Particle Physics after the HL-LHC

Paris Sphicas
CERN & NKUA
Experimental Methods in Particle Physics
JINR, August 8, 2024

- **Introduction**
- **The LHC handover**
- **Long-term future: proposed machines**
- **Long-term future: the physics**
- **JENAA**
- **Outlook**

30 years go… The Famous UCLA Meeting (Feb.1994)

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Igor Golutvin and CMS

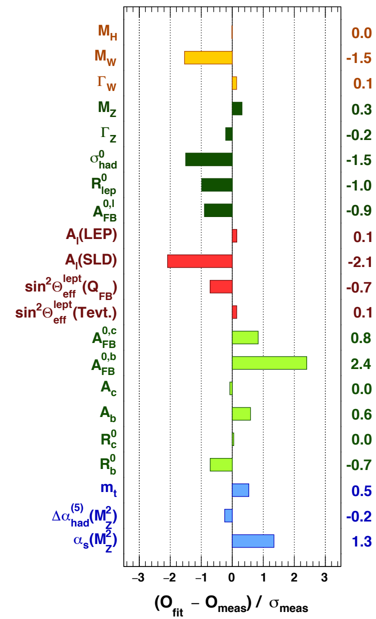
- That same year, Igor put together the RDMS collaboration
  - I heard of him as a "guru" of instrumentation. His vision at UCLA was clear: the magnitude of the problem (CMS) was such that forces had to be combined.
  - Sep 27-28, 1994: meeting in Dubna, 27 Russian and Dubna Member States(RDMS) institutions collaborating on CMS formed the RDMS_CMS collaboration.
    - RDMS spokesperson: Igor Golutvin; RDMS collaboration board: Viktor Matveev
- What followed was a series of meetings with US_CMS colleagues for the construction of the endcaps of CMS
  - In the US we were going through the "Lehman" (DOE) reviews: a series of painstaking reviews of the full LHC program, including the allocation of responsibilities.
  - During the reviews it was said time and again that RDMS, under Igor's leadership, was the crucial partner for the HE and ME1/1 detectors.
    - Especially ME 1/1 was considered the "tough" muon station in the CMS CSC system
  - Subsequently: a long collaboration between RDMS and US_CMS towards the creation of the beautiful CMS detector that has delivered a long stream of forefront physics results – and a discovery.
  - For over three decades, Igor has been inextricably connected to the LHC and CMS

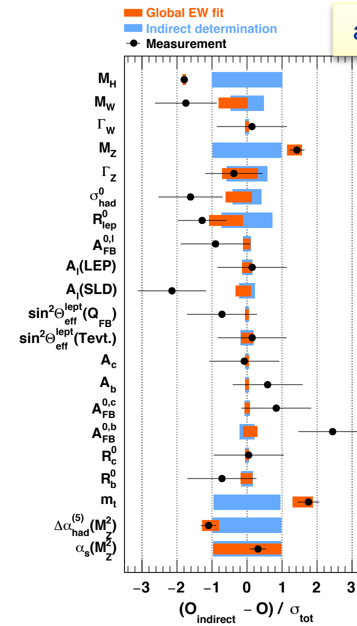
The LHC handover

physics landscape

Physics landscape

- **The LHC completed the Standard Model (SM) of particle physics**
  - **A combined triumph of theory and experiment over 60 years, with unprecedented success in describing all phenomena that can be reproduced in the laboratory**
- **Goodness of fit**
  - **χ^2_{min}=18.6 → Prob= 23%**
- **Fit result often more accurate than measurement**
  - **Small pulls for M_H, M_Z, $\Delta\alpha_{had}^{(5)}(M_Z^2)$, m_c, m_b → input accuracies exceed fit requirements**
- **Knowledge of m_H → huge improvement in:**
  - **m_W (28→11 MeV)**
  - **m_t (6.2→2.5 GeV)**
  - **$\sin^2\theta_W$ (2.3→1.0x10^{-3})**
- **Largest discrepancy:**
  - **$A_{FB}(b)$: 2.5 σ**





arXiv:1803.01853

G fitter

https://project-gfitter.web.cern.ch/

Light blue: fit excluding input from row

The overall picture of the measured/seen Higgs couplings

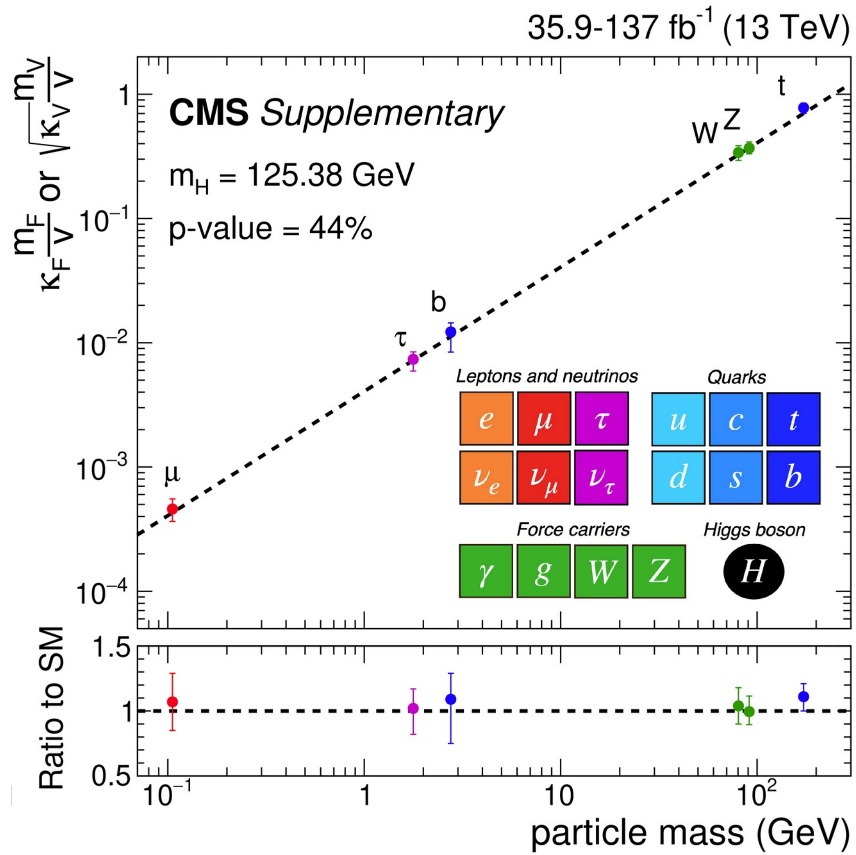
$$\lambda_f = \kappa_f \left(\frac{m_f}{v}\right)$$

$$\left(\frac{g_V}{2v}\right)^{1/2} = \kappa_v^{1/2}\left(\frac{m_V}{v}\right)$$

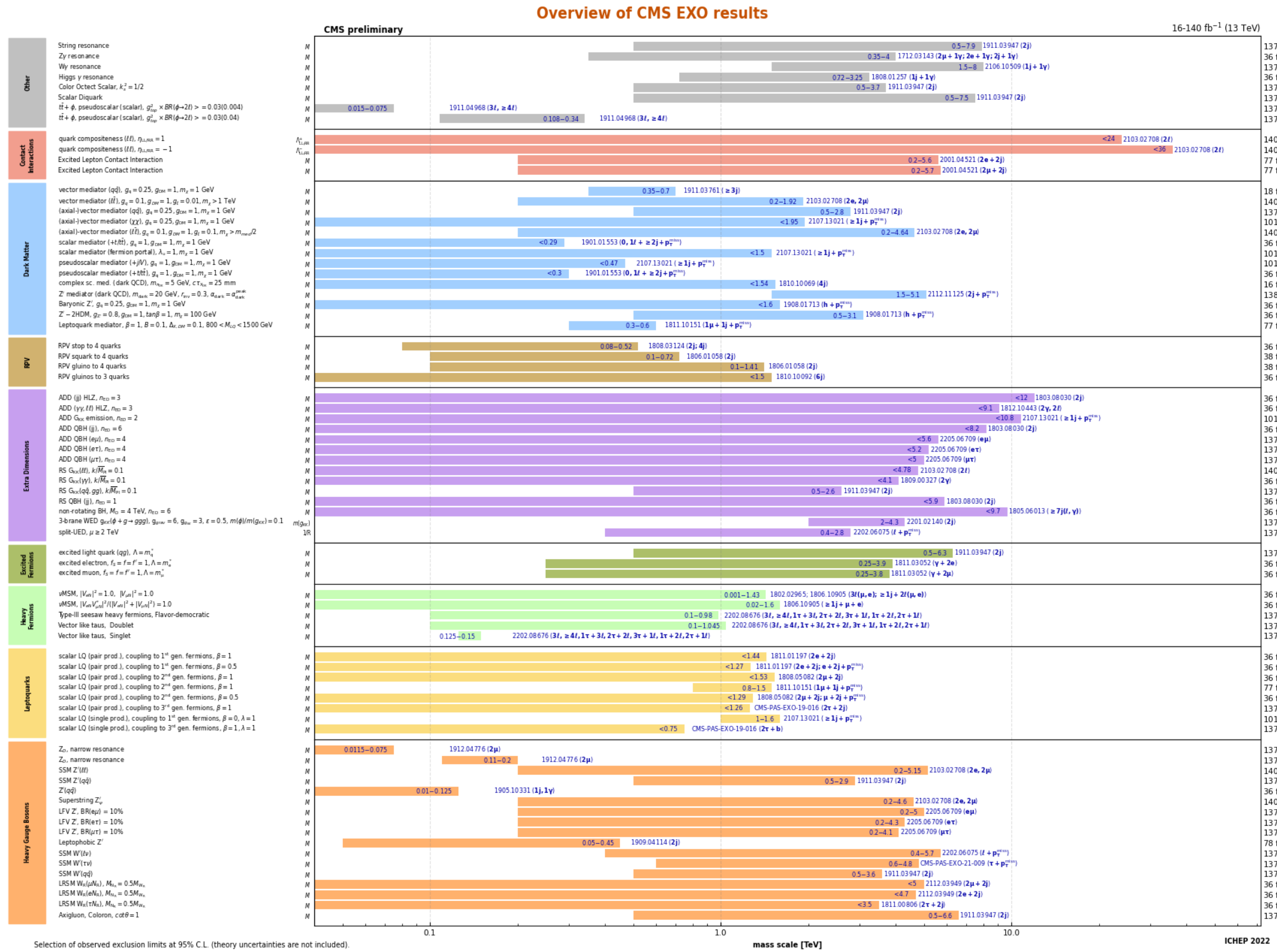
A new kind of "force", with *non-universal couplings to matter (!)*

A particle like no other!

$J^P=0^+$ (vacuum!)



The never-ending search for New Physics: SUSY, Exotica… (and it's not like we didn't look for them)



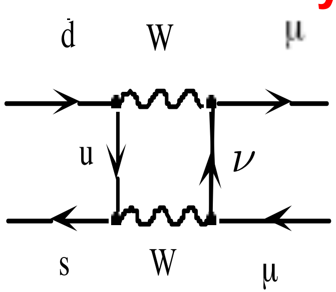
The (potentially deep) meaning of potentially null results

- **With each null search, the mystery deepens. Some famous examples from History…**

- **Michelson-Morley experiment (…)**

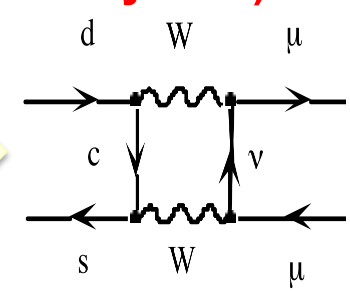
- **Weisskopf (1939): "the self-energy of charged particles obeying Bose statistics is found to be quadratically divergent...,"**
  - $\rightarrow$ **in theories of elementary bosons, new phenomena must enter at an energy scale of m/e**
  - $\rightarrow$ **+ positron, doubling of particles…**

- **Rare Kaon decays: $K_L \rightarrow \mu^+\mu^-$; decay does not occur (…very rare). BUT:**



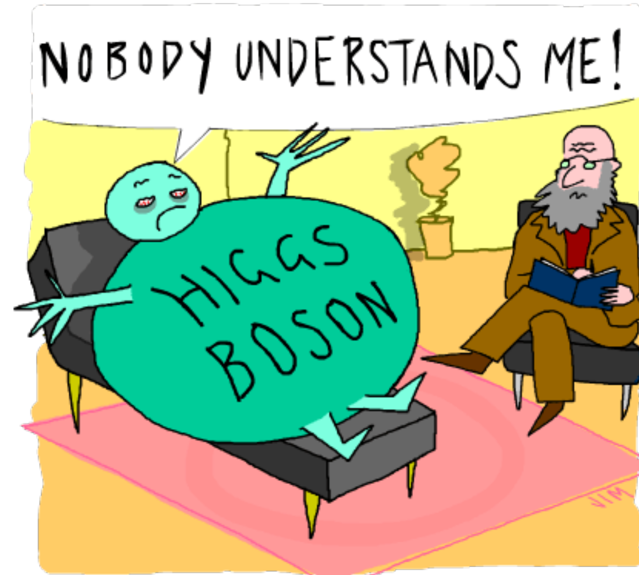
$\sim G\,\Lambda^2 \;\rightarrow$
$\Lambda^2 \sim$ 3-4 GeV^2 !!!

Add c quark:



Higgs boson issues

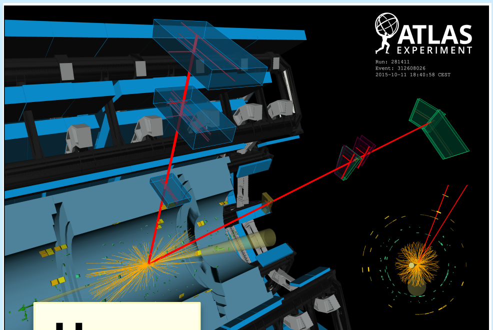
- **The only (?!) spin-0 fundamental (?) particle**
- **What creates the infamous (but so necessary…) couplings to the leptons?**
  - **It's a new interaction! The only non-universal one (it's not a gauge interaction…), with a *free* parameter (Yukawa coupling) for each combination (worse for quarks – mass matrix…)**
  - **How about them neutrinos?!?**
- **What protects its mass and sets it to the EWK scale when it should be at Λ_{pl}?**
  - **There is only one dimensionfull variable in the SM Lagrangian: v=246 GeV (…!?...)**
    - **The rest of the SM is scale-free…**
- **And…. where is all that vaccum energy? Cosmological constant is > 10^{100} times off.**
- **Does the Higgs couple to Dark Matter? Is it a new "portal"?**



Credit: blog.gymlish.com

SM @ the highest E; EWSB ("Higgs" sector)

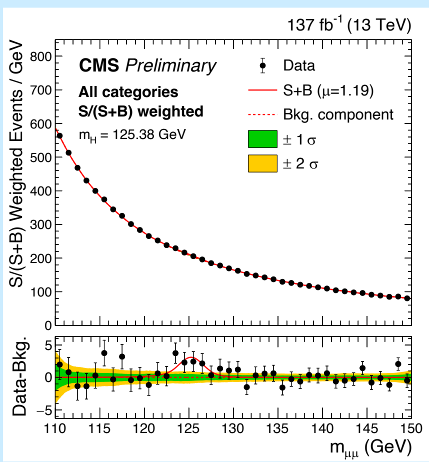
Evidence for H coupling to *2nd-gen fermions: muons*



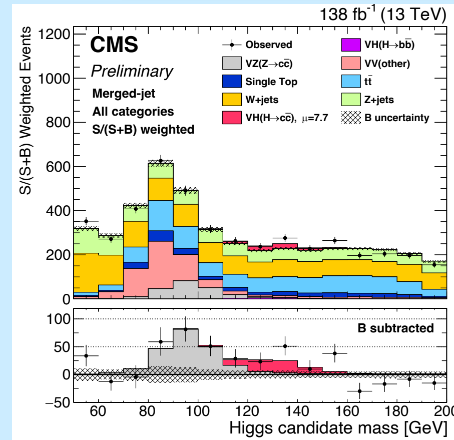
H→μμ

CMS:
obs: 3.0σ (exp: 2.5σ)
ATLAS:
obs: 2.0σ (exp: 1.7σ)

$\mu = 1.2 \pm 0.6$



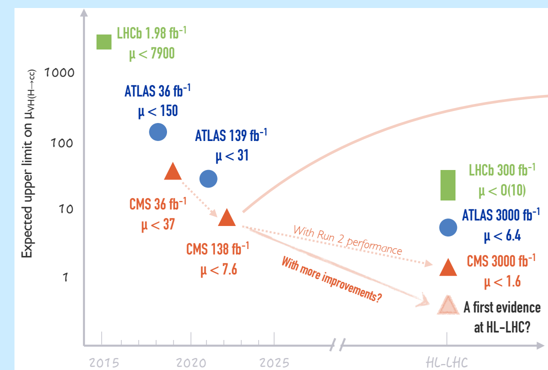
A dream: observe H decaying to charm quarks



First observation of Z→cc at a hadron collider!

$\mu_{VZ(Z\to cc)} = 1.01^{+0.23}_{-0.21}$

$\mu_{VH(H\to cc)} < 14$ (7.6 exp.)

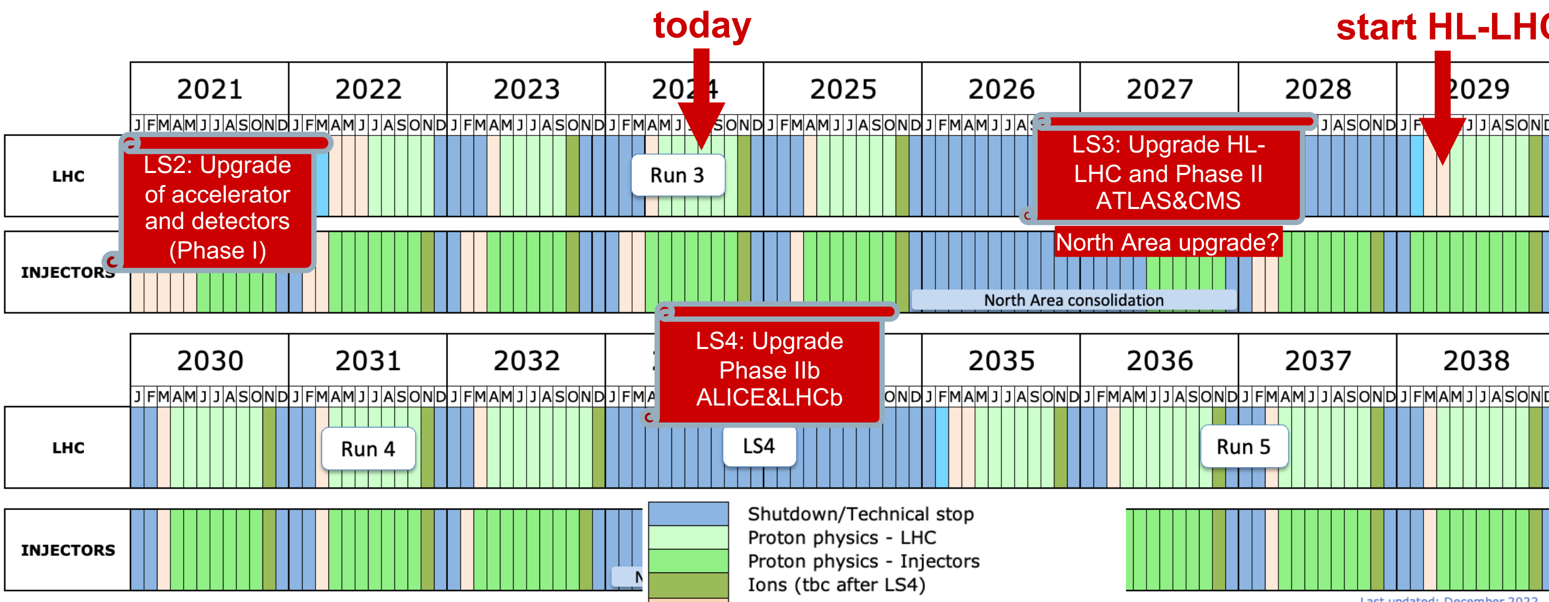


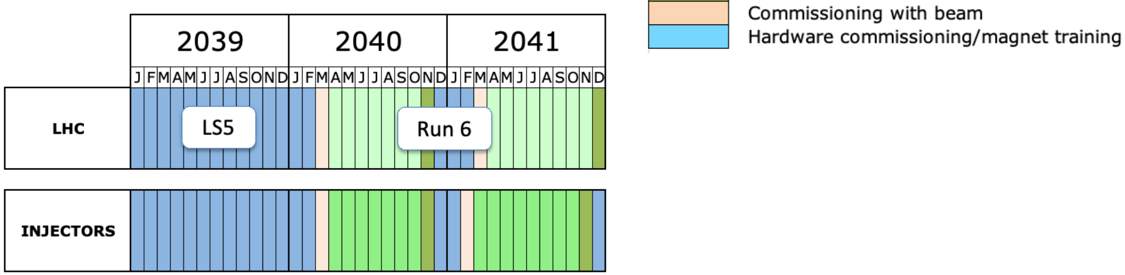
Near-term future

Current running of the LHC

High-Luminosity LHC (HL-LHC)

LHC Timeline



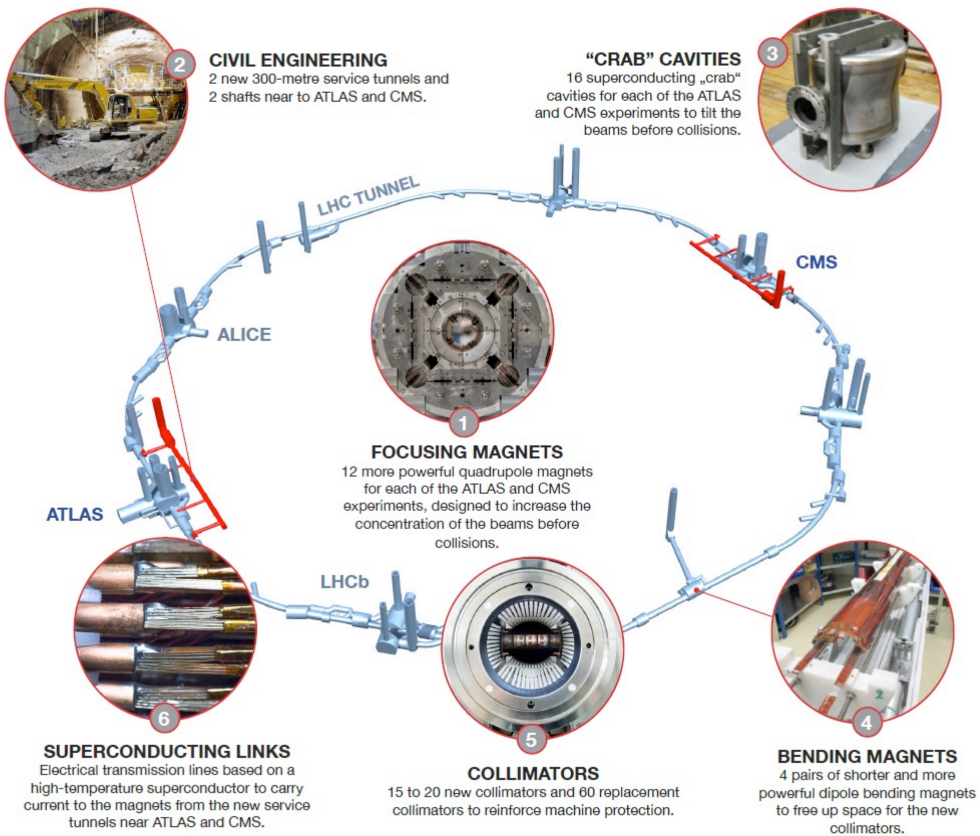


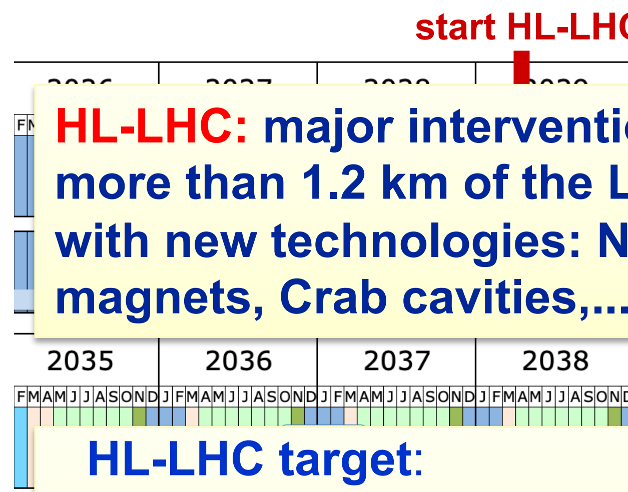
HL-LHC target:

Deliver 3000 fb^{-1} pp luminosity to both ATLAS and CMS

Programme ends in 2041 in view of the next large CERN project, e.g. FCC

LHC Timeline





HL-LHC: major intervention on more than 1.2 km of the LHC with new technologies: Nb_3Sn magnets, Crab cavities,...

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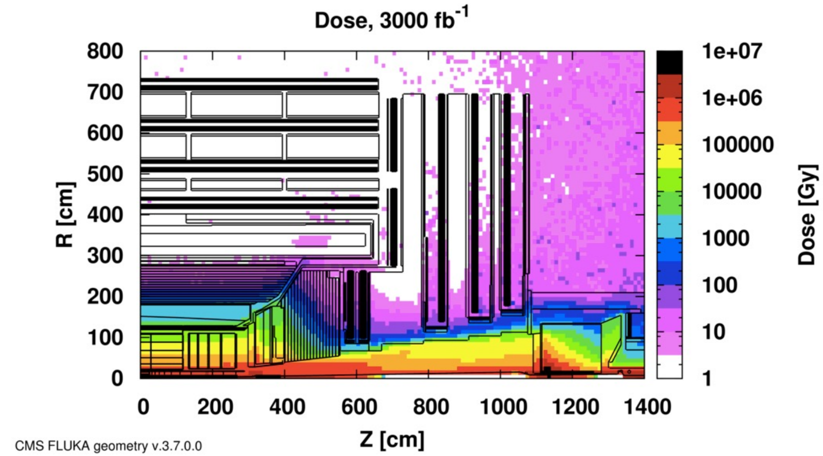
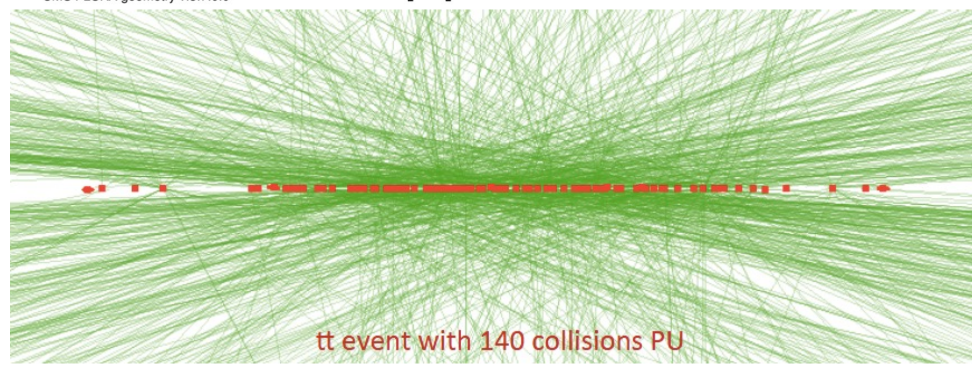
HL-LHC challenges

Annual dose at HL-LHC: similar to total dose from LHC start to LS3



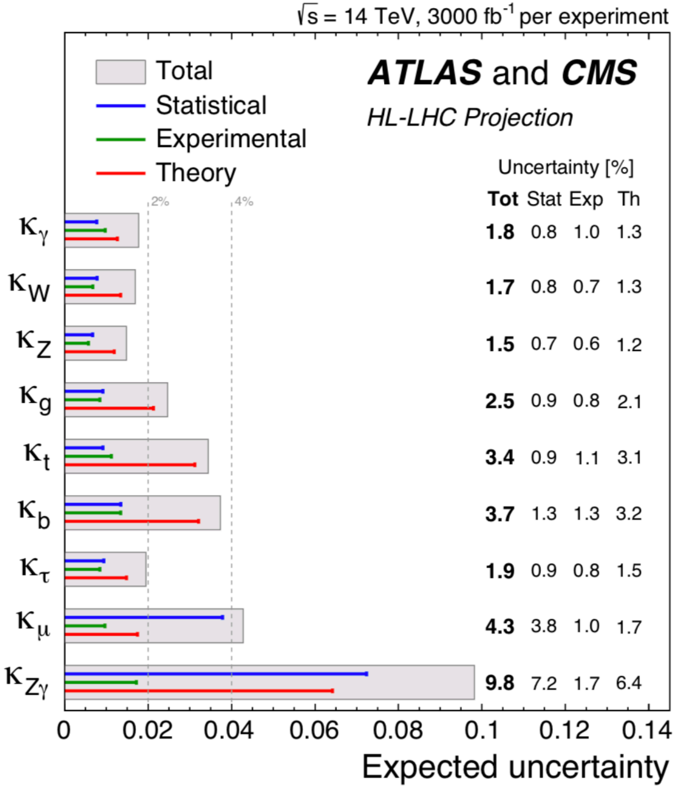
Key to physics: maintain detector performance in the presence of much higher pileup (140-200!)



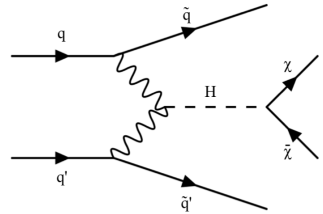
Upgrade several detector components (trackers, calorimeters, redesign some electronics, new detector technologies, Trigger and DAQ

Medium-term Higgs physics: the LHC/HL-LHC program

HL-LHC reach: Higgs

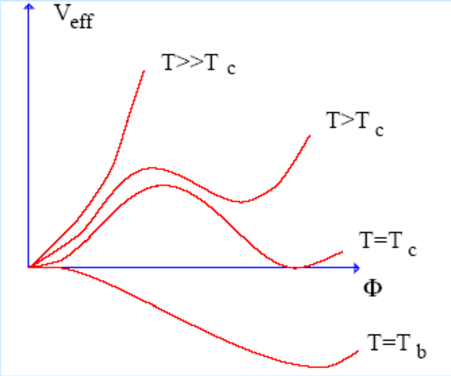


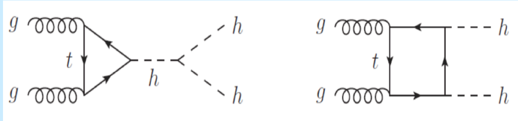
H width to invisible:
h(125)→XX
Includes BSM decays
and rare SM decays: ≤4%

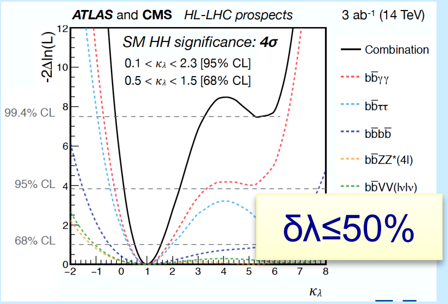


The ultimate frontier: Higgs self-coupling

$$V_h = \frac{m_h^2}{2} h^2 + (1+\kappa_3)\lambda_{hhh}^{SM} v h^3 + \frac{1}{4}(1+\kappa_4)\lambda_{hhhh}^{SM} h^4$$





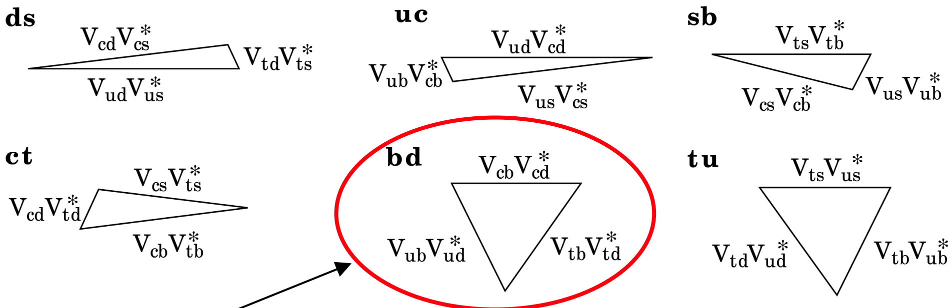


δλ≤50%

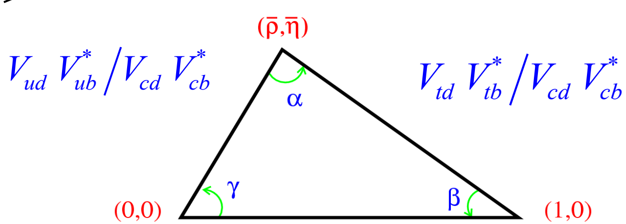
Flavor physics: quark sector

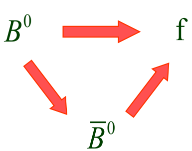
$$V_{CKM} = \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

$$\mathbf{V_{ui}\,V_{uj}^* + V_{ci}\,V_{cj}^* + V_{ti}\,V_{tj}^* = 0}$$



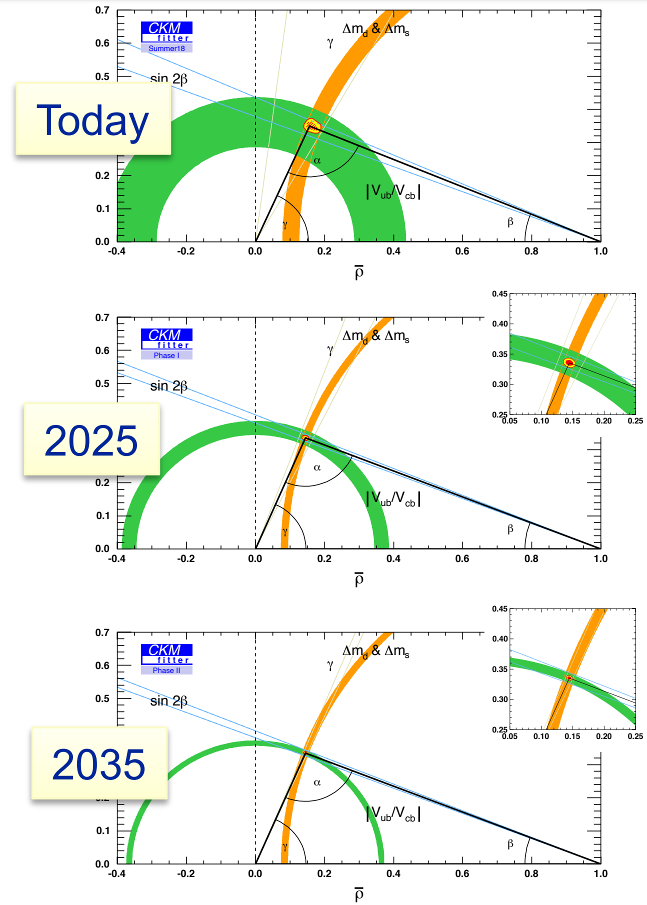
CP ~ sin2ϕ





$$\frac{\Gamma(\bar{B}^0 \to \bar{f}) - \Gamma(B^0 \to f)}{\Gamma(\bar{B}^0 \to \bar{f}) + \Gamma(B^0 \to f)} = -\eta_f\ \sin(2\phi)\ \sin(\Delta M\, t)$$

CKM triangle: extensive precision program en route



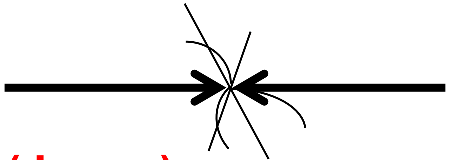
Long-term future: proposed machines

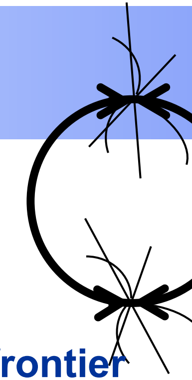
A very brief summary

EU Strategy: High-priority future initiatives

- **"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."**
- **"Accomplishing these compelling goals will require innovation and cutting-edge technology:**
  - ***… should ramp up … R&D effort …***
  - ***… 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…."***

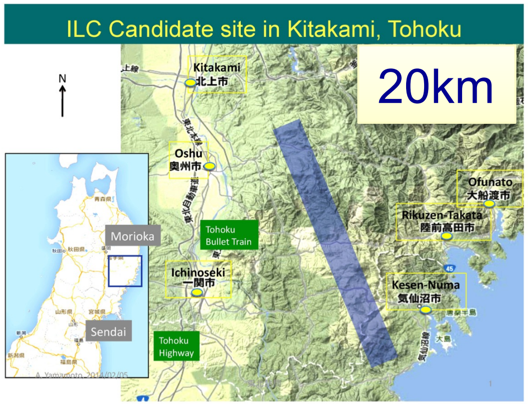
Collider Crib sheet





- **ILC (Japan):**
  - Linear collider with high-gradient superconducting acceleration
  - Ultimate: 0.5-1(?) TeV
  - To secure (…) funding: reduce cost by starting at 250 GeV (H factory)
- **CLIC (CERN):**
  - Linear collider with high gradient normal-conducting acceleration
  - Ultimate: multi-TeV (3) $e+e^-$ collisions
  - Use technology to overcome challenges
  - Stages, for physics and funding
- **FCC-ee/FCC-hh (CERN):**
  - Protons to extend energy frontier
  - 90 km ring with 16T magnets
  - Use FCC-hh tunnel for e^+e^- collider
  - Technology for ee: "standard"
- **CEPC/SppC**
  - Essentially an FCC-ee, then hh with (a) more conservative luminosity estimates and (b) in China
- **Outliers:**
  - "Low-field" (7T) magnets @ FCC (?)
  - Muon Collider (???)

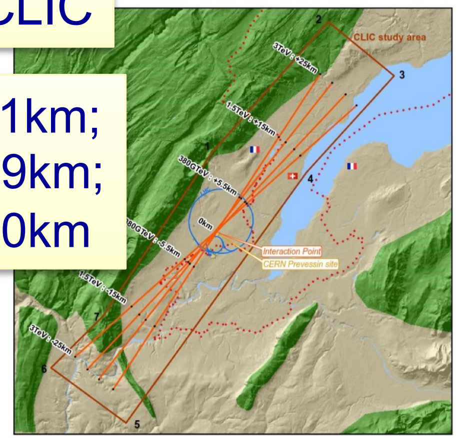
ILC, CLIC, FCC-ee/hh, CEPC

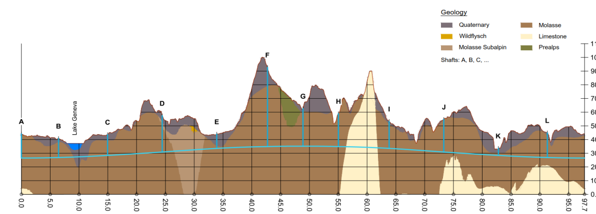


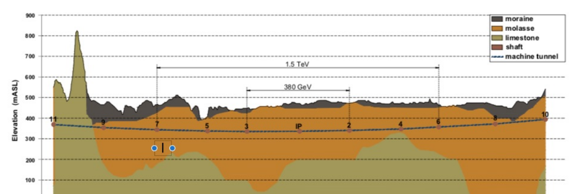
20km

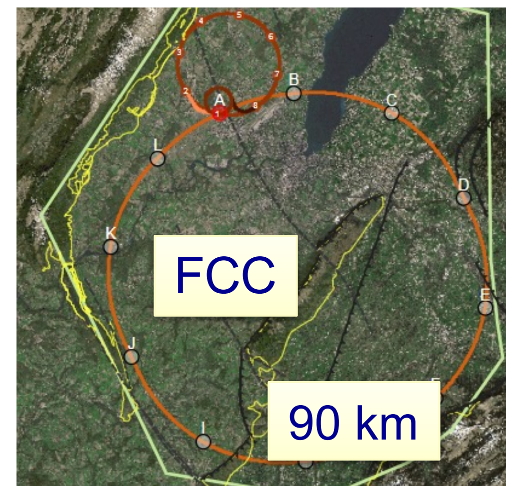
CLIC

11km;
29km;
50km





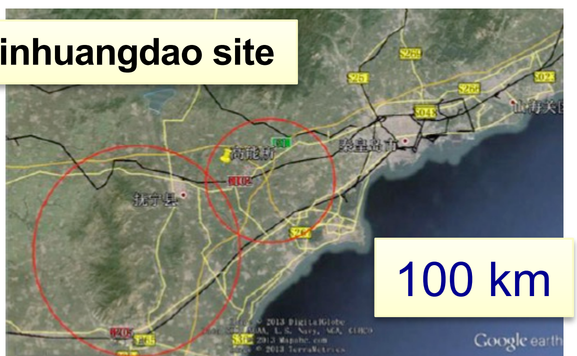




FCC

90 km

Qinhuangdao site

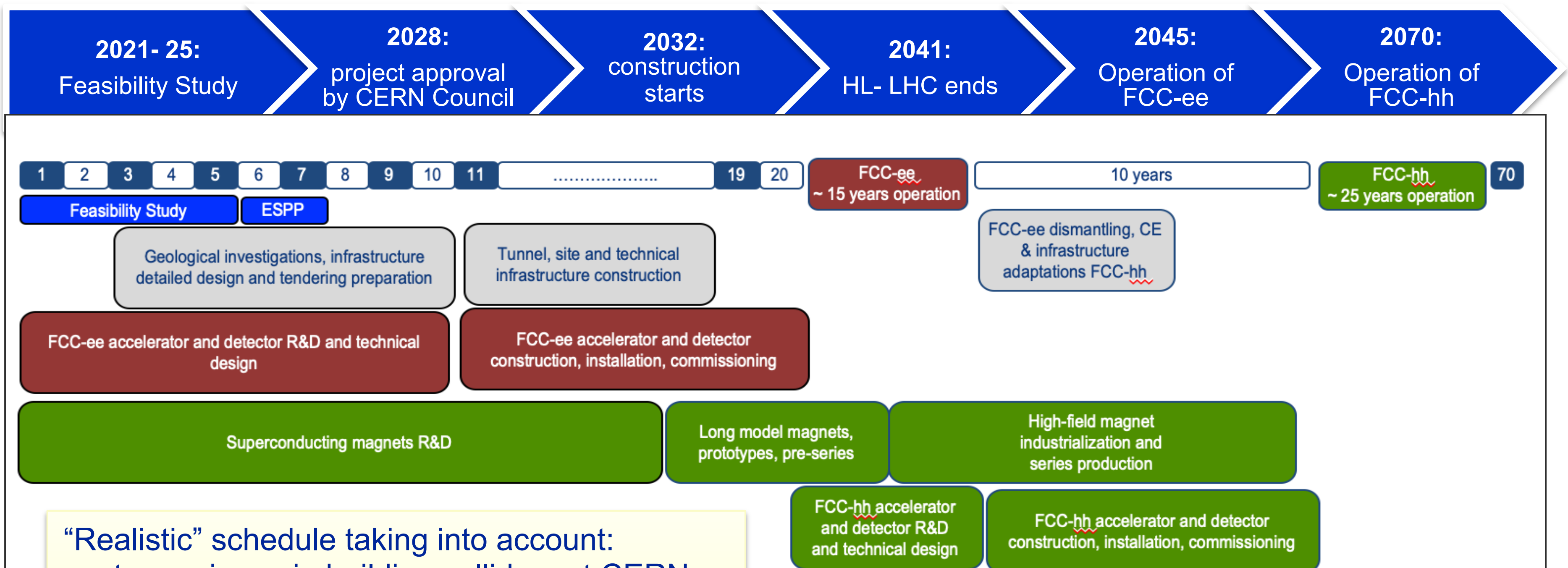


100 km

CEPC: multiple candidate sites in China

FCC integrated program - timeline

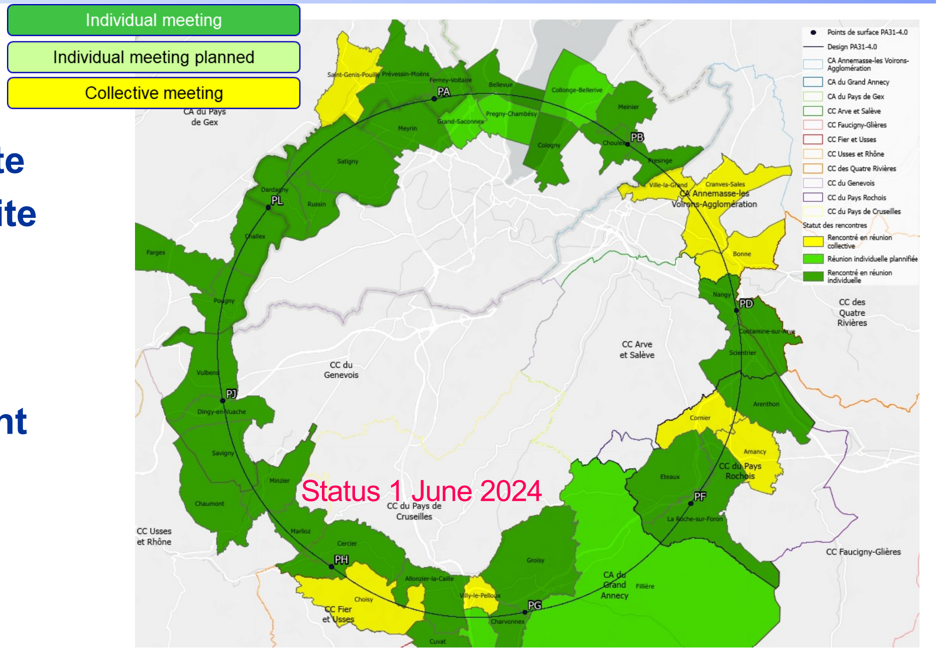
FCC Conceptual Design Study started in 2014 leading to CDR in 2018



"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

Regional implementation activities

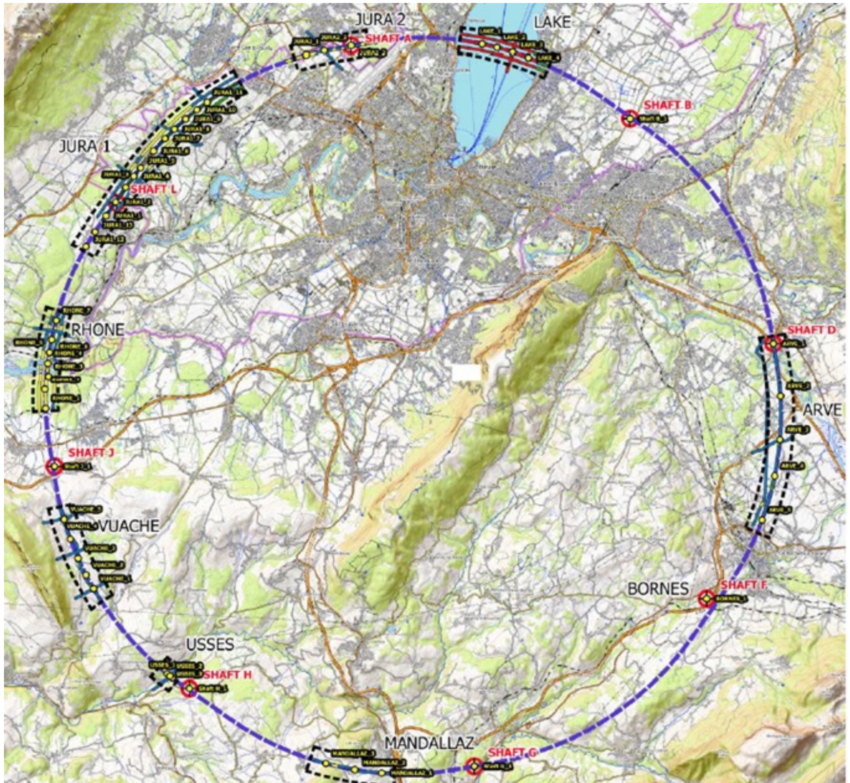
- **Meetings with municipalities in France (31) and Switzerland (10)**
  - **PA – Ferney Voltaire (FR) – experiment site**
  - **PB – Présinge/Choulex (CH) – technical site**
  - **PD – Nangy (FR) – experiment site**
  - **PF – Roche sur Foron/Etaux (FR) – technical site**
  - **PG – Charvonnex/Groisy (FR) – experiment site**
  - **PH – Cercier (FR) – technical site**
  - **PJ – Vulbens/Dingy en Vuache (FR) experiment site**
  - **PL – Challex (FR) – technical site**



→ The support of the host states is crucial (and greatly appreciated) for the further progress in the feasibility study

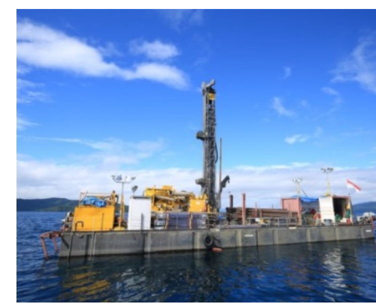
Detailed work with municipalities and host states
- identify land plots for surface sites
- understand specific aspects for design
- identify opportunities (waste heat, techn.)
- reserve land plots until project decision

Site investigations: status



- **Site investigations to identify exact location of geological interfaces:**
  - **Molasse layer vs moraines/limestone**
  - **~30 drillings**
  - **~100 km seismic lines**
  - **→ Start in July/August 2024**
  - **→ Vertical position and inclination**

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



Drilling work on the lake

FCC-ee main machine parameters

Parameter	Z (4 years, 5 x 10^{12} Z, LEP x 10^5)	WW (2 years, > 10^8 WW, LEP x 10^4)	H (ZH) (3 years, 2 x 10^6 H)	ttbar (5 years, 2 x 10^6 tt pairs)
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter x_x / x_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} cm^{-2}s^{-1}]	140	20	≥5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11

F. Gianotti

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	4 years 5 x 10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years 2 x 10^6 H	5 years 2 x 10^6 tt pairs

Up to 4 interaction points:

robustness, statistics, possibility of specialised detectors to maximise physics output

Design and parameters to maximise luminosity at all working points:

- allow for 50 MW synchrotron radiation per beam
- Independent vacuum systems for electrons and positrons
- full energy booster ring with top-up injection, collider permanent in collision mode

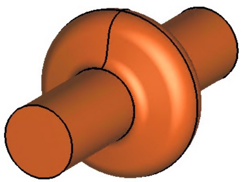
Improvements:

- x 10-50 on all EW observables
- up to x 10 on Higgs coupling (model-indep.) measurements over HL-LHC
- x10 Belle II statistics for b, c, τ
- indirect discovery potential up to ~ 70 TeV
- direct discovery potential for feebly-interacting particles over 5-100 GeV mass range

FCC-ee baseline RF configuration so far

Z

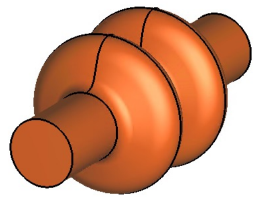
1-cell 400 MHz, Nb/Cu



low R/Q, HOM damping, powered by 1 MW RF coupler and high efficiency klystron

W, H

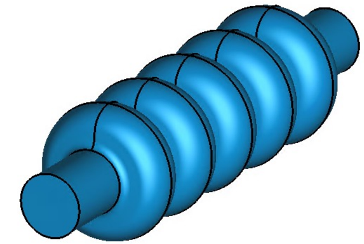
2-cell 400 MHz, Nb/Cu



moderate gradient and HOM damping requirements; 500 kW / cavity, allowing reuse of klystrons already installed for Z

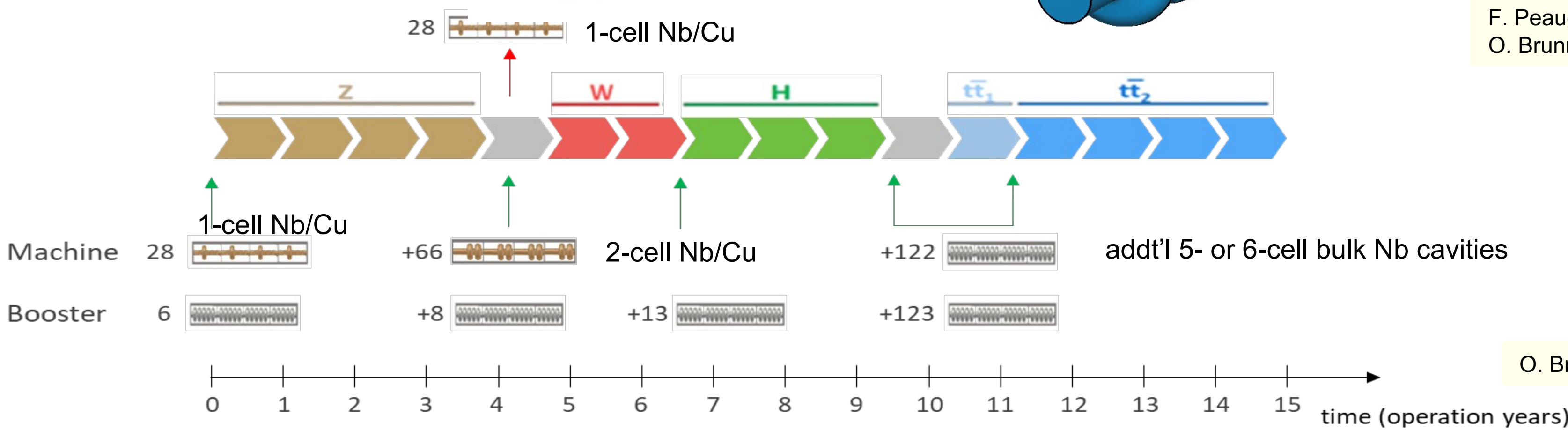
ttbar, booster

5-cell 800 MHz, bulk Nb



high RF voltage and limited footprint thanks to multicell cavities and higher RF frequency; 200 kW/ cavity

F. Peauger, O. Brunner



O. Brunner

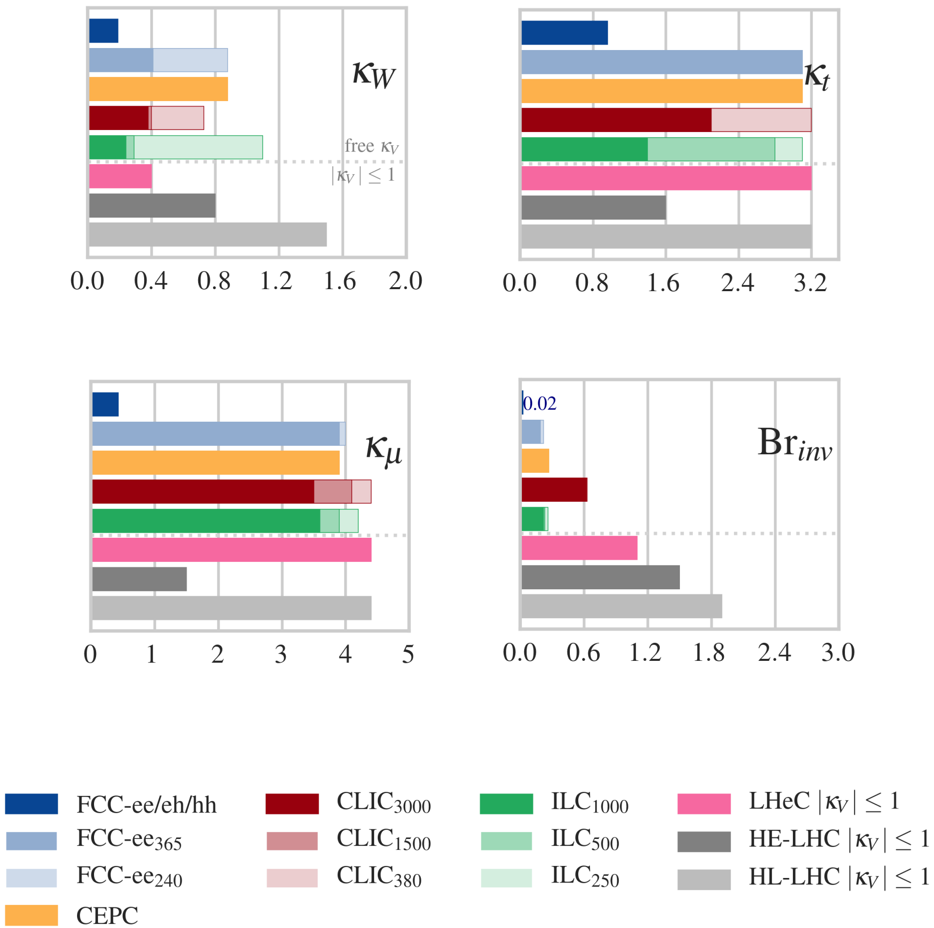
Looking into two-cell RFs for ALL energies: Reverse phase operation (RPO)
→ higher RF cavity voltage *(Y. Morita et al., SRF, 2009)*

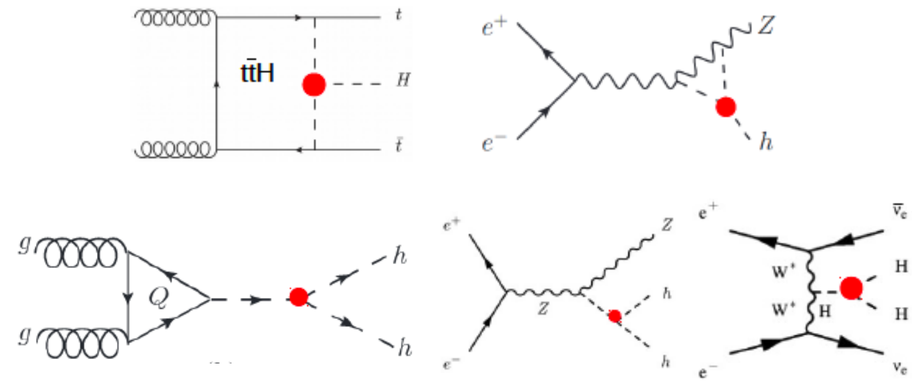
- **Experimentally verified** with high beam loading in KEKB *(Y. Morita et al., IPAC, 2010)*
- **Baseline solution for EIC ESR** *(e.g., J. Guo et al., IPAC, 2022)*

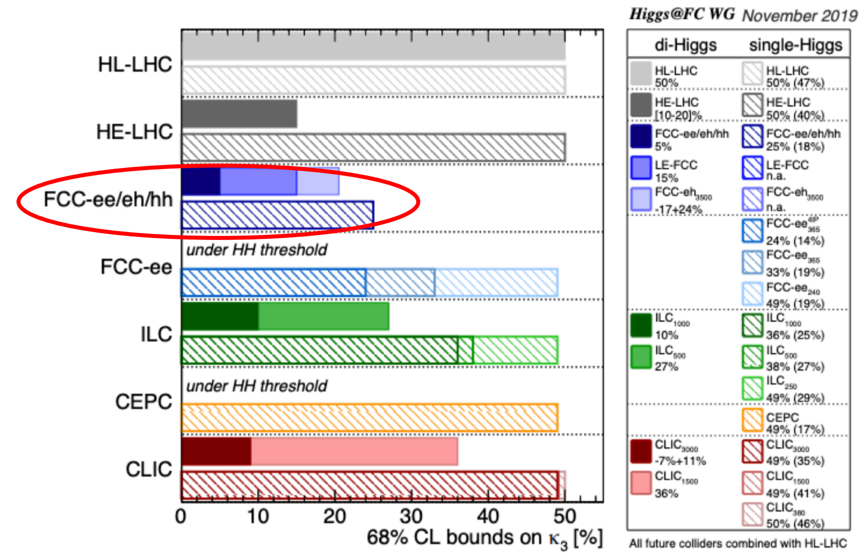
Long-term future: the physics

A very brief summary

The Higgs sector: from the HL-LHC to the "future"





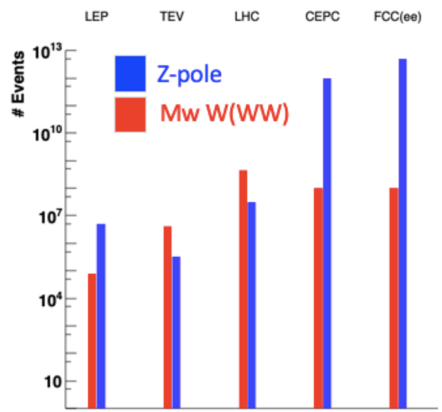


Precision Observables & Searches: examples

- **EWPO: circular ee colliders**

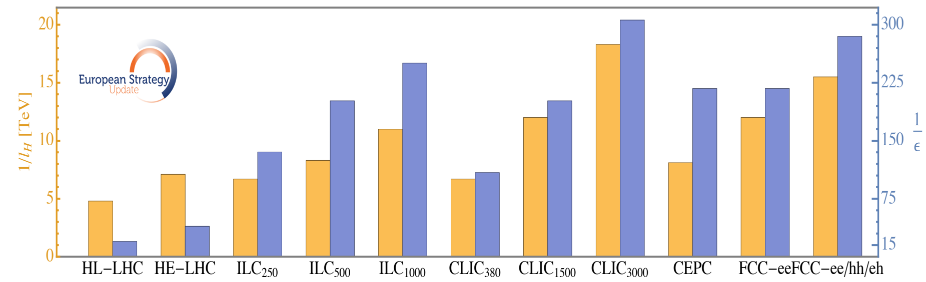
  + linear colliders for $\sin^2\theta_W$.

  Note: currently, discussion/plan for a large Z run for the linear colliders…

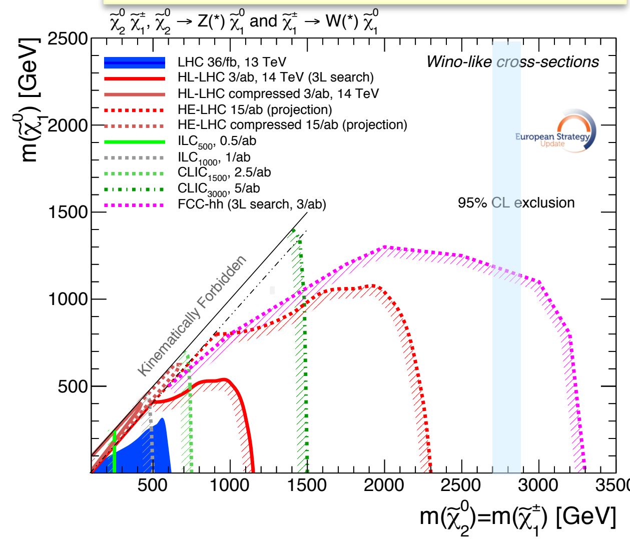


EWPO	Current	CEPC	FCC (ee)
M_Z [MeV]	2.1	0.5	0.1
Γ_Z [MeV]	2.1	0.5	0.1
N_ν [%]	1.7	0.05	0.03
M_W [MeV]	12	1	0.67
$A_{FB}^{0,b}$ [x10^4]	16	1	<1
$\sin^2\theta_W^{\mathrm{eff}}$ [x10^5]	16	1	0.6
R_b^0 [x10^5]	66	4	2–6
R_μ^0 [x10^5]	2500	200	100

Higgs compositeness (?)

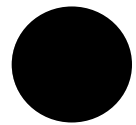


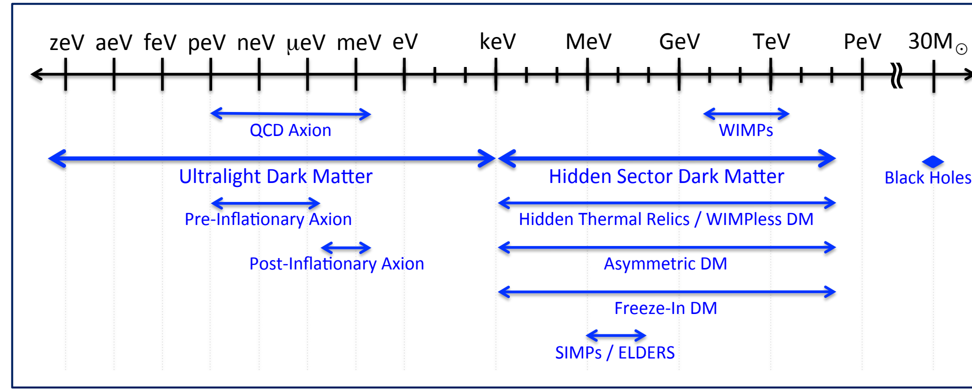
Electroweak SUSY reach



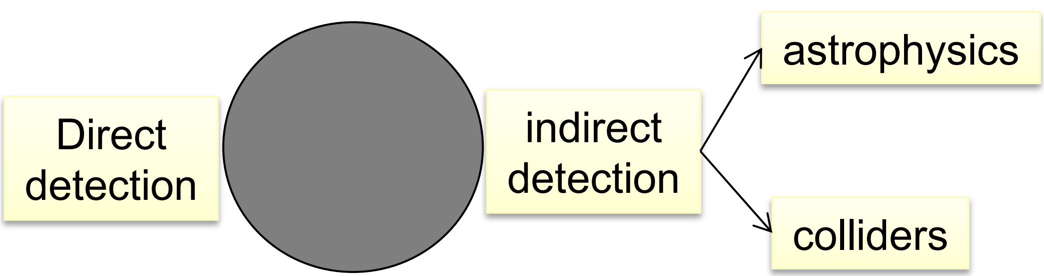
The Dark Sector

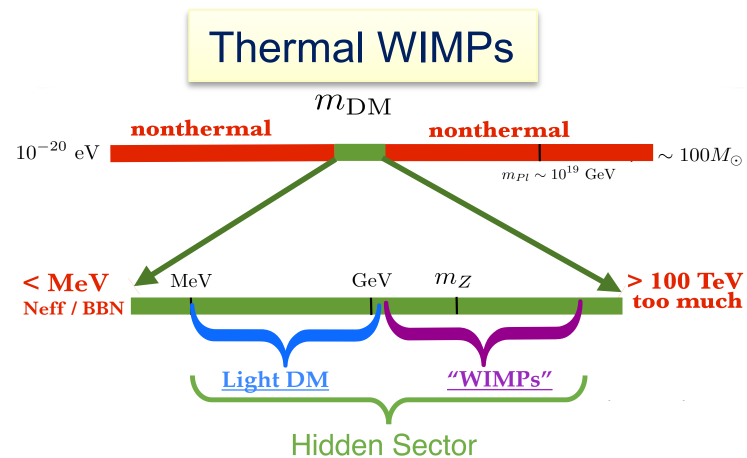
- An experimental fact & yet, still a total mystery
  - And masses span over 80 orders of magnitude
- Nightmare scenario: totally dark
  - Only Gravity to play with…





- More promising: some shade of grey

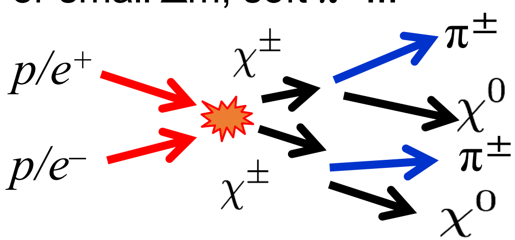




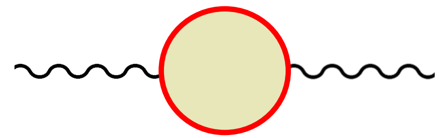
DM: Classic WIMPs

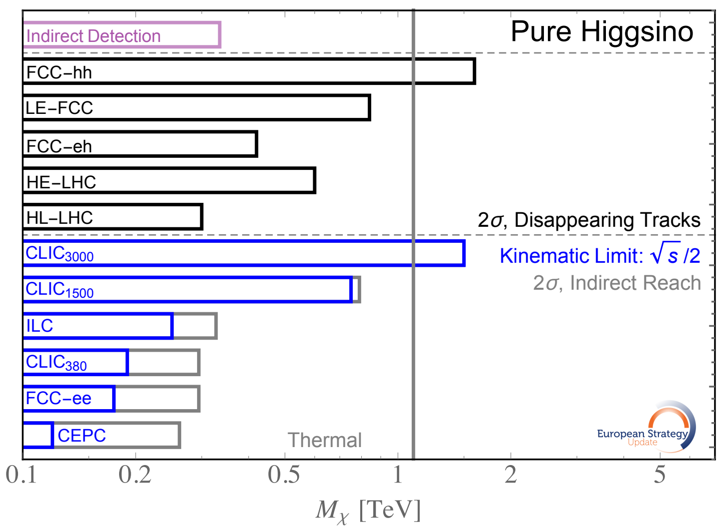
- **Two (SUSY) "extremes", pure Wino, pure Higgsino**
  - **Main "tools": disappearing track, propagator modifications**

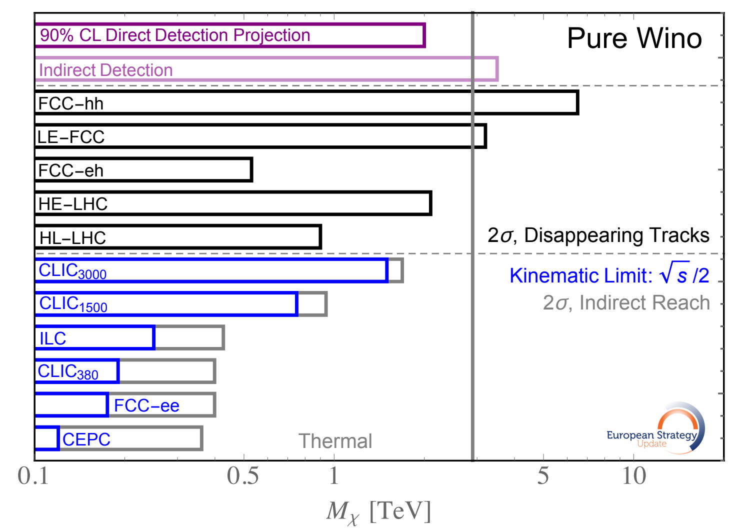
For small Δm, soft $\pi^{\pm}$...



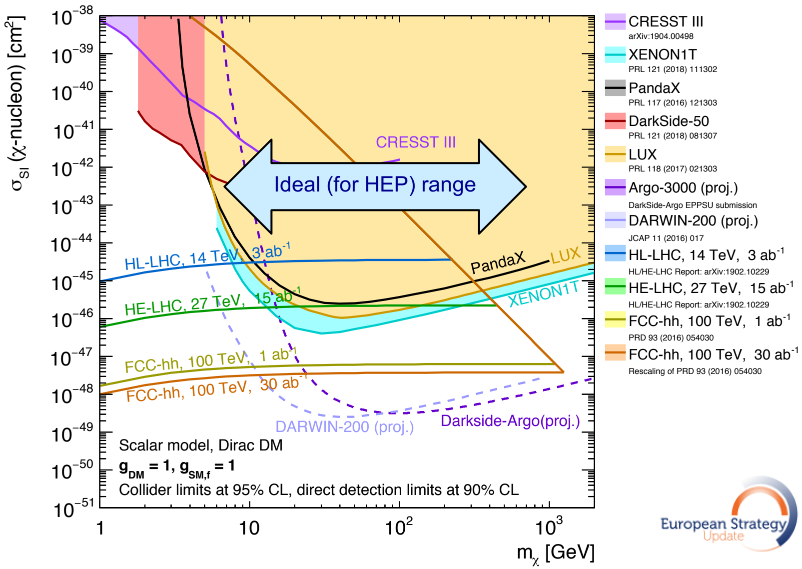
EWKinos in loop change prop (W, Y parameters)

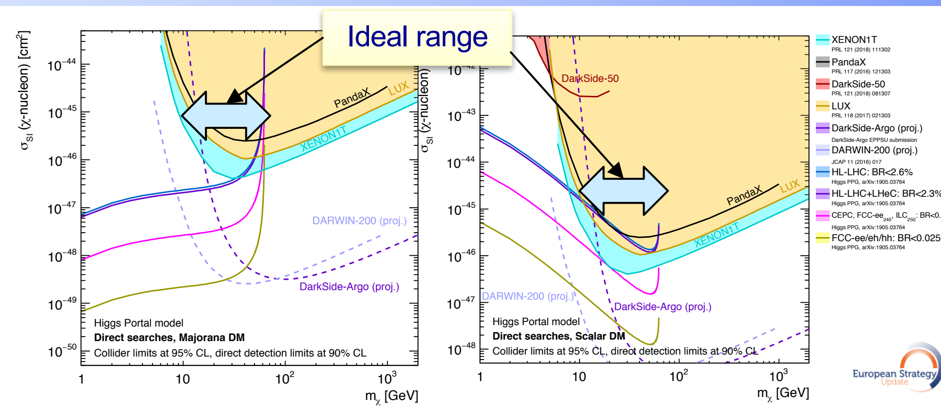


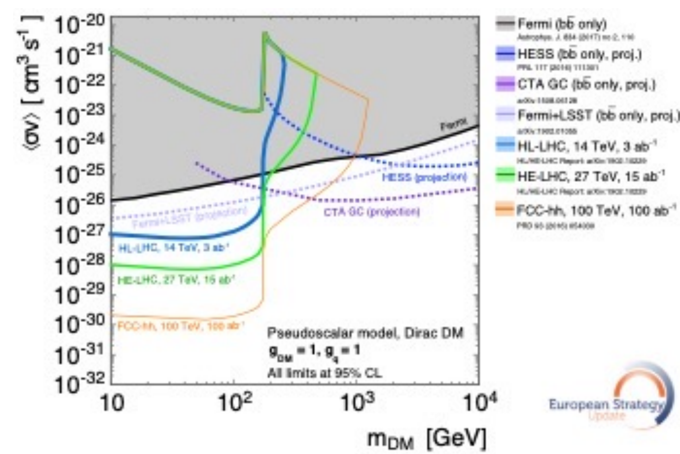




Scalar mediator: Higgs portal and BSM scalar



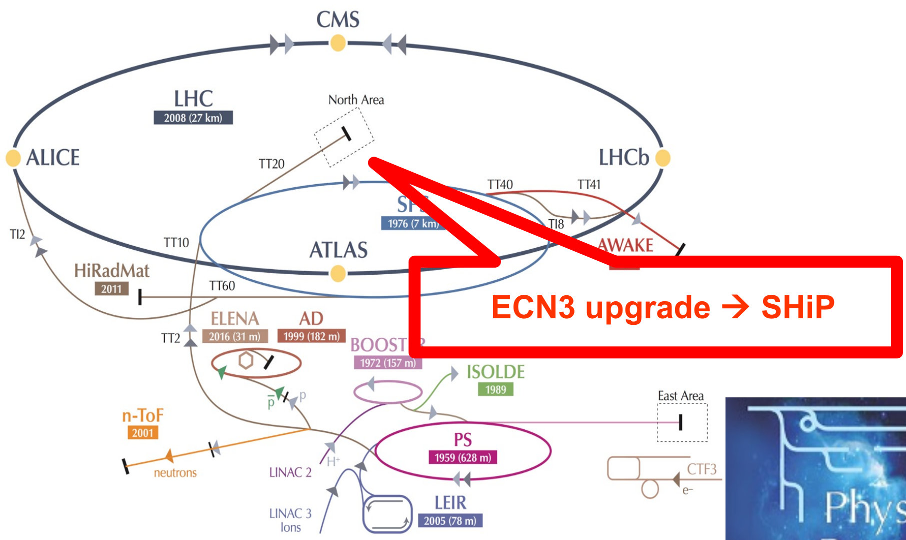


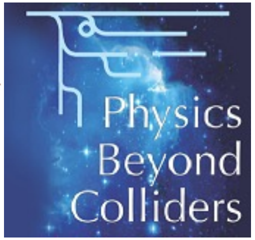


A collider discovery will need confirmation from DD/ID for cosmological origin
A DD/ID discovery will need confirmation from colliders to understand the nature of the interaction

A future collider program that optimizes sensitivity to invisible particles coherently with DD/ID serves us well. Need maximum overlap with DD/ID!

CERN Diversity Programme





Future of the diversity programme discussed in the Physics Beyond Collider study

Topics include:
- ❑ LHC injectors
- ❑ Low energy facilities
- ❑ High energy fixed target
- ❑ Opportunities gamma-factory
- ❑ Precision measurement and rare decays
- ❑ High energy beam dumps
- ❑ Low energy hidden sector (axions, EDM)
- ❑ QCD and Heavy Ion

AD Experiments: Antiproton Decelerator for antimatter studies

AWAKE: proton-induced plasma wakefield acceleration

CLOUD: impact of cosmic rays on aeorosols and clouds

COMPASS → AMBER: hadron structure and spectroscopy

ISOLDE: radioactive nuclei facility

NA61/SHINE: ions and neutrino targets

NA62: rare kaon decays

NA63: radiation processes in strong EM fields

NA64: search for dark photons

NA65: study of tau neutrino production

Neutrino Platform: ν detector R&D for experiments in the US, Japan

n-TOF: n-induced cross-sections

~20 projects with > 1200 scientists

Pseudo-summary

Pseudosummary/Outlook

- **Extremely rich physics program ahead to understand the scalar sector**
  - **The LHC and HL-LHC will get us to ≈2-5% couplings for the Higgs boson;**
  - **All options for a future "Higgs factory" → ~O(10^{-2}–10^{-3}) understanding of couplings.**
  - **Important aspects: EWPO (needs next-gen Z factory) and top threshold.**
  - **Fundamental scalar? Can probe it to 15-18 TeV.**
  - **FCC-ee/hh combination has the largest direct reach to new particles/phenomena. From new particles to Higgs self-coupling to Dark Matter searches…**
  - **Dark Matter: Complementarity with indirect searches at colliders (and astroparticle expts); Next-generation colliders can cover the thermal WIMP scenario.**
- **A rich parallel physics program of measurements and searches**
  - **From nuclear physics, to hadron structure and searches for heavy neutral leptons**
- **The physics at hand, the physics of the next decade, and the physics of the long-term future remains fully exciting. Stay tuned…**
- **And though we will miss Igor and his discerning view for doing excellent physics, we are counting on the people he has trained and brought up through five decades, to continue his legacy.**