Strategia per il futuro della Fisica delle Alte Energie

IFAE 2025

Incontri di Fisica delle Alte Energie

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Aleandro Nisati
INFN Roma

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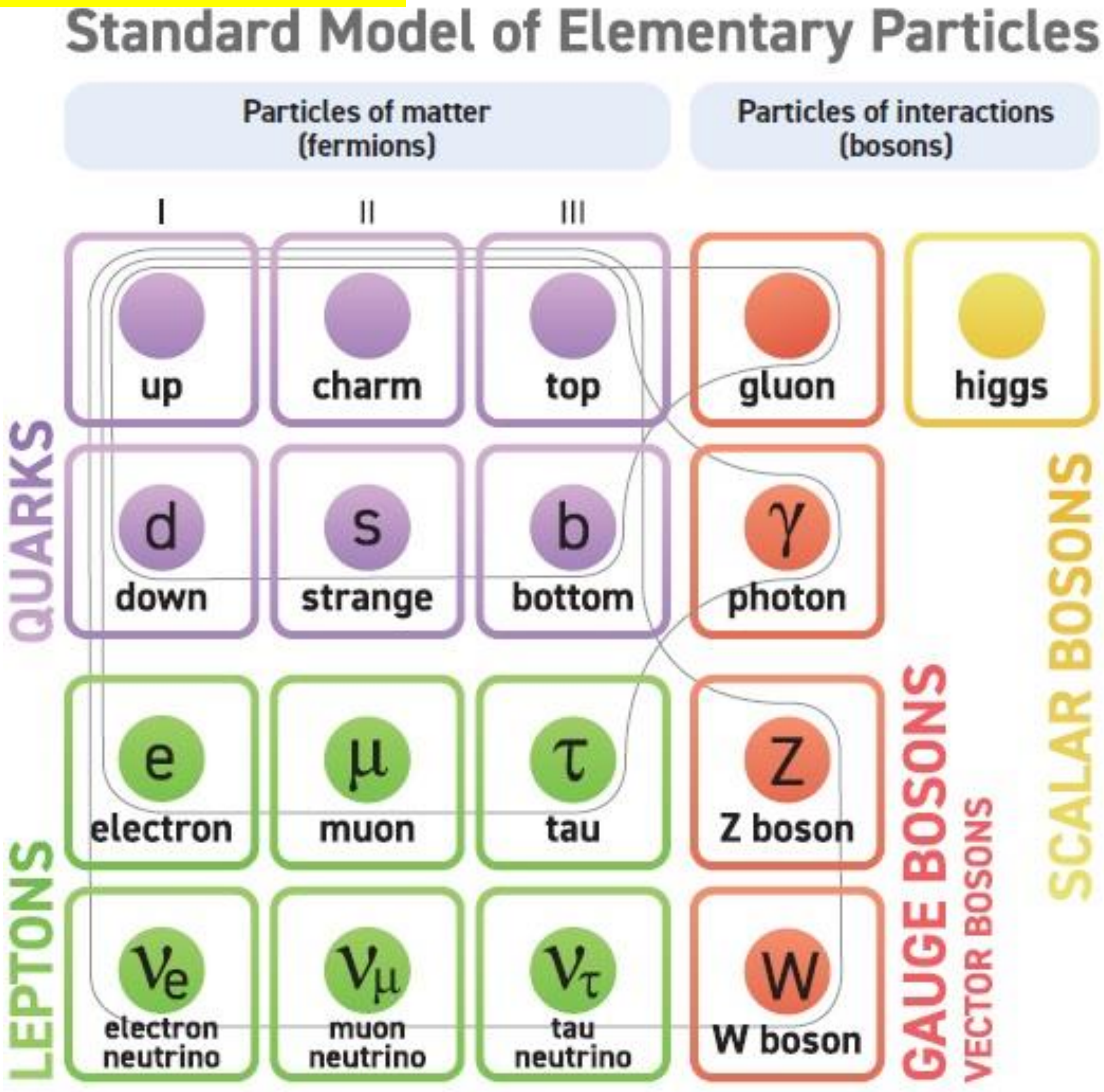
The Standard Model of particles and fields

See previous talk by Fulvio Piccininni

- The **Standard Model (SM)** of particle physics is a well-established theory that describes the fundamental particles quarks, leptons, and gauge bosons, and their interactions via the electromagnetic, weak, and strong forces. The **Higgs field** is a pervasive field that interacts with the SM elementary particles. As a consequence of this interaction, the particles acquire mass. The **Higgs boson** is the "quantum" particle associated to this field.
- With the discovery of the **Higgs boson** in 2012, the **Standard Model** of particle physics is validated as the **most complete and accurate theoretical description of the known fundamental particles and their interactions**.
  - The Higgs boson was the last missing piece of the SM, and its discovery at CERN's Large Hadron Collider (LHC) was a triumph, confirming the existence of the Higgs field.

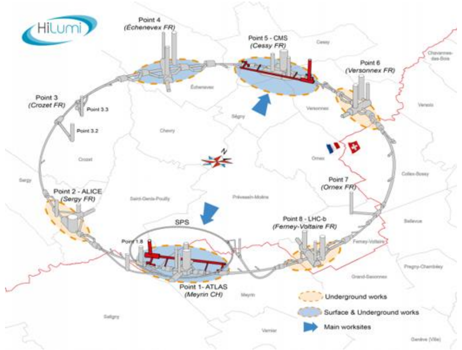


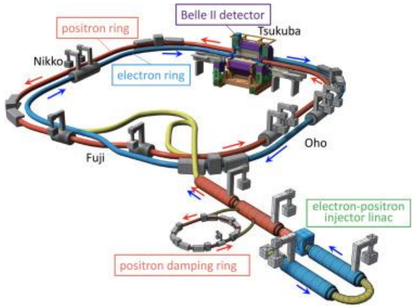
Future Colliders

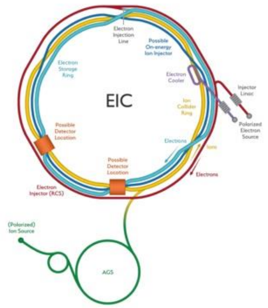
- Future Colliders are essential for addressing the most pressing unanswered questions in the Standard Model and beyond. Two basic paths:
  - **Precision Physics**: Precision measurements are critical for testing the Standard Model's predictions and searching for subtle deviations that may indicate new physics. Key examples:
    - **Higgs Sector:** Higgs boson couplings accurate measurements; understanding the Higgs potential through self-coupling studies to explore electroweak symmetry breaking.
    - more **accurate measurements** of particle properties (e.g., masses, lifetimes, and couplings) and particle production cross sections
  - **Search for new objects and new phenomena**: Searching for new particles and phenomena is the primary way to uncover physics beyond the Standard Model. Examples:
    - **Dark Matter Candidates**
    - **New Gauge Bosons** (Z' or W')
    - **Exotic Phenomena**
    - **Anomaly Detection**

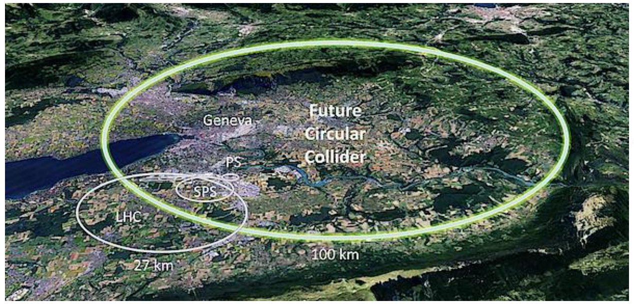
Future Colliders

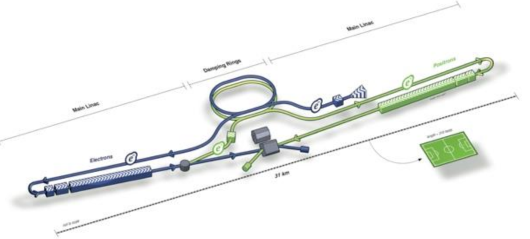
- **Approved Future Colliders:**
  - **High-Luminosity LHC, HL-LHC,** at CERN
  - High-luminosity SuperKEKB (focused on flavor physics, CP violation, and rare decays)
  - EIC $e^{-}p/n$ collider, BNL
  - …
- **Most prominent proposed New Colliders:**
  - **FCC: FCC-ee followed by FCC-hh, at CERN**
  - Linear $e^{+}e^{-}$ Collider, in Japan, or at CERN
  - **Muon Collider** (in USA??)
  - CepC (followed by CppC), in China
  - CCC (also known as C3) in USA
  - Plasma-based linear $e^{+}e^{-}$ collider, at DESY
  - …

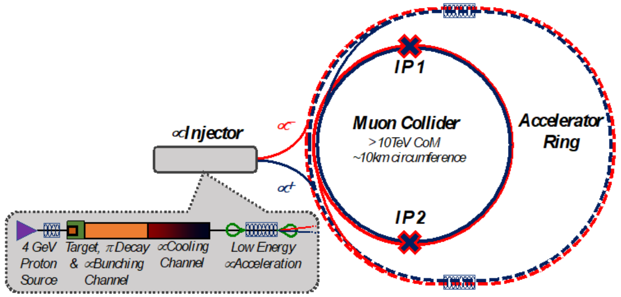


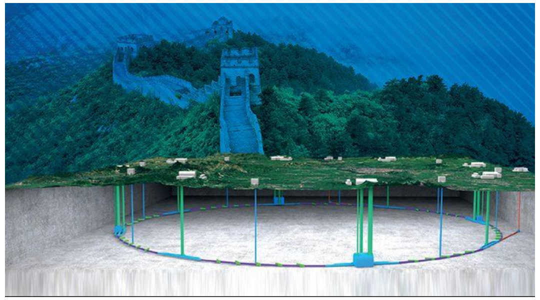


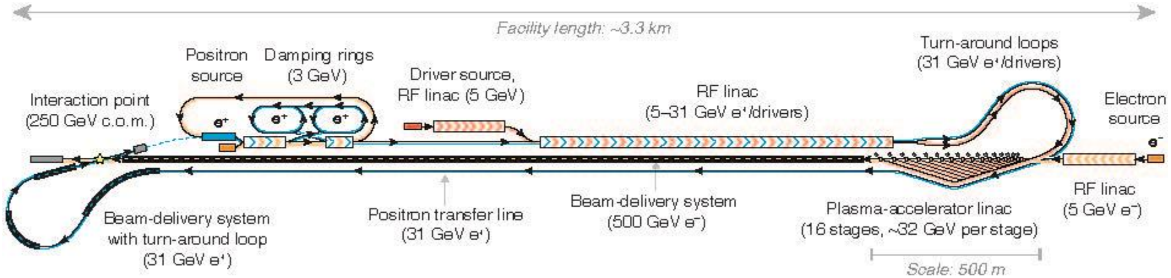








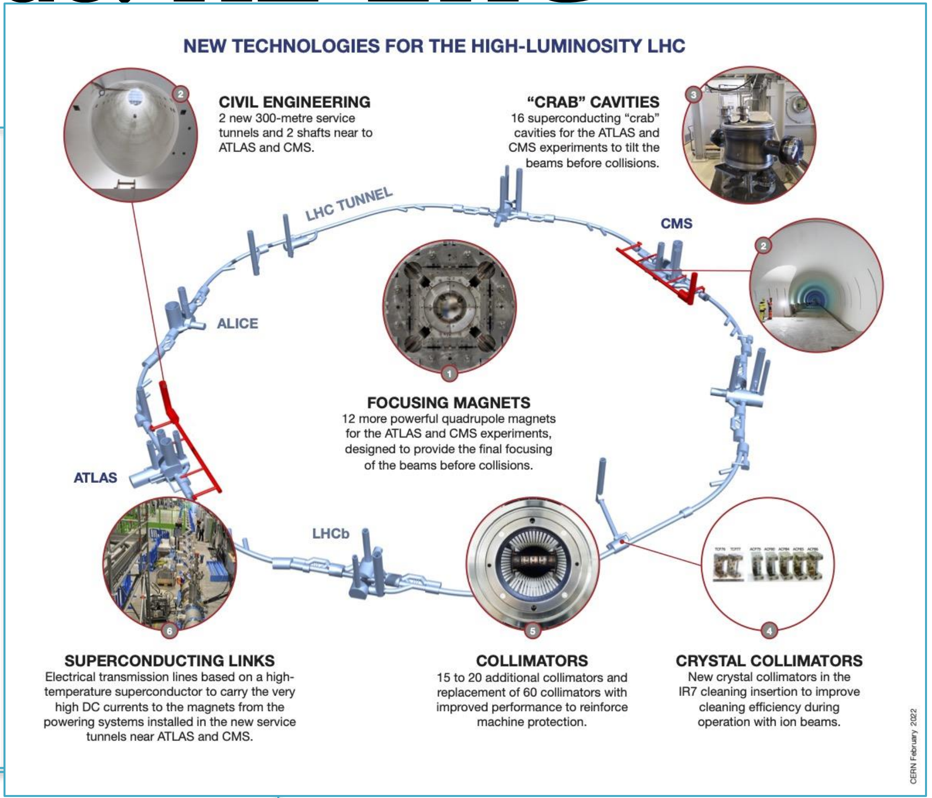




The LHC luminosity upgrade: HL-LHC

Main HL-LHC targets

- A peak luminosity of L_{peak} = **5×10^{34} cm^{-2}s^{-1} with levelling**
- An integrated luminosity of **250 fb^{-1} per year per ATLAS/CMS**, enabling the goal of
- **L_{int} = 3000 fb^{-1}** twelve years after the upgrade, per ATLAS/CMS.
  This luminosity is **more than ten times** the luminosity reach of the first 10 years of the LHC lifetime.
- furthermore:… **√s = 14 TeV**

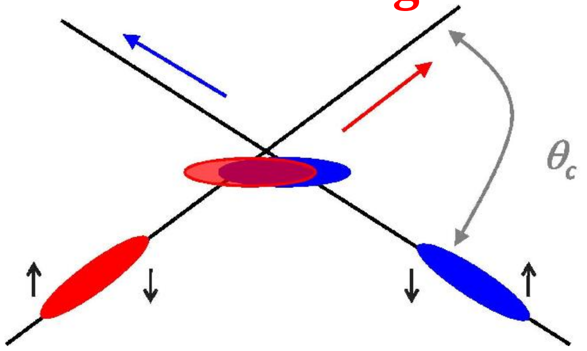


Ultimate performance established 2015-2016: with same hardware and same beam parameters: use of **engineering margins:**

$L_{peak\ ult}$ ≅ 7.5 10^{34} cm^{-2}s^{-1} and **Ultimate Integrated $L_{int\ ult}$ ~ 4000 fb^{-1}**

LHC should not be the limit, would Physics require more

crab-crossing



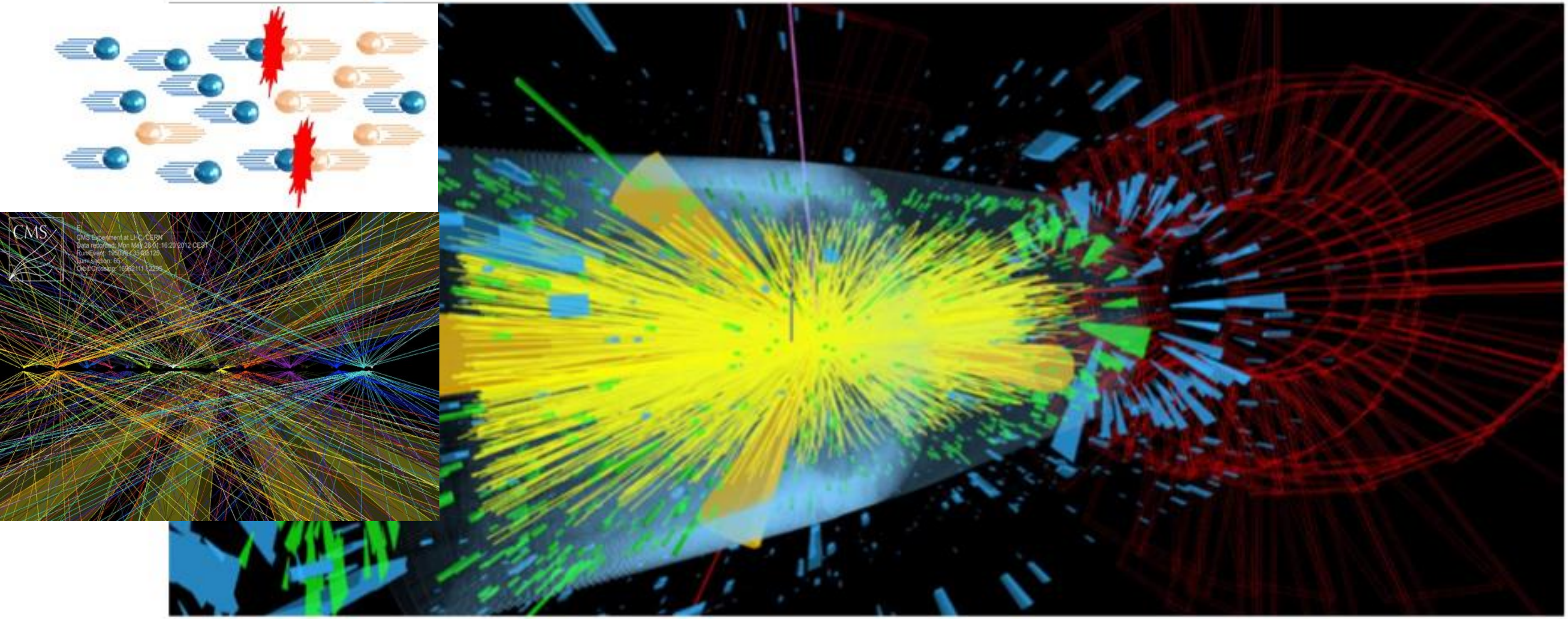
➔ > 1 year until start of Long Shutdown 3 [postponed to 29 June 2026]

➔ > 80% of the project budget of 1.1 BCHF already committed

➔ The project is ready for LS3 installation start in 2nd half of 2026!

Challenge: Pileup

Number of events in pile up: 140, up to 200

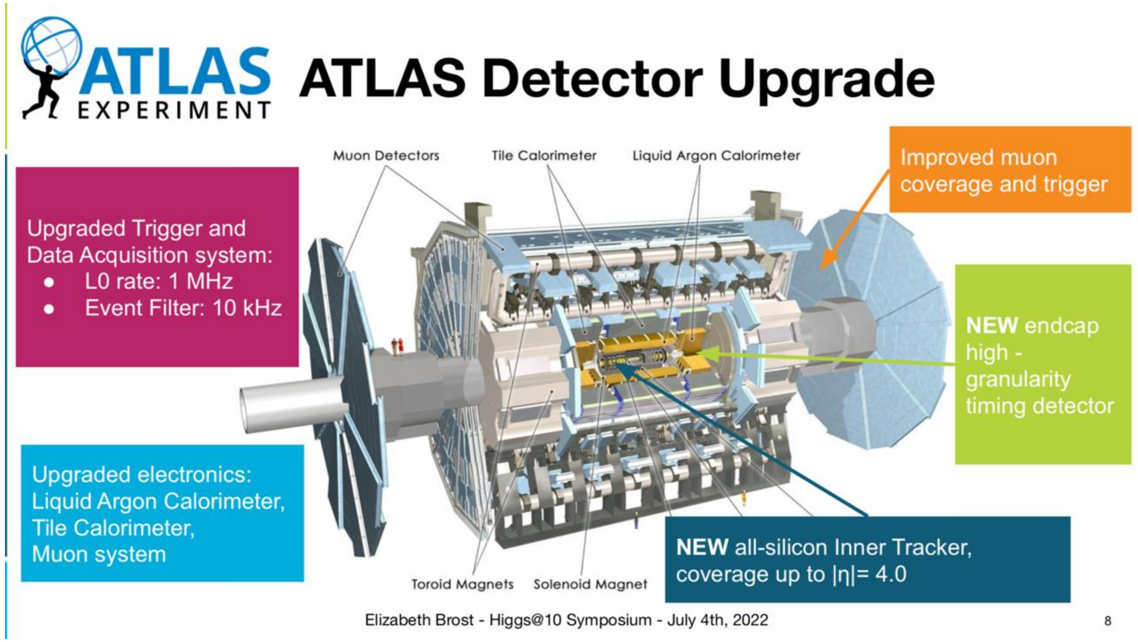


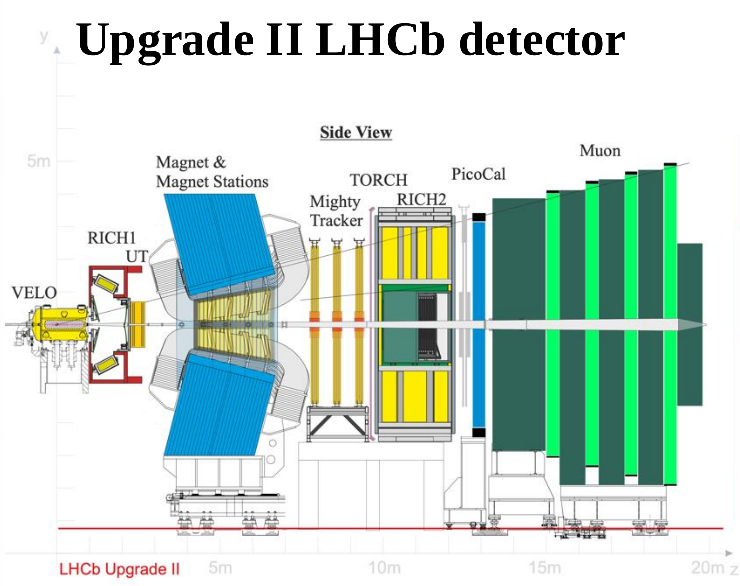
Simulated VBF $H \to \tau\tau$ event in CMS
(with pileup 200)

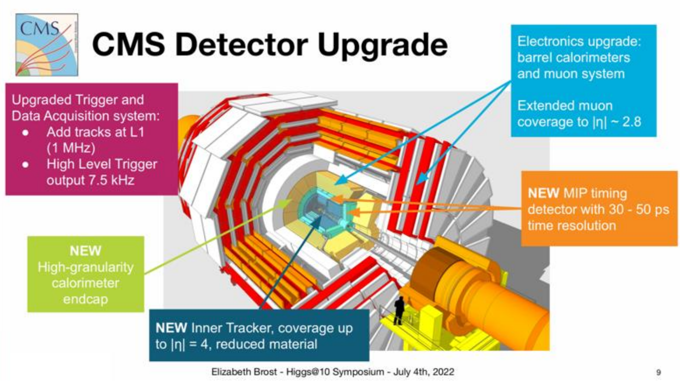
High pileup environment at the HL-LHC brings new challenges: detector irradiation, higher detector occupancy, higher trigger rates

HL-LHC ATLAS, CMS and LHCb detector upgrade

- HL-LHC: the most powerful tool to address these major challenges to our fundamental understanding of nature
- Detectors must be designed to fully exploit the physics potential of the HL-LHC while withstanding the demanding environmental conditions in which they are expected to operate







Higgs couplings @ HL-LHC

Precision Higgs coupling measurement at HL-LHC

Precision on couplings to γ, W, Z and τ < 2 %

Precision on couplings to g, t, b and μ < 5 %

Precision on couplings to $Z\gamma$ < 10 %

Many projections show limitation from theory Uncertainties (despite the assumptions made)

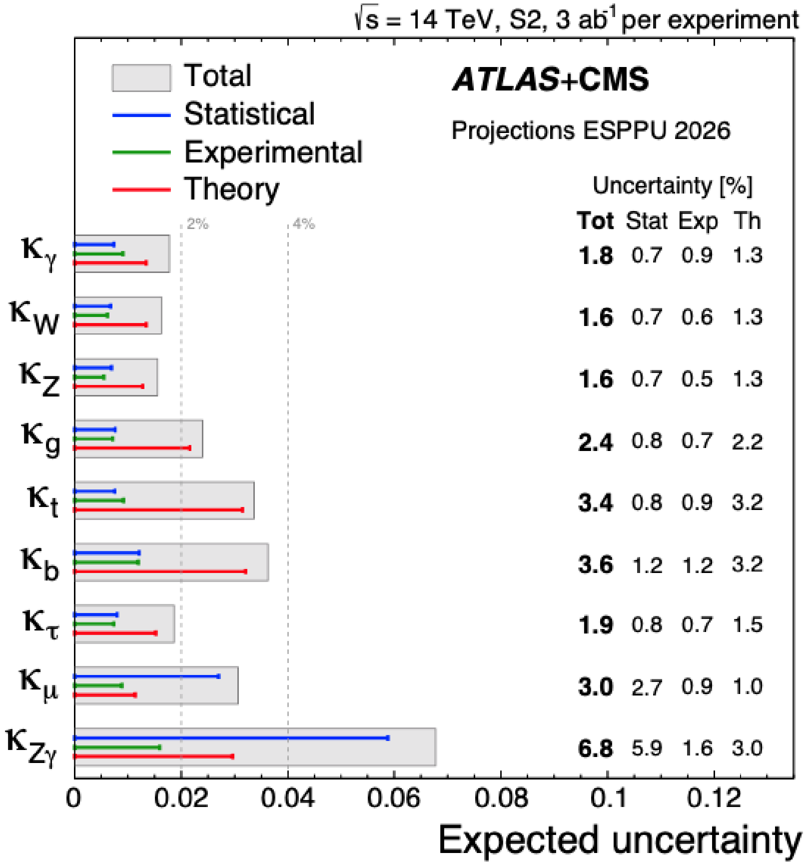
The study was and it still is fundamental for:

- **The European Strategy for Particle Physics Update 2019-2020**
- **The Particle Physics Project Prioritization Panel (P5) in USA, 2023**
- **The European Strategy for Particle Physics Update 2026**
- **P5 Processes in USA**

CERN Yellow Report (ESPPU 2020)
https://e-publishing.cern.ch/index.php/CYRM/issue/view/94/69

ATLAS + CMS new study (ESPPU 2026)
https://arxiv.org/abs/2504.00672

BR(H→BSM decay modes) se to 0



total expected ±1s.d. uncertainties on the coupling modifier parameters for the combination of ATLAS and CMS extrapolations

Dominated by: theory uncertainties, statistics

HH production @ HL-LHC

European Strategy 2019

Combination of 5 HH channels, many based on initial partial Run 2 analysis strategy

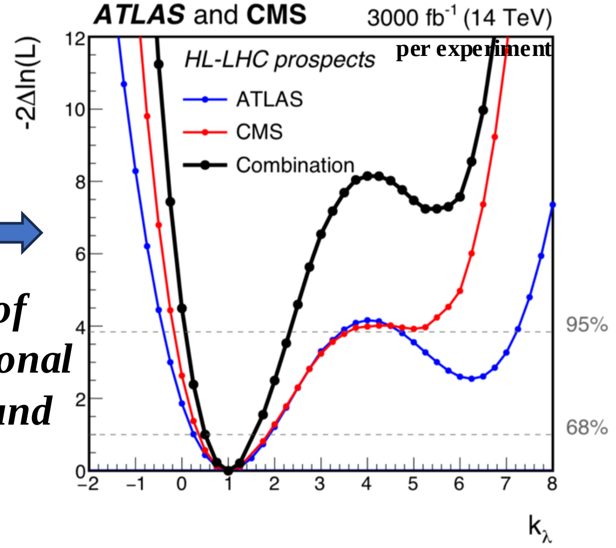
- **bbbb, bb$\gamma\gamma$, bb$\tau\tau$, bbZZ(4l), bbVV(lνlν)**

4σ SM HH significance (ATLAS+CMS)

50% precision on self-coupling

negative-log-likelihood as a function of κ_λ, calculated by performing a conditional signal+background fit to the background and SM signal

ESPPU 2019-2020



NEW!

New HL-LHC prospects results ATLAS+CMS for the
European Strategy for Particle Physics Update 2025-2026

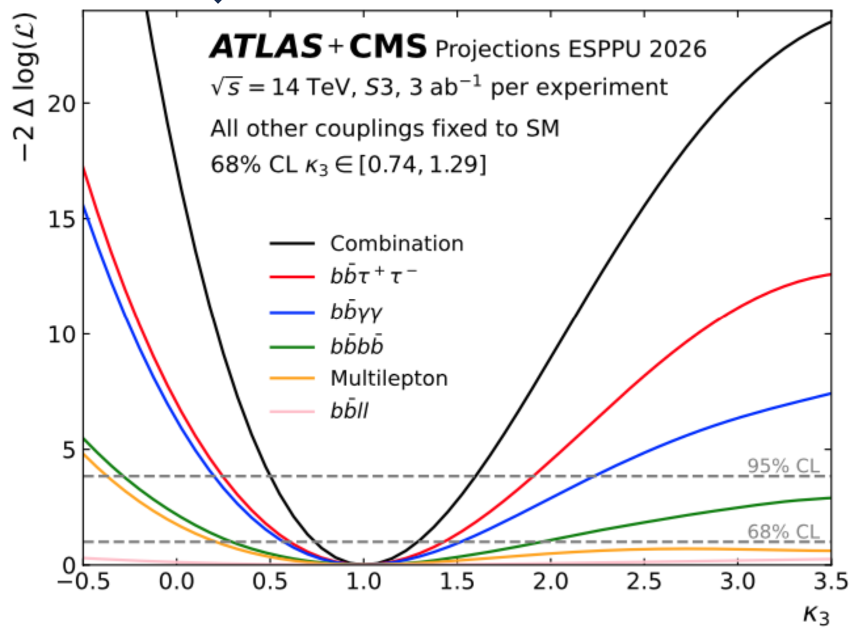
Studies are based on new analyses developed for Run 2 LHC data

- **HH → bbbb, bb$\gamma\gamma$, bb$\tau\tau$, bbll, multilepton finale states**

$\kappa_\lambda = 1.0^{+0.29}_{-0.26}$ ➔ **< 30% uncertainty** (assuming $\kappa_\lambda = k_{SM} = 1$)

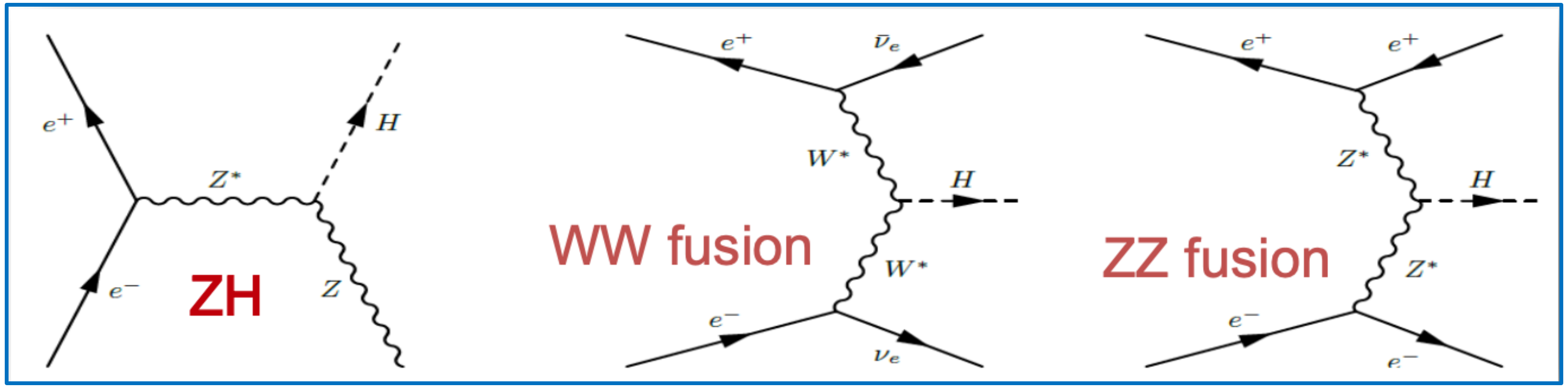
Public document on ATLAS + CMS Combination available
https://arxiv.org/abs/2504.00672

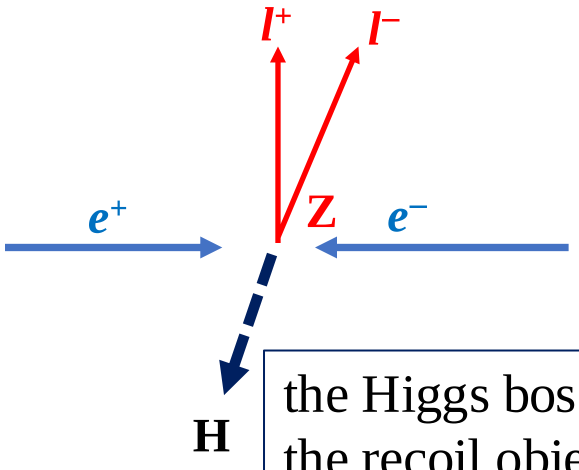
➔ Important Input to the on-going European Strategy for Particle Physics Update



Future Colliders:
e^+e^- (/lepton) Higgs Factories

Measurement of the $e^+e^- \rightarrow ZH$ total cross section recoil mass





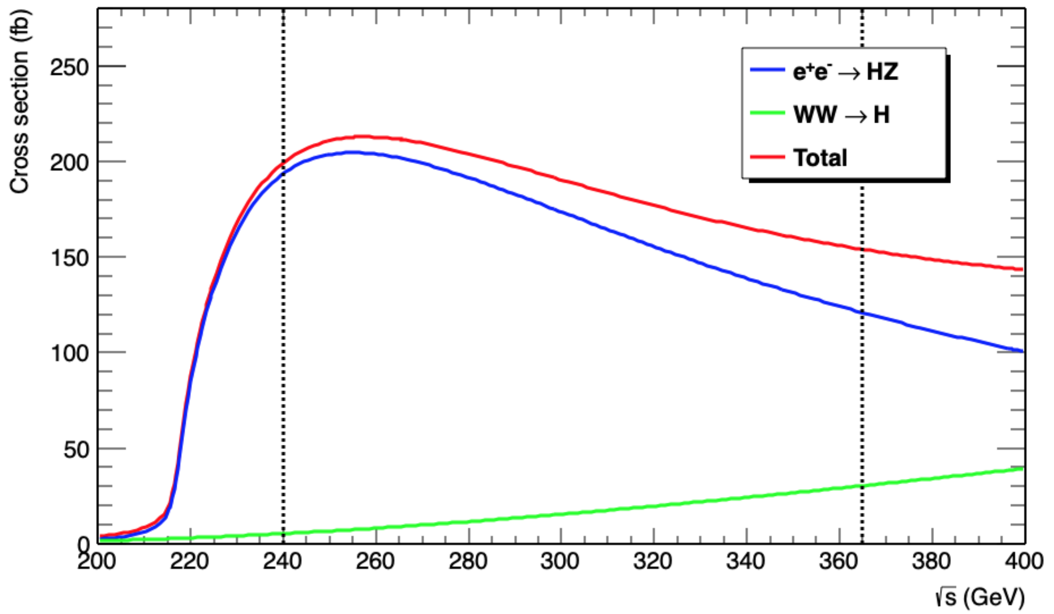
the Higgs boson is the recoil object

- Higgs production at e+e– colliders: $e^+e^- \rightarrow ZH$, $\nu\nu H$, e^+e^-H
- precisely known initial state: the beam particles are elementary, the colliding particles initial state is $\mathbf{P_i} = (1/2\cdot\sqrt{s};\ 0;\ 0;\ 1/2\cdot\sqrt{s})$
- The process e^+e^- colliders: $e^+e^- \rightarrow ZH$ is very clean, the Z can be easily detected and reconstructed thanks to the leptonic decays
- Momentum and energy conservation allow the reconstruction of the "recoil mass"

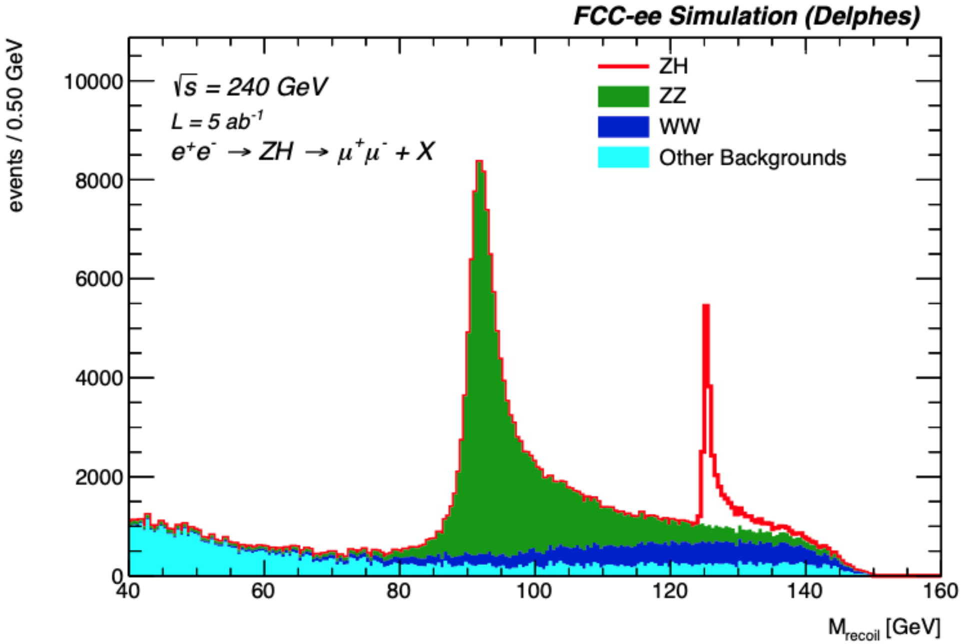
$$M^2_{rec} = (\sqrt{s} - E_{l+l-})^2 - |\mathbf{P}_{l+l-}|^2 = s - M^2_{l+l-} - 2\cdot E_{l+l-}\cdot\sqrt{s}$$

M_{rec} is the **recoil mass**

extraction of the g_{ZZ} Higgs boson coupling - natural width Γ_H



Improved-Born Higgs production cross section (with initial state radiation included) as a function of √s. M_H set to 125 GeV.



Inclusive mrecoil distribution for events with a Z decaying to $\mu+\mu-$ in the mass region 40 ÷ 160 GeV.

- **Higgs Factory: we can produce 0.2×10^6 Higgs boson per 1 ab^{-1} @ √s = 240 GeV**
- The measurement of the ZH production cross section gives access to g^2_{HZZ}: $\sigma(e^+e^- \rightarrow ZH) \propto g^2_{HZZ}$ (no analysis of the Higgs boson decays)
- **Higgs** boson **partial width**: **Γ(HZZ)** is also proportional to g^2_{HZZ}
- Including Higgs boson decays, and considering other Higgs boson production processes, we can extract Γ_H **and of all other Higgs boson couplings in a model independent way** (this is not possible at hadron colliders)

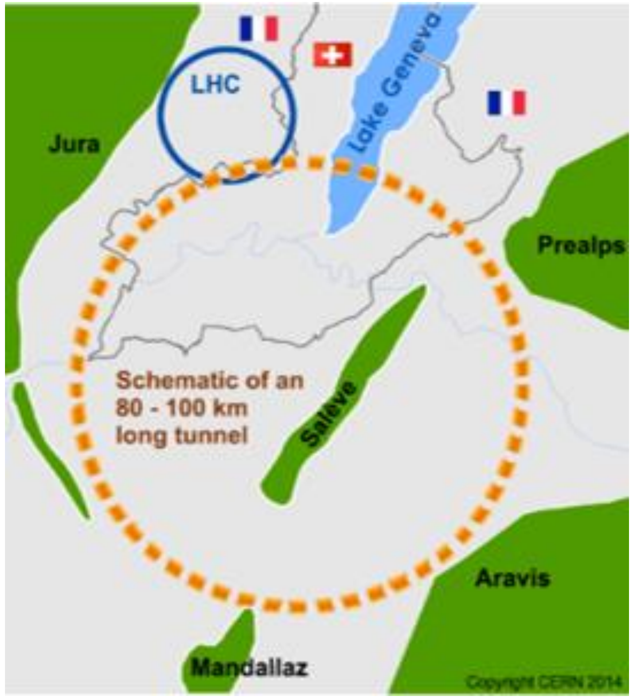
FCC: a new accelerator facility at CERN for future

- The fundamental concept of the FCC project is to establish a new facility at CERN, designed to deliver a comprehensive and extensive scientific programme aimed at addressing the most significant open questions in fundamental physics, through complementary physics initiatives based on particle accelerators.
    - Priorities are set on the base of scientific arguments and machine&detector feasibility
- ➔ The most effective plan we can devise is an infrastructure capable of accommodating high-intensity and high-energy future colliders with multiple particle beams.
- A circular collider is the best solution to develop such a project
    - **This needs the construction of a new, large tunnel in the CERN region**
    - This tunnel can host in an initial phase an e+e– collider to allow the study of the electroweak and Higgs sectors of the Standard Model
    - Subsequently, this tunnel can host a **very high energy p-p collider to allow searches at the energy frontier of new particles and new phenomena beyond Standard Model**
    - Moreover, this facility can be used also for other complementary frontier physics investigations, installing an electron-proton collider, a muon collider(?)or an ion collider(?)

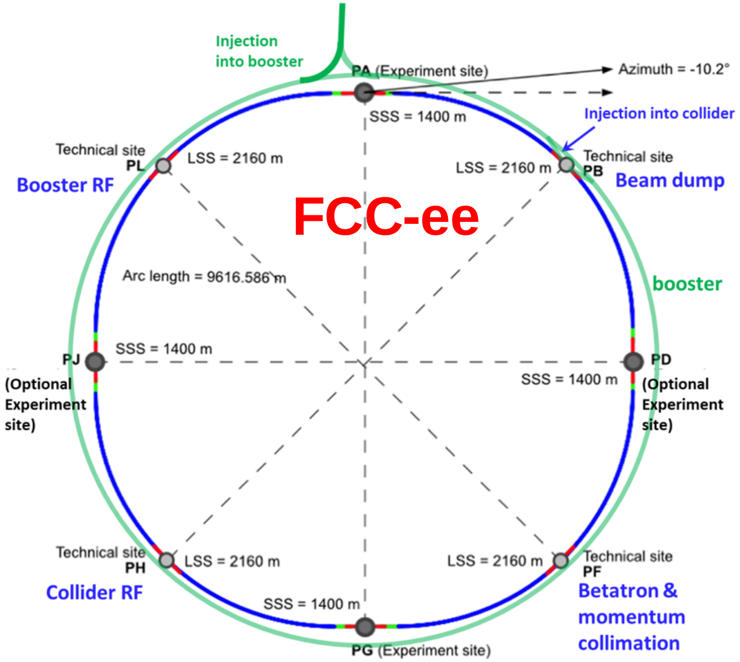
FCC integrated program

comprehensive long-term program maximizing physics opportunities

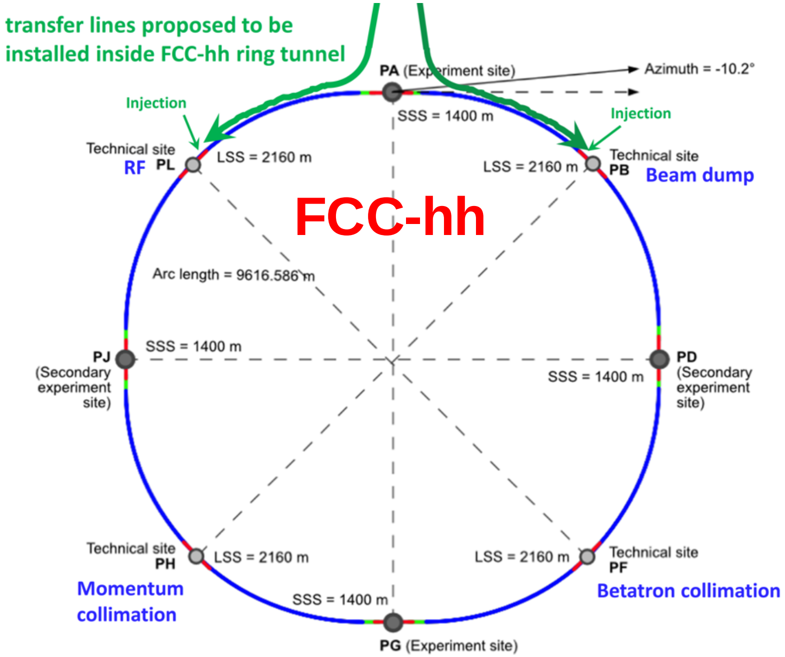
- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option**
- highly synergetic and complementary programme boosting the physics reach of both colliders
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC



2020 - 2045



2045 - 2065



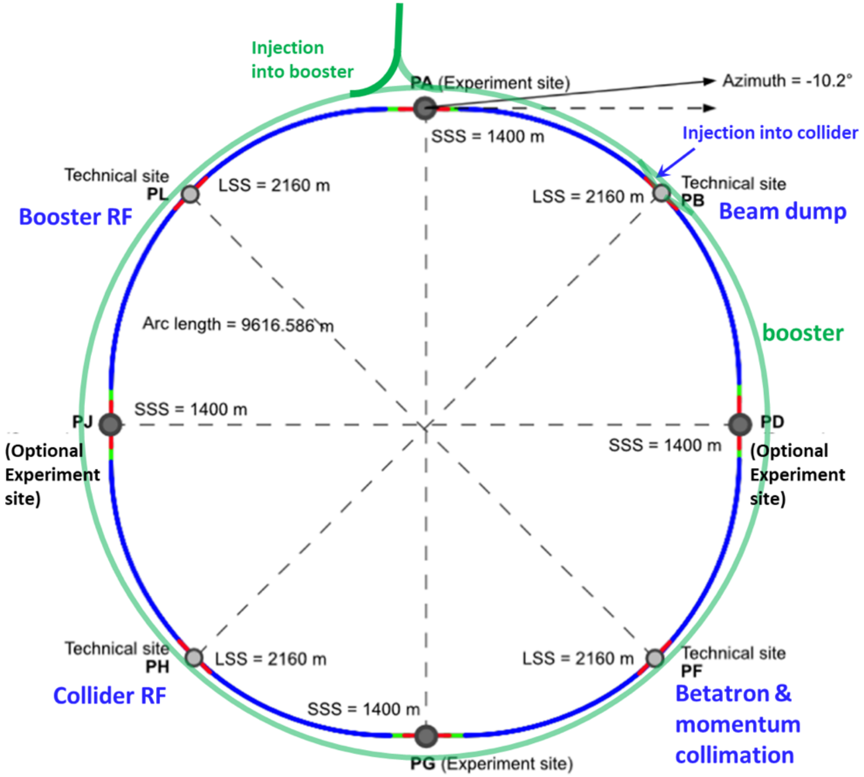
2070 -

Reference layout and implementation: PA31 - 90.7 km

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, 4-fold symmetry



FCC-ee main machine parameters

Parameter	Z	WW	H (ZH)	ttbar
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 ξ_x / ξ_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
	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

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

- ❑ x 10-50 improvements on all EW observables
- ❑ up to x 10 improvement 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

Up to 4 interaction points → robustness, statistics, possibility of specialised detectors to maximise physics output

F. Gianotti

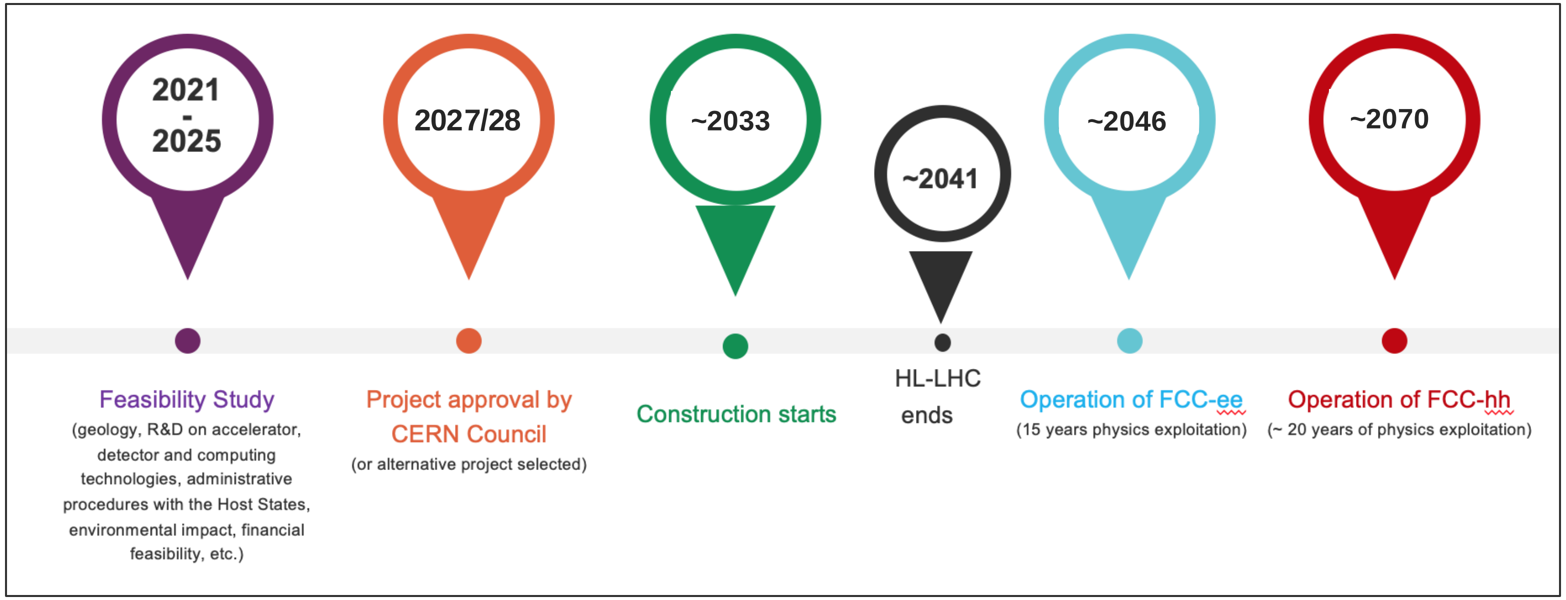
FCC timeline

1st stage collider, FCC-ee:

- e+e- collisions 90-360 GeV, Construction: 2033-2045 → Physics operation: 2048-2063
- Highest luminosities at Z, W, ZH of all proposed Higgs and EW factories; indirect discovery potential up to ~ 70 TeV

2nd stage collider, FCC-hh:

- pp collisions at ~ 100 TeV, Construction: 2058-2070 → Physics operation: ~ 2070-2095
- direct exploration of next energy frontier (**~ x10 LHC**) and unparalleled measurements of low-rate and "heavy" Higgs couplings (ttH, HH)



by Paolo Giacomelli

The IDEA detector @ FCC-ee

Strong INFN involvement on IDEA dector studies

Beam pipe: R~1.0 cm

Vertex:
5 MAPS layers
R = 1.37-31.5 cm

Drift Chamber: 112 layers
4 m long, R = 35-200 cm

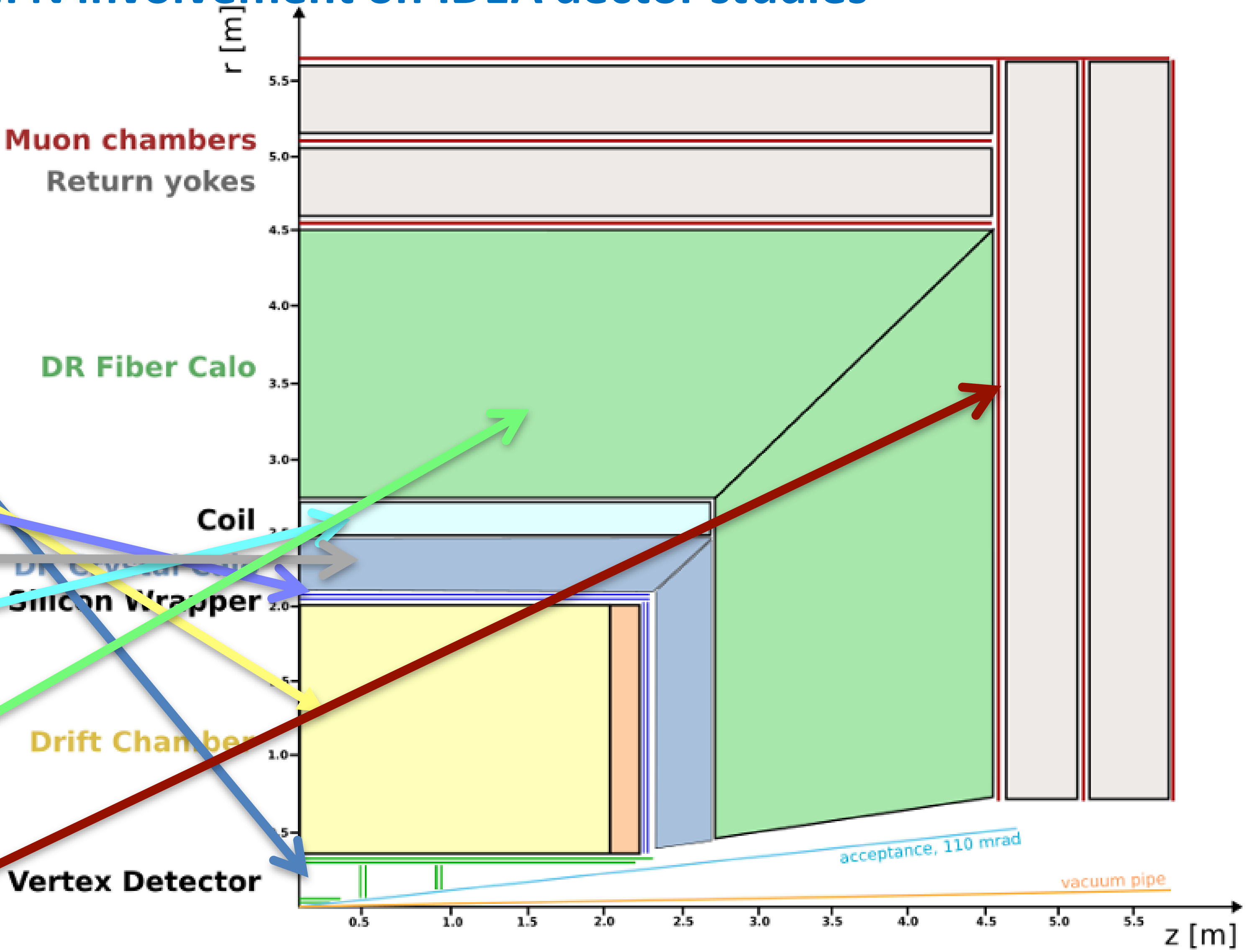
Outer Silicon wrapper:
R = 200-215 cm

DR crystal ecal: ~ 22 X_0
R = 215-250 cm

Superconducting solenoid coil:
3 T, R ~ 2.5-2.8 m

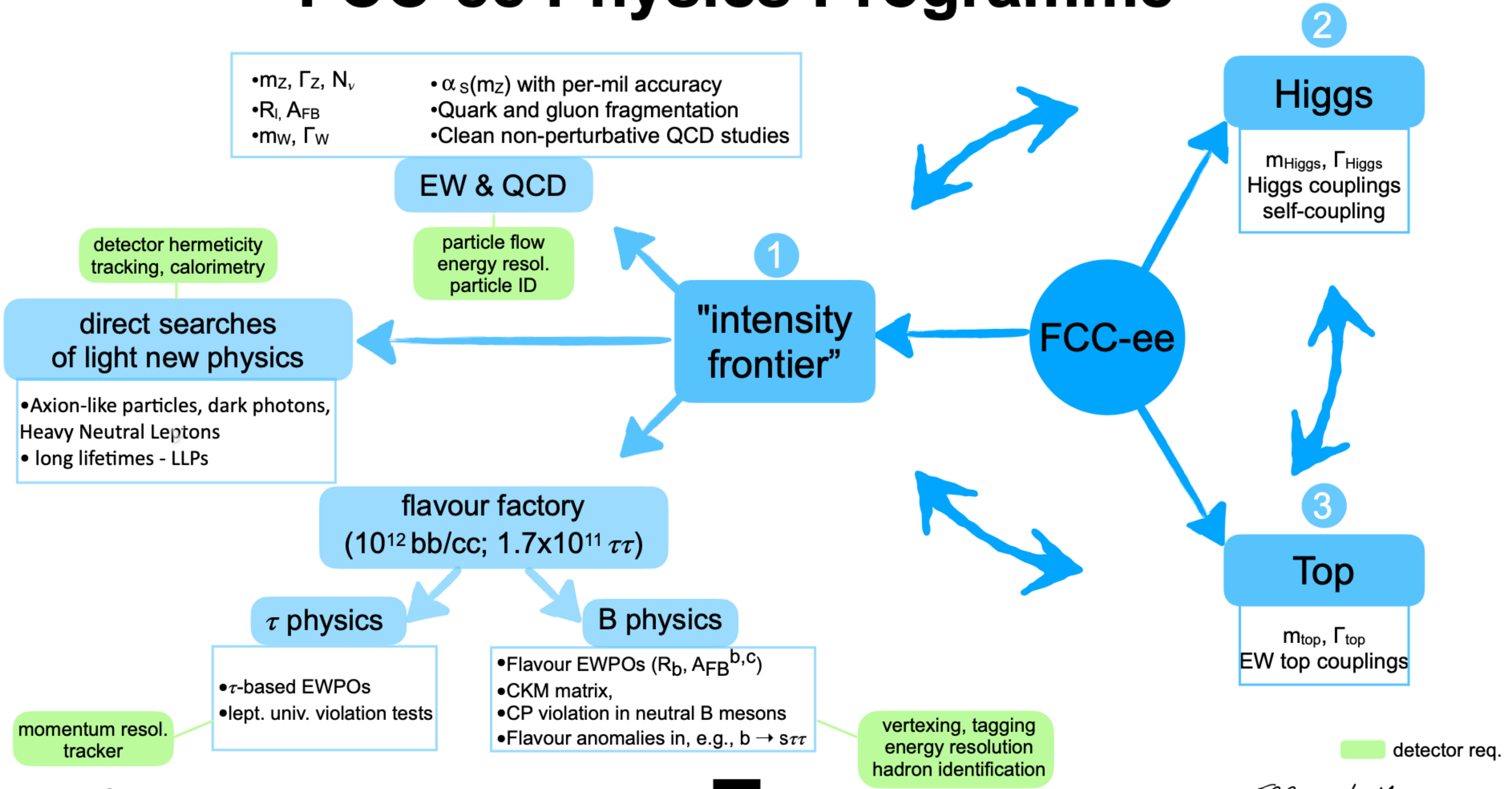
Dual-Readout Calorimeter:
R = 280-460 cm

Yoke + Muon chambers
R = 460-570 cm



Italian community strongly involved

FCC-ee Physics Programme



Higgs boson couplings at FCC-ee

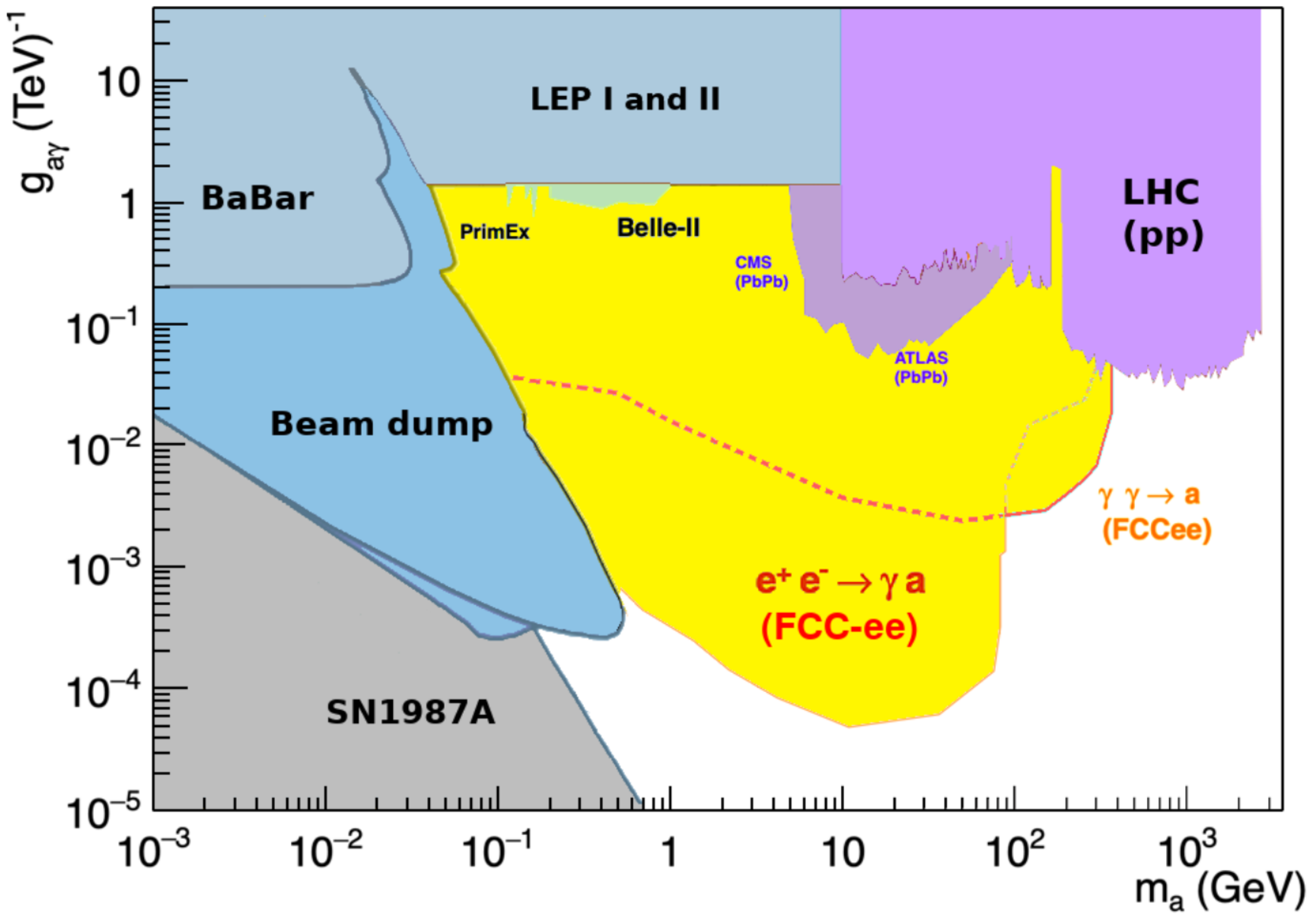
Coupling	HL-LHC	FCC-ee (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.43 / 0.33
κ_Z [%]	1.3*	0.17 / 0.14
κ_g [%]	2*	0.90 / 0.77
κ_γ [%]	1.6*	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10 / 10
κ_c [%]	–	1.3 / 1.1
κ_t [%]	3.2*	3.1 / 3.1
κ_b [%]	2.5*	0.64 / 0.56
κ_μ [%]	4.4*	3.9 / 3.7
κ_τ [%]	1.6*	0.66 / 0.55
$\mathrm{BR}_{\mathrm{inv}}$ (<%, 95% CL)	1.9*	0.20 / 0.15
$\mathrm{BR}_{\mathrm{unt}}$ (<%, 95% CL)	4*	1.0 / 0.88

Expected 68% CL relative precision (%) of the κ parameters at HL-LHC and FCC-ee (combined with HL-LHC).

- corresponding 95%CL upper limits on the untagged, BRunt, and invisible, BRinv, branching ratios are also given.
- HL-LHC case (*): $|\kappa_V|\leq 1$ imposed

- Take away conclusion:
  - Higgs couplings at HL-LHC: accuracy in the order of **few 10^{-2}**
  - Higgs couplings at FCC-ee: accuracy in the order of **~ 10^{-3} to 10^{-2}**
- Furthermore:
  - Higgs self-coupling g_{HHH} can be extracted with an accuracy of 33% (2 IPs) or 24% (4 IPs) studying quantum corrections to single Higgs couplings
  - Higgs boson mass measurement accuracy @ FCC-ee: **< 10 MeV**

Direct New Physics searches at FCC-ee: an example



Projected sensitivity (yellow area) for ALPs in the photon coupling versus ALP mass plane from e+e− → γa →3γ and photon-fusion γγ →a→2γ processes at FCC-ee

- Despite the LHC's exploration of energy scales up to *O*(1) TeV and beyond, FCC-ee can still probe **new physics through precision and rare processes**, enabling **direct searches** for weakly coupled particles
- An example is such as **axions** via their decays into photons (**a→γγ**), as well as other signatures that may have been challenging to detect in the high-background environment of hadron colliders
- In this case intensity (i.e. high luminosity particle colliders) is key.

Precision EW measurements

Observable	present value ± error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
σ_{had}^0 $(\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
$N_\nu(\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	radial alignment
τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**3**	small	from R_ℓ^W
$N_\nu(\times 10^3)$	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	$\pm$ 30%	**0.5 – 1.5 %**	small	From $\sqrt{s} = 365$ GeV run

- The whole FCC-ee run plan is essential (Z,W,top)
  - Important also to better study the Higgs sector
- Huge statistics → precision
  - Real chance to find SM failures → new physics beyond SM
- The reduction of experimental and theoretical systematic uncertainties will be a crucial challenge!
  - m_Z 2200 keV → 100 KeV
  - m_W 10 MeV → 0.3 MeV
  - m_{top} 200 MeV → < 17 MeV
  - Γ_Z 2300 keV → 25 keV
  - Γ_W 42 MeV → 0.3 MeV
  - $\sin^2\theta_W^{eff}$ $160 \cdot 10^{-6}$ → $25 \cdot 10^{-6}$

FUTURE CIRCULAR COLLIDER

FCC-hh main machine parameters

parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	81 - 115	14	
dipole field [T]	14 - 20	8.33	
circumference [km]	90.7	26.7	
arc length [km]	76.9	22.5	
beam current [A]	0.5	1.1	0.58
bunch intensity [10^{11}]	1	2.2	1.15
bunch spacing [ns]	25	25	
synchr. rad. power / ring [kW]	1020 - 4250	7.3	3.6
SR power / length [W/m/ap.]	13 - 54	0.33	0.17
long. emit. damping time [h]	0.77 – 0.26	12.9	
peak luminosity [10^{34} cm^{-2}s^{-1}]	~30	5 (lev.)	1
events/bunch crossing	~1000	132	27
stored energy/beam [GJ]	6.1 - 8.9	0.7	0.36
Integrated luminosity/main IP [fb^{-1}]	20000	3000	300

Baseline dipole field: 14 T
➔ $\sqrt{s}$ = 85 TeV

With FCC-hh after FCC-ee: significant amount of time for high-field magnet R&D, aiming at highest possible collision energies

- Target field range for cryo-magnet R&D

Formidable challenges:

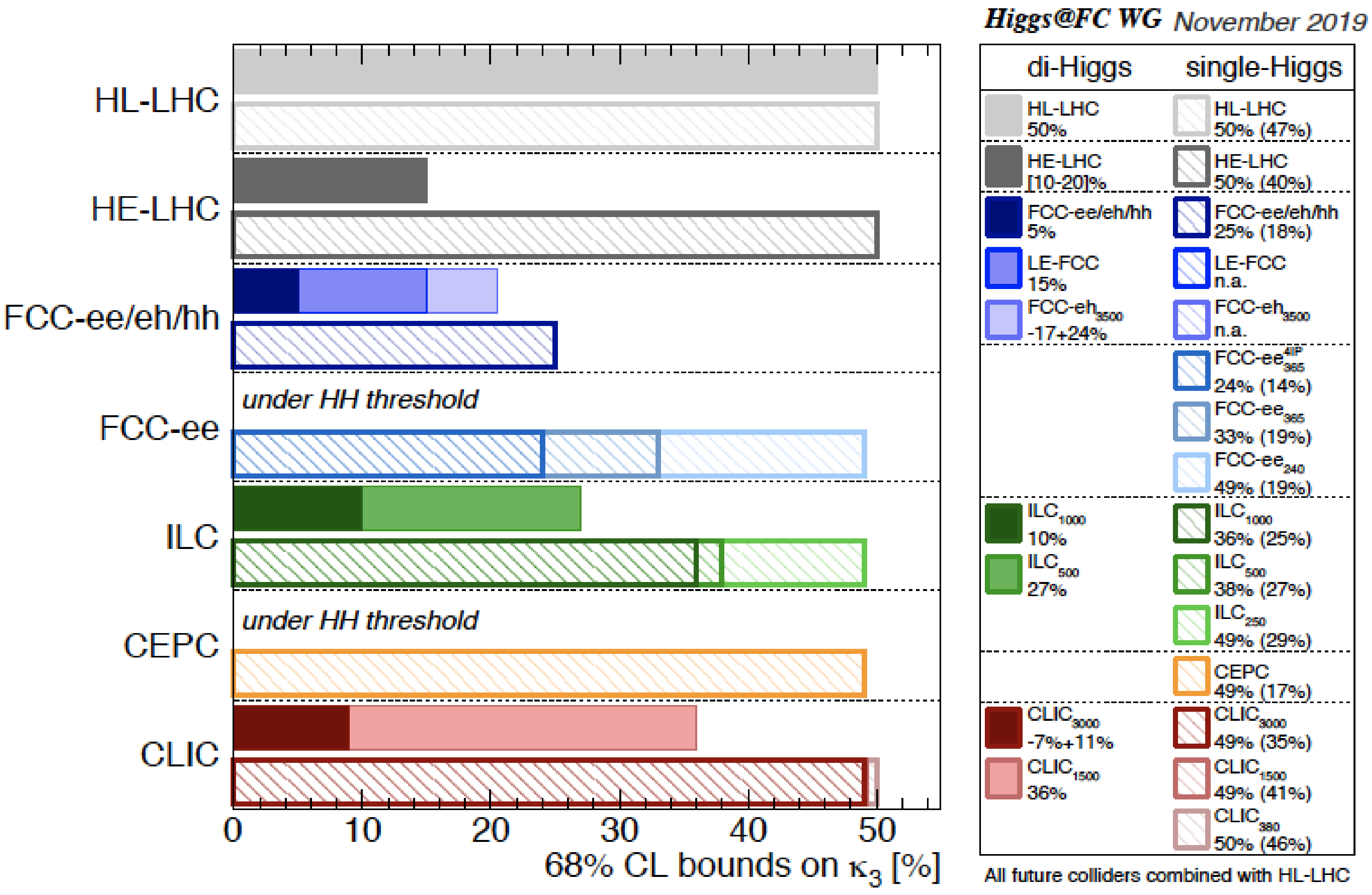
- ❑ high-field superconducting magnets: 14 - 20 T
- ❑ power load in arcs from synchrotron radiation: 4 MW → cryogenics, vacuum
- ❑ stored beam energy: ~ 9 GJ → machine protection
- ❑ pile-up in the detectors: ~1000 events/xing
- ❑ optimization of energy consumption: → R&D on cryo, HTS, beam current, …

Formidable physics reach, including:

- ❑ Direct discovery potential up to ~ 40 TeV
- ❑ Measurement of Higgs self to ~ 5% and ttH to ~ 1%
- ❑ High-precision and model-indep (with FCC-ee input) measurements of rare Higgs decays ($\gamma\gamma$, Zγ, μμ)
- ❑ Final word about WIMP dark matter

F. Gianotti

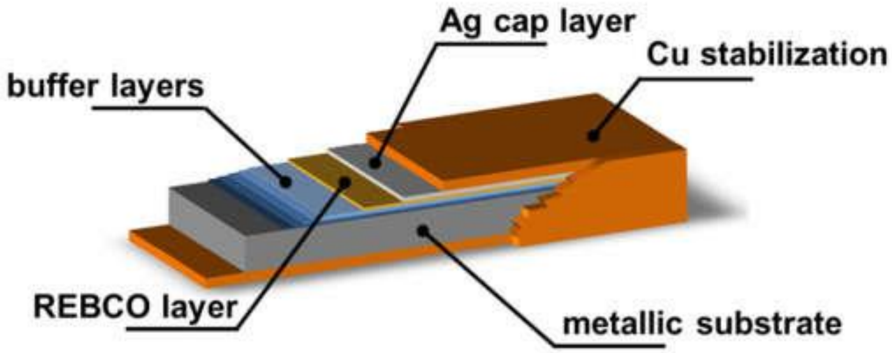
FCC-hh: Higgs boson self-coupling



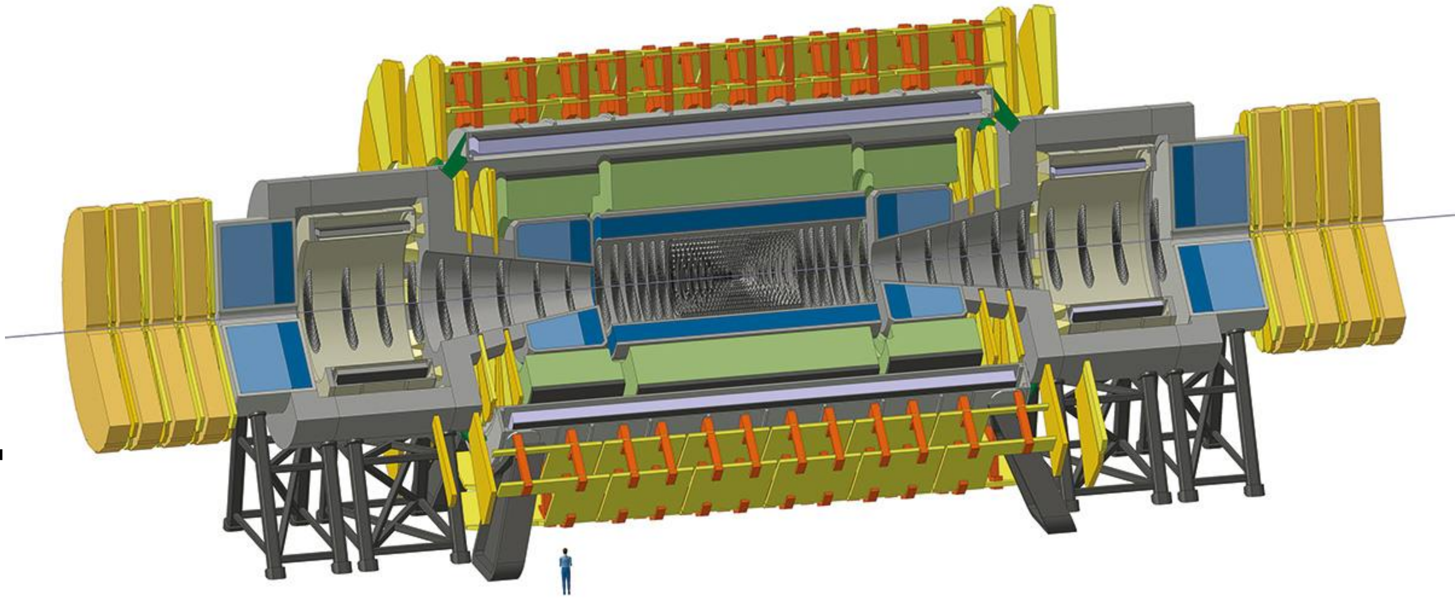
FCC integrated is expected to measure the Higgs selfcoupling with an accuracy of a very few %!

The main challenges for FCC-hh

- The accelerator: High-field Magnets
  - LHC dipole field: 8.33 T (technology: NbTi)
- Two avenues:
  - **Nb_3Sn**: operational field: 14 T (~4 K?)
  - **High-Temperature Superconducting magnets** (HTS; example REBCO): ~ 20 T (~ 20 K)



- The Detector, Trigger, DAQ, offline computing….:



main FCC-hh Detector challenges:

- **Radiation hardness**
- **Large rapidity coverage**
- **High-granularity**
- **4D detection**
- **….**

Alternatives to electron-positron circular colliders

- Because their small mass, electrons loose energy when experiencing large acceleration

e is the elementary charge (1.602×10^{-19} C)
m is the electron mass ($9.1093837 \times 10^{-31}$ kg)
c is the speed of light (3.00×10^{8} m/s)
ε_0 is the vacuum permittivity (8.854×10^{-12} F/m)
R is the radius of curvature of the orbit, in m.

- Larmor formula: $\boldsymbol{P = \frac{e^2 c}{6\pi\varepsilon_0 R^2}\left(\frac{E}{mc^2}\right)^4}$

- If we set the beam Energy E, the synchrotron energy power dissipation per electron depends only by the radius of the orbit R
- The only way to limit the synchrotron energy loss of electron beams of circular colliders is to build large R accelerators
  - **if we put FCC-ee the electron/positron beam parameters, we get 50 MW power per beam**
  - **an FCC twice smaller would imply a synchrotron radiation power loss of 200 MW per beam!!**
- For many years, we considered only one alternative: **linear colliders**
  - these offer beam polarisation as well
- Now the community proposes to accelerate and collide muon beams at the place of electron beams ➔ the **Muon Collider**

Muon Collider

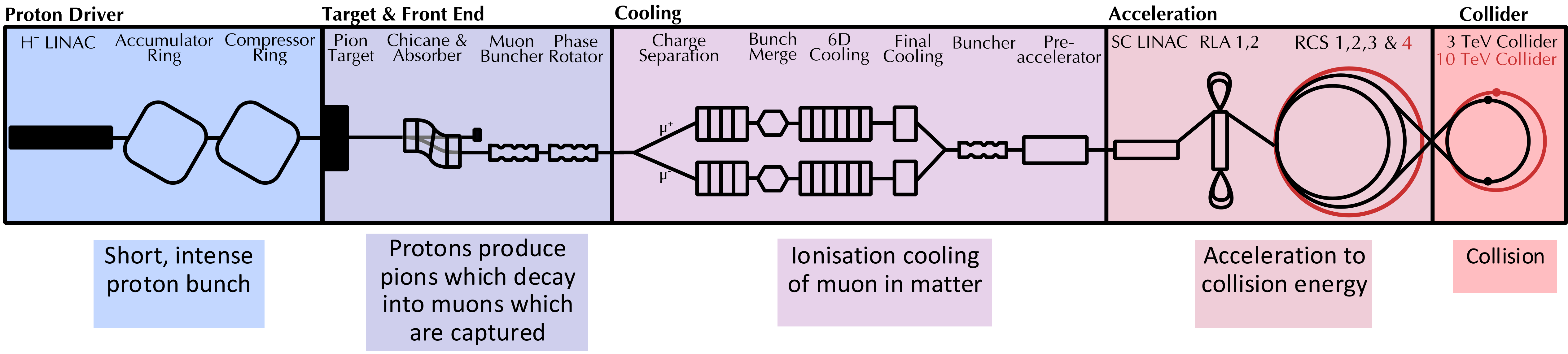
- **This is a revolutionary idea!!**
- But several challenges are ahead of us, due to two basic facts:

1. **Muons are produced with large emittance**
   - Here I assume hadron production of muons, as opposed to lepton production
2. **Muons are unstable: τ_μ = 2.2 μs**
   - They decays most of the time in electrons and neutrinos $\mu^\pm \rightarrow e^\pm \, \nu_\mu \, \nu_e$

- This means that ➔

1. We need to **cool muon beams** before they collide
2. The sequence injection → cooling → acceleration → collision **must occur in a very short time! (fraction of a second!)**: **$\tau_\mu^{lab} = \tau_\mu \cdot \gamma$ = 0.1 s for E_μ=5 TeV**
   - **Equivalent time @ LEP: 2 – 3 hours** (electron/positron beams)
   - **Equivalent time @ LHC: 20 – 30 minutes** (proton beams)
   - Only a small fraction of muons "survives" till the acceleration phase (O(1-10%))

Muon Collider Overview



Key Challenges

Environmental impact
- Neutrino flux mitigation
- Power, cost, CO_2, …

Other technologies are instrumental for performance, cost, power consumption and risk mitigation
- Accelerator physics, cryogenics, superconducting cavities, ….

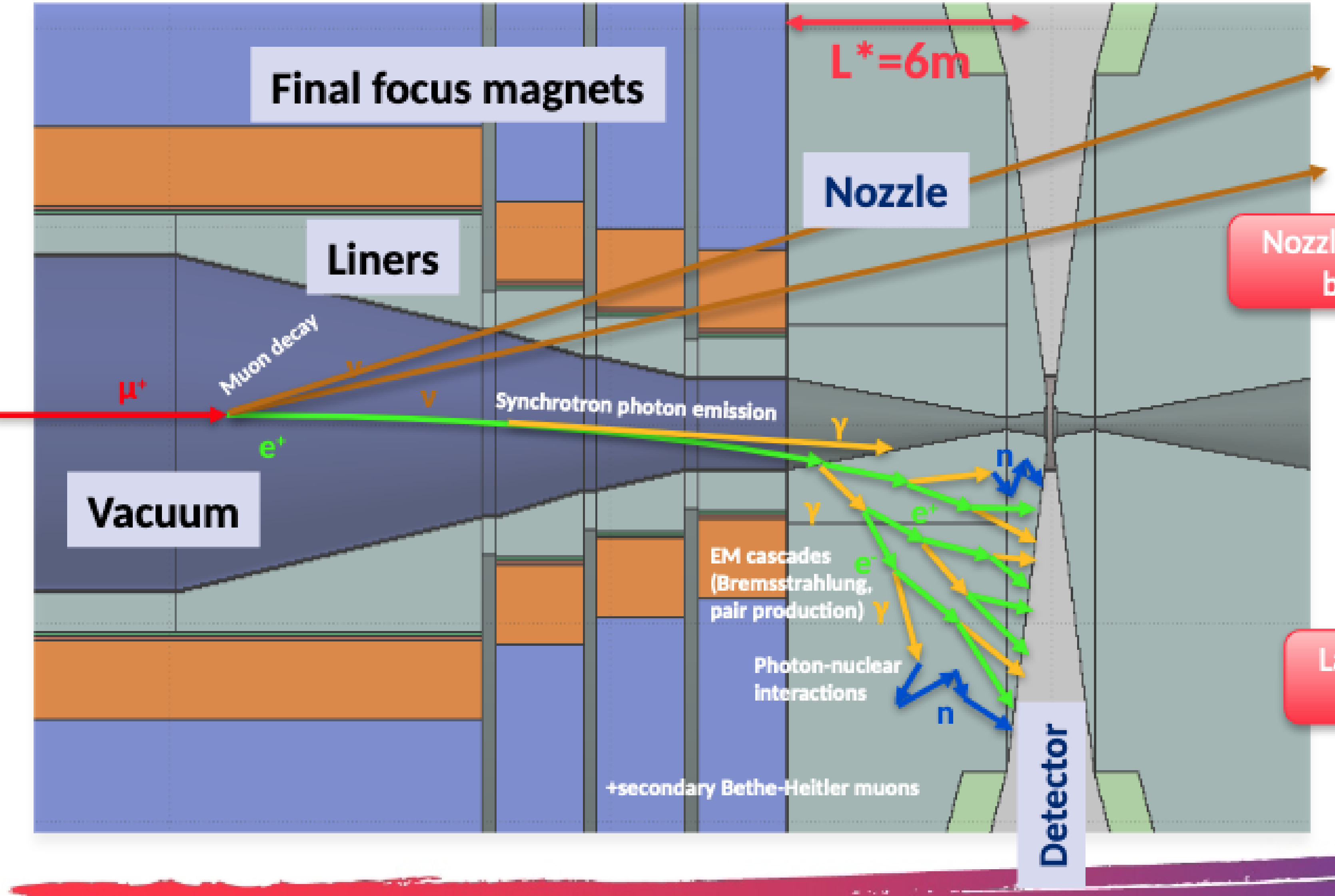
Beam-induced background Decay of stored muons around the collider ring is the dominant source.
Pair creation through the collision of two real or virtual photons emittedby muons of counter-rotating bunches

Key technologies for timeline
- **Magnet technology**
- **Muon cooling technology**
- **Detector**

Other important timeline considerations are
- Civil engineering
- Decision making

Cost and **power** consumption limit energy reach
e.g. 35 km accelerator for 10 TeV, 10 km collider ring
Also impacts **beam quality**

Anatomy of decay-induced background



Nozzle shape and material: Determines spectra, entry positions and directions of secondaries entering detector

Nozzle → Background reduction by orders of magnitude

Lattice and beam aperture: Determine how many decay products are lost near the IP*, but little influence on secondary spectra and entry positions in detector

Lattice → Background reduction by a factor of a few

* Decay products lost on the inside of nozzle are the most relevant for background

by Davide Zuliani

Muon Collider Detector

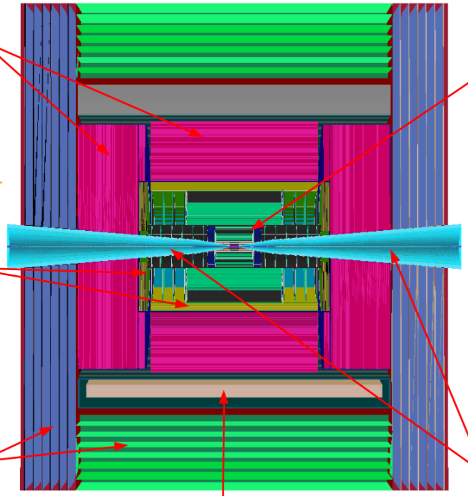
Detector concept at $\sqrt{S} = 3$ TeV was adapted from the CLICdet

Strong Italian contribution

hadronic calorimeter
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

electromagnetic calorimeter
- 40 layers of 1.9-mm W absorber + silicon pad sensors;
- 5x5 mm^2 cell granularity;
- 22 X_0 + 1 λ_I.

muon detectors
- 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- 30x30 mm^2 cell size.

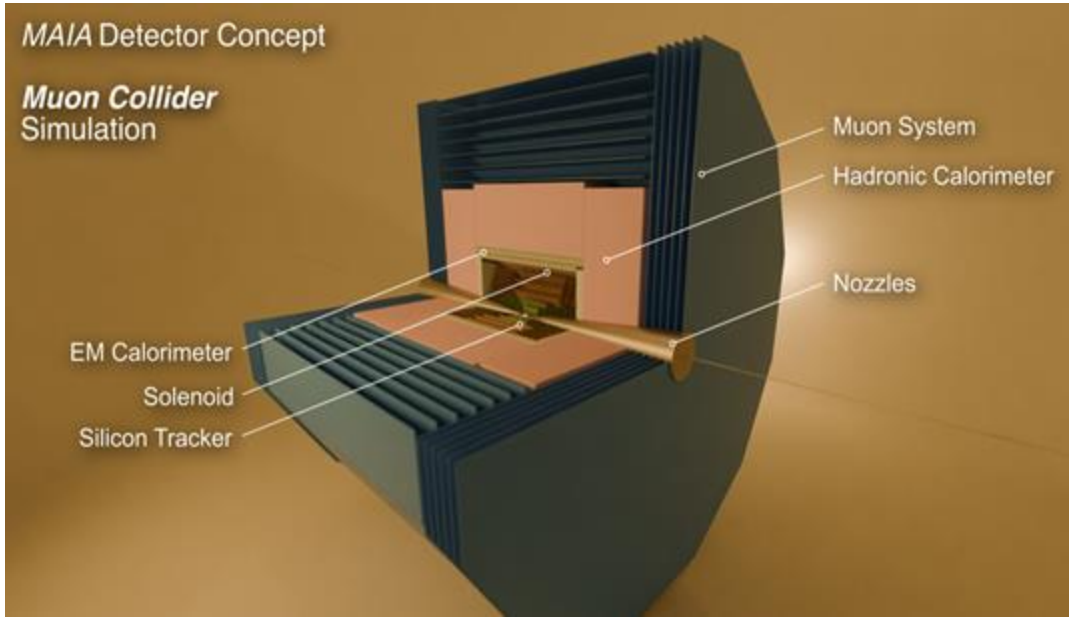


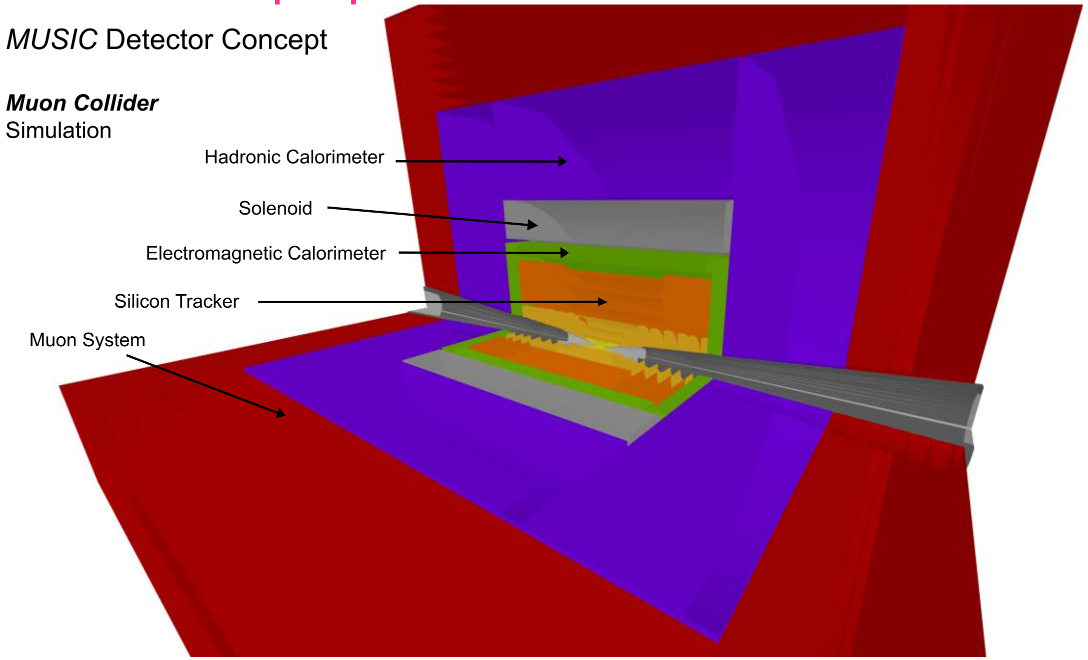
superconducting solenoid (3.57T)

tracking system
- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 μm^2 pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 μm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 μm x 10 mm micro-strip Si sensors.

shielding nozzles
- Tungsten cones + borated polyethylene cladding.

At $\sqrt{S} = 10$ TeV two different detectors are proposed

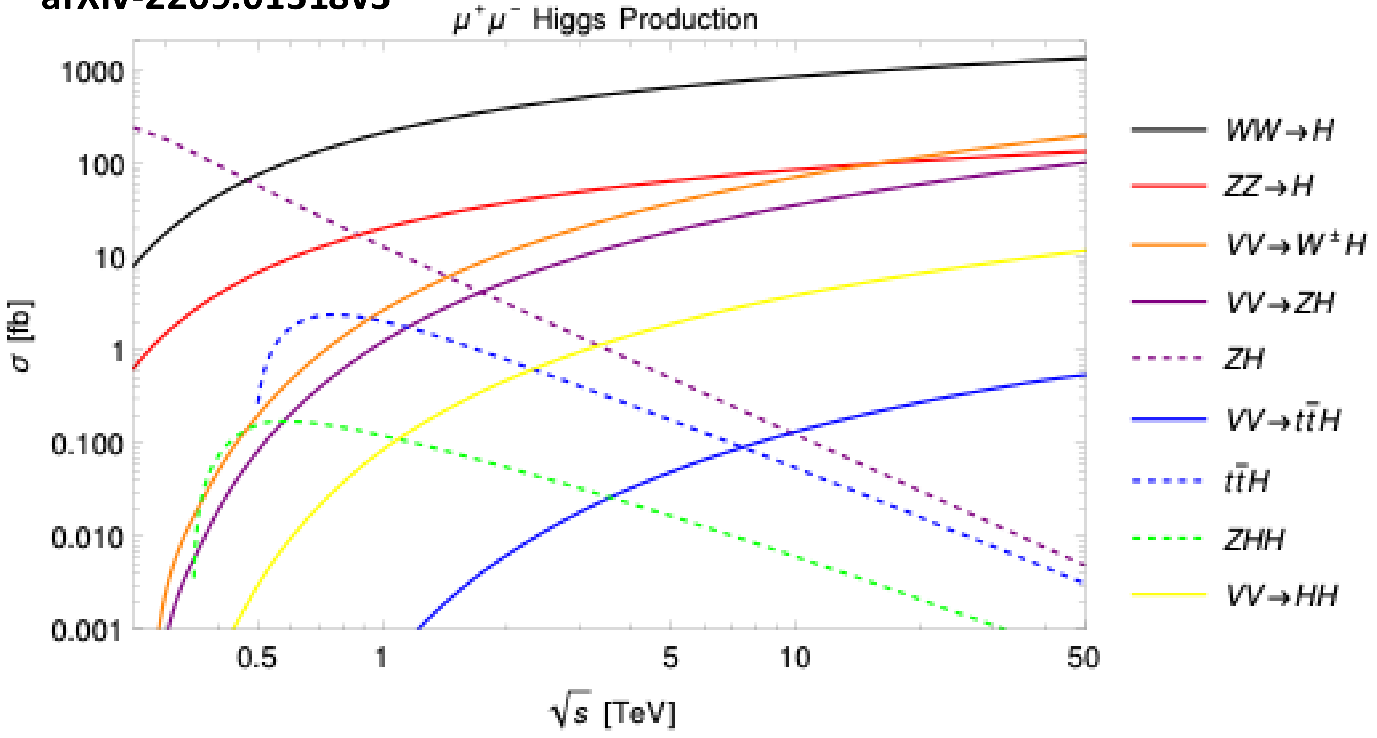




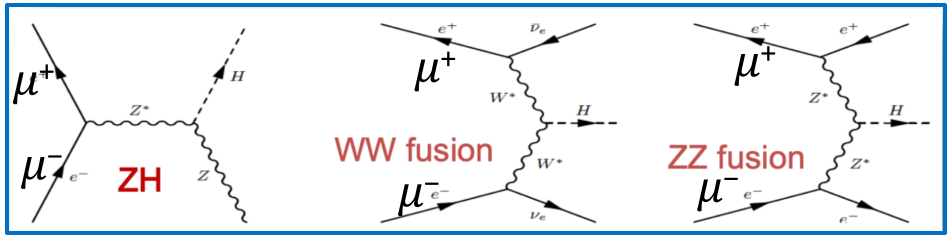
Physics at the Muon Collider – Higgs sector

The Muon Collider allows lepton collisions (in this case $\mu^+\mu^-$) at energies much larger than those produced by circular e^+e^- colliders

arXiv-2209.01318v3



Cross sections for the most important single and double Higgs production modes as a function of energy. Here ZH and ttH are s-channel production while the others are Vector Boson Fusion produced in association with any of ($\nu_\mu \nu_\mu$, $\nu_\mu\ \mu^\pm$, $\mu^+\mu^-$).



multi-TeV muon collider is a W^+W^- collider!

	cross section [fb]		expected events	
	3 TeV	10 TeV	1 ab^{-1} at 3 TeV	10 ab^{-1} at 10 TeV
H	550	930	5.5×10^5	9.3×10^6
ZH	11	35	1.1×10^4	3.5×10^5
$t\bar{t}H$	0.42	0.14	420	1.4×10^3
HH	0.95	3.8	950	3.8×10^4
HHH	3.0×10^{-4}	4.2×10^{-3}	0.30	42

multi-TeV muon collisions produce significant number of single, double and triple Higgs bosons

➔ High-precision Higgs mesaurements including highly accurate Higgs self-coupling studies of HH and HHH production

Muon collider options

Parameter	Unit	Higgs Factory	3 TeV	10 TeV
COM Beam Energy	TeV	0.126	3	10
Collider Ring Circumference	km	0.3	4.5	10
Interaction Regions		1	2	2
Est. Integ. Luminosity	$ab^{-}1$/year	0.002	0.4	4
Peak Luminosity	10^{34} cm^{-2} s^{-1}	0.01	1.8	20
Repetition rate	Hz	15	5	5
Time between collisions	μs	1	15	33
Bunch length, rms	mm	63	5	1.5
IP beam size σ^*, rms	μm	75	3	0.9
Emittance (trans), rms	mm-mrad	200	25	25
β function at IP	cm	1.7	0.5	0.15
RF Frequency	MHz	325/1300	325/1300	325/1300
Bunches per beam		1	1	1
Plug power	MW	~ 200	~ 230	~ 300
Muons per bunch	10^{12}	4	2.2	1.8
Average field in ring	T	4.4	7	10.5

Table 1. A summary of parameters for the primary muon collider options considered by the Forum.

Higgs measurements @ the Muon Collider

https://arxiv.org/abs/2203.07256

	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
$\kappa_{Z\gamma}$	10	7.2	7.1
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
κ_t^*	3.3	3.1	3.1

* No input used for μ collider

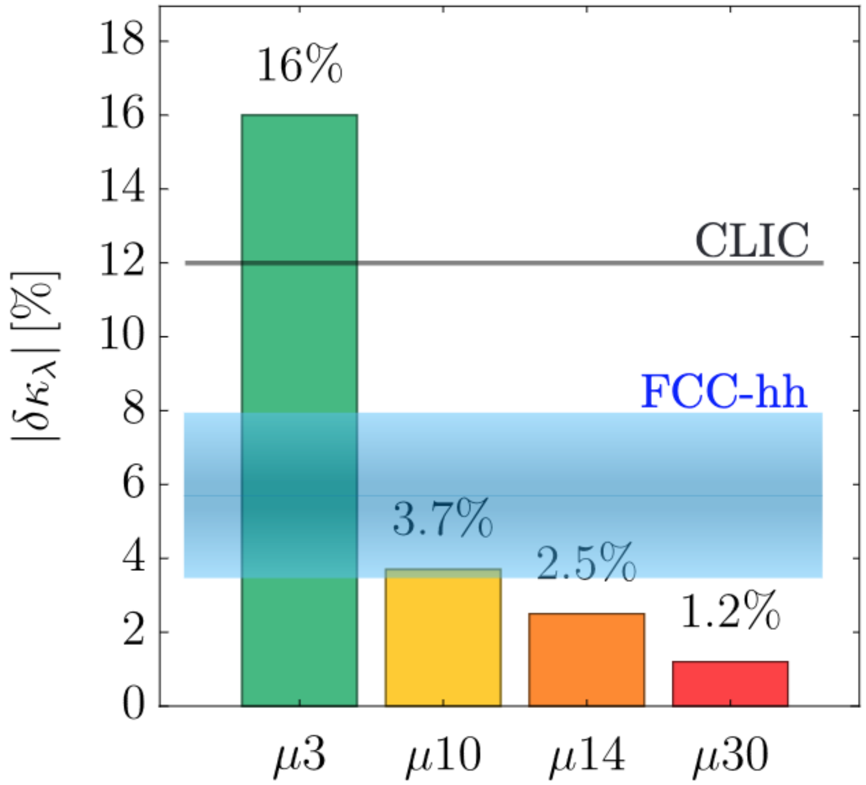


Fig. 5: Left panel: 1σ sensitivities (in %) from a 10-parameter fit in the κ-framework at a 10 TeV muon collider with 10 ab^{-1} [18], compared with HL-LHC. The effect of measurements from a 250 GeV e^+e^- Higgs factory is also reported. Right panel: sensitivity to $\delta\kappa_\lambda$ for different $E_{\rm cm}$. The luminosity is as in eq. (1) for all energies, apart from $E_{\rm cm} = 3$ TeV, where doubled luminosity (of 1.8 ab^{-1}) is assumed [18].

European Strategy for Particle Physics

- The **European Strategy for Particle Physics** is a comprehensive framework **coordinated by CERN Council** to set the **priorities and future directions for particle physics research in Europe**. It aims to guide scientific, technological, and financial decisions in particle physics, in Europe, but not only: it impacts on a global scale due to the international collaboration and to the impact of CERN/Europe on the fundamental research worldwide.
- This process, typically carried out every 7-8 years, is **based on an extensive consultations with the scientific community, stakeholders, and relevant institutions** to ensure that the strategy reflects the latest scientific and technological advancements and addresses emerging challenges.

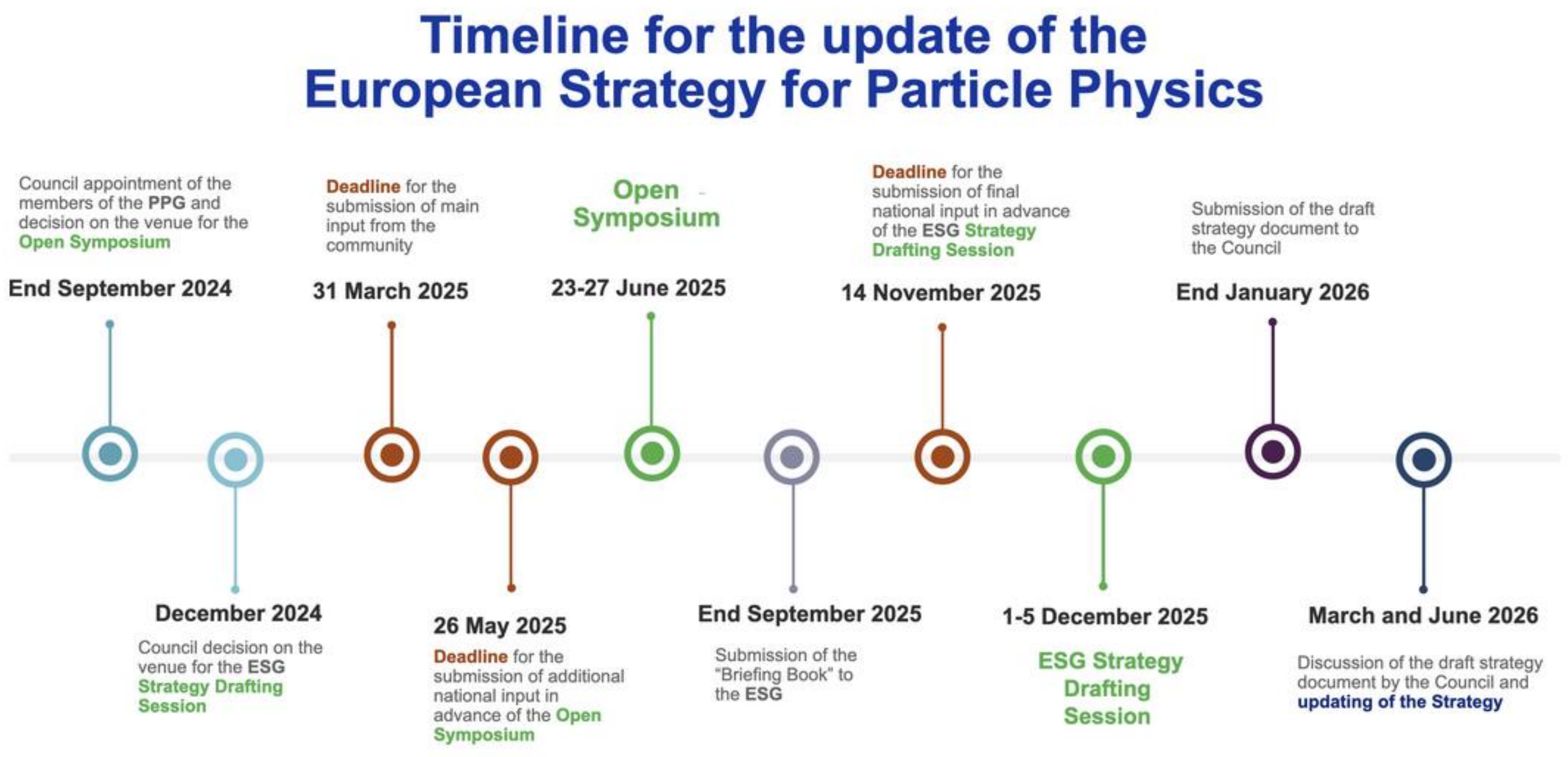
European Strategy Update

The update process and its timeline

2024: year of preparation, establishments of committees, choice of locations for the various meetings

2025: submission of scientific inputs, Open Symposium, drafting of the strategic document

2026 discussion at Council and Strategy update *(in 2027/2028 Council decides…)*



Strategy Secretariat: organising and running the ESPP process

Strategy Secretary (K. Jakobs.)
Paris Sphicas (ECFA Chair)
Hugh Montgomery (SPC Chair)
Dave Newbold (LDG Chair)

European Strategy Group (ESG): Prepares the Strategy Document

Physics Preparatory Group (PPG): collects input from the community, organises the Open Symposium,
prepares the Briefing Book

Inputs from the community will be reviewed by **ESG**: careful and rigorous study of the documentation provided, i.e of the Briefing Book drafted by **PPG** with support of the **Strategy Secretariat**

Open Symposium 23-27 June 2025 - Lido di Venezia ! I do hope to see you there …..

The update pro

2024: year of preparation, estab

2025: submission of scientific in

2026 discussion at Council and

European Strategy Update

Input to the European Strategy for Particle Physics - 2026 update

click here: https://indico.cern.ch/event/1439855/contributions/

September 1, 2024 to April 1, 2025
Europe/Zurich timezone

Enter your search term

- Overview
- Guidelines
- Submit input
- Submitted Input

Submitted Input

263 / 263 Enter #id or search string

273. 2026 EPPSU input from the ANUBIS Collaboration
It is imperative for us as a particle physics community to fully exploit the physics potential of the High-Luminosity LHC. This calls for us not to leave any stone unturned in the search for Beyond the Standard Model (BSM) physics.

255. A Flexible Strategy for the Future of Particle Physics at CERN
This document outlines a strategy to ensure CERN remains at the forefront of particle physics by addressing the most pressing questions of our field in a timely and effective manner. The strategy balances ambition with feasibility—

133. A High-Precision, Fast, Robust, and Cost-Effective Muon Detector Concept for the FCC-ee
We propose a high-precision, fast, robust and cost-effective muon detector concept for an FCC-ee experiment. This design combines precision drift tubes with fast plastic scintillator strips to enable both spatial and timing measurements.

140. A Linear Collider Vision for the Future of Particle Physics
In this paper we review the physics opportunities at linear ee colliders with a special focus on high centre-of-mass energies and beam polarisation, take a fresh look at the various accelerator technologies available or under development

165. A Possible Future Use of the LHC Tunnel
The FCC program at CERN provides an attractive all-in-one solution to address many of the key questions in particle physics. While we fully support the efforts towards this ambitious path, we believe that it is important to prepare a

215. A roadmap for astroparticle theory in Europe
Important and challenging questions remain unanswered about the fundamental constituents of Nature, their interactions, and the evolution of the Universe and its extreme environments. Astroparticle physics, lying at the interface

77. A Silicon-Tungsten ECAL for Higgs Factory Detectors
A highly granular electromagnetic calorimeter, based on silicon sensors associated with tungsten absorbers (SiW-ECAL), is proposed for the Higgs-Factory detectors, based on Particle Flow approach such as the ILD, the SiD, the CEPC baseline, or

271. A Spin-Based Pathway to Testing the Quantum Nature of Gravity
A key open problem in physics is the correct way to combine gravity (described by general relativity) with everything else (described by quantum mechanics). This problem suggests that one or both of these cherished theories may need

tegy Secretariat: anising and running ESPP process

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Inputs from the community provided, i.e of the Briefing Book drafted by
Open Symposium 23-27 Jun

Conclusions

- **The Standard Model's success - t**he Higgs boson discovery in 2012 confirmed the Standard Model's robustness. It successfully describes the results produced in laboratories
  - High-precision studies at the LHC continue validating its predictions.
  - The Higgs sector is "new physics" – never seen a fundamental scalar so far….
- But **the Standard Model is not the final theory**: hierarchy problem, Dark Matter, neutrino masses and their oscillations, and matter-antimatter asymmetry remain unexplained. ➔Need for new physics and possible extensions beyond this theory.
- **Future of High-Energy Physics**
  - **High-Luminosity LHC** will refine precision measurements and explore rare processes.
  - Future colliders aim to push energy frontiers and uncover new physics.
  - **FCC-integrated is the best future project to explore new areas in HE**P
  - It is of paramount importance to study revolutionary ideas, e.g. the Muon Collider
- **The European Strategy for Particle Physics guides priorities**
  - International efforts and technological advancements are key to the next breakthroughs
  - INFN is playing a very important role in the international scenario
- **Fundamental physics stands at a crucial moment - exciting results, and possible discoveries, lie ahead!**

Conclusions

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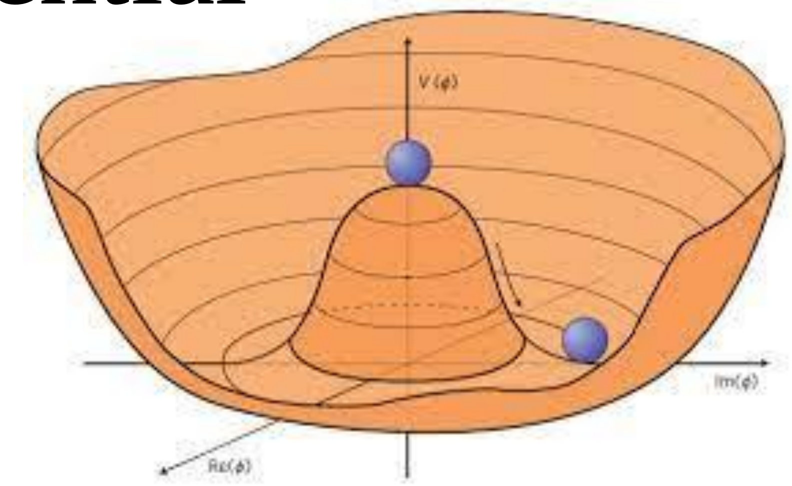
backup

The Higgs Potential

$$\mathcal{L} = T - V = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \left(\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4\right)$$



in SM, this potential is fully defined by two parameters, that can be inferred by the v.e.v. v and the Higgs boson mass m_h

Expanding around the minimum, $\phi = v + h$:

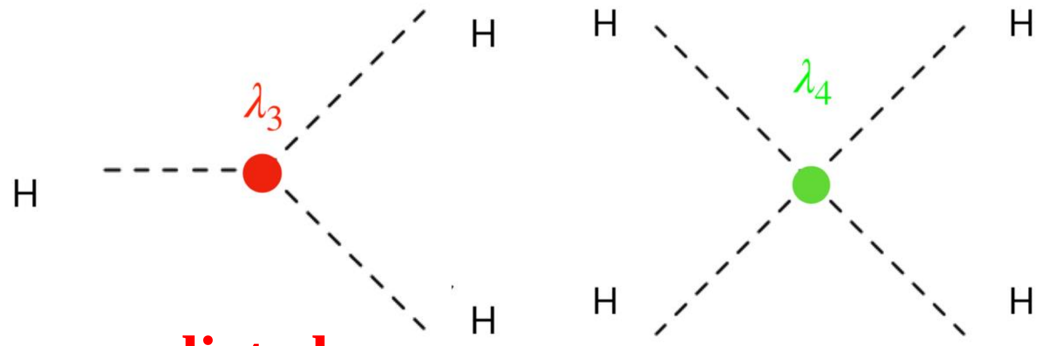
$$V(h) = \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 = \frac{1}{2}m_h{}^2 h^2 + \lambda_3 h^3 + \lambda_4 h^4$$

mass term | **Higgs triple coupling** | **Higgs quartic coupling**

$$m_h{}^2 = 2\lambda v^2 \qquad \lambda_3 = \lambda v = m_h{}^2/2v$$

$$\lambda_4 = \lambda/4 = mh^2/8v^2$$

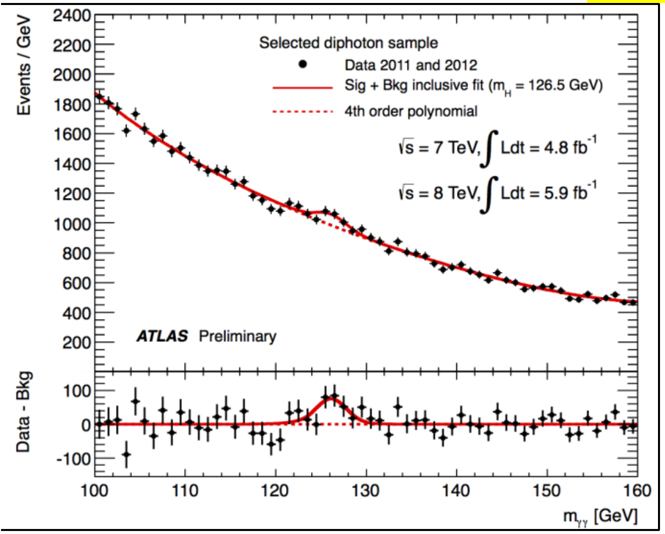
Higgs boson pair (HH) production allows to probe *directly* the Higgs boson self-interaction and, ultimately, the shape of the Higgs potential.

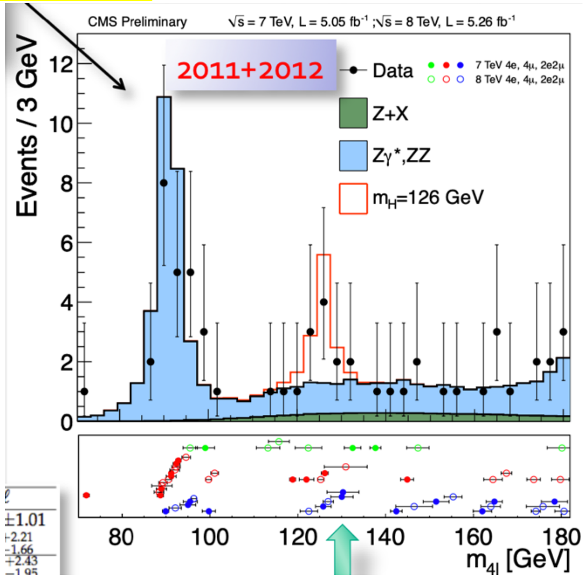


➔Any deviation from the self-interaction predicted by the SM would be a sign of new physics!

The discovery of the 125 GeV Higgs boson

4 July 2012

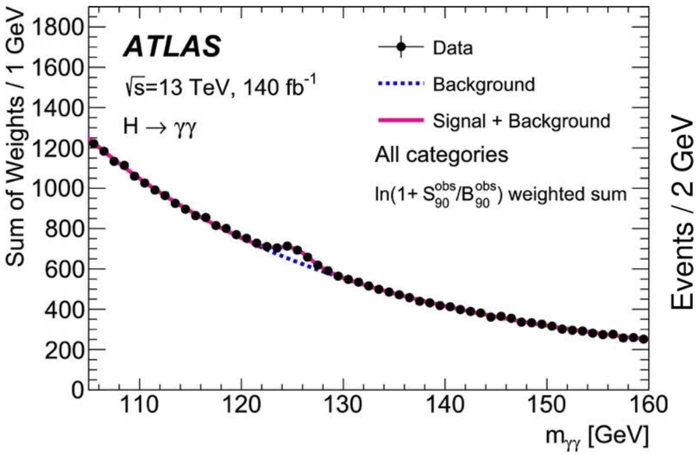


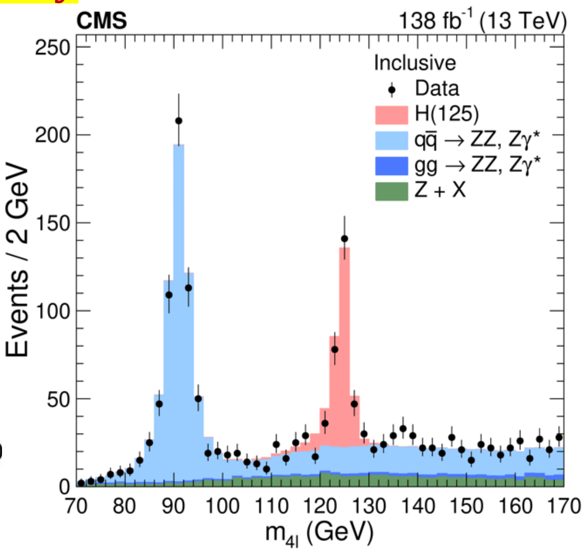


H→γγ

today

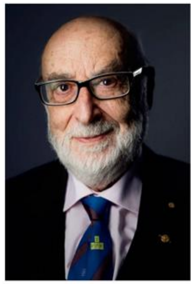
H→ZZ*→4-lepton





- Summer 2011 EPS and Lepton-Photon: Still focused on limits.
- December 2011 CERN Seminar by ATLAS and CMS: first hints.
- **Summer 2012 CERN Council and ICHEP in Melbourne: Discovery!**
- **December 2012 CERN Council: Beginning of a new era!**

Nobel Prize in Physics 2013



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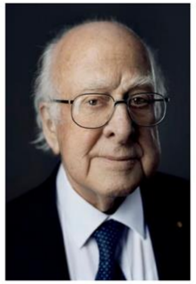
François Englert



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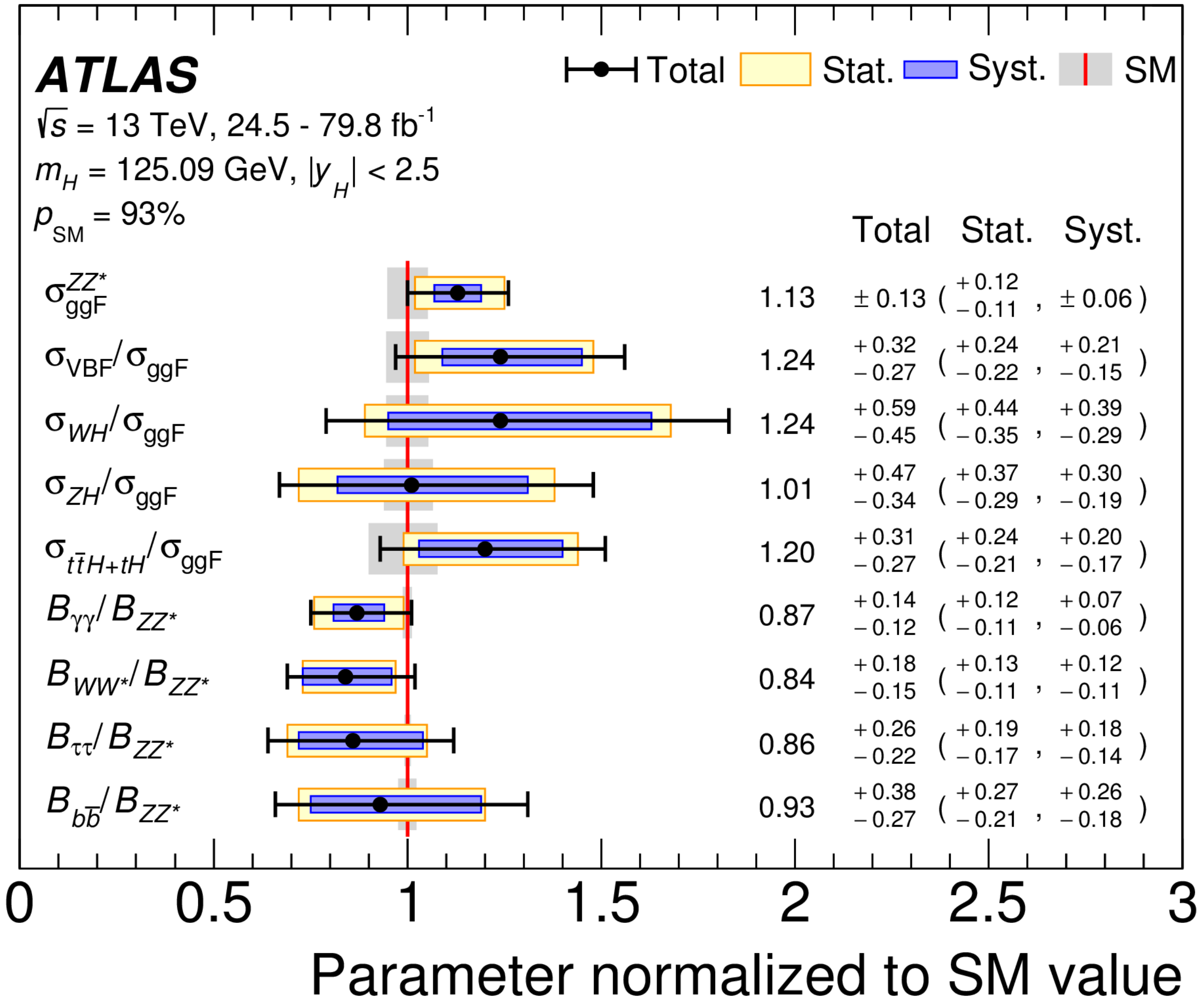
Peter W. Higgs

The Higgs boson - 1



Results of a simultaneous fit for σ_{ggF}^{ZZ}, $\sigma_{VBF}/\sigma_{ggF}$, σ_{WH}/σ_{ggF}, σ_{ZH}/σ_{ggF}, $\sigma_{ttH+tH}/\sigma_{ggF}$, $B_{\gamma\gamma}/B_{ZZ}$, B_{WW}/B_{ZZ}, $B_{\tau\tau}/B_{ZZ}$, and B_{bb}/B_{ZZ}. The fit results are normalized to the SM predictions.

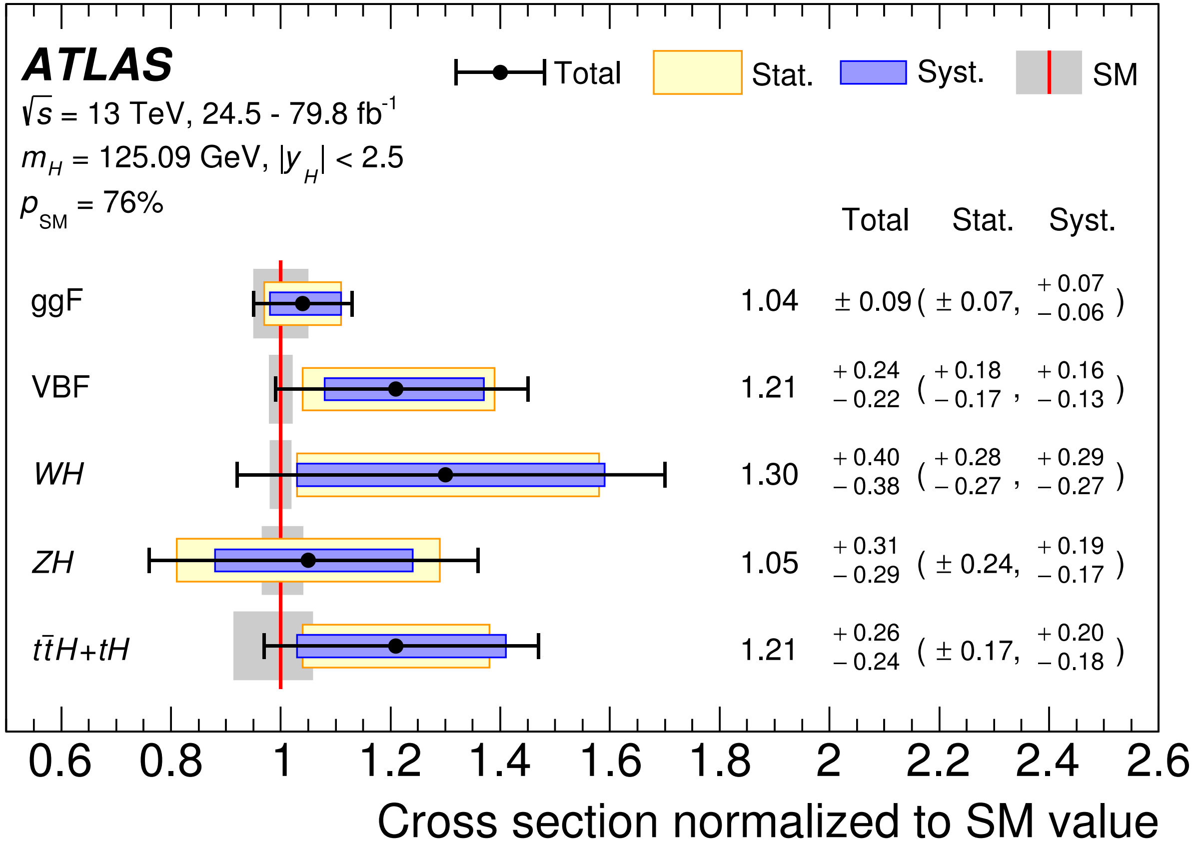
The black error bars, blue boxes and yellow boxes show the total, systematic, and statistical uncertainties in the measurements, respectively. The grey bands show the theory uncertainties in the predictions.

These measurements are *model INDEPENDENT* results:

At LHC is not possible to make a model independent extraction of the Higgs boson naturall width Γ_H

the Higgs boson - 2

Phys. Rev. D 101, 012002 (2020)

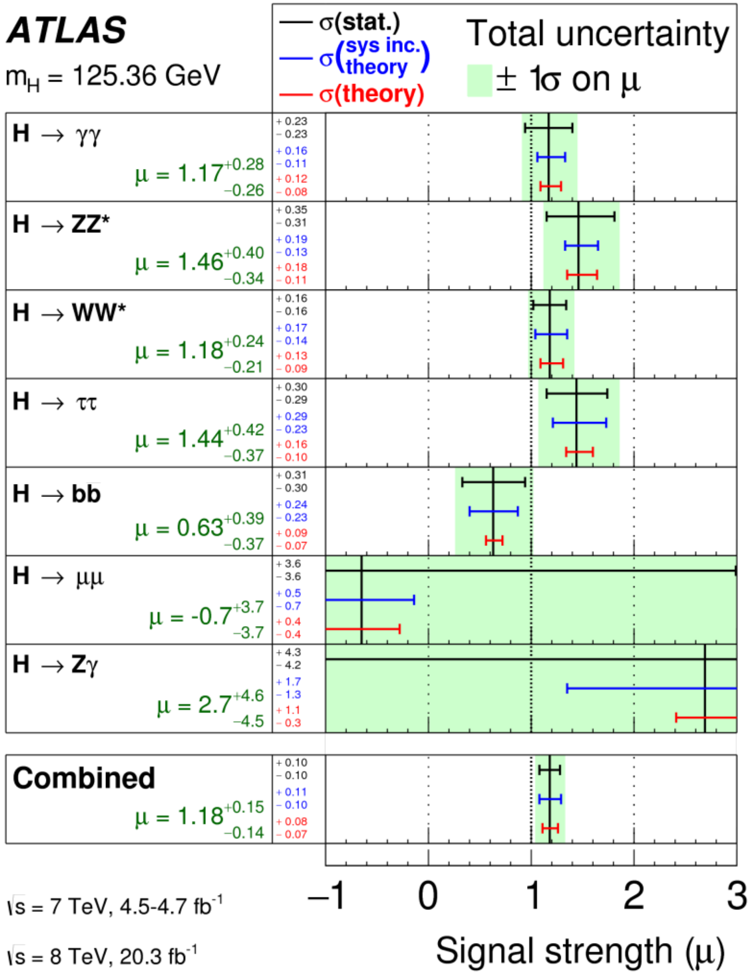


Cross-sections for ggF, VBF, WH, ZH and tt̄H+tH normalized to their SM predictions, measured with the assumption of SM branching fractions.

Signal strength

$\mu = \sigma_{meas} / \sigma_{SM}$

Eur. Phys. J. C (2016) 76:6



The observed signal strengths and uncertainties for different Higgs boson decay channels and their combination for m_H=125.36 GeV, with the assumption of SM of cross-section ratios of different production processes.

Higgs boson signals corresponding to the same decay channel are combined together for all analyses

The Higgs couplings

Assumption:

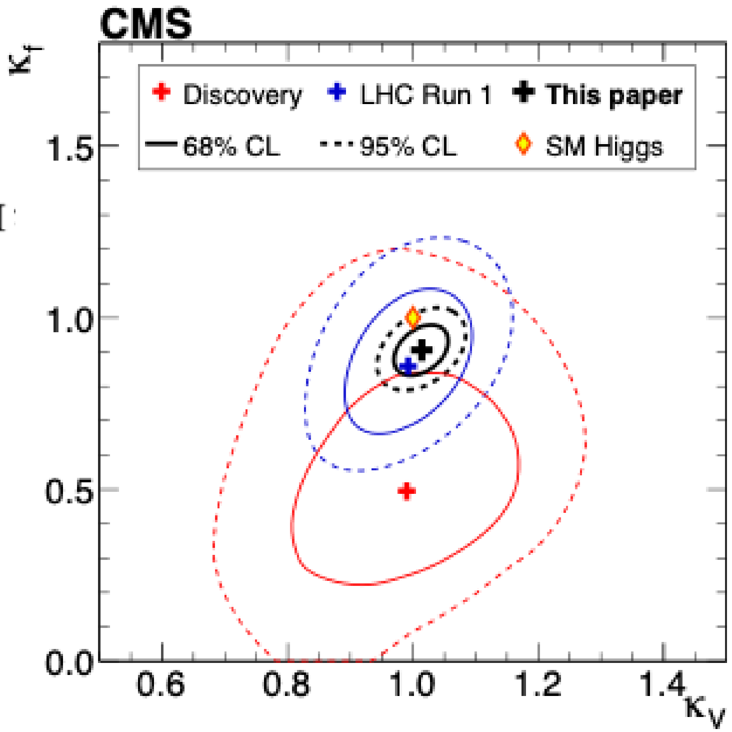
$\kappa_V \leq 1$

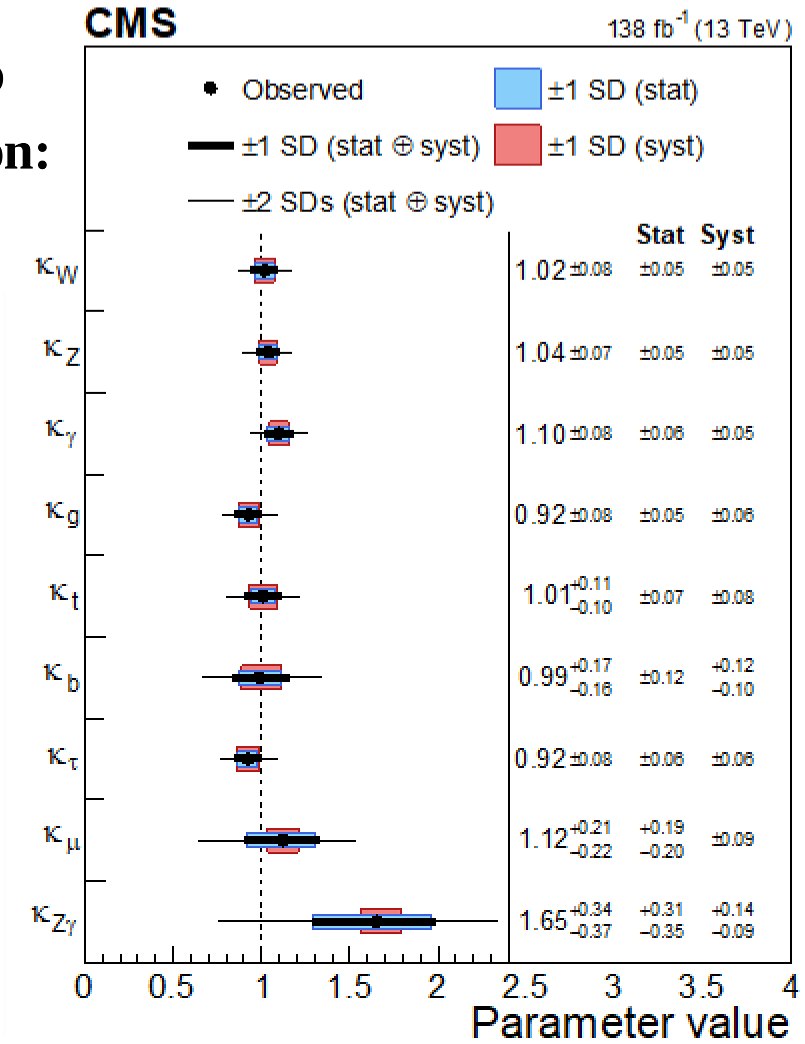
coupling modifiers

$$\kappa_j^2 = \sigma_j/\sigma_j^{\mathrm{SM}} \quad \text{or} \quad \kappa_j^2 = \Gamma^j/\Gamma^j_{\mathrm{SM}}$$

Production **Decay**

SM: $\kappa_i = 1$ (for all i values)





Nature doi 10.1038/s41586-022-04892-x

Constraints on the Higgs boson coupling modifiers to fermions (κ_f) and heavy gauge bosons (κ_V), in different data sets discovery (red), the full LHC Run 1 (blue), and the data presented here (black).

The SM prediction corresponds to $\kappa_V = \kappa_f = 1$ (diamond marker).

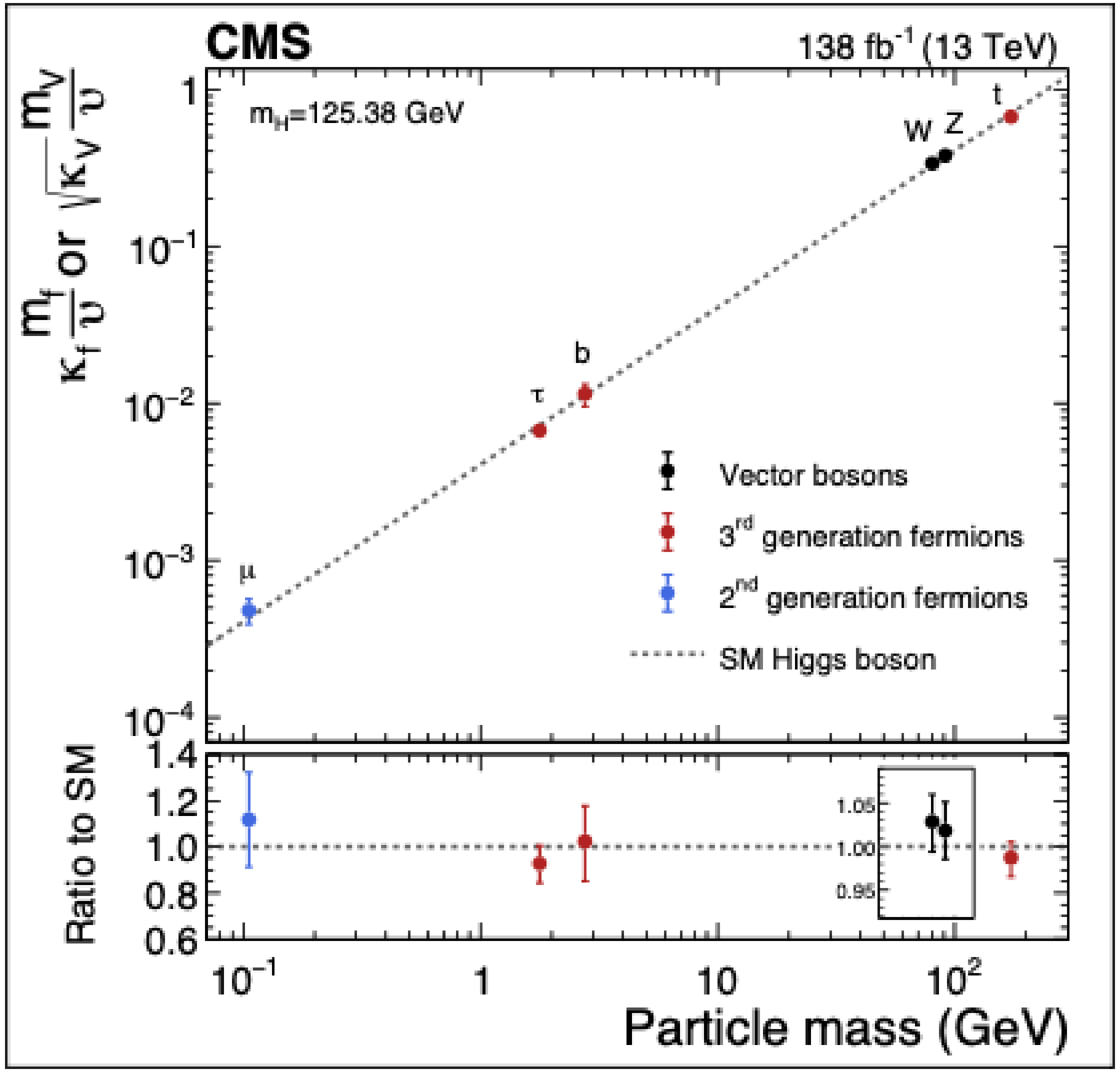
uncertainty of 10%, with the predictions from the SM

Coupling modifiers probed at a level of uncertainty of 10% - except for

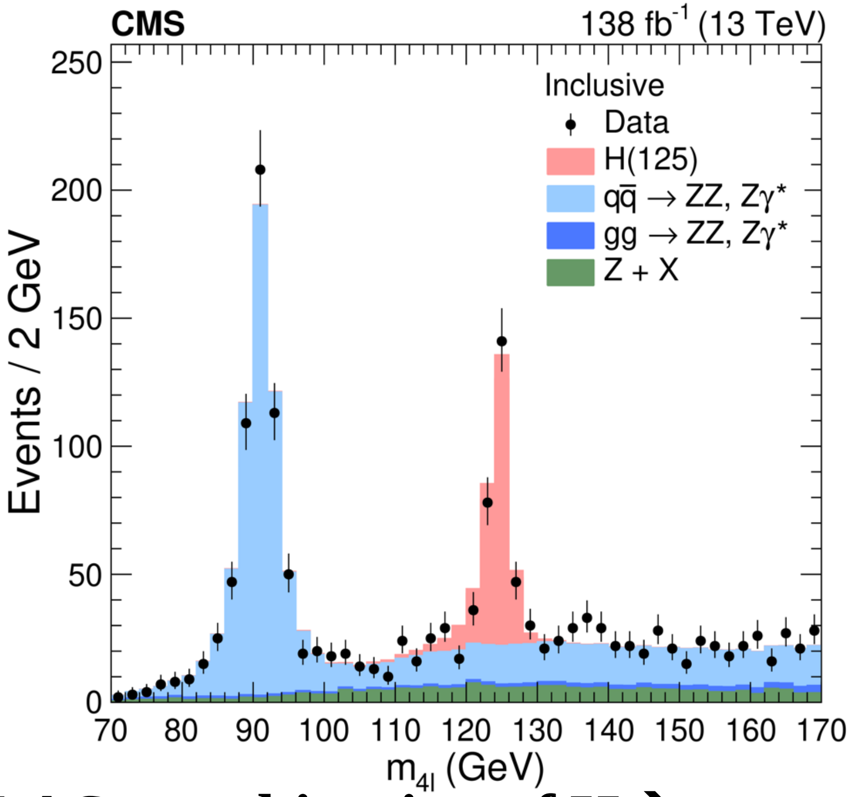
- **κ_b and κ_μ: ≈20%**
- **$\kappa_{Z\gamma}$: ≈40%**

Similar results are obtained by ATLAS

The Higgs couplings and the Higgs boson mass



The measured coupling modifiers of the Higgs boson to fermions and heavy gauge bosons, as functions of fermion or gauge boson mass, υ is the vacuum expectation value of the BEH field



ATLAS: combination of H→$\gamma\gamma$ and 4-lepton final states:

m_H = 125.22 ± 0.11 (stat.) ± 0.09 (syst.) GeV

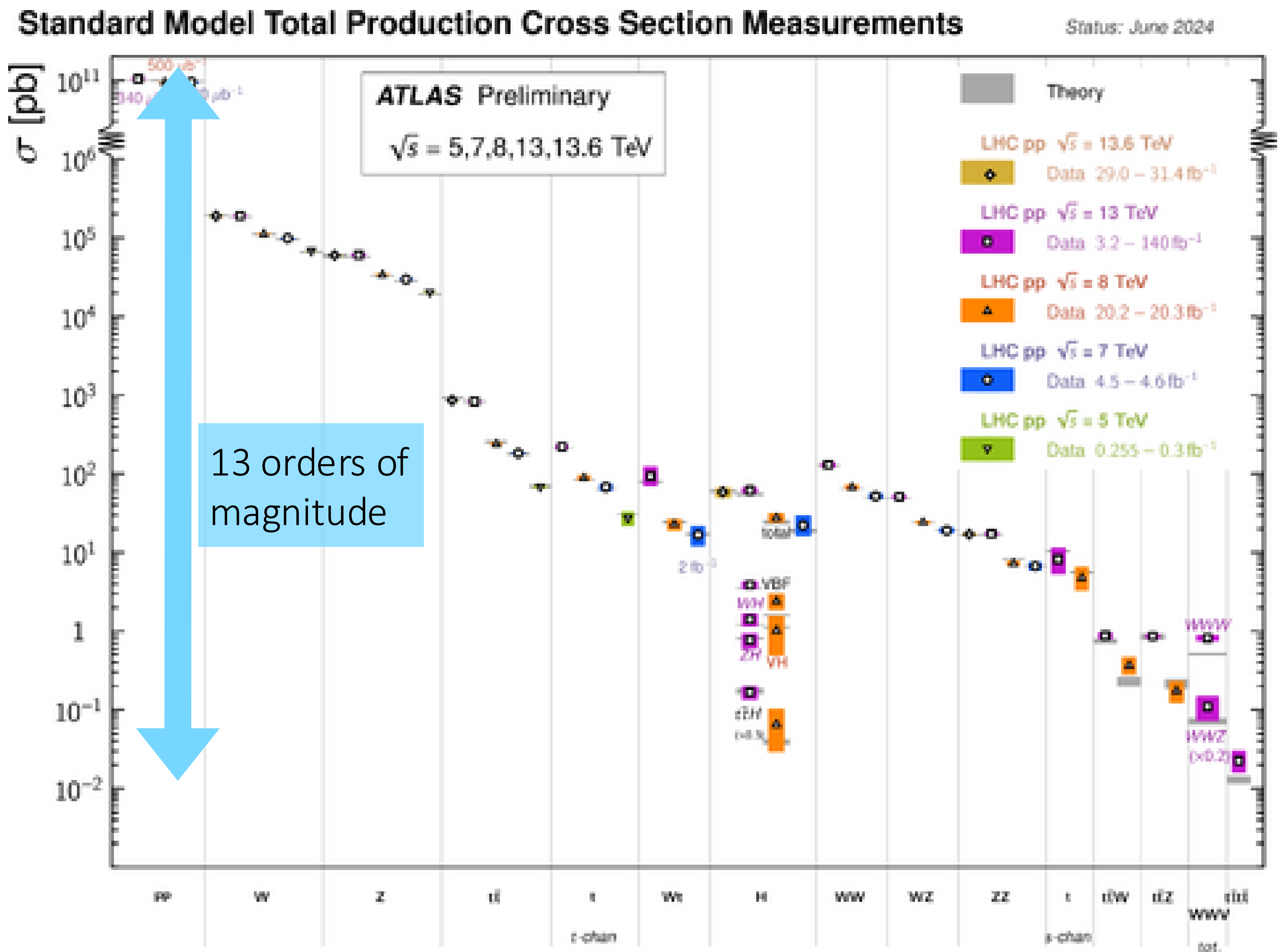
CMS: H→4-lepton final states

m_H = 125.04 ± 0.12 GeV

the triumph of the Standard Model

- A lot of experiments have conducted to the established of the Standard Model, from the experiment proving the existence in nature of the electron (Thomson, 1897), the discovery of the atomic nucleus structure (Rutherford, 1911), the discovery of the J/ψ (BNL, SLAC, 1974), to the discovery of W and Z bosons, validating electroweak unification (CERN 1983), the discovery of the top quark (FNAL 1995), till the Higgs boson discovery at CERN in 2012.
- The Large Hadron Collider (LHC) is conducting an in-depth examination of the Standard Model of particle physics through a plethora of high-precision measurements.
- These efforts not only validate the theory in known regimes but also seek potential deviations that could hint at new physics beyond the Standard Model.

Standard Model precision studies at the LHC

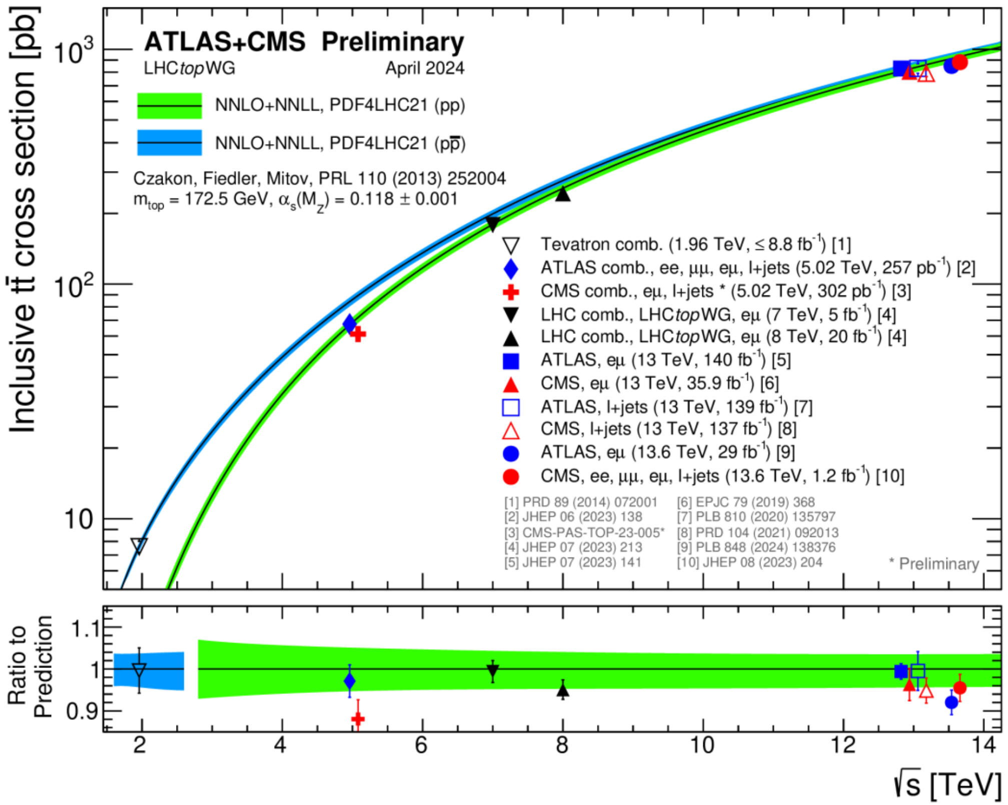


Standard Model cross-section measurements.

- The measurements are corrected for branching fractions, compared to the corresponding theoretical expectations.
- Similar results from CMS

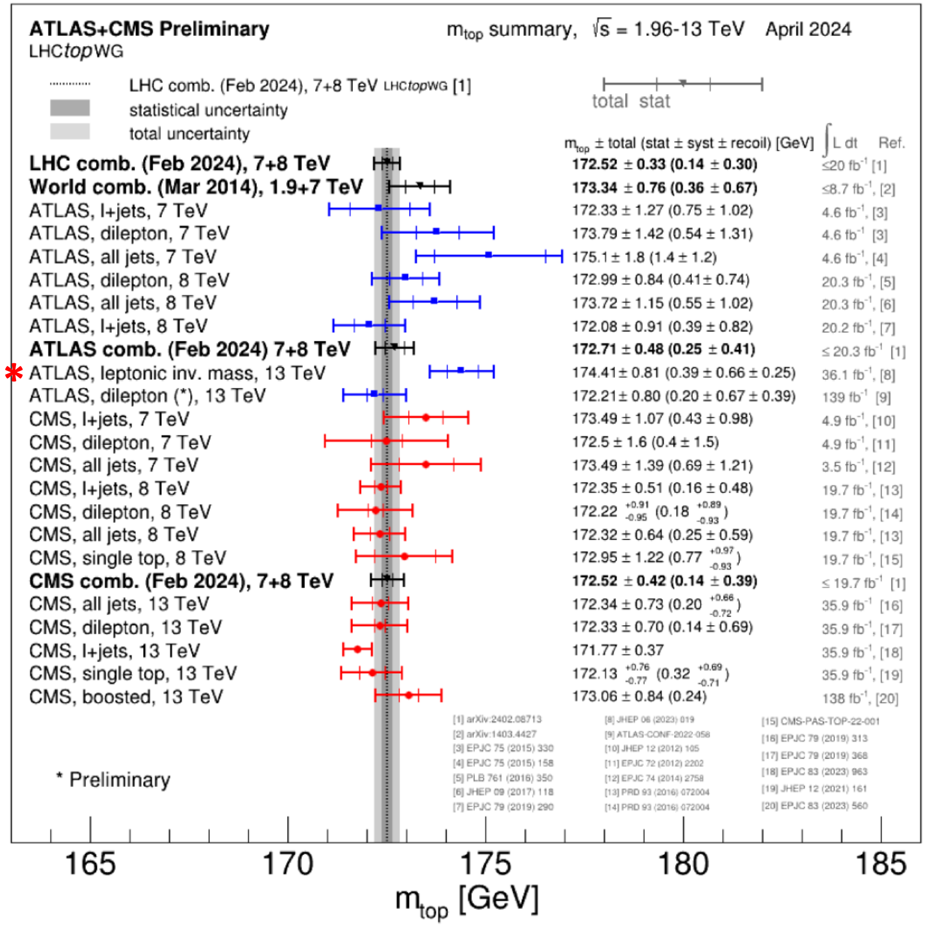
Top quark physics at LHC

ttbar inclusive production cross-section



Summary of LHC and Tevatron measurements of the top-pair production cross-section as a function of the centre-of-mass energy compared to the NNLO QCD calculation complemented with NNLL resummation (top++2.0).

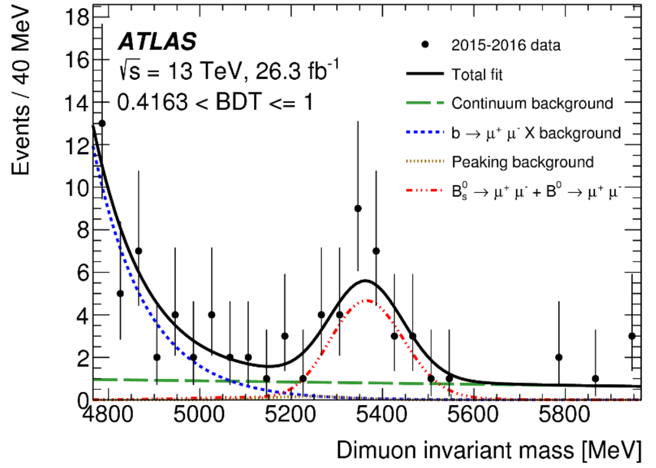
top quark mass mesurement

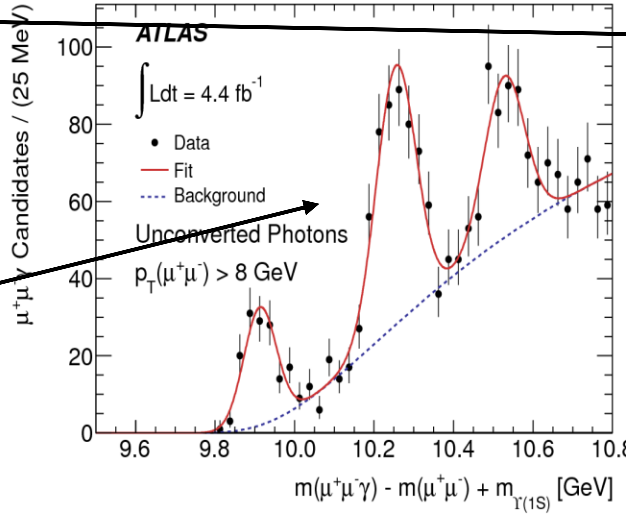


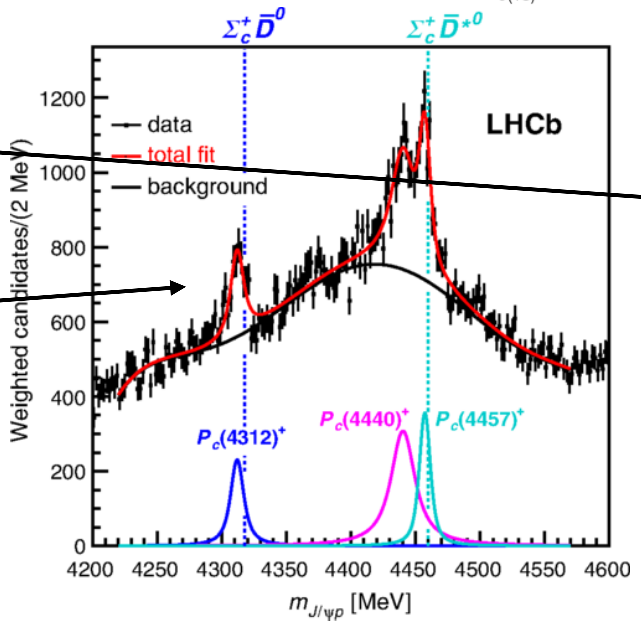
Summary of the ATLAS and CMS measurements from top quark decay. The results are compared with the LHC and Tevatron+LHC m_{top} combinations.

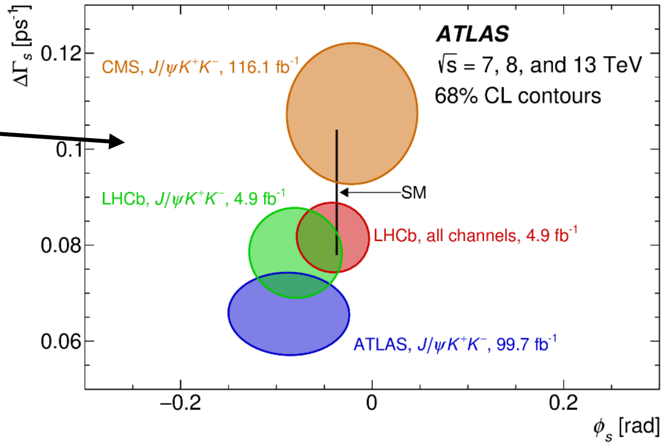
B-Physics

- Measurement of the Branching Fraction of the rare decays (~ 10^{-9}) $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$
- Discovery of a new particle (the first one at LHC): the $\chi_b(3P) \to \Upsilon(1S,2s)\gamma$ (ATLAS)
- Measurement of CP violation weak phase ϕ_s in the $B_s^0 \to J/\psi\phi \to \mu^+\mu^- K^+K^-$ decay channel
- Evidence of pentaquark and tetraquark states (LHCb)
- CP-violation in oscillation of D^0 mesons (LHCb)



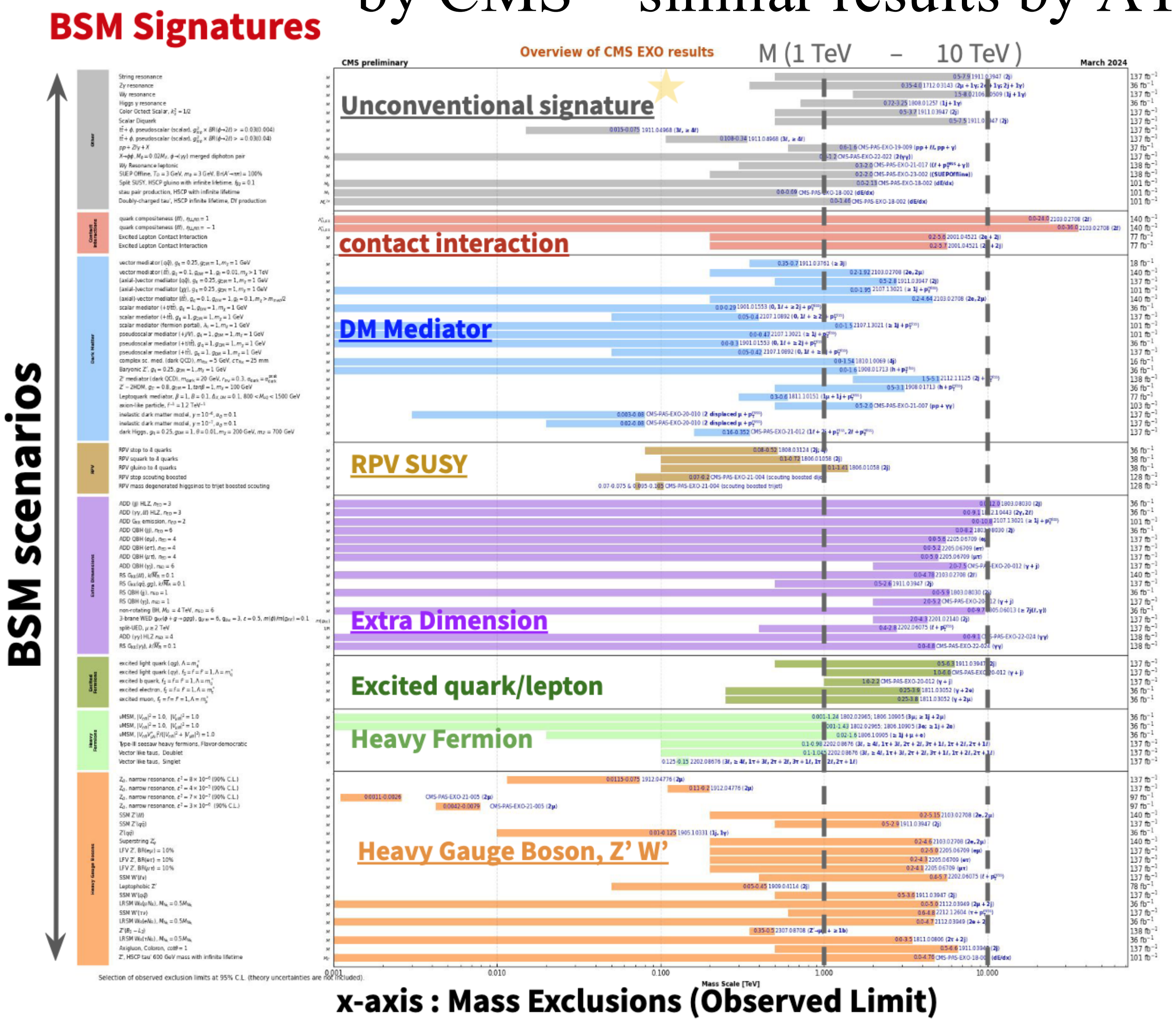


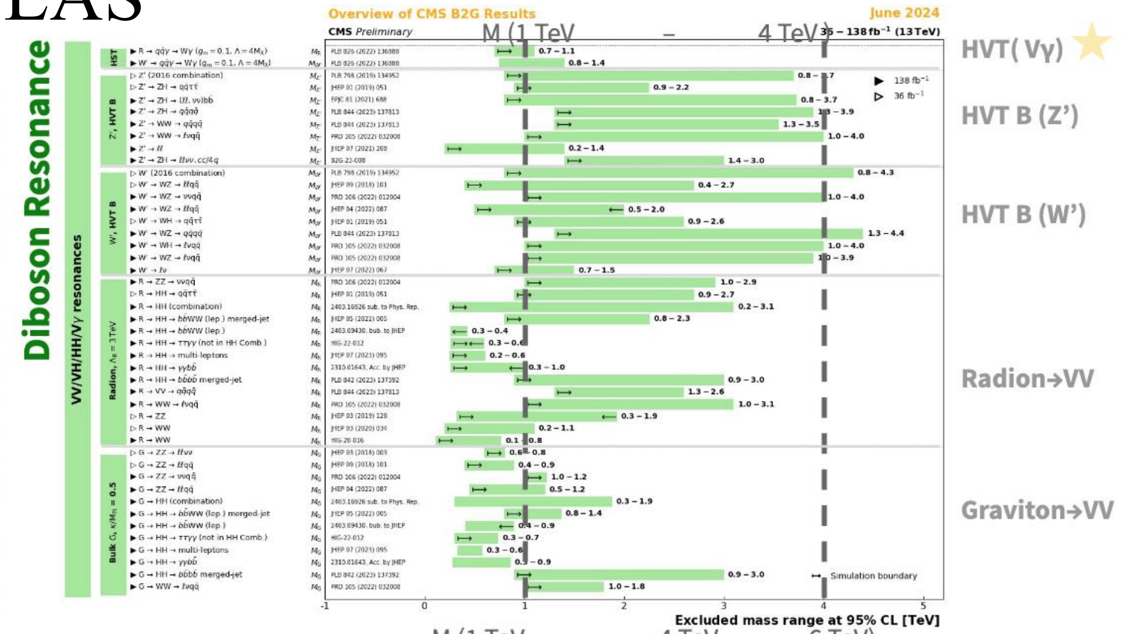


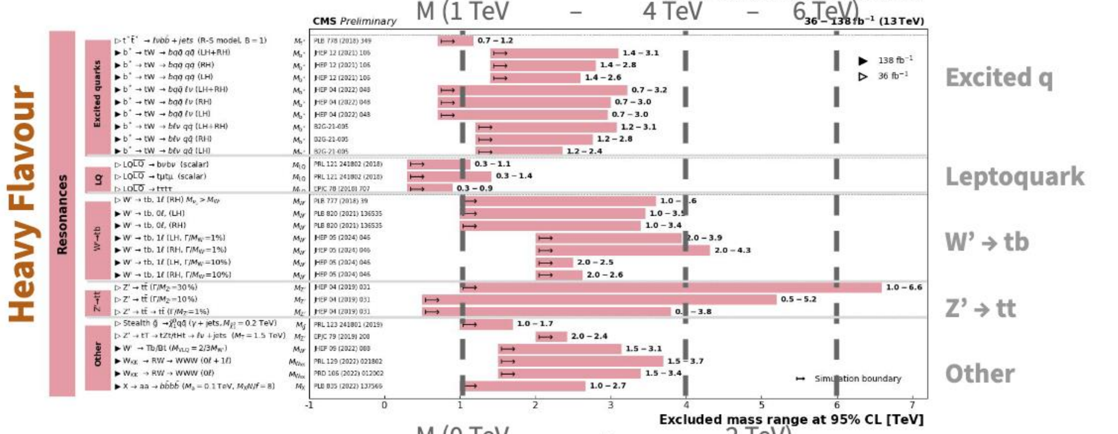


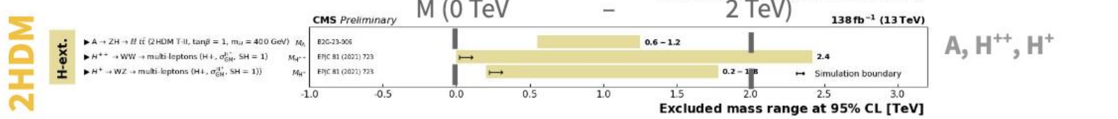
(direct) Searches for BSM signals/signatures

by CMS – similar results by ATLAS









Standard Model is not the ultimate theory of nature!

- The Standard Model, while incredibly successful – see available results from LHC investigations, is clearly not the ultimate theory of nature.
- There are many open points and topics uncovered by this theory
  - **GRAVITY**: The Standard Model does not include gravity, which is described by **General Relativity**. There is no quantum theory of gravity in the Standard Model.
  - **DARK MATTER**: Observations of galaxies and cosmic phenomena indicates the presence of **dark matter**, which interacts gravitationally but not electromagnetically, weakly, or strongly.
  - **DARK ENERGY**: The accelerated expansion of the universe is attributed to **dark energy**, a mysterious force that the Standard Model does not address.
  - **MATTER-ANTI MATTER Asymmetry**: The universe is dominated by matter; The Standard Model includes CP violation (charge-parity asymmetry), but it is insufficient to explain the observed asymmetry

Standard Model is not the ultimate theory of nature!

- **NEUTRINO MASSES**: Neutrinos are massless in the Standard Model, but experiments have shown they have tiny masses and undergo **oscillations** between flavours.
  - New physics, for example seesaw mechanism or sterile neutrinos?
- **IS the 125 GeV SCALAR the STANDARD MODEL HIGGS BOSON?**
  - **HYERARCHY Problem**: The Higgs boson's mass is much smaller than expected given quantum corrections, which should drive it to extremely high values.
  - **Why the Higgs boson is "naturally" light without fine-tuning?**
    - **Higgs not elementary particle? SUperSYmmetry theory? Or other BSM models?**
- **STRONG CP Problem**: The strong force, described by quantum chromodynamics (QCD), does not appear to violate CP symmetry, even though there is no apparent reason it shouldn't.
- **UNFICATION OF FORCES**: is the Standard Model the Energy→0 approximation of a more general theory?
  - The Standard Model describes the electromagnetic, weak, and strong forces but does not unify them into a single framework

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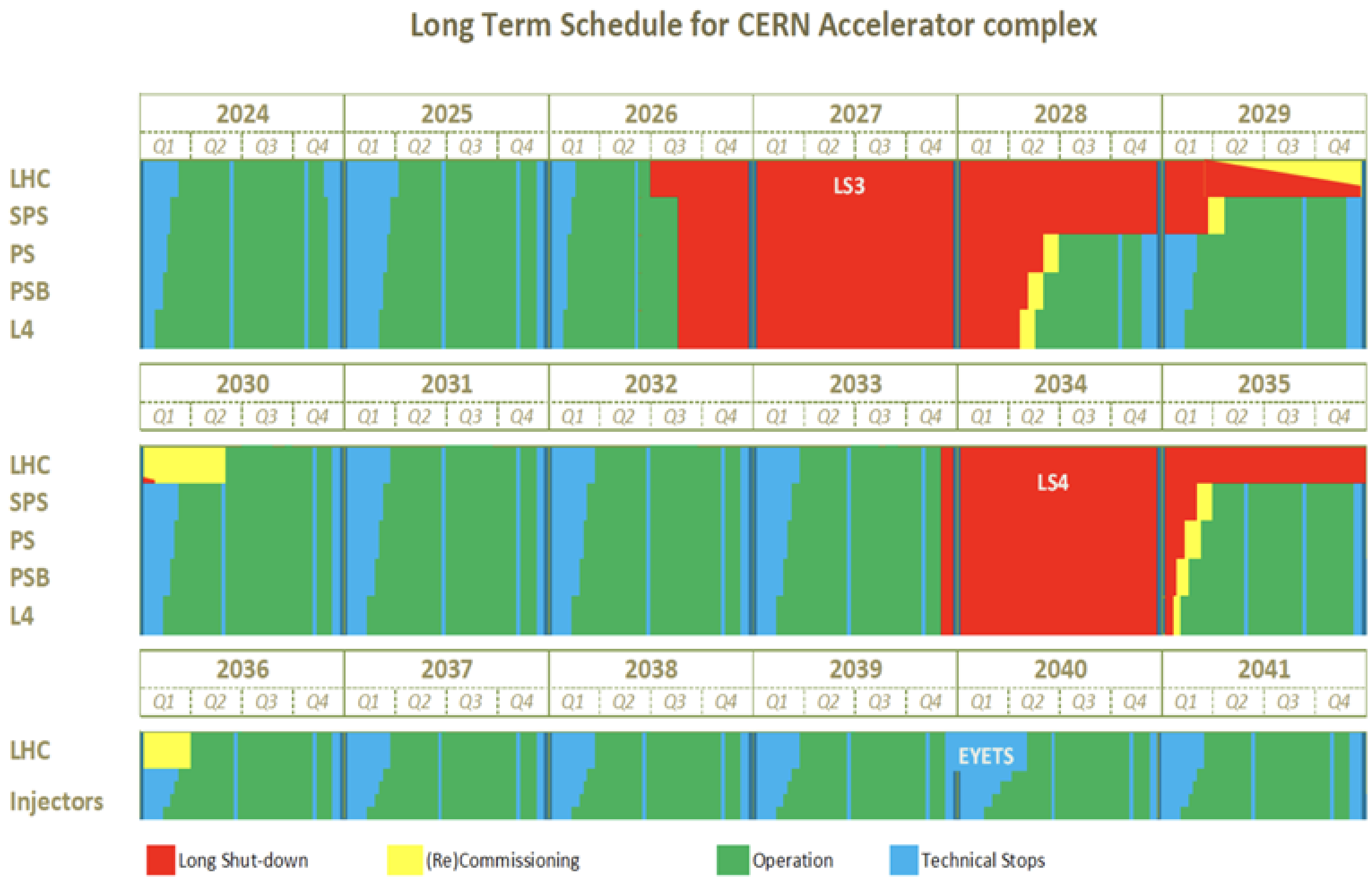
High-Luminosity LHC



➔ > 1 year until start of Long Shutdown 3 [postponed to 29 June 2026]

➔ > 80% of the project budget of 1.1 BCHF already committed

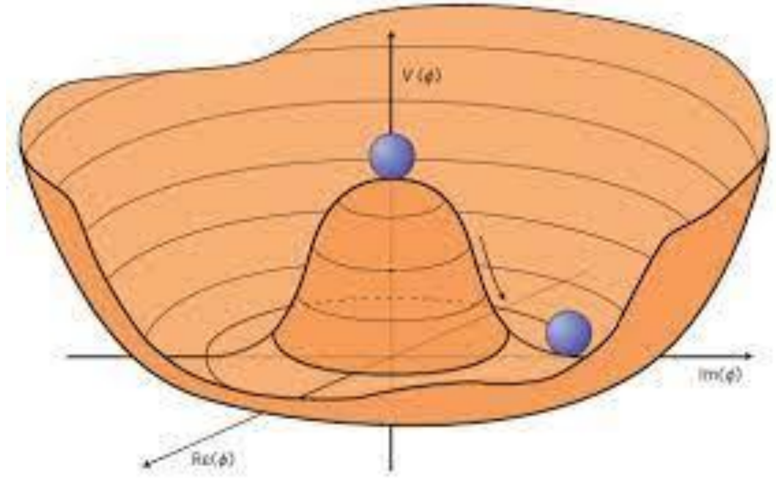
➔ The project is ready for LS3 installation start in 2nd half of 2026!

HL-LHC projections

- **HL-LHC complete full simulation studies very challenging** and very expensive (resources) at this point in time
- **Procedure adopted**:
  - **Start from published LHC Run 2 studies** and/or
  - **Simplified simulation** (using for example, DELPHES)
  - **Adapt to HL-LHC conditions**
    - center-of-mass energy: center-of-mass energy: $\sqrt{s} = 14$ TeV
    - pileup: 30 → 140 or 200
    - Final statistics: 3000 fb^{-1} per experiment
    - simulated detector and reconstruction performance
- **Systematic uncertainties, Baseline Scenario**: the increase of the systematic experimental uncertainties is compensated by the superior HL-LHC detector performance:
  - detector and trigger performance comparable to Run 2:
    - **Studied improvements to object reconstruction and the impact of detector upgrades, using full simulation with pile-up**
  - most experimental uncertainties scaled down with $\sqrt{L}$
  - theoretical uncertainties scaled by 1/2 with respect to current values
  - 1% luminosity uncertainty

The Higgs Potential

$$\mathcal{L} = T - V = \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \left(\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4\right)$$



in SM, this potential is fully defined by two parameters, that can be inferred by the v.e.v. v and the Higgs boson mass m_h

Expanding around the minimum, $\phi = v + h$:

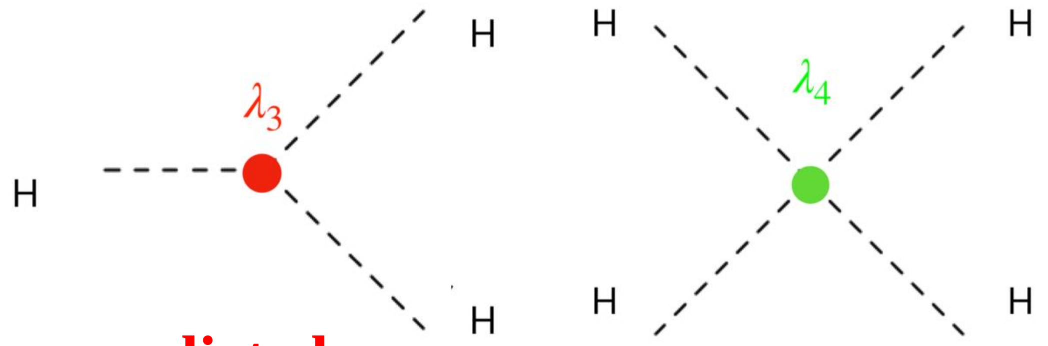
$$V(h) \;=\; \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 \;=\; \frac{1}{2} m_h{}^2 h^2 + \lambda_3 h^3 + \lambda_4 h^4$$

mass term | **Higgs triple coupling** | **Higgs quartic coupling**

$$m_h{}^2 = 2\lambda v^2 \qquad \lambda_3 = \lambda v = m_h{}^2/2v$$

$$\lambda_4 = \lambda/4 = mh^2/8v^2$$

Higgs boson pair (HH) production allows to probe *directly* the Higgs boson self-interaction and, ultimately, the shape of the Higgs potential.



➔Any deviation from the self-interaction predicted by the SM would be a sign of new physics!

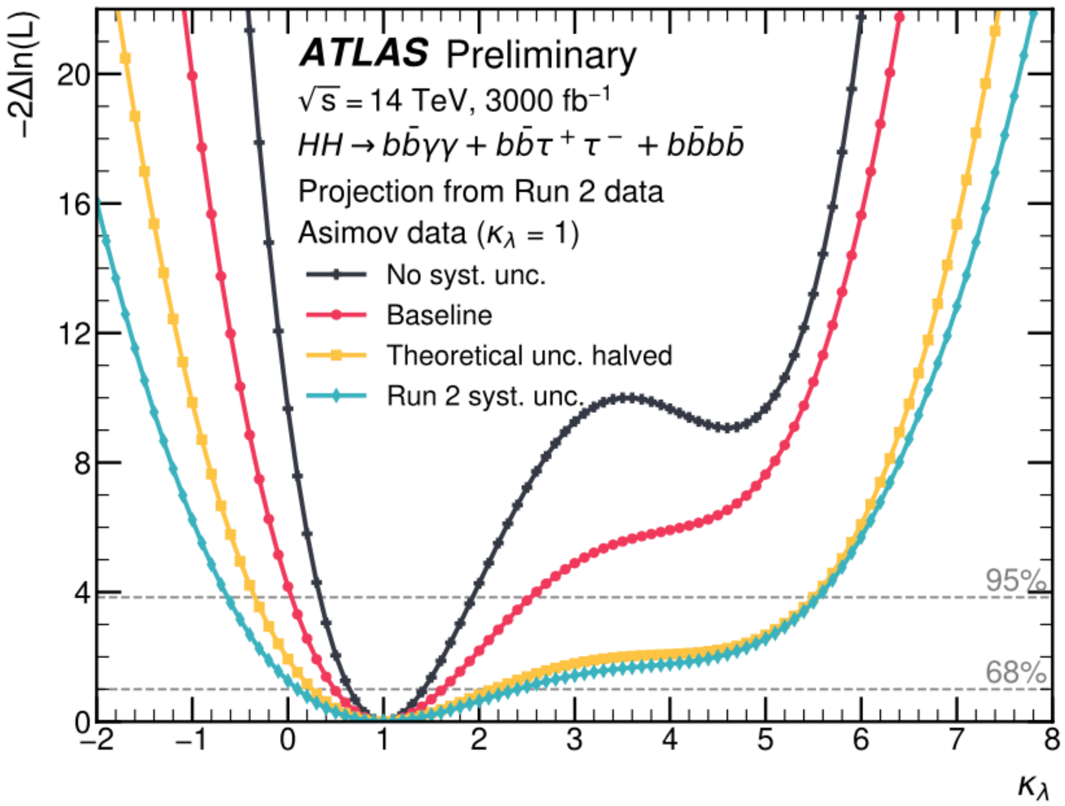
HH production – recent updates

Snowmass update 2021-2022

ATLAS γγbb+bbττ combination: **3.2σ**

CMS updated γγbb results, added γγWW, γγττ, ttHH(bbbb)

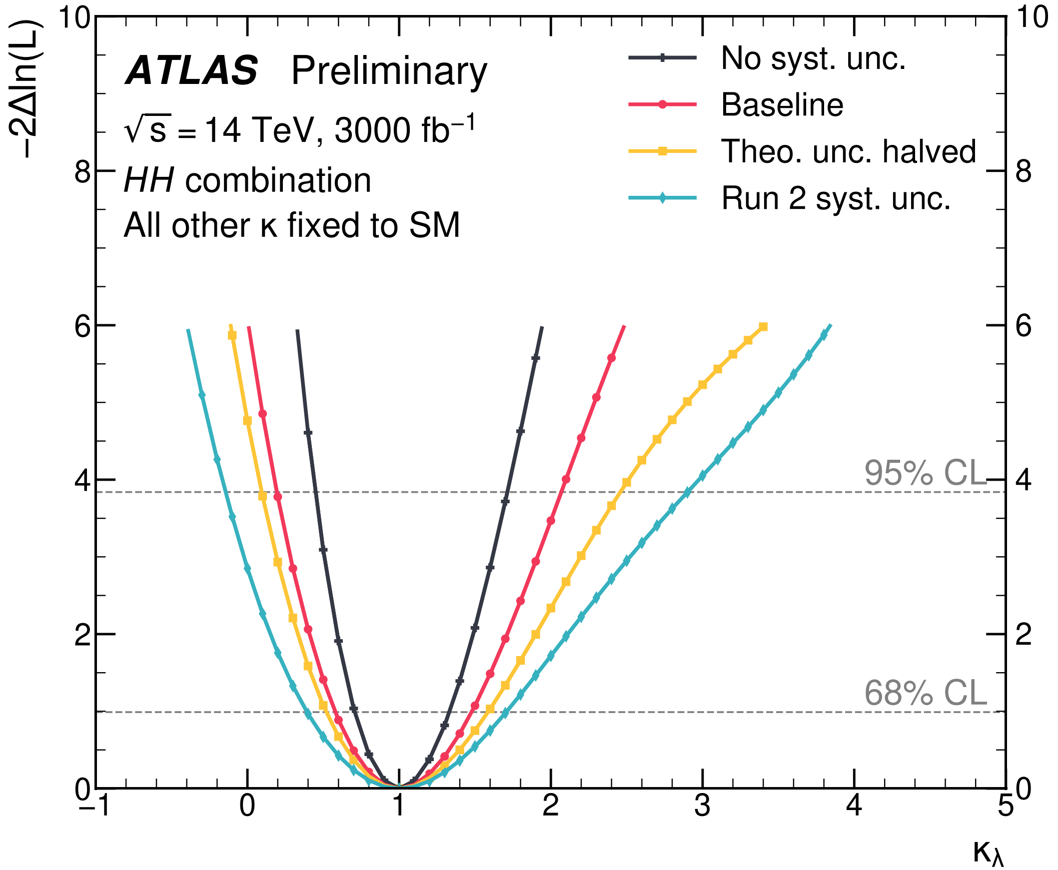
➔ **~5σ SM HH significance** with a back-of-the-envelope calculation



Negative logarithm of the combined likelihood ratio comparing different κ_λ hypotheses to an Asimov dataset constructed under the hypothesis of $\kappa_\lambda = 1$ assuming four different uncertainty scenarios.

NEW!

New HL-LHC prospects results ATLAS for the *European Strategy for Particle Physics Update 2025-206*



- ATLAS and CMS are about to submit new Prospects results for HL-LHC, as input for the ongoing *European Strategy for Particle Physics Update* (ESPPU)
- These studies are based on new analyses developed for Run 2 LHC data
- They produce very exciting new prospects, wrt to what shown in occasion of last ESPPU and Snowmass

$\kappa_\lambda = 1.0^{+0.48}_{-0.42}$ ➔ < 50% uncertainty with just one experiment ➔ expect an accuracy of ~30% when combining ATLAS and CMS prospects!

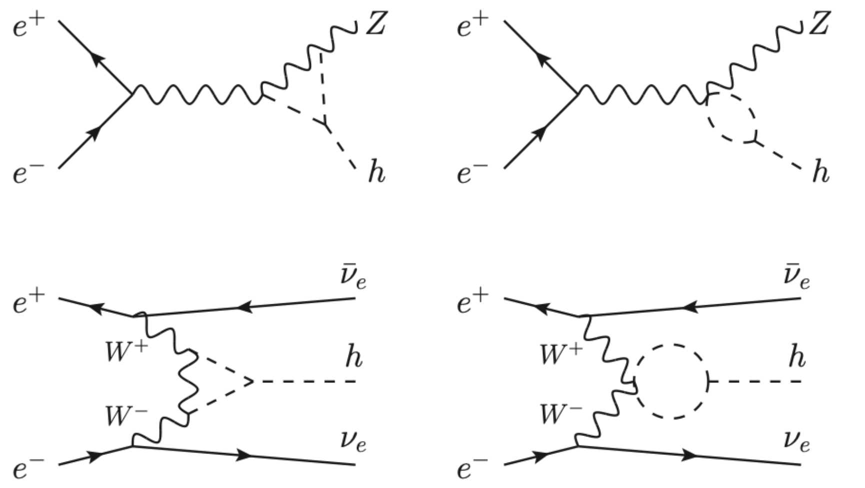
Public document on ATLAS + CMS Combination coming soon, stay tuned!

Higgs couplings and Γ_H at e^+e^- colliders

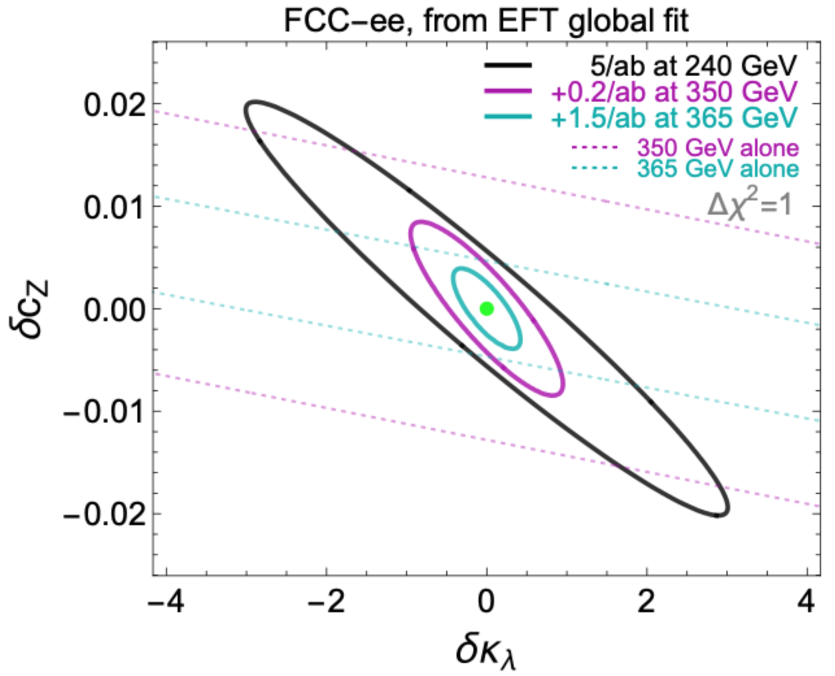
- $\sigma(e^+e^- \rightarrow ZH, H \rightarrow ZZ^*)$ is proportional to $g^2_{HZZ} \cdot BR(H \rightarrow ZZ^*)$ which is proportional to $\boldsymbol{g^4_{HZZ}/\Gamma_H}$ ➔ **extract $\boldsymbol{\Gamma_H}$**
- **The extraction of $\mathbf{g_{HZZ}}$ and $\boldsymbol{\Gamma_H}$ is *model independent***
- **in hadron colliders some model assumption is needed, as shown already**
- **The knowledge of $\boldsymbol{g^2_{HZZ}}$ allows the extraction of all other Higgs boson couplings**
- $\sigma(e^+e^- \rightarrow ZH, H \rightarrow bb) \propto g^2_{HZZ}\, \boldsymbol{g^2_{Hbb}}/\Gamma_H$ ➔ **extract $\boldsymbol{g_{Hbb}}$**
- $\sigma(e^+e^- \rightarrow ZH, H \rightarrow \tau\tau) \propto g^2_{HZZ}\, \boldsymbol{g^2_{H\tau\tau}}/\Gamma_H$ ➔ **extract $\boldsymbol{g_{H\tau\tau}}$**
- …
- but also $e^+e^- \rightarrow \nu\nu H$: $\sigma(e^+e^- \rightarrow \nu\nu H) \propto g^2_{HWW}$
- $\sigma(e^+e^- \rightarrow \nu\nu H, H \rightarrow bb) \propto \boldsymbol{g^2_{HWW}\, g^2_{Hbb}}/\Gamma_H$ ➔ **extract $\boldsymbol{g_{HWW}\, g_{Hbb}}$**
- …

Higgs self-coupling @ FCC-ee

- The accurate measurement of the ZH cross section can also give access to the Higgs boson self-coupling g_{HHH} via loops.
  - Higgs self-coupling contributes t ~ 2% to $\sigma(e^+e^- \rightarrow ZH)$ @ $\sqrt{s}$=240 GeV
- The dependence of the ZH cross section as a function of $\sqrt{s}$ provides and independent, complementary method to access g_{HZZ} and g_{HHH}
- the $e^+e^- \rightarrow$ WWfusion $\rightarrow$ H cross section gives independent contribution to this measurement

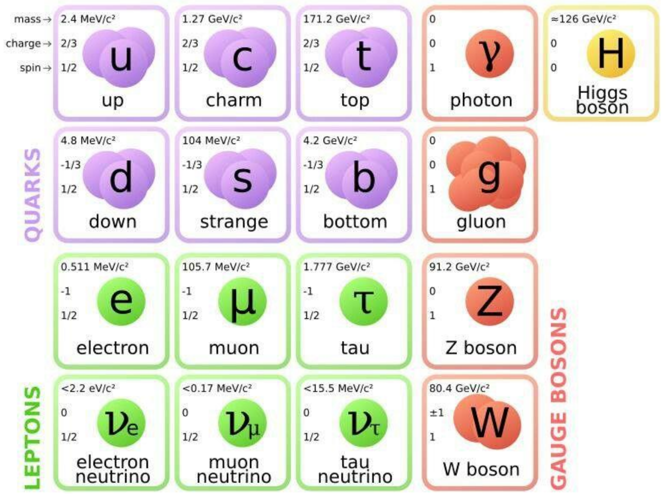


- **Higgs self-coupling g_{HHH} can be extracted with an accuracy of 33% (2 IPs) or 24% (4 IPs)**



δc_Z: correction to the Higgs couplings to the gauge bosons
$\delta\kappa_\lambda$: correction to the trilinear Higgs self-coupling: $\delta\kappa_\lambda$

Flavour Physics



- Peculiar structure of quark and lepton masses and their mixing angles in the Standard Model (SM)
  - these patterns could originate from new physics beyond the SM.
  - approximate flavour symmetries lead to the suppression of flavor-changing processes, which can be used to probe high-energy physics through precision measurements at FCC-ee.
- b and τ decays, and b → τ transitions allow to test with third generation a general feature of many explicit BSM possibilities.

Particle species	B^0	B^+	B^0_s	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times 10^9$)	370	370	90	80	2	720	200

Yields of heavy-flavoured particles produced at FCC-ee for 6×10^{12} Z decays

- Rare b-hadron decays with ττ pairs in the final state.
- Charged-current b-hadrons decays with a τν pair in the final state

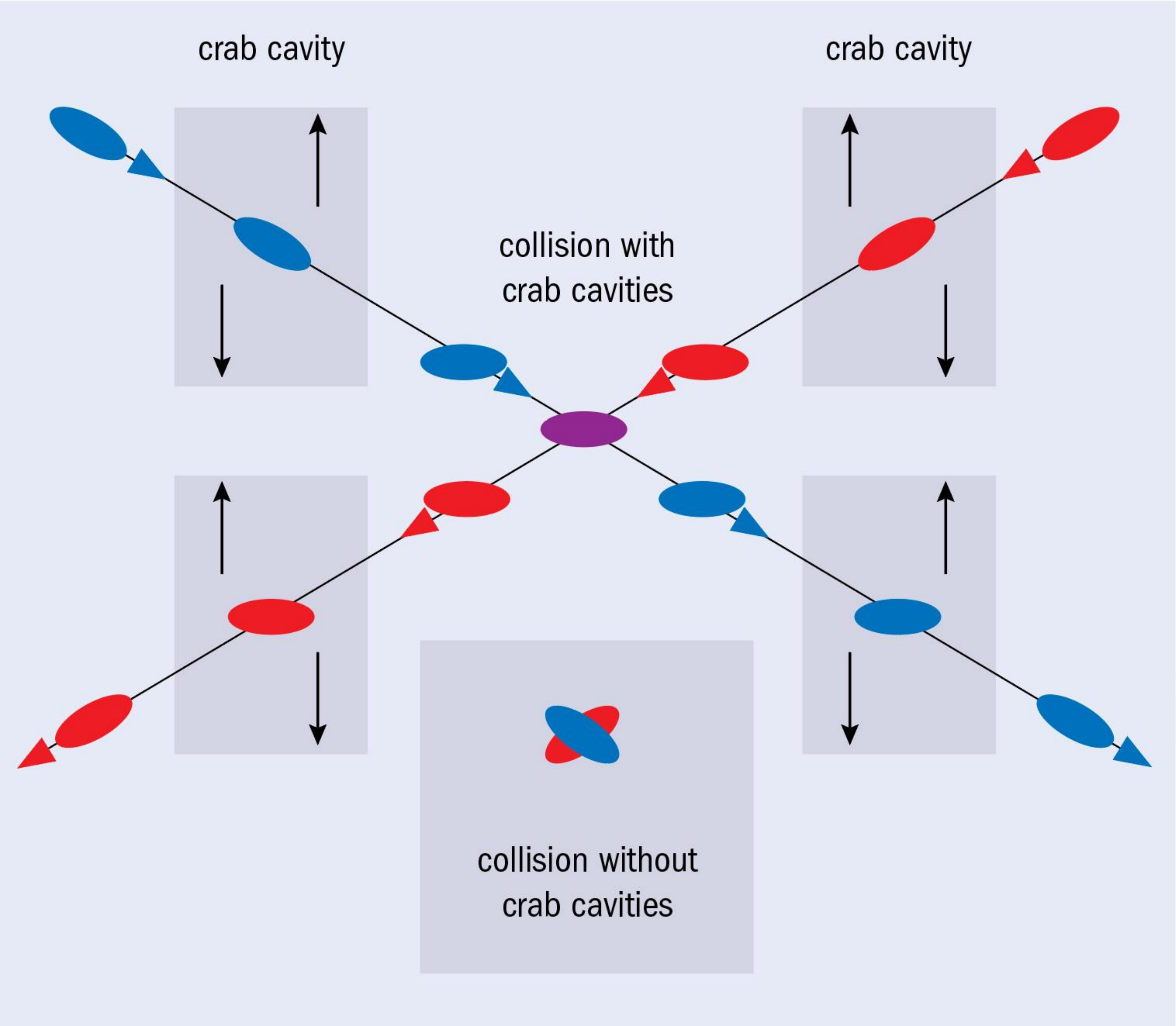
- Lepton flavour violating τ decays
- Lepton-universality tests in τ decays

Rates at FCC-hh for 10 L = ab^{-1} $\sqrt{s}$ = 100 TeV

- **10^{10} Higgs bosons** ➔ 10^4 x today
- **10^{12} top quarks** ➔ 5 10^4 x today
  - ➔ 10^{12} W bosons from top decays
  - ➔ 10^{12} b hadrons from top decays
  - ➔ 10^{11} $t \to W \to \tau$
  - few 10^{11} $t \to W \to charm\ hadrons$

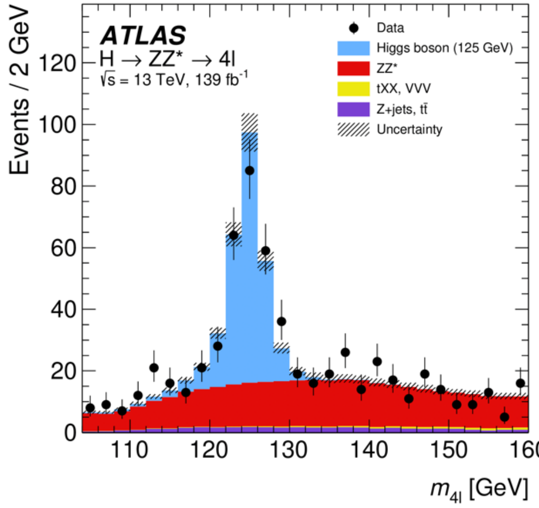
- Frontier energy new physics searches
  - BSM theories an models
  - Rare decays
  - LFV H➔eμ
- Precision mesurements
  - Higgs couplings and selfcoupling
  - Flavour physics
- CP Violation

Amazing potential, extreme detector and event reconstruction challenges

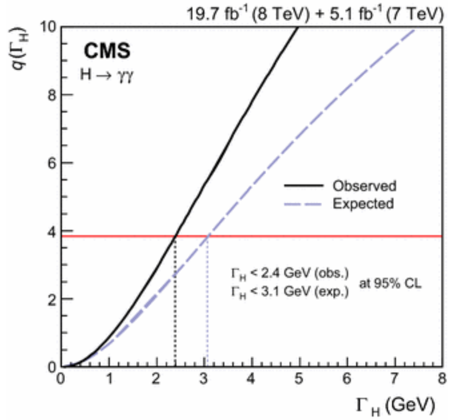

crab cavity
crab cavity
collision with crab cavities
collision without crab cavities

The Higgs boson natural width

- **Predicted Standard Model Higgs boson natural width Γ_H^{SM}: 4.07 MeV**
- this width is too small to be measured directly from the line shape because of the limited mass resolution of order 1 GeV achievable with the present LHC detectors
- ➔ Probe the impact of Γ_H in the "off-shell" region, i.e. studying the line shape of final states such as, for example, – the four lepton final states.

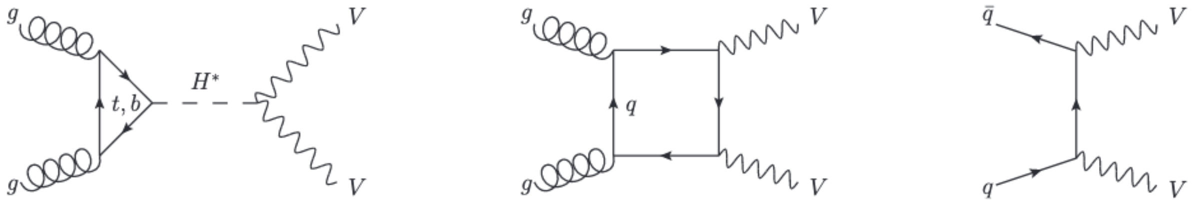


Direct measurement severely limited by detector resolution! One (old) example:



EPJC volume 74, 3076

$\Gamma < 2.4$ GeV @ 95% CL

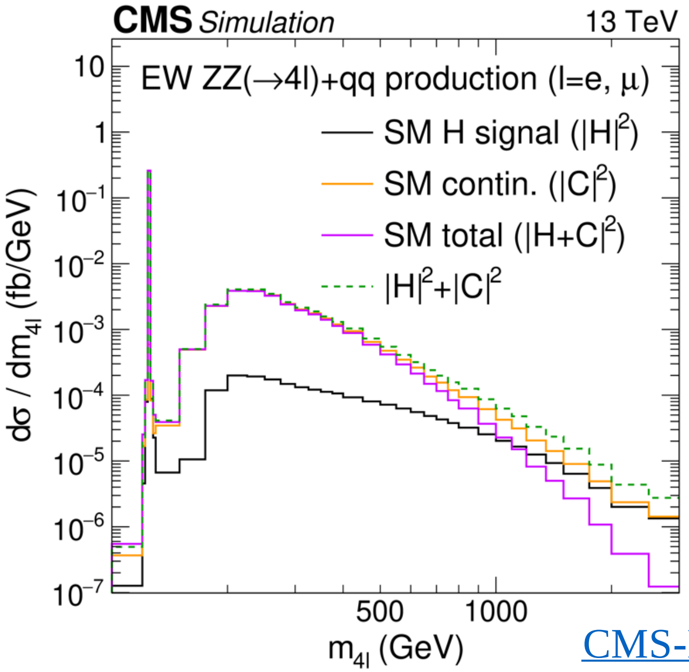


$$\frac{d\sigma_{pp\to H\to ZZ}}{dM_{4l}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4l}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

Assuming on-shell and off shell couplings are equal:

$$\frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}} = \frac{\Gamma}{\Gamma_{SM}}$$

arXiv:1307.4935v3



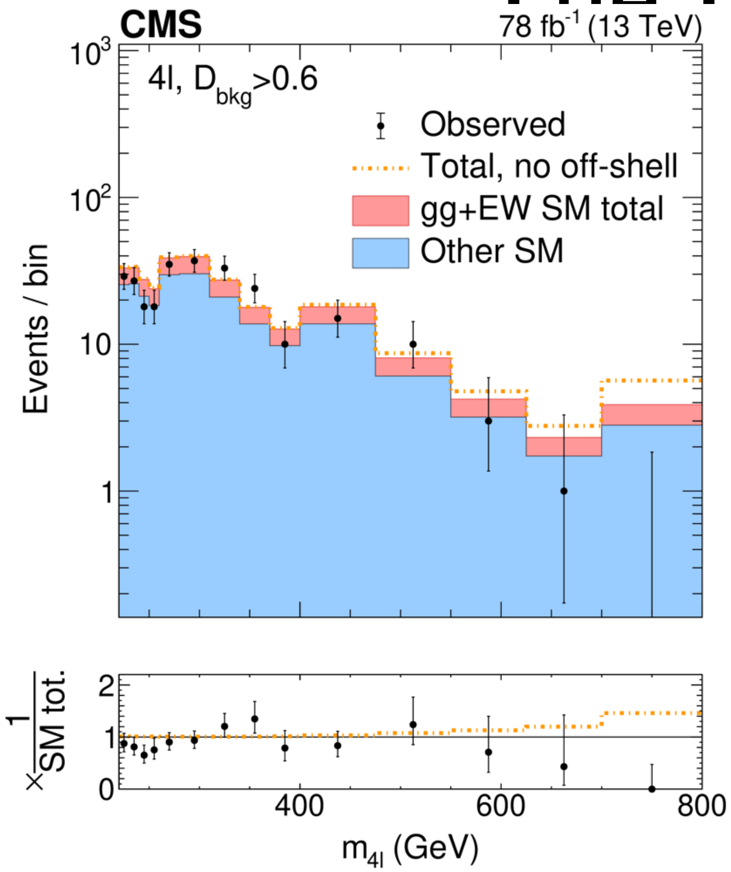
- **Standard Model calculations of $m_{4\ell}$.**
- **Dashed green curve: direct sum without the interference**
- **solid magenta curve: sum with interference included.**

Note that the interference is destructive, and its importance grows as the mass increases.

CMS-HIG-21-013

The Higgs boson natural width

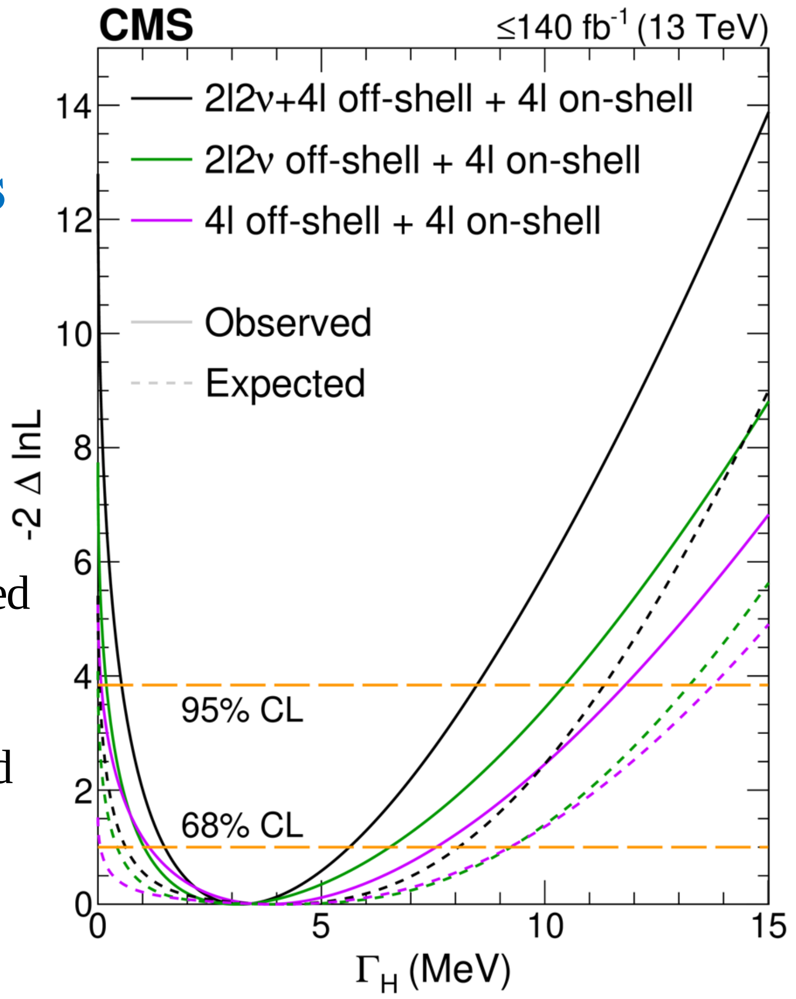
CMS-HIG-21-013



- Distribution of $m_{4\ell}$ in the 4ℓ off-shell signal regions.
- Stacked histograms display the different predicted contributions after a fit to the data with SM couplings.
  - gold dot-dashed line shows the distribution after a fit to the no off-shell (Γ_H= 0 MeV) hypothesis
  - black points show the observed data, which is consistent with the prediction with SM couplings within one standard deviation
  - last bins contain the overflow.
- Bottom pad: ratio of the data or dashed histograms to the stacked histogram.

Study the *2l2ν* off-shell and the *4l* on-shell + off-shell final states

- The observed (solid) and expected (dashed) one-parameter likelihood scans over Γ_H.
- The integrated luminosity reaches up to 140 fb^{-1} as on-shell 4ℓ events are included in performing these scans.
- The exclusion of the no off-shell hypothesis is consistent with 3.6 standard deviations on both panels.



The no off-shell scenario with Γ_H = 0 is excluded at 99.97%

$\Gamma = 3.2^{+2.4}_{-1.7}$ MeV

The kappa-framework

$$(\sigma \cdot \mathrm{BR})(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \cdot \mathrm{BR}_{SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

narrow width approximation

This is example for the Higgs boson produced by gluon-gluon (gg) fusion processes, decaying to $\gamma\gamma$ final states

introduce κ as the ratio between the measured Higgs boson coupling and the one predicted by SM ***κ = measured coupling/predicted coupling***

$$\kappa_j^2 = \sigma_j / \sigma_j^{SM} \quad \text{or} \quad \kappa_j^2 = \Gamma^j / \Gamma^j_{SM} \qquad \Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{SM}}{1 - B_{BSM}}$$

Production **Decay** **Total width**

Reflects the possibility allow for the possibility of Higgs boson decays to invisible or untagged BSM particles.

- **assumes SM like coupling structure** ($J^{CP} = 0^{++}$) → **only account for rates**
- **kappas** correspond to **tree-level H couplings to the different particles**
- **in Standard Model:** $\kappa_i = 1$

From the kappa framework to EFT studies

- The kappa framework is ”easy” to understand, model independent, but it is not appropriate when looking for small deviations of Higgs coupling from SM predictions
- Ideally one would like to combine information from rates, differential distributions, and CP properties
- Also, this framework does not include correlations with other important physics quantities in the theory
- ➔ **move to an approach based to EFT**

dimension-6 dimension-8

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i^{d=6} + \sum \frac{c_i}{\Lambda^4} \mathcal{O}_i^{d=8} + \ldots$$

BSM effects SM particles

- Λ is the scale where new heavy degrees of freedom exists, and the EFT breaks down
- C_i are Wilson coefficients

From the kappa framework to EFT studies

- The kappa framework is ”easy” to understand, model independent, but it is not appropriate when looking for small deviations of Higgs coupling from SM predictions
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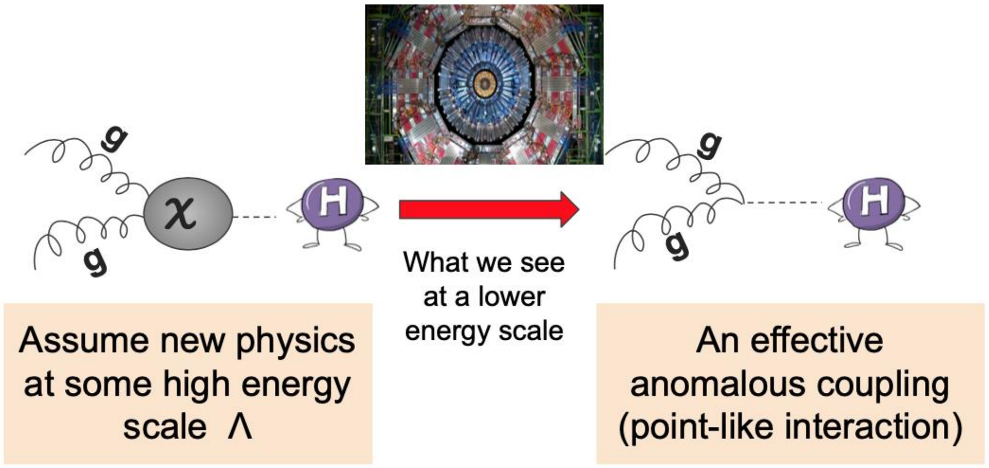
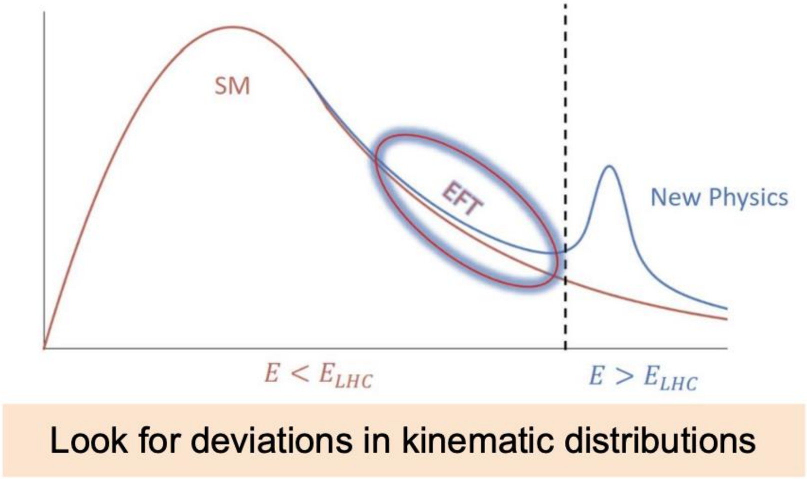
- ➔ **move to an approach based to EFT**



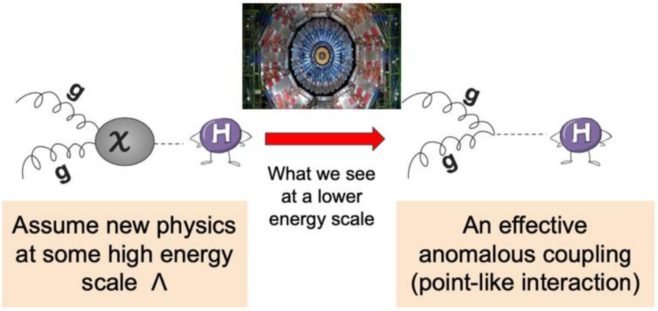


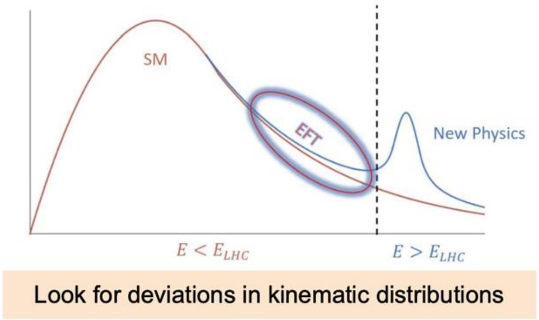
From the κ-framework to EFT studies

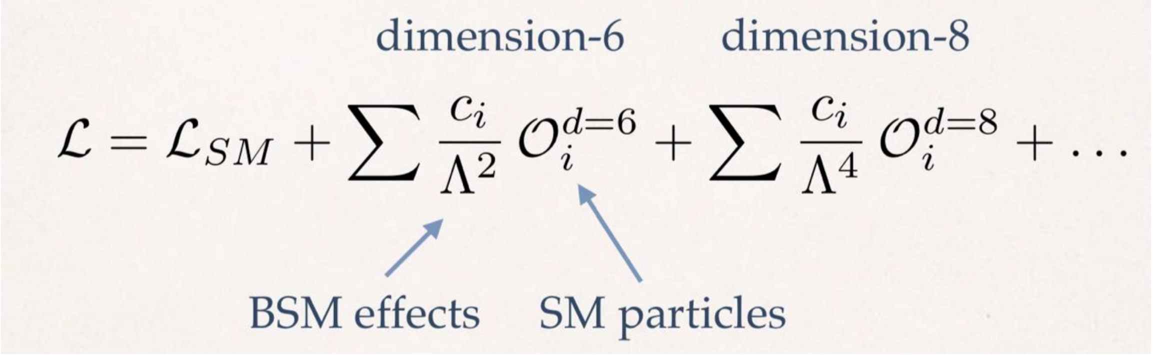
- The κ-framework is ”easy” to understand but it is not appropriate when looking for small deviations of Higgs coupling from SM predictions
- Ideally one would like to combine information from rates, differential distributions, and CP properties
- Also, this framework does not include correlations with other important physics quantities in the theory
- ➔ **move to an approach based to EFT**
  - Well-defined theoretical approach
  - Assumes New Physics states are heavy
  - Write Effective Lagrangian with only light (SM) particles
  - BSM effects can be incorporated as a momentum expansion

Effective Field Theory studies

- Effective Field Theories – EFTs
- Key principles:
  - EFT describes physics at a given energy scale by incorporating relevant degrees of freedom while parametrizing unknown high-energy effects.
  - It provides a universal method to study low-energy phenomena without requiring detailed knowledge of the fundamental high-energy theory.
  - EFT organizes interactions in a power series of suppression factors, typically in terms of the ratio E/Λ, where Λis the cutoff scale of new physics.

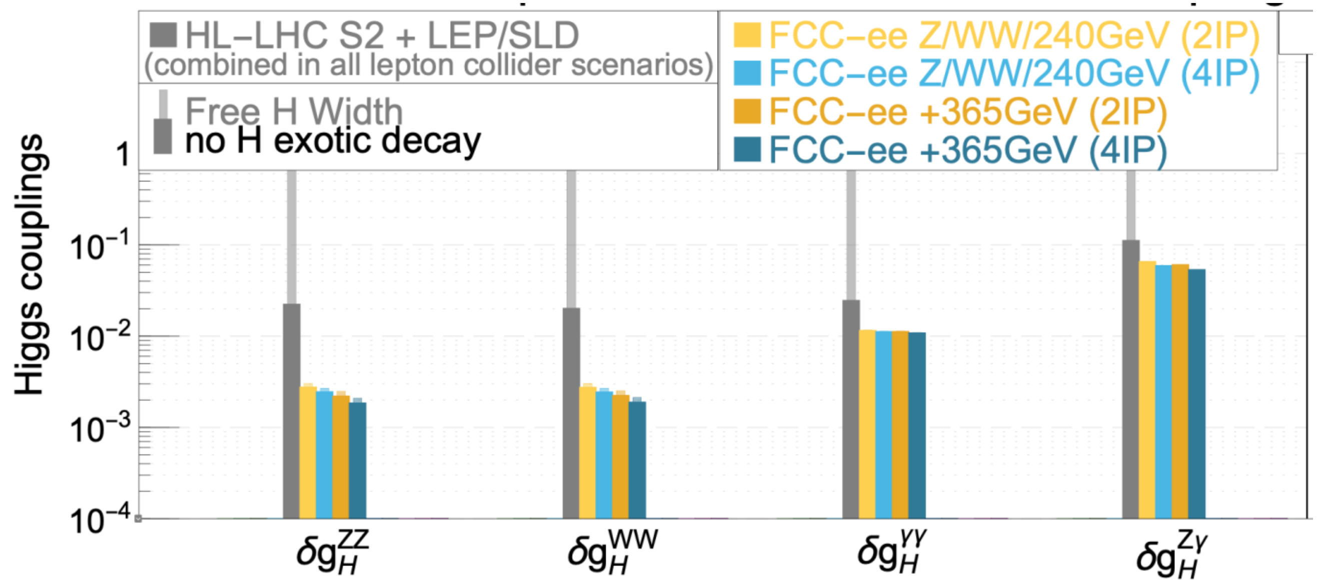






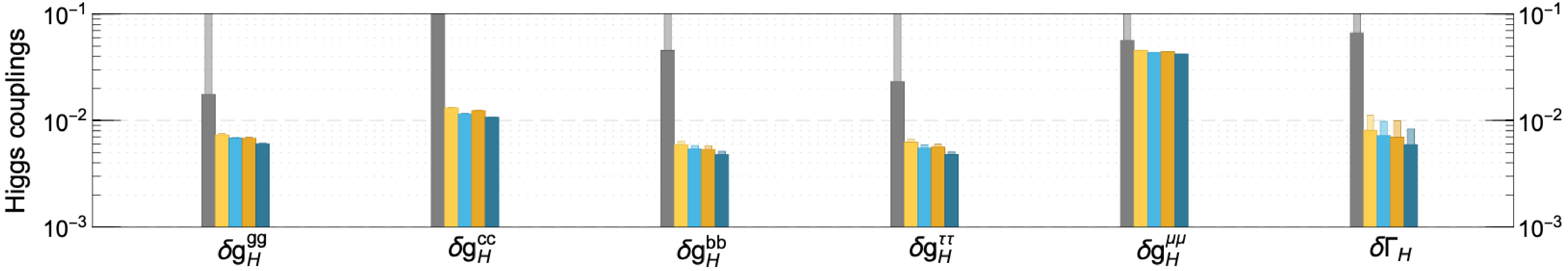
- ***Λ*** is the scale where new heavy degrees of freedom exists, and the EFT breaks down
- C_i are Wilson coefficients

Standard Model EFT – Higgs couplings



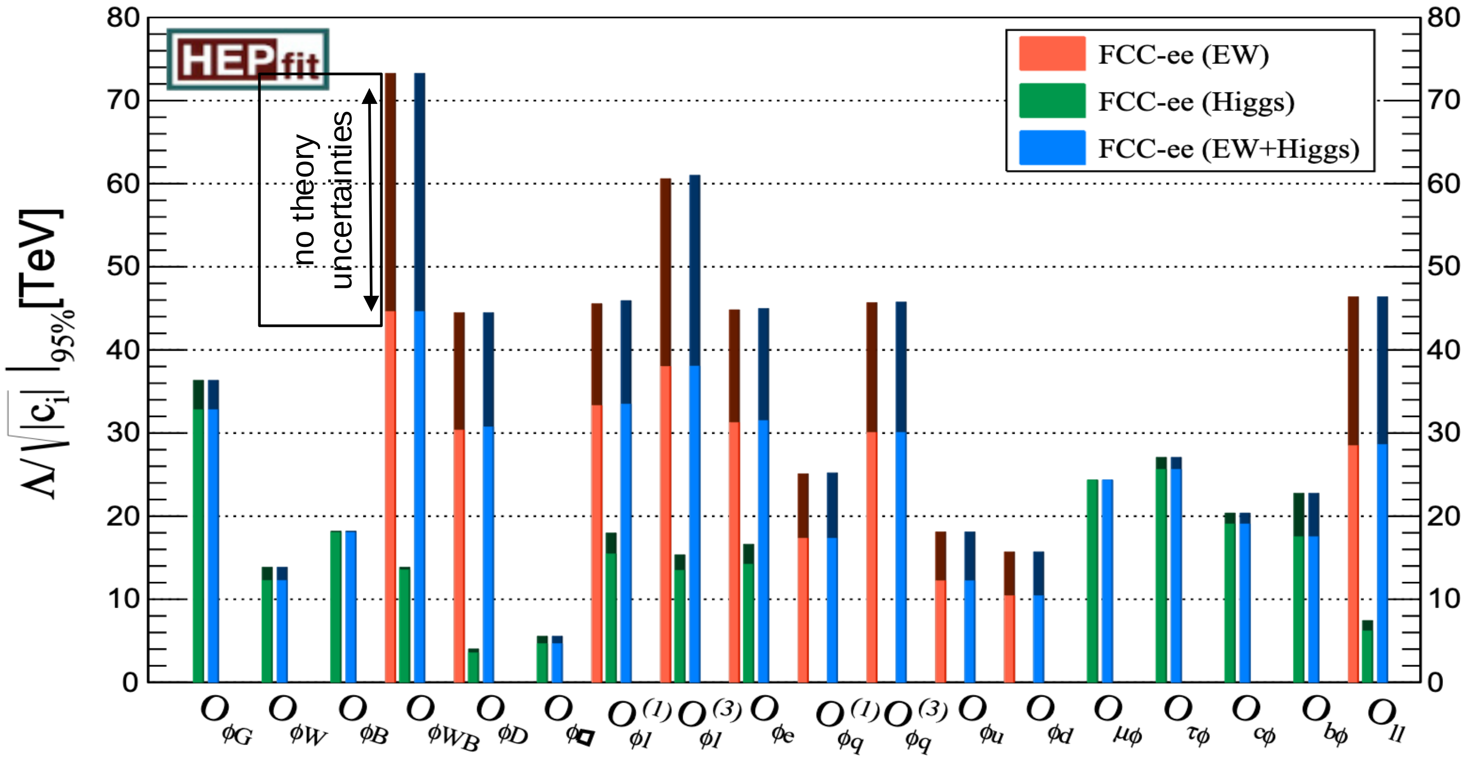
it is critical to progress on the experimental and theoretical accuracy on electroweak quantities: addressing this point is one of the most important points of the FCC scientific programme

- δg_H^{xx} is the accuracy on the coupling of the Higgs boson to xx initial/final states



Higgs couplings estimated with similar or better accuracy than what yielded by the κ-framework

Standard Model EFT: new physics



95% probability bounds on the interaction scale $\Lambda/\sqrt{C_i}$ associated to each displayed Operator.

It's a naïve estimate of when new physics might become relevant, based on Wilson coefficients.

Higgs compositness

Buttazzo, Franceschini, Wulzer

(EFT approach)

Compositeness Reach:

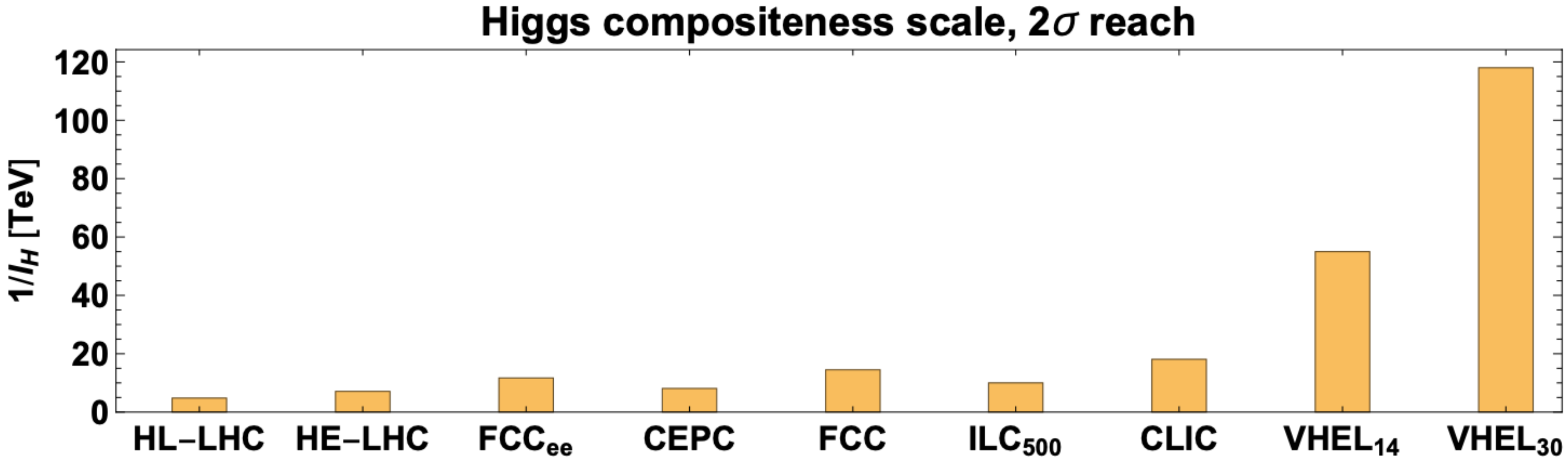
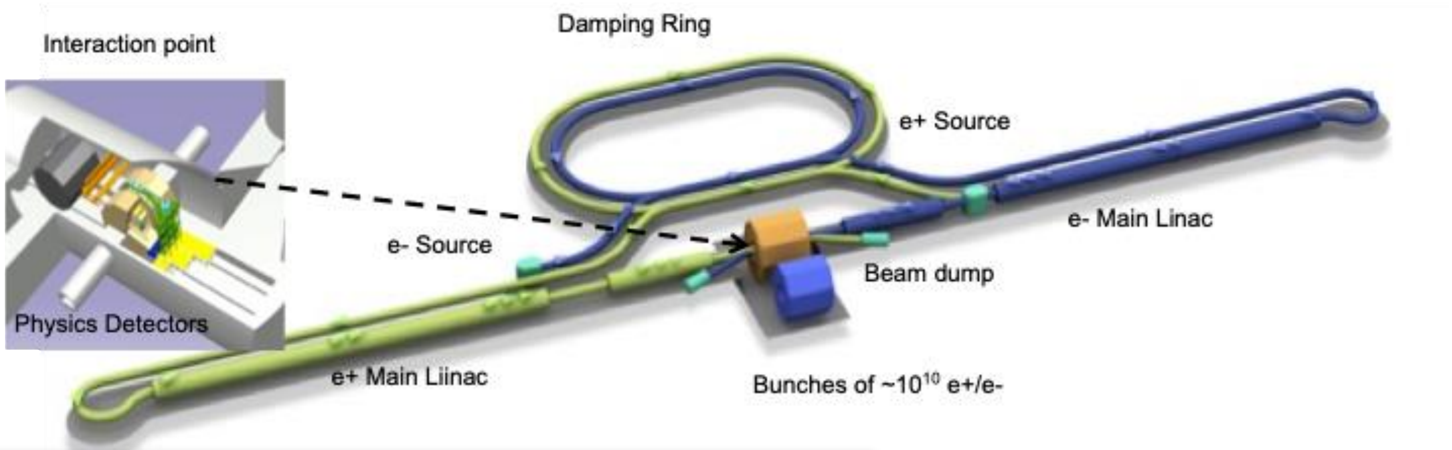
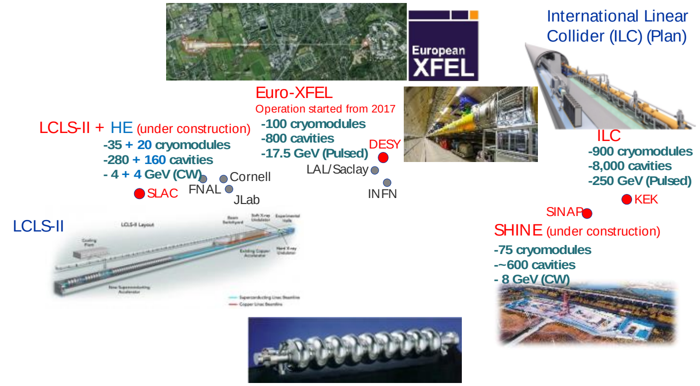


Table 129 The baseline FCC-ee 16-years programme with four interaction points, showing the centre-of-mass energies, instantaneous luminosities for each IP, integrated luminosity per year summed over 4 IPs corresponding to 185 days of physics per year and 75% efficiency, in the order Z, WW, ZH, $\mathrm{t\bar{t}}$. The luminosity is assumed to be half the design value for machine commissioning and optimisation during the first two years at the Z pole, the first two years at the WW threshold, and the first year at the $\mathrm{t\bar{t}}$ threshold. (Should the order of the sequence be modified to either Z, ZH, WW, $\mathrm{t\bar{t}}$ or ZH, WW, Z, $\mathrm{t\bar{t}}$, the ZH stage would start with two years at half the design luminosity followed by two years at design luminosity, while the WW stage would run afterwards for only one year but at design luminosity.) The luminosity at the Z pole (the WW threshold) is distributed as follows: $40\,\mathrm{ab}^{-1}$ at $88\,\mathrm{GeV}$, $125\,\mathrm{ab}^{-1}$ at $91.2\,\mathrm{GeV}$, and $40\,\mathrm{ab}^{-1}$ at $94\,\mathrm{GeV}$ ($5\,\mathrm{ab}^{-1}$ at $157.5\,\mathrm{GeV}$, and $5\,\mathrm{ab}^{-1}$ at $162.5\,\mathrm{GeV}$). The number of WW events include all $\sqrt{s}$ values from $157.5\,\mathrm{GeV}$ up.

Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$\mathrm{t\bar{t}}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	–	3	1	4
Number of events	6×10^{12} Z		2.4×10^{8} WW		1.45×10^{6} ZH + 45k WW $\rightarrow$ H	$1.9 \times 10^{6}\ \mathrm{t\bar{t}}$ +330k ZH +80k WW $\rightarrow$ H	

Linear Colliders (ILC, CLIC, C3,…)





Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade
Centre of mass energy	$\sqrt{s}$	GeV	250	250
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.35	2.7
Polarization for e^-/e^+	$P_-(P_+)$	%	80(30)	80(30)
Repetition frequency	f_{rep}	Hz	5	5
Bunches per pulse	n_{bunch}	1	1312	2625
Bunch population	N_{e}	10^{10}	2	2
Linac bunch interval	Δt_{b}	ns	554	366
Beam current in pulse	I_{pulse}	mA	5.8	8.8
Beam pulse duration	t_{pulse}	μs	727	961
Average beam power	P_{ave}	MW	5.3	10.5
RMS bunch length	σ^*_{z}	mm	0.3	0.3
Norm. hor. emitt. at IP	$\gamma\epsilon_{\mathrm{x}}$	μm	5	5
Norm. vert. emitt. at IP	$\gamma\epsilon_{\mathrm{y}}$	nm	35	35
RMS hor. beam size at IP	σ^*_{x}	nm	516	516
RMS vert. beam size at IP	σ^*_{y}	nm	7.7	7.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$		73 %	73 %
Beamstrahlung energy loss	δ_{BS}		2.6 %	2.6 %
Site AC power	P_{site}	MW	111	128
Site length	L_{site}	km	20.5	20.5

Luminosity: 1.35 – 2.7 10^{34} cm^{-2} s^{-1}

Vertical beam size at the Interaction Point:
rms: 7.7 nm

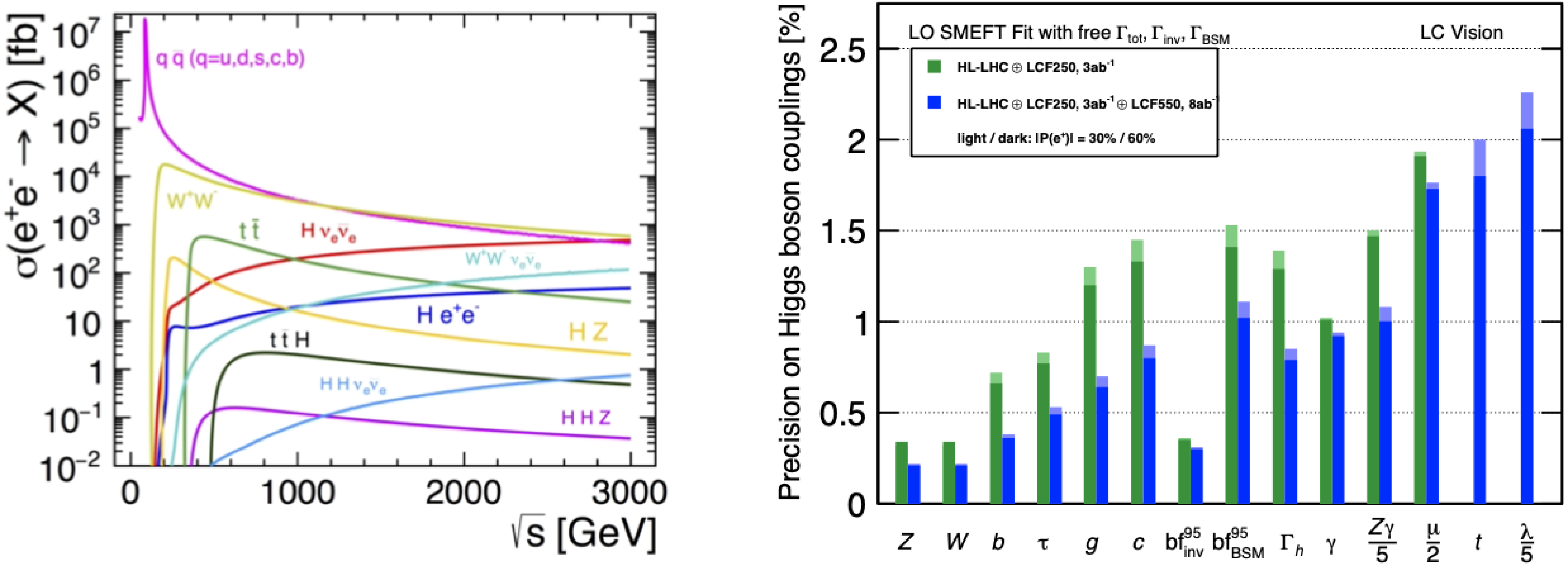
ILC Collaboration: "*…the tiny beams need to be collided with an accuracy of a fraction of their size, **so less than a nanometre**"*

1 nm is ~ 10 atoms of Hydrogen

Parameters and plans for luminosity and energy upgrades are available, including information about relevant SCRF R&D for such upgrades at (Snowmass input)

Z pole	Upgrades		
91.2	500	250	1000
0.21/0.41	1.8/3.6	5.4	5.1
80(30)	80(30)	80(30)	80(20)
3.7	5	10	4
1312/2625	1312/2625	2625	2450
2	2	2	1.74
554/366	554/366	366	366
5.8/8.8	5.8/8.8	8.8	7.6
727/961	727/961	961	897
1.42/2.84*)	10.5/21	21	27.2
0.41	0.3	0.3	0.225
5	5	5	5
35	35	35	30
1120	474	516	335
14.6	5.9	7.7	2.7
99 %	58.3 %	73 %	44.5 %
0.16 %	4.5 %	2.6 %	10.5 %
94/115	173/215	198	300
20.5	31	31	40

Linear Collider Facility



(a) (b)

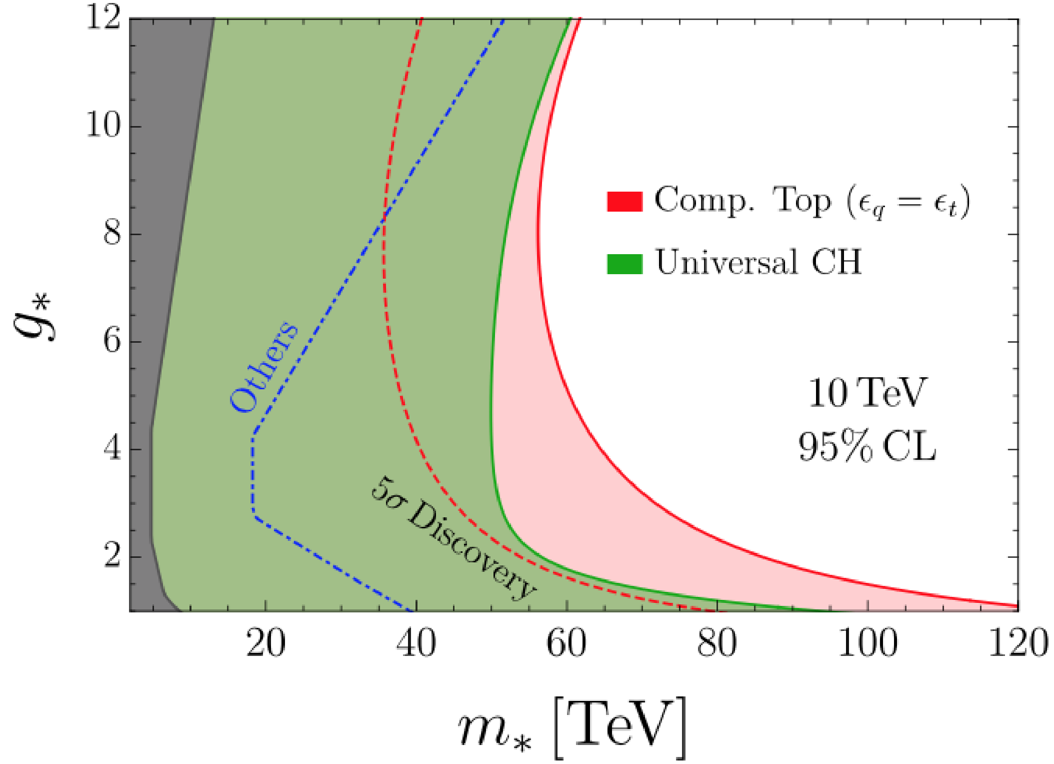
Figure 2: (a) Unpolarised cross-sections of important e^+e^- processes as a function of the centre-of-mass energy [35]. (b) Precisions on various Higgs couplings based on the 250 GeV and 550 GeV runs of Table 1. Sensitivity to probing BSM effects in $H \to s\bar{s}$ has been shown in [37].

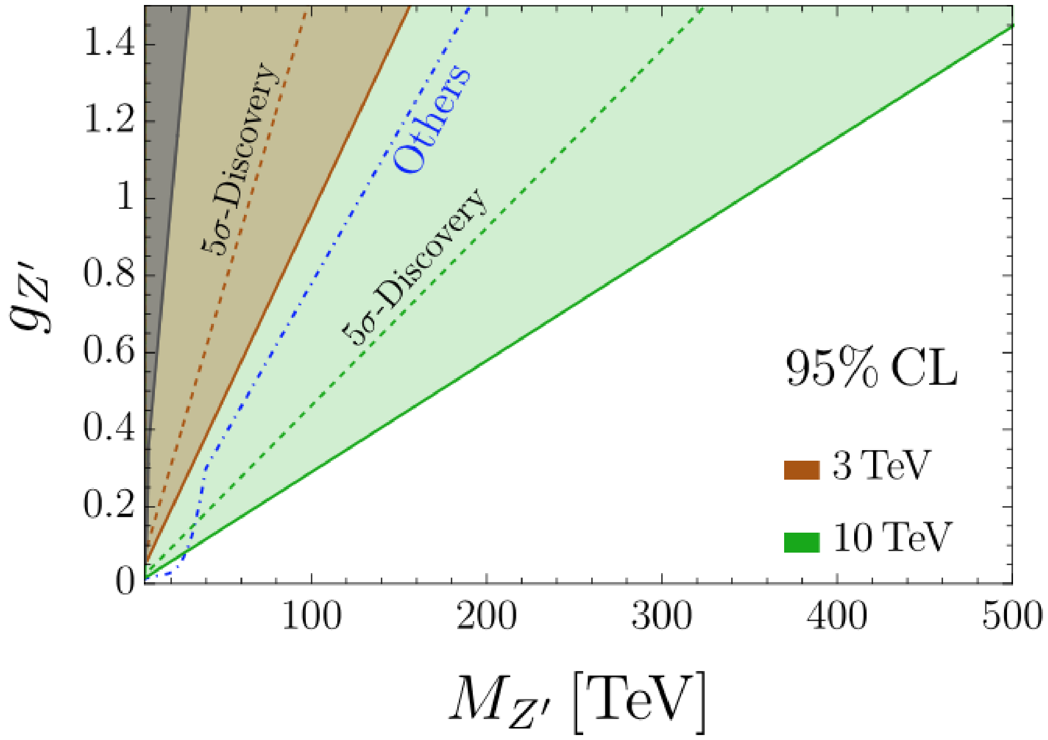
Linear colliders

- Several challenges posed by a high-luminosity, high-energy linear collider. One in particular:
- The ***ILC***: …the tiny beams need to be collided with an accuracy of a fraction of their size, **so less than a nanometre!**
- ATF2 test facility in Japan: *a purpose-built final-focus test beamline in Japan, an international collaboration has developed the controls and -instrumentation needed to achieve these challenging parameters*.
    - Goal 1 - Achievement of small (37 nm) beam size: demonstration of finalfocus system based on local chromaticity correction;
    - Goal 2 - Control of beam position: demonstration of beam orbit stabilization with nano-meter precision at the IP, using intra-pulse feedback.
- ATF2 achieved the result of 65 nm beam size at low bunch charge and with a relaxed $\beta*$
    - ATF2 should have reached a small spot size several years long before the 2011 earthquake that stopped this beam test

Example of new physics @ the Muon Collider

Higgs Compositeness arXiv:2203.07256v2 **Z' boson**





In Higgs compositeness models, the Higgs boson is not an elementary scalar like in the Standard Model (SM) but rather a composite state arising from a new strongly interacting sector.
Sensitivity as a function of the typical coupling g∗ and of the typical mass m∗ of the composite sector that delivers the Higgs boson.

reach on new physics of a 10 TeV muon collider with 10 ab^{-1} integrated luminosity.

"Others" indicates all other proposed future colliders. This includes expectations from FCC-hh

European Strategy for Particle Physics

Steps in the Update Process

ESPP Update 2024-2026

1. **Mandate by the CERN Council:**
   - The update process begins when the CERN Council issues a **mandate to review and update the current strategy**. This mandate outlines the scope, goals, and timeline for the update. ✓
2. **Community Involvement and Call for Input:**
   - A **public call for input is issued**, inviting contributions from the global particle physics community, including researchers, institutions, and national funding agencies. This step ensures that a wide range of perspectives and ideas are considered. ✓
3. **Establishment of the Physics Preparatory Group (PPG):**
   - A **Physics Preparatory Group (PPG)** is formed, consisting of experts from the field. This group is responsible for collecting input, organizing discussions, and preparing a draft of the updated strategy. The PPG typically includes representatives from CERN, member states, and prominent physicists. ✓
4. **Open Symposium:**
   - An **Open Symposium is held**, gathering scientists and stakeholders to discuss the input received and the key scientific questions that the updated strategy should address. This symposium serves as a platform for debate on the future direction of the field, including potential projects, experiments, and technologies. **Lido di Venezia 23-27 June 2025**
5. **Drafting the Strategy Update:**
   1. Based on the discussions and input, the **PPG drafts the updated strategy**. This draft, **the Briefing Book**, outlines the recommended scientific priorities, technological developments, and necessary investments for the coming years. **Monte Verità in Ascona, 1-5 December 2025**
6. **Submit the European Strategy Update recommendations to the CERN Council:**
   - The **Briefing Book is reviewed by the European Strategy Group (ESG)**, which includes representatives from CERN, member states, and observer states. Additional feedback is sought to refine and adjust the recommendations. A final document based is issued by the ESG to the CERN Council

European Strategy Update

INFN: activities & R&D

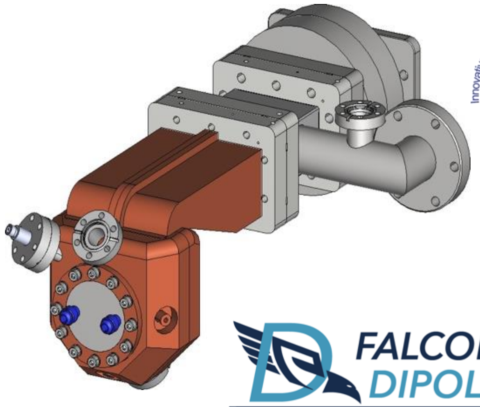
The FCC project poses many technological challenges including:

- The damping ring and the injectors
- Radiofrequency cavities
- Beam dipoles and quadrupoles
- Machine/detector interface

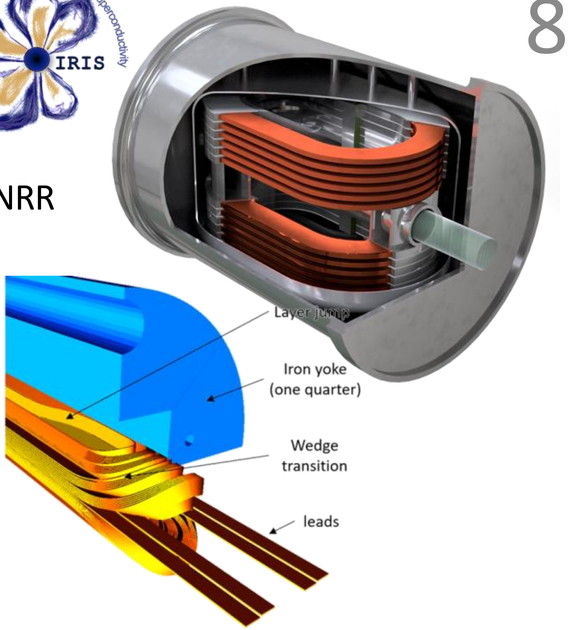
INFN has promoted/financed **specific R&D** projects that can significantly contribute to the current European Strategy and the one in preparation.

Among these projects there is also the **Muon Collider.**

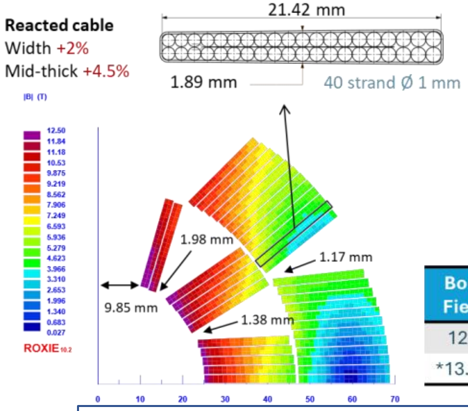
- INFN community involved in the study of SRF cavities, high field magnets for the cooling cell , and in the study of the interaction region, the injector and dumping ring, and the detector
- It is essential to carry out an R&D experiment that demonstrates the feasibility of a high-energy muon collider → Demonstrator



PNRR

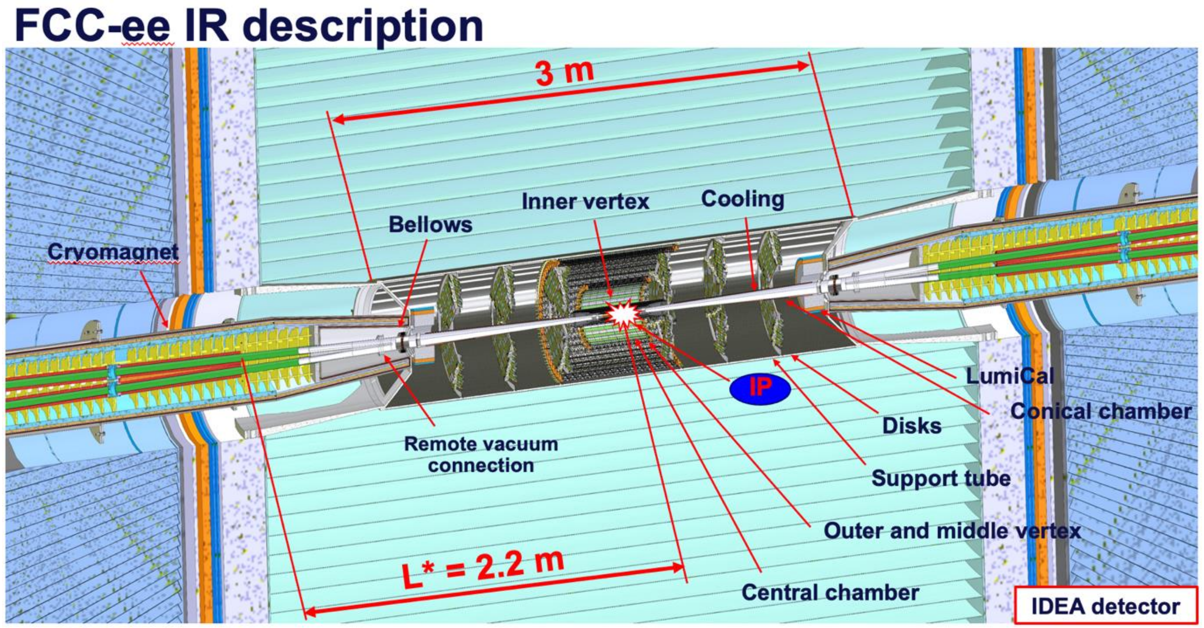


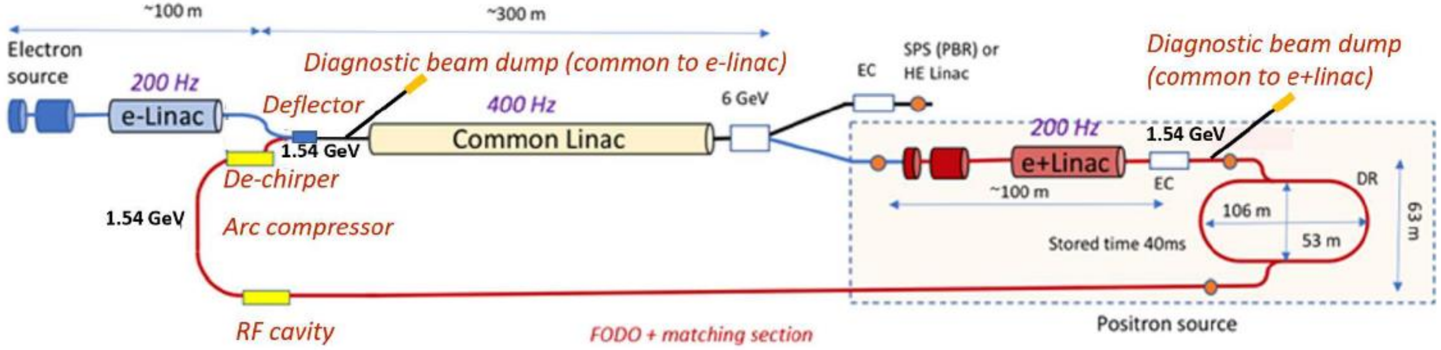
FALCON DIPOLE

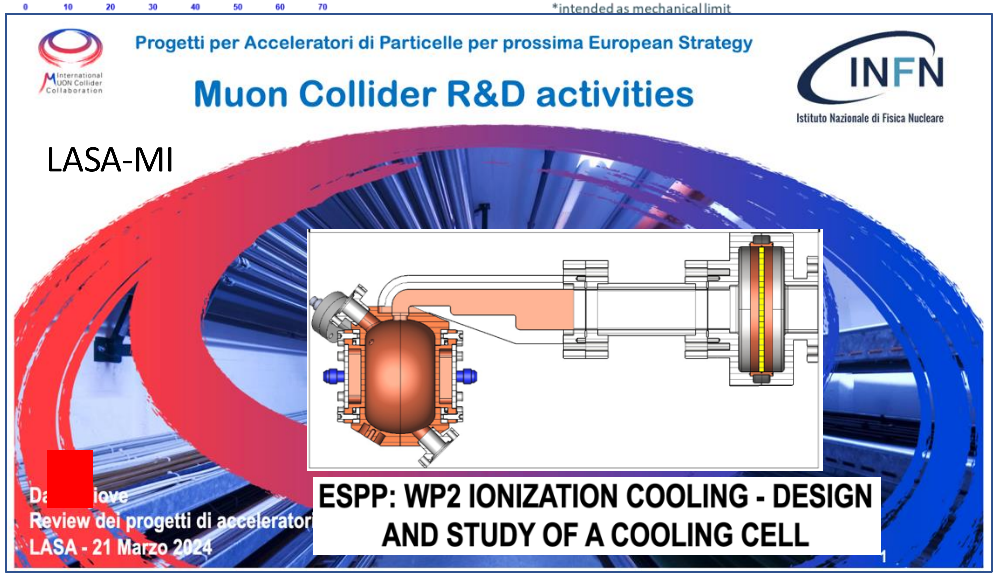


Bore Field	Operating Current	Margin on Loadline @ 1.9 K
12 T	20180 A	24.4%
*13.5 T	23000 A	15%

*intended as mechanical limit





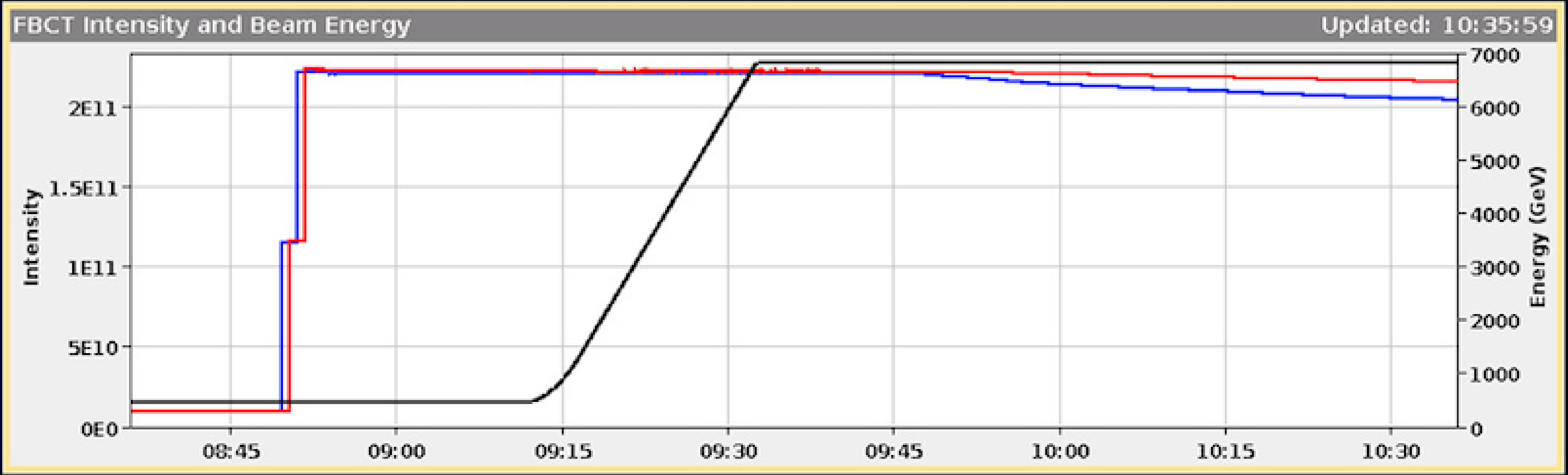


LHC Page1 | Fill: 7679 | E: 6800 GeV | t(SB): 00:00:00 | 31-05-22 10:35:59

BEAM SETUP: ADJUST

Energy:	6800 GeV	I B1:	1.99e+11	I B2:	2.09e+11

Inst. Lumi [(ub.s)^-1] IP1: 0.13 IP2: 0.19 IP5: 0.03 IP8: 0.00

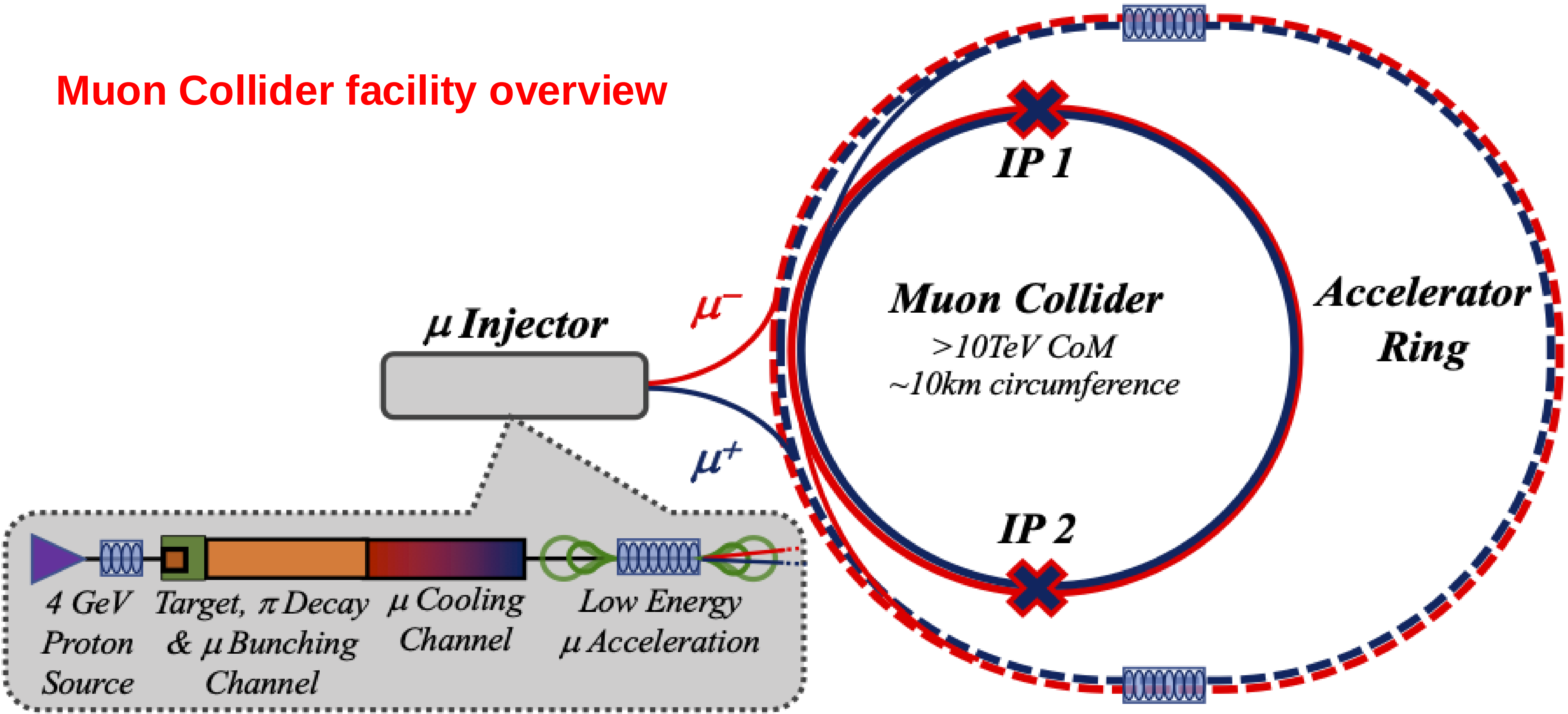


BIS status and SMP flags B1 B2

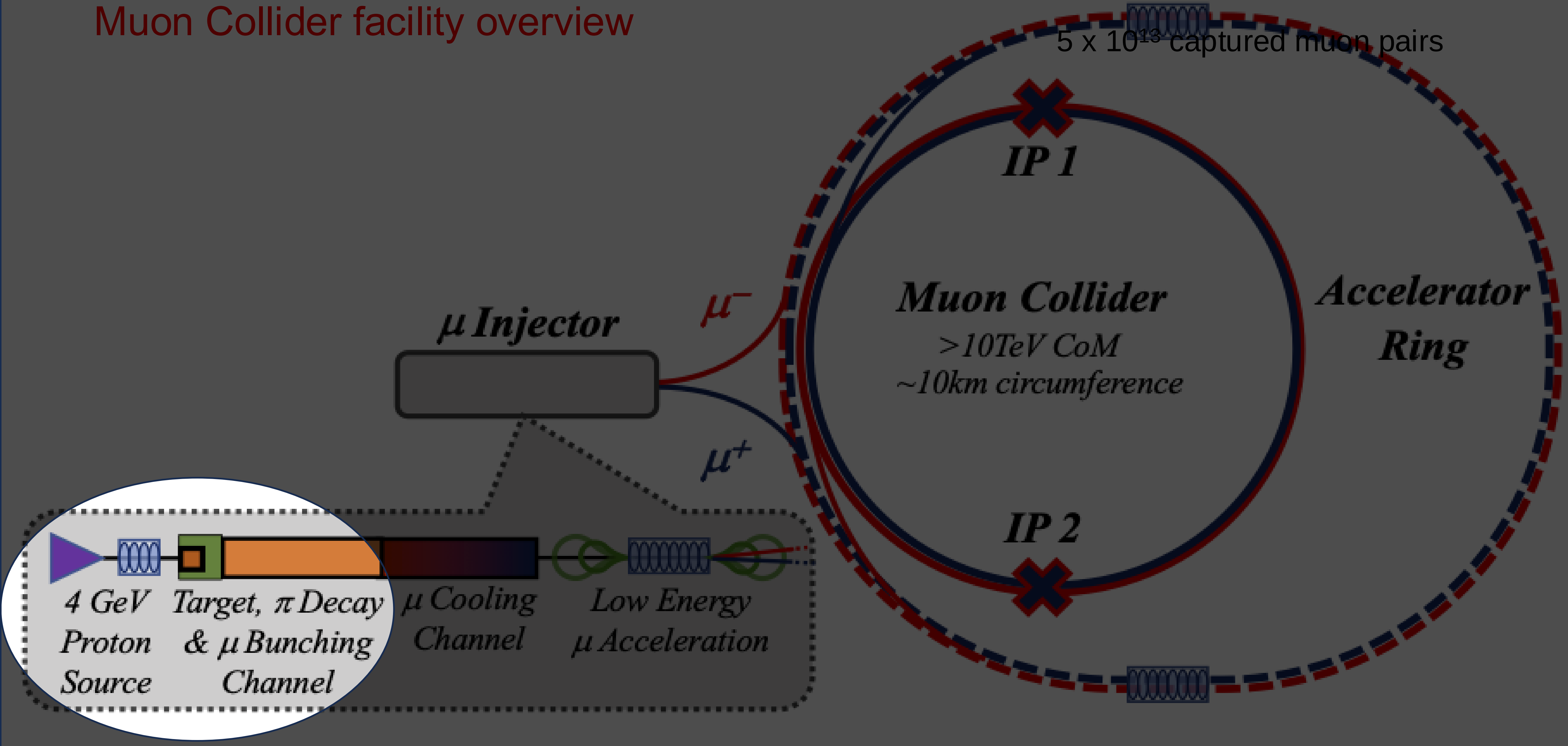
Comments (31-May-2022 10:11:48)

Link Status of Beam Permits true true

Muon Collider facility overview

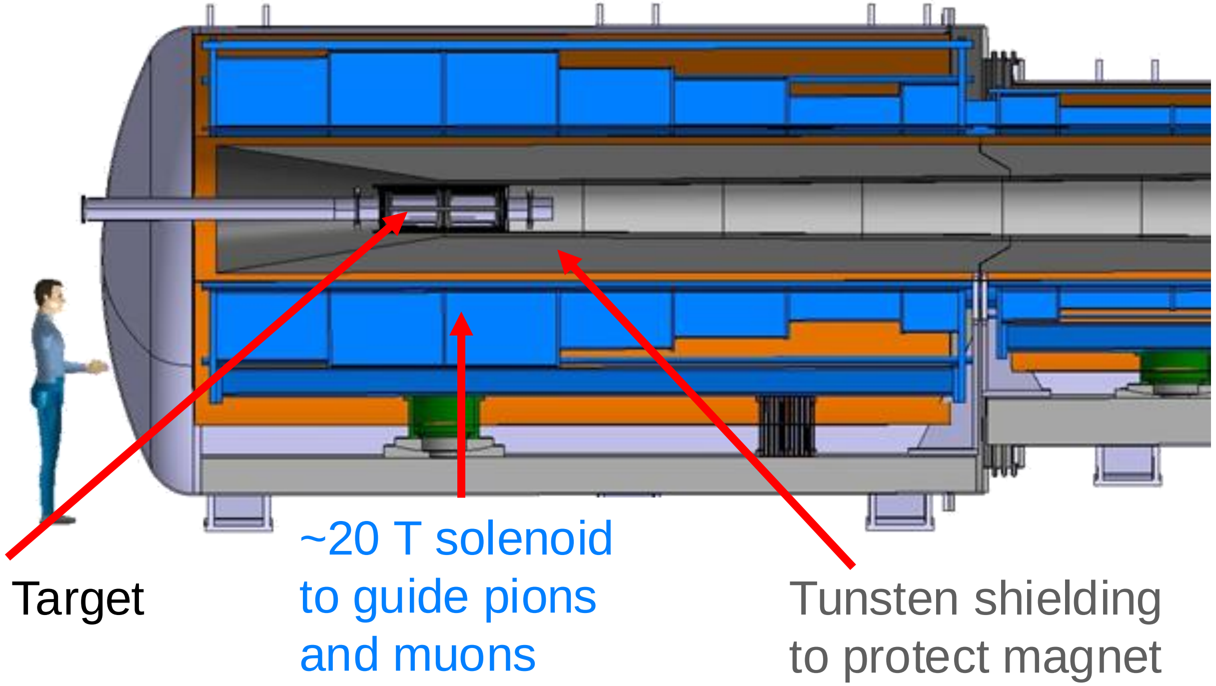


Muon Collider facility overview



4-5 GeV proton beam
400 kJ x 5 Hz = 2 MW

5 x 10^{13} captured muon pairs



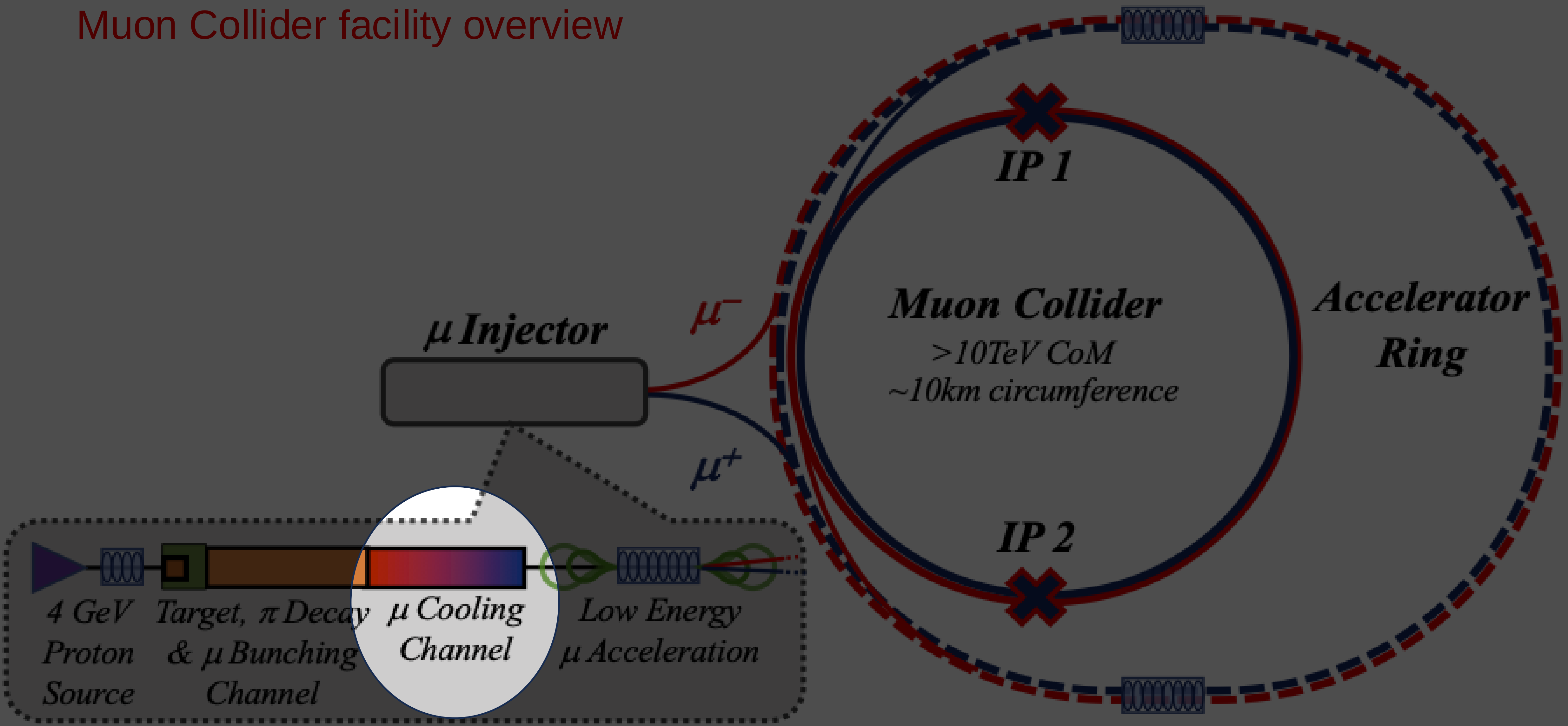
Main R&D

- Investigation of new target materials e.g. liquid target to arrive to 4 MW to have very high intensity muon beam
- 20 T target solenoid design including radiation shielding
- System integration

Synergies with neutrino and neutron facilities

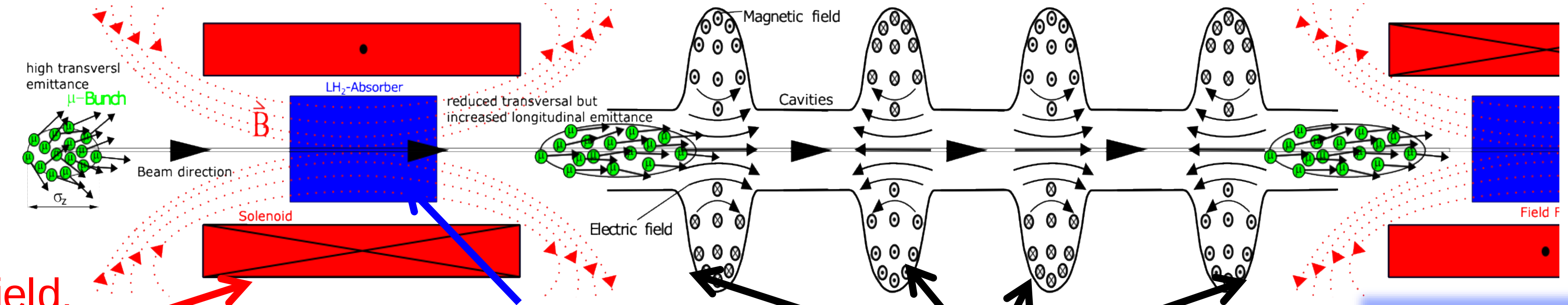
Italian interest and contributions

Muon Collider facility overview



Muon ionization cooling principle

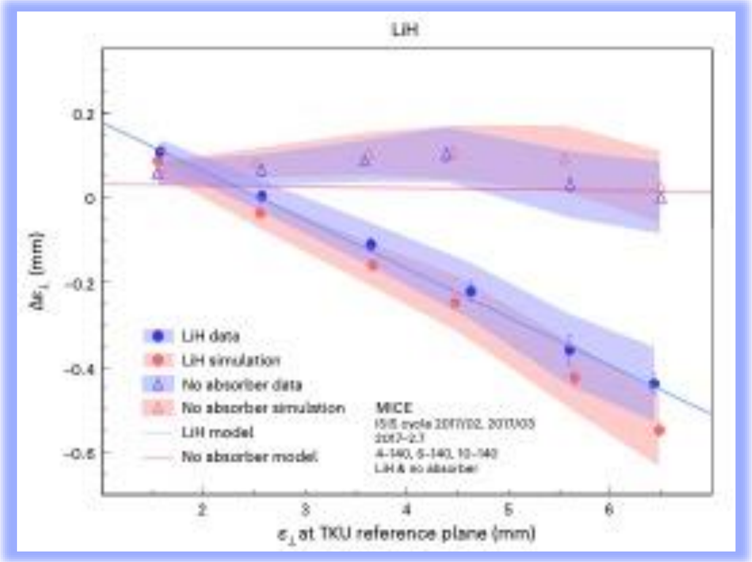
Strong Italian contributions



High-field, superconducting solenoid to minimize multiple scattering effect

Absorbers, Low Z material: Lithium hydride, liquid H

High-gradient normal-conducting RF cavities



Simulation of transverse emittance well reproduced by MICE data

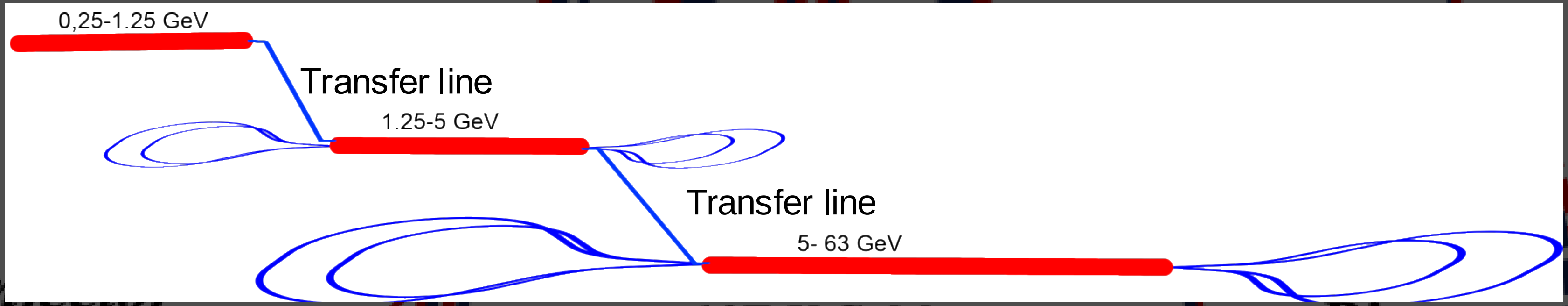
Design and test of the different cells with muon beams one of the core activities of the **muon collider demonstrator program.**

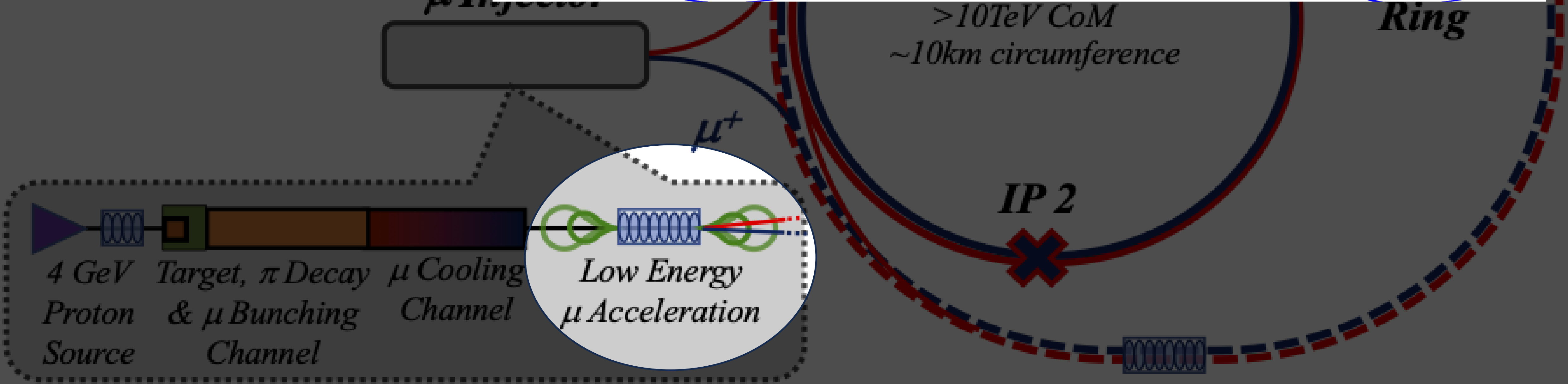
Details on Roberto Losito presentation

Muon Collider facility ov

Rapid acceleration is crucial:

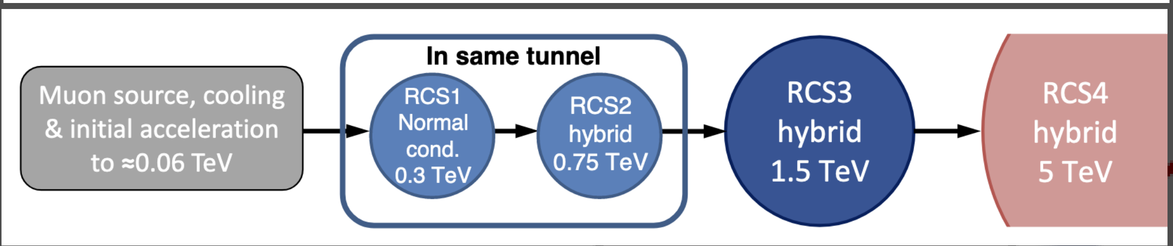
- Linac takes muons at 255 MeV and bring them to 1.25 GeV.
- Two stages of Recirculating Linac, RLA1 from 1.25 GeV to 5 GeV and RLA 2 from 5 GeV to 63 GeV.





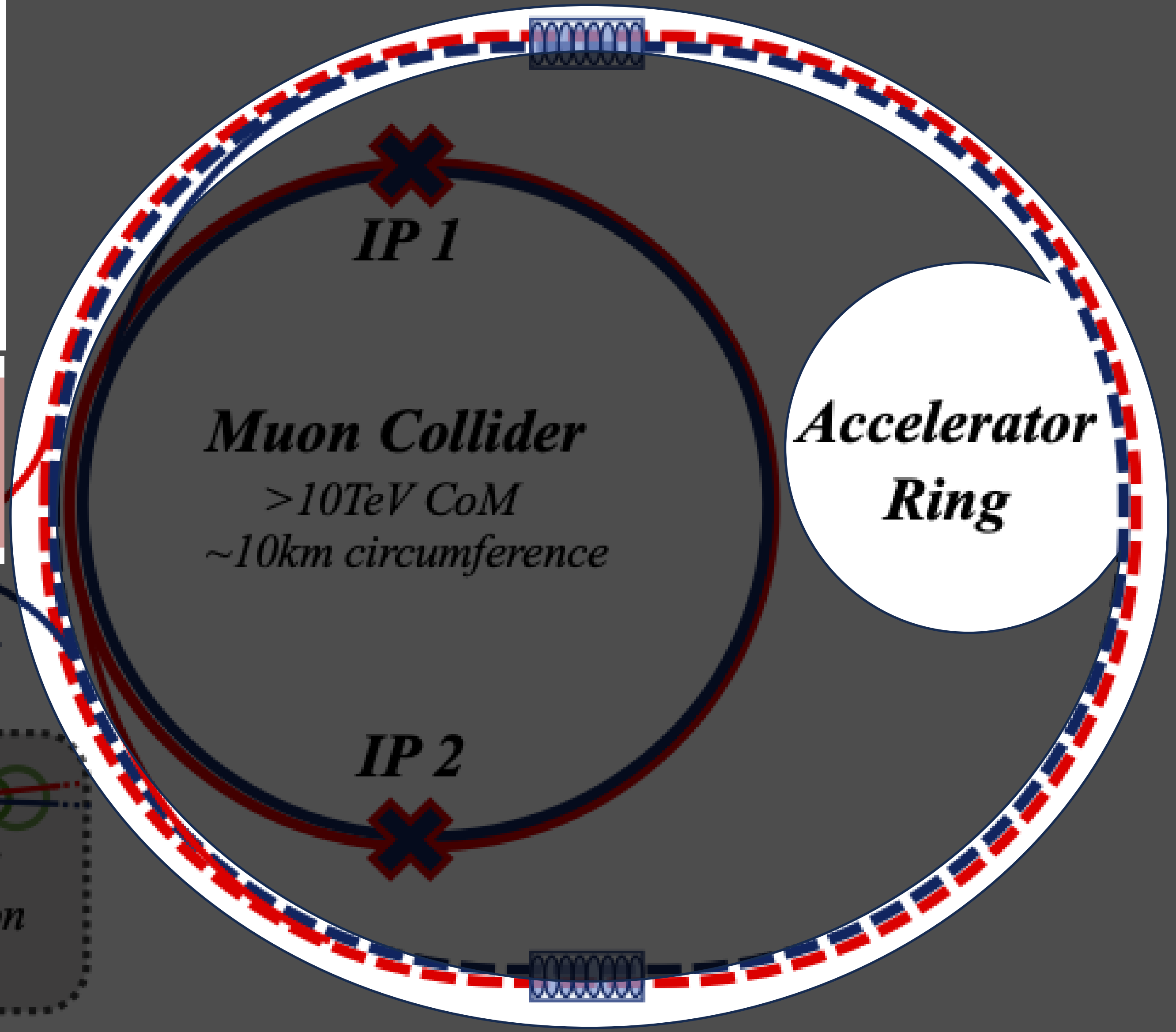
A μ^+ and μ^- bunch must be brought to 5 TeV.
Most promising schema: chain of rapid cycling synchrotrons (RCS) with repetition rate of 5 Hz.
Alternative: Fixed-Field Alternating Gradient.

Survival rate of 90% per RCS required $\longrightarrow$ ultra-fast acceleration, E_{gain} ~10ish GeV per turn.



Study and R&D:

- Magnets
  - hybrid magnets have strong fixed-field, they are superconducting magnets interleaved with normal conducting magnets.
  - shapes of fast ramping magnet and design possible power converter.
- RF: determine the exact frequency

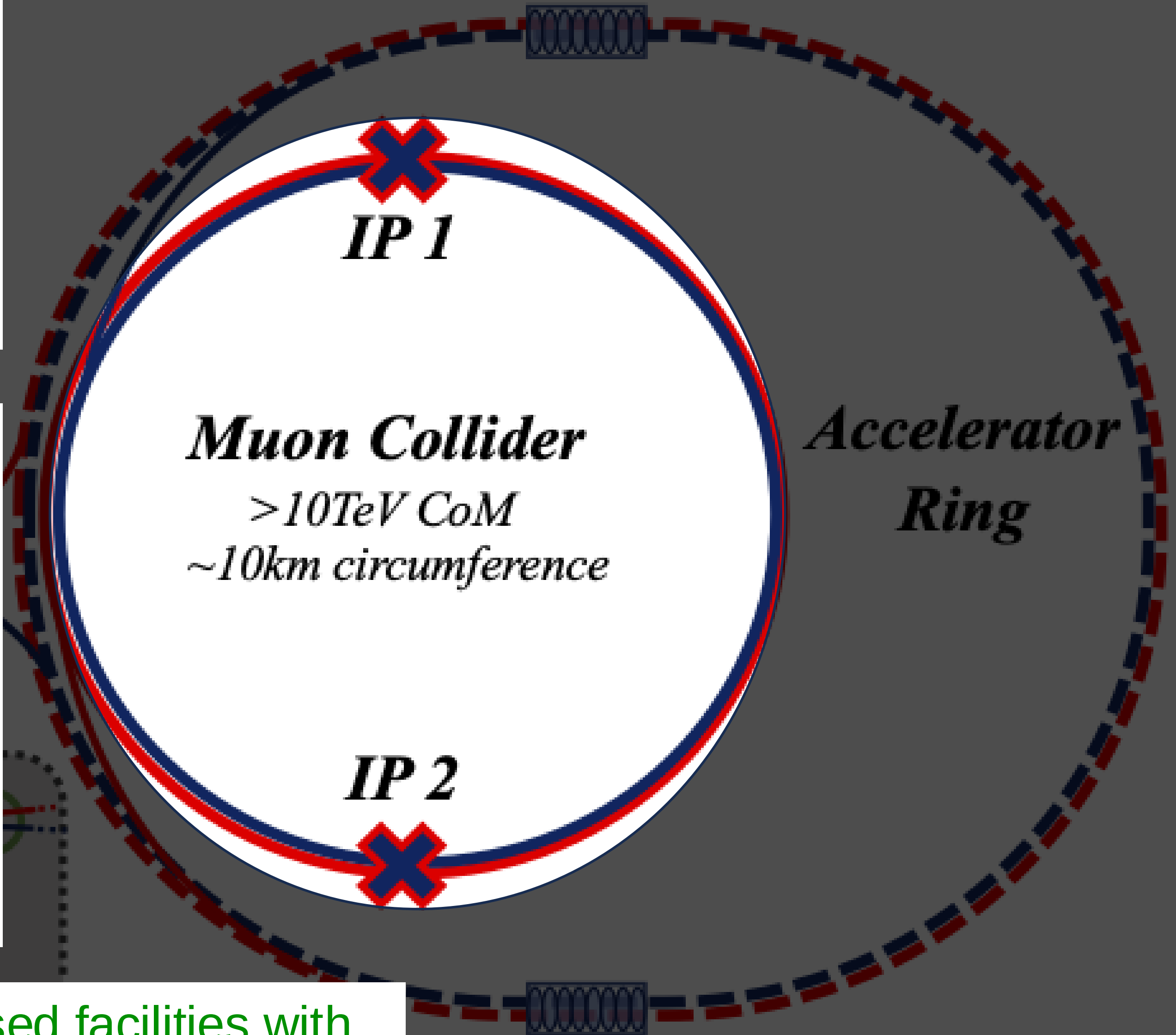


First design of $\sqrt{S} = 10$ TeV collider ring almost complete

Main challenges to have high performance:
- Very small beta-function ~1.5 mm.
- Maintain short bunches.

Magnet: assumed 16 T HTS dipoles or 11 T Nb_3Sn.
Final focus based on HTS.

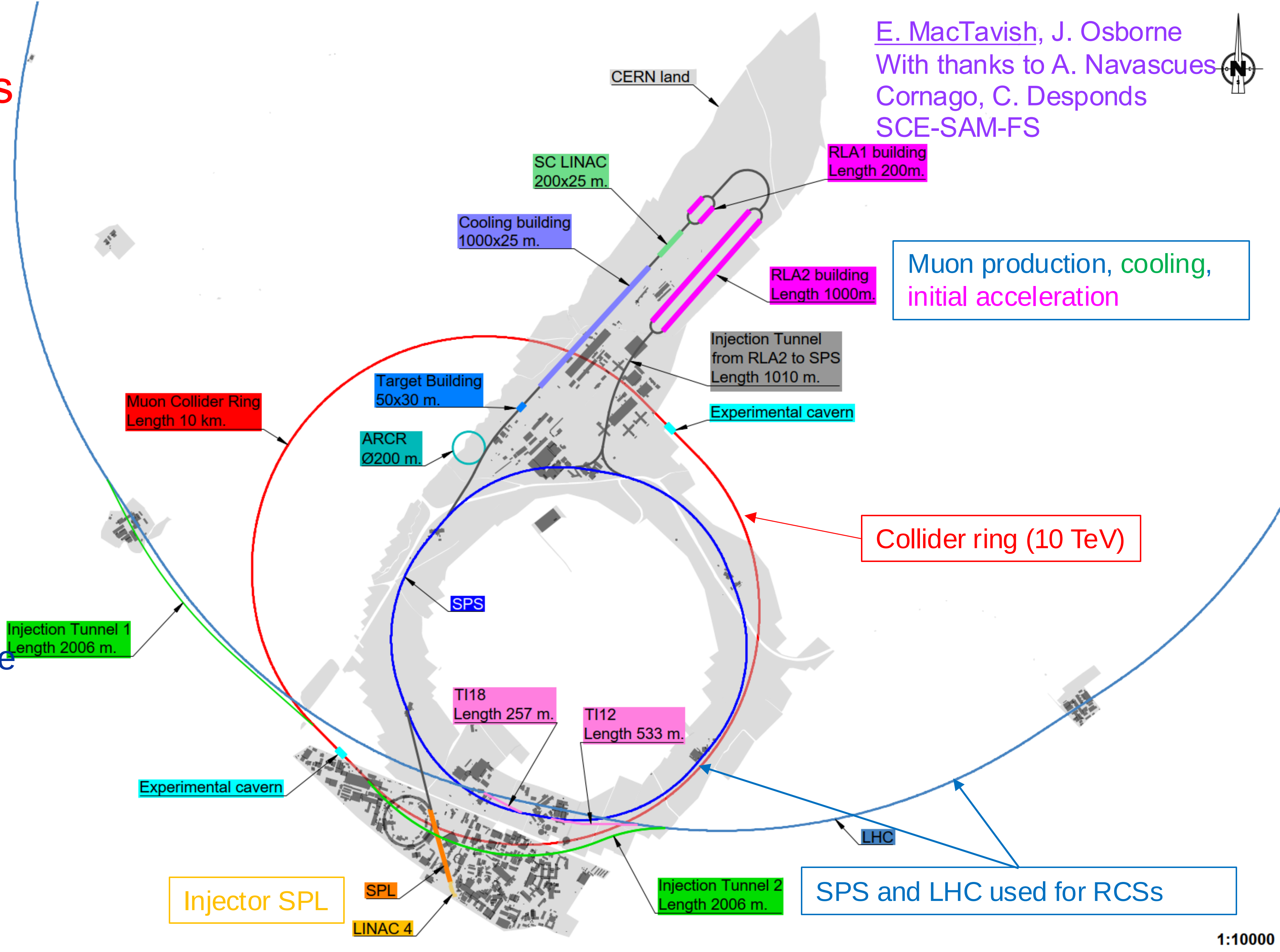
Study and R&D
- Study magnet limitations
  - stress, protection, etc. against bore diameter vs. magnetic field for different conductor material and temperature.



HTS magnets R&D synergic with others proposed facilities with relevant applications in no HEP activities, for example fusion.

Exploratory Site Studies

- Initiates at LINAC 4
- Integrates existing SPL design
- Transfer to Prevessin via SPS
- Series of Cut & Cover construction on Prevessin Site
- Injection to SPS beneath existing buildings.
- Transfer via TI12 & TI18 into the LHC
- Injection from the LHC into the Collider Ring at equidistant points from the Experimental Cavern



Detector concept for $\sqrt{s}$ = 3 TeV

hadronic calorimeter

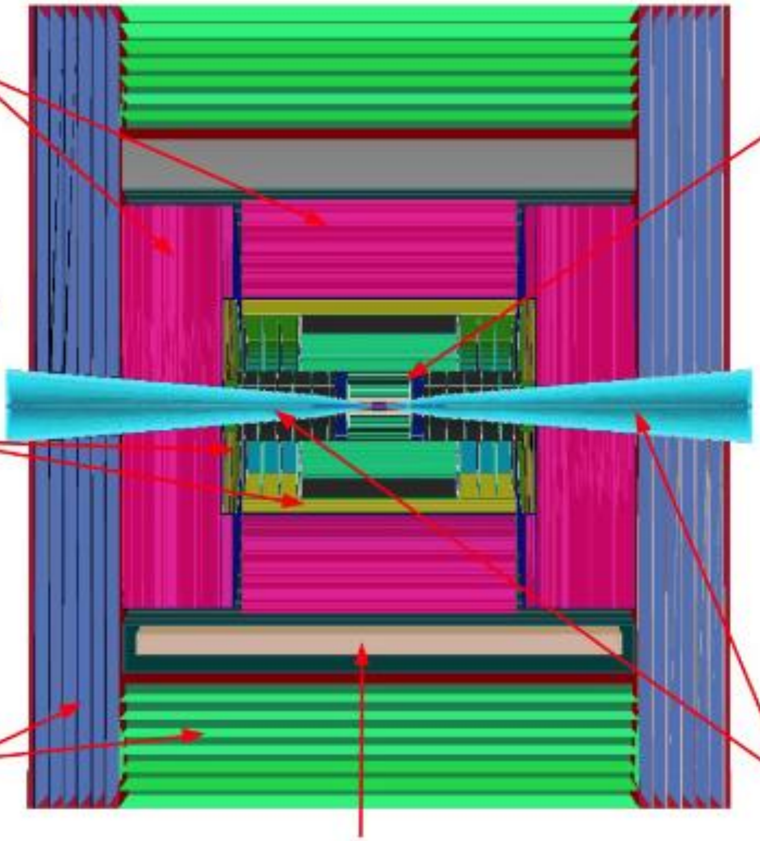
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

electromagnetic calorimeter

- 40 layers of 1.9-mm W absorber + silicon pad sensors;
- 5x5 mm^2 cell granularity;
- 22 X_0 + 1 λ_I.

muon detectors

- 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- 30x30 mm^2 cell size.



superconducting solenoid (3.57T)

tracking system

- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 μm^2 pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 μm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 μm x 10 mm micro-strip Si sensors.

shielding nozzles

- Tungsten cones + borated polyethylene cladding.

- The detector model for 3-TeV studies is based on CLIC's detector concept + the MDI and the vertex detector designed by the US Muon Accelerator Program (MAP).
- The simulation and reconstruction software is derived from CLIC's iLCSoft (transition to the Key4hep framework in progress)
  → github.com/MuonColliderSoft.
- The propagation of the BIB particles in the detector and their interactions with the detector materials are handled by GEANT4.

The following full-simulation detector studies with BIB focus on $\sqrt{s}$ = 3 TeV, but the findings and results also apply to the 10 TeV case because of the similarity in the BIB characteristics.

Preparation of the INFN Input to the ESPPU

- **Kick-off meeting** of the INFN community on **6 and 7 May 2024,** Rome, Centro Congressi Frentani:
  - **strong support for the FCC-integrated project**
  - support for R&D for future innovating particle colliders
- A **Working Group,** coordinated by a **Steering Committee,** was established to foster the contribution of the INFN community to the preparation of the Input to be submitted to the ESPPU (by 31/03/2025)
- **Wrap-up meeting** today (4 February 2025) – Milano Bicocca University/INFN
  - Presentations of the work & documents produced by the WGs.
    - Several of these documents will be submitted to the Strategy along with the National Input

Organisation

Working group：

- Presidents of Scientific Committees
- Directors of National Labs
- Chair of the INFN Machine Advisory Committee (MAC) + Chair of the INFN-Acceleratori
- Chair of the Computing Committee (C3SN)
    - representatives of the INFN Communications Office
- **Steering Group:** C. Borca **(ECR)** , M. Ciuchini, S. Malvezzi, A. Nisati, R. Tenchini

- Various meetings in INFN units and labs
- Some initiatives/workshops organized by theorists
- Two dedicated ECR events (see Cecilia's talk)