I	scenario II	scenario III
δ_μ	stat only	2.2	2.8	3.7
	stat + syst	2.4	3.5	5.1
δ_{κ_λ}	stat only	3.0	4.1	5.6
	stat + syst	3.4	5.1	7.8

Table 7. Combined expected precision at 68% CL on the di-Higgs production cross- and Higgs self coupling using all channels at the FCC-hh with $\mathcal{L}_{int}$ = 30 ab^{-1}. The symmetrized value $\delta = (\delta^+ + \delta^-)/2$ is given in %.

FCC-ee, more than a Higgs factory: Tera-Z

Organising the UV

Suppose SM deviations arise at tree-level from heavy states:

$$\mathcal{O}_1(SM) \underset{\chi_{\mathrm{BSM}}}{\rule{6em}{0.4pt}} \mathcal{O}_2(SM) \Rightarrow \mathcal{O}_{\mathrm{SMEFT}}$$

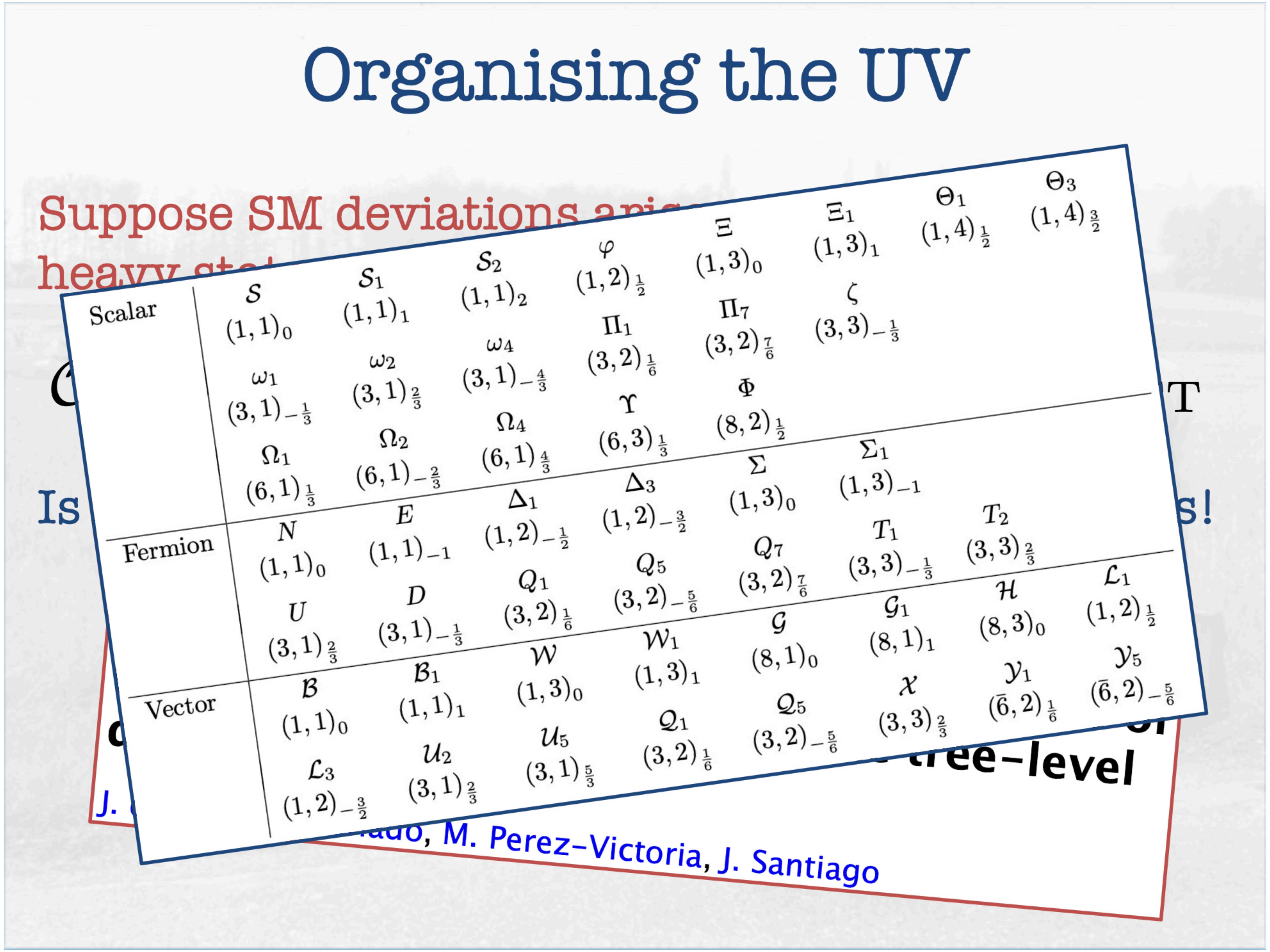
Is it possible to categorise all possible states? Yes!

Effective description of general extensions of the Standard Model: the complete tree-level dictionary

J. de Blas, J. C. Criado, M. Perez-Victoria, J. Santiago

Following slides from Matthew McCullough

FCC-ee, more than a Higgs factory: Tera-Z



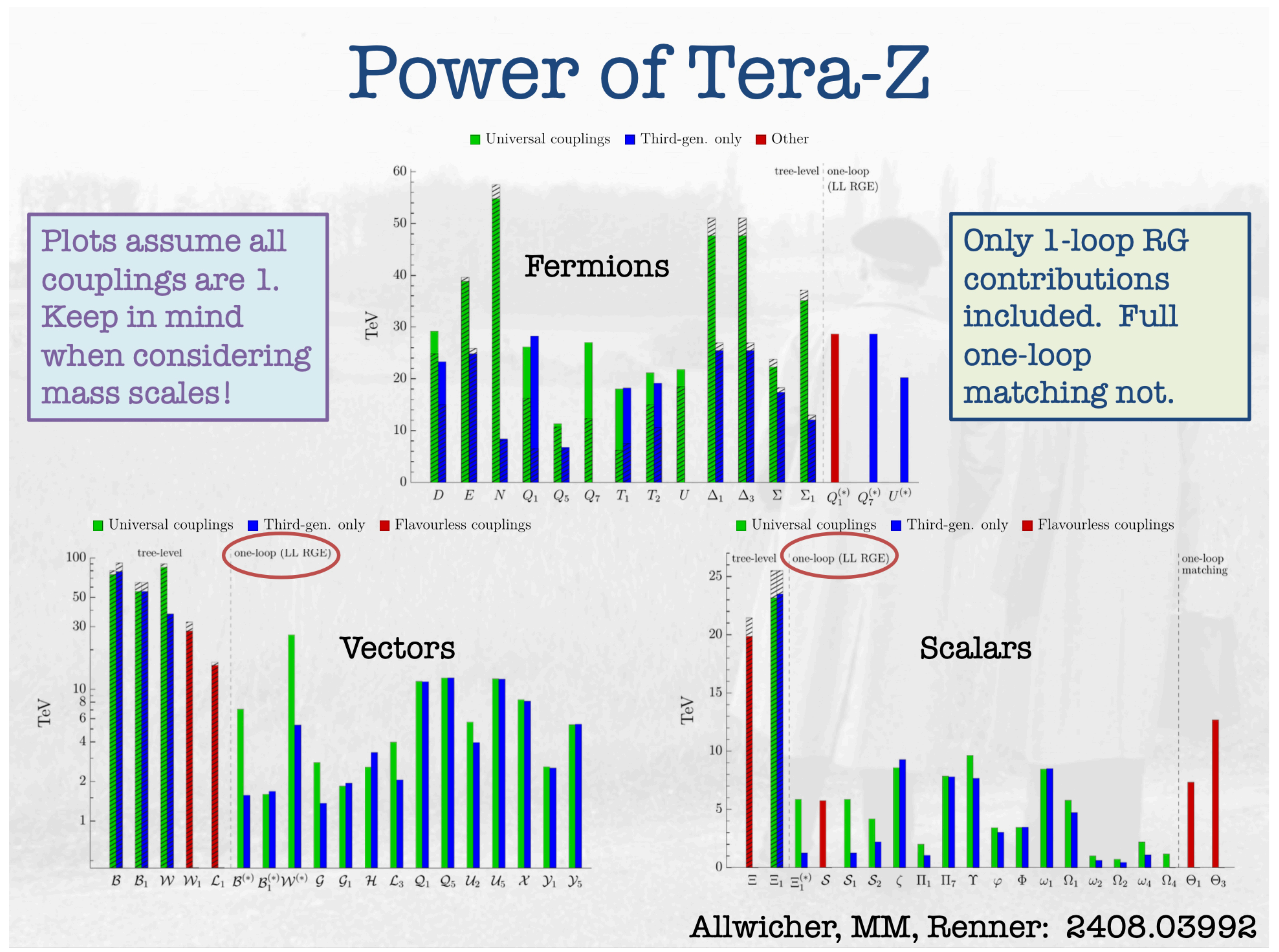
Following slides from Matthew McCullough

Following slides from Matthew McCullough

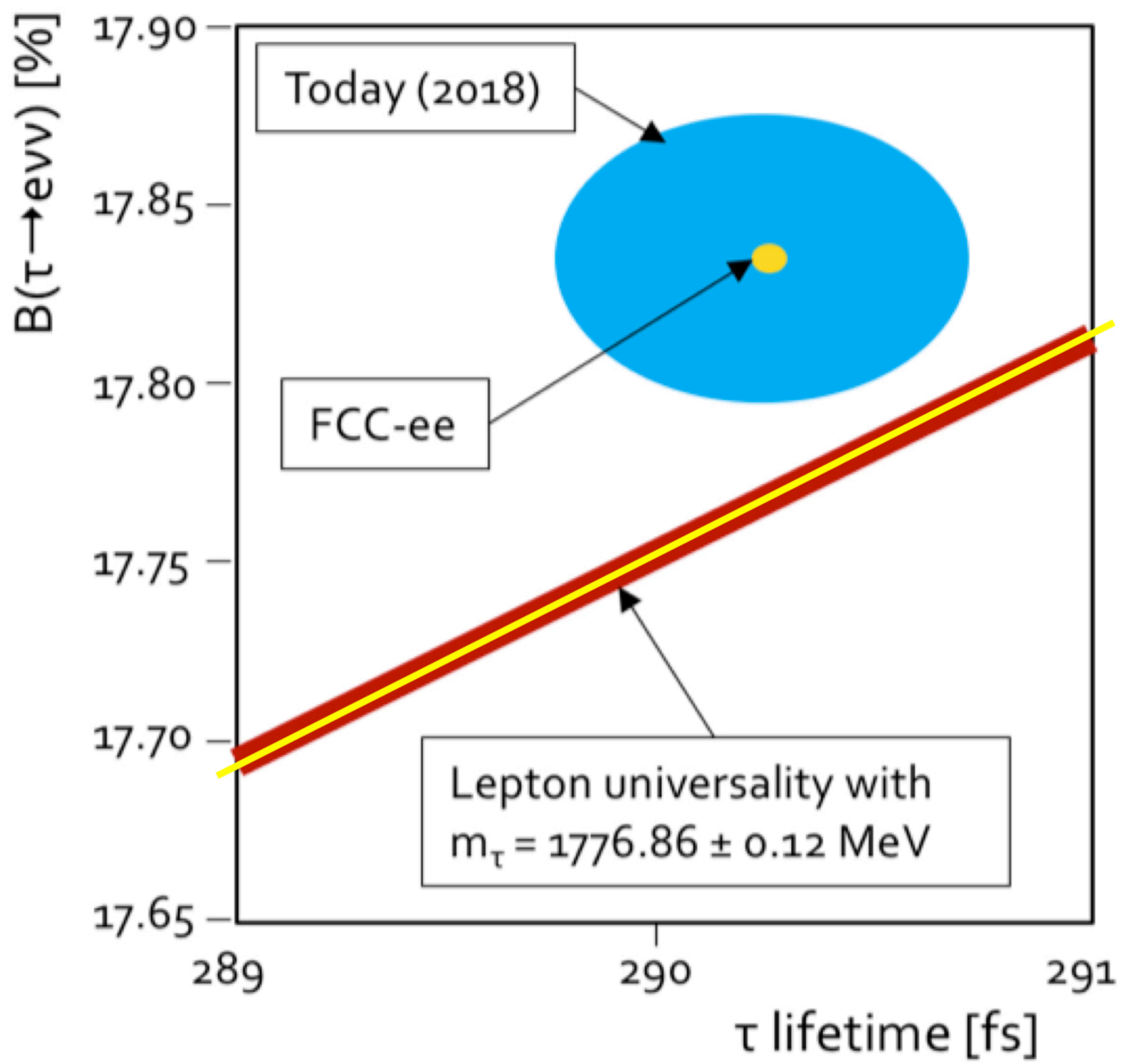
MMC dixit:

- *Tera-Z programme gives comprehensive coverage of new physics coupled to SM*
- *If a signature shows up elsewhere, it will also show up at Tera-Z. Quantum effects play a crucial role.*

Sensitivity can reach several 10's TeV, but in several examples leaves plenty of room for further ***exploration at the highest energies*** *- needed to identify origin of EWPT deviations, or to extend the search beyond Tera-Z*



Flavour probes at FCC-ee Tera-Z: eg lepton universality in tau decays



Lorentz boost crucial!

Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_τ [MeV]	Threshold / inv. mass endpoint	1776.86 ± 0.12	0.004	0.04-0.1	Mass scale
τ_τ [fs]	Flight distance	290.3 ± 0.5 fs	0.001	0.04	Vertex detector alignment
B(τ→eνν) [%]	Selection of $\tau^+\tau^-$, identification of final state	17.82 ± 0.05	0.0001	0.003	Efficiency, bkg, Particle ID
B(τ→μνν) [%]		17.39 ± 0.05			

Direct discoveries at FCC-ee: thorough exploration of rare weak processes at low E scales

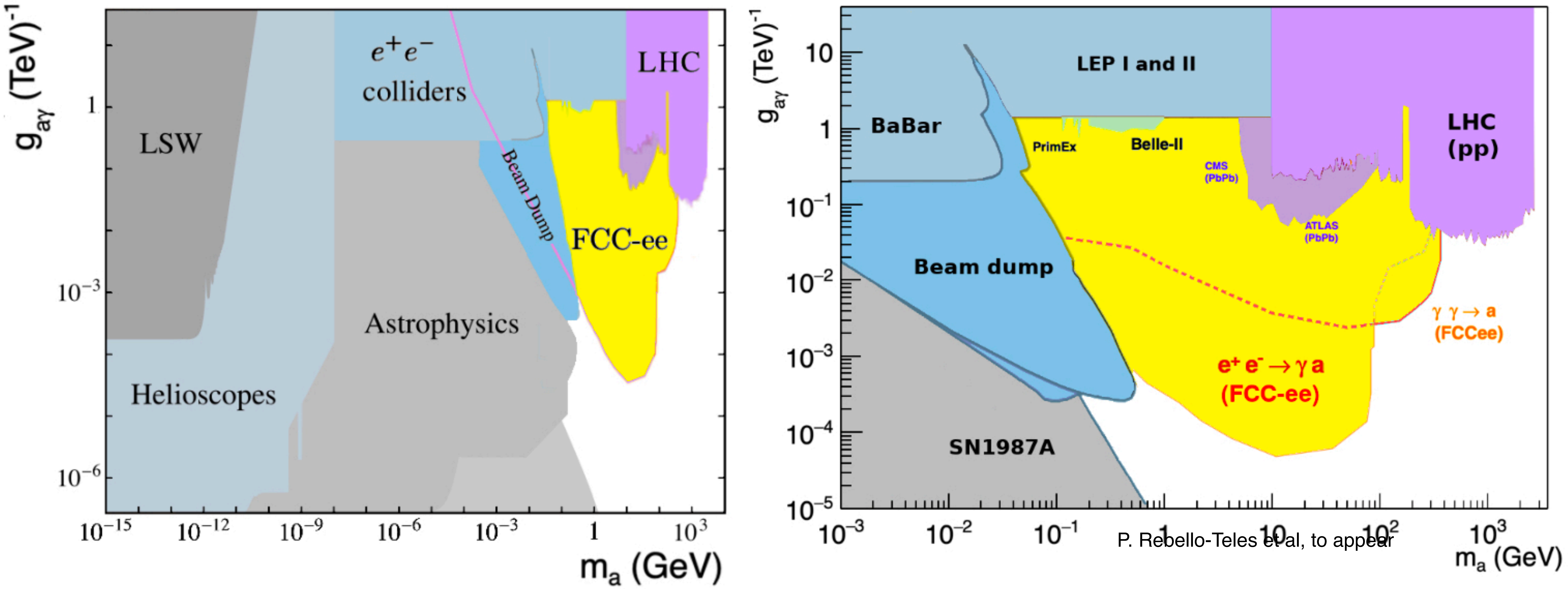
Axion-like particles

In the run at the Z pole, exploit possible channels such as

$$e^+e^- \to a\gamma \qquad\qquad e^+e^- \to e^+e^-a$$

with

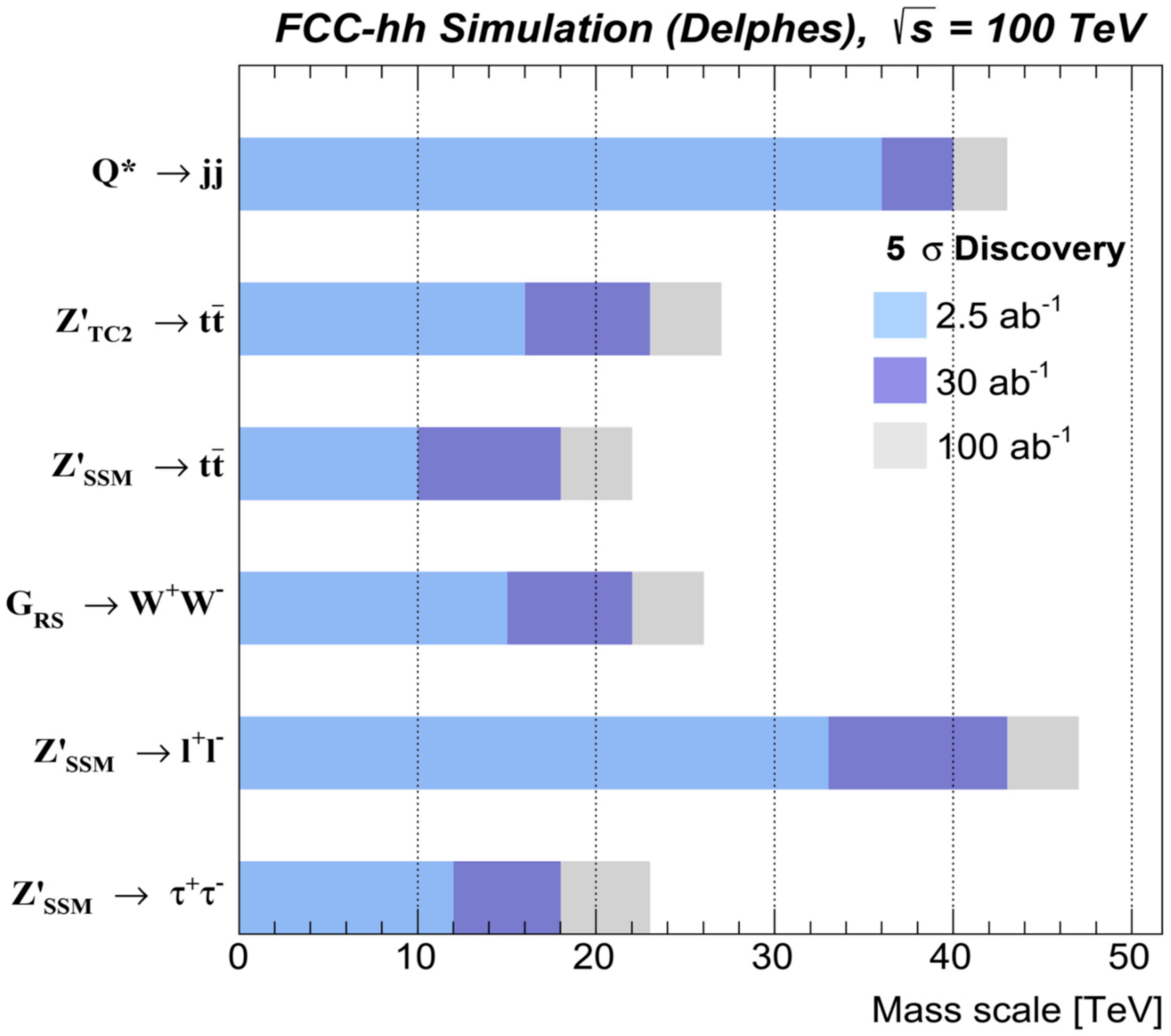
$$a \to \gamma\gamma$$



P. Rebello-Teles et al, to appear

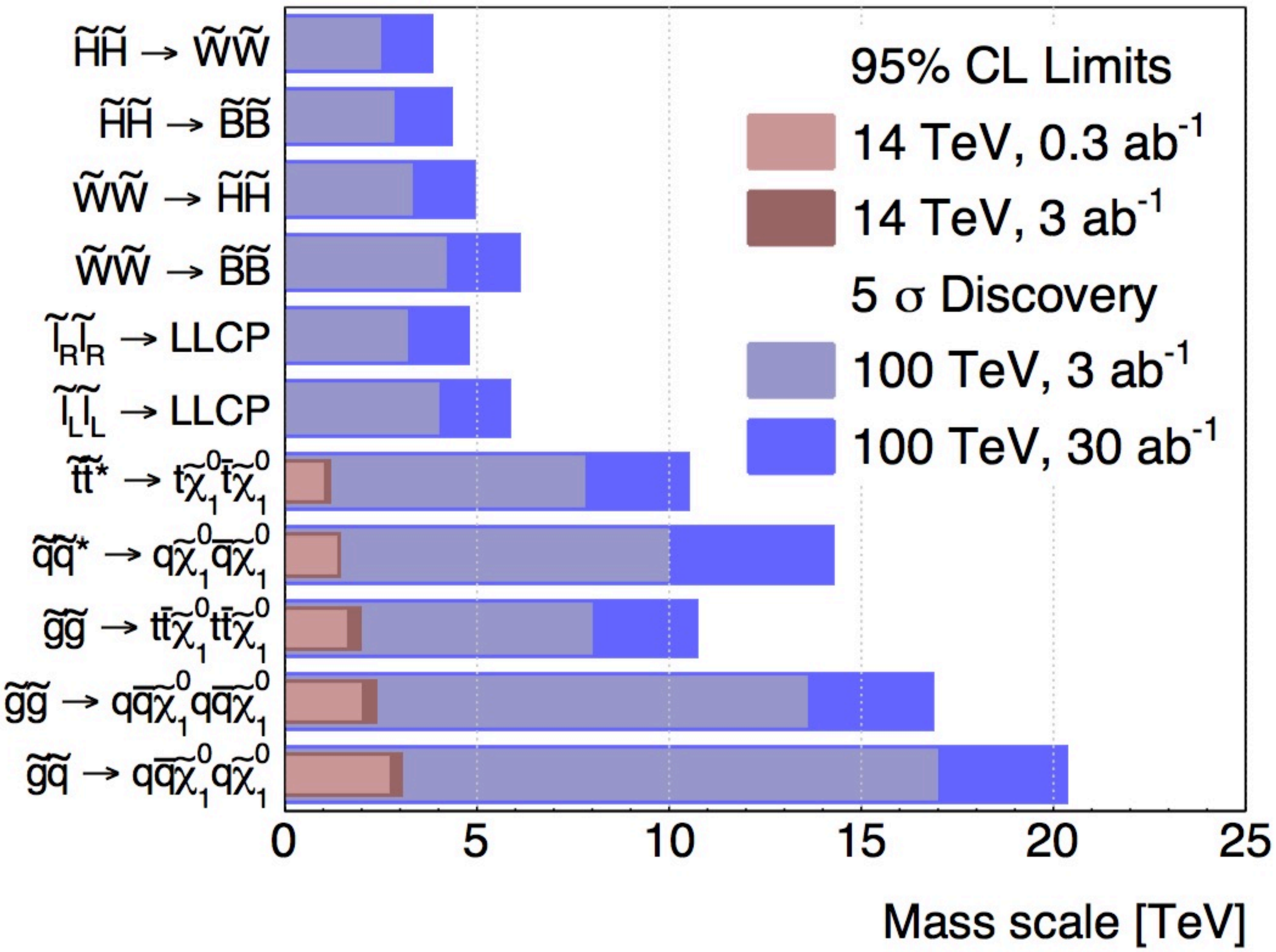
Direct discoveries at FCC-hh: direct access to the multi-10 TeV mass region

s-channel resonances



FCC-hh reach ~ 6 x HL-LHC reach

SUSY reach at 100 TeV



The potential for yes/no answers to important questions

WIMP DM theoretical constraints

For particles held in equilibrium by pair creation and annihilation processes, (χ χ ↔ SM)

$$\Omega_{\rm DM} h^2 \sim \frac{10^9 {\rm GeV}^{-1}}{M_{\rm pl}} \frac{1}{\langle \sigma v \rangle}$$

For a particle annihilating through processes which do not involve any larger mass scales:

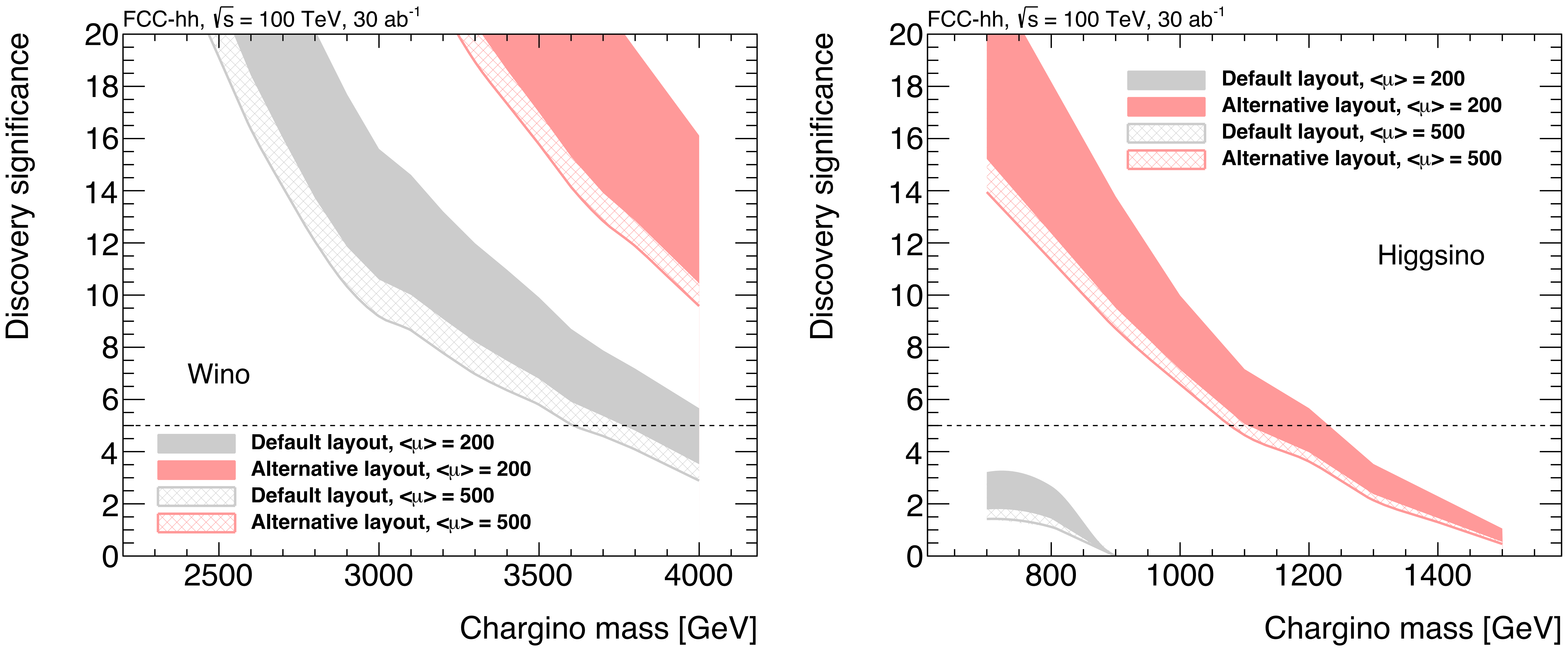
$$\langle \sigma v \rangle \sim g_{\rm eff}^4 / M_{\rm DM}^2$$

$$\Rightarrow \quad \Omega_{\rm DM} h^2 \sim 0.12 \times \left(\frac{M_{\rm DM}}{2\ {\rm TeV}} \right)^2 \left(\frac{0.3}{g_{\rm eff}} \right)^4$$

$$\Omega_{wimp}\, h^2 \lesssim 0.12 \quad \Rightarrow \quad M_{wimp} \lesssim 2\ {\rm TeV} \left(\frac{g}{0.3} \right)^2$$

Disappearing charged track analyses
(at ~full pileup)

K. Terashi, R. Sawada, M. Saito, and S. Asai, *Search for WIMPs with disappearing track signatures at the FCC-hh*, (Oct, 2018) . https://cds.cern.ch/record/2642474.



=> coverage beyond the upper limit of the thermal WIMP mass range for both higgsinos and winos !!

$$M_{wimp} \lesssim 2\ \mathrm{TeV} \left(\frac{g}{0.3}\right)^2$$

Status of the FCC project:

a brief overview,

to highlight the diversity and magnitude of the various challenges,

from technology to environmental impact to integration in the social

and natural environment of the immense area touched by the project

For a more complete, excellent report, see Johannes Gutleber slides at recent FCC Physics Workshop

FUTURE CIRCULAR COLLIDER

FCC Feasibility Study (2021-2025): high-level objectives

- ❑ demonstration of the geological, technical, environmental and administrative feasibility of the tunnel and surface areas and optimisation of placement and layout of the ring and related infrastructure;
- ❑ pursuit, together with the Host States, of the preparatory administrative processes required for a potential project approval to identify and remove any showstopper;
- ❑ optimisation of the design of the colliders and their injector chains, supported by R&D to develop the needed key technologies;
- ❑ elaboration of a sustainable operational model for the colliders and experiments in terms of human and financial resource needs, as well as environmental aspects and energy efficiency;
- ❑ development of a consolidated cost estimate, as well as the funding and organisational models needed to enable the project's technical design completion, implementation and operation;
- ❑ identification of substantial resources from outside CERN's budget for the implementation of the first stage of a possible future project (tunnel and FCC-ee);
- ❑ consolidation of the physics case and detector concepts for both colliders.

Results will be summarised in a Feasibility Study Report to be released at end 2025

F. Gianotti

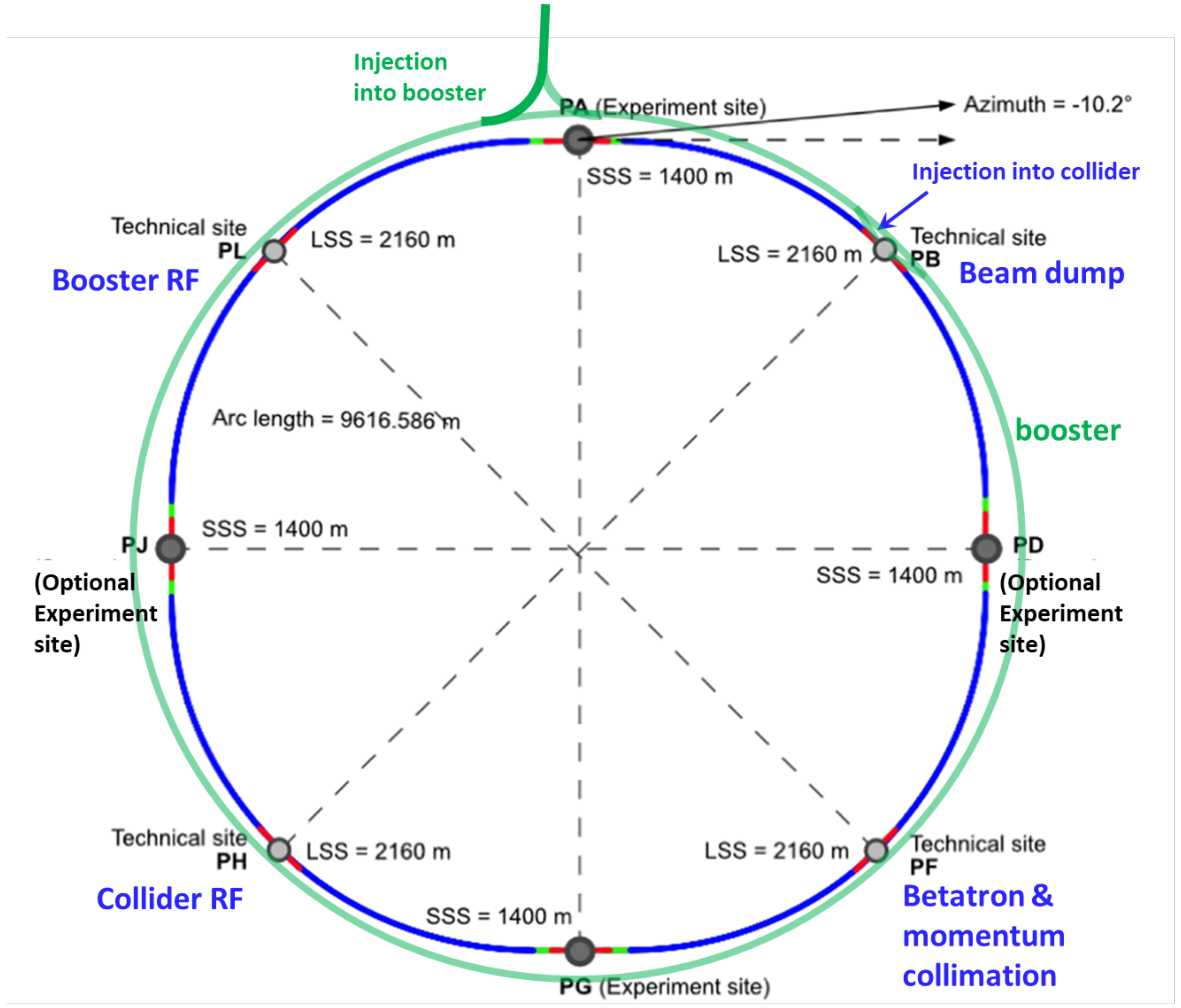
FUTURE CIRCULAR COLLIDER

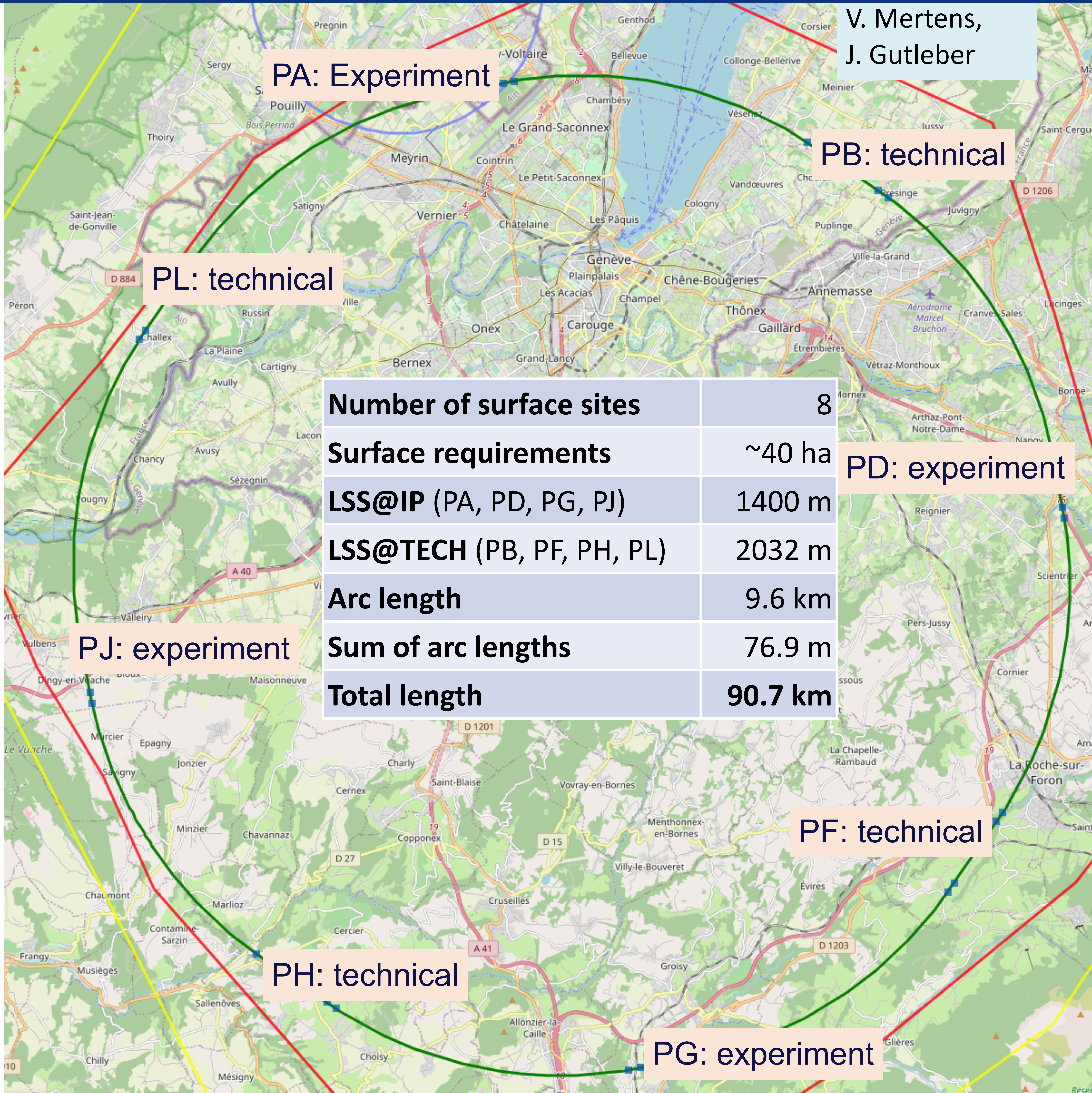
Optimized placement and layout for feasibility study

Layout chosen out of ~ 100 initial variants, based on **geology** and **surface constraints** (land availability, access to roads, etc.), **environment,** (protected zones), **infrastructure** (water, electricity, transport), **machine performance** etc.

“Avoid-reduce -compensate” principle of EU and French regulations

Overall lowest-risk baseline: 90.7 km ring, 8 surface points,
Whole project now adapted to this placement





Number of surface sites	8
Surface requirements	~40 ha
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

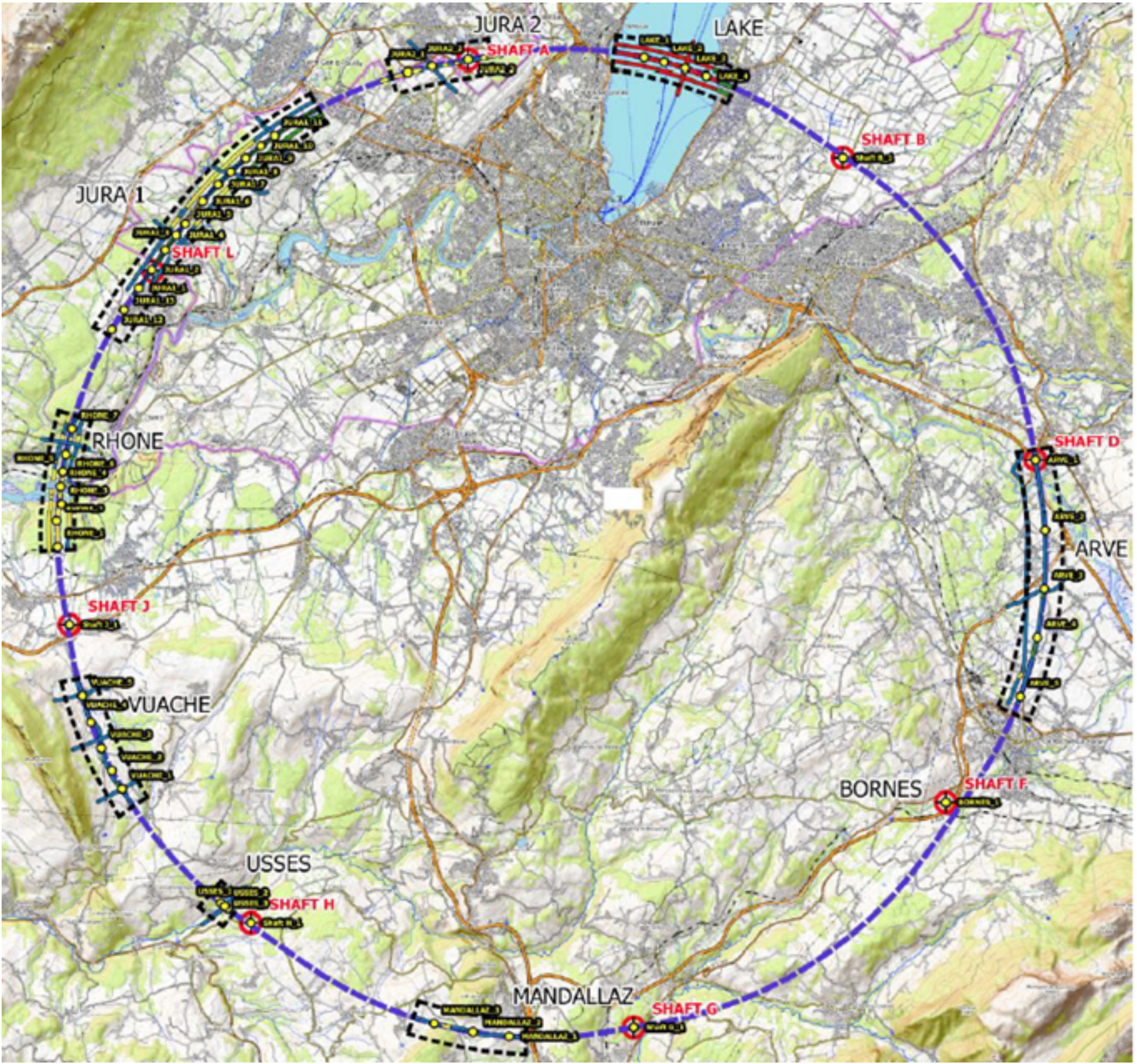
FCC tunnel implementation

Tunnel implementation summary

- 91 km circumference
- 95% in molasse geology for minimising tunnel construction risks
- 8 surface sites with ~5 ha area each.

FUTURE CIRCULAR COLLIDER

Status site investigations



- **Site investigations in areas with uncertain geological conditions:**
  - Optimisation of localisation of drilling locations ongoing with site visits since end 2022.
  - **Alignment with FR and CH on the process for obtaining autorisation procedures. Ongoing for start of drillings in Q2/2024.**

- **Contracts Status:**
  - Contract for engineering services and role of Engineer during works, active since July 2022
  - Site investigations: contract placement **approved** by Council in December 2023 and mobilization from January 2024.

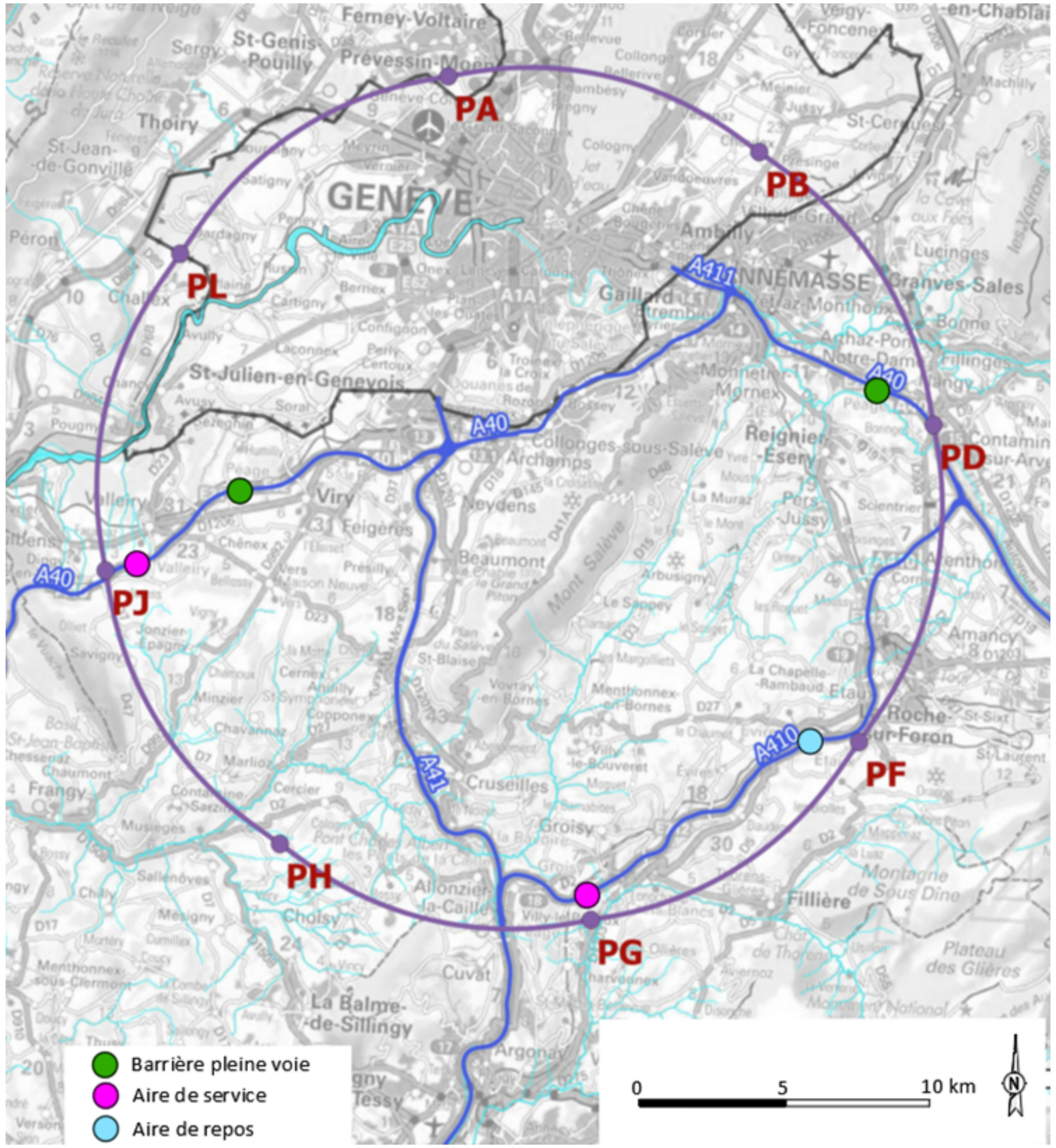
Sondage A89 (2007) incliné de 45° de 125 ml (surface plateforme estimée : 12 x 12 m soit environ 150 m²)

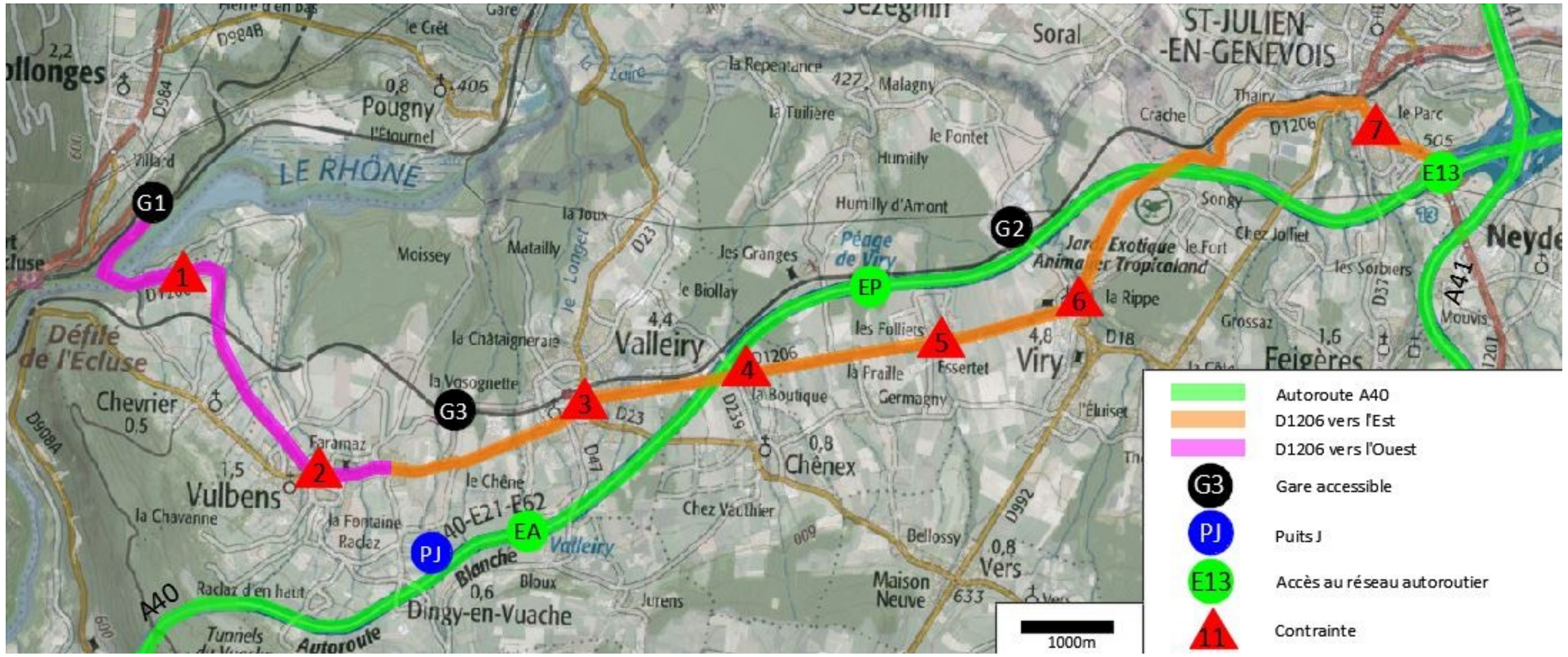
Drilling works on the lake

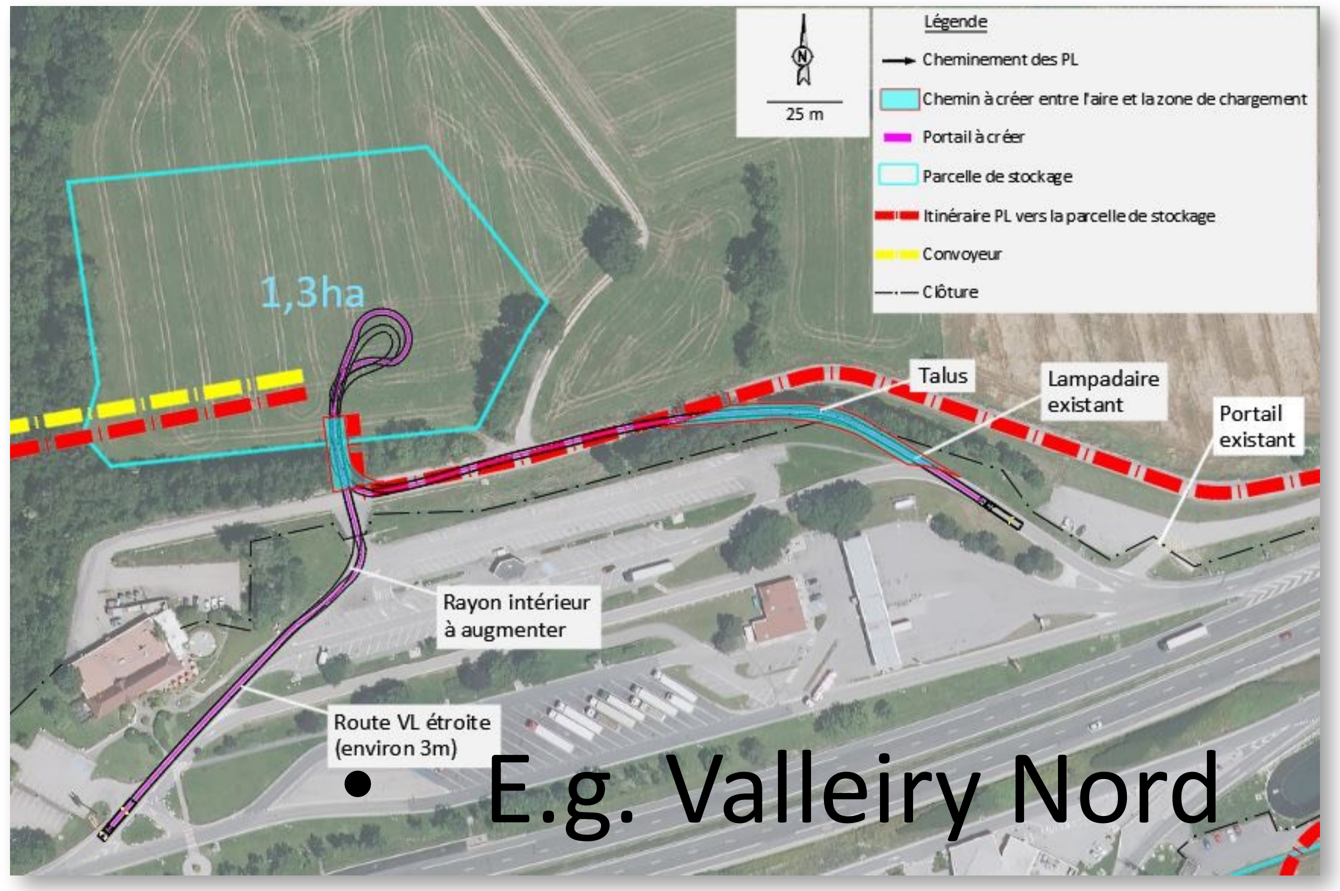
FUTURE CIRCULAR COLLIDER

Connections to transport infrastructure

- Road accesses identified and documented for all 8 surface sites
- Four possible highway connections defined (materials transport)
- Total amount of new roads required < 4 km (at departmental road level)







Detailed road access scenarios & highway access creation study **carried out by Cerema*, including regulatory requirements in France**

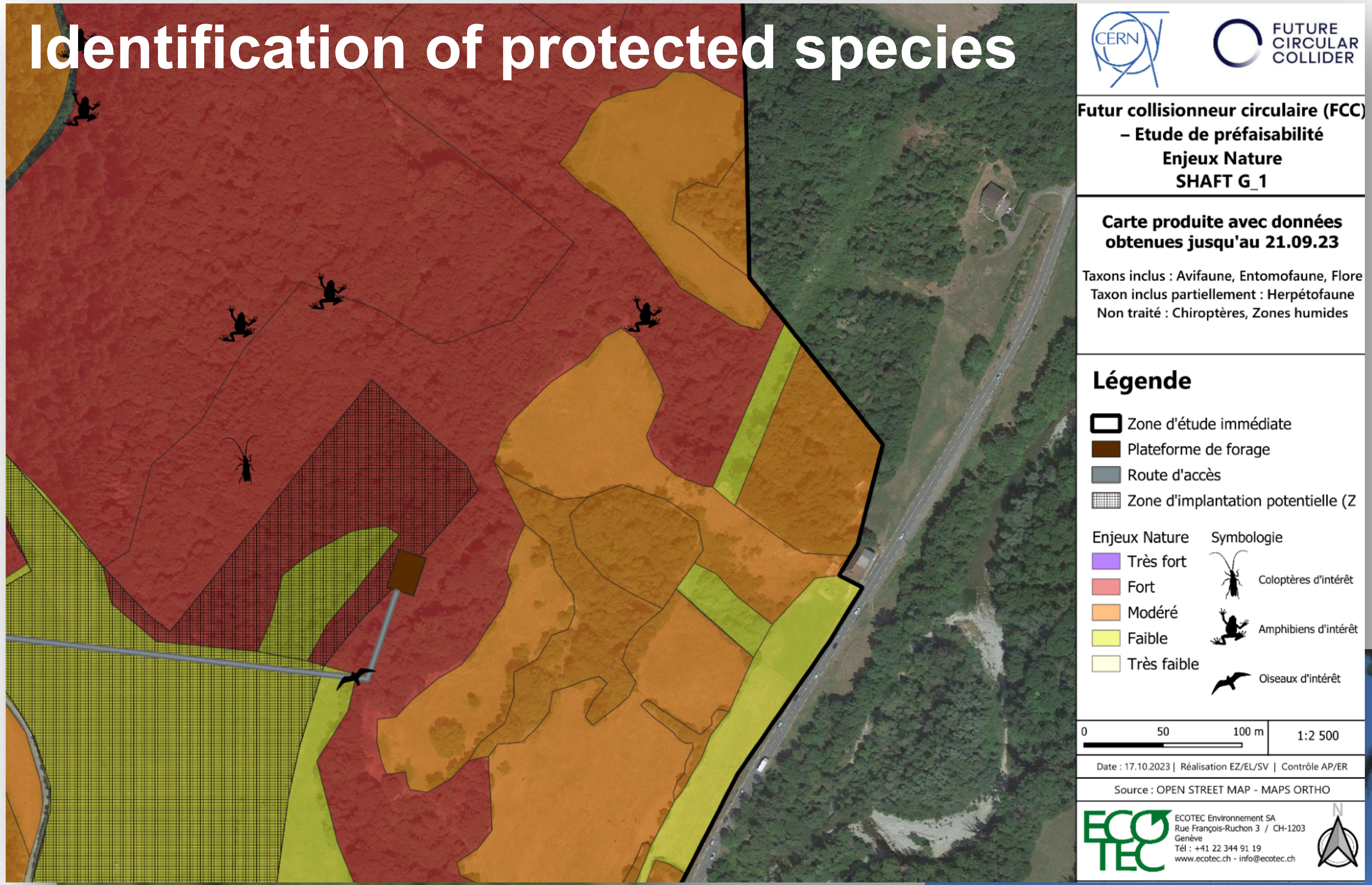
* Centre for Studies and Expertise on Risks, the Environment, Mobility and Urban Planning. CEREMA is **the major French public agency for developing public expertise in the fields of urban planning, regional cohesion and ecological and energy transition** for resilient and climate-neutral cities and regions.

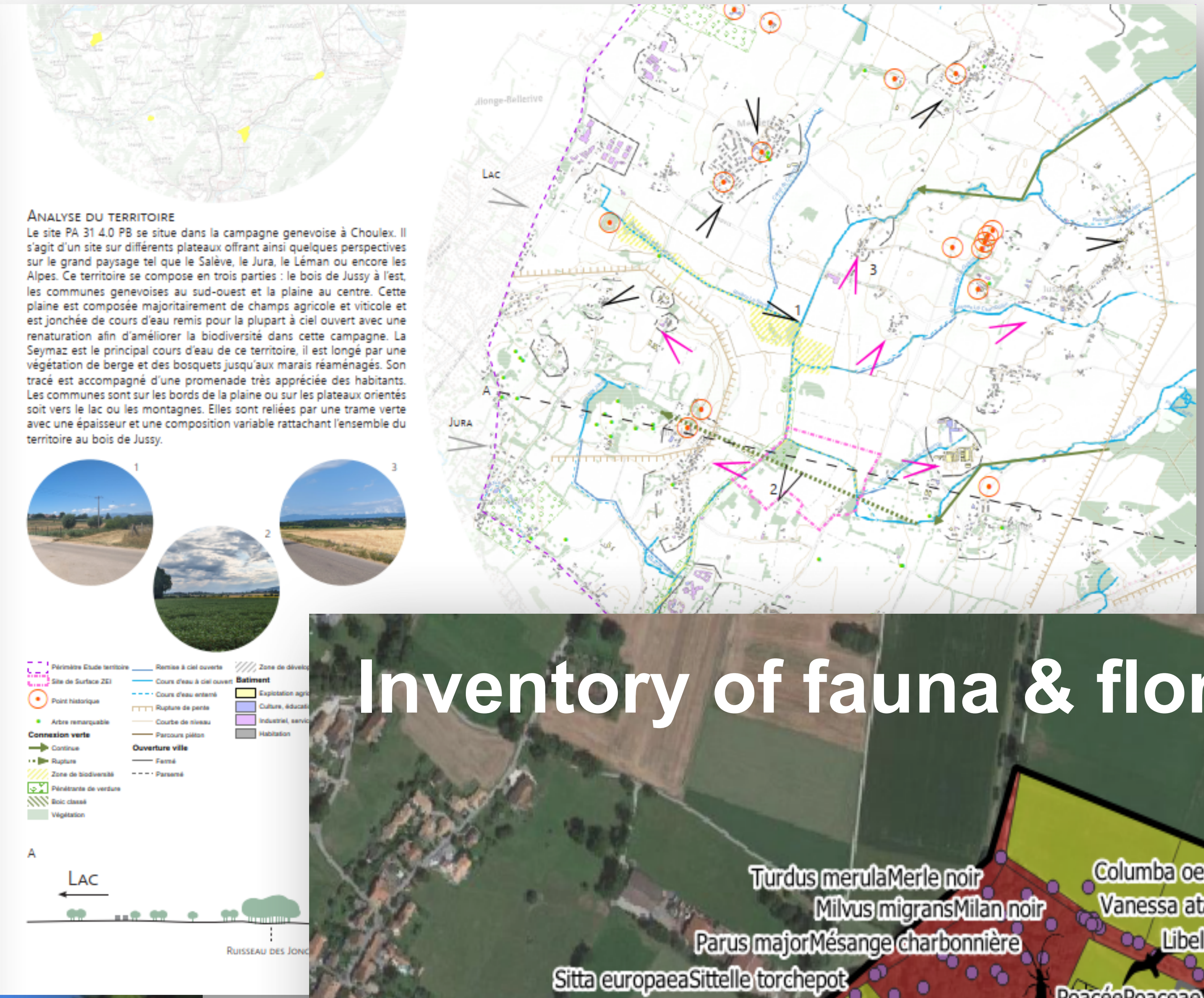
FUTURE CIRCULAR COLLIDER

Studies of environmental aspects ongoing

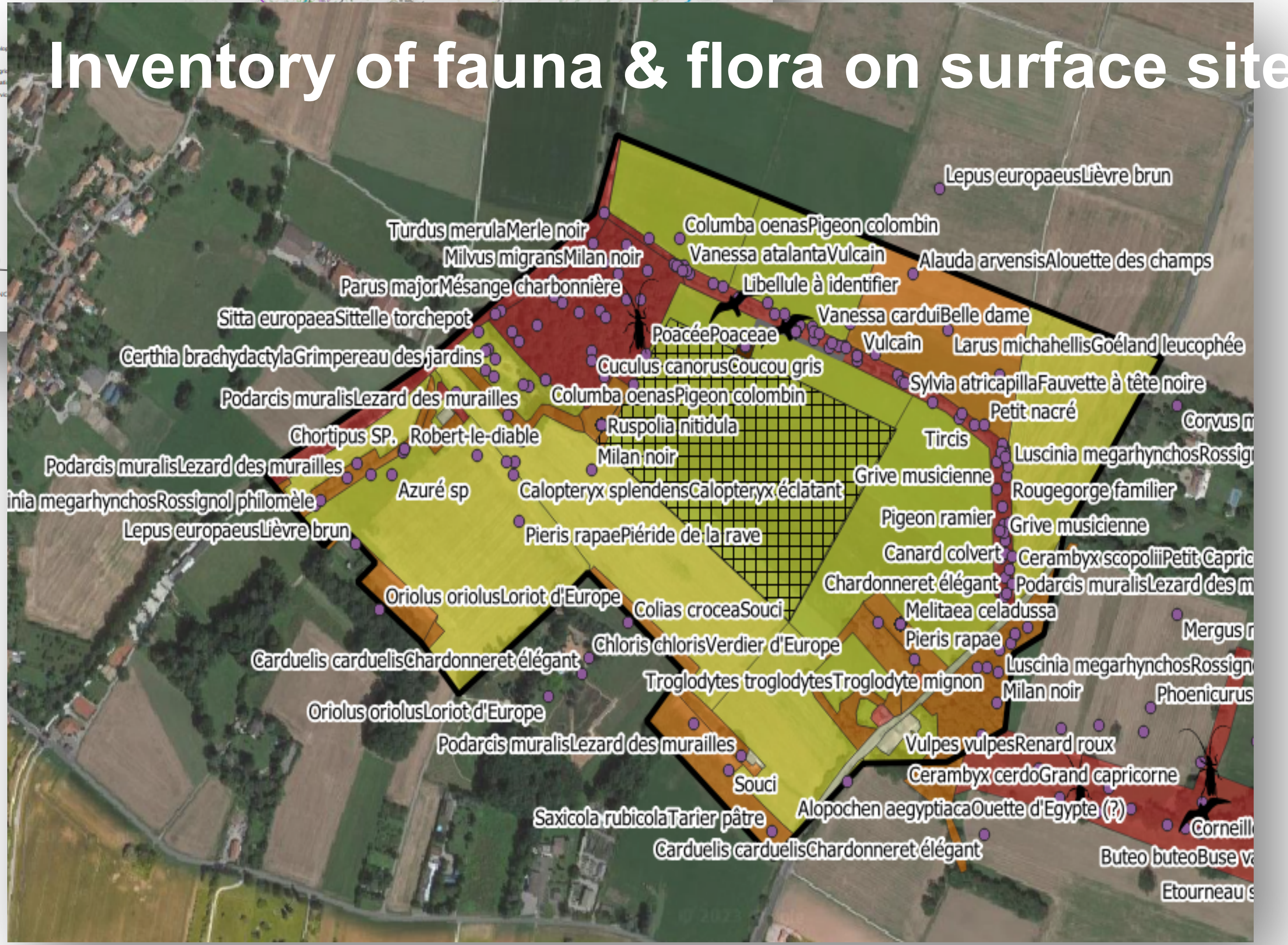
- **Studies of relevant environmental aspects over 18 months (> 4 seasons to see full cycle) with a consortium of specialized companies**
- **Necessary inventory for the "Avoid-reduce-compensate" approach and costing (compensation measures)**
- **Input for surface site designs, installation and operation aspects**
- **Pre-requisite for the required initial state report, before an environmental impact assessment**
- **Exhaustive list of topics covered:**
  - Topography, geology, hydrogeology, surface water, natural risks, urbanistic planning, fauna & flora survey, habitats and wetland analysis, soil quality and pollution, noise, light, radiation, technological risks, demography, economic activities, landscape and visibility, patrimony
- **Central management of all data in an "Environmental Information System" to be able to document the evolutions of the territory, the civil construction designs and the technical infrastructure development integrated with classical "Geographical Information System"**

Examples for field investigations and environmental studies





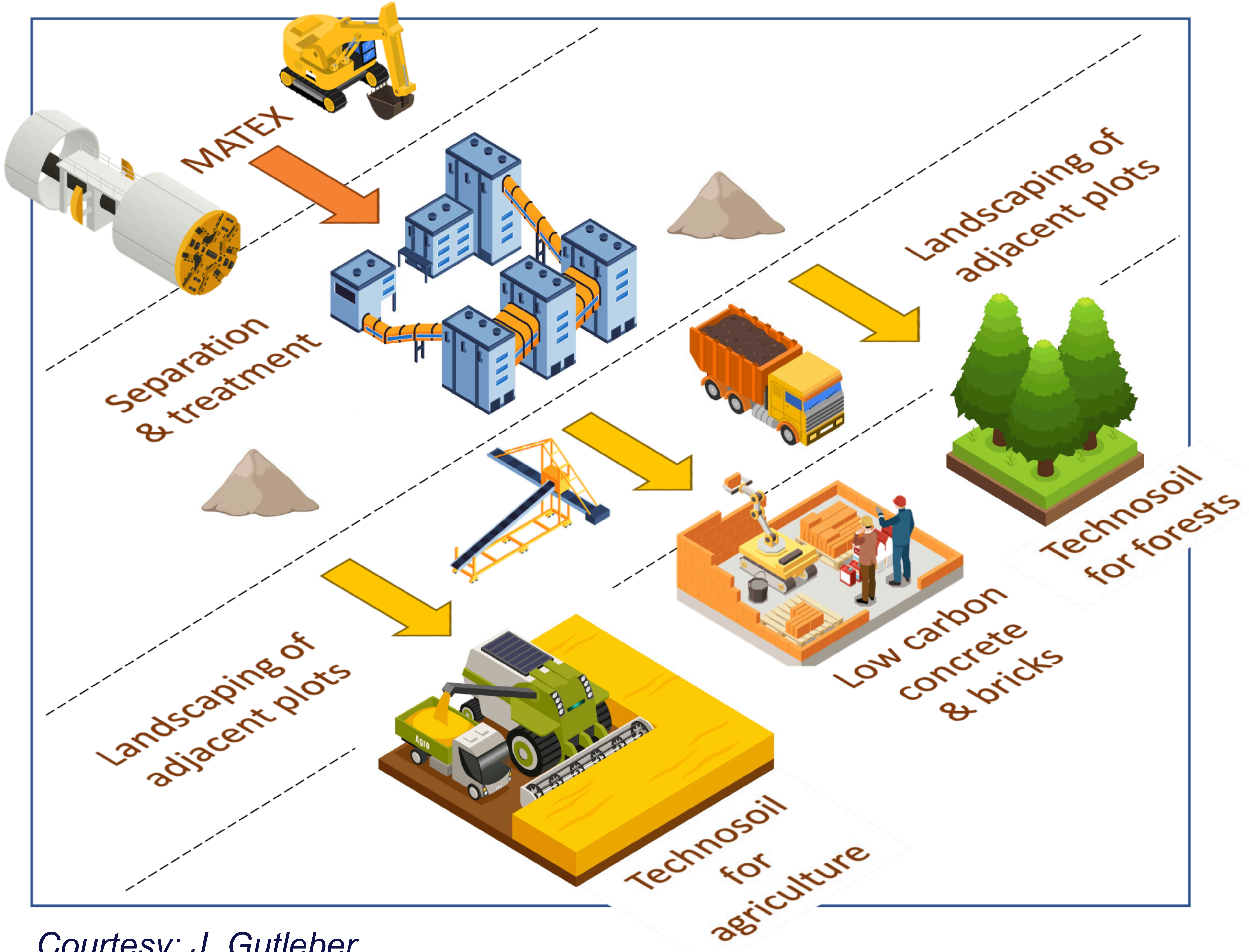
Description of **surrounding, views to be preserved, architectural aspects** to be Considered.



Determination of quality of the top soil and potential pollution, determination of the economic land value

Excavation material management

An innovative local approach for excavated materials:



Courtesy: J. Gutleber

Excavated material from FCC subsurface infrastructures: 6.5 Mm³ in situ, 8.4 Mm³ excavated (bulk factor 1.3)

2021-2022: International competition " **Mining the Future",** launched with the support of the EU Horizon 2020 grant agreement 951754**, to find innovative and realistic ideas for the reuse of Molasse (95% of excavated materials)**

2023: **Definition of the "OpenSky Laboratory" project:**

- **Objective**: Develop and test an innovative process to transform sterile "molasse" into fertile soil for agricultural use and afforestation.
- Duration: **4 years (2024-2027)**

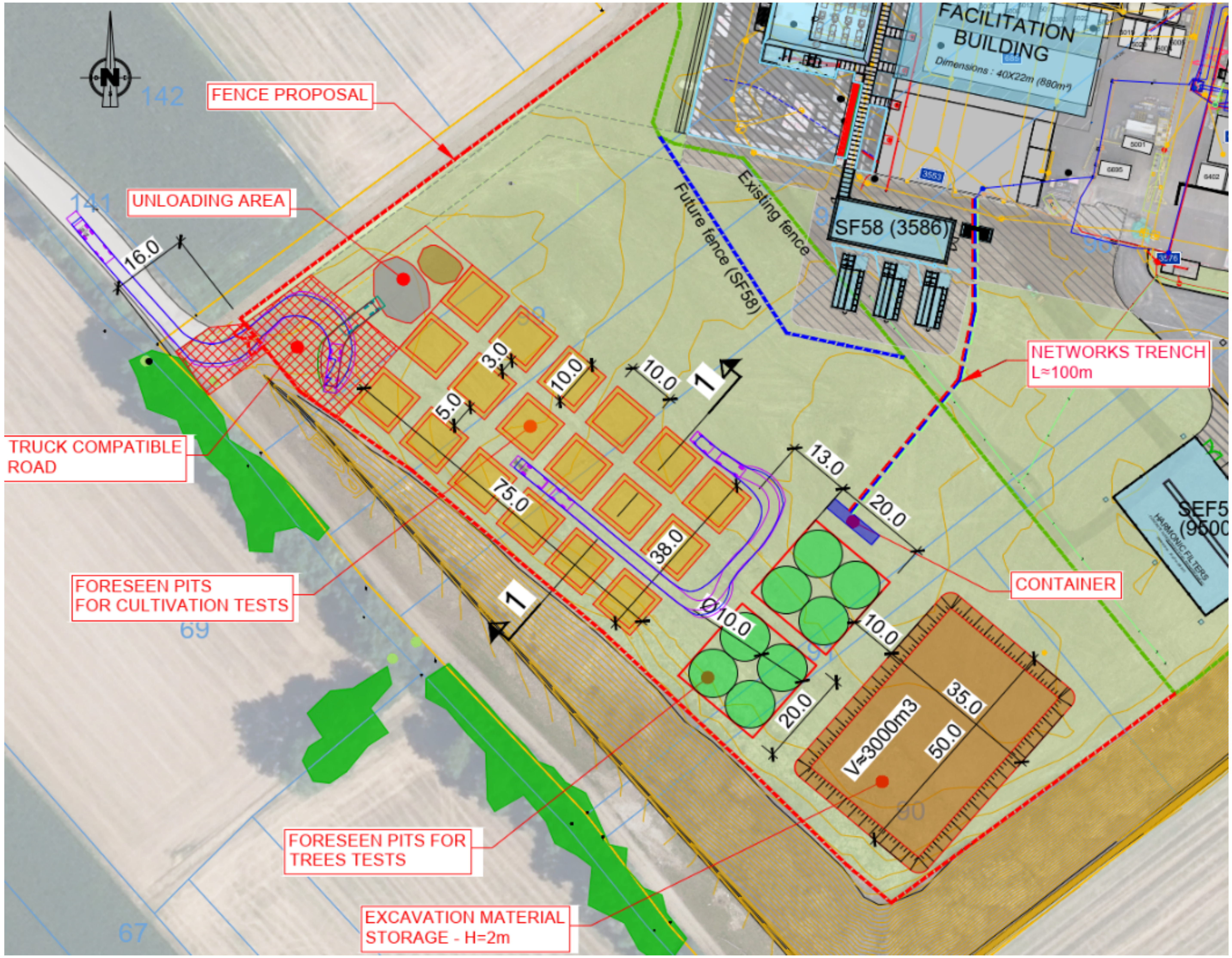
OpenSky Laboratory : HOW?

- 3’000 m² at LHC P5 in Cessy, France.
- **Trial with 5 000 t of excavated local molasse**
- 18 cells for agriculture trials (10*10 m)
- 2 cells for forestry trials (20*20 m)
- Different types of plants selected as function of regional specificities

1) Initial laboratory analysis to **identify** the **most suitable mixing** of molasse and amendments,

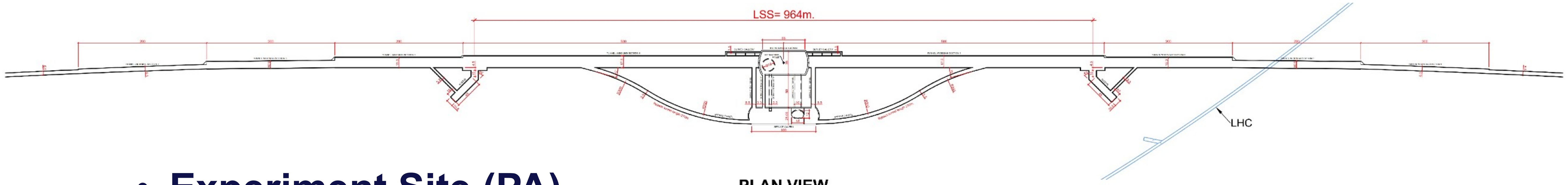
2) **Mixing/spreading** of the molasse with amendments on the trial cells,

3) **Planting and treatment with monitoring** of the field conditions in a **controlled environment.**



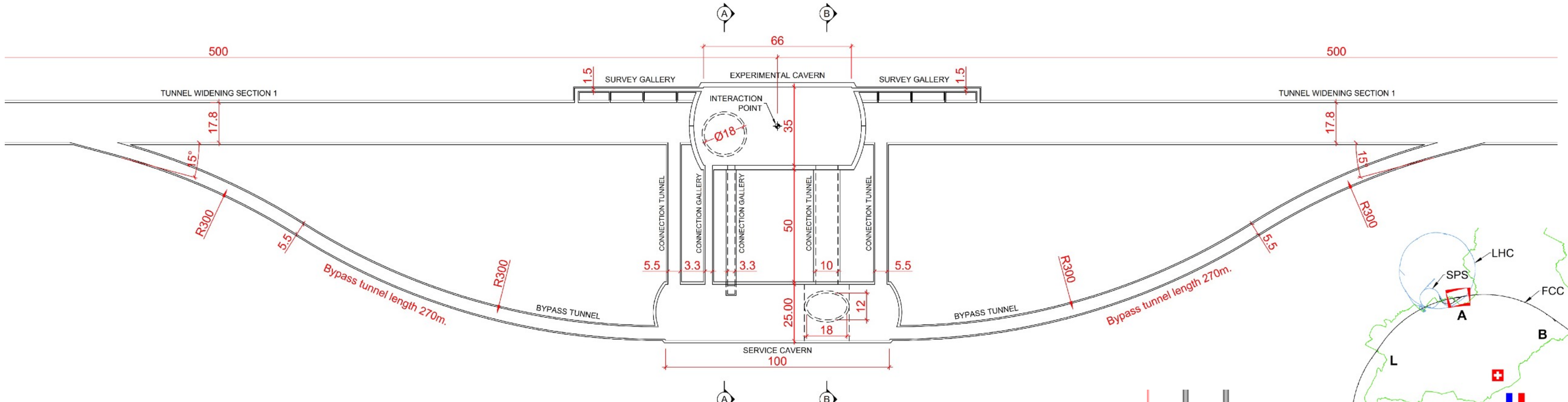
CE underground progress

- **Full 3D model of underground structures as basis for costing exercies**
- **Update of scheduling and costing with external consultant ongoing**
- **Independent second costing exercise based on same bill of quantities will be done**

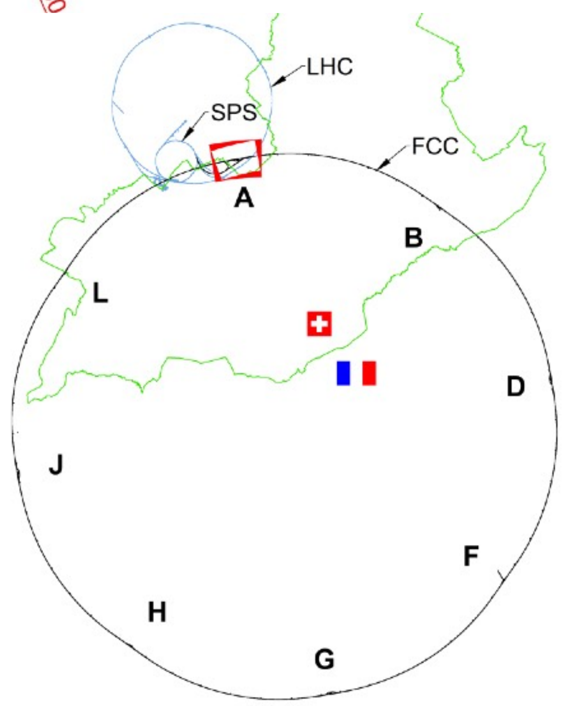


- **Experiment Site (PA)**

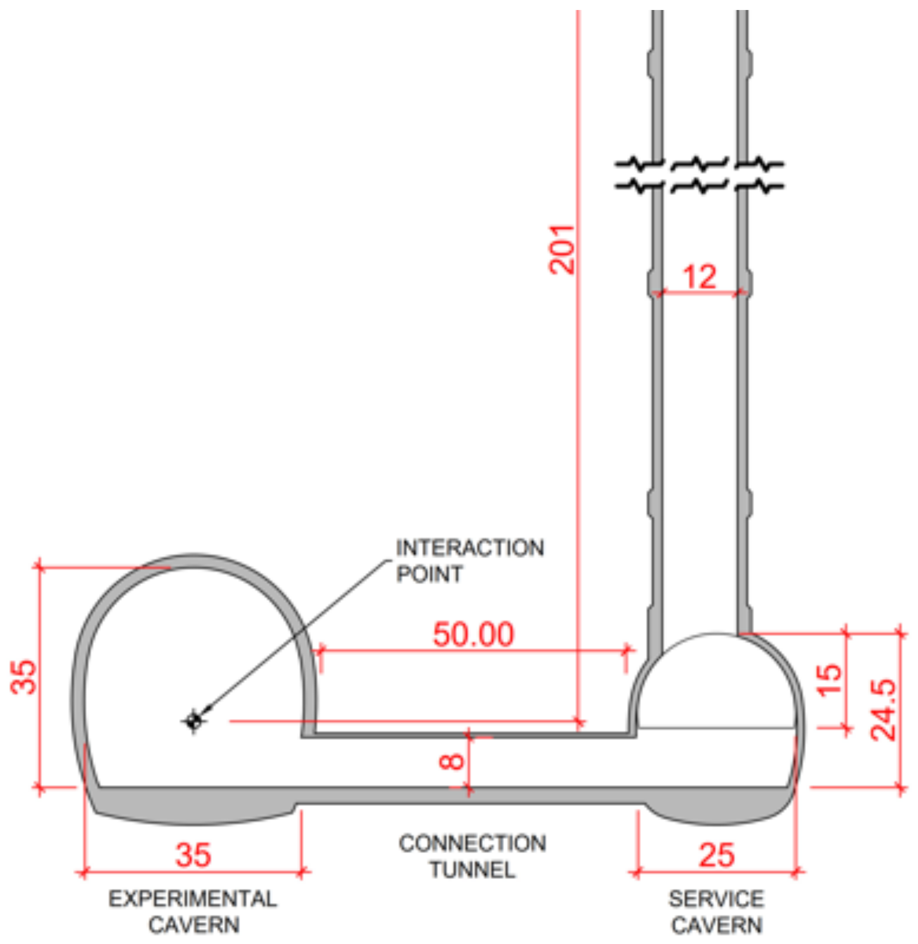
PLAN VIEW
1:3000

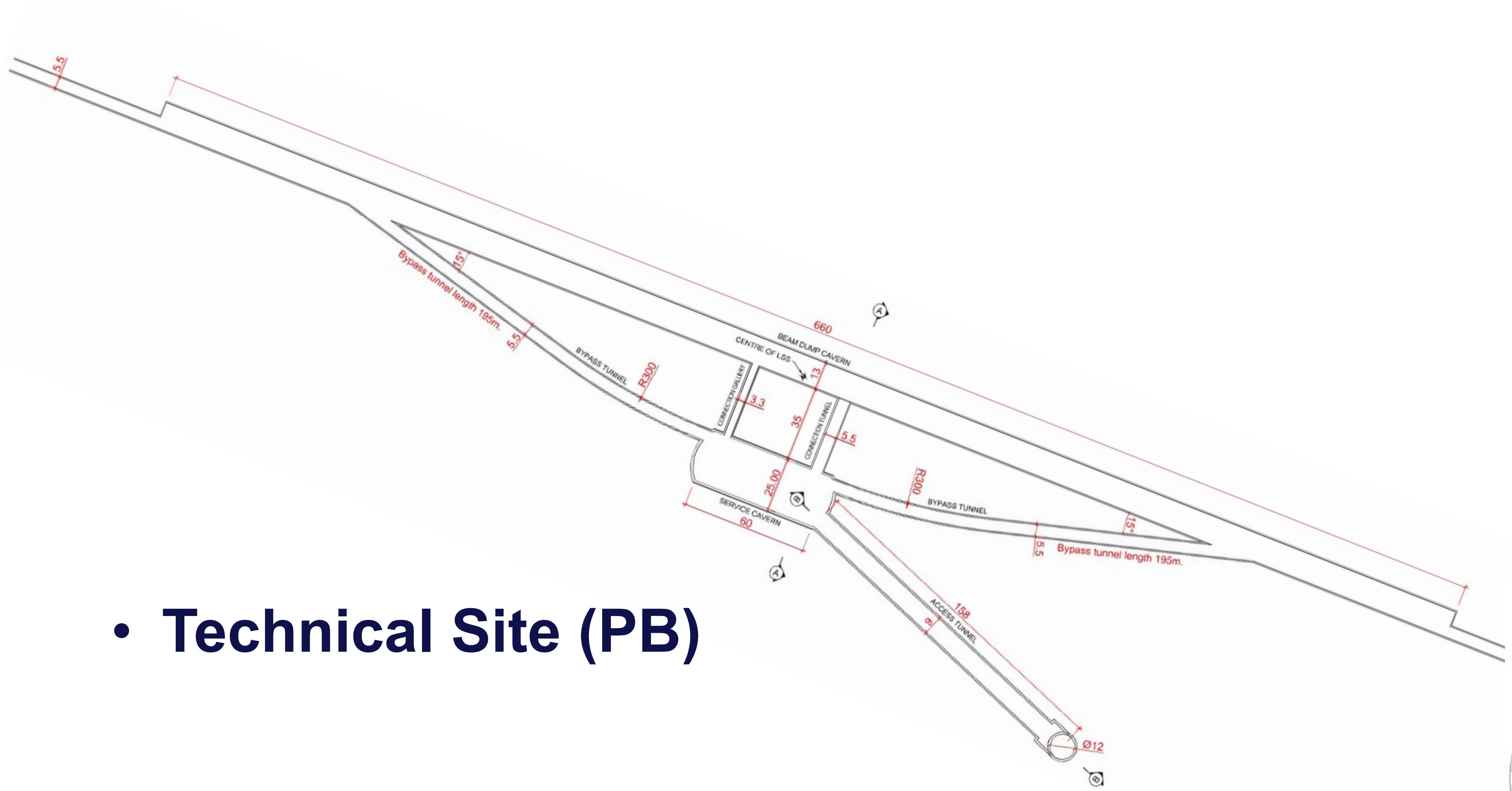


PLAN VIEW
1:1000

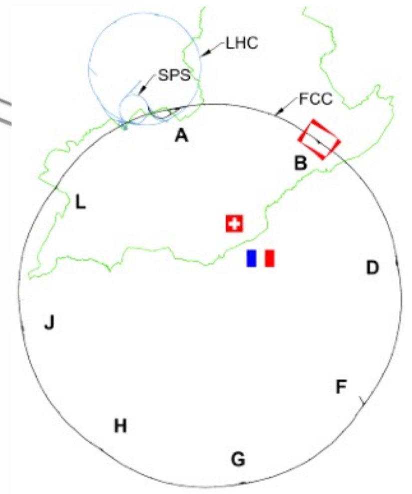


KEY PLAN





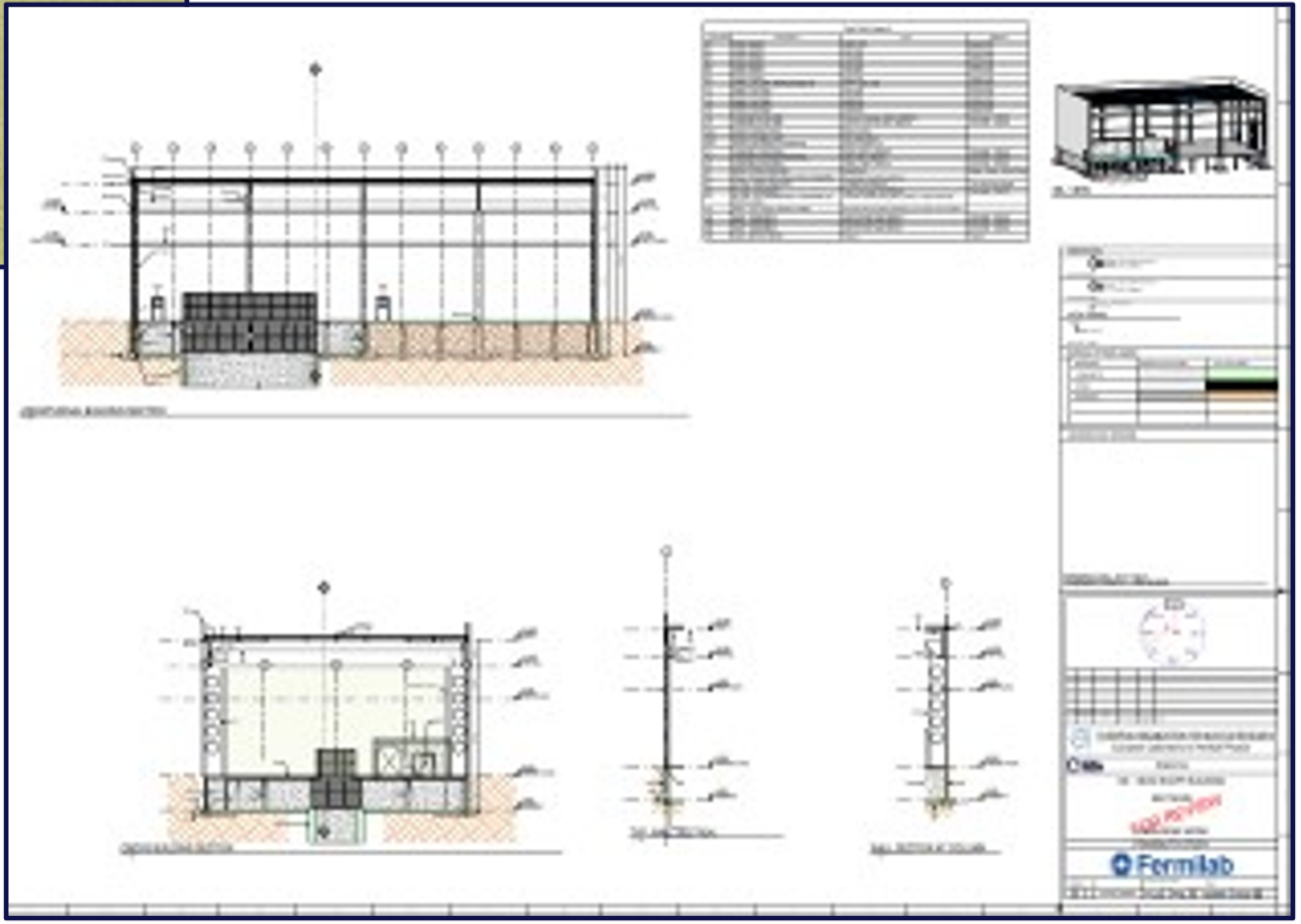
- **Technical Site (PB)**



KEY PLAN

CE surface progress

Generic study of experiment site and technical site by FNAL

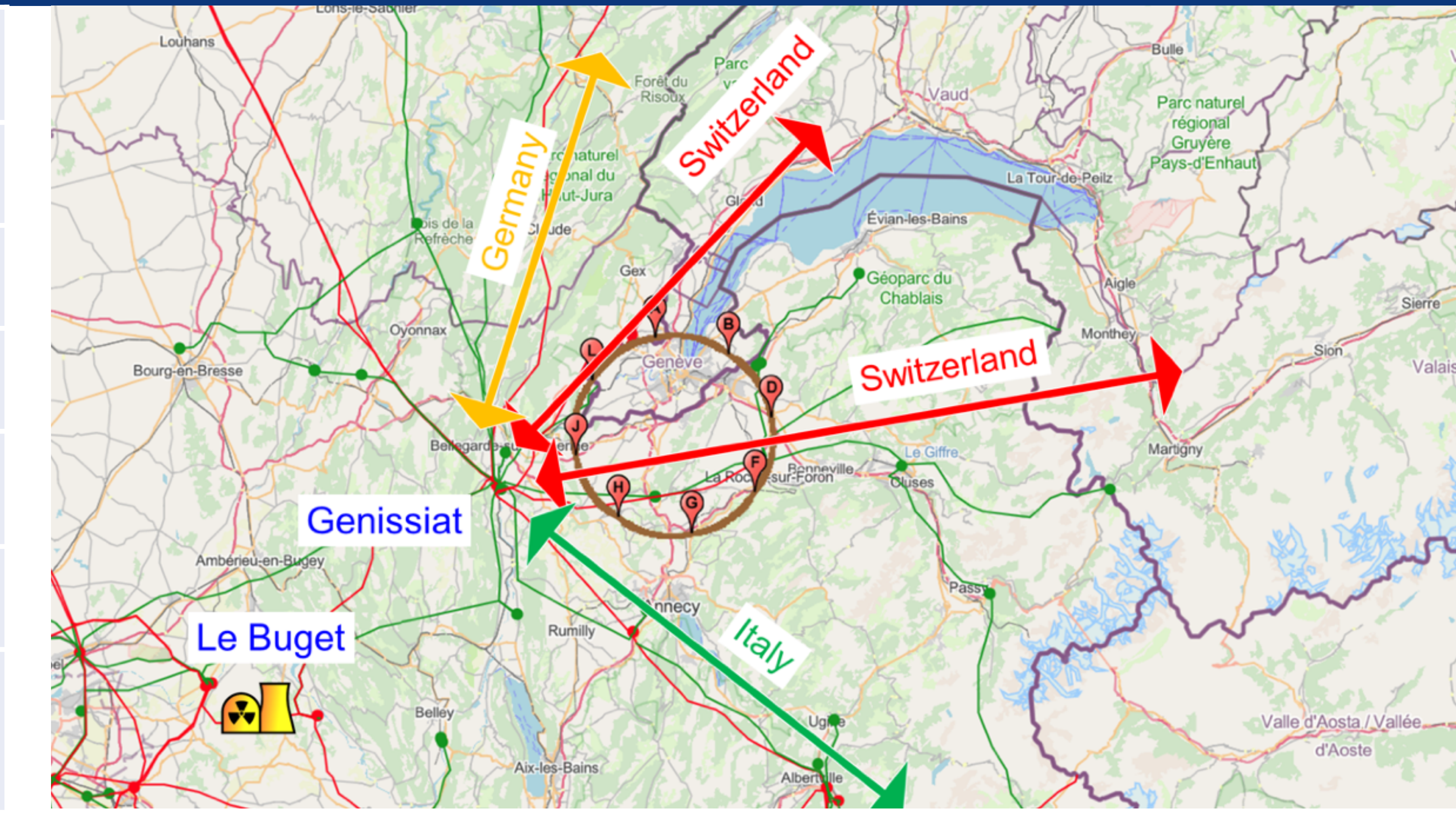


Examples of Fermilab Deliverables

- bills of quantities extracted from FNAL designs
- basis for cost estimate by consultant with experience on industrial constructions in CH-FR area.

Connections to electrical grid infrastructure

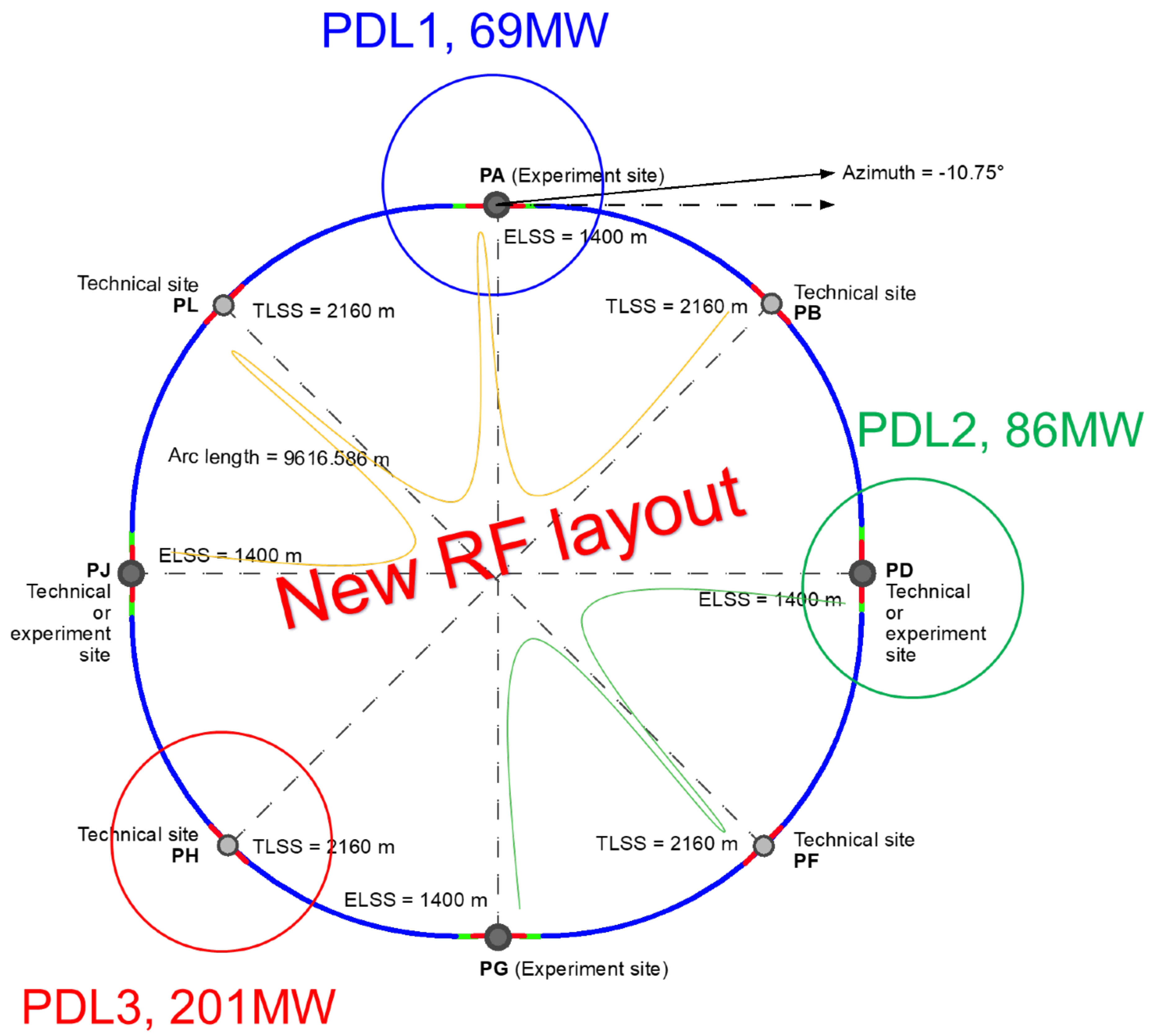
Updated FCC-ee energy consumtion	Z	W	H	TT
Beam energy (GeV)	45.6	80	120	182.5
Max. Power during beam operation (MW)	222	247	273	357
Average power / year (MW)	122	138	152	202
Total FCC-ee yearly consumption (TWh)	**1.07**	**1.2**	**1.33**	**1.77**
Yearly consumption CERN & SPS (TWh)	0.70	0.70	0.70	0.70
Total yearly consumpt. CERN & SPS & FCC-ee (TWh)	**1.77**	**1.90**	**2.03**	**2.47**



The loads could be distributed on three main sub-stations (optimally connected to existing regional HV grid):

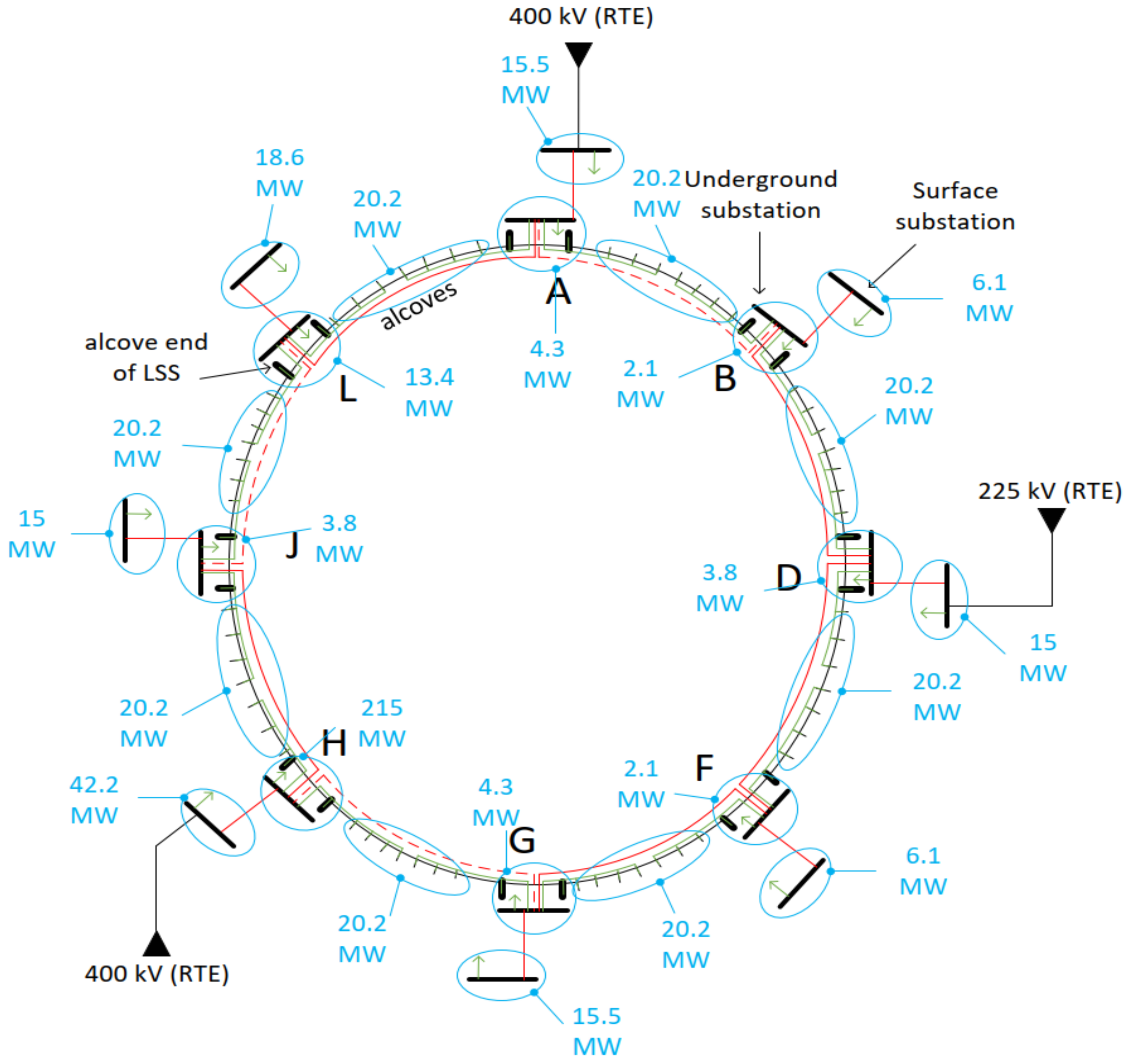
- **Point D with a new sub-station** covering PB – PD – PF – PG
- **Point H with a new dedicated sub-station** for collider RF
- **Point A with existing CERN station** covering PB – PL – PJ

- **Connection concept was studied and confirmed by RTE (French electrical grid operator) ➔ requested loads have no significant impact on grid**
- **Powering concept and power rating of the three sub-stations compatible with FCC-hh**
- **R&D efforts aiming at further reduction of the energy consumption of FCC-ee and FCC-hh**

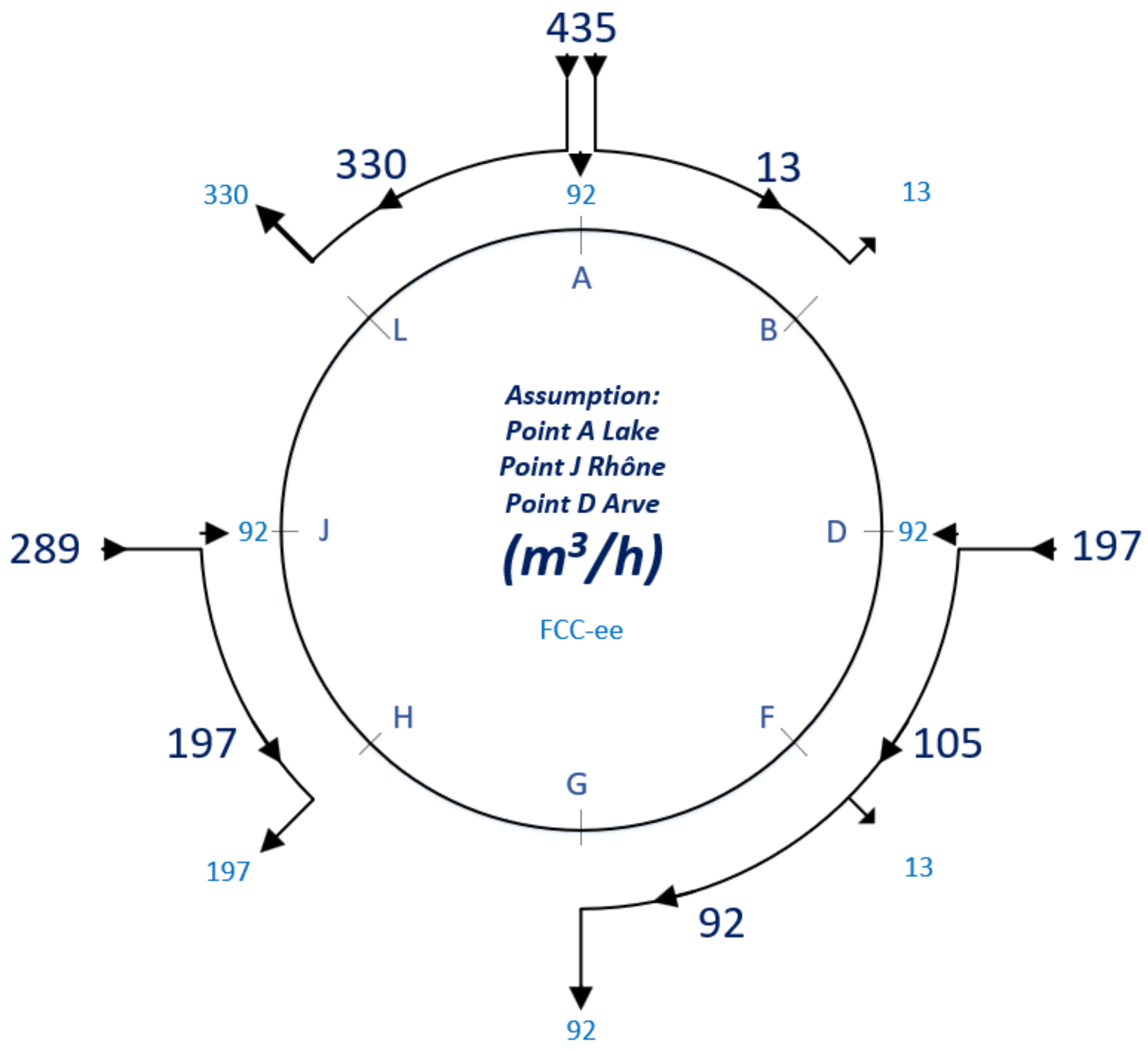


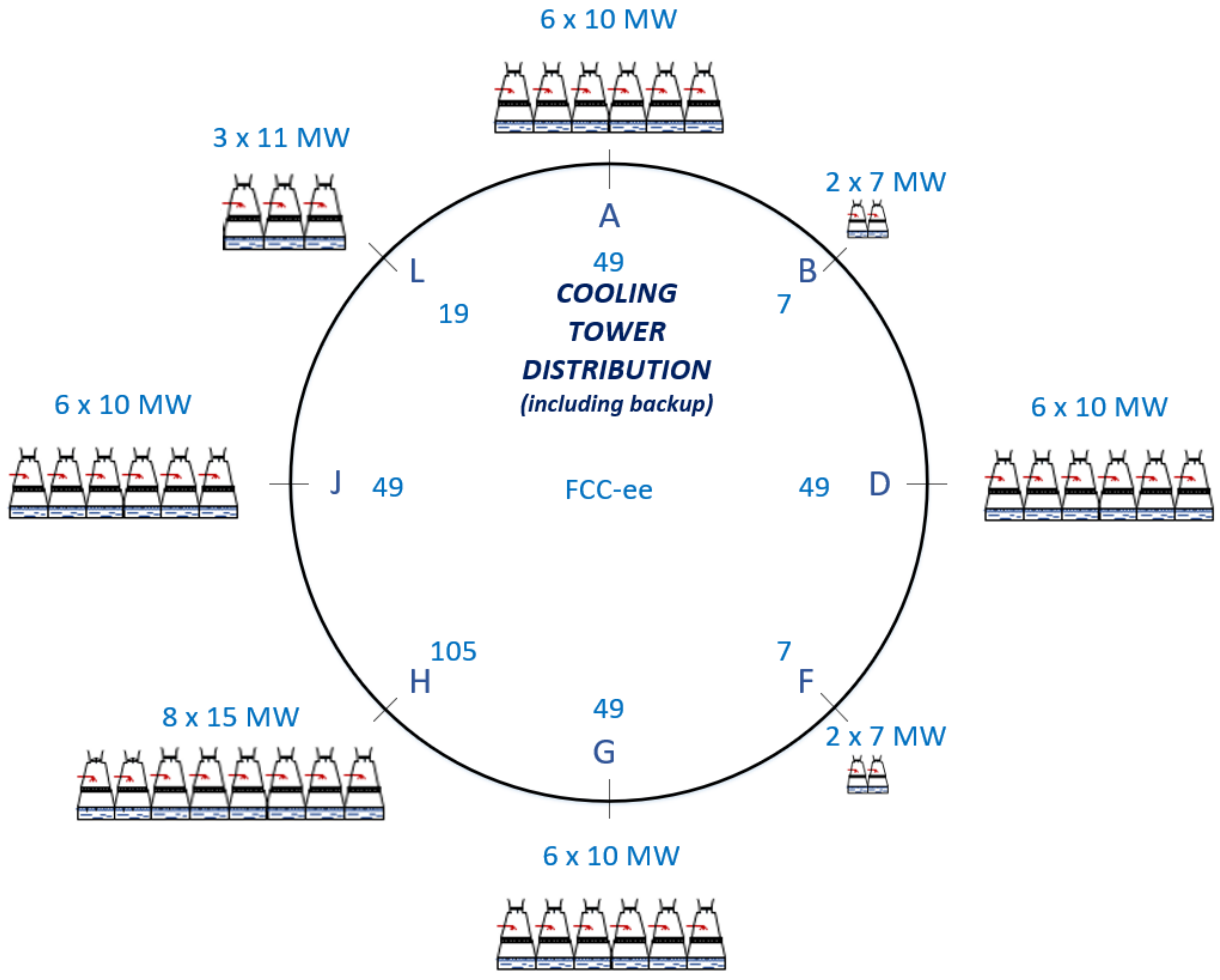
Electrical network

- **Electrical Power from the French network fed into the FCC at three points (A, H and D).**
- **Further distribution via the FCC ring.**
- **Covers all configurations of FCC-ee without need to build new sub-stations.**



Cooling water supply concept





- **Potential sources of cooling water Geneva lake (PA), Rhone (PJ) and Arve (PD).**
- **Existing line with lake water provided by SIG (Service Industriel del Geneve) to CERN LHC P8 (LHCb) sufficient for FCC-ee.**
- **Pipework in the tunnel will connect the remaining points to points PA, PD and PJ.**
- **Main cooling towers placed at experiment points (PA, PD, PG, PJ), and RF sites (PL, PH).**

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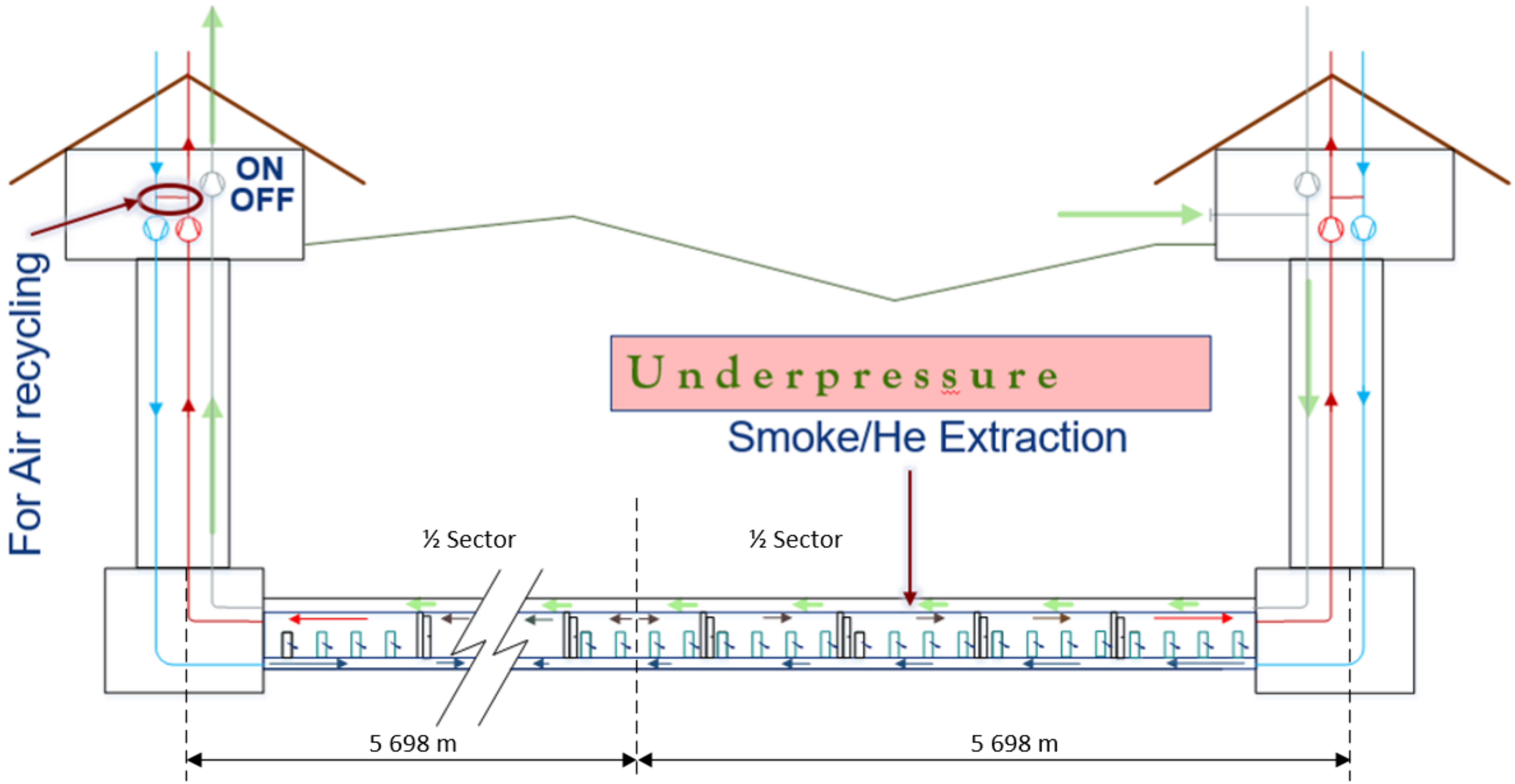
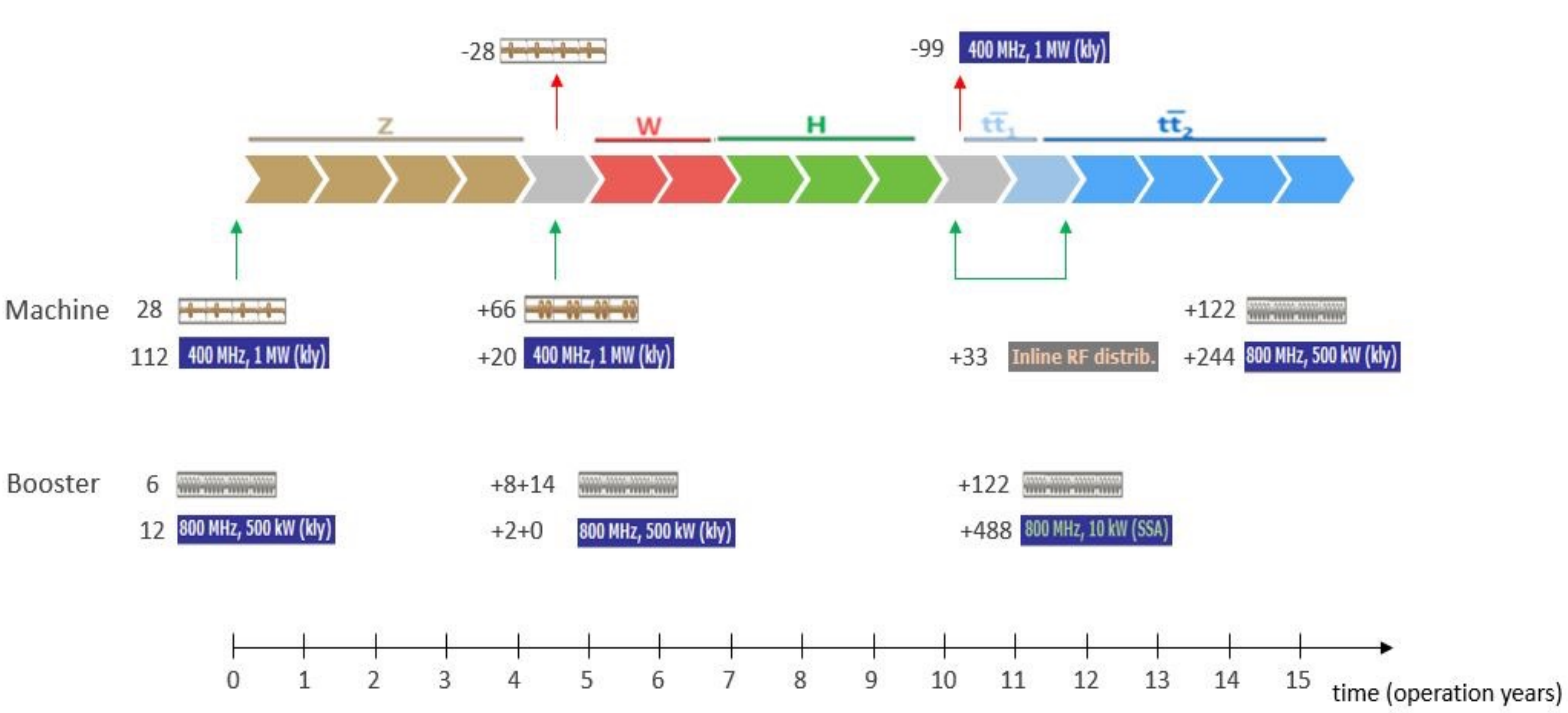
Ventilation concept

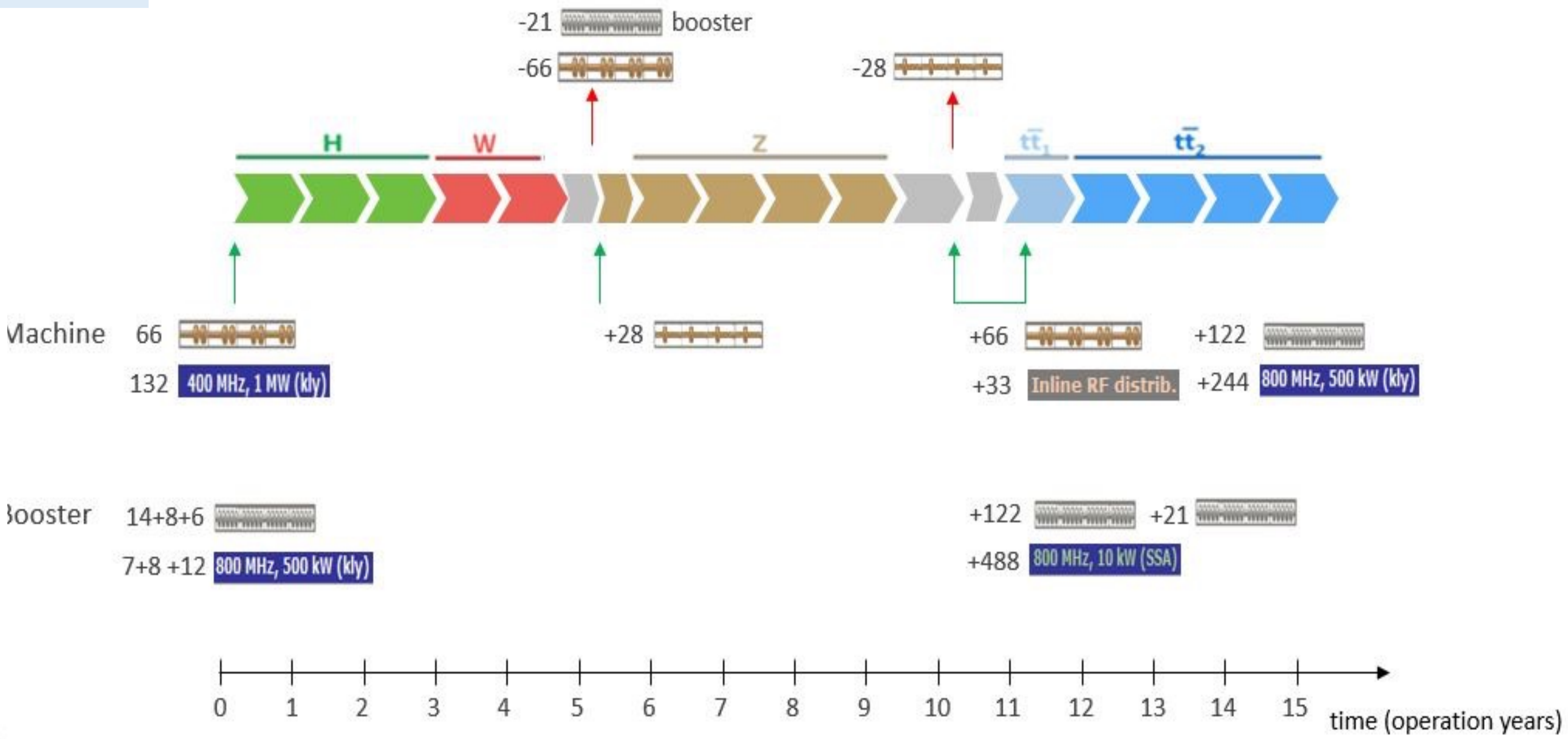


- Operation of the ventilation elements in one sector of the machine tunnel during normal operation.
- Smoke and helium extraction in green, general extraction in red and air supply in blue
- Compartmentalization via fire doors every ~400 m following arc cell structure.

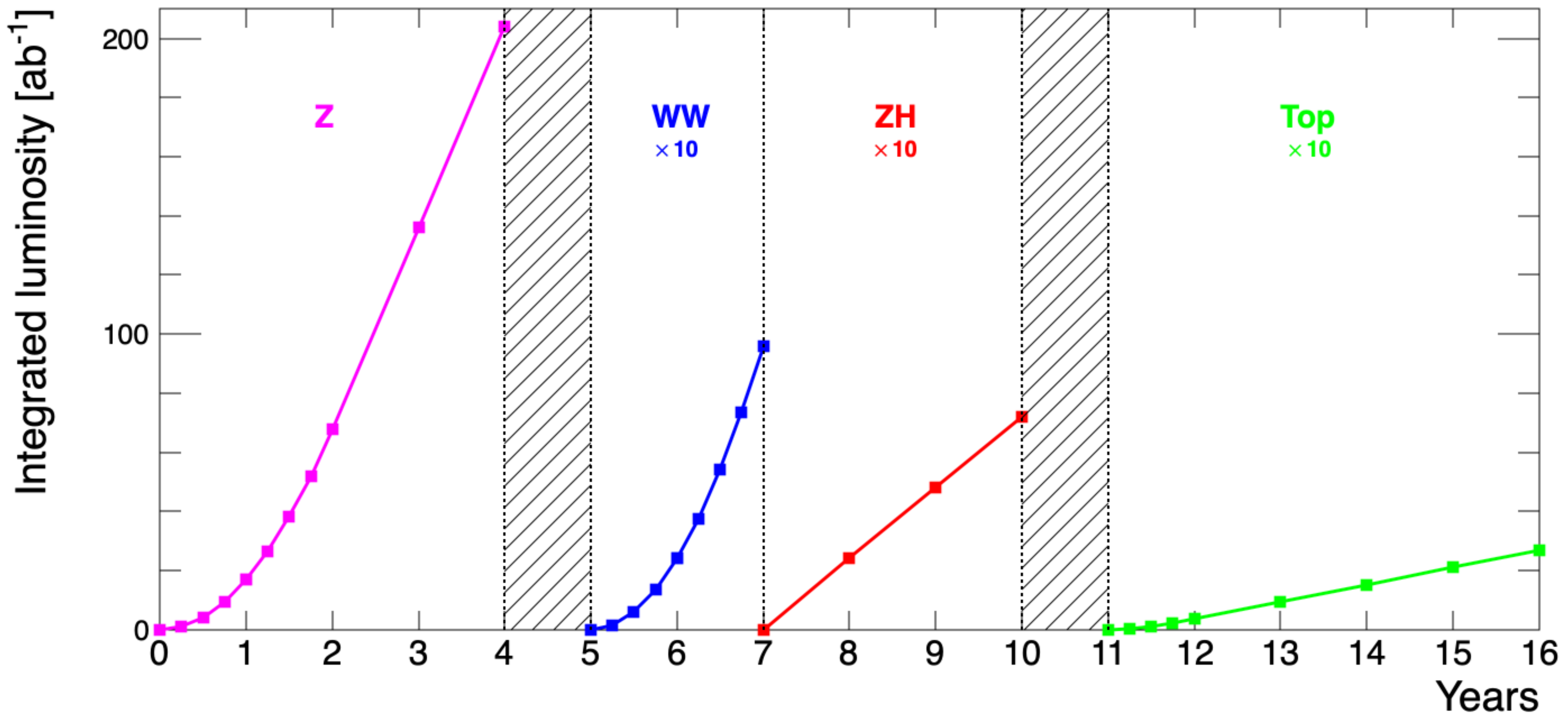
operation sequences for FCC-ee

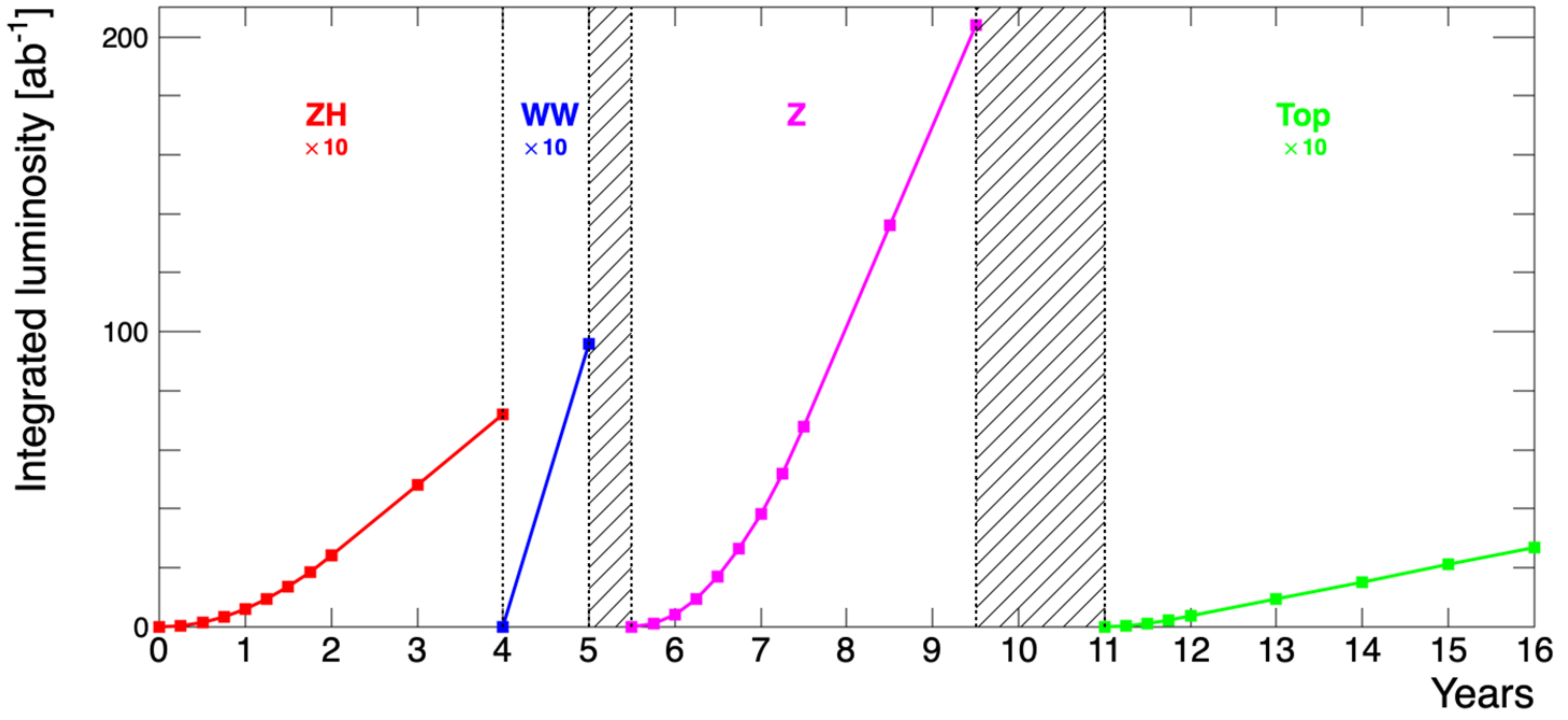
O. Brunner, F. Peauger





P. Janot

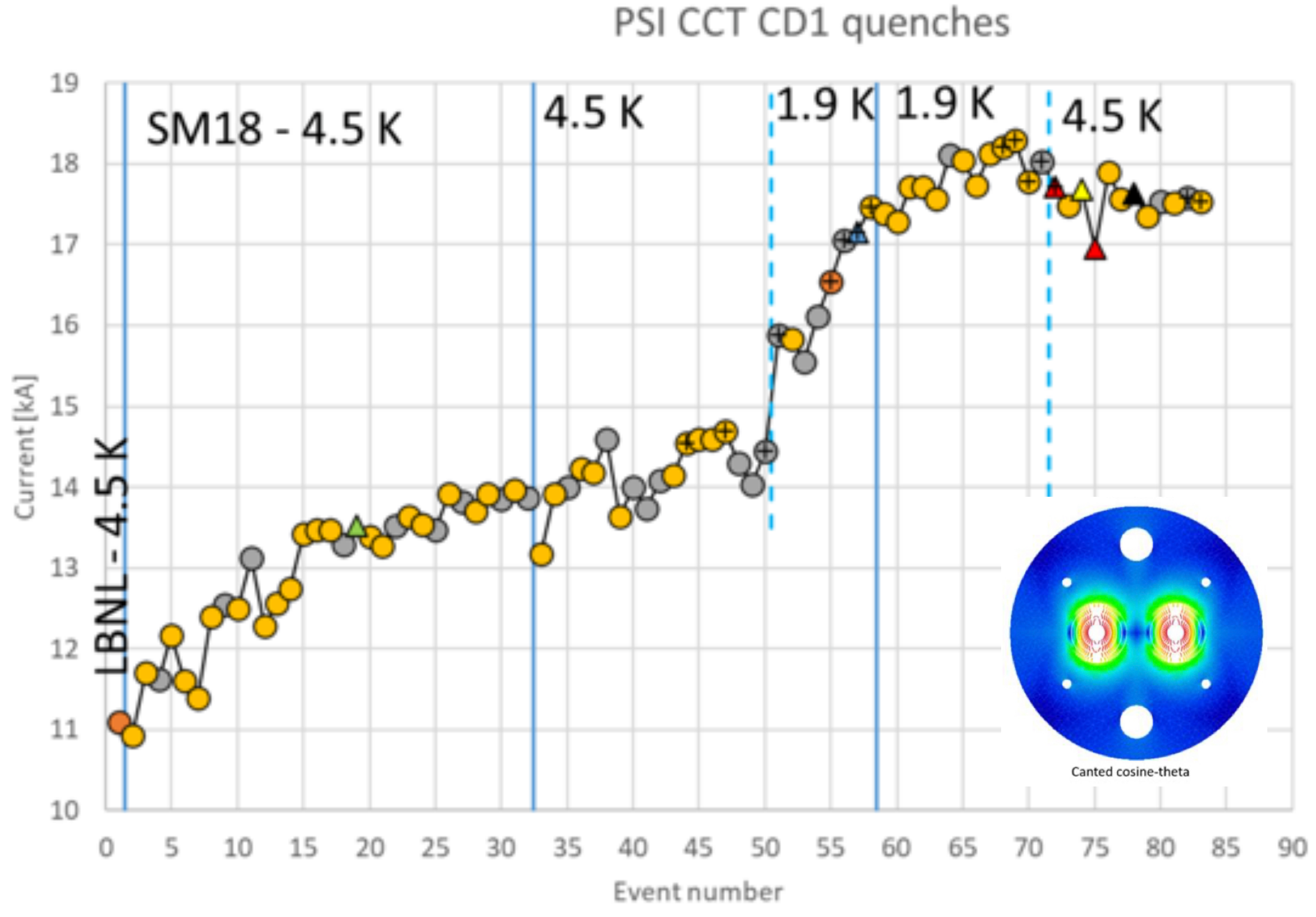




high-field magnets for FCC-hh: Nb_3Sn & HTS R&D

FUTURE CIRCULAR COLLIDER

PSI Nb3Sn CCT «CD1» main test carried out in 2022/23



It trained *A LOT*. **It reached 100% of maximum field at 4.5 K.** No conductor degradation occurred from handling, assembly, powering, or thermal cycling.

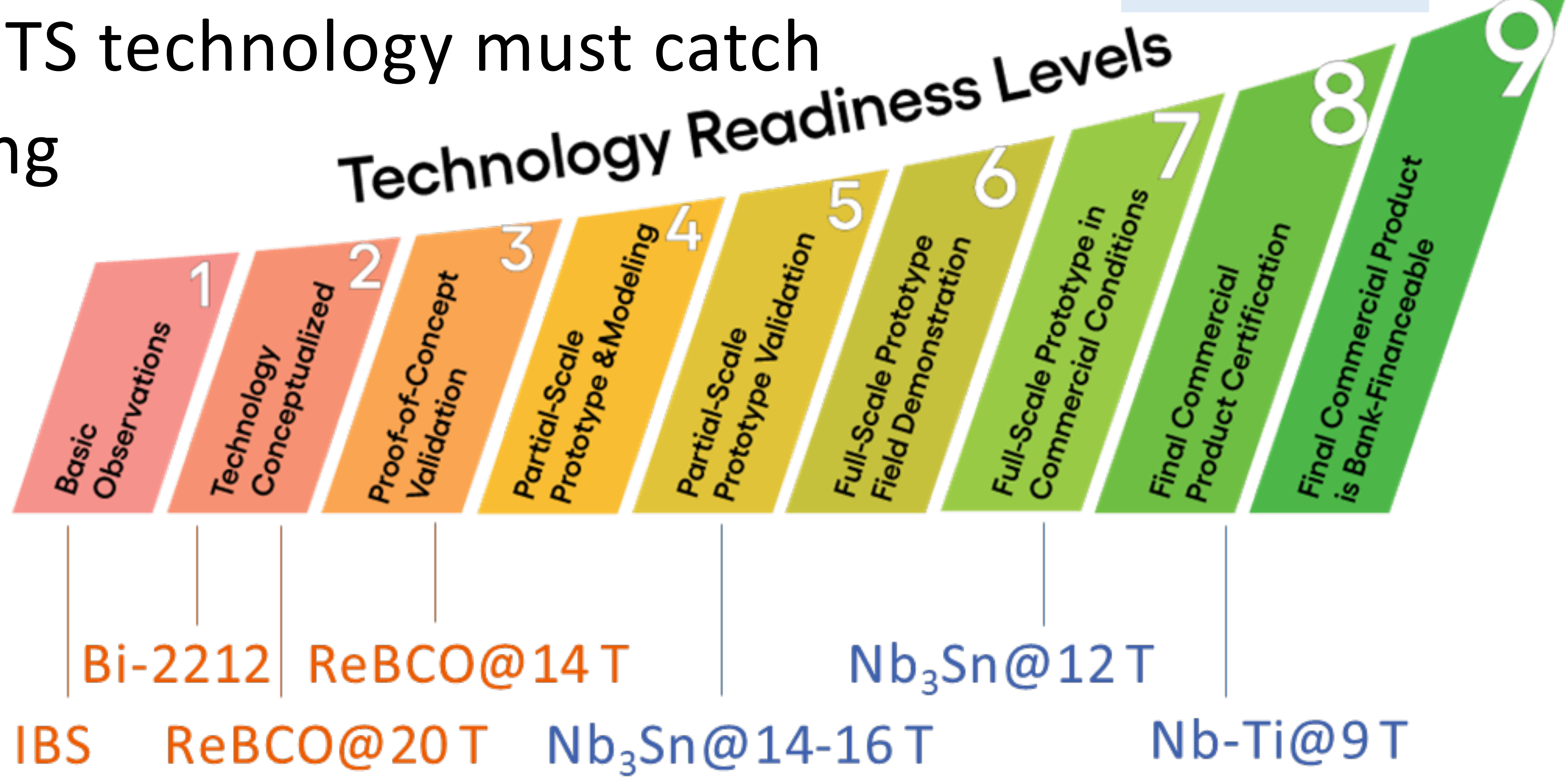
Stress-management works, CD1 is a robust magnet.

B. Auchmann

Rough estimates

Bottom line: HTS technology must catch over the coming 10 years in TRL to LTS

B. Auchmann



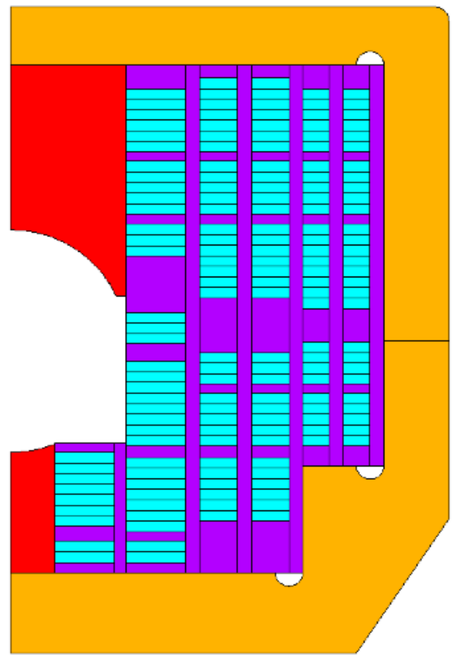
Next: FCC-hh SM-CC Demonstrator

Goal: demonstrate robust and cost-efficient Nb3Sn technology for next ESPPU.

Novel concept: Stress-managed and asymmetric common coils.

D. Araujo

Stainless steel shell
Iron yoke
Coil collar
Former
Non-magnetic poles
Nb_3Sn conductor



B_0 target of 14 T, at T_{op}: 4.2 K

Eng margin of 10%

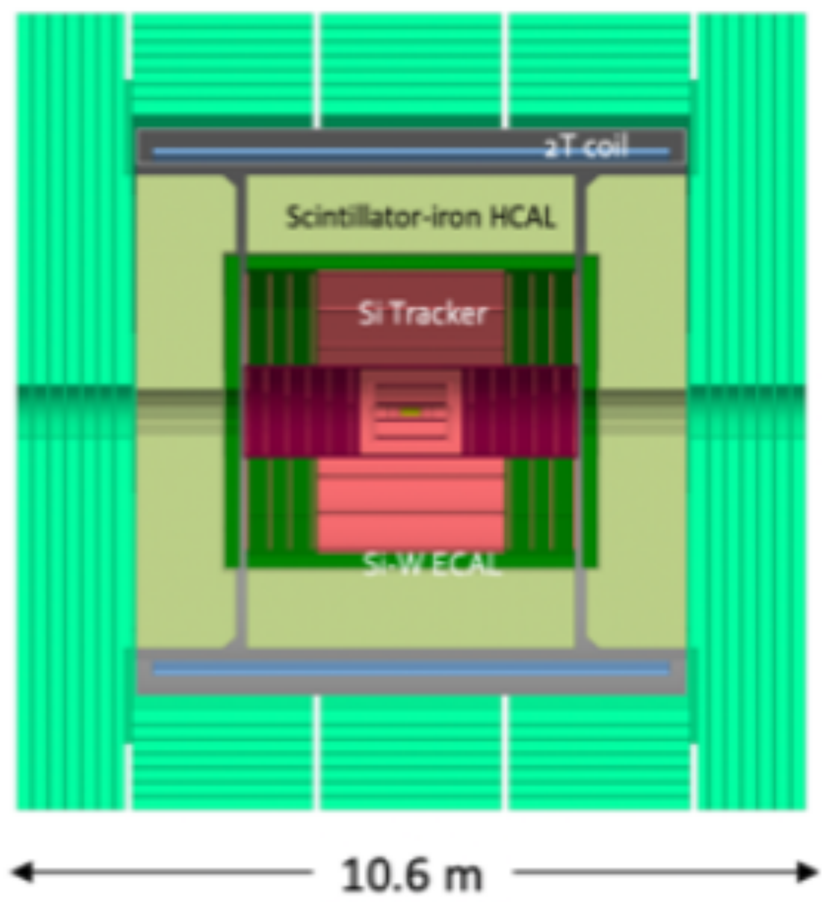
B_0 short sample @ 1.9 K: 16 T

HTS Innovation Funnel for HFM

FCC-ee detector concepts under study

FUTURE CIRCULAR COLLIDER

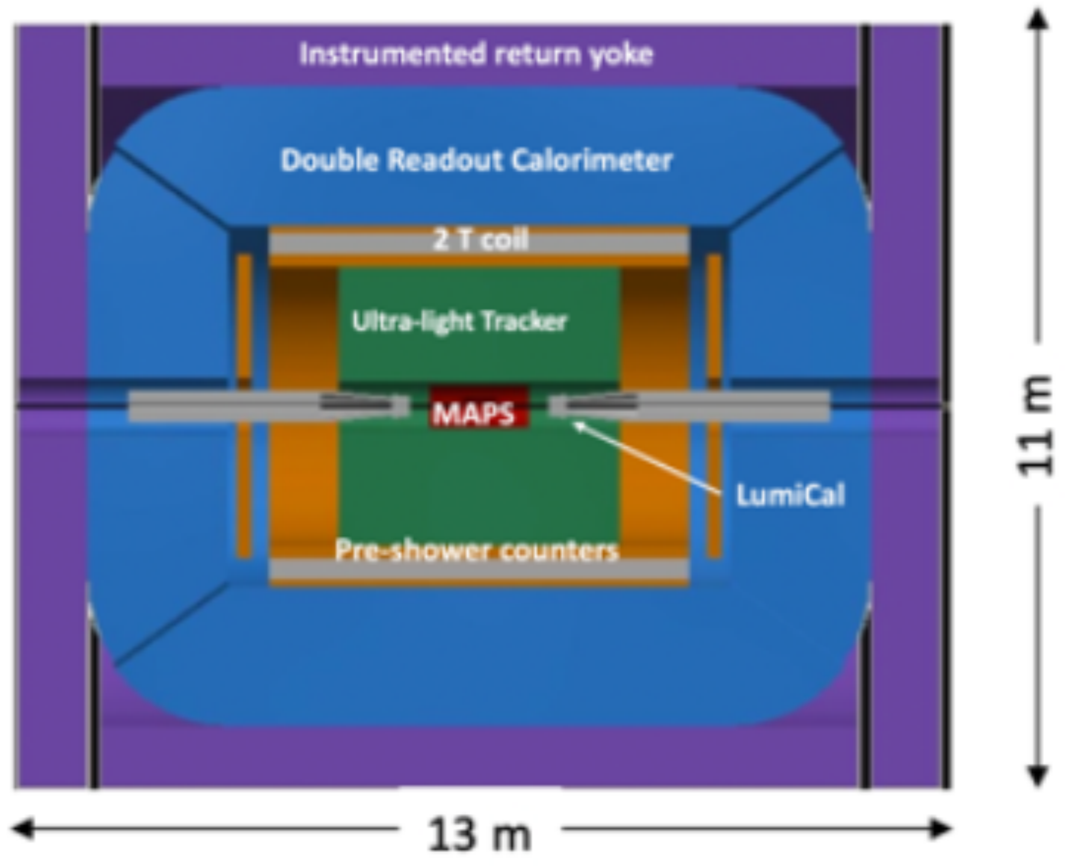
CLD



- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker; CALICE-like calorimetry; large coil, muon system
- Engineering and R&D needed for
  - reduction of tracker material budget
  - operation with continous beam (no power pulsing: cooling of Si sensors for tracking + calorimetry)
- Possible detector optimizations
  - Improved σ_p/p, σ_E/E
  - PID: timing and/or RICH?

CDR

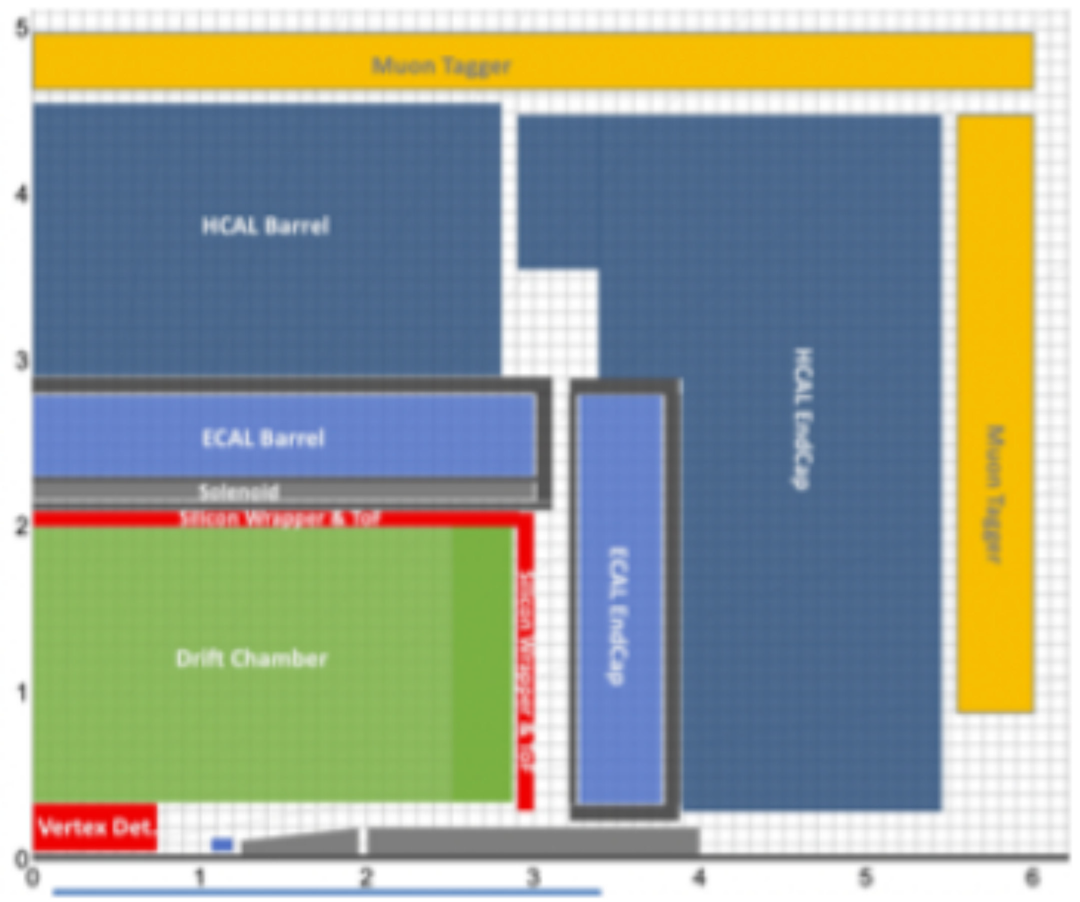
IDEA



- Less established design
  - But still ~15y history: ILC 4th Concept
- Si vtx detector; ultra light drift chamber w powerfull PID; compact, light coil; monolitic dual readout calorimeter; muon system
  - Possibly augmented by crystal ECAL
- Active community
  - Prototype designs, test beam campains, …

Noble Liquid ECAL based

new



- A design in its infancy
- High granularity Noble Liquid ECAL is core
  - Pb+LAr (or denser W+LCr)
- Drift chamber; CALICE-like HCAL; muon system.
- Coil inside same cryostat as LAr, possibly outside ECAL
- Active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

M. Dam, et al.

Opportunities to exploit the facility

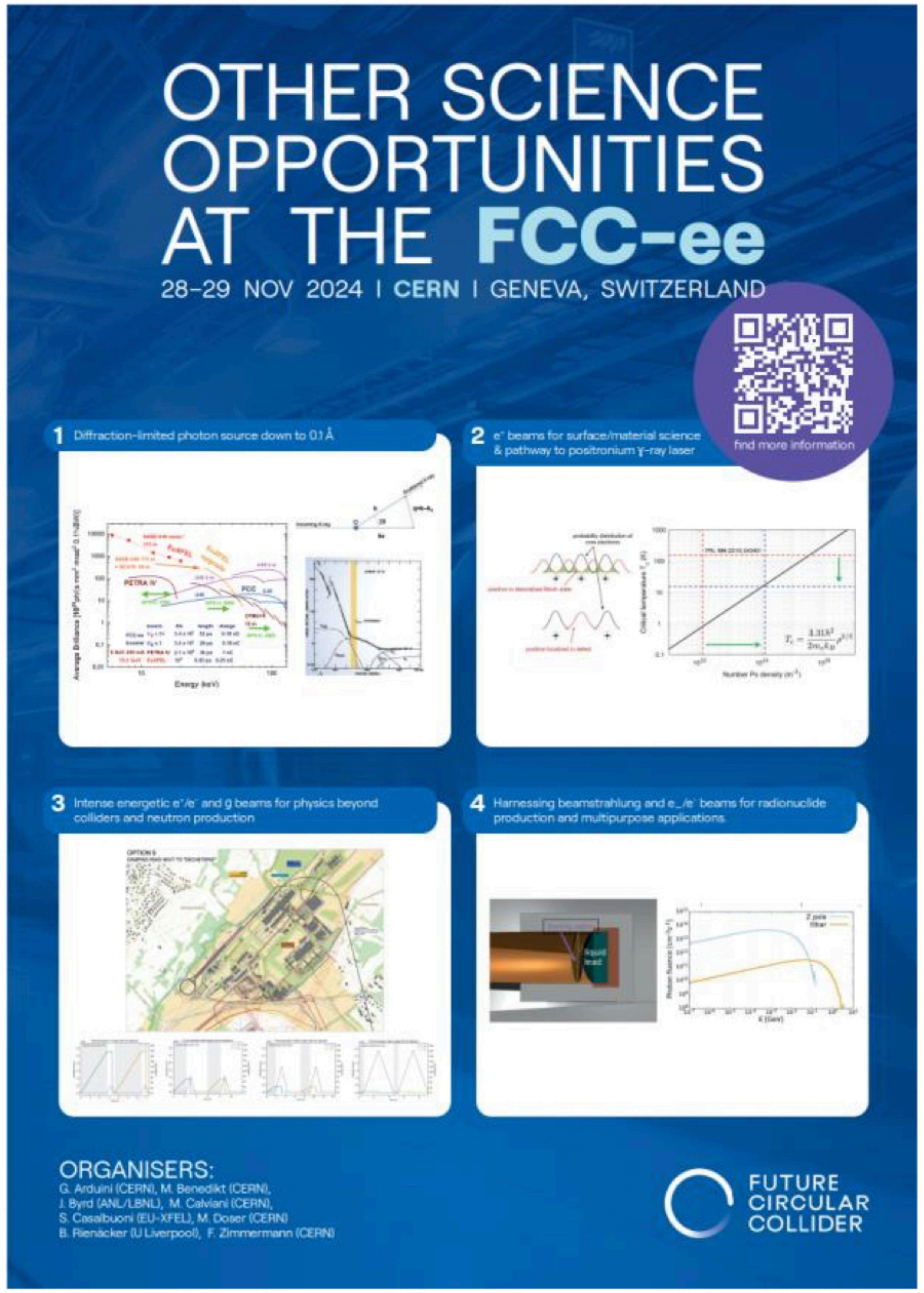
Assure that the entire FCC programme including injector and booster represent an attractive long-term platform for science.

Provide opportunities before the collider enters in operation.

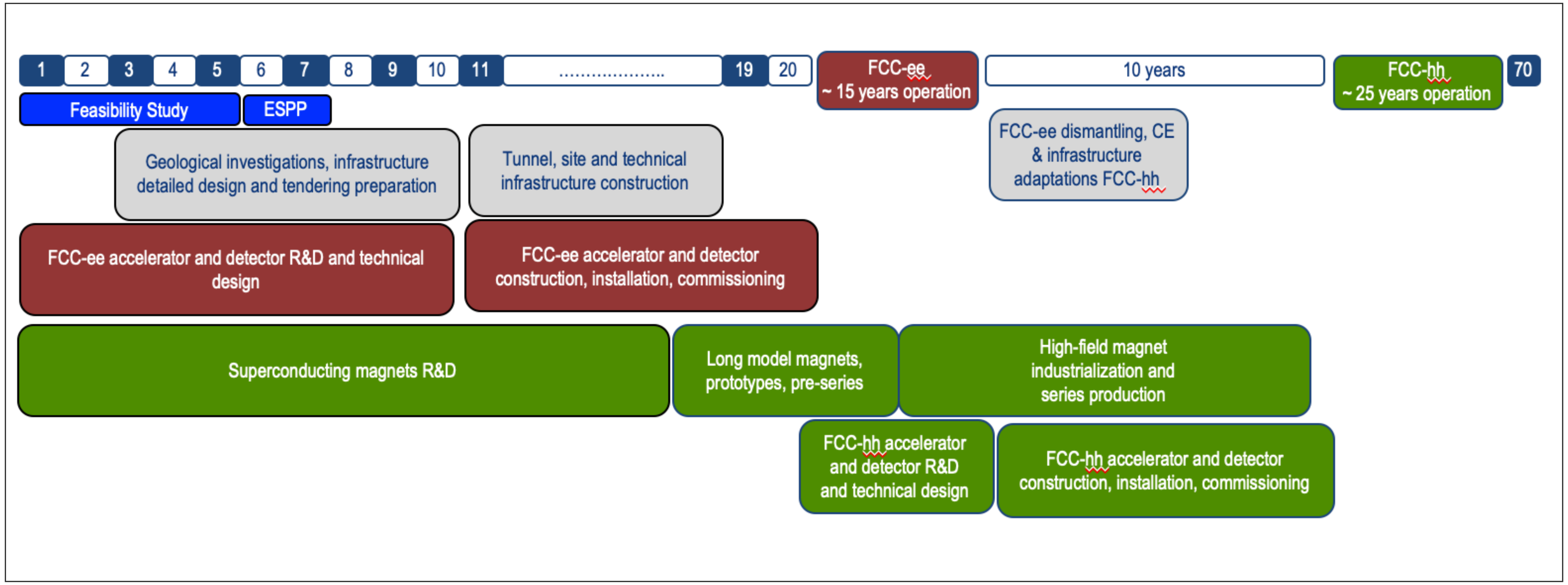
- Non-collider science opportunities at FCC-ee (August 2024)
- Other science opportunities at the FCC-ee (November 2024)

Examples:

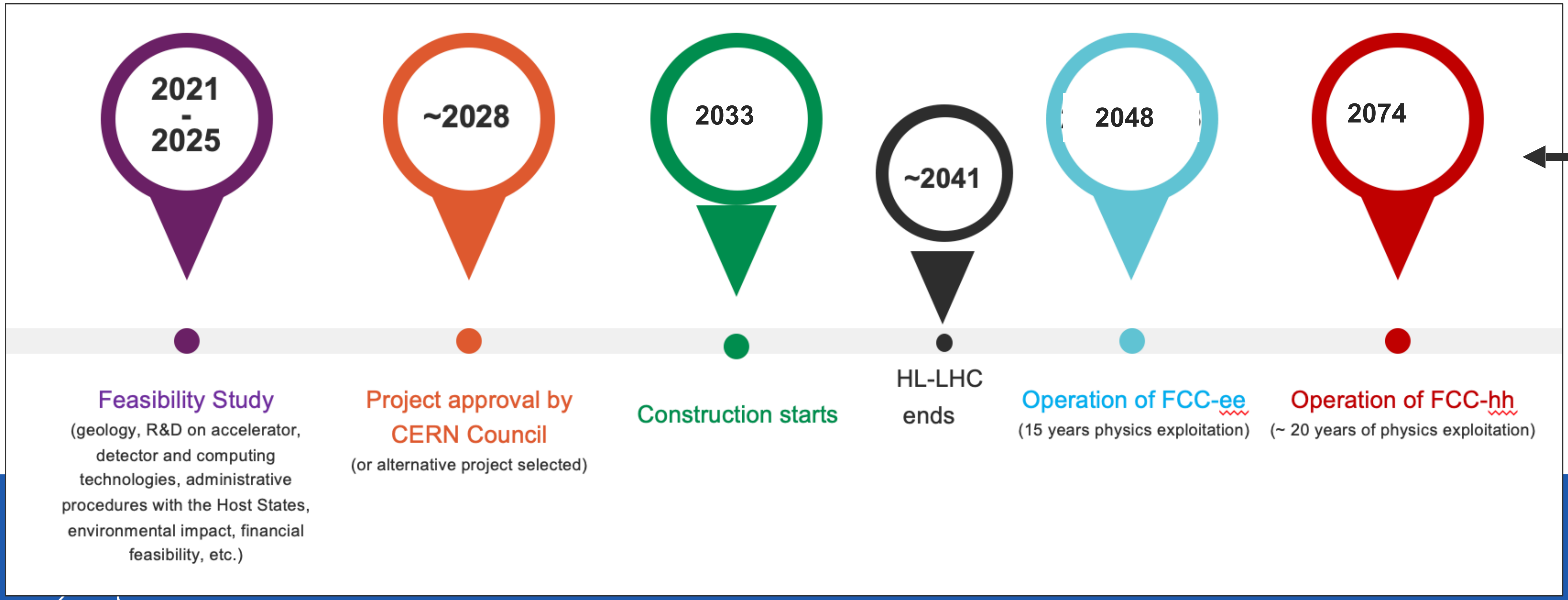
Photon science with high beam current (, positron source for materials science, testbeds for muon colliders, plasma acceleration of positrons, physics beyond colliders and much more.



FCC integrated program - timeline



Note: FCC Conceptual Design Study started in 2014 leading to CDR in 2018



"Realistic" schedule taking into account:
- past experience in building colliders at CERN
- approval timeline: ESPP, Council decision
- that HL-LHC will run until 2041

Can be accelerated if more resources available

Final remarks

- Why FCC? It's the most effective facility to address the diversity of challenges that are open for exploration at colliders

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- “Variations on the theme” will be proposed during the strategy: important to keep options open, also in view of the rapidly evolving world stage, but not at the risk of
  - showing lack of consensus on priorities
  - delaying the approval of the project

Final remarks

- Why FCC? It's the most effective facility to address the diversity of challenges that are open for exploration at colliders
- "Variations on the theme" will be proposed during the strategy: important to keep options open, also in view of the rapidly evolving world stage, but not at the risk of
  - showing lack of consensus on priorities
  - delaying the approval of the project
- Prioritizing, staging, planning, etc cannot neglect hard constraints set by technology, costs, resources and, unavoidably, sociology and politics:
  - at least for what is within our power (ie technology, resources and scientific judgement), let's keep the definition of the project, and thus the strategy discussions, as close to the real axis as we can … while keeping the ambitions high!

Additional material

New FCC-hh scenarios

- Driven by new accelerator layout (90.7 km ring vs 100 km, increased dipole filling factor)

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New FCC-hh scenarios

- Driven by new accelerator layout (90.7 km ring vs 100 km, increased dipole filling factor)
- Driven by assumptions about challenges/options in dipole technology
- Ongoing review of CDR physics potential projections, to assess impact of new scenarios:
  - See https://indico.cern.ch/event/1439072/
  - Goal is NOT to push for an alternative “planA”, but to provide expert answers to questions that may be raised during the Strategy process, eg in the context of “plan-B” discussions

Slides from Frank Zimmermann (link), see also Frank's note

Assumptions & possible parameter range

With present layout of the FCC, and after diligent optimization (by Massimo, Gustavo, and Thys), the following energies can be reached according to the dipole field:

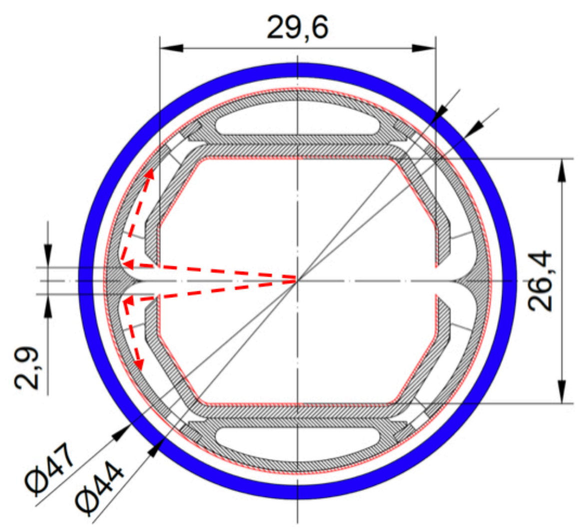
Dipole field [T]	c.m. energy	Comment
12	72	not far above peak field of HL-LHC Nb_3Sn quadrupoles
14	84	Nb_3Sn or HTS
17	102	HTS
20	120	HTS

Increasing the c.m. energy beyond ~100 TeV, **we will assume that the synchrotron-radiation power could not increase, beyond a total of about 4 MW** (which must be removed from inside the cold magnets) **

On the other hand, **when decreasing the beam energy, one can hold either the synchrotron-radiation power** (increasing current up to HL-LHC values) **or the beam current constant**. Also, the **pile-up might need to be limited, e.g. to ~1000 events/crossing**. We thus consider three scenarios for 12 T (0.5 A and 1.12 A beam current, the latter without or with pile-up levelling).

Finally, **further overall lowering the synchrotron radiation power, by reducing the number of bunches, in order to restrict the total power consumption of the future FCC-hh, would decrease peak and integrated luminosity by the same factor.**

** 30 W/m/beam => 5 MW total, released inside magnets operating at 1.9K !!
Absorption by beam screen at 50K to room T => 100MW cryo plant …



Six scenarios

1) A machine based on 12 T dipoles, with a beam current of 0.5 A as considered for the 16 T FCC-hh machine (F12LL).
2) A machine based on the same 12 T technology close to deployment, but with a higher beam current of 1.1 A, as considered for the HL-LHC (F12HL).
3) The same case as F12HL but limiting the pile up not to exceed a value of 1000 (F12PU).
4) A machine based on 14 T dipoles, and 0.5 A current (F14).
5) A machine based on High Temperature Superconductor (HTS) dipole magnets with a field of 17 T, just exceeding 100 TeV c.m., still with 0.5 A (F17).
6) A machine also based on High Temperature Superconductor (HTS) dipole magnets with a field of 20 T, and a beam current of 0.2 A, so that the synchrotron-radiation power is limited to about 2 MW / beam (F20).

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Parameter	Unit	F12LL	F12HL	F12PU	F14	F17	F20	(HL-)LHC
initial L	$nb^{-1}s^{-1}$	175	845	286	172	209	39	(50, lev'd) 10
initial pile up		580	2820	955	590	732	141	(135) 27
opt. run time	h	3.8	3.3	6.3	3.8	3.4	4.2	(18-13) ~10

Parameter	Unit	F12LL	F12HL	F12PU	F14	F17	F20	(HL-)LHC
ideal $\int L\,dt$ /day	fb^{-1}	7.9	17.1	10.8	7.7	7.7	3,1	(1.9) 0.4
$\int L\,dt$ / year	fb^{-1}	950	2000	1300	920	920	370	240 (55)

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!!

More details *(see Frank's note)*

Parameter	Unit	F12LL	F12HL	F12PU	F14	F17	F20	(HL-)LHC
c.m. energy	TeV	72	72	72	84	102	120	14
dipole field	T	12	12	12	14	17	20	8.33
beam current	A	0.5	1.12	1.12	0.5	0.5	0.2	(1.12) 0.58
bunch popul.	10^{11}	1.0	2.2	2.2	1.0	1.0	0.4	(2.2) 1.15
bunches/beam		9500	9500	9500	9500	9500	9500	(2760) 2808
rf voltage	MV	30	30	30	35	43	50	(16) 16
longit. emit.	eVs	6.9	6.9	6.9	8.1	9.7	11.4	2.5
norm. tr. emit.	μm	2.5	2.5	2.5	2.5	2.5	2.5	(2.5) 3.75
IP beta*	m	0.22	0.22	0.65	0.26	0.31	0.37	(0.15) 0.55
initial σ*	μm	3.8	3.8	6.5	3.8	3.8	3.8	(7.1 min) 16.7
initial *L*	$nb^{-1}s^{-1}$	175	845	286	172	209	39	(50, lev'd) 10
initial pile up		580	2820	955	590	732	141	(135) 27
ΔE / turn	MeV	1.3	1.3	1.3	2.4	5.3	10.1	0.0067
SR power/beam	kW	650	1450	1450	1200	2670	2020	(7.3) 3.6
tr.ε damp'g time	h	0.68	0.68	0.68	0.43	0.24	0.15	25.8
init *p*-burnoff time	h	5.1	2.3	6.9	5.1	4.0	8.4	(15) 40

Preliminary assessment of 80 vs 100 vs 120 TeV evolution of key measurements

Assumptions underlying the results shown below:

(1) exptl systematics and S/B independent of E_{CM}

(2) total integrated luminosity independent of E_{CM} (30 ab^{-1})

➡ E_{CM} evolution only driven by E_{CM} - dependence of production cross sections

Note:

- Zimmermann's table shows that (2) is too naive

  ➡ *to be fixed in next iterations*

- for Higgs measurements, potential handicap @ 120 TeV and advantage for 80 TeV

  ➡ *not necessarily so, play with higher boosts to optimize stat vs syst balance, to be studied in ore detail*

Higgs couplings beyond precision reach of H factory

Coupling precision	100 TeV CDR baseline	80 TeV	120 TeV
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	**0.4**	**0.4**	**0.4**
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	**0.65**	**0.7**	**0.6**
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	**0.9**	**1.0**	**0.8**

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Higgs self-coupling

Det performance/systematics scenarios

https://arxiv.org/abs/2004.03505

I. Target det performance: LHC Run 2 conditions
II. Intermediate performance
III. Conservative: extrapolated HL-LHC performance, with today's algo's (eg no timing, etc)

$$\frac{\sigma_{HH}(80\mathrm{TeV})}{\sigma_{HH}(100\mathrm{TeV})} \sim 0.72$$ => reduce δ_{stat} by 15%

$$\frac{\sigma_{HH}(120\mathrm{TeV})}{\sigma_{HH}(100\mathrm{TeV})} \sim 1.3$$ => increase δ_{stat} by 15%

$\delta\kappa_{HHH}(\%)$

100 TeV	s I	s II	s III
stat	3.0	4.1	5.6
syst	1.6	3.0	5.4
tot	3.4	5.1	7.8

80 TeV	s I	s II	s III
stat	3.5	4.7	6.4
syst	1.6	3.0	5.4
tot	3.8	5.6	8.4

120 TeV	s I	s II	s III
stat	2.6	3.6	4.9
syst	1.6	3.0	5.4
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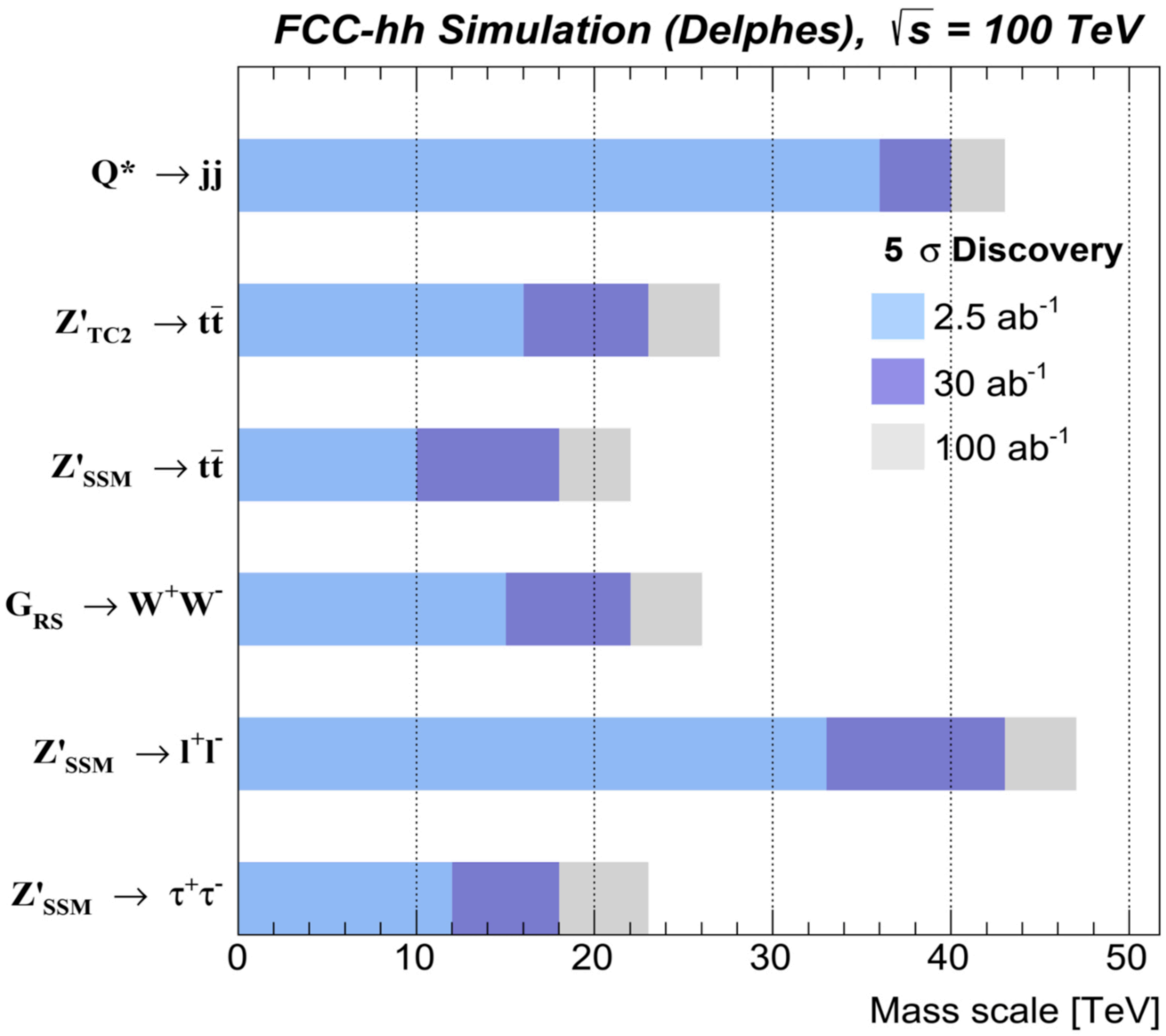
Remarks:

- Similar +/– 15% changes for Htt coupling
- Differences within the uncertainty range of detector performance. Run 2 performance keeps $\delta\kappa_{HHH}$ well below 5%

s-channel resonances



CilliderReach ECM extrapolation of 5σ 30ab^{-1} discovery reach

	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
$Z'_{SSM} \to \tau\tau$	18	15	20

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

100 vs 80 vs 120: remarks

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- 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

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  ➡ the decision of 80 vs 120 vs 100 is probably final, and unlikely to lead to an upgrade path

The HE-LHC “plan-B” option,

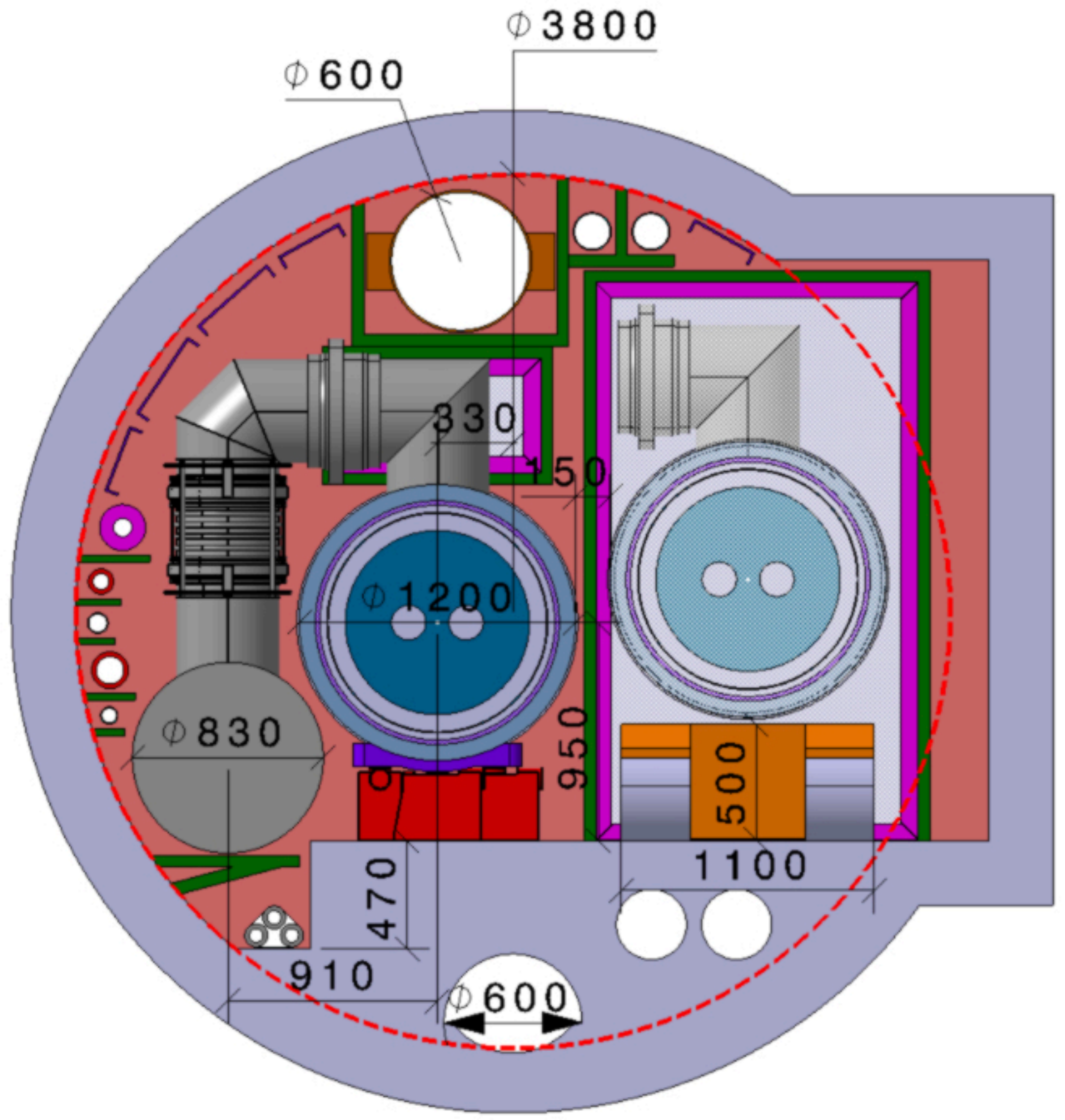
(eg to fast-track an “affordable” post-LHC hadron collider, or to react to CEPC, or in case a 90 km tunnel is not built)

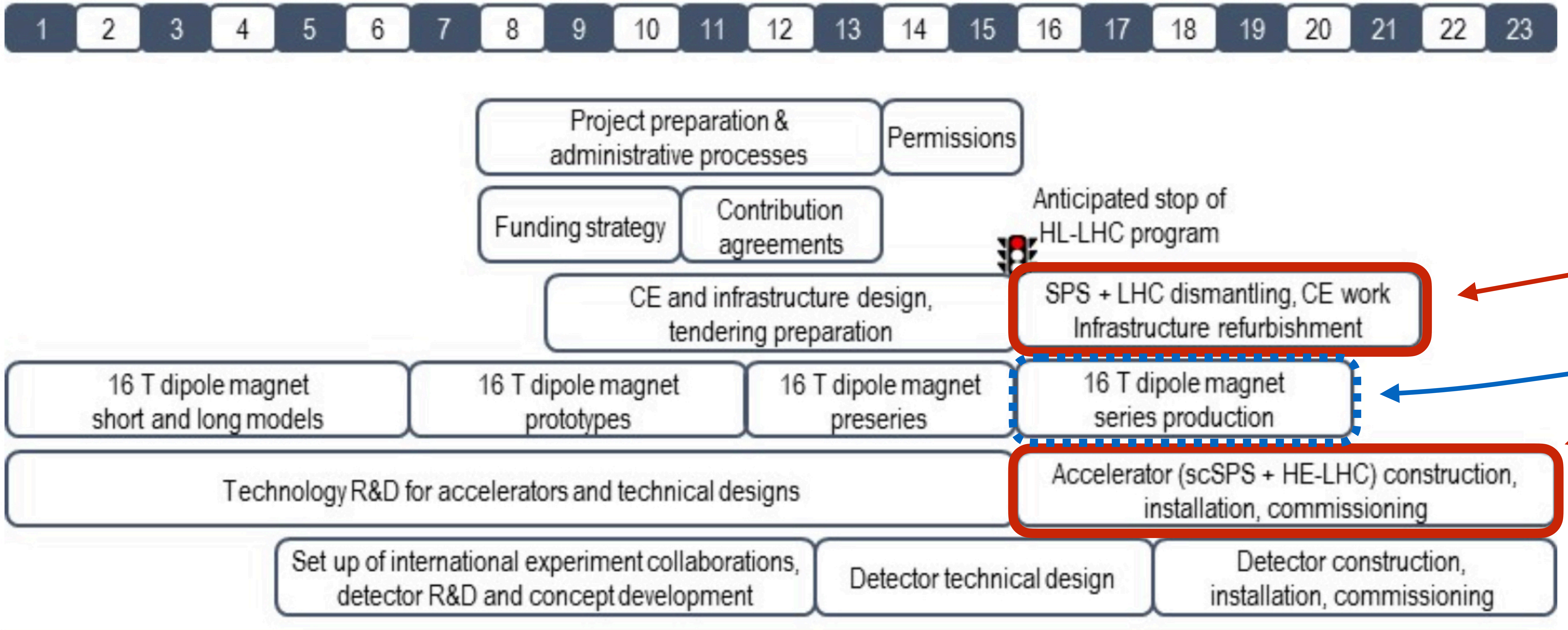
(results shown below for 16 T dipoles =~ 27 TeV)

Essential requirements:

1) total removal of current accelerator installation (magnets, QRL)
2) major infrastructure upgrade, including CE work on tunnel and ancillary surface/tunnel facilities to host enhanced power/cryo systems
3) upgrade of injector chain (eg super-conducting SPS)
4) magnets must be ready at end of HL-LHC for industrial mass-production
5) new detectors

(probably weaker demands on (2) and (3) if 12 T dipoles instead of 16 => 20 TeV)





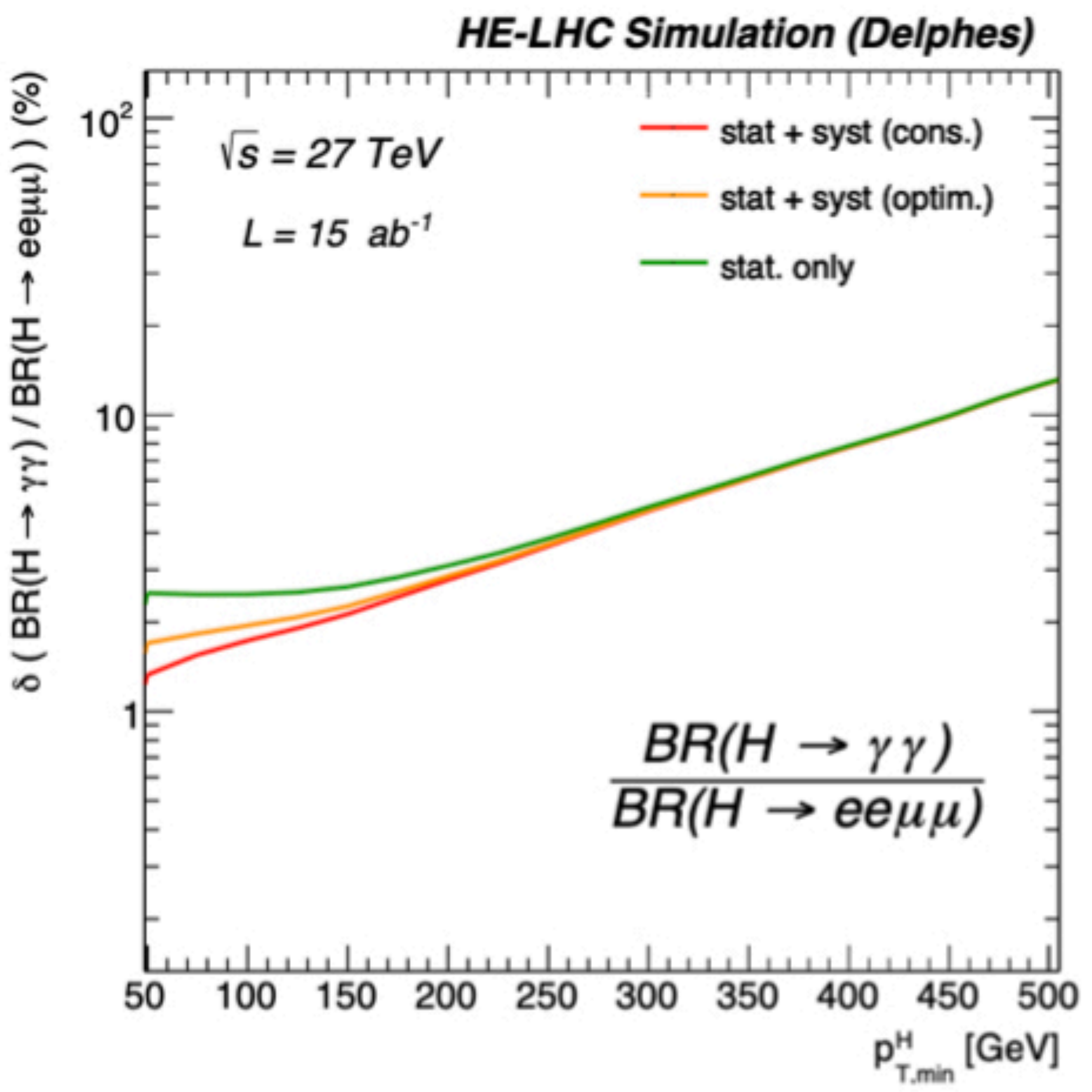
6yrs post HL-LHC just for CE and infrastructure

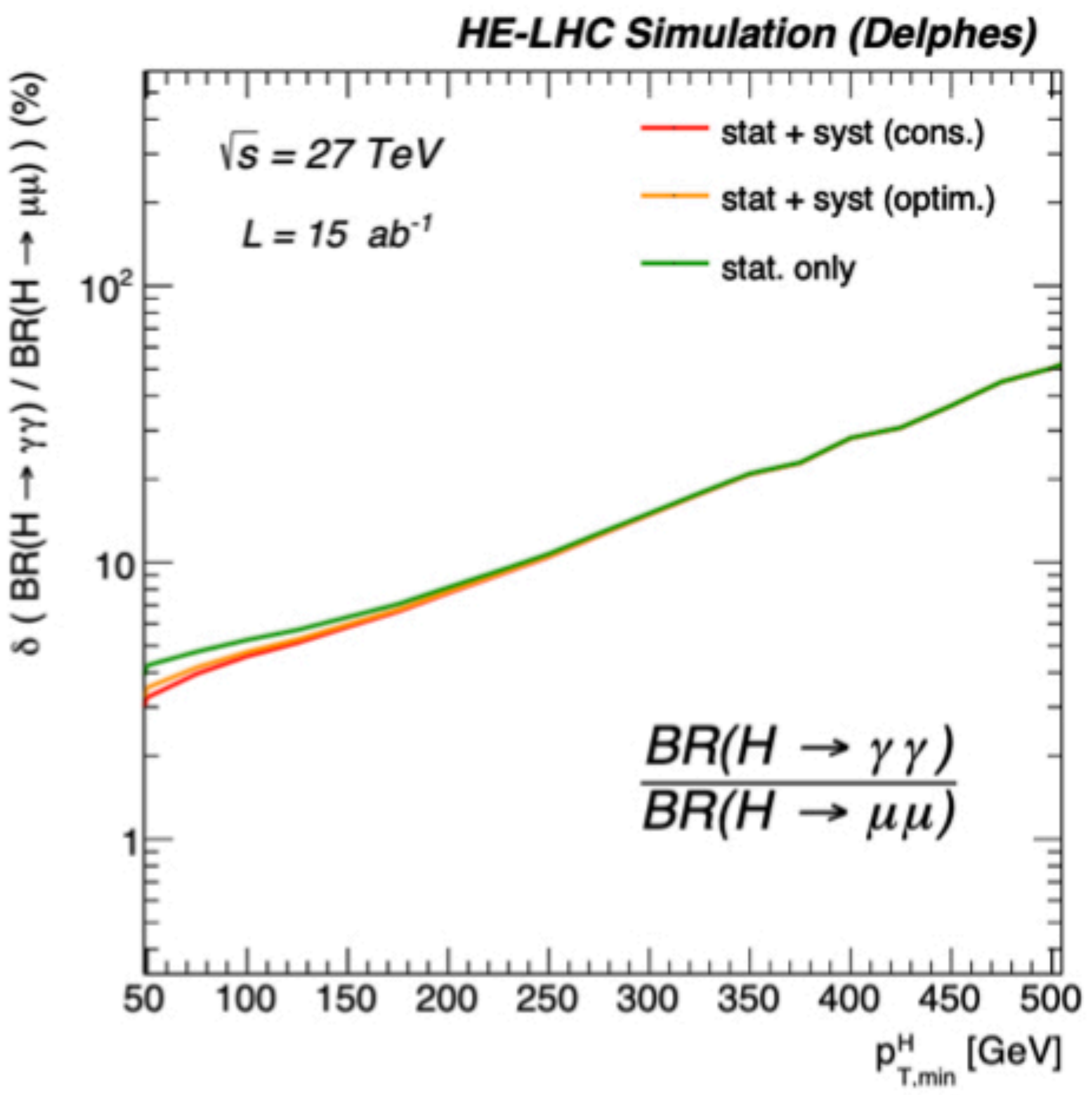
8yrs post HL-LHC to complete accelerator/inj's, assuming readiness of magnet series production before HL-LHC ends

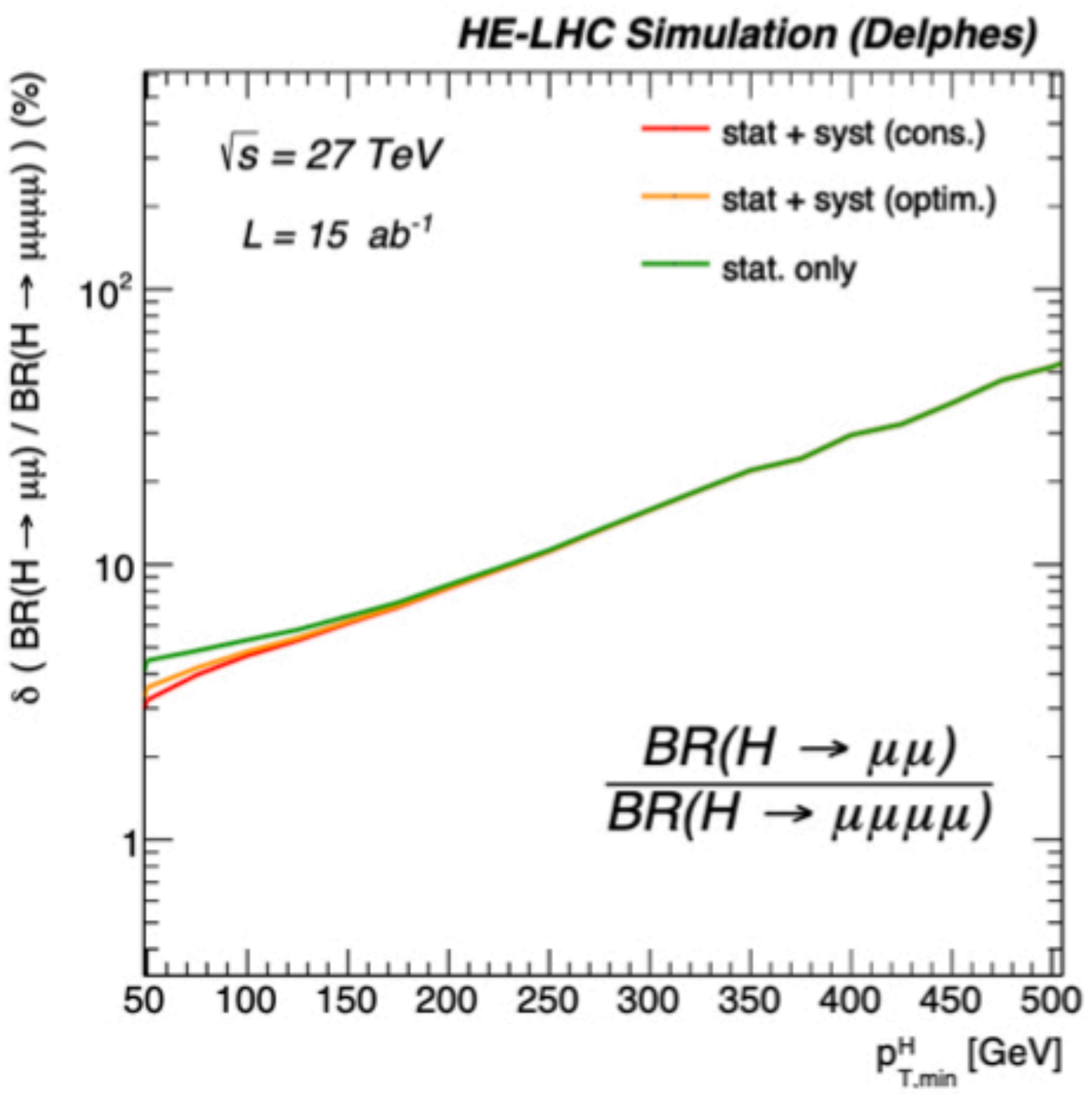
Table 4.3: Higgs production event rates for selected processes at 100 TeV (N_{100}) and 27 TeV (N_{27}), and statistical increase with respect to the statistics of the HL-LHC ($N_{100/27} = \sigma_{100/27\ \mathrm{TeV}} \times 30/15\ \mathrm{ab}^{-1}$, $N_{14} = \sigma_{14\ \mathrm{TeV}} \times 3\ \mathrm{ab}^{-1}$).

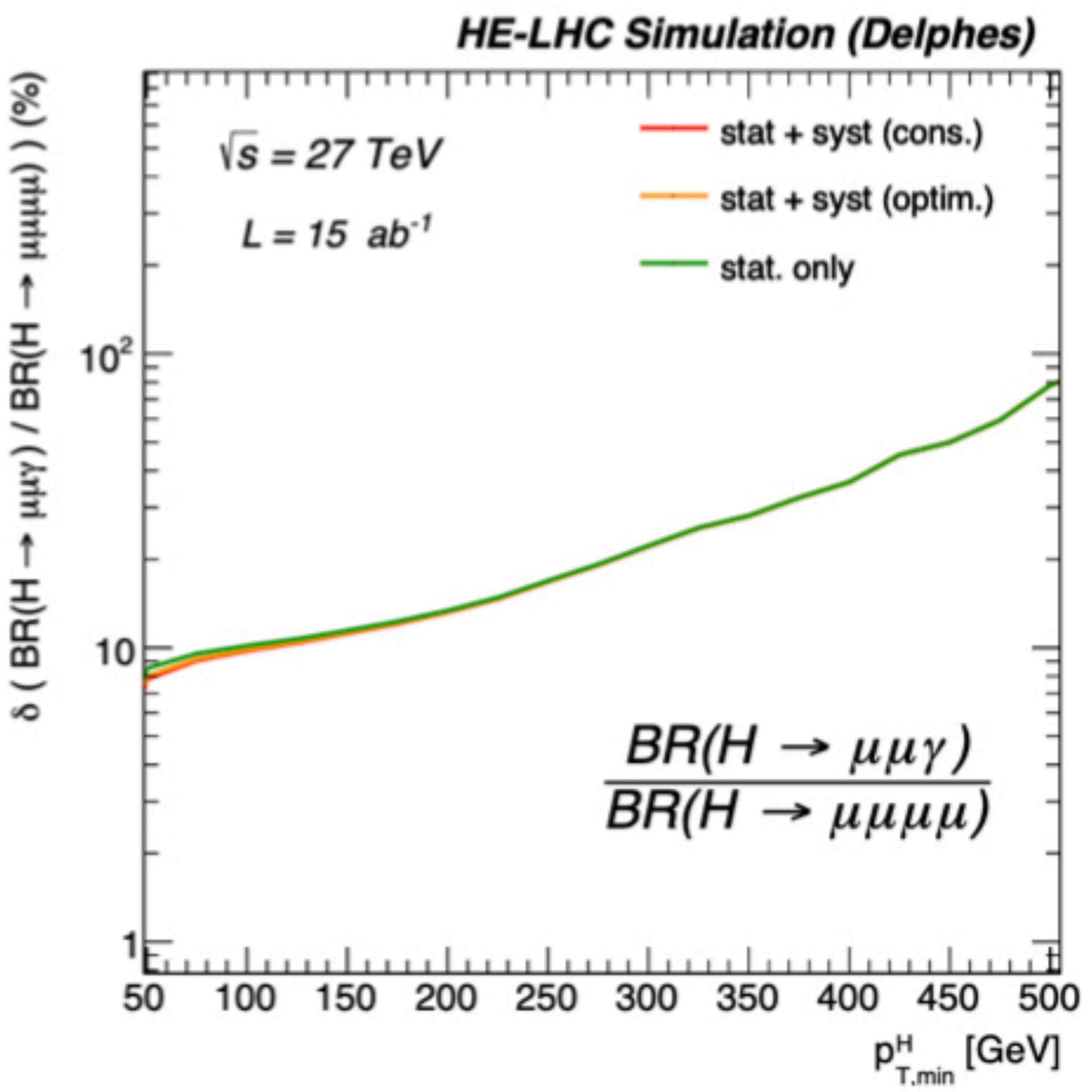
	gg→H	VBF	WH	ZH	$t\bar{t}$H	HH
N_{100}	24×10^9	2.1×10^9	4.6×10^8	3.3×10^8	9.6×10^8	3.6×10^7
N_{100}/N_{14}	180	170	100	110	530	390
N_{27}	2.2×10^9	1.8×10^8	5.1×10^7	3.7×10^7	4.4×10^7	2.1×10^6
N_{27}/N_{14}	16	15	11	12	24	19

- Loss of statistics at the level of 10-20 wrt 100 TeV
- Lack of absolute normalization of Higgs couplings to HZZ and ttH in absence of ee input

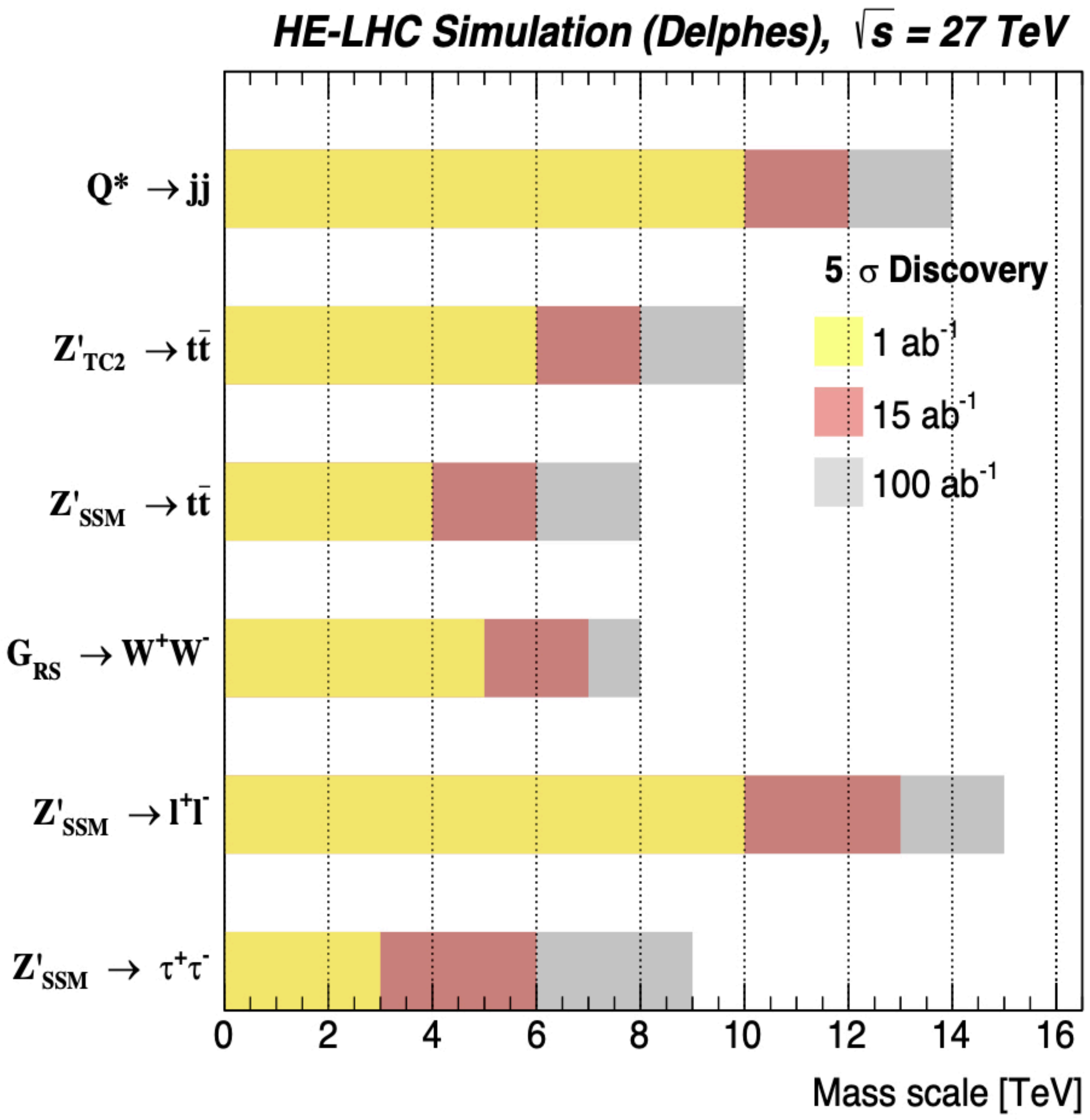








High-mass reach



WIMP DM reach

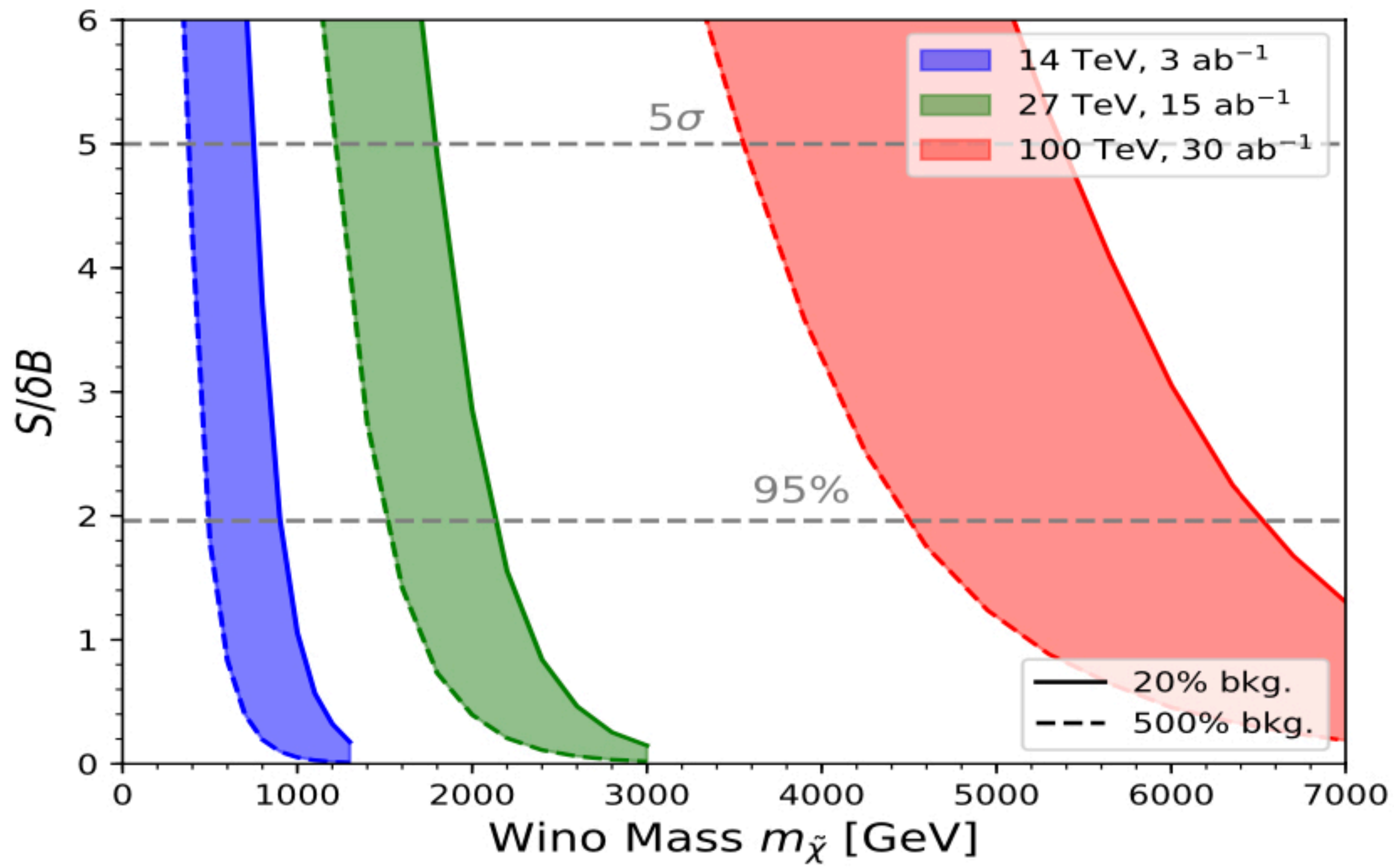


Figure 3: Sensitivity reach for wino-like DM WIMP candidates.

=> loss of yes/no answer to WIMP DM scenarios

2018 costs as documented in the FCC CDR

HE-LHC

Domain	Cost in MCHF
Collider	5,000
Injector complex	1,100
Technical infrastructure	800
Civil Engineering	300
TOTAL cost	**7,200**

assumes 2.3 MCHF/dipole ~2.9 BCHF
(cfr ~ 1 MCHF/ LHC dipole)

includes SC SPS

FCC-ee

Domain	Cost [MCHF]
Collider and injector complex	3,100
Technical infrastructure	2,000
Civil Engineering	5,400
TOTAL cost	**10,500**

NB: FCC-ee new estimate (2024) ~13B.
No update available for HE-LHC

NB: If no 90km tunnel built, HE-LHC to be compared with LEP3 for prioritization: a different talk…

The low-E FCC "plan-B" option,

for a fast-track "*cheaper*" FCC-hh

(results for LHC dipoles in a 100km tunnel => 37.5 TeV)

Low-E FCC-hh physics reach

	$gg \to H$	VBF	WH	ZH	ttH	HH
σ(37.5 TeV) (pb)	230	19	5	3	5.8	0.26
27/14	2.7	2.7	2.3	2.4	4.8	3.8
37.5/14	4.2	4.4	3.3	3.5	9.5	7.0
100/14	15	16	10	13	53	34
37.5/27	1.6	1.6	1.5	1.5	2.0	1.8
100/37.5	3.6	3.6	3.0	3.7	5.6	4.9

4-10 x LHC

50% - 2 x HE-LHC

$\delta R/R$	HE-LHC	LE-FCC	FCC-hh
$R = \mathrm{B}(\mathrm{H}\to\gamma\gamma)/\mathrm{B}(\mathrm{H}\to 2e2\mu)$	1.7%	1.5%	0.8%
$R = \mathrm{B}(\mathrm{H}\to\mu\mu)/\mathrm{B}(\mathrm{H}\to 4\mu)$	3.6%	2.9%	1.3%
$R = \mathrm{B}(\mathrm{H}\to\mu\mu\gamma)/\mathrm{B}(\mathrm{H}\to\mu\mu)$	8.4%	6%	1.8%
$R = \mathrm{B}(\mathrm{H}\to\gamma\gamma)/\mathrm{B}(\mathrm{H}\to 2\mu)$	3.5 %	2.8%	1.4%

- **Minor improvement HE-LHC => LE-FCC**
- **In the region above pt~100 GeV, LE-FCC stat limited for rare decays, while FCC is still syst-dominated** ***(=> room for improvement of asymptotic precision)***

Low-E FCC-hh physics reach

	$gg \to H$	VBF	WH	ZH	ttH	HH
σ(37.5 TeV) (pb)	230	19	5	3	5.8	0.26
27/14	2.7	2.7	2.3	2.4	4.8	3.8
37.5/14	4.2	4.4	3.3	3.5	9.5	7.0
100/14	15	16	10	13	53	34
37.5/27	1.6	1.6	1.5	1.5	2.0	1.8
100/37.5	3.6	3.6	3.0	3.7	5.6	4.9

4-10 x LHC

50% - 2 x HE-LHC

$\delta R/R$	HE-LHC	LE-FCC	FCC-hh
$R = \mathrm{B}(\mathrm{H}\to\gamma\gamma)/\mathrm{B}(\mathrm{H}\to 2e2\mu)$	1.7%	1.5%	0.8%
$R = \mathrm{B}(\mathrm{H}\to\mu\mu)/\mathrm{B}(\mathrm{H}\to 4\mu)$	3.6%	2.9%	1.3%
$R = \mathrm{B}(\mathrm{H}\to\mu\mu\gamma)/\mathrm{B}(\mathrm{H}\to\mu\mu)$	8.4%	6%	1.8%
$R = \mathrm{B}(\mathrm{H}\to\gamma\gamma)/\mathrm{B}(\mathrm{H}\to 2\mu)$	3.5 %	2.8%	1.4%

- **Minor improvement HE-LHC => LE-FCC**
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Example: s-channel resonances

Collider	$Z'_{SSM}\to\tau^+\tau^-$	$Z'_{SSM}\to t\bar{t}$	$G_{RS}\to WW$	$Z'_{TC}\to t\bar{t}$	$Q^*\to jj$	$Z'_{SSM}\to\ell^+\ell^-$
FCC [4] (TeV)	18	18	22	23	40	43
HE-LHC [4] (TeV)	6	6	7	8	12	13
FCC/HE-LHC	3	3	3.1	2.9	3.3	3.3
FCC/HE CR	2.7	2.7	2.9	2.9	3.1	3.2
LE-FCC CR (TeV)	7.5	7.5	9	10	16	17
LE-FCC/HE-LHC	1.25	1.25	1.3	1.25	1.3	1.3

- **$M_{max}(37.5) \sim 0.35\ M_{max}(100)$**
- **$M_{max}(37.5) \sim 1.25\ M_{max}(27)$**

Low-E FCC-hh physics reach

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50% - 2 x HE-LHC

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Table 3. 5σ discovery reach for WIMP DM particles at HL-LHC, HE-LHC and FCC-hh [7]. Columns 4 and 5 present the CR extrapolations from HL-LHC to HE-LHC, and from HE-LHC to FCC, respectively. Column 6 gives the extrapolation from HE-LHC to LE-FCC, augmented by a factor 1.3, as discussed in the text.

M(GeV)	HL-LHC	HE-LHC	FCC	HE-LHC (CR)	FCC (CR)	LE-FCC (1.3×CR)
wino	550	1500	4500	1100	3500	2300
higgsino	200	450	1250	420	950	650

LE-FCC comes short of the upper mass limits for a wino (higgsino) WIMP, namely 3 TeV (1 TeV)

from M. Benedikt (2019 cost projection, needs update)

Cost scaling FCC-hh to FCC-NbTi-6T

Main cost items concerned are magnets and cryogenics:

- **Magnet system:**
  - **Complete magnet system 3.5 BCHF** (about 75% main dipoles, i.e. 2.8 BCHF and 25% for quads, inserations, all other magnets 0.7 BCHF ("best estimate that can be done" dixit MSC group leader)
    - Corresponding **cost per main dipole** of 2800/4500 = **620 kCHF**
    - This it the ***"best estimate that can be done"*** dixit MSC group leader

- **Cryogenics system:**
  - New estimate done, based on FCC-hh type beam-screen and temperature layout and 1.9 K operation temperature
  - **1.4 BCHF** (this is a factor 2.6 wrt LHC cryosystem), compared to 2.5 BCHF for FCC-hh.

- Further revised estimates and assumed scalings and associated cost:
  - **Vacuum system 480 to 410 MCHF** (smaller and round cooling tubes, no SR absorbers in inter connects)
  - **Cooling system 490 to 420 MCHF** (reduced number of cooling towers)
  - **25% reduction of beam transfer, power converters/cabling, collimation, dump systems = 825 MCHF** (instead of 1.1 BCHF)
  - **20% reduction of EL infrastructure cost = 560 MCHF** (instead of 700 MCHF)

- Other accelerator, injector and infrastructure systems unchanged.

- **Total cost with above assumptions 14.9 BCHF. → "Realistic" goal is perhaps 14.5 – 15 BCHF.**